

**PhD Qualifying Exam
Nuclear Engineering Program**

Part 1 – Core Courses
(Solve 3 problems only)

8:00 – 11:00 am, April 6, 2018

(1) Nuclear Reactor Analysis

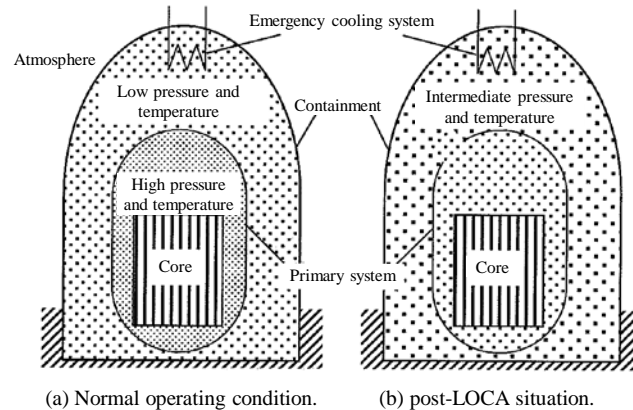
A homogenous spherical reactor of radius R is placed in a vacuum. If the reactor is critical, and if the extrapolation distance is significantly smaller than R ,

- a) (41%) Derive a formulation for the flux distribution in the reactor
- b) (59%) Derive a formulation for the constant coefficient of flux in terms of reactor power (P)

[Hint: $\nabla^2 = \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial}{\partial r} \right) + \frac{1}{r^2 \sin \vartheta} \frac{\partial}{\partial \vartheta} \left(\sin \vartheta \frac{\partial}{\partial \vartheta} \right) + \frac{1}{r^2 \sin^2 \vartheta} \frac{\partial^2}{\partial \varphi^2}$]

(2) Reactor Thermal Hydraulics

An advanced helium-cooled graphite-moderated reactor generates a nominal thermal power of 300 MW. To prevent air ingress in the core during a Loss Of Coolant Accident (LOCA), the reactor containment is filled with helium at atmospheric pressure and room temperature. The reactor also features an emergency cooling system to remove the decay heat from the containment during an LOCA. To function properly, this system, which is passive and based on natural circulation of helium inside the containment, requires a minimum containment pressure of 1.3 MPa.



- (40%) Find the containment volume, so that the pressure in the containment is 1.3 MPa immediately after a large-break LOCA occurs (see above figure). (Assume that thermodynamic equilibrium within the containment is achieved instantaneously after the break.)
- (60%) Assuming that the emergency cooling system removes 2% of the nominal reactor thermal power, calculate at what time the pressure in the containment reaches its peak value after the LOCA as well as the peak temperature and pressure.

Assumptions:

- Treat helium as an ideal gas. The ideal gas equation is given as $PV = nRT$.
- Neglect the heat contribution from fission and chemical reactions.
- Neglect the thermal capacity of the structures.
- The decay power Q can be calculated by: $Q = 0.066 Q_0 t^{-0.2}$, where Q_0 and t are the normal operating power and time after reactor shutdown, respectively.

Data:

- Gas volume in the primary system: 200 m^3
- Initial primary system temperature and pressure: 673 K, 7.0 MPa
- Initial containment temperature and pressure: 300K, 0.1 MPa
- Helium-specific heat at constant volume: $c_v = 12.5 \text{ J}/(\text{mol} \cdot \text{K})$
- Helium atomic weight : $M = 0.004 \text{ kg/mol}$
- The universal gas constant: $R = 8.314 \text{ J}/(\text{mol} \cdot \text{K})$

(3) Advanced Nuclear Materials

The student can select one of the following three problems. Answer only one of the questions below.

Question 1:

- a. (25%) Explain the mechanism behind radiation-induced solute segregation.
- b. (25%) Explain the mechanism behind radiation-induced precipitation.
- c. (25%) What is radiation-enhanced diffusion?
- d. (25%) How does interstitial dislocation loop form under irradiation?

