APPENDIX H

PANEL MEMBER DETAILED PIRT SUBMITTALS FOR TRISO FUEL DESIGN

The INEEL submittal is provided in Appendix H.1 (pages H-2 through H-24).

The ORNL submittal is provided in Appendix H.2 (pages H-25 through H-48).

The SNL submittal is provided in Appendix H.3 (pages H-49 through H-71).

Appendix H.1

Detailed PIRT Submittal by the INEEL Panel Member

D. A. Petti

TRISO Fuel PIRT: Design

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Fuel Element	Specification of material properties
	Matrix material specification (common)	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 7	Remedy:
Rationale: The matrix material must provide protection for the coated particles during compaction or pressing of the pebble. Specifications for previous German and US are fairly well known. Specifications are placed on the properties of the pitch, and filler grades, matrix additives, filler crystallite sizes, and filler or shim particle sizes. The overall matrix composition is also generally specified. Unclear what the future material will be given a different supply of graphitic material.	Rationale: Knowledge is based heavily on experience from Ft. St. Vrain for US historical compacts and AVR and THTR for pebbles.	Closure Criterion:

Additional Discussion

See the following report for examples of specifications and rationale for historical US compacts

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

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Fuel Element	Volume fraction of particles in fuel zone
	Particle packing fraction (common)	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 8	Remedy:
Rationale: Packing fraction differs in the pebble bed and prismatic gas reactors. In the pebble bed, the fuel pebble packing fraction is small (~ 10-15%). In prismatic design, the fuel compacts have packing fractions ranging from 35 to 50%. The packing fraction determines the power generated in the fuel element, which influences temperature gradients in the fuel element. Some fuel failure mechanisms and the transport of some fission products are strong functions of the temperature gradient across the fuel body.	Rationale: Irradiation performance of pebbles versus compacts has been linked to the level of acceleration in the irradiation and the power in the fuel body (which is sometimes translated into a power per particle). Generally, it is felt that the low packing fraction of particles in pebbles contributes to their superior performance. The higher packing fraction in prismatic fuel compacts can put the particles at greater risk for failure and fission product release under irradiation because of the impact on power generation in the fuel body and the induced temperature gradients. See reference below for details of irradiation performance review.	Closure Criterion:

Additional Discussion

See for example

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

Life Cycle Phase	**Factor, Characteristic or Phenomenon**	**Definition**
Design	Fuel Element	Unconfined heavy metal outside SiC layer (common)
	Unconfined heavy metal outside SiC layer (common)	

Importance Rank and Rationale	**Knowledge Level and Rationale**	**Remedy for Inadequate Knowledge/Issue Closure Criteria**
Rank: H	Level: 9	Remedy:
Rationale: The unconfined heavy metal outside the SiC layer consists of the tramp uranium in the matrix material, any tramp uranium picked up by the particles in the coaters and fabrication process and any initially failed or defective particles produced during manufacture. Specifications limit the amount of unconfined heavy metal from both sources in the US; they are a combined specification in German pebble fuel.	Rationale: Burn leach testing is used as a QA technique to establish this value on each batch or lot of fuel produced.	Closure Criterion:

Additional Discussion

Values for the German and US fuel specification and values actually achieved in manufacture can be found in

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

The technical basis for the US values can be found in

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

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Fuel Element	The degree of homogeneity of the particles in the fuel element
	Particle distribution in fuel element	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 7	Remedy:
Rationale: Inhomogeneities can in principle lead to hot spots. There is a specification on homogeneity for compacts (see ref 1).	Rationale: The large overcoating in pebble fuel makes the particles tend to clump when the final matrix material is applied. The overcoating and final matrix material is applied in a rotating drum to ensure uniformity. In the compact fuel, graphite shim is added to the coated particles to ensure a uniform mixture in the mold before the liquid matrix material is injected.	Closure Criterion:

Additional Discussion

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

Life Cycle Phase	**Factor, Characteristic or Phenomenon**	**Definition**
Design	Fuel Element	Unfueled carbonaceous layer on outside of pebble
	Fuel free zone (Pebble)	

Importance Rank and Rationale	**Knowledge Level and Rationale**	**Remedy for Inadequate Knowledge/Issue Closure Criteria**
Rank: M	Level: 7	Remedy:
Rationale: The fuel free zone in pebbles helps protect the fuel pebble from abrasion during its transit through the reactor. The fuel free zone absorbs any mechanical shock upon contact with other pebbles or metal and graphitic surfaces during transport of the pebble.	Rationale: The fuel free zone can hold up fission products. Diffusion of fission products in the matrix material has been measured. See reference below.	Closure Criterion:

Additional Discussion

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

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Fuel Element	Layer on outside of outer PyC added after coating
	Particle overcoat (pebble)	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 8	Remedy:
Rationale: 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 condittions	Rationale: The use of the overcoat reduces the number of particles that were broken during the manufacturing process.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Outer PyC layer	Layer thickness and its standard deviation
	Thickness	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 8	Remedy:
Rationale: The OPyC layer is primarily used to provide a compressive stress to the SiC layer under irradiation. (The PyC layers shrinkage under fast neutron irradiation). The OPyC layer will retain fission gases but not fission metals like Cs, Ag and Pd. It plays a moderate role in the structural integrity of the particle based on recent fuel performance model assessments (see ref 1 below). The rationale for the thickness is found in ref 2 below.	Rationale: It's thickness and standard deviation are very well characterized in the fabrication process. Examples of typical specifications and values achieved during manufacturing are in reference 3 and 4 below.	Closure Criterion:

Additional Discussion

1. G. K. Miller et al., "Statistical Approach and Benchmarking for Modeling of Multi-dimensional Behavior in TRISO-coated Fuel Particles," J. Nuclear Materials, forthcoming

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

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

4. 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
Design	Outer PyC layer	Mass per unit volume
	Density	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 9	Remedy:
Rationale: The density of the OPyC layer is an important variable in describing the shrinkage of the layer. If the density is too high then the shrinkage is too great. If the density is too low then for US compacts, too much of the liquid matrix material can infiltrate the layer, causing it to fail under irradiation due to matrix shrinkage. Shrinkage rates as a function of temperature, density, and anisotropy are found in Ref. 1. The rationale for the specification for US compacts is found in Ref. 2.	Rationale: Density is easily measured and controlled during fabrication. See reference 3 and 4 for typical values.	Closure Criterion:

Additional Discussion

1. CEGA, 1993, *NP-MHTGR, Material Models of Pyrocarbon and Pyrolytic Silicon Carbide Report,* CEGA-002820.

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

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

4. 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**
Design	SiC Layer	Layer thickness and its standard deviation
	Thickness	

