

Preliminaries

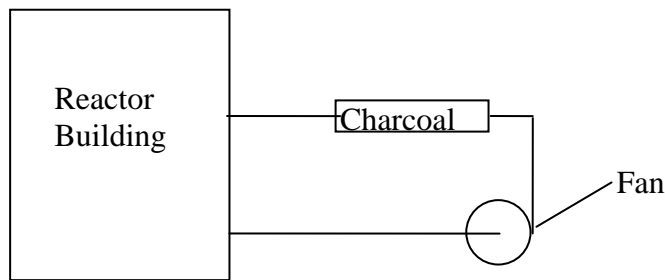
1. The fission of the nucleus of U^{235} releases approximately 200 MeV. How much energy (in kilowatt-hours and megawatt-days) is released when 1 g of U^{235} undergoes fission?
2. Consider the case of 3 nuclei of each having a mass number of 2 fusing into 2 nuclei of mass 3, compute the energy per reaction, if the difference in binding energy per nucleon between the nucleus of mass 3 and that mass 2 is 2 MeV.
3. For the isotope $^{232}_{90}\text{Th}$, state the Z and A of the product if it undergoes the following reactions:
(i) β^- decay, (ii) β^+ decay, (iii) alpha decay, (iv) (n, α) and (v) (n, γ)
4. Indian reactors discharge fuel from the reactor after the fuel has produced approximately 8000 Mega Watt-days/metric tonne of Uranium metal. If the plant electrical to thermal conversion efficiency can be assumed as 32%, and if it has been decided to allocate 10 paise per kW-hr of electrical energy produced towards coverage of waste management, estimate the money available for the disposal of radioactive waste in Rs/kg-fission product. You may assume the mass of fission product is equal to mass of the fuel consumed, energy per fission = 200 MeV, A for the fuel = 237

Radioactivity

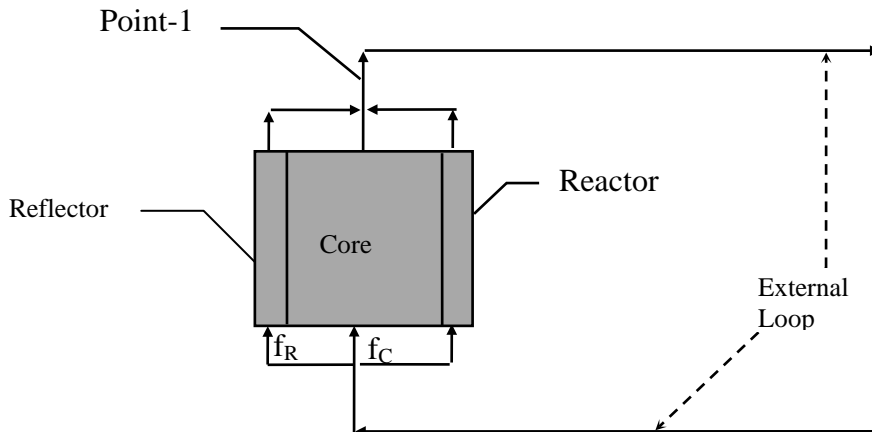
1. Rutherford had postulated that at the time of earth's birth, U^{235} and U^{238} had equal concentration. Assuming that their ratio today is 0.007 to 0.993, compute the Rutherford's estimate for the age of earth. The respective half lives of U^{235} and U^{238} are, 0.709×10^9 and 4.47×10^9 years.
2. Polonium ($A = 210$, density = 9.24 g/cc) has a half life of 138.4 days and emits alpha particles of energy 5.408 MeV for every disintegration. How much volume it will occupy today, if this material has to produce 100 W one year later?
3. 1 gram of Radium ($A = 226$, density = 5.0 g/cc, $T_{1/2} = 1602$ years) is sealed in a container of volume 1 cm^3 free volume (volume available for gas). Estimate as to how much will be the pressure inside after 1 year, as a result of helium produced (each alpha nuclei released from radioactive disintegration will become 1 atom of helium). You may assume that the temperature is 300 K, and one mole of helium (at 1 bar and 300 K) will occupy 22.4 litres.
4. Consider reduction of radioactive substances that enter a living organism. The substance has two simultaneous removal mechanisms. One is the natural radioactive process and the other is the process of excretion (removed by the process of digestion and released out of the body as waste). Let us assume that each of this is an exponential law with characteristic constants λ_{radio} and λ_{bio} . Express the effective half life of the combined process in terms of the half lives of the individual processes.
- 5(a) Radioactive C^{14} is generated in atmosphere because of cosmic rays. As a consequence, all carbon compounds in nature emit beta particles at an average rate of 255/s per kg of carbon (due to presence of C^{14}) with $T_{1/2} = 5730$ years. Determine the weight percent of C^{14} in carbon.
(b) Radio carbon dating is based on the absorption C^{14} by living material through consumption of food that contains C. After death, absorption ceases and C^{14} decays. Estimate the age of a fossil dug out that had a weight fraction of C^{14} in carbon to be equal to 1.09×10^{-12} .
6. Consider a radioactive fission product 'A' is formed in 6% of fissions in a 3200 MW(th) reactor. If the activity of A has reached its equilibrium activity, estimate what fraction of core

inventory disintegrates in one year of operation (after equilibrium has reached). Assume 1 fission = 200 MeV, $\lambda_A = 1 \text{ (day)}^{-1}$

