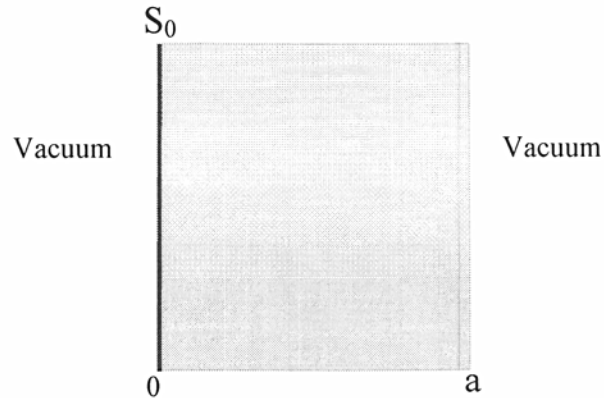**PhD Qualifying Exam**
Nuclear Engineering Program

Part 1 – Core Courses
(Solve 3 problems only)

9:00 am – 12:00 noon, April 29, 2017

(1) Nuclear Reactor Analysis

An isotropic planar source is placed at the left boundary of a slab that is surrounded by a vacuum as depicted below

S_0

Vacuum   Vacuum

0   a

i) Solve for neutron flux distribution within the slab.   (55%)

ii) Consider the above slab is extended in size, by reflecting it about a line of symmetry at x=a. Solve for the neutron flux within this extended slab.   (45%)

Hints:

One-speed diffusion equation is expressed by

$$-D\frac{d^2\phi}{dx^2} + \Sigma_a\phi(x) = S(x)$$

Considering diffusion approximation, the positive and negative partial currents are expressed by

$$J_\pm = \frac{\phi(x)}{4} \mp \frac{D}{2}\frac{d\phi(x)}{dx}$$

Trigonometric identities;

$$\cosh(x \pm y) = \cosh(x)\cosh(y) \pm \sinh(x)\sinh(y)$$

$$\sinh(x \pm y) = \sinh(x)\cosh(y) \pm \cosh(x)\sinh(y)$$

(2) Reactor Thermal Hydraulics

A nuclear fuel plate sandwiched between two cladding layers is operating at steady state with a uniform heat generation rate per unit volume of q'''. The half-thickness of the fuel is a, and the thickness of each cladding layer is δ_c. The fuel and cladding have constant thermal conductivities k_f and k_c, respectively. The coolant flowing outside the cladding has a bulk temperature of T_∞ and a convective heat transfer coefficient of h_∞. Heat conduction in y and z directions can be neglected. It can be assumed that the temperature profile is symmetric around the center plane ($x = 0$). The 1-D steady heat conduction equation with heat source is given as follows:

$$k_f \frac{d^2 T}{dx^2} + q''' = 0.$$
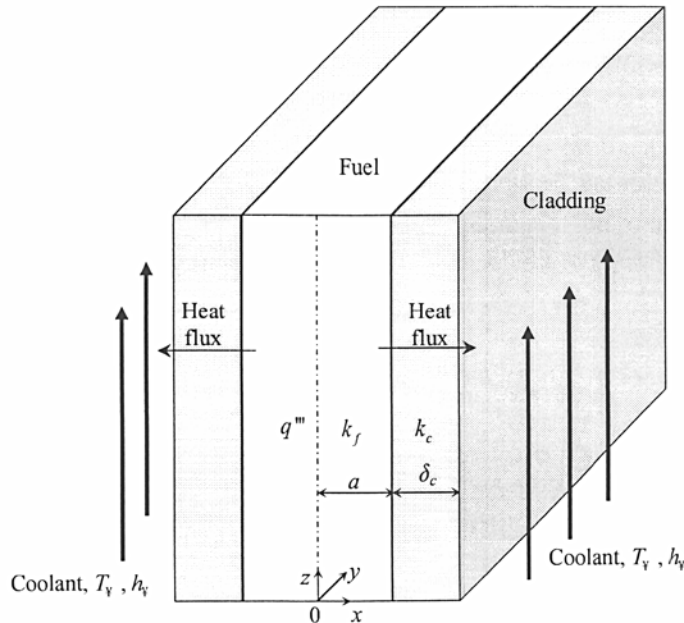
a) Use energy balance method, determine the heat flux q'' at the cladding-coolant interface ($x = a + \delta_c$). (10%)

b) Determine the temperature at the cladding-coolant interface T_{cc}. (15%)

c) Determine the temperature distribution along x in the cladding $T_c(x)$ for $a \leq x \leq a + \delta$. (15%)

d) Determine the temperature at the fuel-cladding interface T_{fc}. (10%)

e) Determine the temperature distribution along x in the fuel $T_f(x)$ for $0 \leq x \leq a$. (25%)

f) Assume $k_f < k_c$, sketch the temperature profile in the fuel and cladding ($0 \leq x \leq a + \delta_c$). (25%)