Importance Rank and Rationale	**Knowledge Level and Rationale**	**Remedy for Inadequate Knowledge/Issue Closure Criteria**
Rank: H	Level: 9	Remedy:
Rationale: The thickness of the SiC layer is important in structural integrity of the particle (see ref 1) and determines the ability of fission products to escape the particle. (The thicker the layer, the harder it is for diffusing fission products to escape or "attacking" fission product like Pd to completely traverse the SiC layer under design service conditions.) Many fission product models scale with the thickness of the layer. (see ref 2) the basis for the thickness is found in ref 3.	Rationale: The thickness and standard deviation is measured routinely with high accuracy. (see references 4 and 5)	Closure Criterion:

<u>Additional Discussion</u>

1. G. K. Miller et al., "Statistical Approach and Benchmarking for Modeling of Multi-dimensional Behavior in TRISO-coated Fuel Particles," J. Nuclear Materials, forthcoming

2. R. C. Martin, "Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design," ORNL/NPR-91/6, Oct. 1993.

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

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

5. 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
Design	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: 9	Remedy:
Rationale: Density is important to obtaining the proper strength of the SiC and ensuring there is not significant porosity that would allow fission products to be released. The diffusivity of metallic fission products is a function of the density. The technical basis for the density is found in Ref. 1.	Rationale: Density is measured routinely and is within specification. Coating temperature and MTS/H2 ratios are used to control the density during fabrication. Typical values are found in References 2 and 3.	Closure Criterion:

Additional Discussion

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

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

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**
Design	Inner PyC layer	Layer thickness and its standard deviation
	Thickness	

Importance Rank and Rationale	**Knowledge Level and Rationale**	**Remedy for Inadequate Knowledge/Issue Closure Criteria**
Rank: H	Level: 9	Remedy:
Rationale: The IPyC serves two major functions: (a) to protect the kernel from Cl attack during MTS decomposition during SiC layer formation and (b) to provide compression to the SiC layer during its shrinkage under irradiation. Both are very important. Mechanical modeling of the coated fuel particle suggests that the thickness is very important to the stress that could develop in the SiC layer were the IPyC to crack under irradiation (see references 1 and 2). The technical basis for the IPyC thickness for US fuel is found in Reference 3. In th NP-MHTR fuel, the thickness was set too high (~ 53 microns instead of the traditional 35 microns) to provide protection from Cl attack of the kernel. This had a deleterious effect on the overall in-pile performance under irradiation. (see ref. 4 and 5)	Rationale: The layer thickness is easy to characterize and meets specifications during manufacture (see Ref 5 and 6).	Closure Criterion:

Additional Discussion

1. G. K. Miller et al., “Statistical Approach and Benchmarking for Modeling of Multi-dimensional Behavior in TRISO-coated Fuel Particles,” J. Nuclear Materials, forthcoming
2. 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.
3. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992
4. D. A. Petti et al., “Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance,” INEEL/EXT-02-00300, June 2002.
5. B. J. Leikind et al., “MHTGR TRISO-P Fuel Failure Evaluation Report,” DOE-HTGR-90390, Oct. 1993.
6. 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
Design	Inner PyC layer	Mass per unit volume
	Density	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 9	Remedy:
Rationale: The density of the IPyC layer is an important variable in describing the shrinkage of the layer. If the density is too high then the shrinkage is too great. If the density is too low then the Cl from the MTS decomposition during CVD of the SiC layer can infiltrate the layer and attack the uranium kernel causing the production of uranium chloride. All of this can lead to excessive heavy metal dispersion in the TRISO coating. Shrinkage rates as a function of temperature, density, and anisotropy are found in Ref. 1. The rationale for the specification for US compacts is found in Ref. 2.	Rationale: Density is easily measured and controlled during fabrication. See reference 3 and 4 for typical values.	Closure Criterion:

Additional Discussion

1. CEGA, 1993, *NP-MHTGR, Material Models of Pyrocarbon and Pyrolytic Silicon Carbide Report,* CEGA-002820.

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

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

4. 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**
Design	Buffer Layer	Layer thickness and its standard deviation
	Thickness	

Importance Rank and Rationale	**Knowledge Level and Rationale**	**Remedy for Inadequate Knowledge/Issue Closure Criteria**
Rank: H	Level: 9	Remedy:
Rationale: The buffer layer provides two functions: to accommodate fission recoils and fuel kernel swelling and to provide voidage to accommodate fission gas and CO (UO2 only) release from the kernel with burnup. Thus the buffer thickness and density determine the void volume and hence the pressure loading on the TRISO coating of the fuel particle. Because of its importance in pressure loading, there is a specification to limit the number of particles with very thin or missing buffers to limit pressure vessel failure of the particles. See reference 1 for technical basis for historic US fuel.	Rationale: The thickness is easily measured and is well within specification. See references 2 and 3 for typical values	Closure Criterion:

<u>Additional Discussion</u>

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

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

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**
Design	Buffer Layer	Mass per unit volume
	Density	

Importance Rank and Rationale	**Knowledge Level and Rationale**	**Remedy for Inadequate Knowledge/Issue Closure Criteria**
Rank: L	Level: 9	Remedy:
Rationale: The exact density of the buffer is not a critical parameter. Given its function (i.e., to accommodate fission recoils and fuel kernel swelling and to provide voidage to accommodate fission gas and CO (UO_2 only) release from the kernel with burnup) a low-density material is required. It is usually about 50% theoretical density but in principal could probably be somewhat more or less and still be accommodated in the design. The technical basis is found in Ref. 1	Rationale: Well known and measured. See reference 2 and 3 for typical values.	Closure Criterion:

Additional Discussion

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

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

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
Design	Kernel	Design diameter with standard deviation
	Diameter	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 7	Remedy:
Rationale: Different kernel diameters have been used historically. Small kernels have been specified for HEU systems with larger kernels for LEU systems. Fertile particles also have a different size. (In most recent actinide burning scenarios of MHTGRs, the kernel size is set to optimize self shielding of the fuel) The size determines the moles of fission gases produced and the number of moles of non-gaseous fission products produced. Structurally, the size of the kernel has less importance than other factors in the stress developed in the coatings. The buffer volume is sized to accommodate changes in kernel size	Rationale: There has never been any definitive proof that satisfactory performance depends on the size of the kernel. Different size kernels have been made to appropriate specifications.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Kernel	Mass per unit volume
	Density	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 9	Remedy:
Rationale: The density of the kernel is less important from a performance standpoint, especially for fuel that will be irradiated to high burnup. High density kernels will initially retain fission gases and non-gaseous fission products better than low density kernels. However, the high burnups proposed for current designs will essentially destroy the structure of the kernel making the density less important in terms of fission product release. In the US both high and low density (so called WAR kernels) were tested. (see ref 1). The rationale for the kernels used in the NP-MHTGR is found in reference 2.	Rationale: Kernels made with sol-gel process are typically 95% theoretical density. The density is easily controlled and measured to be within the given specifications. Typical values are found in references 1 and 3.	Closure Criterion:

Additional Discussion

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

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
Design	Kernel	Maximum and minimum axis lengths of particles
	Sphericity (max/min diameter)	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 7	Remedy:
Rationale: The lack of sphericity in particles has been looked at as a cause for particle failure (and hence fission product release). Structural calculations suggest that the effect is moderate for typical sphericities encountered in fabrication. (see ref 1). Tabling techniques are used to separate the most out of round particles both the kernel stage and the final coated product stage. (see ref 2) in addition, there are numerous photomicrographs of irradiated fuel with slight asphericity that have remained intact following irradiation and/or accident heating tests.	Rationale: Sphericity is measured during fabrication and techniques are used (tabling) to remove out of spec kernels. See reference 2 for values of as-manufactured sphericities.	Closure Criterion:

Additional Discussion

1. G. K. Miller and D.C. Wadsworth, “Treating Asphericity in Fuel Particle Pressure Vessel Modeling,” Journal of Nuclear Materials, Vol. 211, pp 57-69, 1994.

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

Life Cycle Phase	**Factor, Characteristic or Phenomenon**	**Definition**
Design	Kernel	Oxygen to uranium atomic ratio for UO_2 fuel
	Stoichiometry: Uranium to oxygen	

Importance Rank and Rationale	**Knowledge Level and Rationale**	**Remedy for Inadequate Knowledge/Issue Closure Criteria**
Rank: H	Level: 8	Remedy:
Rationale: The O/U ratio determines the oxygen potential in the fuel, which in turn determines the chemical forms and mobility of key fission products in the fuel. See ref. 1	Rationale: The value is measured and specifications are used to ensure an acceptable O/U ratio. Typical values for German UO_2 are found in reference 2.	Closure Criterion:

Additional Discussion

1. D. Olander, “Fundamental Aspects of Nuclear Reactor Fuel Elements,” ID-26711-P1, 1976.

2. 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
Design	Kernel	Oxygen:carbon:uranium ratio for UCO
	Stoichiometry: Uranium to carbon and uranium to oxygen	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy: Measurements of oxide and carbide phases must be performed at the particle level to ensure that the values at a particle level are acceptable relative to the batch average specification values currently in use.
Rationale: The O/U and C/U ratios determine the stoichiometry of UCO fuel. The purpose of UCO fuel is to add enough UC_2 to prevent formation of CO during operation. The UC_2 acts as a buffer to prevent any free oxygen released during fission from reacting with carbon in the buffer to produce CO. If too much UC_2 is added then rare earth fission products will form carbides that are too mobile under off-normal conditions. There is a specification to ensure the proper amount of oxygen and carbon in the kernel to get the fission product chemistry correct. The overall theory is discussed in References 1 and 2. The technical basis for the specification is found in reference 3.	Rationale: The values are measured on a batch basis. There is some concern that at the individual particle level the ratios could be different but would still meet the batch average values. (For example, you could mix in appropriate proportions UO_2 kernels and UC_2 kernels and still meet the specification but the performance would be unacceptable.) At the high burnups envisioned for GT-MHR, an oxide-rich particle or a carbide rich particle could fail under either irradiation or high temperature accident conditions. Typical specification values are found in Reference 4 and 5. Information on particle specific values from studies conducted during the NPR program is found in Reference 6.	Closure Criterion:

Additional Discussion

1. Homan, F.J., et al., 1977, “Stoichiometric Effects on Performance of High-Temperature Gas-Cooled Reactor Fuels from the U-C-O System,” *Nuclear Technology,* Vol. 35, pp. 428-441.
2. McCardell, R.K., et al., 1992, *NP-MHTGR Fuel Development Program Plan*. Idaho National Engineering Laboratory, Report EGG-NPR-8971 (Revision C).
3. NP-MHTGR Fuel Product Specification Basis Report, CEGA-000396, June 1992
4. Bryan, M.F., 1992, *Evaluation of NP-MHTGR Performance Test Fuel Quality Control Data*, INEEL. Report EGG-NPR-10130.

5. D. A. Petti et al., “Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance,” INEEL/EXT-02-00300, June 2002
6. 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
Design	Kernel	Elemental constituents and amounts other than design
	Purity	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 7	Remedy:
Rationale: Impurities in the kernel can potentially migrate during irradiation and pose a threat to the SiC. There are certain elements that can reduce SiC chemically, especially the transition elements. The rationale behind the impurity limits for US fuel is found in reference 1. (Note impurities from other parts of the fabrication process may be more important).	Rationale: The elemental limits have been established and are easy to control in fabrication. These elements have not been found to be a serious problem related to particle failure and fission product release from this fuel. Values of the limits and manufacturing values are found in Reference 2 and 3.	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.
3. D. A. Petti et al., “Key Differences in the Fabrication, Irradiation, and Safety Testing of U.S. and German TRISO-coated Particle Fuel and Their Implications on Fuel Performance,” INEEL/EXT-02-00300, June 2002

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Kernel	Weight fraction U-235 in total uranium
	Enrichment	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 9	Remedy:
Rationale: Enrichment is very well known in the particles. It determines the ultimate burnup that can be achieved given reactor constraints relative to reactivity etc. The enrichment determines the fission rate, which is of secondary importance in some fission gas release models at low temperature. (see Reference 1). However this effect is rather small compared to the effects of burnup and temperature on fission gas release	Rationale: Is easily measured and meets the specification with high precision.	Closure Criterion:

Additional Discussion

W. K. Terry (editor) "Modular Pebble-Bed Reactor Project: Laboratory Directed Research and Development Program FY-2001 Annual Report," INEEL/EXT-2001-1623, December 2001.

Appendix H.2

Detailed PIRT Submittal by the ORNL Panel Member

R. Morris

TRISO Fuel PIRT: Design

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Fuel Element	Specification of material properties
	Matrix material specification (common)	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy: Investigate the key aspects of fuel element formation and irradiation behavior if new materials and methods are introduced.
Rationale: The matrix binds the particles together and serves as a structural and heat transfer medium. Many carbon materials dimensionally change under processing and unirradiation and these changes can affect the fuel performance. In addition, impurities and fuel element processing can damage particles.	Rationale: Scores of fuel compacts and pebbles have been made with generally good results, especially in the case of pebbles. However, in some cases a switch in the matrix material from petroleum pitch to thermosetting resin is under consideration. Less is known about this resin in the case of compacts, although no deleterious behavior is anticipated.	Closure Criterion: Generate data that shows fuel particles are not damaged by the resin during fuel element formation and satisfactory irradiation performance results.