7. Consider an accident situation in a reactor building, where all the volatile fission products of Iodine are released. For simplicity, we can assume that all iodine is of a single specie with a characteristic decay constant λ . It may be assumed that all the iodine is in vapour form as long as it is there in the reactor building. The total initial iodine activity (at $t = 0$) is α_0 . To decontaminate the building, a filtration circuit is activated after some delay. As shown in the figure, it consists of a fan and a charcoal bed. During its operation, the contaminated air is circulated through the charcoal bed, which traps all the active iodine from the air and returns clean air back into the building. The volumes of the charcoal bed and reactor building are v and V respectively, and the volumetric flow rate of the air through the charcoal bed is Q .
- Derive an expression for the change of total activity in the building before the fan is started.
 - Assuming that the fan is started at time T , derive an expression for the change of total activity in the building (you may assume that the activity is always uniform in the building)
 - Derive an expression for the build up of activity in charcoal bed.
 - Get an expression for the maximum activity in the filter, and the time from initiation of the accident at which the maximum activity occurs.



8. In many water cooled reactors water acts as moderator and reflector. The schematic view of the water circuit is shown in the figure. The fraction of water flowing in the core may be assumed to be f_c and the remaining fraction flowing in the reflector may be taken as f_r . The time spent by water in core, reflector and the external loop are T_C , T_R and T_L respectively. Now consider production of isotope by activation (neutron reaction) in the circulating coolant of a reactor system. The decay constant of the radio-isotope may be assumed as λ . It may be assumed that its production rate inside the core region is constant at P_C nuclei/cc-s and the same in the reflector region is P_R nuclei/cc-s. Assuming that the activation process has reached equilibrium, (production-decay in the core and reflector, and its decay in the external loop are balanced), derive an expression for the activity at point-1 marked in the figure.



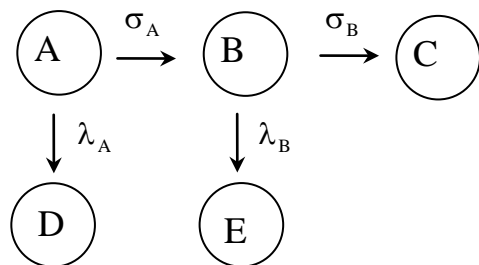
9. The fission product ^{131}I has a half life of 8.05 days and is produced with a yield of 2.9 % (0.029 atoms per fission). Calculate the equilibrium activity of this isotope in a reactor operating at a thermal power of 3300 MW.

Nuclear Reactions and Fission

1. Compute the neutron-proton mass difference in MeV.
- 2(a) Define the 'Q' value of a nuclear reaction:

$$X_1 + X_2 \longrightarrow X_3 + X_4$$
- (b) Some tables tabulate the mass excess 'Δ', defined as the M-A, where M and A are the rest mass of the neutral atom and the mass number of a given element expressed in energy units respectively. Derive a relation for the Q value in terms of $\Delta_{X_1}, \Delta_{X_2}, \Delta_{X_3}$ and Δ_{X_4}
- (c) Given the values of Δ's of $^3\text{H}, ^2\text{D}, ^4\text{He}$ and ^1_0n are 14.950, 13.136, 2.425 and 8.071 MeV respectively, compute the Q value for the reaction,

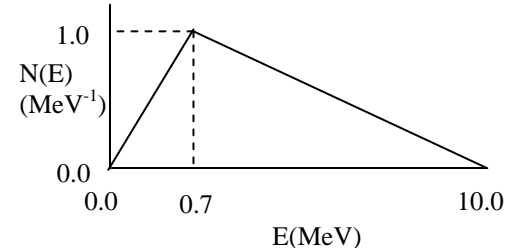
$$^3_1\text{H} + ^2_1\text{D} \longrightarrow ^4_2\text{He} + ^1_0\text{n}$$
- (d) Compute the binding energy of the last neutron for $^{236}_{92}\text{U}$, given that the Δ values in MeV for $^{235}_{92}\text{U}, ^{236}_{92}\text{U}$ and ^1_0n are 40.93, 42.46 and 8.071 respectively.
3. Assuming that the fissioning nucleus is ^{235}U , compute the value of β, defined as the mass of the fuel consumed per unit energy release. You may assume that 200 MeV is released per fission and the value of capture to fission ratio is 0.17.
4. Consider a branched chain reaction taking place inside a nuclear reactor represented by the following diagram, where both radioactive decay and neutron absorption reactions proceed simultaneously. The relevant decay constants and absorption cross sections are as shown. The reactor may be assumed to be operating at a constant flux.



- (a) Write down the rate equations that describe the time variation of concentrations of the nuclei, A, B, C, D and E.
- (b) Solve for the variations of the concentrations of the nuclei, A, B, C, D and E with time. You may assume that the concentrations of A, B, C, D and E at time = 0 are $N_{A0}, N_{B0}, N_{C0}, N_{D0}$ and N_{E0} respectively.
- (c) If the reactor operates for a time t and then shut down, sketch the variation of the concentration of A, B, C, D and E with time for $0 < t < 2t$. Give qualitative arguments justifying the nature of curves. If multiple trends are possible, show all of them.

5. Two nuclei A and B are $1/v$ -type. The absorption cross-section for A at 0.025 eV is 5 barns and the same for B at 1 MeV is 1 barn. If these nuclei having same number densities are irradiated in a reactor, what will be their ratio of the reaction rates.
6. Natural boron has a number density $N = 0.128 \times 10^{24}$ atoms/cc and $\sigma_a = 764$ b at an energy of 0.025 eV. Assuming the boron to be a $1/v$ absorber, calculate the thickness of boron required to reduce the intensity of an incident beam by 50%, if the neutron energy is 0.5 MeV.

