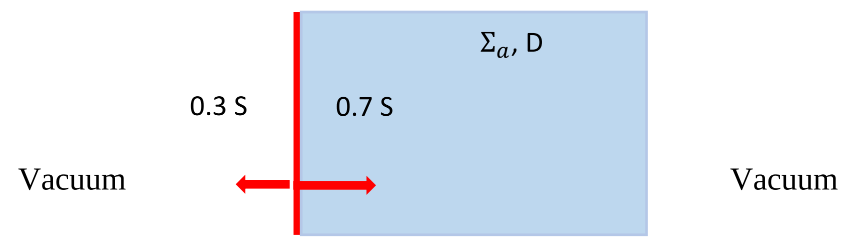
PhD Qualifying Exam
Nuclear Engineering Program

Part 1 – Core Courses
(Solve 3 problems only)

8:15 – 11:45 am, Oct 25, 2019

(1) Nuclear Reactor Analysis

A one-region slab of thickness (***a***) is placed in a vacuum, and an anisotropic planar source, S, is placed at its left boundary as depicted below.



a) (50%) Solve the one-speed diffusion equation to obtain a formulation for the neutron flux distribution within the slab.

b) (50%) Determine the albedo at both left and right boundaries of the slab.

Hint: The one-speed diffusion equation is expressed by: $-D\nabla^2\phi(\vec{r}) + \Sigma_a\phi(\vec{r}) = S(\vec{r})$.

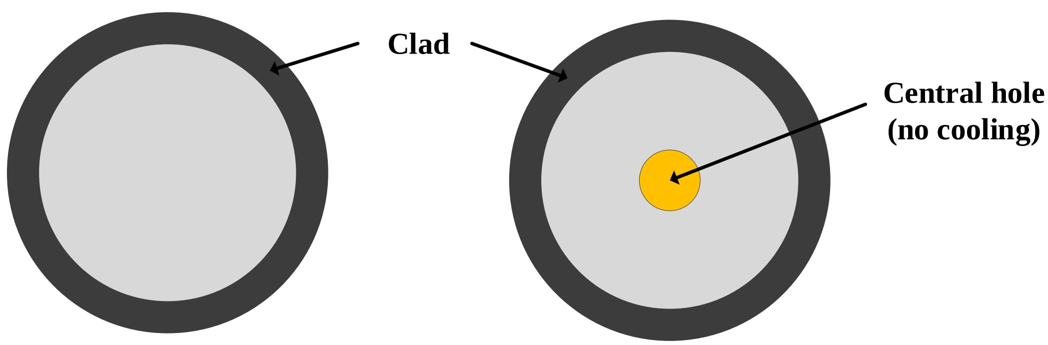
(2) Reactor Thermal Hydraulics

Two different heater rods are being considered for a heat transfer experiment (see figure below). The standard heater design (heater thermal conductivity of 2 W/m-K and a nominal uniform linear power of 20 kW/m) is cylindrical (7 mm heater rod diameter), and encased in cladding with a thickness of 0.5 mm (thermal conductivity of 15 W/m-K with a total diameter of 8 mm; we ignore the gap between the heater and clad). In the new design, the heater rod is fabricated with a central hole (2 mm in diameter) and is to be operated at the same uniform linear power. If the cladding outer surface temperature is maintained at 350 K by pressurized-water cooling:

a) (80%) Derive an expression for the steady-state operating temperature T(r) for each heater design (fuel and clad regions).

b) (10%) What is the qualitative effect of the presence of the hole in the heater rod with regard to the maximum steady-state operating temperature?

c) (10%) Considering the hole in the new fuel rod design, what is the change in maximum temperature rise within the new heater rod design compared to the old design?



(3) Advanced Nuclear Materials

For a molten salt system, the structural materials are composed of metal A and B. A^{3+} and B^{3+} are in the salt and there is no other impurity. The equilibrium potentials of A^{3+}/A and B^{3+}/B and their polarization curves are shown in Figure 1.

1) (33%) What are the anodic and cathodic corrosion reactions?

2) (33%) If the charge transfer coefficient (α_A) and exchange current density (i_A^0) of A^{3+}/A redox reaction are known and the corrosion is activation controlled, deduce the corrosion current density using E_A and E_0,

3) (34%) Based on corrosion current density you obtained in (2), deduce the exchange current density of B^{3+}/B redox reaction if α_B is given.

Note: All the parameters are in SI units.