Additional Discussion

The German pebble bed technology has used a thermosetting resin for pebble fabrication while the US has used a petroleum pitch. Early experience at GA has shown that if a resin is substituted for pitch in the injected molded compact the particle matrix bond is too strong and coatings can be damaged as the matrix shrinks during subsequent processing. This interaction does not take place in the pebble because of the lower amounts of binder material. The US examined the compacting issue in the 1990's and will revisit this issue during the upcoming work on the GT-MHR. Thermosetting resins have some process advantages. Modest changes to the compacting process are expected to resolve this issue.

For a past comparison (1984) of German and US fuel systems see:

Review of Pebble Bed HTGR Fuel and Graphite Technology for Potential Application in the US, GA Document Number 907634.

For a description of the German fuel system see:

Status of Qualification of High-Temperature Reactor Fuel Element Spheres, Nuclear Technology, W. Heit, et. al., 69 (1985), page 44.

Spherical Fuel Elements for Advanced HTR Manufacture and Qualification by Irradiation Testing, A. W. Mehner, et.al., Journal of Nuclear Materials, 171 (1990), pages 1-18.

Long Time Experience with the Development of HTR fuel Elements in Germany, Nuclear Engineering and Design, H. Nickel, et. al., 217 (2002), pages 141-151.

A recent reference (1994) containing much useful background material on the subject of fuel element fabrication is:

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

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Fuel Element	Volume fraction of particles in fuel zone
	Particle packing fraction (common)	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 7	Remedy: None required at present unless radical changes are made in the process
Rationale: This parameter helps determine the heat production of a fuel element and particle damage during fabrication is more likely at the higher particle loading.	Rationale: This parameter has been investigated to a fair extent over the years. Higher packing fractions (>35%) can result in greater particle breakage if the admixture method is used, limiting the choice to the injection method.	Closure Criterion: Satisfactory irradiation and accident performance.

Additional Discussion

Over the years, two main methods have been used for fabricating fuel elements. The first involved the use of a binder with high filler content. The particles were overcoated with a mixture of binder/filler and then pressed together with additional binder/filler (admixture compaction) to form the green fuel element. This method has advantages with respect to element shrinkage during both sequent process and irradiation. A disadvantage is that it is limited to a particle packing fraction of about 35%. An injection method can be used to achieve a higher packing fraction of about 60%. The particles and any shim are placed into a mold and a hot fluid pitch is injected under pressure into the mold. The disadvantage is that the pitch mixture has a lower filler content and the compact matrix has a higher shrinkage, which tends to show up as mircocracks and increased matrix porosity.

Volume packing fraction differences are a direct result of the smaller volume fraction available for fuel in the prismatic designs versus the pebble designs. Higher reactivity fuel such as plutonium may reduce the required packing fraction and allow the admix process to be used for the GT-MHR.

For excellent source of background material (some 15 different fuel element methods have been used) on the subject see:

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

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Fuel Element	Unconfined heavy metal outside SiC layer (common)
	Unconfined heavy metal outside SiC layer (common)	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 8	Remedy: None
Rationale: Unconfined heavy metal results in fission products in the primary circuit and potential for releases under accident conditions as well as possible maintenance concerns.	Rationale: Tests are available (burn-leach, HCl-leach, carbon analysis, TRIGA irradiation) that can detect low levels of U contamination. These tests are routinely done during fabrication.	Closure Criterion: None

Additional Discussion

Unconfined heavy metal can come from several sources. Some sources are: defective particles, particles broken during green fuel element fabrication, particles damaged during heat treatment of the green fuel element, and matrix/resin U impurities. Some of this U can be removed from fuel elements by leaching with hot HCl.

For a general discussion of the fuel fabrication and SiC defect issues 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

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

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Fuel Element	The degree of homogeneity of the particles in the fuel element
	Particle distribution in fuel element	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 8	Remedy: None
Rationale: Inhomogeneous particle distribution within fuel elements can result in hot spots and possible fuel damage. Also, particles touching each other could result in damage.	Rationale: Fuel particle distribution can and has been investigated by X-ray scans, sectioning, plane-by-plane deconsolidation, and gamma scanning. Inhomogeneous packing and clustering is fairly easy to see.	Closure Criterion: None

Additional Discussion

For compact type elements uranium fuel homogeneity can be determined by gamma counting both halves of a fuel compact at the green stage. The relative spectrums or counts can be compared to each other and the relative loading determined. Similar methods can be used for other fuel types. Sectioning provides information, but is destructive. Uranium shows up well against the carbon background for X-ray analysis. Since there have been considerable developments both in gamma spectrometry and X-rays analysis, it is likely that an evaluation of the two techniques will be done before a new fuel facility is built.

For historical (1988) general QA issues see:

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

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Fuel Element	Unfueled carbonaceous layer on outside of pebble
	Fuel free zone (Pebble)	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 8	Remedy: None
Rationale: The fuel pebble requires a fairly strong outer layer to shield the inner-fueled region from damage as the pebble is dropped several meters during its transient into the reactor.	Rationale: The Germans have studied this layer extensively and have had few failures with their high quality material.	Closure Criterion: None

Additional Discussion

The pebble is unique in that it is required to withstand being dropped from a height of several meters. Now only does it need a hard outer layer to withstand this impact, the outer layer must be tightly bound to the fuelled region to insure integrity of the pebble and good heat transfer throughout the life of the pebble.

For a description of pebble fabrication history see:

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

For a description of the German pebble manufacturing process see:

Fuel Elements for the High Temperature Pebble Bed Reactor, L. Wolf, et. al., Nuclear Engineering and Design, 34, (1975), pages 93-108

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Fuel Element	Layer on outside of outer PyC added after coating
	Particle overcoat (pebble)	

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. 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
Design	Outer PyC layer	Layer thickness and its standard deviation
	Thickness	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 8	Remedy: None needed for these dimensional parameters
Rationale: This layer performs a structural function during irradiation by placing a compressive force on the SiC layer.	Rationale: The layer thickness and its standard deviation can be fairly easily measured. The major uncertainties are in the material properties.	Closure Criterion: None.

Additional Discussion

According to the fuel models, the outer PyC functions as an important load-bearing component of the fuel particle. The major uncertainties associated with the layer come from material properties and not dimensional uncertainties.

