1. **(10 min)** An alloy has the composition 50 wt % Ni – 30 wt % Fe – 15 wt % W – 5 wt % C. What is the composition of this same alloy in atom percent?

   \[
   \begin{align*}
   M_{\text{Ni}} &= 58.69 \text{ g/mol} \\
   M_{\text{Fe}} &= 55.85 \text{ g/mol} \\
   M_{\text{W}} &= 183.84 \text{ g/mol} \\
   M_{\text{C}} &= 12.01 \text{ g/mol}
   \end{align*}
   \]

2. **(30 min)** Consider a scenario where one element is homogeneously introduced into Fe as an alloy solute. The atomic radius of this element is smaller than that of Fe. Answer the following questions:

   (a) If this element occupies an Fe lattice site, describe the nature of structural relaxation around the element. Schematically sketch the position changes of atoms surrounding Fe atoms.

   (b) In comparison with pure Fe, will adding the element increase or decrease the yield strength? Explain why.

   (c) If the solute diffuses and interacts with an edge dislocation strain field, sketch the edge dislocation and mark the trapping region for the solute.

   (d) Describe how the substitutional solute interacts with radiation induced point defects. Name the type of point defects (vacancies vs. interstitials) which prefer to be trapped by the solute atoms.

   (e) As the alloy experiences particle-induced irradiation damage, describe the elemental profile changes across the grain boundary (unchanged, enriched, or depleted)? Explain why.

3. **(15 min)** Defect population changes during radiation damage are often modeled by the continuum method which uses a series of equations to describe defect diffusion and interactions. This method is also called rate theory. Write down one equation to calculate the time rate change of interstitial population. Introduce all parameters needed and define them. The following must be considered: (a) point defects (interstitials and vacancies) present in the system are allowed to diffuse with independent diffusivities, (b) interstitials and vacancies are allowed to recombine, and (c) interstitials are allowed to form di-interstitials (i.e., where two interstitials meet to form one di-interstitial defect).

4. **(15 min)** Consider a charged particle (e.g. an energetic fission fragment) which penetrates a solid crystal structure and answer the following.
(a) Sketch a plot of the nuclear and electronic stopping powers as a function of particle energy. The stopping powers are the energy loss per unit flying distance. Present a wide range of energies to show the typical energy dependence features of both stopping powers.
(b) On the sketch from part (a), identify the energy regions in your plot that correspond to the maximum creation of ionization and maximum creation of displacements, respectively.
(c) Will increasing the initial energy of the charged particle always increase the number of total defects (interstitials and vacancies) created in an infinite solid?

5. (20 min) Answer the following:
   (a) (5 min) Write the Arrhenius-type expression defining the number of thermal vacancies, \( N_v \), formed within a crystal and define all terms.
   (b) (5 min) Sketch the typical \( \ln(N_v) \) vs. \( 1/T \) representation for this thermally-activated behavior. Label the axes carefully and identify the meaning of the slope of the curve.
   (c) (10 min) If the equilibrium number of vacancies in a metal increases by a factor of 2.7 when the temperature is increased from 1000 K to 1200 K, calculate the activation energy, \( Q_v \) (in kJ/mol), for vacancy formation.

   *Assume density changes are negligible over this temperature range.*

   \[ R = 8.314 \text{ J/mol-K} \]

6. (20 min) Delta (\( \delta \)) phase plutonium exists with a face centered cubic structure. Assume the atomic radius is 0.174 nm and its atomic mass is nominally 244 amu.
   (a) Calculate the theoretical density of Pu using these parameters
   (b) Schematically draw a face centered cubic structure unit cell and calculate the atomic packing factor for the cell.
   (c) Re-draw an FCC unit cell and draw the (101) plane. Identify the magnitude and Miller indices of the lowest energy Burgers vector in the cell.
   (d) Unlike many elements in the periodic table that have very precise atomic masses, why are we limited to using nominal values for Pu with a limited number of significant figures?

7. (10 min) Compare the benefits and weaknesses of oxide, metal, and nitride nuclear fuels with respect to at least two material properties. Specify the type of reactor that each fuel may be best suited for and explain why you made that selection.