(3) Advanced Nuclear Materials

1) Describe the interstitial, vacancy, and interstitialcy diffusion mechanism. (25%)
2) Describe the inverse Kinkerdall Effect. (25%)
3) Under neutron irradiation, swelling occurs in fuel claddings. Explain the plausible causes of swelling. (25%)
4) What are the major causes of irradiation hardening? (25%)

(4) Radiation Detection and Shielding

Detecting Radioactivity on Moving Vehicles:

The Department of Homeland Security has installed radiation portal monitors that look for radioactivity in cargo containers that are being transported inland by truck. Each truck must pass by a radiation detector at a speed of 5 m/s (or about 11.2 mph).

Assume the following geometry:
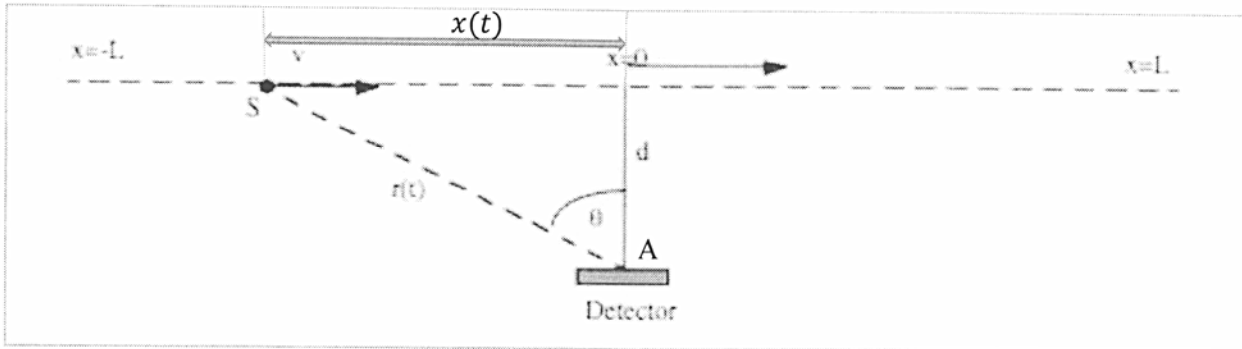
a) In this set up a cylindrical detector has an area, $A = 100 \ cm^2$, with an intrinsic counting efficiency $\varepsilon_i = 80\%$ and is placed a distance d = 3 meters from the road, with the trucks moving at a speed past the detector of $v = 5 \ m/s$. Assume the truck contains a radioactive source in the cargo container. Find the minimum source activity, S, in μCi that would have to be present in the cargo container in order to achieve $N = 100 \ counts$ on the detector as the truck moves from a distance of $-L$ to $+L$ along the road where $L = 10 \ m$. (70%)

For this calculation, assume the background is negligible and there is no attenuation of the radiation in air or through the cargo container. This result will be a best case scenario.

For this geometry the solid angle seen by the detector from the source can be written as $\Omega(t) = \frac{A\cos\vartheta}{r^2(t)}$. Write the counts $N(t)$ as a function of $x(t)$ and S, where we can write $dt = \frac{dx}{v}$, and then integrate with respect to x from $-L \ to \ +L$. Finally solve for S with $N = 100 \ counts$.

b) Taking into account that you want to have a minimum number of trucks pass the detector per day so as not to delay the shipment of the cargo containers unnecessarily, which parameters above can you vary to improve upon the minimum value of S that can be detected? Discuss which way (increase or decrease) you would vary the parameter. (30%)

See attached Integral Tables and Trigonometric Identities.

