NPRE 402

Nuclear Power Engineering

Spring 2019

Number	Date Assigned	Due Date	Description
1	1/14	1/23	i) On the Kardashev Scale, identify the power needs in Watts for Type I, II and III civilizations. What is the current position of human civilization on that scale? In how many years is humanity expected to achieve a Type I status? ii) List the components of the envisioned Internet of Things (IoT) for a future energy system. iii) Once built and operational, nuclear power plants become cash cows for their operators. Consider a 1,000 MWe nuclear power plant costing about $5,000 per installed kWe of capacity. Calculate: 1. The capital cost of the plant in billions of dollars. 2. If it operates for 60 years at a capacity factor of 90 percent, the amount of electricity in kW.hr it would produce per year. 3. Sold to electrical consumers at a profit over expenses of 6 cents / kW.hr, the generated profit stream in $ million /year. 4. The total profit in $ billion over its 60 years of operation.
2	1/16	1/23	Identify the following Technical Specifications (Tech Specs) 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 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). 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 neutrons at 0.025 eV.
3	1/18	1/25	Apply conservation of charge and of nucleons to balance the following fissile breeding reaction:

			$_{0}n^{1} + {}_{92}U^{238} \rightarrow {}_{92}U^{?}$ $_{92}U^{?} \rightarrow {}_{-1}e^{0} + {}_{?}?^{?}$ $_{?}?^{?} \rightarrow {}_{-1}e^{0} + {}_{?}?^{?}$ $--------------$ $_{0}n^{1} + {}_{92}U^{238} \rightarrow 2\,{}_{-1}e^{0} + {}_{?}?^{?}$ 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.
4	1/23	1/30	Apply conservation of charge and of nucleons to balance the following fissile breeding reaction: $_{0}n^{1} + {}_{90}Th^{232} \rightarrow {}_{90}Th^{?}$ $_{90}Th^{?} \rightarrow {}_{-1}e^{0} + {}_{?}?^{?}$ $_{?}?^{?} \rightarrow {}_{-1}e^{0} + {}_{?}?^{?}$ $--------------$ $_{0}n^{1} + {}_{90}Th^{232} \rightarrow 2\,{}_{-1}e^{0} + {}_{?}?^{?}$ Access the Table of the Nuclides data warehouse and data-mine for the half-lives for the following isotopes: 1. U^{234} 2. U^{235} 3. U^{238} 4. Th^{232} 5. K^{40} 6. C^{14} 7. T^{3} 8. Cs^{137} 9. I^{131} 10. Sr^{90}
5	1/25	2/1	List the power levels in MWth of the following reactors: 1. Chicago Pile Number 1, CP-1, 2. Graphite Reactor X-10, 3. Hanford Piles, 4. Typical modern Pressurized Water Reactor (PWR) or Boiling Water Reactor (BWR).

			Apply conservation of charge and of nucleons to 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 fusion reaction). 5. ${}_1T^3 + {}_1T^3 \rightarrow 2\,{}_0n^1 + ?$ (neutron multiplier reaction) 6. ${}_0n^1 + {}_5B^{10} \rightarrow {}_2He^4 + ?$ (neutron absorption reaction)
6	1/28	2/4	The yield from the Hiroshima device was 12.5 kT of TNT equivalent, and the yield from the Nagasaki device was 22 kT of TNT. Assume that one critical mass of lead-reflected U^{235} Oralloy at about 30 kgs, and one critical mass of Pu^{239} at about 10 kgs were used to generate these yields. Compare the energy release efficiencies of the two devices as the fraction or percentage of the weight of fissile material converted into energy in the case of the Hiroshima gun barrel concept versus the Nagasaki implosion process. Hint: Use data from Table 2, Part I, Chapter 1.
7	2/1	2/8	Balance the following fission reactions: 1. ${}_0n^1 + {}_{92}U^{235} \rightarrow 3\,{}_0n^1 + {}_{53}I^{137}$ + ? 2. ${}_0n^1 + {}_{92}U^{235} \rightarrow 3\,{}_0n^1 + {}_{54}Xe^{136}$ + ? 3. ${}_0n^1 + {}_3Li^6 + \rightarrow ?+?$ (tritium breeding reaction) 4. ${}_0n^1 + {}_3Li^7 + \rightarrow {}_0n^1 + ?+?$ (tritium breeding reaction)
8	2/4	2/11	What do the following acronyms stand for: CP1 TNT kT mT NPT IAEA NATO MAD ICBM MIRV ABM LTBT CTBT SALT INF THAAD START ICAN The reported time for an ICBM to travel from the continental USA to its assigned target is about t = ½ hour. To cover a distance of 6,000 miles, calculate the speed of travel of the missile in miles / hour. What would the hypersonic Mach Number be? Hint: Use the speed of sound as 761.2 miles /hour.

