22.312 ENGINEERING OF NUCLEAR REACTORS

Tuesday, December 16th, 2014, 9:00 a.m. – 12:00 p.m.

OPEN BOOK FINAL EXAM 3 HOURS

Problem 1 (20%) – Power Uprate in a PWR Core

Consider the hot channel in a PWR core. You wish to increase the power in that channel by 30%, without changing the outlet temperature and pressure. You are to evaluate two alternative approaches:

A. Reduced inlet temperature; same mass flow rate

B. Increased mass flow rate; same inlet temperature

Please answer the following questions:

i) If the value of the MDNBR in the reference case is 1.6, what is the value of the MDNBR in approaches A and B? You may assume the heat flux in the channel is axially uniform. (15%)

ii) Which approach would you choose? In answering this question, please consider the results in Part 'i', but also any other design and operation aspects that you deem appropriate. (5%)

Problem 2 (15%) – Use of a Spring to Reduce the Cladding Stresses

As a means to reduce the stresses in the cladding of a BWR fuel rod, a nuclear engineer proposes to use a spring that compresses the fuel pellets, as shown in Figure 1. The rod outer diameter and cladding thickness are 11.2 and 0.5 mm, respectively. During operations the pressure inside the rod (due to the filler gas and fission gases) is 3 MPa and the coolant pressure is 7 MPa. At these conditions the spring is compressed by 1 cm. Calculate the rigidity constant of the spring [N/m] that will result in a zero axial stress (σ_z) in the cladding.

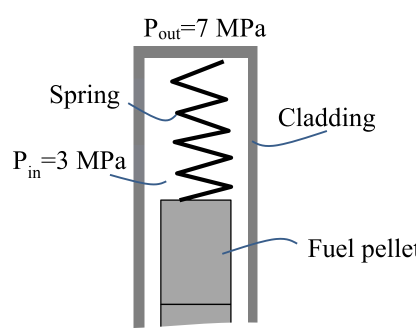

Figure 1. Schematic of the fuel rod end (not to scale)

Problem 3 (65%) – Debris Transport following a LOCA in a PWR Containment

The occurrence of a Large-Break Loss of Coolant Accident (LB-LOCA) in a Pressurized Water Reactor (PWR) would cause the generation of large amounts of debris within the containment, i.e. mostly fibers from the insulation around primary system pipes and components. Such debris would be washed to the containment sump along with any dirt normally present within the containment. Water that accumulates in the sump is used by the Emergency Core Cooling System (ECCS), i.e. the sump pump injects that water into the reactor vessel. This situation is shown schematically in Figure 2. There is a concern that the debris could be transported to the core by the sump pump and there clog the fuel channels, thus preventing core cooling in the long term. To minimize the probability of debris transport, it is desirable to limit the coolant flow rate from the sump pump to the minimum flow rate required to remove the decay heat.

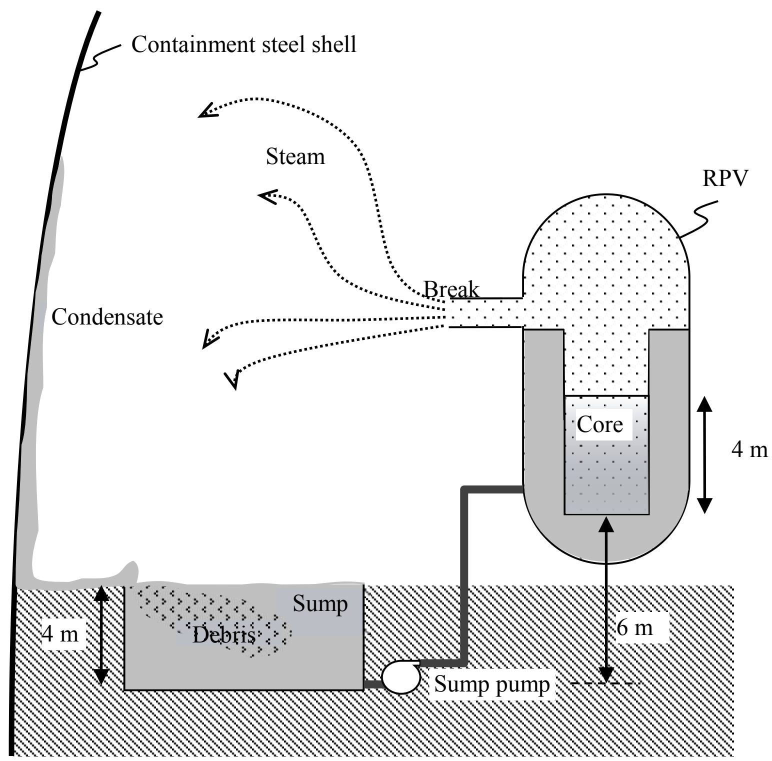

Figure 2. Post-LOCA recirculation within containment

In answering the following questions, please state and justify all your assumptions. The properties needed for this problem are reported in the table on the last page of this exam.

