N.E. Ph.D. Qualifier Exam
Section 1
Fall Quarter 1997

# GEORGIA INSTITUTE OF TECHNOLOGY

## The George W. Woodruff School of Mechanical Engineering

**Ph.D. Qualifiers Exam - Fall Quarter 1997**

Nuclear Engineering Ph.D. Qualifying Exam
EXAM AREA

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# GEORGIA INSTITUTE OF TECHNOLOGY

# NE PhD Examination

## October 1997

Fall Quarter, 1997

## Section 1

## Monday - AM

## Questions 1.1-1.4

### Instructions

1. This is a closed book, closed notes examination.
2. No reference material is allowed.
3. Answer all questions.
4. Write your assigned exam number on each question.

## Undergraduate Engineering Fundamentals

NE.1.1. A counter flow heat exchanger is used to cool lubricating oil from 160 °F to 90 °F. The oil mass flow rate and specific heat are 12,000 $lb_m/hr$ and 0.5 $Btu/lb_m°F$, respectively. Chilled water ($C_p$ = 1.0 $Btu/lb_m°F$) at an entrance temperature of 50 °F and flow rate of 9000 $lb_m/hr$ is to be used to cool the oil. The overall heat transfer coefficient is 50 Btu/hr $ft^2$ °F.

a. Determine the exit water temperature, the logarithmic mean temperature difference, and the heat transfer area.

b. Due to an installation error, the water inlet and exit connections in the above heat exchanger were reversed so that the exchanger would operate in a parallel flow mode. Determine the corresponding water and oil exit temperatures. Assume the overall heat transfer coefficient, heat exchanger area, water and oil flow rates and inlet temperatures to remain the same as part "a" above.

## Undergraduate Physics Fundamentals

NE.1.2. An electron in the picture tube of a TV set is accelerated from rest through a potential difference of 5000V:

(a) What is the change in the potential energy of the electron (in eV)?
(b) What is the speed of the electron as a result of the acceleration?
(c) Is the electron relativistic? Why or why not?

Data: $m_e = 9.1\left(10^{-31}\right)kg$

electron charge $= 1.6\text{x}10^{-19}\text{C}$

$\text{c} = 3\text{x}10^{10}\ \text{cm} / \text{sec}$

# Undergraduate Math Fundamentals

NE.1.3. Find constants a and b for which F (a,b) is a minimum.

$$F(a,b) = \int_0^{\pi}\left[\sin x - \left(ax^2 + bx\right)\right]^2 dx$$

## Fundamentals of Radiation Protection

NE.1.4. Design a spherical aluminum ($_{13}$Al) and lead shielding system (try to use the materials as economically as possible) that will stop all beta and attenuate a 1 Ci point source of P-32 to 0.5 mR/h at 1 meter. State all your assumptions clearly. Specify the required thicknesses for both aluminum and lead shieldings and how you would like to arrange them. (Hint: The attenuation of bremsstralung photons in aluminum can be neglected. Bremsstralung emission can be considered to come from a point source. Ignore the buildup factor.)

Data:

1) aluminum density = 2.7 g/cm$^3$

2) $R = 412\, E^{1.265-0.0954\ln E}$, for $0.01 \le E \le 2.5$ MeV

where R = range, mg/cm$^2$
E = maximum beta-ray energy, MeV

3) $E_{\beta,max}$ = 1.71 MeV and yield rate = 100% of P-32

4) the fraction of incident beta energy converted into photons, $f = 3.5 \times 10^{-4}\, ZE_{max}$, where Z is the atomic number of the metal.

5) linear energy absorption coeff. for photons with energy of 1.71 MeV in air is $2.92 \times 10^{-5}$ cm$^{-1}$

6) linear attenuation coeff. for photons with energy of 1.71 MeV in lead is $5.5 \times 10^{-1}$ cm$^{-1}$

7) air density = 0.001293 g/cm$^3$

N.E. Ph.D. Qualifier Exam
Section 2
Fall Quarter 1997

# GEORGIA INSTITUTE OF TECHNOLOGY

The George W. Woodruff
School of Mechanical Engineering

## Ph.D. Qualifiers Exam - Fall Quarter 1997

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# GEORGIA INSTITUTE OF TECHNOLOGY

# NE PhD Examination

## October 1997

Fall Quarter, 1997

## Section 2

## Monday - PM

## Questions 1.5-1.8

**Instructions**

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# Fundamental of Fission Reactors

NE.1.5. Derive the two-group steady-state diffusion equation by performing a neutron balance in an infinitesimally small volume. Assume that the group-averaged cross sections are known and that the Fick's law of diffusion is valid in each group.

