NE 120 - Nuclear Materials
Fall 2007

Schedule: TTh 2:00-3:30, W 1:00-2:00, 3102 Etcheverry Hall

Professor: Brian D. Wirth, 4165 Etcheverry Hall
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Course description: Radiation effects on the properties and performance of materials in nuclear reactors. Topics include properties of uranium dioxide fuel and cladding; fission product swelling and release; and microstructural and mechanical property changes in structural alloys.

Prerequisites: E45, E115 (or ME105, ChemE141)

Grading:	Homeworks (about 7), (3) laboratory reports and in-class quizes:	30%
	Two midterm exams:	40%
	Midterm 1: Oct. 18, Midterm 2: Nov. 29	
	Final exam:	30%

Late homework will receive only partial credit. Partial credit determined by (100 - days late x 20)%, Homework will typically not be accepted more than 3 days late. (Everyone must do all assignments!)

Homework solutions will be posted on-line, after all homeworks are turned in.

Textbooks: Reference text: D. R. Olander, “Fundamental Aspects of Nuclear Reactor Fuel Elements”, TID-26711-P1, National Technical Information Services (1976) (on reserve in Engineering Library)
Course Reader: Available for download from Website

References:

- J.T.A. Roberts, *Structural Materials in Nuclear Power Systems*, Plenum Press, N.Y. (1981).
- T.J. Dolan, *Fusion Research: Principles, Experiments and Technology*, Pergamon Press, N.Y. (1980).
- J. Gittus, *Irradiation Effects in Crystalline Solids*, Appl. Sci. Pub. Ltd., London (1978).
- P. Shewmon: *Diffusion in solids*, 2nd Ed., TMS, PA (1989)
- C. Kittel, Introduction to Solid State Physics, Wiley, N.Y. (1976)

Course computer accounts:
- All students can get course computer accounts from DECF.

\- Class accounts: DECF - 1171/1109 Etcheverry Hall, http://www.decf.berkeley.edu

NE 120 - Course objectives and outcomes

Course objectives:

• Review aspects of fundamental solid state physics necessary to understand the effects of high-energy particle irradiation on crystalline solids

• Describe the processes by which irradiation, particularly by fast neutrons, effects the microstructure, mechanical properties and performance of fuel, cladding, and structural materials in a reactor core.

• Quantitatively explain the production of heat in a nuclear reactor fuel rod and the temperature distribution in a fuel pellet.

• Provide understanding of fission product behavior in ceramic fuel, including fission product formation and migration behavior, and how fission products effect fuel performance.

Course Outcomes: At the completion of the course, students will be able to...

• Calculate the maximum temperature of an operating fuel pin; understand the effect of the heat transfer resistance due to the fuel-cladding gap; understand how the thermal analysis inside the fuel rod is connected to the thermal analysis of the flowing coolant that is covered in the course NE 161.

• Solve steady state diffusion problems beginning from Fick's law; understand how the diffusion coefficient is related to the mobility of atoms in the crystalline lattice.

• Understand point defects in solids; calculate the concentration of point defects at thermal equilibrium and at steady-state conditions during neutron irradiation;understand how point defects agglomerate to form voids in metals or grow gas bubbles in the fuel.

• Analyze the processes of fission gas release and swelling of reactor fuel.

• Understand how the grain structure of ceramic UO_2influences properties such as thermal and irradiation creep rates and fission product release.

• Understand the concept and quantitative properties of dislocations, and how irradiation-produced point defect clusters influence dislocation motion and hence material properties.

• Know the principal effects of irradiation on microstrucural evolution in metals: the "black dot" structure, stacking fault tetrahedra, dislocation loops, voids, precipitates, and helium bubbles.

NE 120 - Course Outline
Lectures

1. **Introduction: Materials degradation in nuclear environments**
   1.1. Course organization, objectives and outcomes
   1.2. Radiation effects: Causes and consequences
   1.3. Nuclear fuel, cladding and structural material conditions in fission and fusion reactors
   1.4. Fabrication and processing of nuclear fuel, cladding and nuclear fuel elements
   1.5. Thermal analysis of nuclear fuel pin

2. **Review of Thermodynamics**
   2.1. Thermodynamic quantities (Free energies, chemical potentials, activity)
   2.2. Phase equilibria of alloys
   2.3. Case study: UO_2 phase diagram

3. **Crystal structures**
   3.1. Lattice types, close-packed directions and planes
   3.2. Miller indices
   3.3. Ionic solids

4. **Point defects**
   4.1. Types formed in ionic and metallic crystals
   4.2. Equilibrium defect concentrations in metallic and ionic crystals, effects of doping on Schottky defect concentrations

5. **Diffusion in Solids**
   5.1. Fick's law, the diffusion equation and mathematical solutions
   5.2. Atomic diffusion mechanisms and diffusion coefficients
   5.3. Diffusion in ionic solids

NE 120 - Course Outline
Lectures

6. Mechanical properties

6.1. Elasticity theory, definition of stresses and strains
6.2. Stress analysis (thermal and membrane/pressurized thin wall tubes)
6.3. Thermal stresses in pellets and cladding
6.4. Plastic deformation and dislocations
6.5. Mechanical properties (uniaxial tension, creep deformation and rupture, and multiaxial loading)
6.6. Creep deformation

7. Cavities in Solids

7.1. Cavity definition: pores, voids and gas bubbles
7.2. Cavity growth and shrinkage
7.3. Bubble nucleation, growth, re-solution and swelling (Booth model)
7.4. Grain size effects in polycrystalline solids, sintering and grain growth

8. Fission product behavior

8.1 Fission product yields
8.2 Swelling due to solid fission products
8.3 Fission gas behavior and fuel swelling from fission gas bubbles
8.4 Fission gas release (Booth model, including grain size effects)

9. Radiation effects in metals

9.1. Atomic collisions and energy-loss mechanisms of high-energy ions
9.2. Defect production and collision cascades
9.3. Defect balance equations
9.4. Observed microstructural defects in fcc and bcc metals
9.5 Irradiation hardening & flow localization
9.6 Time-dependent deformation (creep), creep-fatigue damage

NE 120 - Course Outline
Discussions and Laboratory Demonstrations

A. Thermal analysis of nuclear reactor fuel elements

B. Mechanical testing of irradiated materials and reactor pressure vessel embrittlement
- Charpy V-notch test, uniaxial tensile and fracture toughness tests
- Engineering model development
- Physically-based model development

C. Experimental methods to determine point defect properties
- Cryogenic ion and electron irradiation
- Electrical conductivity measurements
- Positron annihilation spectroscopy
- Isochronal annealing

D. Hydrogen embrittlement of zirconium cladding

E. Microstructural characterization techniques to investigate irradiation effects
- Transmission electron microscopy
- Atom probe tomography
- Neutron and x-ray scattering
- Positron annihilation spectroscopy