Over the years there have been many, many papers and models published for HTGR fuel performance. A simple model to gain a conceptual understanding is:

Considerations Pertaining to the Achievement of High Burn-ups in HTR Fuel, D.G. Martin, Nuclear Engineering and Design, 213 (2002), pages 241-258

Also see (useful primer, but dated on fission product release):

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

A very short list of historical model references is:

A Mathematical Model for Calculating Stresses in a Pyrocarbon and Silicon Carbide Coated Fuel Particle, J. KAAE, Journal of Nuclear Materials, 29 (1969), page 249

Evaluation of High Temperature Gas Cooled Reactor Fuel Particle Coating Failure Models and Data, Tokar, NUREG-0111

An Explicit Solution for Stresses in Pyrocarbon-Coated Fuel Particles, Stevens, D.W., Nuclear Technology, 10, page 301

Improvement of a Method for Predicting Failure Rates of Coated Particles During Irradiation, Bongartz, K., Nuclear Technology, 35, page 379

A Mathematical Model for Calculating Stresses in a Four-Layer Carbon-Silicon-Carbide-Coated Fuel Particle, Kaae, J.L., Journal of Nuclear Materials, 32, (1969), page 322.

The Mechanical Design of TRISO-Coated Particle Fuels for the Large HTGR, T.D. Gulden, et. al., Nuclear Technology, 16 (1972), pages 100-109.

The modeling field is becoming active again and recent efforts are to employ much more complex structural and chemical models. Consult the researchers in the field for the most up to date models and theories.

A relatively recent design manual (these specifications may or may not be used in future fuel fabrication) by General Atomics is:

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

A recent review on the performance of pyrocarbon and its effect on fuel performance is:

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.
All these references tend to point to material properties and their uncertainties as the major issues.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Outer PyC layer	Mass per unit volume
	Density	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy: Investigate pyrocarbon properties as a function of irradiation performance. Investigate new methods of characterizing pyrocarbon.
Rationale: The density of the PyC layer is connected to its material properties so it is important to control it.	Rationale: One can measure density fairly well, but the implications of the measurement are not clear. The PyC dimensionally changes under irradiation and this property is connected to the density among other things. Density can also affect the permeability of the coating. Connecting measurable material properties to pyrocarbon irradiation performance has been difficult and no foolproof method has been found to date.	Closure Criterion: A method or process for verifying pyrocarbon behavior under irradiation. (The German fuel has a defined process.)

Additional Discussion

The pyrocarbon layers have been the most difficult to characterize. The goal of relating measurable properties to irradiation performance has remained elusive leaving process conditions as part of the fuel QA. Density is one parameter, but so are others such as rate of material deposition in the coater. Density alone is not a complete enough specification for design.

For a general review of pyrocarbon fabrication see:

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

For an evaluation of US and German pyrocarbons 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.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	SiC Layer	Layer thickness and its standard deviation
	Thickness	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 8	Remedy: None needed for these dimensional parameters
Rationale: This layer performs a structural function during irradiation and acts as the major fission product barrier.	Rationale: The layer thickness and its standard deviation can be fairly easily measured. The major uncertainties are in the material properties.	Closure Criterion: None

<u>Additional Discussion</u>

The major issues with SiC are material properties rather than dimensions. The manufacturing QA has reached the point that missing and grossly out of specification material is extremely rare. See the pyrocarbon entries for model references and a discussion of past US problems.

Life Cycle Phase	**Factor, Characteristic or Phenomenon**	**Definition**
Design	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: 6	Remedy: Investigate SiC properties as a function of irradiation performance. Investigate new methods of characterizing SiC.
Rationale: The density of the SiC layer is connected to its material properties so it is important to control it.	Rationale: The density measurement is fairly well defined, but it is not sufficient to characterize the material. Density may affect the permeability of the coating to fission products. Connecting measurable material properties to irradiation performance has been difficult and no foolproof method has been found to date.	Closure Criterion: A method or process for verifying SiC behavior under irradiation and accident conditions. (The German fuel has a process.)

Additional Discussion

The density and the grain structure of the SiC help determine the fission product retention ability of this layer. Deposition rates and temperatures determine the final product. See the entries on pyrocarbon for references on design models.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Inner PyC layer	Layer thickness and its standard deviation
	Thickness	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 8	Remedy: None needed for these dimensional parameters
Rationale: This layer performs a structural function during irradiation by placing a compressive force on the SiC layer. The layer also shields the fuel kernel from HCl during fabrication.	Rationale: The layer thickness and its standard deviation can be fairly easily measured. The major uncertainties are in the material properties.	Closure Criterion: None

Additional Discussion

The design models and past US results have shown that the IPyC layer is structurally important. Counter to intuition, too thick of a layer can increase the failure probability by increasing the stresses in the IPyC and those transmitted to the SiC, especially if the layer cracks. See the model references in the pyrocarbon entry, but also see:

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

for some of the issues that arise from a too thick IPyC

Since the IPyC shields the kernel from the HCl produced during SiC coating, a trade off condition is encountered. Thinner, higher porosity IPyC may be desirable for irradiation performance, but thicker, less porous IPyC is desired to limit the attack of the kernel from the HCl. In addition, the reactivity of the kernel is an issue as well.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Inner PyC layer	Mass per unit volume
	Density	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy: Investigate pyrocarbon properties as a function of irradiation performance. Determine the tradeoff between irradiation behavior and kernel attack. Investigate new methods of characterizing pyrocarbon.
Rationale: The density of the PyC layer is connected to its material properties so it is important to control it.	Rationale: One can measure density fairly well, but the implications of the measurement are not clear. The PyC dimensionally changes under irradiation and this property is connected to the density among other things. Density can also affect the permeability of the coating to HCl and thus attack of the kernel during SiC coating. Connecting measurable material properties to pyrocarbon irradiation performance has been difficult and no foolproof method has been found to date.	Closure Criterion: A method or process for verifying satisfactory IPyC behavior under coating and irradiation.

Additional Discussion

See the previous entry for some of the issues relating to IPyC and the design tradeoffs. Also contact researchers as this issue is again under active investigation.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Buffer Layer Thickness	Layer thickness and its standard deviation

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 8	Remedy: None needed for these dimensional parameters
Rationale: This layer attenuates recoils and provides a collection volume for the released gases	Rationale: The layer thickness and its standard deviation can be fairly easily measured.	Closure Criterion: None

Additional Discussion

The buffer layer has not been a subject of great controversy.

