NPRE 402
Nuclear Power Engineering

Spring 2016

<table>
<tr><th>Number</th><th>Date Assigned</th><th>Due Date</th><th>Description</th></tr>
<tr><td>1</td><td>1/20</td><td>1/27</td><td>1. Using a plotting routine (e. g. Excel) generate a histogram or pie chart of the share of electricity production from different energy sources in the USA according to data provided by the Energy Information Administration (EIA).
2. A 1,000 MWe nuclear power plant operates at an overall thermal efficiency of 33.3 percent.
a) Calculate its thermal power generation in MWth.
b) Estimate a utility’s daily and yearly income from the sale of electricity at 6 cents / (kW.hr) in millions of dollars.</td></tr>
<tr><td>2</td><td>1/22</td><td>1/29</td><td>Identify the following Technical Specifications of the Chicago Pile number 1 (CP-1) reactor.
1. Thermal power in Watts(thermal), Wth.
2. Fuel material
3. Moderator material
4. Control rods material
5. Safety (Scram) material
Access the world-wide-web (www) and compare the same technical specifications for a contemporary nuclear power plant of your choice.</td></tr>
<tr><td>3</td><td>1/25</td><td>2/1</td><td>Calculate the speed in meters per second of neutrons possessing the following energies:
a. Fast neutrons from fission at 2 MeV,
b. Intermediate energy neutrons at 10 keV,
c. Thermal energy (kT) neutrons at 0.025 eV.</td></tr>
<tr><td>4</td><td>1/27</td><td>2/3</td><td>Fill out the following table describing the energy partition of energy release in a single fission reaction;
<table>
<tr><th>Distribution of Fission Energy</th><th>Energy (MeV)</th><th>Fraction, [percent]</th></tr>
<tr><td>Kinetic energy of fission fragments</td><td></td><td></td></tr>
<tr><td>Prompt gamma rays energy</td><td></td><td></td></tr>
<tr><td>Kinetic energy of fission neutrons</td><td></td><td></td></tr>
<tr><td>Beta particles from fission products</td><td></td><td></td></tr>
<tr><td>Delayed gamma rays from fission products</td><td></td><td></td></tr>
<tr><td>Antineutrinos from the fission products</td><td></td><td></td></tr>
<tr><td>Gammas from radiative capture in structure</td><td></td><td></td></tr>
<tr><td></td><td>_____</td><td>_____</td></tr>
<tr><td>Energy release per fission event</td><td></td><td></td></tr>
</table></td></tr>
<tr><td>5</td><td>1/29</td><td>2/5</td><td>If a single fission reaction produces about 180 MeV of energy, use Avogadro’s law to calculate the number of grams of the fissile elements:
1. U^{235}
2. Pu^{239}
3. U^{233}
4. Np^{237}
that would release 1 kT of TNT equivalent of energy.</td></tr>
</table>

			Assume that all the energy release is available, except for the energy carried away by the antineutrinos, as well as the delayed fission products beta particles and gamma rays, which is not fully recoverable. Hint: Use Avogadro's law to estimate the number of nuclei in a given weight of the fissile material: $N[nuclei] = \frac{g[gm]}{M[amu]} A_v, \quad A_v = 0.6\times 10^{24}[\frac{nuclei}{mole}]$
6	2/1	2/8	Access the Table of the Nuclides data warehouse and data mine for the following data for the naturally occurring isotopes for the given elements of interest in nuclear power generation: a) Natural abundances in atomic percent (a/o), b) Atomic mass in atomic mass units (amu). 1. Uranium, 2. Thorium, 3. Lithium, 4. Carbon, 5. Hydrogen, 6. Lead, 7. Calcium, 8. Beryllium, 9. Boron, 10. Sodium. Balance the following nuclear reactions: 1. ${}_1D^2 + {}_1T^3 \rightarrow {}_0n^1 + ?$ (DT fusion reaction) 2. ${}_1D^2 + {}_1D^2 \rightarrow {}_1H^1 + ?$ (Proton branch of the DD fusion reaction) 3. ${}_1D^2 + {}_1D^2 \rightarrow {}_0n^1 + ?$ (Neutron branch of the DD fusion reaction) 4. ${}_1D^2 + {}_2He^3 \rightarrow {}_2He^4 + ?$ (Aneutronic or neutronless DHe^3 reaction). 5. ${}_0n^1 + {}_3Li^6 + \rightarrow ?+?$ (tritium breeding reaction) 6. ${}_0n^1 + {}_3Li^7 + \rightarrow {}_0n^1 + ?+?$ (tritium breeding reaction) 7. ${}_1T^3 + {}_1T^3 + \rightarrow 2\,{}_0n^1 + ?$ (neutron multiplier reaction) 8. ${}_0n^1 + {}_5B^{10} \rightarrow {}_2He^4 + ?$ (neutron absorption reaction)
7	2/3	2/10	1. Access the Table of the Nuclides data warehouse and data mine for the following information about the naturally occurring isotopes of Uranium: a) Natural abundances in atomic percent (a/o), b) Atomic mass in atomic mass units (amu). Apply conservation of charge and of nucleons to balance the following fissile breeding reaction: ${}_0n^1 + {}_{92}U^{238} \rightarrow {}_{92}U^?$ ${}_{92}U^? \rightarrow {}_{-1}e^0 + {}_?\,?^?$ ${}_?\,?^? \rightarrow {}_{-1}e^0 + {}_?\,?^?$ ――――――――――――――― ${}_0n^1 + {}_{92}U^{238} \rightarrow 2\,{}_{-1}e^0 + {}_?\,?^?$ 2. Access the Table of the Nuclides data warehouse and data mine for the following information about the naturally occurring isotope of Thorium: a) Natural abundances in atomic percent (a/o), b) Atomic mass in atomic mass units (amu).

