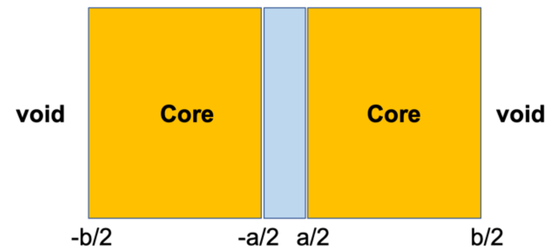
PhD Qualifying Exam
Nuclear Engineering Program

Part 1 – Core Courses
(Solve 3 problems only)

8:30 am – 12:00 pm, October 29, 2021

(1) Nuclear Reactor Analysis

The central region of a slab reactor is filled with a moderating material as depicted in the figure. The core region contains a homogeneous mixture of a low-enriched fuel and a neutron moderator material. Using the one-speed diffusion equation,



a) (60%) derive an equation expressing the '*criticality condition'* of this reactor;
b) (20%) given the reactor power is ***P***, derive a formulation for the one-speed flux distribution in the reactor;
c) (10%) if the central moderator is replaced with a pure absorber, give an expression for the interfacial boundary condition? Explain;
d) (10%) if the inner region is replaced with a void, give an expression for the interfacial boundary condition? Explain.

Note: In parts $\boldsymbol{c}$ and $\boldsymbol{d}$, you do not need to re-solve the problem.

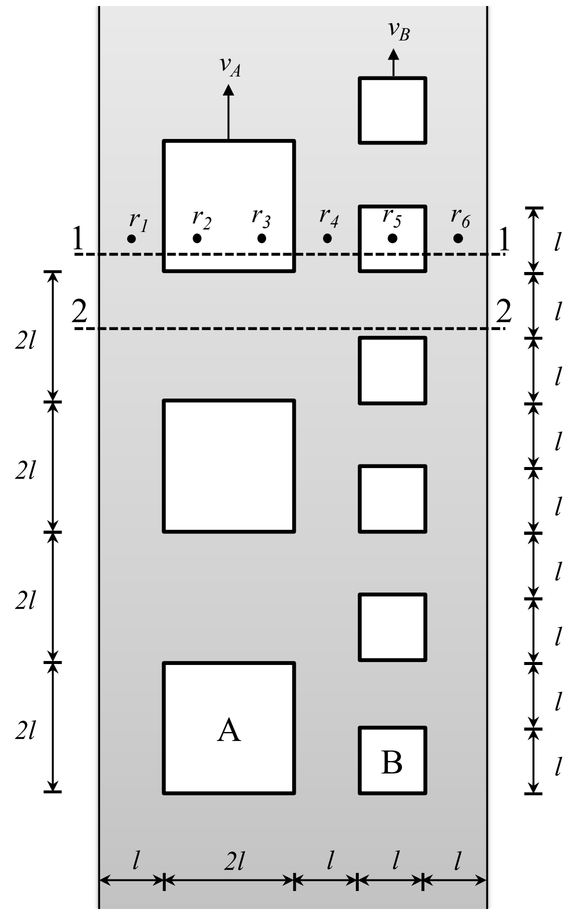
Hint: useful formulations:

$$\sin(x \pm y) = sinx\ cosy \pm cosx\ siny$$

$$\cos(x \pm y) = cosx\ cosy \mp sinx\ siny$$

(2) Reactor Thermal Hydraulics

A vertical two-phase flow consists of two types of gas bubbles as shown in the right figure. The problem can be considered as two-dimensional, and the bubble pattern repeats itself in the long flow channel. Type A bubbles can be considered as squares of side length $2l$ and velocity v_A. Type B bubbles are squares of side length l and velocity $v_B = 0.5\ v_A$. The size and spacing of the bubbles are indicated in the figure. Six probes (r_1 to r_6) are placed in the flow to measure the local void fraction. Each probe outputs a signal of 1 when it is in a bubble and 0 when it is liquid.



a) (15%) Sketch the signal output versus time for probes r_1, r_2, and r_5.

b) (15%) Determine the local time-averaged void fraction for all six probes.

c) (20%) Determine the area average of the time-averaged local void fractions at the plane of the probes.

d) (20%) Determine the area-averaged void fraction at cross-sections 1 and 2 (indicated as dashed lines) at the instant illustrated in the figure.

e) (10%) Sketch the variation of the area-averaged void fraction versus time at position 1.

f) (20%) Determine the time average of the instantaneous area-averaged void fraction at the plane of the probes. Compare it with the result of part (c).

