Nuclear Materials Engineering
Fall 2008

1. (**10 min**) When a material is irradiated, an equal quantity of interstitials and vacancies are created. If defect recombination were perfect, radiation damage will be self-repaired. However, irradiated metal alloys always develop voids. Why?

2. (**15 min)** Three typical methods for strengthening stainless steel are: (1) work hardening, (2) martensitic hardening, and (3) precipitation hardening.

> (10 min) Select two of these methods and explain the fundamental hardening mechanism for each.
> (5 min) In comparison, explain how radiation hardens steel.

3. (15 min) For the mechanism of defect clustering, what is the difference between coalescence, Ostwald ripening and the reverse Ostwald ripening process. Why do most alloys exhibit Ostwald ripening?

4. (20 min) Fuel Restructuring.

> (5 min) Sketch the radial cross section of high burnup UO_2 fuel pellet and label all the key features.
>
> (5 min) Explain the mechanism that drives the formation of columnar grains and a central hole/void.
>
> (10 min) Describe the physical state, chemical form, and physical location of the various types of fission products present in the fuel pin at high burnup.

5. (10 min) Assume you have a structural material with a thermal displacement cross section of ~1 b, and a number density of ~10^{22} atoms/cm^3. Assume the reactor operates for 300 days a year with a nominal thermal flux of 10^{13} n/cm^2•s and the nominal value for ν is ~1000 displacements/pka.

> (5 min) How long must you irradiate it in an LWR to achieve a damage level of 1 dpa?
> (5 min) What fluence has this material been exposed to at 1 dpa?

6. (15 min) Describe two mechanisms that cause the thermal conductivity of UO_2 to change with high burnup and discuss their implications (in other words, "what happens and why do we care?")

7. (20 min)

Table: Free Energy of Formation (ΔG_f = -RTlnK in kcal/mole)

Temp. (ºC)	$U + O_2 \rightarrow UO_2$	$2Gd + 1.5O_2 \rightarrow Gd_2O_3$	$Mo + O_2 \rightarrow MoO_2$
500	-227	-386	-106
1000	-207	-353	-86
1500	-178	-320	-67
2000	-160	-286	-48

(10 min) Construct an Ellingham-style stability diagram (ΔG vs. T) for the oxides listed above based on the tabulated data to compare (per mole O_2) the relative stability of the various oxides.

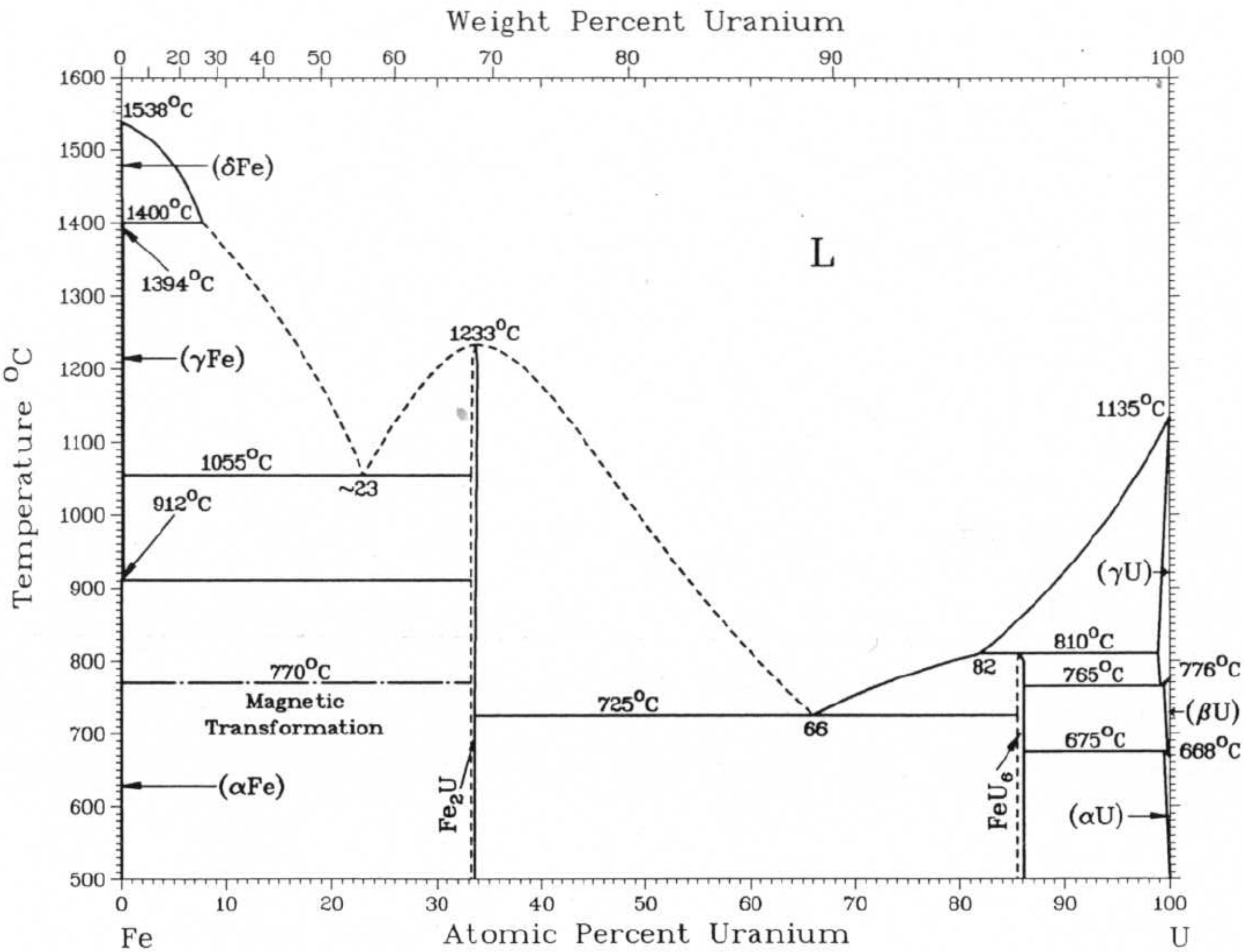
(5 min) Gd is a common burnable poison. If it is embedded in UO_2, will it be an oxide or a metal?

(5 min) Mo is a common fission product. If generated in UO_2 fuel, will it be an oxide or a metal?

8. (15 min) Use the U-Fe phase diagram on the next page to answer questions about cooling a U-20 wt% Fe hypoeutectic alloy from 1500ºC:

(5 min) Estimate the liquidus temperature for this composition. Sketch the equilibrium microstructure at room temperature (label phases) that will form as the alloy is cooled slowly.

(10 min) Calculate the volume fraction of each phase present at this composition at room temperature.



Weight Percent Uranium
Temperature °C
Atomic Percent Uranium
Fe
U
L
1538°C
(δFe)
1400°C
1394°C
(γFe)
1233°C
1135°C
1055°C
~23
912°C
(γU)
810°C
82
776°C
765°C
770°C
Magnetic
Transformation
725°C
66
(βU)
675°C
668°C
Fe2U
FeU6
(αFe)
(αU)