			Apply conservation of charge and of nucleons to balance the following fissile breeding reaction: ${}_0n^1 + {}_{90}Th^{232} \rightarrow {}_{90}Th^?$ ${}_{90}Th^? \rightarrow {}_{-1}e^0 + {}_??^?$ ${}_??^? \rightarrow {}_{-1}e^0 + {}_??^?$ --------------- ${}_0n^1 + {}_{90}Th^{232} \rightarrow 2\,{}_{-1}e^0 + {}_??^?$
8	2/5	2/12	Balance then calculate the Q values or energy releases in MeV from the following nuclear reactions: 1. ${}_1D^2 + {}_1T^3 \rightarrow {}_0n^1 + ?$ (DT fusion reaction) 2. ${}_1D^2 + {}_1D^2 \rightarrow {}_1H^1 + ?$ (Proton branch of the DD fusion reaction) 3. ${}_1D^2 + {}_1D^2 \rightarrow {}_0n^1 + ?$ (Neutron branch of the DD fusion reaction) 4. ${}_1D^2 + {}_2He^3 \rightarrow {}_2He^4 + ?$ (Aneutronic or neutronless DHe^3 reaction). 5. ${}_0n^1 + {}_3Li^6 \rightarrow ?+?$ (tritium breeding reaction) 6. ${}_0n^1 + {}_3Li^7 \rightarrow {}_0n^1 + ?+?$ (tritium breeding reaction) 7. ${}_1T^3 + {}_1T^3 \rightarrow 2\,{}_0n^1 + ?$ (neutron multiplier reaction) 8. ${}_0n^1 + {}_5B^{10} \rightarrow {}_2He^4 + ?$ (neutron absorption reaction) 9. ${}_0n^1 + {}_{92}U^{235} \rightarrow 3\,{}_0n^1 + {}_{53}I^{137} + {}_{39}Y^{96}$ (fission reaction) 10. ${}_0n^1 + {}_{92}U^{235} \rightarrow 3\,{}_0n^1 + {}_{54}Xe^{136} + {}_{38}Sr^{97}$ (fission reaction) 11. ${}_0n^1 + {}_{92}U^{235} \rightarrow 2\,{}_0n^1 + {}_{56}Ba^{137} + {}_{36}Kr^{97}$ (fission reaction)
9	2/8	2/15	Apply conservation of momentum and of mass/energy to estimate the apportionment of kinetic energy among the product nuclei of the following fusion reactions: 1. ${}_1D^2 + {}_1T^3 \rightarrow {}_0n^1 + ?$ (DT fusion reaction) 2. ${}_1D^2 + {}_1D^2 \rightarrow {}_1H^1 + ?$ (Proton branch of the DD fusion reaction) 3. ${}_1D^2 + {}_1D^2 \rightarrow {}_0n^1 + ?$ (Neutron branch of the DD fusion reaction) 4. ${}_1D^2 + {}_2He^3 \rightarrow {}_2He^4 + ?$ (Aneutronic or neutronless DHe^3 reaction) 5. ${}_1p^1 + {}_3Li^6 \rightarrow {}_2He^4 + ?$ (Aneutronic or neutronless pLi^6 reaction) 6. ${}_1D^2 + {}_3Li^6 \rightarrow {}_2He^4 + ?$ (Aneutronic or neutronless DLi^6 reaction)
10	2/10	2/17	1. Adopt the exponential form of the law of radioactive decay and use a plotting routine to generate the decay curve $N(t)/N_0$ for tritium, ${}_1T^3$, as a function of time t. Tritium is the radioactive isotope of hydrogen, the potential fuel of future fusion reactors, and a fuel in thermonuclear devices. 2. Plot the decay curve for potassium-40, ${}_{19}K^{40}$. This isotope of potassium is very long lived and exists as part of the potassium composing the human body. Hint: Data mine for the half-lives of these isotopes in the Table of the Nuclides.
11	2/12	2/19	1. Calculate the activity of 1 gm of the radium isotope Ra^{226} in Becquerels and Curies. Discuss the relationship to the Ci unit of activity. 2. $Radon^{222}$ as a daughter in the decay chain of uranium is gaseous at room temperature. It is an inert or noble gas that does not interact chemically in the body. However it decays into Pb^{210} which attaches itself to vegetation such as tobacco leaves as a solid and subsequently decays into Po^{210} which emits an energetic alpha particle with 5.3 MeV of energy. The inhalation of these two isotopes in the particulate matter of cigarettes smoke delivers to the average smoker a radiation dose equivalent or dose equivalent of 8 rems (radiation equivalent man) per year to the basal cells of the bronchial tissue. The "cancer dose" is the total radiation dose that if spread through a population would cause one additional cancer death and is considered to be approximately 2,000 rems. Calculate the ensuing radiological risk in units of cancer deaths per year in a population of one million smokers.

