**NE 795-014 Advanced Reactor Materials and Materials Performance**

**Exam 1**

Please provide your responses to the following questions. Point values indicated expected depth of response.

1. What are some key differences between high-temperature gas reactors and light water reactors? (8 pts)

Key differences are numerous between HTGRs and LWRs. Coolants: He versus water. Pressure: high pressure in LWRs and low pressure in HTGRs. Fuel system: UO2 pellets versus TRISO particles with a UO2 or UCO fuel kernel. Cladding: Zirconium cladding in LWRs versus the IPyC/SiC/OPyC layered structure in HTGR TRISO particles. Graphite is also the most common material in a HTGR core, whereas LWRs contain no graphite. HTGRs have a much larger temperature delta over the core, reaching much higher temperatures at the coolant exit. HTGRs are also often coupled with secondary systems which can utilize this heat for other processes. And so on…

1. What are the individual layers in a TRISO particle? What purpose does each layer have? (14 pts)

Fuel kernel: Fissile material. Often UO2 or UC2/UO2 (UCO). Generates heat.

Buffer: Porous graphite layer surrounding the fuel kernel. Allows for fuel expansion while mechanically decoupling the fuel kernel from the external layers. Porosity allows for gas generation without overpressurization.

IPyC: Inner pyrolytic carbon, highly dense graphite. Layer serves are a substrate for the SiC deposition, protects SiC from fission products, provides compressive stresses on SiC.

SiC: Primary fission product barrier and primary pressure vessel. Failure of the SiC constitutes a failure of the particle.

OPyC: Outer pyrolytic carbon, highly dense graphite. Protects the SiC layer during fabrication. Provides compressive stresses on SiC.

1. What are the trade-offs between carbide and oxide fuel kernels? (10 pts)

UO2 fuel kernels are well understood and relatively easy to manufacture, while also effectively retaining a large portion of the fission products. However, excess oxygen generated during fission interacts with graphite in TRISO particles to generate CO, leading to pressurization of the particle. UC2 fuel removes oxygen from the system, thereby eliminating the generating of CO during fission. However, UC2 is more challenging to fabricate and does a worse job retaining fission products. Thus, a heterogeneous mixture of UO2 and UC2 is commonly adopted to utilize the effective fission product retention of UO2, while providing a fissile getter of oxygen in the form of UC2 to limit the production of CO.

1. How does the nature of irradiation damage accumulation change with irradiation temperature in SiC? (12 pts)

SiC has four temperature regimes with respect to radiation damage accumulation. At very low T, SiC goes amorphous. At low T above the amorphization temperature, the microstructure is dominated by black spot defects which are likely interstitial clusters. As the temperature increases, more recombination is allowed as defect diffusivities increase, and the concentration of BSDs is reduced. Thus, defect-induced swelling decreases with increasing temperatures at low temperatures (below 1000C). The BSD-induced swelling saturates at a given level of dose for a given temperature. At medium to high temperatures, interstitial loops are seen to form from the clustering of the individual small interstitial clusters. At high temperature, vacancies become sufficiently mobile to form voids and the microstructure becomes dominated by void swelling.

1. How does thermal conductivity change in SiC with irradiation? What are the primary phonon scatterers, and why can someone determine the thermal conductivity from the swelling in SiC? (10 pts)

The thermal conductivity in SiC is mediated by phonons. The primary phonon scatterers are point defects, primarily the BSDs generated at low to medium temperatures. These defects generate a resistivity to thermal conductivity. The swelling due to point defects is directly proportional to the resistivity they induce on the thermal conductivity. Thus, one can judge from the swelling the amount of BSDs that are present, and the effective degradation of the thermal conductivity. Since the defect concentrations decrease with temperature, the thermal conductivity slightly increases with irradiation temperature. In the void swelling regime, BSDs no longer dominate, and the voids do not scatter phonons as effectively as BSDs. Thus, the thermal conductivity is higher for a microstructure dominated by void swelling.

1. Discuss the role of fission products on the failure of TRISO particles? (10 pts)

Fission products can impact failure in two primary ways. The first is via the release of fission gases from the fuel leading to an increase in the pressure inside of the TRISO particle. Fission gases are constantly being generated and released, and thus continuously increase the pressure inside the particle. The buffer layer can mitigate some of the effects of overpressurization. The second primary failure impact is due to fission product corrosion on the SiC layer. The main fission product responsible for degradation of the SiC is Pd, where a number of Pd-Si-C precipitates can form, chiefly along the grain boundaries, embrittling and wasting away the SiC layer. Other impacts of fission products include diffusion through the SiC and plating out on primary coolant system components.

1. How does graphite dimensionally change under irradiation? Why does this behavior happen? (14 pts)

Graphite displays anisotropic dimensional change under irradiation. Interstitials form in graphite in between two adjacent planes. The effect of this is to cause an expansion in the c direction and a contraction in the a direction. Vacancies form along the basal planes and lead to a further contraction in the a direction. Due to fabrication conditions, graphite will form with a number of Mrozowski cracks, which are preferentially oriented along the basal plane in graphite. Thus, we have contraction in a, expansion in c, but cracks which can incorporate the expansion in c without leading to overall dimensional growth in c. Therefore, we have a resultant shrinkage in graphite under irradiation. As growth continues, these cracks close and can no longer accommodate the expansion in c, and the graphite begins to swell. This is called graphite turnaround.

1. List three types of failure mechanisms for TRISO particles. (8 pts)

Overpressurization: Generation of fission gases and CO lead to a sufficiently high pressure to exceed the strength of the individual layers of the TRISO particle, causing failure.

Kernel migration: Primarily occurring in UO2 kernels, C, in the form of CO, can migrate along the temperature gradient inside the TRISO particle, leading to migration of the fuel kernel within the IPyC. This generates hot spots and anisotropic heating and stresses.

SiC decomposition: SiC decomposes above approximately 2000C into its constituents. Under a severe accident where temperatures exceed this value, the SiC layer will fail, releasing fission products.

There are several others covered in class.

1. Provide one example of an advanced TRISO concept and explain why it is of interest. (8 pts)

Multi-layering. Inner layers of PyC and SiC/PyC can be manufactured to provide a sacrificial layer of fission-product retaining materials to getter the problematic fission products, such as Pd, to remove the source term of corrosive fission products to the outer SiC layer, which is the primary pressure vessel and fission product barrier.

There are several others covered in class.

1. What are three phenomena/behaviors that need to be accounted for in fuel performance modeling of TRISO fuels? What is one data need for fuel performance modeling? (6 pts)

Thermal conductivity of the individual layers and how it degrades with time. Irradiation growth/creep of PyC layers on the impact on the stress state of SiC. Fission gas release and CO generation leading to pressurization of the particle.

Better irradiation creep correlations for graphite.