NUCE 497I

Exam 2 Solution

(Based on Chapters 5 and 6)

1. (**15**) Please discuss the assumptions and deficiencies of the neutronics and burnup models (given in Equations 5.1 through 5.4 in Chapter 5) utilized in fuel performance calculations.

   Answer:

   The models are very simplified based on one-group diffusion theory with one set of microscopic cross-sections (usually these cross-sections change with burnup because of spectrum changes).

   The models are one-dimensional i.e. take into account only radial dimension. No treatment is provided for azimuthal dimension and in axial direction the fuel rods are considered infinite and this dimension is not treated also or provided as input in form of axial power distribution form other calculations. The models are designed for single fuel rod modeling with no provisions for accounting of the neighboring rods i.e. the core environment.

   For burnup equations the linear heat generation rate (LHGR) and time step duration are input values and the neutron flux is assumed constant when solving these equations. Furthermore, the distribution of plutonium production is described by an empirical function.

2. (**10**) Discuss the mechanisms behind the rim formation in fuel pellet and how it affects the power and burnup distribution at high burnups and subsequently fuel behavior.

   Answer:

   The formation of high burn-up structure (HBS, also known as "rim structure formation" or "rim effect") occurs in nuclear fuel materials as a consequence of excessive fission damage and in-growth of fission products. HBS is also referred to as rim structure, as it is first formed near the outer surface (rim) of UO_2 fuel pellets where the burn-up is highest because of resonance neutron capture by ^{238}U forming fissile ^{239}Pu. Rim structure formation starts at the pellet periphery where the number of fissions is highest due to the build-up of plutonium.

   At BOL, the typically low enrichment of the ^{235}U isotope (3 to 5%) constitutes the only fissile isotope, and the radial distribution of ^{235}U is uniform. The thermal neutron flux level is only slightly depressed in the center relative to the edge, resulting in a nearly uniform radial distribution of volumetric heat generation. As burnup proceeds, fission *consumes ^{235}U, but ^{238}U captures resonance energy neutrons, resulting in a limited buildup of plutonium, including the fissile plutonium isotopes ^{239}Pu and ^{241}Pu. Because of the large value of the capture cross section at resonance energies, this plutonium buildup occurs preferentially, but not exclusively, at the pellet edge.*

The plutonium content in the pellet builds asymptotically towards approximately 1% pellet average and 3 to 4% in the pellet rim. Thus the fissile plutonium concentration at the rim begins to significantly exceed that in the remainder of the pellet as burnup accumulates, and the radial distribution of the volumetric heat generation becomes progressively edge-peaked. The radial distribution of fuel burnup (in relation to the initial concentration of heavy metal atoms) also becomes progressively edge-peaked.

3. (**15**) Describe how the CRUD deposition causes Axial Offset Anomaly (AOA) and will this affect any fuel safety criteria?

   Answer:

   Large porous CRUD depositions in PWRs can lead to boron pick-up, thereby causing distortion of the core axial power profile. When substantial CRUD build-up occurs in the upper part of a PWR core, especially in high-power assemblies, fission rates are reduced due to boron containing species ($LiBO_2$, Ni_2FeBO_5) being absorbed into the CRUD layer. As a result, the power distribution shifts towards the bottom of the core, causing a reduction in Shut-Down Margin (SDM) and an increase in local peaking. During plant operation an anomalous, bottom peaked, power distribution is observed; should the power shift persist, burn-up effects will eventually reverse the power shift setting off a top peaked power distribution near the end of the cycle.

   The bottom peaked power distribution will tend to reduce SDM, thereby causing deviations in the estimated critical position of control rods, and will also tend to increase local peaking. This phenomenon, called axial offset anomaly (AOA), has been observed mainly in high energy cores at several PWRs in the United States.

   It is not expected that AOA will directly affect any of the fuel safety criteria. The actual numbers of some safety criteria, notably SDM, may change for those power plants (i.e. PWRs with high energy cores) affected.

4. **(10)** Please discuss how the Rod Ejection Accident (REA) in a PWR affects in principal the fuel and cladding behavior. What are the most important REA parameters determining the magnitude of these effects and corresponding consequences.

After the rod is being ejected, the temperature of the fuel pellet can rise above the maximum centerline limit of UO2(2000 C) and melting point for Zr(1852 C). REA can lead to the cladding and fuel failures. One of the most important REA parameters in determining the magnitude of the REA impact and its consequences is the lifetime of the fuel: fresh vs burnt. REA has a significant effect at lower fuel enthalpies for irradiated fuel than for fresh fuel. Also, the vulnerability of fuel failure and cladding increases with increase in the fuel burnup. Fuel and cladding properties change with burnup, which increases the fuel transmutation and radiation damage, waterside corrosion, and the consequences of these change are even more amplified under REA.
Another effect that determines the magnitudes of the REA is the power condition at which REA takes place. The most limiting case is at HZP, because the control rods are further insereted into the core at their insertion limits with a higher rod worths, which will lead to a much greater reactivity insertion in contrast to the HFP core condition.

There are four possible fuel failures under REA:

- PCI under heating (lower temperature) phase for high burn up fuel with higher corroded cladding.
- At high temperature: cladding ballooning and burst
- At high temperature: disruption of the cladding as a consequence of embrittlement due to oxidation
- At high temperature: melting of the cladding and the fuel pellets

Important parameters that determine the magnitude of these effects under REA:

For fuel pellets: heat transfer rates, melting, fragmentation, and fuel swelling due to fission gas and fission gas release

For cladding: heat transfer rates, melting, deformation, oxidation and failure.