Question 2:

(100%) In a molten salt-based electrorefiner for U and Pu separation. The anode is U-Pu alloy with a mole ratio U:Pu=1:1. U^{3+} and Pu^{3+} are the stable ions in the salt. The mass transfer coefficient of the both ions are K , and the surface area of the anode is A . U has a mole fraction concentration of X_U in the salt and there is no Pu in the salt at the beginning. If a constant current I is applied, deduce the expression of partial current of Pu^{3+} and U^{3+} at the beginning of operation.

All the parameters are in SI units.

Question 3:

Using metal additives is one of the methods to stabilize fission products when using U-Zr in a sodium-cooled fast reactor. During U-Zr fabrication, the additive can dissolve into the fuel matrix as a metal solute or form a compound ZrA_n (A is the additive). During operation, the fission products can react with the additive and ZrA_n . Considering a fission product B which is assumed to be uniformly produced in the fuel matrix as a solute and can form a compound BA_m .

- 1) (40%) Identify all the chemical reactions that lead to BA_m formation
- 2) (60%) If all the reaction constants are known for each reaction, deduce all the mathematical equations for the rate of BA_m formation, and B and Zr redistribution.

(4) Radiation Detection and Shielding

Answer both questions below.

1. (50%) The U.S. Navy has a rule of thumb that the expected dose-equivalent rate in air from a 1 Curie Cobalt-60 radioisotope point source will be 1 rem/hour at a distance of 1 meter. Derive the dose-equivalent rate for this case and compare your result to the rule of thumb used by the U.S. Navy. You may use the data/equation sheet attached for assistance.

2. A designer of a radiation counting system has the option of either doubling the signal from the source or reducing the background by a factor of 2. From the standpoint of counting statistics (i.e. smaller error), which option should be chosen under the following conditions (you must justify your answer with calculations) (you may use the data/equation sheet attached for assistance):

(a) (25%) The signal is large compared with background.

(b) (25%) The signal is small compared with background.

Radiation Detection Data and Equation Table

Exposure Rate Constants, Γ_δ	(Roentgen · cm ²)/(hr · mCi)
Cesium-137	3.3
Cobalt-60	13.2
Potassium-40	0.9

$$\left(\frac{\mu}{\rho}\right)_c = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i$$

$$I(x) = I_0 e^{-(\mu/\rho)\rho x}$$

$$I(x) = I_0 B(x, E_\gamma) e^{-\mu x}$$

1 Roentgen = 2.58×10^{-4} coulombs/kg

For γ -ray absorbed dose in air, 1 coulomb/kg = 33.8 joules/kg = 33.8 Grays

1 Sievert = 100 rem

General error propagation formula for a calculated variable $u(x, y, z, \dots)$:

$$\sigma_u^2 = \left(\frac{\partial u}{\partial x}\right)^2 \sigma_x^2 + \left(\frac{\partial u}{\partial y}\right)^2 \sigma_y^2 + \left(\frac{\partial u}{\partial z}\right)^2 \sigma_z^2 + \dots$$

The optimal division of counting time:

$$\left. \frac{T_{S+B}}{T_B} \right|_{\text{opt}} = \sqrt{\frac{S+B}{B}}$$

Figure of merit:

$$\frac{1}{T} = \epsilon^2 \frac{S^2}{(\sqrt{S+B} + \sqrt{B})^2}$$

where $T = T_{S+B} + T_B$, and $\epsilon = \frac{\sigma_S}{S}$,

$$S = \frac{N_{S+B}}{T_{S+B}} - \frac{N_B}{T_B}, \text{ and } B = \frac{N_B}{T_B}$$

Critical level:

$$L_C = 2.33\sigma_{N_B}$$

$$N_D = 4.65\sqrt{N_B} + 2.71, \text{ "Currie equation"}$$

(5) Advanced Engineering Mathematics

For a parallelepiped of size $(a * b * c)$ with a constraint expressed by

$$Q^2 = \left(\frac{\pi}{a}\right)^2 + \left(\frac{\pi}{b}\right)^2 + \left(\frac{\pi}{c}\right)^2$$

Determine a relation among a, b & c for achieving a minimum volume (100%).