# Fundamentals of Fusion

NE.1.6. Discuss the principles of magnetic confinement of a plasma in a tokamak. How do magnetic fields confine a plasma? What different magnetic fields are needed for confinement in a tokamak, and what specific purpose does each serve?

# Fundamentals of Radiation Detection

NE1.7 A 1.0-inch diameter spherical $^3$He gas proportional counter was used to measure thermal neutrons in the thermal column of the Ga Tech Research Reactor. The thermal neutron absorption cross section for a $^3$He nucleus is 5400 barns, and the gas pressure of $^3$He in the detector was 4 atm. Assume neutrons in the thermal column are purely thermal and isotropic, estimate the intrinsic efficiency of the detector for detecting thermal neutrons in the column.

## Fundamentals of Radiation/Nuclear Physics

NE1.8. 1-MeV deuterons bombard a stationary target containing tritium and produce neutrons by the $^3$H(d,n)$^4$He reaction, having a Q value of 17.6 MeV.

(5 pts) (a) find the maximum and the minimum energy of the emergent neutrons,

(5 pts) (b) assume the neutrons are emitted isotropically in the center-of-mass system, what percentage of neutrons are emitted in the forward direction in the laboratory system?

N.E. Ph.D. Qualifier Exam
Section 3
Fall Quarter 1997

[illegible]

# GEORGIA INSTITUTE OF TECHNOLOGY

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## GEORGIA INSTITUTE OF TECHNOLOGY

# NE PhD Examination

## October 1997

Fall Quarter, 1997

## Section 3

## Wednesday - AM

## Questions 2.1-2.4

### Instructions

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# Monte Carlo

NE.2.1. A fuel rod can be represented as a line source for some shielding applications. The gamma ray source strength of a spent fuel rod is distributed in the following functional form $S_o \sim \sin\left(\frac{\pi y}{h}\right)$ where the variables are as given below.

a. What is the properly normalized cumulative distribution function that would be used to sample the gamma ray emission on the line source in a Monte Carlo simulation?

b. In a particular application, the gammas emitted at the upper end of the fuel rod are more important for solving the shielding problem of interest. Being a good Monte Carlo simulator, you decide to sample the emission location using the function $f(y) = e^{\alpha y}$, where $\alpha > 0$, instead of the actual source distribution to guarantee adequate sampling of the spatial region of importance.

   (1) What is the cumulative probability function that must now be sampled?

   (2) What must you do to ensure that the game is still fair, i.e. that you have not changed the mean score of the quantity of interest? Be as quantitative as possible.

c. In another situation, the ends of the fuel rod are important source regions. You decide to use the following biased unnormalized source distribution to sample gamma-ray emission:

$$f(y) = \begin{cases} \left(\frac{h}{2} - x\right) & x \le \frac{h}{2} \\ 2\left(x - \frac{h}{2}\right) & x > \frac{h}{2} \end{cases}$$

How would you sample this distribution and adjust the particle weights?

## Diffusion Theory

NE.2.2. Using the P-1 approximation, compute (derive) the linear extrapolation (*l.e.d.*) distance starting from the Marshak vacuum boundary condition, $\int\limits_{\mu=\hat{n}\cdot\hat{\Omega}<0} d^2\hat{\Omega}(\hat{n}\cdot\hat{\Omega})\psi(z,\hat{\Omega})$, for a semi-infinite half space ($0 < z < \infty$). The *l.e.d.* is defined as the distance beyond the boundary where the linearly extrapolated flux drops to zero.

**HINT:** P-1 approximation: $\psi(z,\mu) = \dfrac{\phi(z)}{4\pi} + \dfrac{3\mu J(z)}{4\pi}$

# Transport Theory

NE.2.3. Starting with the one-speed Boltzman transport equation in slab geometry, derive the diffusion theory equation. State each assumption and discuss how it limits the applicability of diffusion theory. Discuss the applicability of diffusion theory for nuclear reactor analysis.

# Kinetics

NE.2.4. A control rod bank is scrammed in an initially critical reactor. The signal of a neutron detector drops instantaneously to one-third of its pre-scram level, then decays exponentially. Assume one group of delayed neutrons with $\beta = 0.0075$, $\lambda = 0.08\ s^{-1}$ and a reactor lifetime $\Lambda = 10^{-4}$ s. What is the reactivity worth of the control rod bank? How long is needed for the power level to reach 10% of the initial, pre-scram level?