9	2/6	2/13	In a possibly future matter/antimatter reactor, use the mass to energy equivalence relationship to calculate the energy release in ergs, Joules and MeV from the complete annihilation of: a. An electron/positron pair. b. An antiproton/proton pair. Consider the following masses: $m_{electron} = m_{positron} = 9.10956 \times 10^{-28}$ gram $m_{proton} = m_{antiproton} = 1.67261 \times 10^{-24}$ gram. Combine the two equations for the energy of a mass m and the energy of radiation with a frequency υ and a wave length λ: $E = mc^2 [ergs]$ $E = h\nu = h\frac{c}{\lambda}$ to deduce an equation that establishes the equivalence of mass and radiation: $m = R\nu$ where: $R = \frac{h}{c^2} = 7.365864 \times 10^{-48} \frac{erg.sec^3}{cm^2}$ is a constant of nature.
10	2/8	2/15	Balance then calculate the Q values or energy releases in MeV from the following nuclear reactions: 1. ${}_0n^1 + {}_3Li^6 \rightarrow ?+?$ (tritium breeding reaction) 2. ${}_0n^1 + {}_3Li^7 \rightarrow {}_0n^1 + ?+?$ (tritium breeding reaction) 3. ${}_0n^1 + {}_{92}U^{235} \rightarrow 3\ {}_0n^1 + {}_{53}I^{137} + {}_{?}?^{?}$ (fission reaction) 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)
11	2/11	2/18	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. Use a logarithmic scale for the time variable in part 2 of the question.
12	2/13	2/20	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. $Radon^{222}$ 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.
13	2/15	2/22	Draw a diagram of the Geiger-Muller tube as a radiation detection device. Match the following radiological quantities to their respective equivalents: 1 Curie 100 [ergs/gm] 1 Becquerel 1[Joule/kg] 1 rad 1 [trans/sec] 1 Gray 3.7×10^{10}[trans/sec] Tritium, an isotope of hydrogen used in fusion systems and a nanotechnology and Micro Electro Mechanical Systems (MEMS) power source devices, decays through the following reaction: $_1T^3 \rightarrow {}_{-1}e^0$ + ______ Using the law of radioactive decay calculate the fraction of the tritium isotope $(N_0-N(t))/N_0$ decaying into the He^3 isotope. The half-life of tritium is 12.33 years. 1. Within 1 year. 2. Within 12.33 years. 3. Within 24.66 years.
14	2/18	2/25	The isotope $_{81}Thallium^{204}$ has a half-life of 3.78 years and can be used as a nanotechnology power source device. It decays through beta emission into $_{82}Pb^{204}$ with a branching ratio of 97.1 percent with an average 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 a decay energy of 0.347 MeV. 1. Calculate the energy release per decay event in [MeV/disintegration], 2. Calculate its total specific activity in [Becquerels / gm], 3. Calculate its total specific activity in [Curies / gm], 4. Calculate the specific power generation in [Watts(th) / gm]. 5. For a 100 Watts(th) of thermal power in a Radioisotope Heating Unit (RHU) power generator, how many grams of $_{81}Thallium^{204}$ are needed? 6. After 3.78 years of operation, what would its thermal power become? Use: 1 MeV/sec=1.602×10^{-13} Watts, $A_v=0.602\times10^{24}$ [nuclei/mole], 1 Curie=3.7×10^{10} Bq.
15	2/20	2/25	The isotope $_{38}Strontium^{90}$ is a pure beta emitter without gamma-rays emissions. This makes it particularly suitable for radio-isotopic power generation. Its half-life is 29 years and its beta disintegration energy is 0.546 MeV. We can initially ignore its $_{39}Y^{90}$ daughter product. 1. Calculate its specific activity in Becquerels per gram (Bq/gm) and Curies per gram (Ci/gm). 2. Calculate its specific thermal power generation in Watts(th)/gm. 3. 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 1/3, what would be the needed thermal power? i) How many grams of $_{38}Sr^{90}$ are needed to generate this amount of power? ii) After 29 years of operation, what would its electrical power become? Use: 1 Curie=3.7×10^{10} Bq, 1 MeV/sec=1.602×10^{-13} Watts, $A_v=0.602\times10^{24}$. Calculate the ratio of heat convection in rocks to that of incident solar radiation. Compare the result to the ratio of energy available in photosynthesis, storage in plants, and fossil fuels to the incident solar radiation. Discuss the implication concerning geothermal energy and bioenergy and fossil fuel sources.