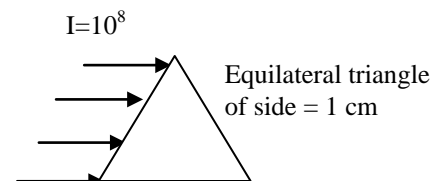
7. Consider the spectrum shown in the figure. Compute the average neutron energies (mean, median and mode)



8. A nuclear fuel consists of a 12.5 mm pellet made of natural uranium-dioxide. It is clad with 0.5 mm thick Zirconium. Given that the density of UO_2 and Zr to be 10.5 and 6.5 g/cc respectively and the cross sections of the materials be as given, compute the homogeneous absorption cross section of the fuel element.

Material	σ_a (barns)
U^{235}	681
U^{238}	2.7
Zr^{91}	0.198
O	0.0

- 9(a) Consider Cs^{137} formed in a reactor as a fission product with a yield of Y (fraction of nuclei per fission). Assuming that the macroscopic fission cross section of the reactor core is Σ_f , and the flux is uniform at ϕ , write down the equation that will determine the change in concentration of Cs^{137} in the reactor.
- (b) What will be the equilibrium concentration of Cs^{137} ?
- (c) Given that Cs^{134} and Cs^{137} are formed as fission products with equal yield, find the ratio of the equilibrium concentration of Cs^{134} and Cs^{137} , if their half lives are 2.05 year and 30 year respectively.
- 10(a) We had derived a criterion for thin target approximation, wherein the intensity of neutrons can be assumed to be uniform throughout the target. Now consider the other extreme, which may be called black target approximation. A black target may be defined as a target that absorbs all neutrons incident on it. For engineering purposes, let us assume that if 99% of the incident neutrons are absorbed, then the target may be called black. Arrive at a suitable criterion for the same.
- (b) Boron (B^{10}) is used in reactor as a control material. Natural Boron has B^{10} and B^{11} in the atomic ratio 0.198:0.802, and has a density of 2.3 g/cc. The neutron absorption cross section of B^{10} is 3837 barns and that of B^{11} is negligible. Calculate the minimum thickness of natural Boron above which it could be considered as black
- (c) Now consider a target made of natural Boron in the form of equilateral triangle with each side measuring 1 cm. If a neutron beam of intensity 10^8 neutrons/cm²-s is impinging on the target as shown in the figure, estimate the actual neutron absorption



rate. Compare this with that obtained using the black target approximation

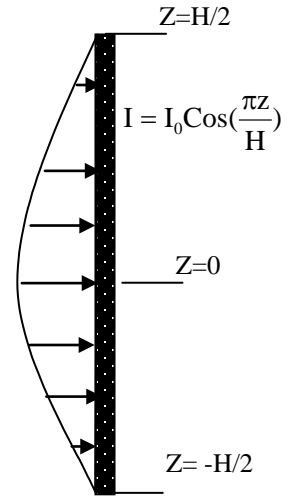
- 11(a) Natural UO_2 (ratio of number of $\text{U}^{235}:\text{U}^{238} = 7:993$) with a density of 10.5 g/cc is used as a fuel in a reactor. Assuming the properties given at the end of the problem, compute the macroscopic absorption cross section of the fuel.
- (b) Consider a fuel element of natural UO_2 of 9 mm diameter. Using the diameter as the characteristic dimension, check whether thin target approximation is valid.
- (c) Irrespective of your answer in part (b), let us assume that the thin target approximation is valid. If the height of the fuel element is 3.6 m and is placed in a reactor such that the axial neutron intensity variation is given by,

$$I = I_0 \cos\left(\frac{\pi Z}{H}\right),$$

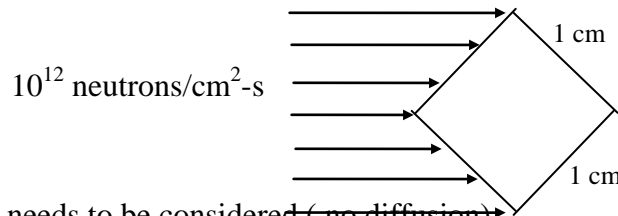
where $I_0 = 10^{12}$ neutrons/cm²-s, H is height of fuel element (refer figure), estimate the power generated in the rod. Assume 1 fission releases 200 MeV.

Relevant data:

Material	σ_a (barns)	σ_f (barns)
U^{235}	680	580
U^{238}	2.7	0.0
O	0.0	0.0



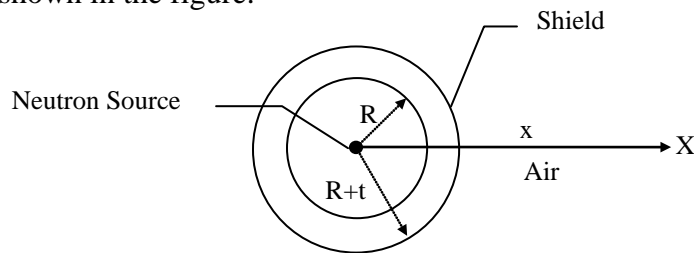
12. Gold consists of 100% ^{197}Au and captures neutrons ($\sigma_a = 96$ barns) to form radioactive ^{198}Au (half life = 2.7 days) which emits beta particles. Consider a thin foil of 50 mg placed in a nuclear reactor for 10 minutes. After 2 hours of the removal from the reactor, the foil is found to emit 300 betas per second. Calculate the neutron flux in the reactor at the point the foil was placed. (1.740×10^9 n/cm²-s)
13. Consider a square fuel element 1cm X 1cm intercepting a monoenergetic thermal neutron beam of intensity of 10^{12} neutrons/cm²-s as shown in the figure. Compute the heat generated per unit length (perpendicular to the paper) in the fuel in W/m, given the following:



- (a) Only absorption needs to be considered (no diffusion).
- (b) Fission neutrons being energetic do not react with fuel.
- (c) Σ_f and Σ_a for the fuel are 29.2 cm⁻¹ and 33.8 cm⁻¹ respectively
- (d) Energy released per fission = 200 MeV.
(Note that thin target approximation is not valid.)
14. A nuclear reactor is made of fuel rods of 1 cm in diameter and arranged in a square pitch of 1.3 cm. The moderator fills the gap between these rods. The macroscopic absorption cross

sections of the fuel and moderator (in their pure state) are given to be 0.2 cm^{-1} and 0.05 cm^{-1} respectively. If η (eta) for the fuel is 1.5, calculate the infinite multiplication constant

15. Neutrons when impinging on structural materials cause radiation damage by (n- α) reactions. The α 's turn into helium gas and accumulates in the matrix of the material and generates swelling in the material. This eventually leads to structural failure. You are asked to estimate the volume of the helium gas generated (due to ^{56}Fe (n- α) reaction) in cm^3 , per cm^3 of stainless steel (SS) sheet of 1 cm thickness, with iron (^{56}Fe) fraction of 0.72 by weight and exposed to a neutron flux of 10^{14} neutron/ cm^2 -s for 1 year. The density of SS is 7.8 g/cc, $\sigma_{(n,\alpha)}^{\text{Fe}} = 0.1$ barns. ($R = 8.314 \text{ J/Mole-K}$). If you are using approximations for the computation of reaction rates, then, you have to justify suitably.
16. From health safety considerations it is necessary to protect working personnel from neutrons. Consider an application where a point source emitting S neutrons per second has to be shielded as shown in the figure.



- (a) Consider a spherical shell of radius r and thickness dr . Perform neutron balance to obtain a differential equation describing the variation of neutron intensity I with radius. You may assume that the neutron absorption cross section (macroscopic) of the material as Σ_a (Neglect scattering)
- (b) Take a special case when $\Sigma_a = 0$ (air can be assumed not to absorb neutrons). Integrate the differential equation with suitable boundary condition at the source to obtain the intensity at $r = R$ (inner surface of the shield)
- (c) Now proceed similarly to solve for obtaining the neutron intensity at the outer surface of the shell. Note that the thickness of the shell is t , and the neutron absorption cross section is Σ_a .
- (d) Estimate the neutron intensity at the point X, which is at a distance x from the source.

Collision and moderation

1. A neutron collides with C^{12} at rest. The neutron is elastically scattered at an angle of 60° to the original direction. Estimate the fractional energy lost by the neutron. Determine the angle of scatter of the carbon nuclei to the original direction of the neutron,
2. A 2-MeV neutron travelling in water has a head-on collision with an O^{16} nucleus.
 - (a) What are the energies of the neutron and nucleus after the collision?
 - (b) Would you expect the water molecule involved in the collision to remain intact after the event?
3. A 1-MeV neutron strikes a C^{12} nucleus that is initially at rest. If the neutron is elastically scattered through an angle of 90° ,
 - (a) What is the energy of the scattered neutron?
 - (b) What is the energy of the recoiling nucleus? (c) at what angle does the recoiling nucleus appear?

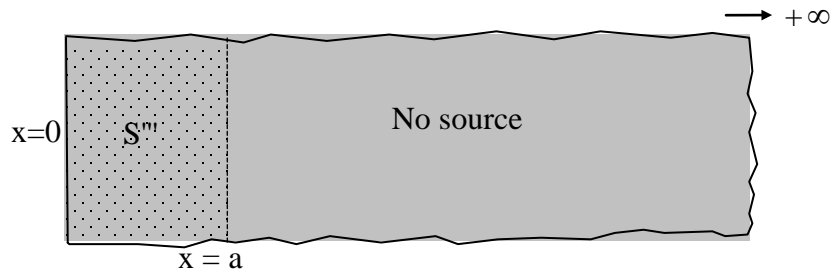
4. Show that the average fractional energy loss in percent in elastic scattering for large A is given

approximately by, $\frac{\overline{\Delta E}}{E} \cong \frac{200}{A}$

5. Calculate the average number of collisions required to reduce the energy of a neutron from 2 MeV to 0.025 eV in H^1 and C^{12} .