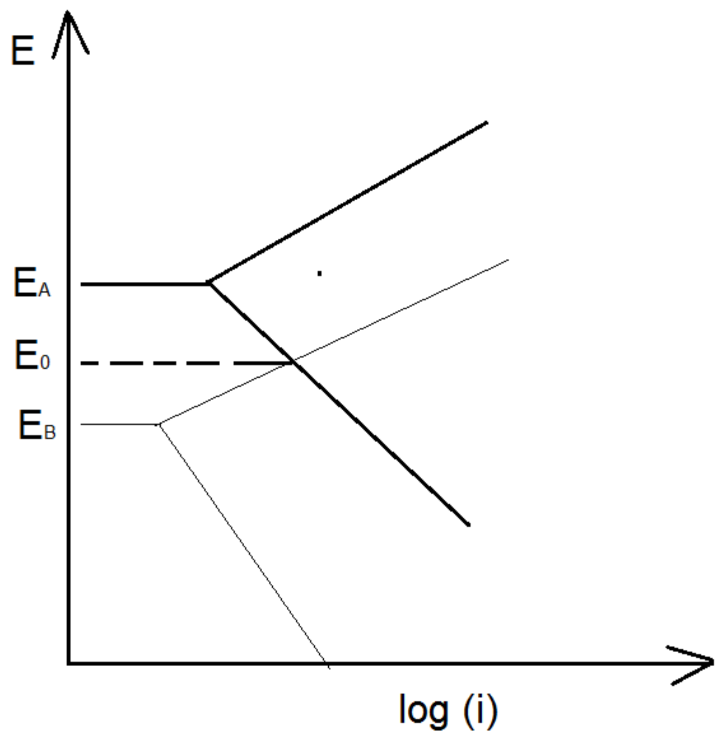


Figure 1

(4) Radiation Detection and Shielding

The Potassium-Argon dating method is widely used for determining the age of igneous rocks. It can be used in dating rocks from as young as 100,000 years old up to billions of years old. In fact, it has even been used to date rock samples from Mars (on the Mars Rover) and asteroids that have struck the earth. Igneous rocks are formed when cooled from magmas or after eruption of lava flows. While in the magma or lava state all of the Argon gas escapes from the rock leaving behind the other solid materials such as potassium. When the rock cools and solidifies, it starts with zero Argon and then Argon-40 starts to build up from decay of Potassium-40. By using a ratio of ^{40}Ar to ^{40}K one can then determine the age of formation of the rock.

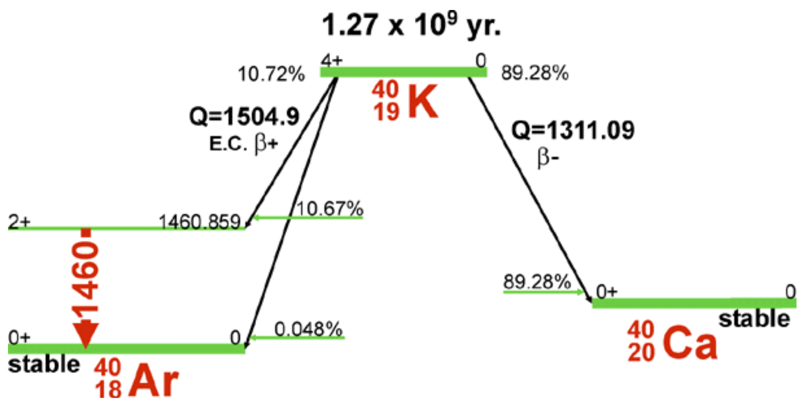


Figure 1: K-40 Decay Scheme

(a) (30%) The radioisotope ^{40}K undergoes branched decay. See Figure 1 above. The two dominant decay paths are via β^- decay (branching ratio 89.28%) and electron capture decay (branching ratio 10.72%). Note that 89.28% of the time ^{40}K decays into ^{40}Ca. Since a lot of natural Calcium already exists in the rock, this isotope cannot be used for this method. One must then use the ratio with ^{40}Ar. When the half-life is calculated using data from only one branch of the decay, it is called a partial half-life and like-wise we can specify a partial decay constant such that the overall decay constant for ^{40}K can be represented by $\lambda_t = \lambda_1 + \lambda_2$. ^{40}K has a decay half-life of 1.248 x 10^9 years. Natural Potassium consists of a mixture of three isotopes with the following abundances: ^{39}K at 93.2581%, ^{40}K at 0.0117%, and ^{41}K at 6.7302%. Only the isotope ^{40}K is radioactive. In preparation for part (b) below, calculate the ^{40}K partial half-life and partial decay constant for the decay branch that produces ^{40}Ar.

(b) (70%) For a given rock sample using mass spectroscopy, we find that the ratio of ^{40}Ar atoms to ^{40}K atoms is 1 to 56 (1:56). Calculate the estimated age of this rock.

(5) Advanced Engineering Mathematics

(100%) Random variable x has a density function expressed by

$$f(x) = 1 + x, \quad \text{for} \quad 0 \le x \le 1.$$

If function ***g(x)*** is expressed by

$$g(x) = cx,$$

Determine the parameter ***c*** such that the variance of ***g(x)*** is minimized.

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

1:00 pm – 4:00 pm, Oct 25, 2019

Specialty - Nuclear Fuel Cycle and Radioactive Waste Management

Question #1 (30%): One mole of spent fuel (0.8 mole U, 0.1 mole Pu, 0.1 mole RE) is put in the anode basket and 10 moles of molten salt (KCl-LiCl-UCl3) with 0.5 moles U^{3+} are used. It is known that RE^{3+}, U^{3+} and Pu^{3+} are the stable oxidation states in the molten salt and there is no U dissolution before RE and Pu are completely dissolved.

1) When all the RE and Pu are completely dissolved into the salt, how much U deposits at the cathode?

2) If 0.5 moles of U deposits at the cathode, how much U dissolves at the anode?

3) When Pu and RE completely dissolves, the solid electrode for U collection is replaced by a liquid cadmium electrode. The Pu+U will be collected at the cadmium electrode. If the product from the cadmium is 0.09 moles Pu + 0.01 moles U, how much U^{3+} is in the salt?

Question #2 (30%): The PUREX process was the source of most of the high-level radioactive waste generated in the U.S.

1) Outline and describe the major steps in the PUREX process. Include in your description the primary reagents used at each step.

2) For each major step in the PUREX process, discuss what radioactive waste types are produced.

3) Give and explain at least two methods to avoid pure Pu production based on the aqueous process.

Question #3 (40%): Halide volatility and the pyrometallurgical process are two main dry processes for UNF treatment.

1) Draw a simple flow sheet for halide volatility for uranium oxide fuel treatment, explain how to separate U, Pu, and Am from the other actinides.

2) Draw a simple flow sheet for the pyrometallurgical process for U-Zr metal fuel treatment using molten salt and explain how to clean or recycle the molten salt (at least give two methods).