16	2/22	2/25	Assuming that heat rejection occurs at an ambient temperature of 20 degrees Celsius, for the average heat addition temperatures T_a given below, compare the Carnot cycle thermal efficiencies of the following reactor concepts: 1. PWR, 168 °C. 2. BWR, 164 °C. 3. HTGR, 205 °C. 4. LMFBR, 215 °C. A radioactive isotope for space power applications operates at a hot end temperature of 650 °C and rejects heat through a radiator to the vacuum of space with a cold end temperature at 120 °C. Calculate its ideal Carnot cycle efficiency. List the principles governing the processes of energy extraction and conversion from the environment and their corollaries.
17	2/27	3/6	List the Engineered Safety Features (ESFs)of the following reactor concepts: 1. PWR. 2. BWR.
18	3/1	3/11	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 3°F 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. 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].
19	3/4	3/11	Construct a table comparing the physical properties of the following materials: 1. H_2O, 2. D_2O. Identify the level of U^{235} enrichment in: a. Natural uranium, b. LWR: BWR and PWR, reactor fuel, c. Depleted uranium discharge from enrichment plant, d. Burnt-out discharged reactor fuel.
20	3/6	3/13	An executive at an electrical utility company needs to order natural uranium fuel from a mine. The utility operates a single 1000 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 U^{235} burned up by the reactor?
21	3/11	3/27	An executive at an electrical utility company needs to order natural uranium fuel from a mine. The utility operates a single 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?

			An executive at an electrical utility company needs to order uranium fuel from a mine. This utility operates a single 500 MWe PWR power plant operating at an overall thermal efficiency of 33.33 percent. The fuel needs to be enriched to the 5 w/o level 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. Note: 1 metric tonne = 1 mt = 1,000 kgs.
22	3/13	3/27	1. List the methods used in the isotopic separation of the heavy isotopes. 2. Compare the ratio in the separation radii (R_1 / R_2) in the electromagnetic separation method (Calutron) for the separation of the ions of the isotopes and molecules: a) U^{235} and U^{238}, b) Li^6 and Li^7. 3. Read, then write a one paragraph summary about: **http://mragheb.com/Thirty%20years%20on.pdf** **World Wide Web Foundation, March 11, 2019,** **https://webfoundation.org/2019/03/web-birthday-30/**
23	3/15	3/27	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.
24	3/25	4/1	Complete the two steps reactions for a typical fuel cell: Oxidation half reaction: $2H_2 \rightarrow 4H^+ + ?$ Reduction half reaction: $O_2 + ? + ? \rightarrow 2H_2O$ Overall Cell Reaction: $? + ? \rightarrow ?$ 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 (Faraday's constant) = 96,487 [Coulombs] or [Joules/Volt]. What is the implication concerning fuel cells operation?
25	3/27	4/3	High Temperature Electrolysis (HTE) has a high efficiency: $\eta_{electrolysis} > 0.90.$ Calculate the efficiency of a hydrogen production system: $\eta_{hydrogen} = \eta_{electrolysis} . \eta_{electrical}$ for the cases of: 1. A nuclear system using the Steam Cycle, 2. A nuclear system using the Brayton Gas Turbine Cycle. Discuss the implications of your results.