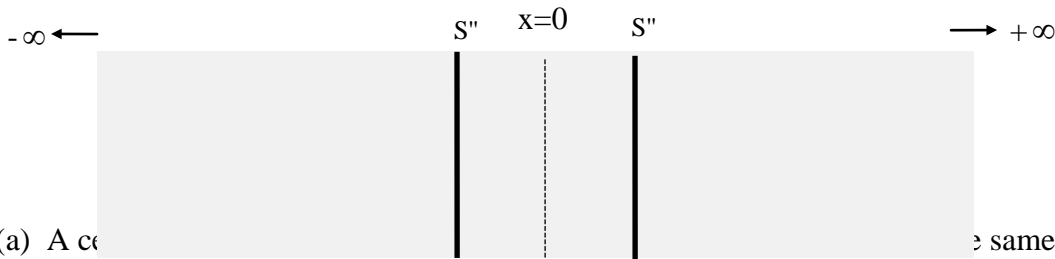
Diffusion

- The mono-energetic neutron beams of intensities 2×10^{10} and 1×10^{10} neutrons/cm²-s respectively, intersect an angle of 30°. Calculate the neutron flux and current in the region where they intersect.
- Consider a planar ring source with an inner radius of 5 cm and outer radius of 10 cm, emitting neutrons at a rate of 10^{12} neutrons/cm²-s. This disc is suspended in a very large pool of liquid ($D = 0.5$ cm⁻¹, $L = 100$ cm). If you are given that the expression for the flux at a distance 'r' from the point source in an infinite media is given by $\phi = \frac{S}{4\pi D} \frac{e^{-r/L}}{r}$, compute, by using method of superposition, the flux at a distance of 100 cm along the axis of the disc. (Hint take a small element in appropriate coordinate system so that it can be treated as a point source, apply the formula given and integrate with proper limits)
- Consider a semi-infinite region with a distributed source as represented by:
 $S'''(x) = S''$, for $0 < x < a$ and $S'''(x) = 0$, for $a < x < \infty$, as shown in the figure.



The diffusion coefficient and the diffusion length of the region may be assumed to be D and L respectively. Compute the flux distribution using diffusion theory. For the source region, use constant as a particular solution (note that you need to determine the constant)

- Derive an expression for the flux distribution due to two infinite planar sources emitting S'' neutrons/cm²-s in an infinite region as shown in the figure. The diffusion coefficient and the diffusion length of the region may be assumed to be D and L respectively.



- 1(a) A cylinder of the same material is shaped as a cylinder with $D=H$, what will be its critical size.

- (b) Using one-speed approach, calculate the ratio of the neutron non-leakage probability

- (c) If both the reactors are producing the same power, compute the ratio of the maximum neutron flux in both the reactors
2. A very large homogeneous reactor is built with uranium salt and water. Based on the composition, the parameters computed are: $\sigma_a(U^{235}) = 581$ b, $\sigma_c(U^{235}) = 100$ b, $\nu = 2.5$, $\epsilon = 1.03$, $N(U^{235}) = 10^{21}$ atoms/cc, $N(\text{others}) = 4 \times 10^{21}$ atoms/cc, $\sigma_a(\text{others}) = 25$ b, Calculate (a) η and f , (b) estimate the value of p for criticality.
3. At a fuel reprocessing plant, aqueous solution of Uranyl Sulphate ($U^{235}O_2SO_4$) is to be stored in cylindrical pipes. If the maximum concentration of the Uranyl Sulphate in the solution is expected to be 100 g/litre, what is the maximum size (radius) of the pipe which can be safely used to avoid any accidental criticality. Assume pipe to be an infinite cylinder and use one group approach. You may assume for simplicity that the density of UO_2SO_4 solution is 1g/cc. Additional data:

Material	σ_a (barns)	σ_f (barns)	ν	L (cm)
U^{235}	681	581	2.5	---
H_2O	0.664	---	---	2.85
O^{16}	0.0	0.0	---	---
S^{32}	0.0	0.0	---	---

4. A spherical nuclear reactor (fast) of 0.5 m radius, is fuelled with mixed $Pu^{239}O_2 - U^{235}O_2$ (density = 10.5 g/cc) with weight per cent of PuO_2 being 15%. Further, the reactor has Fe^{56} (structural material, 7.9 g/cc) and Na^{23} (coolant, 0.97 g/cc) such that the volume fractions of fuel, Fe and Na respectively are, 0.3, 0.2 and 0.5. Using the average properties as specified in the table, compute the diffusion length of the reactor system as given by one speed theory.

Material	σ_a (barns)	σ_f (barns)	ν
U^{235}	0.404	0.05	2.5
Pu^{239}	2.4	1.95	3.0
Na^{23}	0.0018	---	---
Fe^{56}	0.0087	---	---
O	0.0	0.0	---

5. A fission core large enough to have negligible neutron leakage is composed of only two nuclides having the following cross sections:

Nuclide	σ_c	σ_f	$\nu\sigma_f$
1	100	500	1250
2	100	0	0

Find the ratio if N_1/N_2 that will just achieve criticality

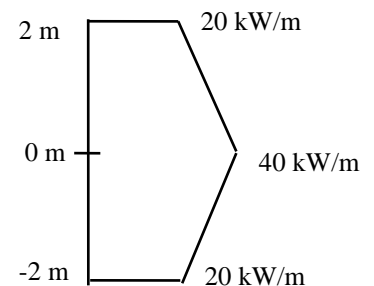
6. In a particular reactor system the following are the computed macroscopic cross sections: Σ_f of fuel = 0.5 cm^{-1} , Σ_a of fuel = 0.6 cm^{-1} . ν of fuel = 2.5, Σ_a of moderator = 0.4 cm^{-1} and Σ_a of others = 0.2 cm^{-1} .
- (a) Compute the fraction of neutrons leaking out of the reactor, if it is operating steadily.

- (b) Now assume that a perfect reflector is wrapped around the reactor reducing the neutron leakage to zero. How much in terms of Σ_{absorber} has to be added to maintain criticality.
- (c) As this reactor operates, the fissile content will reduce, thereby reducing Σ_f . To compensate for this, Σ_{absorber} has to be decreased to maintain criticality. Calculate the maximum fraction of the fuel nuclei that can be consumed after which the reactor can no longer maintain its criticality. For simplicity you may assume that the fission products do not absorb neutrons. 2.