N.E. Ph.D. Qualifier Exam
Section 4
Fall Quarter 1997

# GEORGIA INSTITUTE OF TECHNOLOGY

## The George W. Woodruff
## School of Mechanical Engineering

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GEORGIA INSTITUTE OF TECHNOLOGY

# NE PhD Examination

## October 1997

Fall Quarter, 1997

## Section 4

## Wednesday - PM

## Questions 2.5-2.8

### Instructions

1. This is a closed book, closed notes examination.
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## Depletion & Fission Products

NE.2.5. A U-235 fueled nuclear reactor operates with a thermal flux level of $3 \times 10^{14}$ n/cm$^2$s. The reactor has been operating at constant power level for two weeks when it becomes necessary to scram the control rods to shut down the core. After detailed investigation it is determined that the scram signal was erroneous and it is now necessary to return the reactor to full power operation; 12 hours have passed since shutdown. The control rods are withdrawn to the critical, pre-scram position and the reactor is brought to temperature. Is the reactor critical? If not, how would you determine how long it was necessary to wait until the reactor would be critical at temperature and at the pre-scram rod position. Write the governing equations.

# Numerical Methods

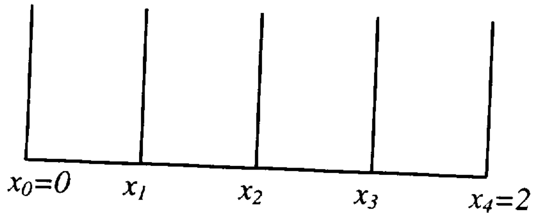
NE.2.6. Consider the following diffusion equation which describes the neutron balance in a purely scattering slab of thickness "4":

$$\frac{d^2\phi(x)}{dx^2} = 0$$

$\phi(x = 0) = 2$ and $\phi(x = 0) = 0$

(a) Derive the finite difference equations for the above system.

(b) Solve these finite difference equations by the Gauss-Seidel iterative algorithm using 5 equally spaced mesh points as shown in the figure below.



Perform only 3 iterations using the following initial guess:

$\phi_1^{(0)} = 1$, $\phi_2^{(0)} = 0.8$, $\phi_3^{(0)} = 0.4$

# Reactor Criticality

NE.2.7. Using two-group diffusion theory, determine the geometric buckling for a critical reactor with the following group constants:

$\Sigma_{R1} = 0.03\ cm^{-1}$ $\Sigma_{s12} = 0.02\ cm^{-1}$ $\Sigma_{a2} = 0.09\ cm^{-1}$

$\Sigma_{tr1} = 0.22\ cm^{-1}$ $\Sigma_{tr2} = 1.11\ cm^{-1}$

$\upsilon\Sigma_{f1} = 0.008\ cm^{-1}$ $\upsilon\Sigma_{f2} = 0.15\ cm^{-1}$

Assume all fission neutrons appear as fast neutrons.

## Energy-Dependent Diffusion Theory

NE.2.8. Consider spatially constant cross sections, as a function of a dimensionless energy $E$, given by

$$\Sigma_c(E) = 1/E \quad \Sigma_s(E) = 2/E \quad \Sigma_f(E) = 3/E$$

(a) Obtain one-group results for $\overline{\Sigma}_c$, $\overline{\Sigma}_s$, $\overline{\Sigma}_f$ and $\overline{D}$ assuming a Maxwellian spectrum:

$$\phi(x,E) = Ee^{-E/T(x)}$$

where, $T(x)$ is a dimensionless spatially dependent temperature.

(b) As we know, in general, $\overline{D} \neq 1/3\overline{\Sigma}_{total}$. Then, what type of flux spectrum $\phi(x,E)$ would lead to $\overline{D} = 1/3\overline{\Sigma}_{total}$?

**NOTE** : $\int dyy^n e^{ay} = \frac{y^n e^{ay}}{a} - \frac{n}{a}\int dyy^{n-1}e^{ay}$

N.E. Ph.D. Qualifier Exam
Section 5
Fall Quarter 1997

# GEORGIA INSTITUTE OF TECHNOLOGY

## The George W. Woodruff School of Mechanical Engineering

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# GEORGIA INSTITUTE OF TECHNOLOGY

# NE PhD Examination

## October 1997

Fall Quarter, 1997

## Section 5

## Friday - AM

## Questions 3.1-3.4

### Instructions

1. This is a closed book, closed notes examination.
2. No reference material is allowed.
3. Answer all questions.
4. Write your assigned exam number on each question.

