Ph.D. Qualifying Examination
Fission Engineering

1. (15 min.) A uranium oxide fuel pin of diameter 2.4 cm is operating at a linear power of 175 W/cm. The maximum centerline temperature is 1614°C, and the thermal conductivity is 0.025 W/cm°C. The ∆T between the fuel pellet surface temperature and the coolant temperature is 50°C.

This fuel pin is replaced with a fuel pin of identical dimensions containing nitride fuel. The clad materials and the coolant conditions remain the same. The thermal conductivity of nitride fuel is 2.1 W/cm°C, and the density of nitride is higher, 14.6 g/cm³ compared to 10.96 g/cm³ for oxide.

What is the centerline temperature for the nitride fuel pin?

2. (15 min.) A Pb-cooled fast reactor design with a capacity of 1500 MW(thermal) will be used to supply process heat. The industrial production process requires 50,000 MW(thermal) over a 15 minute period. This cycle is repeated every hour. The system is designed with an intermediate thermal storage facility to accumulate the energy, then discharge it to the industrial production process as needed. For this situation,

(a) What capacity will be needed for the intermediate thermal storage facility?

(b) How many reactors at what load or capacity factor will be needed to supply this system?

(c) What design would you propose for the intermediate thermal storage facility to meet this requirement?

3. (30 min.) An advanced boiling water reactor operates at electrical output of 1000 MWe. Its thermodynamic efficiency is 32%. The core inlet enthalpy is 1200 kJ/kg, and the inlet mass flow rate is 1.25 x 10⁴ kg/s. The reactor pressure is 7.0 MPa.

(a) Find the average core outlet enthalpy.

(b) Find the average outlet quality.

(c) Find the total steam flow out of the reactor.

(d) Under the assumption of homogeneous flow, what is the outlet void fraction? To what flow regime does this correspond?

(The Steam Tables are included for your use.)
4. (25 min.) Assume that a Westinghouse-type PWR power plant is operating under normal steady-state conditions, producing 10% of its full power. Following operation of considerable length at this power level, a 5% of full power step increase is introduced to the plant.

(a) (85%) Sketch the transient responses of the following variables starting from the time the step load change is introduced, until a new steady-state is achieved:

(1) (10%) Secondary steam pressure (steam dome pressure),
(2) (10%) Steam generator downcomer water level,
(3) (10%) Cold-leg temperature,
(4) (10%) Hot-leg temperature,
(5) (15%) Average core coolant temperature,
(6) (15%) Neutronic power,
(7) (15%) Total core reactivity.

(b) (15%) Assuming that no external reactivity is added to or removed from the core, would a change in the demanded load always result in a new steady-state operating condition? Explain.

5. (15 min.) Consider a loss-of-coolant accident in an advanced Westinghouse AP-1000, a 1000 MWe pressurized water reactor. As the reactor depressurizes, cold water is injected into the core through the passive safety systems. To perform an analysis for this event, would it be best to use homogeneous, drift flux, or two-fluid two-phase models? Justify your selection.
6. (20 min.) You are the design engineer in charge of selecting the coolant for a whole new reactor design. You may use either water or sodium, but the goal of your selection process is to achieve maximum heat transfer capability with minimum pumping power requirements. You decide to compute the dimensionless ratio \( \frac{q}{W} \), where \( q \) is the heat transfer from the cladding to the coolant (MW) and \( W \) is the pumping power (MW). You analyze the generic fuel pin-coolant channel shown below.

![Diagram of a fuel pin-coolant channel]

\[ q = h_{db} PL(T_c - T_{bulk}) \]  
Heat Transfer to Coolant

- \( h_{db} \) - single phase heat transfer coefficient
- \( T_c \) - core average cladding temperature
- \( T_{bulk} \) - core average coolant temperature

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(a) Form the dimensionless ratio \( \frac{q}{W} \) and simplify as possible.

\[
\begin{pmatrix}
\frac{q}{W} \\
\end{pmatrix}_{\text{water}}
\]

(b) Form the dimensionless ratio \( \frac{q}{W} \) and simplify as possible.

\[
\begin{pmatrix}
\frac{q}{W} \\
\end{pmatrix}_{\text{sodium}}
\]

Assume the channel geometry, coolant velocity and \( T_c - T_{\text{Bulk}} \) are the same for the water and sodium designs.

(c) For the properties listed below, evaluate your answer from Part (b) and explain the coolant you would select.

\[
\begin{align*}
C_p \left( \frac{\text{BTU}}{\text{lbm} \cdot ^\circ \text{F}} \right) & \quad K_f \left( \frac{\text{BTU}}{\text{hr} \cdot \text{ft} \cdot ^\circ \text{F}} \right) & \quad \mu \left( \frac{\text{lbm}}{\text{ft} \cdot \text{hr}} \right) \\
\text{water} & \quad 1.51 & \quad 0.292 & \quad 0.210 \\
\text{sodium} & \quad 0.312 & \quad 43.8 & \quad 0.835
\end{align*}
\]

\[
W_p = A_c V f \frac{L}{D_e} \rho \frac{V^2}{2} \quad \text{Pumping Power}
\]

\( D_e \) - channel equivalent hydraulic diameter

\( f \) - friction factor = 0.79 \( \text{Re}^{-0.2} \)

You may find the following dimensionless numbers useful:

Nusselt number \( = \frac{h D_e}{K} \)

Reynolds number \( = \frac{\rho V D_e}{\mu} \)

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Prandtl number \[ = \frac{\mu C_p}{K} \]

Mach number \[ = \frac{V}{\sqrt{\frac{C_p}{C_v} RT}} \]

Stanton number \[ = \frac{h}{\rho V C_p} \]
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Note: The table continues with similar data entries.