Heat Generation

1. A commercial reactor has the following specifications: Power = 2440 MW(th), pellet diameter = 0.964 cm, clad OD = 1.118 cm, active fuel length = 3.6 m, The core contains 14 X 14 lattice fuel positions (less 20 per sub-assembly for control rods). Compute the following core averaged parameters, (a) heat rate per fuel pin (kW), (b) linear heat rate (kW/m), (c) heat flux from the clad (in kW/cm²) and volumetric heat generation in fuel pellet (in W/cc)
2. Consider a PHWR 6 m in diameter and 6 m long, rated to operate at 750 MW(th). The general power profile may be assumed as $q' = q'_{\text{max}} \cos\left(\frac{\pi z}{L}\right) J_0\left(\frac{2.405r}{R}\right)$. Answer the following: (a) If the reactor has 306 coolant channels, the radial peaking factor is 2.63, compute the power generated in the central channel.
 - (a) If the central channel has 19 fuel rods (of 6 m length) in it, and these rods may be assumed to behave identically, estimate the maximum linear heat rate q'_{max} for a single rod.
 - (b) The above reactor having operated for a long time at its rated power is shut down. Compute the minimum coolant flow rate of fluid that must be maintained in the central channel after 1 hour so that the increase in coolant temperature is limited to 30°C. You may assume that the c_p coolant = 4.2 kJ/kg-K.
 - (c) If the central channel consists of 82 mm coolant channel with 19 rods of 16 mm diameter, compute the maximum rod surface temperature and its location. You may assume the value of heat transfer coefficient to be 8000 W/m²-K.
3. The core of a Light Water Reactor consists of fuel rods of 1 cm diameter and 4m length. The reactor operates with a thermal power of 3000 MW and has a maximum calculated heat flux of 1.7×10^6 W/m² with an overall hot channel factor of 2.8. Calculate the total heat transfer area and the number of fuel rods in the core.

4. Consider a vertical fuel rod of 8 mm diameter wetted with a coolant mass flow of 0.5 kg/s. If the linear heat generation rate is as shown in the figure, and the coolant enters at 267 °C, compute the location at which the coolant will boil. You may assume that the saturated temperature of water at the fluid pressure is 285.8 °C, $c_p = 5.444$ kJ/kg-K. If the heat transfer coefficient at that location is 8000 W/m²-K, compute the clad surface temperature.

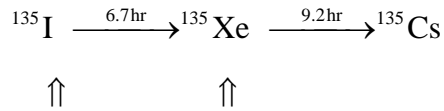


5. A reactor is made up of channels with fuel rods of 10 mm diameter. The associated coolant flow area is 1.5 cm². The coolant enters at 10 Mpa at a velocity of 3.6 m/s and 250 °C. The exit temperature of the coolant is 295 °C. The axial power profile in the channel may be assumed to vary as, $q'' = q''_0 e^{\frac{\pi z}{H}} \sin\left(\frac{\pi z}{H}\right)$, where H represents the height of the core, which is 3.6

m, z=0 represents the bottom of the core and q_0'' is a constant. Compute the location of the maximum fuel surface temperature, given the following: $\rho_f = 732.3 \text{ kg/m}^3$, c_p of the coolant = 5.51 kJ/kg-K. Convective heat transfer coefficient = 10 kW/m²-K.

Reactor Kinetics

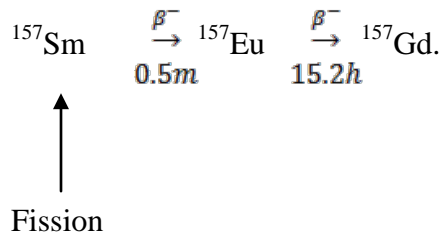
1. A ²³⁵U fueled reactor originally operating at a power of 1 milliwatt is placed on a positive 10 minute period. At what time will the reactor power level reach 1 megawatt? You can assume that $\beta = 0.0065$ and $\lambda = 0.08 \text{ s}^{-1}$ (Hint from T_p get ρ , and then t)
2. Fifty cents in reactivity is suddenly introduced into a fast reactor fueled with ²³⁵U. What is the period of the reactor? You can assume that $\lambda = 0.08 \text{ s}^{-1}$
3. The reactor in problem 1 is scrammed by the instantaneous insertion of 5 dollars in negative reactivity after having reached a power level of 1 megawatt. Approximately how long does it take the power level to drop to 1 milliwatt?
4. When a certain research reactor operating at a power of 2.7 megawatts is scrammed, it is observed that the power drops to a level of 1 watt in 15 minutes. How much reactivity was inserted when the reactor was scrammed? $\beta = 0.0065$ and $\lambda = 0.08 \text{ s}^{-1}$. (This will need an iterative solution. You can use Goalseek function in Excel to solve. The first guess of ρ can be obtained by assuming that prompt jump does not exist)
5. An infinite reactor consists of a homogeneous mixture of ²³⁵U and H₂O. The fuel concentration is 5 percent smaller than that required for criticality. What is the reactivity of the system? Take η for ²³⁵U = 2.068 (Hint: Comparison is done with $K_\infty = 1$; hence $f_0 = 1/\eta$. Now proceed to compute $\frac{\sum_{a0}^{Mod}}{\sum_{a0}^{Fuel}}$. Note that for the actual case, $\sum_a^{Mod} = \sum_{a0}^{Mod}$ and $\sum_a^{Fuel} = 0.95 \sum_{a0}^{Fuel}$. Now compute f and finally ρ).
6. An infinite ²³⁵U fueled, water moderated reactor contains 20 percent more ²³⁵U than required to become critical. What concentration of (a) boron in ppm or (b) boric acid in g/litre is required to hold down the excess reactivity of the system?
7. A pressurized water reactor fueled with stainless steel clad fuel elements is contained in a stainless steel vessel which is a cylinder 1.8 m in diameter and 2.4 m high. Water having an average temperature of 300°C occupies approximately one-half of the reactor volume. How much water is expelled from the reactor vessel if the average temperature of the system is increased by 5°C? [Note : The volume coefficients of expansion of water and stainless steel at 300°C are 3×10^{-3} per °C and 4.5×10^{-5} per °C, respectively.]
8. The thermal utilization of the reactor in Problem 7 is 0.682 at 300°C. Using the results of that problem and ignoring the presence of structural material in the core, estimate $\alpha_T(f)$ at approximately 300°C.
9. A ²³⁵U fueled reactor operating at a thermal flux of 5×10^{13} neutrons/cm²-sec is scrammed at a time when the reactor has 5 percent in reserve reactivity. Compute the time to the onset of the dead time and its duration. Use cross sections given in the class notes. Use Excel to make life easier.
10. Consider a chain reaction