(3) Advanced Nuclear Materials

a) (50%) What are the main classes of materials used in nuclear reactors (reactor pressure vessels, nuclear fuels, claddings, control rods, moderators)? Explain why these materials are used.

b) (50%) How can we improve the corrosion properties of metallic uranium?

(4) Radiation Detection and Shielding

Background Information

Dead time: Two models of dead time behavior of counting systems have come into common usage: paralyzable and nonparalyzable response. We will use the following notation:

n = the true interaction rate (or count rate) of radiation in the detector,
m = the recorded or observed count rate by the detector, and
τ = the system dead time following a radiation detection event.

Note that due to the dead time of the detector some of the true interactions are not counted so typically $m < n$.

For the nonparalyzable model, if we know the dead time τ we can calculate the true rate n from the measured rate m as follows: $n - m = nm\tau$, or solving for the true count rate $n = \frac{m}{1-m\tau}$.

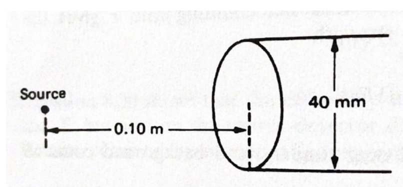
Solid angle: The solid angle Ω (in steradians) subtended by a cylindrical detector at the source can be determined from the following formula:

$$\Omega = 2\pi\left(1 - \frac{d}{\sqrt{d^2 + a^2}}\right),$$

where d is the distance that the source is from the detector face and a is the radius of the detector face.

Problem

The geometric setup shown below was used to measure the strength of a radioactive source S.



The following data were obtained:

The total measured counts of the sample (with background present) were 6,000 counts over a sample counting time of 10 minutes. The background counts, without the source present, were 400 counts over a counting time of 10 minutes (assume deadtime is negligible for the background count rate). The deadtime of the detector, τ, was determined to be 100 μsec. The deadtime of this detector is better represented using the nonparalyzable model. The intrinsic peak efficiency, ϵ_{ip}, of the detector for the energy of the particles emitted by the source is 0.60 ± 0.005.

See next page for questions.

a) (35%) Find the true net counting rate r, in counts per minute (cpm), for particles striking the detector from the source.

b) (35%) What is the actual source strength S in particles per minute emitted?

c) (30%) If the only errors are due to the measurements of counts and the detector efficiency, what is the fractional standard deviation in percent for the calculated source strength S?

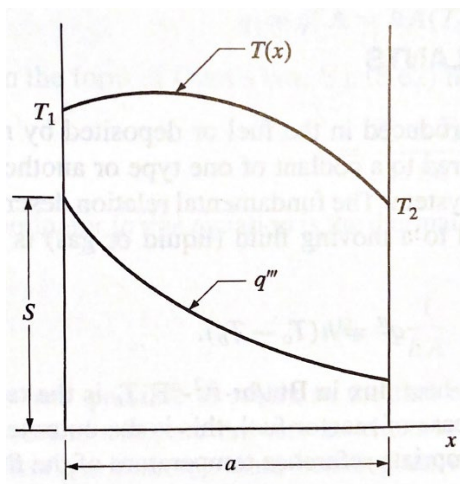
(5) Advanced Engineering Mathematics

The steady-state heat conduction equation in a slab can be written in the form of a Poisson's equation:

$$\nabla^2 T + \frac{q'''}{k} = 0, \qquad (1)$$

where T is the temperature as a function of position (x, y, z) in the slab, k is the thermal conductivity of the slab, and q''' is the rate at which heat is produced per unit volume in the slab.

It is often necessary to calculate the temperature distribution and heat transmission in reactor shields and pressure vessels in which radiation energy is deposited more or less exponentially. Consider a slab of thickness a whose surfaces are held at the constant temperatures T_1 and T_2, as shown in the figure below.



If x is measured from the surface of the slab as indicated in the above figure, the heat source distribution is given by

$$q''' = Se^{-\mu x}, \qquad (2)$$

where S and μ are constants. For γ-rays, μ may be taken to be the linear absorption attenuation coefficient.

a) (70%) Using equation (2) in equation (1) and assuming this problem can be represented as a 1-dimensional problem in terms of the independent variable, x, the distance into the slab, find the unique solution to equation (1) using the Dirichlet boundary conditions of: $T(0) = T_1$, and $T(a) = T_2$.

b) (30%) Derive an expression, using the constants from above, for the location of the point x_m where the temperature in the slab $T(x)$ is at a maximum.