(5) Advanced Engineering Mathematics

The solid angle $(d\Omega)$ is given by

$$d\Omega = d\mu d\varphi, \quad for \ -1 \le \mu \le 1 \quad and \ \ 0 \le \varphi \le 2\pi$$

and unit vector $\widehat{\Omega}$ is expressed by

$$\widehat{\Omega} = \Omega_x \hat{\imath} + \Omega_y \hat{\jmath} + \Omega_z \hat{k}$$

where,

$$\Omega_x = \sqrt{1-\mu^2}\,\cos\varphi$$
$$\Omega_y = \sqrt{1-\mu^2}\,\sin\varphi$$
$$\Omega_z = \mu$$

Prove the following equalities:

1) $\quad \int_{4\pi} d\Omega\,\Omega_x = 0$ $\hfill$ (20%)

2) $\quad \int_{4\pi} d\Omega\,\Omega_x\Omega_y = \left\{ \begin{array}{ll} \frac{4\pi}{3} & for\ x = y \\ 0 & for\ x \ne y \end{array} \right\}$ $\hfill$ (40%)

3) $\quad \int_{4\pi} d\Omega\,\Omega_x^\ell\,\Omega_y^m\,\Omega_z^n = 0,$ $\ if\ \ell, m,\ or\ n\ is\ an\ odd\ number$ (Here, prove only for an odd m. i.e.,
$\quad m = 2k+1$) $\hfill$ (40%)

Hint:
$$\cos(2\varphi) = \cos^2\varphi - \sin^2\varphi$$
$$\sin(2\varphi) = 2\sin\varphi\cos\varphi$$

Attachment

Trigonometric Identities

$$\csc \theta = \frac{1}{\sin \theta}$$

$$\sec \theta = \frac{1}{\cos \theta}$$

$$\sin^2 \theta + \cos^2 \theta = 1$$

$$1 + \tan^2 \theta = \sec^2 \theta$$

$$1 + \cot^2 \theta = \csc^2 \theta$$

Integral Table

$$\int \sqrt{x^2 \pm a^2}\, dx = \frac{1}{2}x\sqrt{x^2 \pm a^2} \pm \frac{1}{2}a^2 \ln|x + \sqrt{x^2 \pm a^2}|$$

$$\int \sqrt{a^2 - x^2}\, dx = \frac{1}{2}x\sqrt{a^2 - x^2} + \frac{1}{2}a^2 \tan^{-1}\frac{x}{\sqrt{a^2 - x^2}}$$

$$\int \frac{1}{\sqrt{x^2 \pm a^2}}\, dx = \ln|x + \sqrt{x^2 \pm a^2}|$$

$$\int \frac{1}{\sqrt{a^2 - x^2}}\, dx = \sin^{-1}\frac{x}{a}$$

$$\int \frac{dx}{(a^2 + x^2)^{3/2}} = \frac{x}{a^2\sqrt{a^2 + x^2}}$$

$$\int \frac{x^2}{\sqrt{x^2 \pm a^2}}\, dx = \frac{1}{2}x\sqrt{x^2 \pm a^2} \mp \frac{1}{2}a^2 \ln|x + \sqrt{x^2 \pm a^2}|$$

$$\int \tan ax\, dx = -\frac{1}{a}\ln \cos ax$$

$$\int \sec x\, dx = \ln|\sec x + \tan x|$$

$$\int x \cos x\, dx = \cos x + x \sin x$$

PhD Qualifying Exam
Nuclear Engineering Program

Part 2 – Specialty Part
Nuclear Materials

2:00 pm – 5:00 pm, April 29, 2017

Specialty – Nuclear Materials (1) (40%)

Under irradiation, how does the point defects concentration evolve as a function of sink strength?

Specialty – Nuclear Materials (2) (40%)

Describe an efficient material microstructure that would minimize the point defect concentration under irradiation.

Specialty – Nuclear Materials (3) (20%)

Describe an efficient material microstructure that would optimize the mechanical properties under irradiation.

PhD Qualifying Exam
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Part 2 – Specialty Part
Thermal Hydraulics and Safety

2:00 pm – 5:00 pm, April 29, 2017

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

The high pressure injection (HPI) emergency core cooling system (ECCS) in a nuclear power plant has two pumps and four valves as shown in the following figure. In the event of an accident an actuation signal is delivered to the two identical pumps and the four identical valves. The pumps then start up, the valves open and water coolant is delivered to the primary system. The following failure probabilities are found to be significant:

$p_{ps} = 10^{-5}$ year $^{-1}$, probability that a signal will not be delivered to the pump and valve actuators in the event of an accident.

$p_p = 2 \times 10^{-2}$ year $^{-1}$, probability that a pump will fail to start up when the actuation signal is received.

$p_v = 10^{-1}$ year $^{-1}$, probability that a valve will fail to open when the actuation signal is received.