$$Y_I = 0.06 \quad Y_{Xe} = 0.01$$

It may be observed that both I and Xe are produced in fission with a yield (nuclei/fission) of 0.06 and 0.01 respectively and their corresponding half lives are 6.7 and 9.2 hours respectively. Further, the neutron absorption cross sections for Iodine and Xenon are 0 and 2.65×10^6 barns respectively.

- Set up the governing equations for the rate of change in concentrations of Iodine and Xenon in a reactor with an average flux of ϕ
 - Compute the equilibrium concentrations of Iodine and Xenon, if the Power of the reactor is 750 MW and average flux is 10^{13} neutrons/cm²/s (you can assume 200 MeV per fission).
 - Assume that the reactor has been in operation for a long time for Iodine and Xenon to have attained equilibrium. At this time, the reactor is shut down instantly. Rewrite the governing equations for the new situation. Also state the initial conditions.
 - Solve the equations in (c) to obtain expressions for the variation of Iodine and Xenon concentrations with time. Sketch qualitatively the result.
 - What are the maximum concentrations of I and Xe, and at what times these occur after the reactor is shut down
11. Gadolinium -157 is a stable nuclide having an absorption cross section at 0.0253 eV of 240,000 b. It is formed from the decay of the fission product ¹⁵⁷Sm according to the following chain:

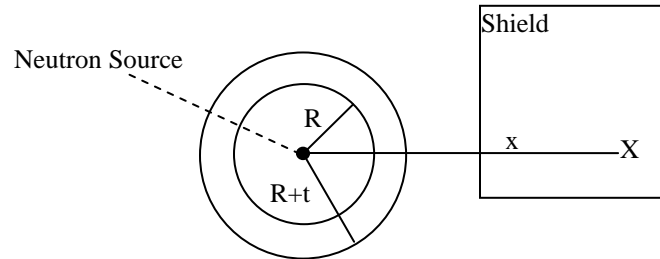


Neither ¹⁵⁷Sm nor ¹⁵⁷Eu absorbs neutrons to a significant extent. The ²³⁵U fission yield of ¹⁵⁷Sm is 7×10^{-5} atoms per fission. (a) What is the equilibrium reactivity tied up in ¹⁵⁷Gd in a reactor having an average thermal flux of 2.5×10^{13} neutrons / cm²-sec? (b) What is the maximum reactivity due to this nuclide after the shutdown of the reactor in part (a)?

Health Effects

- From health safety considerations it is necessary to protect working personnel from neutrons. Consider an application where a point source emitting S neutrons per second has to be shielded as shown in the figure.
 - Consider a spherical shell of radius r and thickness dr. Perform neutron balance to obtain a differential equation describing the variation of neutron intensity I with radius. You may assume that the neutron absorption cross section (macroscopic) of the material as Σ_a

- (b) Take a special case when $\Sigma_a = 0$ (air can be assumed not to absorb neutrons). Integrate the differential equation with suitable boundary condition at the source to obtain the intensity at $r = R$ (inner surface of the shield)
- (c) Now proceed similarly to solve for obtaining the neutron intensity at the outer surface of the shell. Note that the thickness of the shell is t , and the neutron absorption cross section is Σ_a .
- (d) Estimate the neutron intensity at the point X, which is at a distance x from the source.



2. Fallout from a nuclear blast reached a man's home at the time T_0 after detonation. The man immediately enters a fallout shelter where there is zero exposure. He spends the time T_S in the shelter and then emerges. (a) Show that the factor by which his total dose is reduced by having gone into the shelter is given by

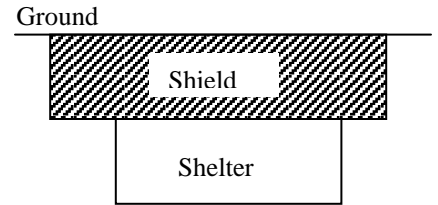
$$\frac{H_{Shelter}}{H_{No-Shelter}} = \left(1 + \frac{T_S}{T_0} \right)^{-0.2}$$

Here you assume that the activity after time t falls as $t^{-1.2}$, where t is expressed in s.