[Hint: you can use the Lagrange Multiplier Approach, its formulation is expressed by

$$\mathcal{L} = A + \lambda\alpha,$$

Where A is a quantity that has to be minimized, α is a constraint, and λ is the Lagrange multiplier coefficient]

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Part 2 – Specialty Part
Thermal Hydraulics and Reactor Safety

1:00 pm – 4:00 pm, April 6, 2018

Specialty – Thermal-hydraulics and Reactor Safety (1) (25%)

The design criterion for the A.C. power system for a reactor is that it must have a failure probability of less than $2 \times 10^{-5} \text{ year}^{-1}$. Off-site power failures may be expected to occur about once in five years.

- a) If the on-site A.C. power system consists of two independent diesel generators, each of which is capable of meeting the A.C. power requirements, what is the maximum failure probability per year that each diesel generator can have if the design criterion is to be met. [60%]
- b) If three independent diesel generators are used in parallel, what is the value of the maximum failure probability? [40%]

Specialty – Thermal-hydraulics and Reactor Safety (2) (37.5%)

Consider a fully developed turbulent flow in a round pipe,

- Sketch the velocity profile, and compare it with laminar flow. [30%]
- Sketch the radial distributions of the viscous, turbulent and total shear stresses. [30%]
- Briefly explain how to derive the Reynolds-averaged Navier–Stokes equation,

$$\frac{\partial \rho \bar{v}}{\partial t} + \nabla \cdot \rho \bar{v} \bar{v} = -\nabla \bar{p} + \left[\mu \nabla^2 \bar{v} - \nabla \cdot \overline{\rho v' v'} \right] + \rho \bar{g},$$

from the local instantaneous formulation,

$$\frac{\partial \rho v}{\partial t} + \nabla \cdot \rho v \bar{v} = -\nabla p + \mu \nabla^2 v + \rho g. \quad [40\%]$$

Specialty – Thermal-hydraulics and Reactor Safety (2) (37.5%)

- a) For adiabatic, air-water, two-phase upflows in a vertical pipe, (i) sketch the four major flow regimes, briefly discuss their characteristics, and (ii) describe briefly the three components in the total pressure loss from the inlet to the exit of the pipe. [50%]
- b) For a single bubble in an infinite medium, (i) define the particle Reynolds number $N_{Re\infty}$, (ii) sketch the variation of drag coefficient versus the particle Reynolds number, and (iii) describe how drag coefficient changes with void fraction for bubbly and slug flows, respectively. [50%]

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Part 2 – Specialty Part
Nuclear Fuel Cycle and Radioactive Waste Management

1:00 pm – 4:00 pm, April 6, 2018

Specialty - Nuclear Fuel Cycle and Radioactive Waste Management

Problem #1 (40%)

Spent MOX fuel can be reprocessed using PUREX and Dry electrochemical separation, explain all the steps and the products of each step, and give key chemical/electrochemical reactions

Problem #2 (30%)

There is a “liquid-like” transport mechanism to explain the lanthanide fission product transport in a U-Zr in operation.

- 1) Explain what the mechanism is and how to use it to explain the La transport phenomena
- 2) Deduce all the mathematic equations and reactions for the mechanisms

Problem #3 (30%)

Corrosion is a big concern in each step of a nuclear fuel cycle. Considering a corrosion system, the mass transfer rate can be expressed by:

$$J_M = K_M(C_w - C_b)$$

where C_w and C_b are the concentration at the wall and the concentration in the bulk flow. If the reaction rate can be simply expressed by:

$$J_R = K_R C_w$$

- a) For a steady state corrosion, if C_b , K_M , K_R are known, deduce the expression of corrosion rate R_C
- b) For an unsteady state corrosion, if C_b , K_M , K_R are known and constant, and the reaction thickness at the wall is given as δ , deduce the corrosion rate R_C