Radiation Effects - Reactor Materials

Radiation Swelling: stainless steels
- He stabilized voids $\Leftrightarrow$ density decreases or volume increases

Radiation Growth: Zircaloys
• no voids are observed in Zrys;
• no change in volume;
• grain orientation anisotropy or texture leads to length increase of fuel rods since in Zr single crystal (hcp) c-axis decreases and a-axis increases following radiation exposure

c/a ratio decreases or the single crystal becomes short and fat

Corrosion & Oxidation:
Radiation exposure leads to increased rates of corrosion and oxidation

3 basic effects on materials (e.g., Zircaloys):
1. Oxidation/corrosion (see below)
2. Hydriding (figures in JTA – ch. 2)
3. SCC and Corrosion-Fatigue (leads to PCI – JTA – ch. 2)

Mechanisms of Radiation Effects on Corrosion:

a. Radiolytic/Radiation Decomposition of water
b. disruption of thin protective film on surfaces (ZrO$_2$ on Zry cladding)
c. radiation effect on corrosion and SCC

- Formation of
  - Hydrogen
  - Oxygen
  - Hydroxyl (OH) ions
  - Hydrogen Peroxide

- all these products promote and increase rates of corrosion, particularly oxidation

Oxidation: Metal oxide (ZrO$_2$) forms leading to weight gain $\rightarrow$ “breakaway” --- longer the time for breakaway, the better the material: selection of materials made using steam exposure tests

b. Disruption of Protective Layer or cracks in the layer (formed due to $\Delta T$, mechanical, etc.,) --- lead to enhanced corrosion attack $\Leftrightarrow$ Crevice Corrosion

  $\Rightarrow$ nodular vs uniform (see figures in JTA – Ch. 2)

c. Applied or in-service Stress: lead to decreased rupture time ($t_r$) and endurance limit (in fatigue): $\sigma$ vs $t_r$, $\Delta \sigma$ vs $N_f$
**LMFBRs**

Liquid metal corrosion  

due to thermodynamic imbalance between structural metal and liquid metal  
(Na, K, Li, NaK, etc.)

a. due to dissolution and precipitation (because of $\Delta T$, ...) depends on the solubility of liquid in the solid  
b. particle migration / diffusion of solid metal into liquid and vice versa  
c. penetration of the liquid metal atoms into solid metal (structural) mainly through GBs leading to rupture

- radiation has minor effect on liquid metal embrittlement but in general enhances due to decomposition of liquid metal, or transmutation of atoms/nuclei
- 304, 316 SS are excellent candidates – due to good high temperature creep, etc.; but swelling could be a major limiting factor

**Fission Reactors**

Zircalloys – commonly used as cladding materials for LWRs as well as HWRs  
Prone to

a. oxidation and corrosion  
(uniform and nodular)  
– function of composition and heat treatment

b. hydriding (sunburst)  
– minimize problem thru texture, elimination of moisture in fuel pellets, eliminating hydriding centers, etc.

c. SCC / PCI (I, Cd, etc)
PCI (model – scenario)

Example: Dresden 3 (BWR)

Unirradiated - iodine vapor at 300C

Irradiated - iodine vapor at 300C

Fuel element failed after increase of power in a test reactor

Elimination / Minimization of PCI-failures

1. reduced ramp rates (ΔΦ, ΔT) – not a good solution

2. coated (barrier) fuel
   - surface coated with proper lubricant (?)

3. barrier cladding
   - ID coated with graphit, copper or pure zirconium
   - BWRs: crystal-bar Zr and Zry-2 co-extruded to form a thin Zr liner

Figure 7-11. Micrographs illustrating the four states of iodine-induced cladding failure. (Figure taken from Figure 7-1 of Reference 15 but corrected because photographs 3 and 4 were incorrectly placed there.)