Life Cycle Phase	**Factor, Characteristic or Phenomenon**	**Definition**
Design	Buffer Layer	Mass per unit volume
	Density	

Importance Rank and Rationale	**Knowledge Level and Rationale**	**Remedy for Inadequate Knowledge/Issue Closure Criteria**
Rank: H	Level: 7	Remedy: Performance is not a major issue.
Rationale: The density of the PyC layer is connected to its material properties so it is important to control it. In particular, one wants to control void volume.	Rationale: The PyC dimensionally changes under irradiation and this property is connected to the density among other things. This layer has minimal structural properties so it is less of an issue than the inner and outer pyrocarbons. At present, void volume has not been an issue.	Closure Criterion: None

Additional Discussion

Density and microstructure affects irradiation performance. Great structural integrity is not required of the buffer layer, but minimal cracking is desired to limit kernel extrusion.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Kernel	Design diameter with standard deviation
	Diameter	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 8	Remedy: None required for these dimensional measurements
Rationale: The diameter of the kernel affects the power generated and the gas production in a fuel particle. Off-sized kernels may affect coating behavior.	Rationale: Kernel diameters are fairly easy to measure and a considerable experience base exists in their manufacture.	Closure Criterion: None

Additional Discussion

Considerable experience exists in the manufacturing and measurement of kernels. Diameter measurement is not a major issue with fuel performance.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Kernel	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 required for this measurement
Rationale: The kernel density affects the power generated, the gas production, and perhaps the reactivity with HCl	Rationale: Kernel densities are fairly easy to measure and a considerable experience base exists in their manufacture	Closure Criterion: None

Additional Discussion

Measuring kernel density is not a major issue, but related items may be. One issue is reactivity to HCl liberated during SiC deposition. Kernels that are sensitive to HCl may require that the designer use thicker and/or less porous IPyC. This compromise could result in a less robust particle design unless a way to limit kernel reactivity is found.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Kernel	Maximum and minimum axis lengths of particles
	Sphericity (max/min diameter)	

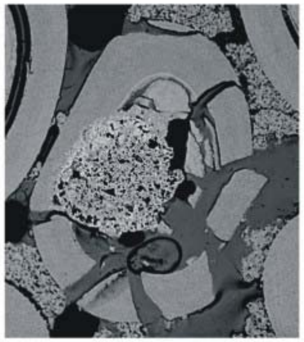
Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 8	Remedy: None
Rationale: The kernels need to be fairly round to be easily handled and free flowing during processing, but no serious irradiation effects have been noted for slightly out-of-round particles.	Rationale: There is a considerable experience base with kernel fabrication and inspection. Simple methods are available to remove deformed particles.	Closure Criterion: None

Additional Discussion

Detailed structural studies have reviewed the issue of non-spherical particles:

Treating Asphericity in Fuel Particles Pressure Vessel Modeling, G.K. Miller, D.C. Wadsworth, Journal of Nuclear Materials, 211 (1994), pages 57-69

Some additional problems could be forthcoming for seriously deformed particles, but in practice modest deviations seem to cause no serious problems. See photos at right. Current QC methods limit particles to those that are quite round and the odd shapes are no longer a problem.



Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Kernel	Oxygen to uranium atomic ratio for UO_2 fuel
	Stoichiometry: Uranium to oxygen	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: M	Level: 8	Remedy: None
Rationale: The stoichiometry affects the amount of oxygen available for release and thus the particle gas pressure. The stoichiometry of UO_2 is not a big issue as radical changes are unlikely.	Rationale: Stoichiometry is not a problem for UO_2 and a great deal of experience is available for its production.	Closure Criterion: None

Additional Discussion

There is a great deal of experience with UO_2 fuels and controlling the stoichiometry within the desired limits is not considered to be a problem. Large deviations are not a problem.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Kernel	Oxygen:carbon:uranium ratio for UCO
	Stoichiometry: Uranium to carbon and uranium to oxygen	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 6	Remedy: Investigate the production methods for UCO to assure they produce the desired product
Rationale: The stoichiometry affects the amount of oxygen available for release and thus the particle gas pressure. The stoichiometry of UO_2 is not a big issue, but it matters greatly for UCO.	Rationale: Stoichiometry is a more difficult problem for UCO as the material is harder to produce. Less experience is available for UCO large-scale production.	Closure Criterion: Satisfactory production of UCO.

Additional Discussion

UCO is a two-phase material that is much more difficult to make than UO_2. Significant deviations in the O/C ratio are important because the purpose of the material is to control the oxygen potential within the particle. Modest changes in the ratio can result in considerably more CO pressure in the kernel and the designer must bear in mind the implications for his fuel design.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Kernel	Elemental constituents and amounts other than design
	Purity	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 9	Remedy: None
Rationale: Impurities can affect the neutronic behavior of the kernel and, in larger amounts, the chemical behavior of the kernel fabrication process.	Rationale: Chemical analysis of fuel is well developed.	Closure Criterion: None

Additional Discussion

Uranium handling and chemical analysis is well-understood process. The sources of the impurities may not be known, but their presence can be detected.

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Kernel	Weight fraction U-235 in total uranium
	Enrichment	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: H	Level: 9	Remedy: None
Rationale: The enrichment determined the nuclear properties of the kernel	Rationale: The methods of analyzing isotopic compositions are well developed	Closure Criterion: None

<u>Additional Discussion</u>

There is a considerable amount of experience in the isotopic analysis of uranium and it is not an issue.

Appendix H.3

Detailed PIRT Submittal by the SNL Panel Member

D. A. Powers

TRISO Fuel PIRT: Design

We have two peculiar situations in this section. The first of these unusual situations is that it is not possible now to produce fuel that reliably meets the reactor designer's own specifications. Though design specifications may exist, they are for fuel that will not be used in a power reactor. We don't know what it will take to produce fuel that reliably meets design requirements and must assume that changes to the current design will have to be done. Right now many, are operating in the belief that some relatively small changes in process have to be made to meet the standard set some 20 years ago by "German" fuel that itself cannot now be made. Such small changes may not be enough and it may be necessary to make radical changes in the design of the fuel to achieve the sought after level of reliability. We have to assume that eventually this level of reliability will be reached. When it is, the specifications for the fuel will be known with great accuracy. These specifications will most likely be in the form of tolerance ranges that really will not be especially useful for those predicting the performance of fuel in the reactor including fission product release during normal operations, upset conditions and during accidents.

The second peculiarity is most of the items listed below will be needed for the prediction of fission product release. But, it is not the specification values of these quantities that are needed except for gross exploratory calculations. What will be needed for realistic calculations and likely to be needed for regulatory processes involving advanced reactor is what actually gets manufactured and the way these quantities evolve during operations for the most part and during accidents in a few cases. In most cases there will be distributions of the values that are needed.

