

22.312

ENGINEERING OF NUCLEAR REACTORS

Wednesday, December 17<sup>th</sup>, 2008, 9:00am-12:00 pm

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FINAL EXAM

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NAME:

**PART A (20%)**

CLOSED BOOK

i) Define (two sentences max) the following two-phase flow and heat transfer terms, and mark if the associated phenomena occur at *normal operating conditions* in the PWR core, BWR core, or both. (Please write your answers on this sheet)

**Flow boiling** .....

.....

PWR....      BWR....

**Subcooled boiling**.....

.....

PWR....      BWR....

**Nucleate boiling**.....

.....

PWR....      BWR....

**Film boiling**.....

.....

PWR....      BWR....

**Pool boiling**.....

.....

PWR....      BWR....

**Transition boiling**.....

.....

PWR.... BWR....

**Departure from nucleate boiling (DNB)** .....

.....

PWR.... BWR....

**Dryout**.....

.....

PWR.... BWR....

**Critical Flow**.....

.....

PWR.... BWR....

ii) For a given fluid, and fixed operating pressure and mass flow rate, rank the following heat transfer modes in descending order of heat transfer coefficient (1 = highest htc, 4 = lowest htc):

Single-phase (liquid) convection: .....

Subcooled nucleate boiling: .....

Saturated nucleate boiling: .....

Film boiling: .....

Please give your Part A answers to the instructor BEFORE starting to work on Part B.

**PART B (80%)**

OPEN BOOK

**Problem 1 (40%) – PWR fuel pin with a thin gap and no fill gas**

A bright 22.312 student wants to reduce the gap thickness in the fuel pin of a PWR, in the hope to decrease the thermal resistance of the gap, and thus be able to operate the fuel at lower temperatures. He also wants to eliminate the helium fill gas, to cut manufacturing costs. His new fuel pin design has the following *as-manufactured* dimensions:

- UO<sub>2</sub> pellet radius: 4.1 mm
  - Gap thickness: 10 μm
  - Zircaloy clad thickness: 0.4 mm
- i) During normal operation, the fuel pellet radius expands by 0.5% due to irradiation effects. As a result, the clad and pellet make contact. Assuming a coolant pressure of 15.5 MPa, calculate the value of the force per unit area exerted by the fuel pellet on the clad,  $P_i$ , in this situation. ( *Hint*: assume that the fuel pellet is perfectly rigid). (20%)
- ii) For the situation described in ‘i’, calculate the principal stresses in the clad and judge their acceptability using the Tresca criterion. (15%)
- iii) What are the merits and shortcomings of the student’s idea? (5%)

*Assumptions*

Treat the clad as a thin shell.

*Properties of Zircaloy at the temperatures of interest*

Yield strength: 200 MPa

Density: 6600 kg/m<sup>3</sup>

Young’s modulus: 80 GPa

Poisson’s ratio: 0.35

## Problem 2 (40%) – Thermal-Hydraulic Analysis of a Boiling Test Facility

The Reactor Heat Transfer team at a national lab is designing a loop to conduct thermal-hydraulic experiments with water at 5 MPa. The test section of the loop is going to be an annular channel of 1-m length with an inner wall of 1-cm diameter and an outer wall of 2-cm diameter. The inner wall is uniformly heated, while the outer wall is adiabatic. In the first series of experiments the team wishes to maintain the test section inlet and outlet temperatures at 200 °C and 250°C, respectively.

- i) Find the mass flow rate and power at which the boiling crisis occurs in this situation. You may assume that the specific heat is constant in the subcooled region. To predict the boiling crisis, use either the Tong-68 or the CISE-4 correlation (given below), whichever is appropriate for the situation of interest. (25%)

*Tong -68 correlation*

$$q''_{DNB} = K_{Tong} \frac{G^{0.4} \mu_f^{0.6} h_{fg}}{D_e^{0.6}} \text{ with } K_{Tong} = [1.76 - 7.433x_e + 12.222x_e^2] \cdot \left[ 1 - \frac{52.3 + 80x_e - 50x_e^2}{60.5 + (10P)^{1.4}} \right],$$

$P$  in MPa

*CISE-4 correlation*

$$x_{cr} = \frac{P_h}{P_w} a \frac{L_b}{L_b + b} \text{ with } a = (1 - P/P_{cr})/(G/1000)^{1/3} \text{ and } b = 0.199(P_{cr}/P - 1)^{0.4} GD_e^{1.4},$$

$G$  in kg/m<sup>2</sup>s and  $D_e$  in m.

- ii) Now assume that the operating conditions are as follows: power = 50 kW, mass flow rate = 0.5 kg/s, inlet temperature = 260°C. Estimate the flow quality at the channel outlet. (10%)
- iii) Everything else being the same (i.e., flow rate, pressure, power, inlet temperature), would you expect the void fraction (at any location) in the test section to be higher or lower or the same, if the direction of the flow were upward vs downward? (5%)

**Table 1. Properties of water at 5 MPa**

Parameter	Value
$T_{sat}$	264°C
$\rho_f$	780 kg/m <sup>3</sup>
$\rho_g$	25 kg/m <sup>3</sup>
$h_f$ 1155	kJ/kg
$h_g$ 2795	kJ/kg
$C_{p,f}$	5.0 kJ/(kg°C)
$C_{p,g}$	4.4 kJ/(kg°C)
$\mu_f$	$1 \times 10^{-4}$ Pa·s
$\mu_g$	$2 \times 10^{-5}$ Pa·s
$k_f$	0.6 W/(m°C)
$k_g$	0.05 W/(m°C)
$\sigma$	0.02 N/m

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