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<tr><td>12</td><td>2/15</td><td>2/22</td><td>A space probe needs a radioisotope power generator to generate electrical power for its equipment in the darkness of space away from the sun. The thermal to electrical conversion efficiency is 40 percent.
1. The isotope Pu^{238}, an alpha emitter is used in space applications and can produce the needed electrical energy. Calculate the specific activity of this isotope.
2. Calculate the specific power of this isotope.
3. For an electrical power of 100 Watts(e) what would be the weight needed for this generator in grams and in ounces?
Access the Table of the Nuclides and mine for the data concerning the half-lives, and the energy emitted in the alpha radioactive decay of Pu^{238}.</td></tr>
<tr><td>13</td><td>2/17</td><td>2/24</td><td>The isotope $_{81}$Thallium^{204} has a half-life of 3.78 years. It decays through beta decay to $_{82}Pb^{204}$ with a branching ratio of 97.1 percent with decay energy of 0.764 MeV. It also decays through electron capture to $_{80}Hg^{204}$ with a branching ratio of 2.9 percent with decay energy of 0.347 MeV.
a. Calculate its total specific activity in [Becquerels/gm].
b. Calculate its total specific activity in [Curies/gm].
c. Calculate the specific thermal power generation in [Watts(th)/gm].
d. For a 100 Watts of thermal power in a Radioisotope Heating Unit (RHU) power generator for a Mars mission, how many grams of $_{81}$Thallium^{204} would be needed?
e. The Cassini space probe to Saturn needs an electrical supply of 1 kiloWatt(e) of power. If it were powered by a Radioisotope Thermoelectric Generator (RTG) operating at a conversion efficiency of 29 percent, what would be the needed amount of $_{81}$Thallium^{204}?</td></tr>
<tr><td>14</td><td>2/19</td><td>2/24</td><td>1. For the following radiological quantities, fill out the table showing the corresponding units and their abbreviations.
<table><tr><th>Radiological quantity</th><th>Conventional System Unit</th><th>SI System Unit</th></tr><tr><td>Absorbed dose</td><td></td><td></td></tr><tr><td>Activity</td><td></td><td></td></tr></table>
2. Assuming that heat rejection occurs at an ambient temperature of 20 degrees Celsius, for the average heat addition temperatures Ta given below, compare the Carnot cycle thermal efficiencies of the following reactor concepts:
1. PWR, 168 ºC.
2. BWR, 164 ºC.
3. CANDU, 141 ºC.
4. HTGR, 205 ºC.
5. LMFBR, 215 ºC.</td></tr>
<tr><td>15</td><td>2/22</td><td>2/24</td><td>A Stirling cycle engine using a radioactive isotope for space power applications operates at a hot end temperature of 650 ºC and rejects heat through a radiator to the vacuum of space with a cold end temperature at 120 ºC.
Calculate its ideal Stirling cycle efficiency.</td></tr>
<tr><td>16</td><td>2/26</td><td>3/4</td><td>Construct a table comparing the Engineered Safety Features (ESFs) of the two reactor concepts:
1. PWR,
2. BWR.</td></tr>
<tr><td>17</td><td>2/29</td><td>3/7</td><td>A Boiling Water Reactor (BWR) produces saturated steam at 1,000 psia. The steam passes through a turbine and is exhausted at 1 psia. The steam is condensed to a subcooling of 3oF and then pumped back to the reactor pressure. Compute the following parameters:
a. Net work done per pound of fluid.
b. Heat rejected per pound of fluid.</td></tr>
</table>

