NE 795 Advanced Reactor Materials and Materials Performance

Exam 4

The associated point values provide an indication of the expected thoroughness of response.

1. Why are different cladding/structural materials required for advanced reactor systems? (8 pts)

Materials such as zircaloy or stainless steels are either susceptible to void swelling, embrittlement, excessive creep, high corrosion rates, or a loss of properties at high temperatures. Existing materials qualified for LWRs likely do not possess the material properties to withstand the high temperature, high flux/fluence, and corrosive environments in advanced reactors. Zircaloy has compatibility issues, undergoes phase changes, exhibits anisotropic properties, and a lack of high T mechanical performance. Stainless steels undergo excessive void swelling, display high rates of corrosion, and have high irradiation creep rates. Ferritic or F/M steels and Ni alloys offer property domains which are more suitable to the harsh and novel environments in advanced reactors.

1. What are some considerations when optimizing the composition for F/M steels? (8 pts)

Solid solution strengthening, precipitation hardening, corrosion resistance, irradiation creep resistance, phase stabilization, corrosion, microstructure, formability, etc. Properties of F/M steels offer some fundamental advantages with regards to high temperature behaviors and resistance to void swelling, but many properties can be modified or tailored via small additions of alloying elements. Examples include Cr for oxidation corrosion resistance, C for precipitate hardening, Mo for solid solution strengthening.

1. Why do ferritic steels swell considerably less than austenitic steels? (6 pts)

There are likely a confluence of factors which contribute to the improved swelling resistance of ferritic steels over austenitic steels. 1) the relaxation volume for interstitials is large in ferrite than in austenite, 2) the migration barrier of vacancies in ferrite is much lower than in austenite, 3) excess vacancies can be trapped at carbide particles as the C-vacancy binding energy in ferrite is twice that in austenite, 4) the way dislocations and solutes interact in ferrite makes them strong sinks, generating strain fields that attract vacancies, 5) the complex microstructure of martensite laths and a ferrite matrix inherently produces a very high density of sinks.

1. What role do the oxide particles play in ODS steels? (5 pts)

Oxide particles play two key roles in ODS steels. First, they act as sinks for vacancies, interstitials, and solute particles, which dramatically increases their radiation resistance, including resistance to void swelling. Second, they act as obstacles and pinning locations for dislocations and grain boundaries, improving strength and creep resistance.

1. What are some advantages and disadvantages of Ni alloys? How is strength improved in Ni alloys? (8 pts)

Ni alloys have excellent high temperature mechanical properties, good resistance to corrosion, FCC with isotropic properties and wide solubilities, can be precipitation hardened, good void swelling resistance, compatible with salts, liquid metals, water, etc. Negatives include Ni transmutation leading to large quantities of He which can embrittle the material, irradiation hardening leads to strong decreases in ductility, and high doses can decrease strength as well. Ni alloys can be susceptible to SCC/IASCC. Ni alloys can be either solution annealed with alloying species or precipitation hardened to improve strength.

1. What are the unique features of conditions inside research reactors compared to LWRs? (10 pts)

Very low temperatures (below 200 C), medium to high linear powers, no fission gas plenum or release, very high burnup reached, plate-type fuels, etc. Different materials are thus of interest, including U-Mo (or other intermetallic) fuels and aluminum cladding. Heat generation is not of primary concern, but the generation of neutrons to perform irradiation or transmutation is often the goal.

1. Why is amorphization of concern in research reactors? (6 pts)

Amorphized systems can potentially increase the rate of diffusion of fission products, leading to more rapid, and larger magnitudes of, fission gas swelling. Such fission gas swelling can become sufficiently high to fail the plates. Not all amorphization is equally bad, as some amorphized phases exhibit relatively stable gas bubble structures.

1. What are benefits and drawbacks of U-Si fuel compared to U-Al fuel? Why is there a push towards U-Mo fuel? (6 pts)

U-Si has a substantially higher uranium density than U-Al fuels. U-Si is often U3Si2 compounds, whereas U-Al is a combination of UAl2, UAl3, and UAl4. While the power density can be much higher in U-Si fuels, they can exhibit amorphization and large amounts of fission gas swelling. To maintain high powers but to reduce enrichment, higher uranium densities are required that that offered by U-Si fuels. Thus, U-Mo fuels, both dispersion and monolithic, are being pursued.

1. Describe the differences in U3Si and U3Si2 swelling. (6 pts)

Both U-Si phases become amorphous under irradiation, but U3Si swells significantly more. The observed microstructures of irradiated and amorphous dispersed fuel particles show the U3Si2 has a uniform swelling behavior, with medium-sized bubbles throughout the entire particle, leading to homogeneous swelling. U3Si micrographs show large variations in bubble sizes, with very large and small bubbles being present. These very large bubbles will contribute to larger amounts of swelling.

1. The gamma phase of U-Mo is not the thermodynamically stable phase at research reactor temperatures. Why is this phase the dominant phase in-reactor? (7 pts)

First, the gamma phase can be quenched to room temperature. Mo is a very effective gamma stabilizer, and the transformation kinetics are quite sluggish, leading to a metastable gamma phase at low temperatures. Also, any decomposed phases which are present (alpha-U and U2Mo) will revert back to gamma U-Mo under irradiation due to ballistic mixing. Thus, only the gamma phase will exist in the operating reactor.

1. What effect does the solidus/liquidus gap have on fabrication of U-Mo fuels? (6 pts)

Mo-rich areas will solidify first due to the nature of the solidus/liquidus lines in the phase diagram. This can lead to Mo-rich areas of solidified fuels, as Mo-rich islands can form within the liquid dispersoids. This effect also leads to Mo depletion along the grain boundaries in monolithic fuel.

1. Discuss the evolution of fission gas bubbles in U-Mo fuel as a function of burnup. (10 pts)

Fission gas initially forms a superlattice in an FCC structure, consisting of nm sized bubble. This structure can contain a large amount of fission gas with minimal swelling. As burnup progresses, radiation damage accumulation leads to a grain refinement process. This grain refinement converts micron sized grains into ~200nm size grains. This process also destroys the fission gas superlattice, sweeping intragranular gas bubbles to the grain boundaries, forming large intergranular fission gas bubbles which have a measurable impact on swelling.

1. What is the role of the Zr layer in U-Mo monolithic fuels? (6 pts)

The Zr layer is placed on both sides of the monolithic fuel foil, to act as an interdiffusion barrier between the fuel and the cladding. This prevents the formation of an interaction layer, observed in dispersion U-Mo fuels, which can become amorphous and contribute to breakaway swelling.

1. Why is Al ideally suited for the research reactor environment when it is unable to be used in LWRs? (8 pts)

Aluminum has a very low neutron absorption cross section, excellent oxidation resistance, is easily formable, and is very cheap. Because RTRs operate at such low temperatures, this allows for the utilization of Al as a cladding material, despite the low melting point of Al. Additionally, despite the low strength of Al, the strength is sufficient for the purposes of plate-type fuels.