## Thermal-Hydraulics

NE.3.1. **[16 page attachment]** - Consider a Pressurized Water Reactor Response following failure of a pressurizer PORV. The primary pressure rapidly decreases until it reaches the saturation pressure at the average coolant temperature. The reactor trips due to primary system low pressure, while the emergency core cooling system (ECCS) is automatically actuated to compensate for the loss of primary coolant inventory through the failed PORV. Decay heat is removed by heat transfer to the secondary system through the steam generators and by convective heat removal by the injected ECCS water. At some point during the transient, the conditions listed in Table 1 prevailed. Determine the primary system cooldown rate (i.e. rate of change of primary coolant average temperature) and the corresponding rate of change of primary coolant pressure.

TABLE 1

| | |
|---|---|
| Core decay heat | 40 MWt |
| Primary coolant pressure | 1400 psia |
| Primary coolant condition | Saturated Liquid |
| ECCS water injection flow rate | 700 gpm |
| ECCS water inlet temperature | 80 °F |
| Pressurizer PORV liquid discharge rate | 700 gpm |
| Pressurizer PORV liquid discharge condition | Saturated liquid |
| Steam generators feedwater flow rate | 300 gpm |
| Steam generators feedwater inlet temperature | 80 °F |
| Steam generators pressure | 1000 psia |
| Steam outlet condition | Saturated vapor |
| Total Primary System Volume (including Pressurizer) | 6,600 $ft^3$ |

## Thermal-Hydraulics

NE.3.2. The core of a 3300 MWt PWR contains 193 fuel assemblies, each containing 207 fuel rods with an active length of 380 cm. The rods contain cylindrical UO2 fuel pellets 9.4 mm in diameter surrounded by Zircaloy cladding 9.7 mm ID and 10.7 mm OD with a helium gap in between. At steady state full power operating conditions, the heat flux hot spot factor in the core is 2.5.

a. Determine the volumetric heat generation rate in the fuel material, the surface heat flux, and the linear heat rate at the hot spot.

b. Ignoring heat generation in the cladding and structure, determine the maximum fuel material temperature at the hot spot. The coolant temperature and heat transfer coefficient at the hot spot are 300 °C and 30 kW/m$^2$ °C, respectively. [Assume the thermal conductivity of the fuel material, gas gap, and clad to be constant and equal to 3.0, 0.28, and 18.7 W/m°C, respectively].

c. Assuming the average enrichment in the core to be 2.8%, the fuel material density to be 90% of the theoretical value and the average moderator temperature to be 277 °C, estimate the average thermal neutron flux in the core. [Theoretical density of UO$_2$ = 10.97 g/cc; for U$^{235}$: $\sigma_{fo}$ = 577 b for $T_o$ = 293 °K].

## Thermal-Hydraulics

NE.3.3. a) Schematically plot the two-phase flow regimes, boiling mechanisms, and axial variations of wall and fluid temperatures in a vertical upflow boiling channel.

b) Display the ranges of forced-convection boiling regimes on a boiling curve (heat flux versus wall superheat).

c) Explain the phenomenology of departure from nucleate boiling (DNB) and dryout, and explain where they occur.

## Thermal-Hydraulics

NE.3.4. Using macroscopic momentum and mechanical energy conservation equations, derive a relation for irreversible pressure loss across a sudden expansion in a one-dimensional, adiabatic and homogeneous two-phase flow. Assume that void fraction remains constant, and gas and liquid phases are both incompressible.

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# GEORGIA INSTITUTE OF TECHNOLOGY

## NE PhD Examination

## October 1997

Fall Quarter, 1997

## Section 6

## Friday - PM

## Questions 3.5-3.8

### Instructions

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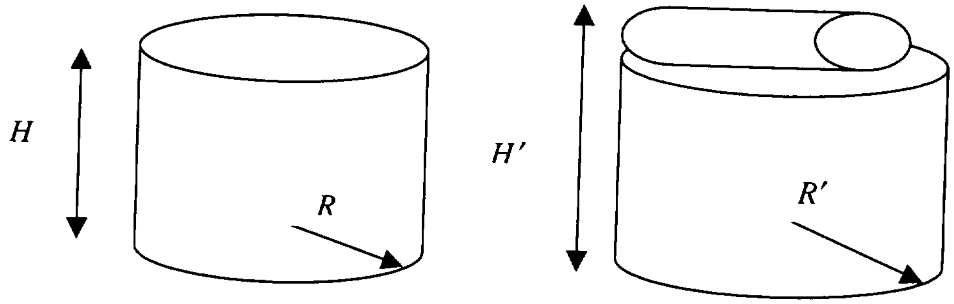
# Nuclear Materials

NE.3.5. Describe at the atomistic level what happens to the crystal structure of a material when it is subjected to nuclear reactor irradiation and how are the material properties altered?