i) Calculate the minimum flow rate required to remove the decay heat by boiling, one hour after shutdown, for a PWR of nominal power equal to $\dot{Q}_0$ =4000 MWt. Assume the sump water is saturated at 0.101 MPa. Assume the reactor had operated for an infinite period of time prior to shutdown. (10%)

Now focus on the debris in the water that accumulates in the sump. The total volume of water in the sump is 100 m^3 and its depth is 4 m.

ii) Calculate the debris terminal velocity for gravity settling, V_d. You may assume the debris are spherical, have a density of 3500 kg/m^3, and a constant drag coefficient, $C_d \equiv F_d /(A_d \rho_f V_d^2 /2)$, equal to 3, where F_d is the drag force, $A_d = \pi D^2 / 4$ is the frontal area of the debris, D=100 μm is the effective average diameter of the debris, and ρ_f = 958 kg/m^3 is the density of water in the sump. (10%)

iii) Using the results in Parts 'i' and 'ii', compare the time scale for debris settling in the sump to the time scale for debris flow through the sump, and determine if the debris actually settle to the bottom of the sump. (5%)

Steam exits the primary system through the break and is condensed somewhere in the containment; the condensate drips back into the sump, from which it is pumped to the core, effectively realizing a loop (see Figure 2).

iv) Calculate the power required by the sump pump to deliver a coolant mass flow rate of 23 kg/s to the core. (10%)
In answering your question you may make use of the following assumptions:
- Steady-state operation
- The pump has an isentropic efficiency of 85%
- Neglect all friction and form pressure losses in the loop except for the pressure loss in the core, which can be modeled as a single form loss with coefficient K_{core} = 150. Use the density of steam ρ_g and the flow area of the core (6 m^2) to calculate the form pressure loss.
- Neglect all acceleration pressure changes in the loop.
- Consider gravity pressure changes throughout the loop. Relevant elevations are shown in Fig. 2.
- Assume the steam quality varies linearly in the core from zero (inlet) to one (outlet); use HEM to calculate the average density in the core.

Now focus on the containment shell, which is 3-cm thick and made of steel with thermal conductivity 35 W/m°C. There is air at 40°C circulating on the outer surface with a heat transfer coefficient of 40 W/m^2°C. Condensation of steam at 100°C occurs on the inner surface with a heat transfer coefficient of 800 W/m^2°C.

v) What is the minimum containment surface area required to condense 23 kg/s of steam? (10%)

vi) What design changes would you consider if you wished to reduce the minimum surface area requirement in Part 'v'? A qualitative answer is acceptable. (5%)

Now focus on the containment as a whole. Its free volume is $V_c = 60{,}000$ m^3. The total mass of air is $M_a = 7\times10^4$ kg. At a certain time after the LB-LOCA the temperature in the containment atmosphere is 100°C and the total amount of water (steam + liquid) is $M_w = 3\times10^5$ kg.

vii) What is the volume occupied by the liquid and what is the volume occupied by the steam? In answering this question you may assume the liquid water/steam mixture in the containment is saturated. (10%)

viii) What is the total pressure in the containment? Treat air as a perfect gas (R=286 J/kg-K, c_v=719 J/kg-K). (5%)

Properties of saturated water at 0.101 MPa

Parameter	**Value**
T_{sat}	100°C
ρ_f	958 kg/m^3
ρ_g	0.6 kg/m^3
h_f	419 kJ/kg
h_g	2676 kJ/kg
c_f	4.22 kJ/(kg°C)
c_g	2.03 kJ/(kg°C)
μ_f	2.8×10^{-4} Pa·s
μ_g	1.2×10^{-5} Pa·s
k_f	0.681 W/(m°C)
k_g	0.025 W/(m°C)
σ	0.059 N/m