$p_r = 0.5 \times 10^{-5}$ year $^{-1}$, probability that the reservoir will be empty at the time of the accident.

a. Draw a fault tree for the failure of the system to deliver any coolant to the primary system in the event of an accident. [60%]

b. Evaluate the probability that such a failure will take place in the event of an accident. (you may assume that each failure probability is small compared to one.) [40%]
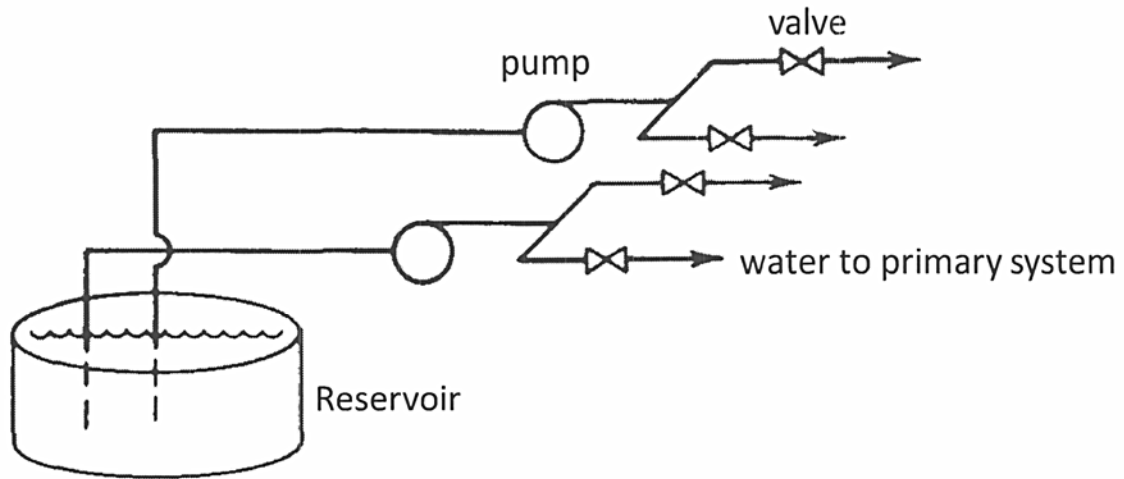
Specialty – Thermal-hydraulics and Reactor Safety (2) (37.5%)

Consider a pressurized water reactor (PWR) nuclear power plant,

a) Draw the line diagram and identify the major components of the primary and secondary loops. [35%]

b) Briefly describe the energy transfer and/or conversion processes involved in these components. [25%]

c) Describe the phenomena in the pressurizer when the primary system pressure increases. [10%]

d) Explain the source of the decay heat, sketch the decay power curve as a function of time following the reactor shutdown. [20%]

e) Explain why the nuclear regulatory commission (NRC) requires that the peak cladding temperature shall not exceed 2200 °F (1204 °C) during a reactor accident. [10%]

Specialty – Thermal-hydraulics and Reactor Safety (3) (37.5%)

The following figure shows a steady-state, single-phase natural circulation loop consisting of four pieces of pipes and elbows. Heat is added at l_h section and removed at l_c section, each with a constant heat flux at the inner wall of the pipe. The height difference between the centers of the above two sections is l_{th}. A schematic of the loop and other known parameters are given below.
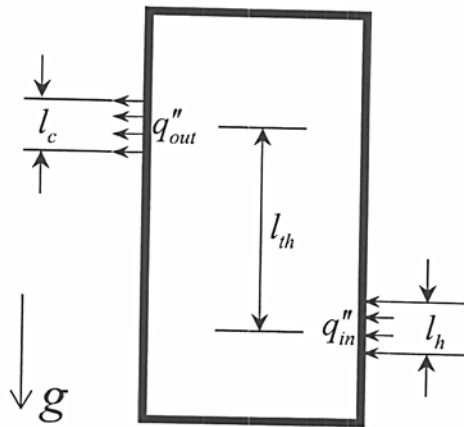
Other Known Parameters

Pipe inner diameter: D

Total pipe length: L

Heated length: l_h

Heat flux: q''_{in}

Reference density: ρ_r

Thermal expansion coefficient: β

Specific heat of coolant: c_p

Darcy friction factor: f_D

Total minor loss coefficient: K_t

a) Determine the total pressure losses including major and minor losses. [15%]

b) Calculate the temperature rise (ΔT) over l_{core} by assuming that velocity u is known. [20%]

c) Explain the Boussinesq assumption, write the One-D momentum equation for the loop. [25%]

d) Based on the results from b) and c), solve for the velocity as a function of known parameters. [25%]

e) Discuss the potential ways to enhance natural circulation. [15%]