Consequently, the 'design' values for the quantities discussed below are just not very important. These same questions need to be addressed for the manufactured materials. The answers here, then, are nearly always, "The design specifications really are not very important. The design specifications will eventually be known rather well, but they are still nearly irrelevant."

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Fuel Element	Specification of material properties
	Matrix material specification (common)	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank**: L**	Level 8	Remedy: No need for remediation
Rationale: The analysis of anticipated fuel behavior during operations upset conditions and accidents requires that the materials and their properties be known. What is needed is not the design specifications of the materials. What is needed is the nature of the materials of the actual fuel and how this nature has evolved during operations	Rationale: The level of knowledge now of the material specifications is not high. It will be by the time fuel is ready to be added to the reactor.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Fuel Element	Volume fraction of particles in fuel zone
	Particle packing fraction (common)	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 8	Remedy: No need for remediation
Rationale: The particle packing fraction will be an important quantity for the analysis of fuel behavior under conditions of operations, upsets or accidents. It is, however, not the design packing fraction that is of interest. It is the packing fraction of the fuel that is actually produced and installed in the reactor	Rationale: Though the design packing fraction cannot be specified with any definitiveness now, it will be specified quite well by the time the fuel is ready to be incorporated into the reactor. The specification will not be a number. It will be a range of packing fractions which will not be very useful of analysis of fuel performance. What will be needed is the actual distribution of packing fractions that actually go into the reactor	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Fuel Element	Unconfined heavy metal outside SiC layer (common)
	Unconfined heavy metal outside SiC layer (common)	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 8	Remedy: No need for remediation
Rationale: The design specification of this quantity is not of any importance. What is important is what is the heavy metal contamination outside the SiC layer in material that is actually introduced into the reactor	Rationale: It will be very easy to provide a specification for this quantity. It will be rather more difficult to ascertain that this specification has been met. The specification will most likely be a range and what will needed for the analysis of fuel performance will be the distribution of values within this range – again, not the design specification, but the actual distribution for fuel going into the reactor.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Fuel Element	The degree of homogeneity of the particles in the fuel element
	Particle distribution in fuel element	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 5	Remedy: No need for remediation except there will very much be a need to develop techniques to measure the homogeneity of the particle distribution in fuel compacts that are actually produced
Rationale: This will be a quite important quantity for the estimation of local neutronic behavior in compacts as well as understanding of the thermal environment for the particles both during operations and during accident or upset conditions. But, the design specification is not what is important. It is the actual homogeneity of fuel in the reactor that is important	Rationale: It is unlikely that a very high level of knowledge of the distribution will ever be generated. Rather some idealized approximate description of the distribution of particles in a fuel compact will be generated and used as a specification	Closure Criterion: What is really needed here is some description of what exactly needs to be measured and how well. This probably requires some careful neutronic analysis and some careful heat transfer analysis.

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Fuel Element	Unfueled carbonaceous layer on outside of pebble
	Fuel free zone (Pebble)	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 8	Remedy: No need for remediation
Rationale: The unfueled carbonaceous layer could have a significant impact on the estimation of temperatures and fission product releases from the fuel. But, the layer of interest is that actually produced in fuel in the reactor and not the design specification of this layer	Rationale: Presumably the fuel design specifications will provide a range for the carboneceous layer – perhaps as a set of bounds which will not be of great use for the prediction of fission product release. Detailed knowledge of this specification is not know available because there is not an acceptable fuel that can be routinely and reliably produced	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Fuel Element	Layer on outside of outer PyC added after coating
	Particle overcoat (pebble)	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 8	Remedy :no need for remediation
Rationale: This outer layer has some importance in fuel behavior. The design specification is inconsequential. What is important is what is done on fuel actually in the reactor	Rationale: Presumably, once an acceptable fuel can be produced reliably and routinely this specification will be provided. Without doubt, the specification will be in a form of limited utility for analysis of fuel performance.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Outer PyC layer	Layer thickness and its standard deviation
	Thickness	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 8	Remedy: no need for remediation
Rationale: The outer PyC layer thickness will be of some importance for the analysis of fission product release as well as for estimation of local temperatures and temperature gradients. The specification, pe se, is not important. What actually gets produced is important and the evolution of this layer thickness and integrity with time will be important	Rationale: Because an adequate fuel cannot now be produced, there is little knowledge of this thickness nor of its standard deviation. But eventually when reliable fuel can be produced this layer thickness will be specified well, one presumes.	Closure Criterion: What is really needed is an agreed upon reliable method for measuring the layer thickness and its standard deviation in fuel that is manufactured. And also to monitor how it evolves under the operating conditions of the reactor which will not be uniform – that is, it will not be spatially uniform and certainly no temporally uniform. Even locally the system will be in thermal gradient and not in a uniform temperature.

<u>Additional Discussion</u>

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Outer PyC layer	Mass per unit volume
	Density	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 8	Remedy no need for remediation:
Rationale: The density of the outer PyC layer will be modestly important for estimating fission product transport and for the calculation of temperatures in local regions. Again, the specification will not be of any importance. What will be important is what the distribution of densities that actually exist in the fuel . This is beyond even what is manufactured since this density will evolve during operations.	Rationale: One can safely assume that once some method for manufacture of reliable fuel is available this specification will be known well.	Closure Criterion: There will be a very significant need to have a way to measure the density of the outer PyC layer in manufactured fuel and predict how it evolves in the environment of the reactor during operations.

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	SiC Layer	Layer thickness and its standard deviation
	Thickness	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 8	Remedy no need for remediation:
Rationale: See discussion above for the outer PyC layer since it applies as well for this layer	Rationale: See discussion above for the outer PyC layer since it applies as well for this layer	Closure Criterion: See discussion above for the outer PyC layer since it applies as well for this layer

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	SiC Layer	Mass per unit volume
	Density	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 8	Remedy: No need for remediation
Rationale: See discussion above for the outer PyC layer since it applies as well for this layer	Rationale: See discussion above for the outer PyC layer since it applies as well for this layer	Closure Criterion See discussion above for the outer PyC layer since it applies as well for this layer:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Inner PyC layer	Layer thickness and its standard deviation
	Thickness	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 8	Remedy :No need for remediation
Rationale: See discussion above for the outer PyC layer since it applies as well for this layer	Rationale: See discussion above for the outer PyC layer since it applies as well for this layer	Closure Criterion: See discussion above for the outer PyC layer since it applies as well for this layer

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Inner PyC layer	Mass per unit volume
	Density	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 8	Remedy: No need for remediation
Rationale: See discussion above for the outer PyC layer since it applies as well for this layer	Rationale: See discussion above for the outer PyC layer since it applies as well for this layer	Closure Criterion: See discussion above for the outer PyC layer since it applies as well for this layer