26	3/29	4/5	In the high temperature Iodine Sulfur (IS) thermochemical production of hydrogen, the following chemical reactions occur: $2H_2SO_4 \rightarrow ?+?+O_2$ $2I_2+2SO_2+4H_2O \rightarrow ?+2H_2SO_4$ $4HI \rightarrow 2H_2+?$ The overall reaction is: $2H_2O \rightarrow ?+?$ Briefly describe the main characteristics of the CANDU Heavy Water Reactor: http://mragheb.com/NPRE%20402%20ME%20405%20Nuclear%20Power%20Engineering/Heavy%20Water%20Reactor.pdf Write a one page summary, including a diagram, about ***one*** of the Generation IV nuclear power plants designs under consideration, e. g. The Molten Salt Breeder Reactor.
27	4/1	4/8	Using a diagram, briefly describe the main characteristics of the Modular Integral Compact Underground Reactor: http://mragheb.com/NPRE%20402%20ME%20405%20Nuclear%20Power%20Engineering/Modular%20Integral%20Compact%20Underground%20%20Reactor.pdf Briefly describe the NuScale Battery Reactor concept: http://mragheb.com/NPRE%20402%20ME%20405%20Nuclear%20Power%20Engineering/Autonomous%20Battery%20Reactors.pdf
28	4/3	4/8	List nine examples of physical processes governed by the Transport Equation. Write the integro-differential form of the neutron Transport Equation.
29	4/5	4/8	Calculate the total reaction rate density for an isotope with total macroscopic cross section $\sum_t$ = 0.1 $cm^{-1}$and a neutron beam intensity of 10^{10} [neutrons / (cm^2.sec)].
30	4/10	4/17	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. Calculate the total cross sections and the mean free paths of thermal neutrons in the following moderators: 1. H_2O 2. D_2O A stainless steel composition is 69 w/o Fe, 17 w/o chromium, 12 w/o nickel and 2 w/o molybdenum. Calculate its absorption macroscopic cross section and its absorption mean free path for thermal neutrons.
31	4/12	4/19	Use Cartesian Coordinates to prove that the divergence of the gradient leads to the Laplacian operator in the leakage term of the neutron diffusion equation: $\nabla.(-D\nabla\phi) = -D\nabla^2\phi$ Hint: Use D = constant.

32	4/15	4/22	Using the exponential attenuation law, calculate the thickness of a shield with a macroscopic total cross section of 0.1 cm^{-1} that would attenuate a beam of neutrons by a factor of: a) One million times (10^{-6}). b) One billion times (10^{-9}). Through direct substitution prove that the different general forms given for the solution of the Simple Harmonic Oscillator in its forms: a) $\ddot{x}(t) = -\omega^2 x(t)$, b) $\ddot{x}(t) = +\omega^2 x(t)$ do indeed satisfy the underlying differential equations.
33	4/17	4/24	Calculate the "fluxes" and the "currents" in the following situations: 1. At the center of a line of length ' ℓ ' with two sources of strength S at each end. 2. A square of side length ' ℓ ' at the center and at the midpoint of one side, where neutron sources of strengths S [neutrons/second] are placed at each one of the vertices. Carry on the calculations: a. In a vacuum, b. In a diffusing medium with a diffusion coefficient D and a diffusion length L. Note: Fick's Law applies only in the case of a diffusing medium.
34	4/19	4/26	

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.