			c. Heat added by the reactor per pound of fluid. d. The turbine heat rate defined as: [(Heat rejected +Net turbine work)/Net turbine work] in units of [BTU/(kW.hr)] e. Overall Thermal efficiency. You may use the following data: From the ASME Steam Tables, saturated steam at 1,000 psia has an enthalpy of h = 1,192.9 [BTU/lbm]. At 1 psia pressure the fluid enthalpy from an isentropic expansion is 776 [BTU/lbm]. The isentropic pumping work is 2.96 [BTU/lbm]. The enthalpy of the liquid at 1 psia subcooled to 3 oF is 66.73 [BTU/lbm]. 1 [kW.hr] = 3,412 [BTU]
18	3/2	3/9	For heat rejection at 20 degrees Celsius, compare the Carnot cycle efficiencies for an HTGR operating in the following modes: a) Process heat, b) Electrical power generation, c) Hydrogen production.
19	3/4	3/14	Write a one-page summary about one of the Generation IV nuclear power plants designs under consideration, e. g. The Molten Salt Breeder Reactor. Include a diagram of the described concept..
20	3/7	3/14	Describe the main characteristics, including a diagram of the Babcock & Wilcox small integral reactor design.
21	3/9	3/16	Identify the level of enrichment in U^{235} of: 1. Natural uranium, 2. Enrichment level of Depleted Uranium, DU, 3. Level of enrichment for LWRs.
22	3/14	3/30	An executive at an electrical utility company needs to order natural uranium fuel from a mine. The utility operates a single 1,500 MWe power plant of the CANDU type using natural uranium, and operating at an overall thermal efficiency of 33.33 percent. What is the yearly amount in metric tonnes of: a. U^{235} burned up by the reactor? b. U^{235} consumed by the reactor? c. Natural uranium metal that the executive has to contract with the mine per year as feed to his nuclear unit? Note: 1 metric tonne = 1,000 kgs.
23	3/16	3/30	An executive at another electrical utility company needs to order uranium fuel from a mine. This utility operates a single 1,500 MWe PWR power plant operating at an overall thermal efficiency of 33.33 percent. The fuel needs to be enriched to the 3 w/o in U^{235}. Consider that the enrichment plant generates tailings at the 0.2 w/o in U^{235} level. Calculate the yearly amount of natural uranium metal that the executive has to contract with the mine as feed to his nuclear unit. Compare the natural uranium fuel needs in the case of the PWR design to the CANDU design.
24	3/18	3/30	1. List the known methods for the separation and enrichment of the heavy isotopes of uranium. 2. Compare the *ratios* in the separation radii in the electromagnetic separation method (Calutron) for the separation of the ions of the isotopes: a) U^{235} and U^{238} for fission applications, b) Li^6 and Li^7 for fusion applications.
25	3/28	4/4	Compare the voltages generated by a single fuel cell element when it is operated at: a. 20 ^oC, b. 100 ^oC.

			Use: $\Delta S = 163.2 \ J / K$, $\Delta H = 285,800\, J$, F (Farady's constant) = 96,487 [Coulombs] or [Joules/Volt].
26	3/30	4/6	Access the Chart of the Nuclides for 2,200 m/sec or thermal neutrons, and determine the total microscopic cross sections for the following isotopes: 1. U^{235} 2. Pu^{239} 3. Be^{9} 4. C^{12} Estimate their: 1. Number densities, 2. Total macroscopic cross-sections, 3. Total mean free paths.
27	4/1	4/8	In a neutron flux of 10^8 [n / (cm^2.sec)], what is the neutron absorption rate in 1 cm^3 of a material with a macroscopic absorption cross section of 0.1 cm^{-1}?
28	4/4	4/11	List the Transport Equation for neutrons. Define its terms.
29	4/6	4/13	Prove that the divergence of the gradient leads to the Laplacian operator in the leakage term of the neutron diffusion equation: $\nabla.(-D\nabla\phi) = -D\nabla^2\phi$
30	4/8	4/13	Using the exponential attenuation law, calculate the thickness of a shield made out of: a) Water. b) Graphite. that would attenuate a beam of neutrons by a factor of: a) Ten million times (10^{-7}). b) Ten billion times (10^{-10}).
31	4/11	4/13	

Assignments Policy

Assignments will be turned in at the beginning of the class period, one week from the day they are assigned.
The first five minutes of the class period will be devoted for turning in, and returning graded assignments.
Late assignments will be assigned only a partial grade. Please try to submit them on time since once the assignments are graded and returned to the class, late assignments cannot be accepted any more.
If you are having difficulties with an assignment, you are encouraged to seek help from the teaching assistants (TAs) during their office hours. Questions may be e-mailed to the TA's, but face-to-face interaction is more beneficial.
Although you are encouraged to consult with each other if you are having difficulties, you are kindly expected to submit work that shows your individual effort. Please do not submit a copy of another person's work as your own. Copies of other people's assignments are not conducive to learning, and are unacceptable.
For further information, please read the detailed assignments guidelines.