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Buffer Layer	Layer thickness and its standard deviation
	Thickness	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 8	Remedy: No need for remediation
Rationale: See discussion above for the outer PyC layer since it applies as well for this layer	Rationale: See discussion above for the outer PyC layer since it applies as well for this layer	Closure Criterion: See discussion above for the outer PyC layer since it applies as well for this layer

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Buffer Layer	Mass per unit volume
	Density	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 8	Remedy No need for remediation:
Rationale: See discussion above for the outer PyC layer since it applies as well for this layer	Rationale: See discussion above for the outer PyC layer since it applies as well for this layer	Closure Criterion: See discussion above for the outer PyC layer since it applies as well for this layer

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Kernel	Design diameter with standard deviation
	Diameter	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 8	Remedy No need for remediation:
Rationale: The bounding design specification of kernel diameters will have no importance in the estimation of fuel performance and fission product release. What will be needed is what actually goes into the reactor fuel and how these kernels evolve in geometry under the conditions of thermal gradients thermal cycling and intense irradiation when adjacent to a reactive material like carbon.	Rationale: Currently reliable fuel cannot be produced. Once presumes that current thoughts on kernel design will evolve in the effort to produce reliable fuel. So one has to admit that the current specification for the kernel diameter is not well known. But, once reliable fuel can be made, the specification of the kernel diameter will be known well. It will likely be a range. For analysis of fuel performance what will be needed is not the specification but what actually goes into the reactor cast in the form of a continuous probability distribution	Closure Criterion: There is a need for a reliable technique to measure what is actually in the fuel and to monitor how the kernel geometry evolves under the conditions of irradiation, thermal gradients and thermal cycling while in contact with a reactive material like carbon.

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Kernel	Mass per unit volume
	Density	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 7	Remedy No need for remediation:
Rationale: The initial fuel density will affect its performance during reactor operations. But what is needed is not the density specification. The need is for the density of fuel that actually goes into the reactor	Rationale: Not known well now, but will be known well once fuel can be reliably produced	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Kernel	Maximum and minimum axis lengths of particles
	Sphericity (max/min diameter)	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 3	Remedy: No need for remediation
Rationale: Lack of sphericity of the kernel is very important since it can make the codes used for predicting diffusive process like fission product release and heat transfer complicated. The design specification on this quantity is inconsequential. What is needed is information on the lack of sphericity of the fuel that goes into the reactor and how it evolves with operation.	Rationale: This probably is not getting a great deal of attention from those designing specifications for fuel	Closure Criterion: What will be very much needed is an agreed upon way to measure the deviation from sphericity both in fuel that goes into the reactor and in fuel as it evolves within the reactor

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Kernel	Oxygen to uranium atomic ratio for UO_2 fuel
	Stoichiometry: Uranium to oxygen	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 5	Remedy: No remediation needed
Rationale: The stoichiometry of fuel affects the diffusion of fission products through that fuel. It also affects the potential for the fuel to react with the carbon. The design specification is not important and probably won't characterize the fuel very well. What will be needed is the O to M ratio for fuel that actually goes into the reactor and a model of how this O to M ratio varies during operation in light of internal buffering by the MoO2/Mo equilibrium as well as reaction with the carbon adjacent to the fuel kernel.	Rationale: control of O to M ratios in urania based fuels has reached sufficient sophistication that fairly tight specifications can be imposed	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Kernel	Oxygen:carbon:uranium ratio for UCO
	Stoichiometry: Uranium to carbon and uranium to oxygen	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level:3	Remedy Need models of the UOC system :
Rationale: The phase relations in the U-O-C system are not known well enough to predict with certainty how sensitive fuel behavior is to the precise stoichiometry	Rationale: Current knowledge of the U_O_C system even at the thermodynamic level is at best rudimentary. There is limited understanding of the effects of non-stoichiometry and the effects of irradiation in a thermal gradient on non-equilibrium phase separation. Transport properties of non-stoichiometric materials in the U-O-C system remain largely unexplored.	Closure Criterion: We are going to have to have predictive modeling of both the thermodynamics of the U-O-C system and the transport properties of materials in this system to have specifications of composition of fuel. Existing modeling is not at all encouraging because of the complexities of non-stoichiometry

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Kernel	Elemental constituents and amounts other than design
	Purity	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 8	Remedy: No remediation needed
Rationale: The effects of impurities on the behavior of urania-based fuels have been relatively well established for conventional reactor fuels. Though important levels of impurities such as chloride and some metal oxides such as iron oxide can drastically affect behavior, the fluorite structure is amazingly forgiving for most commonly encountered levels of impurity. Where the material is unforgiving is gas generation such as the reaction during operation of carbon impurities with the oxide to form CO that pressurizes the cladding. In the case of the SiC 'pressure vessel' for coated particle fuel, this may not be a concern since the reaction with buffer carbon will occur regardless of the purity of the fuel. Still chloride contamination will be a concern as will iron oxide contamination.	Rationale: The specification of urania purity to avoid deleterious fuel behavior has been established by experience with conventional fuel behavior. Experience with the urania in coated particle fuel is, of course quite limited, but, still, there should be no problem providing a specification that will remove this issue from consideration in the analysis of fuel performance and fission product release during normal operations, upset conditions and accidents.	Closure Criterion:

Additional Discussion

Life Cycle Phase	Factor, Characteristic or Phenomenon	Definition
Design	Kernel	Weight fraction U-235 in total uranium
	Enrichment	

Importance Rank and Rationale	Knowledge Level and Rationale	Remedy for Inadequate Knowledge/Issue Closure Criteria
Rank: L	Level: 9	Remedy: No need for remediation
Rationale: The enrichment of the fuel does not normally enter into the analysis of most severe reactor accidents except that it may affect the fission product inventory. Enrichment will affect reactivity insertion accident analysis from the point of susceptibility and energy input during the accident. The energy input will, of course, affect the fission product release associated with the event in a fairly complicated, and not too strong a way. Enrichment of the fuel also determines the extent of burnup of the fuel. As burnup gets high , the fuel kernel geometry and integrity gets degraded very badly to the point it will be difficult to identify a kernel at burnups in excess of about to GWd/t. This makes the usual approaches to analysis of fission product release exceptionally difficult. This kind of distortion of the kernel from idealized spherical symmetry is very likely to happen as a consequence of the kernel being in a thermal gradient during operations and reacting with the adjacent carbon, so it is an issue that the modelers of fission product release are going to have to confront for a variety of reasons.	Rationale: Presumably the reactor design will specify rather exactly what the enrichment of the fuel will be.	Closure Criterion:

<u>Additional Discussion</u>