5. **(10)** Please discuss the consequences of PWR REA for fresh fuel and what safety limits are reasonable to use in this case.

In the event of the REA for PWR the gap in the pellet can accommodate the resulting thermal expansion (net strain is less than 1 %), and Zr cladding for the fresh fuel can handle this deformation, and thus PCI will not lead to cladding failure for fresh fuel.

Large oxide layers on the inside and outside cladding surfaces will not be developed during REA for fresh fuel. Although, cladding failure can occur at lower temperature during the cool down period due to the lack of oxides.

Based on the various empirical data and experiments: *no cladding failure, fuel dispersal, or steam would be expected for LWR for fresh fuel in REA.*

Reasonable Safety Limits:

A limiting value of 170-cal/g total enthalpy rise is the level at which cladding failure can occur as a result of increase in temperature. Cladding failure of RIA will result in some releases of fission products. However, the main concern in is the consequences related to a possible steam explosion.

Enthalpies greater than 275 cal/g will lead to some meltdown of UO2. At higher enthalpies, thermal expansion will cause the ejection of melted hot fuel particles into the coolant.

6. **(10)** Please discuss the consequences of PWR REA for high-burnup fuel and what safety limits are reasonable to use in this case.

High-burnup fuel is much more affected by the REA in contrast to fresh fuel due to a higher buildup of Pu near the pellet surface, which will result in very high temperature of the fuel during the power transients. These higher fuel surface temperatures will increase the thermal expansion of the pellet at much higher magnitudes in contrast to the fresh under REA.

Another factor under consideration in REA is the pellet-to-cladding gap. This gap closes due to fuel pellet swelling during normal operations with an increase in burnup, and this will have a much large impact of thermal stresses on the cladding during the REA.

Other factor of importance in the formation of hydrates that will harden the cladding and lead to its imbritllement, which subsequently can lead to PCMI failure. As hydrogen formation increases, the cracks in the cladding outside diameter become greater and further propagate through the cladding walls, hence the risk of cladding failure increases, which can result in the steam exposure.

Reasonable limits:

The enthalpies limits for burnt fuel depend on the hydrogen amount present. At lower hydrogen concentration, the enthalpies around 170 cal/g will lead to fuel failure. At higher hydrogen formation, the limit reduces to 50-70-cal/g which will cause PCMI for irradiated fuel in REA near the higher rod worths.

7. **(10)** Please discuss how the Loss Of Coolant Accident (LOCA) in a PWR affects in principal the fuel and cladding behavior. What are the most important LOCA parameters determining the magnitude of these effects and corresponding consequences.

During LOCA voids formation in coolant significantly increase and system pressure drops, which leads to an increase in the cladding and fuel temperatures due to decay heat. Damage caused to the fuel will depend on its ductility at the time accident takes place, and whether the fuel is fresh or irradiated.

With an increase in the fuel pellet temperature, Zr cladding undergoes various phase changes, and its strength will vary depending on the phase. The increased internal pressure within the fuel rod will cause the cladding to deform and swell and to experience "ballooning". When this happens, the pellets could be already creaked, and with increasing swelling in the cladding, the deformed fuel pieces will fill the ballooning regions with continuous heat production from radioactive decay of fission production. As the result, the local linear power density will increase, which can lead to fuel melt.

8. **(10)** Please discuss the consequences of PWR LOCA for fresh fuel and what safety limits are reasonable to use in this case.

Depending on the timeline development of the LOCA, temperature rise will cause vari process in the cladding , such as diffusion and oxidation, ballooning rapture , phase change, quenching.

During LOCA, the outside system pressure is decreased and the internal differential press inside the fuel pellet cladding increases. The cladding will become softer and ballooning rupture would take place with phase change progression, which cause a local deformation result in the rupture. Maximum burst strain remains at maximum at about 800 C, which is limiting value for the Zr phase change from alpha to beta. However, Strains will be reduce the transit between two phases during the rupture.

The consequences of ballooning and rupture under LOCA is the reduction of the flow area of coolant, but it won't result in increase in temperature due to an increase of the surface available for cooling. Another consequence of ballooning is the thinning of the clad w leading to higher oxidation inside and outside of the cladding diameter.

LOCA lead to higher oxidation rates and diffusion of oxygen onto metal than during nor operation, which can lead to transformation form alpha to beta phase and to subsequ imbrittlemnt due to hydrogen formation. As a result there is a is a limit imposed on oxy during the alpha phase. Transition to ductile to brittle phase is fond at 17 percent ECR based the C-P correlation for Zr alloy.

NRC limits criteria:

- Maxim fuel temperature should not exceed 2200 F
- Total oxidation of the cladding should not exceed 17% time of the total cladding thickness
- The rate of energy release , hydrogen generation and cladding oxidation should be calculated by using Baker-Just equation

9. **(10)** Please discuss the consequences of PWR LOCA for high-burnup fuel and what safety limits are reasonable to use in this case.

Same characteristics of burnt fuel are applied under LOCA conditions but in a different way. The consequences of the LOCA for high burnup fuels are related to formation of think corrosion layers, high hydrogen concentration in the cladding and pellet-cladding bonding. Hydrogen will increase the rate of oxygen diffusion during LOCA and accelerate the embittlemnet process in the lower limit than 17 % ECR for fresh fuel.

Another consequence related to pellet - to - cladding gap closure, which will result in bonding and oxygen pick leading to diffusion in the inner and outer diameters of the cladding at about 50 GWd/t .

Other consequence of LOCA is the fuel relocation, where fuels pellets cracks at even lower burnups rates.