3. During emergency situations, it may be necessary for radiation workers to receive doses in excess of the MPD. The ICRP has recommended that emergency work shall be planned on the basis that the individual will not receive a dose in excess of 12 rem. This shall be added to the occupational dose accumulated up to the time of the emergency exposure. If the sum then exceeds the maximum value permitted by the formula, $H = 5(N - 18)$, the excess will be made up by lowering the subsequent exposure rate, so that within a period not exceeding 5 years, the accumulated dose will conform with the limits set by the formula. Suppose that a man is first employed in the nuclear industry at the age of 18. During the next three years, he receives an average annual dose of 4 rems. At the end of this time, he engages in an emergency rescue operation and receives an acute dose of 12 rems. If ICRP recommendations are followed, what average dose may this man receive in subsequent years?
4. Consider the explosion of a 20 kiloton nuclear warhead. If there was no attenuation of the y-rays in the atmosphere and all of the fission y-rays escape from the warhead, approximately what would be the y-ray dose received by a person standing (a) 1,000 meters and (b) 5,000 meters from the point of the blast? [Note: Take the energy release per fission to be 200 MeV, of which 7 MeV is in the form of fission y-rays. Also, 1 kiloton = 2.6×10^{25} MeV.]
5. Whether inhaled or ingested, iodine, in most chemical forms, quickly enters the bloodstream, and much of this element flows to and is taken up by the thyroid gland. Shortly after an injection of iodine, the retention function for the thyroid is given approximately by $R(t) = 0.3e^{-0.00502t}$ where t is in days. Suppose that a patient is given an injection of 1 mCi of ^{131}I for diagnosis of a thyroid condition. (a) What is the biological half-life of iodine in the

thyroid? (b) What total dose will the patient's thyroid receive from the single injection? The mass of the thyroid is 20g.

6. The sterilization of bacon requires an absorbed dose of approximately 5 million rads. What uniform concentration of ^{60}Co on a planar disc 1.5 m in diameter is required to produce this dose 0.3 m from the center of the disc after 1 hr exposure? [Note: For simplicity, assume that ^{60}Co emits two 1.25 MeV γ -rays per disintegration.]
7. An isotropic point source emits 10^{10} γ -rays/sec with an energy of 1 MeV. The source is surrounded by a lead shield 10 cm thick. Calculate at the surface of the shield: (a) the flux in the absence of the shield; (b) the uncollided flux; (c) the buildup flux; (d) exposure rate in the absence of the shield; (e) exposure rate without the buildup of scattered radiation; (f) exposure rate with buildup.
8. At the time T_0 , 5 hours after the detonation of a nuclear warhead, the fission products are distributed as fallout uniformly over a certain area at a density of 6.2×10^{-5} Ci/cm². A man enters a fallout shelter as shown in the figure at this time and remains there for T_s hours.
 - (a) Show that if his total exposure is not to exceed X , then his initial exposure rate in the shelter must not exceed



$$X_0 = \frac{X}{5T_0} \left[1 - \left(\frac{T_0}{T_0 + T_s} \right)^{0.2} \right]$$

- (b) How thick must the concrete roof of the shelter be for the man to receive an exposure of $2R$ over 2 weeks? [Note: For simplicity, take the roof to be infinite in extent and assume the γ -rays have an energy of 0.7 MeV]
9. Thermal neutrons are incident on a slab of water 30 cm thick. As the neutrons diffuse about in the slab, they disappear by radiative capture in hydrogen according to the reaction $^1\text{H}(n,\gamma)^2\text{H}$, where the γ -ray has an energy of approximately 2 MeV. Given that the thermal flux in the slab dies off according to the relation $\phi(x) = \phi_0 \exp(-x/L)$ where $\phi_0 = 1.08$ and $L = 2.85$ cm, calculate at the far side of the slab (a) the thermal neutron dose rate; (b) the uncollided flux of γ -rays; (c) the buildup flux of γ -rays; (d) the γ -ray dose rate.

Short Questions

1. Sketch a curve that explains the stability of nuclei. Using this curve, rationalise as to why neutrons are released during a fission event.
2. Why is it not necessary to worry about change of mass with energy during neutron moderation process in nuclear reactors?
3. Why are neutrons important as a particle to induce reactions in comparison to charge particles?
4. Sketch the decay of the concentration of a radioactive isotope with time. Why is it that the half life is defined for these isotopes rather than the full life? Relate half life of an isotope to its decay constant.
5. State any three nuclei for which the binding energy of last neutron is larger than critical energy for fission.
6. An element X has the binding energy of last neutron as 8 MeV, Critical Energy for fission as 6 MeV and $\bar{\nu} = 0.8$. State its usefulness as a reactor fuel.
7. When is a reactor called super critical? Can a reactor ever be super critical? When and why?
8. What is resonance in cross section? What is its physical interpretation?
9. Which material has the best slowing down capability for a neutron? What is its limitation?
10. Why is heavy water preferred to light water as moderator for Indian Reactors?
11. Describe the physical interpretation of diffusion length, L. Is it good to have a higher value of L? why?
12. Describe in words what you understand by k_{∞} .
13. If a neutron collides with a nucleus of mass number A, what is the minimum possible energy of the neutron after collision?
14. Why are PHWRs usually pressure tube type?
15. Why natural uranium can be used in Pressurised Heavy Water Reactors?
16. Arrange them in increasing order of critical volume, for a given core material composition: slab, cylinder and sphere.
17. Why Light Water Reactors (LWRs) are necessarily pressure vessel type?
18. Why natural uranium can be used in Pressurised Heavy Water Reactors?
19. Why is the coolant in a fast reactor, a liquid metal?
20. Why is there an Intermediate Heat Exchanger in a fast reactor?
21. What is the function of containment? What is its characteristic shape? why?
22. Sketch the following and clearly label the axes.
 - (a) Maxwellian spectrum
 - (b) Stability curve
 - (c) Binding energy curve
 - (d) Variation of absorption cross section with energy
 - (e) Axial variation of bulk coolant and clad surface temperature in a channel with constant heat flux
 - (f) Axial variation of DNBR for a coolant channel with cosine heat variation
 - (g) Boiling curve
 - (h) Fission product distribution