Ph.D. Qualifying Examination
Fission Engineering

1. (20 min.) The Advanced High Temperature Reactor (AHTR) is an innovative new concept that combines a number of attractive features from existing systems. In the AHTR, the core is based on the prismatic high temperature gas reactor in which the fuel consists of bonded coated particles inserted into graphite blocks. The graphite blocks have axial channels through which the coolant flows. However, for the coolant, instead of high-pressure helium, heat is removed by means of flowing molten salt operating at near ambient pressures.

   (a.) (50%) Core power is 1000 MWth. Qualitatively sketch the temperature rise along one of the coolant channels for the two different coolants, helium and molten salt. Assume that the channel exit temperature is 1000 °C for both cases. Explain the differences.

   (b.) (50%) Several salt mixtures can be used. What would be desirable characteristics for the molten salt coolant from the thermal hydraulics perspective?

2. (20 min.) Although there have been no nuclear plants built in the U.S. in the past 10 years, the fraction of electricity generated by nuclear power has increased. This has occurred for two reasons. The first has been the reduction in the outage times for refueling so that a plant is generating electricity a greater percentage of each year. The second reason is that several plants are applying for and receiving approval from the Nuclear Regulatory Commission for “power uprates.” This is possible because many conservative assumptions were used to develop the original designs. However, with the advent of more sophisticated computational techniques and improved data, it has been determined that existing plants can operate at higher powers with little or no change in the plant itself. Some of the uprates are for as much as a 20% increase in power.

   For a particular nuclear power plant, the fuel element dimensions consist of a fuel pellet with a diameter of 0.94 cm and a clad outer diameter of 0.98 cm. The heat flux into the coolant is 48.72 W/cm².

   After the power uprate and pellet re-design, the heat flux into the coolant is increased by 20% over its original value. The dimensions of the new fuel element are a fuel pellet diameter of 0.91 cm, and an outer clad diameter of 0.95 cm.

   Determine the ratio of the average volumetric heat source, q′′′(W/cm³), for the uprated case compared with the heat source for the original design.
3. (25 min.) Consider a $^{235}\text{U}$ fueled reactor operating in the Intermediate Power Range, i.e., above neutron source effects (10^{-8}\% Power) and below feedback effects (10^{-2}\% Power). Two separate power transients are described below. For both transients power passes through 10^{-7}\% at time "t".

(a.) (50\%) With the reactor at steady-state, $k_{\text{eff}} = 1$, and at 10^{-7}\% Power, 0.0010 (k-1)/k units of reactivity are rapidly added to the core.

Sketch (on the attached graph paper) the trace of power versus time starting from the initial steady-state condition and continuing until a stable reactor period develops. Explain the relevant neutronic phenomena which govern this transient.

(b.) (50\%) For the next transient, reactor power has been brought to 10^{-8}\% Power. A stable period is established by the addition of 0.0010 (k-1)/k units of reactivity and power is allowed to increase. As the power is increasing through the value of 10^{-7}\% Power, 0.0010 (k-1)/k units of reactivity are rapidly added to the core.

On the same axes as Part (a), sketch the trace of power versus time and explain the relevant neutronic phenomena. In particular, explain how and why the Part (b) transient differs from the Part (a) transient.

4. (30 min.) Commercial reactor fuel pins are fabricated with an initial helium gas charge to aid in heat transfer and structural aspects. The design of the fuel pin includes the selection of an initial helium charge pressure.

Fuel pin designers select an internal pressure which puts the cladding in a tensile stress state under the following conditions:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>$T_i$</td>
<td>fuel/gas ambient temperature 68°F</td>
</tr>
<tr>
<td>$p_p$</td>
<td>fuel internal pressure at ambient temperature – to be determined</td>
</tr>
<tr>
<td>$p_{i}$</td>
<td>primary coolant pressure (at ambient temperature) 15 psig</td>
</tr>
</tbody>
</table>

The fuel pin is in a compressive stress state at normal plant operating temperature and pressure given by:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_f$</td>
<td>normal gas temperature 610°F</td>
</tr>
<tr>
<td>$p_f$</td>
<td>primary pressure during normal operation 2250 psig</td>
</tr>
</tbody>
</table>

For purposes of this problem, consider only the cladding hoop stress.

Find the initial helium charge pressure, $p_p$, which results in the magnitude of the tensile stress at ambient conditions being equal to the magnitude of the compressive stress at normal operating conditions.
5. (25 min.) During shutdown conditions in a PWR, primary coolant flow is driven by natural circulation at a rate corresponding to about 1% of the flow rate provided by the pumps. The total flow rate is 4686 kg/s when driven by the pumps.

The single steam generator in the plant under consideration has approximately 3800 tubes of 0.0222 m inside diameter and average length 16.5 m.

(a.) For shutdown conditions, determine:

(i) Whether the flow in the steam generator tubes is turbulent or laminar.
(ii) The value of the friction factor.
(iii) The frictional pressure loss between the inlet and outlet of the tubes.

Use $\rho = 1000 \text{ kg/m}^3$, $\mu = 0.001 \text{ kg/m} \cdot \text{s}$ and the accompanying Moody chart.

(b.) For the condition of full flow through the steam generator, find the same quantities asked for in part (a).

(c.) Compare and discuss the friction factors and pressure drops of the two cases.
Figure 9-20 Moody's chart for friction factors: Friction factor for use in the relation \( \Delta p \) for pressure drop for flow inside circular pipes. (From Moody [20].)