## Criticality Safety

NE.3.6. A fuel assembly of cross-sectional area (A) and height (H) is dropped while being removed from a shipping cask full of fuel. The cask can be thought of as a cylindrical reactor core with radius (R) and height (H). If the dropped assembly lands directly on top of the cask, derive an equation based on a buckling argument, which will allow one to determine whether or not the subcritical reactivity of the system will increase or decrease as a result of this fuel dropping accident:



$R$ = radius before dropped fuel

$H$ = radius before dropped fuel

$R'$ = radius after dropped fuel

$H'$ = radius after dropped fuel

Recall:

$$B^2_{geometric} = \left(\frac{2.405}{R}\right)^2 + \left(\frac{\pi}{H}\right)^2$$

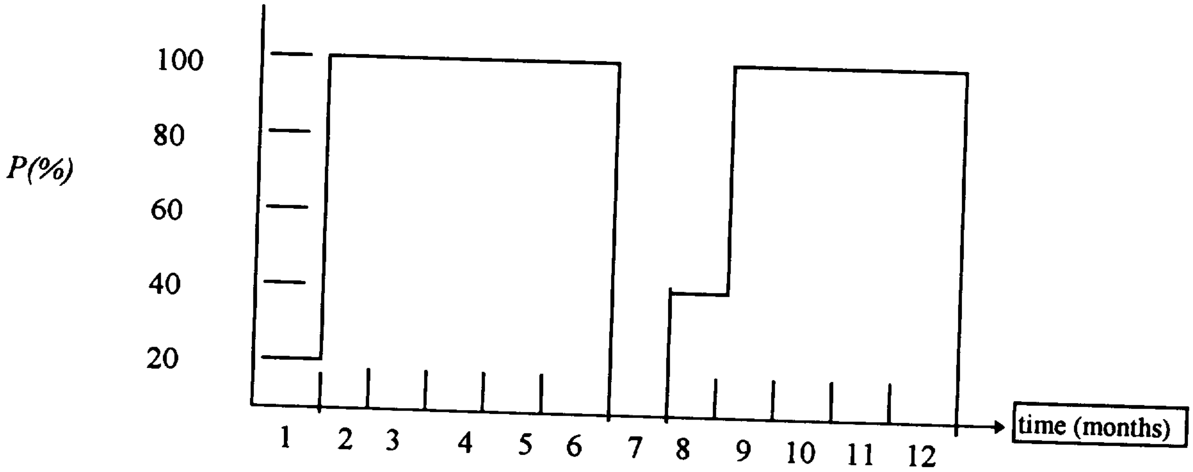
## Waste Management/Fuel Cycle

NE.3.7. For the reactor power history shown, calculate:

(a) the availability factor
(b) the capacity factor
(c) the effective full-power days during the 12 month period
(d) the burnup during the 12 month period
(e) decay power in the core at 1 month after shutdown

Assume all power was generated by $^{235}U$ fission. The core contains 85 tonnes of uranium and generates 1100 MWe with an efficiency of 31%.

Date: $P(*,\infty)/P_0 = 0.266e^{-.335}$



## Nuclear Design

NE.3.8. An accelerator-based neutron source can produce $5x10^{20}$ n/s within a spherical volume of 0.1 $m^3$. The source neutron spectrum is highly energetic, with most neutrons having energy greater than 10 MeV. You are asked to design an assembly containing depleted nuclear reactor fuel to be placed around the neutron source for the purpose of "burning out" (by neutron transmutation and fission) the long-lived fission products and actinides in the spent fuel. Describe an initial design concept that might be investigated for such an assembly (i.e. choice of materials and configuration). Discuss what would have to be taken into consideration to optimize the assembly to burn out fission products and actinides. Discuss the likely physical limitations on the performance of the assembly. Describe the set of design analyses that you would perform to evaluate your design concept.