CE 11 Engineered Systems & Sustainability: Midterm 1	Total Score ↓
Date: 09.28.2021, Total questions: **8** Total points: **88**	
Name: Time: 1 hr 10 min	

Question:	1	2	3	4	5	6	7	8	Total
Points:	15	15	15	15	15	5	5	3	88
Score:									

Instructions:

1. **Show your work. When needed, use words to explain your reasoning.**
2. **The exam is open-book, open-notes. Important constants and unit conversions will be provided to you.**
3. **No use of the internet or communication with other people is allowed while taking the exam.**
4. **Exam will end at 12:20pm to allow for time to upload exams to gradescope.**

[15] 1. **Planetary Energy Balance:** Suppose the average temperature on Earth increases from 15 °C to 21 °C. Ignoring any greenhouse effects, what would be the change in total black body radiation emitted from the Earth? Report your answer in watts.

Solution:

First, we can find the change in outgoing longwave radiation by using the Stefan–Boltzmann Law:

$$L = \sigma T^4$$

We need to convert our temperatures to Kelvin:

$$T_0 = 15 + 273.15\text{ K} = 288.15$$

$$T_f = 22 + 273.15\text{ K} = 295.15$$

$$\Delta L = L_f - L_0 = \sigma T_f^4 - \sigma T_0^4 = \sigma(T_f^4 - T_0^4)$$

$$\sigma = 5.67 \times 10^{-8}\text{W}/(\text{m}^2\text{K}^4)$$

$$\Delta L = 5.67 \times 10^{-8}\text{W}/(\text{m}^2\text{K}^4)((294.15\text{ K})^4 - (288.15\text{ K})^4) = 33.59\text{ W}/\text{m}^2$$

Now to calculate total radiative output in watts, we just need to multiply by the surface area of the Earth:

$$\Delta E = 33.59\text{ W}/\text{m}^2 \times 4\pi R_E^2$$

$$\Delta E = 33.59\text{ W}/\text{m}^2 \times 4\pi(6.3781 \times 10^6\text{ m})^2$$

$$\Delta E = 1.7 \times 10^{16}\text{ W}$$

$\boxed{15}$ 2. **Drying Food Waste:** A startup has pitched a countertop device that dries and deodorizes your food waste for you (I am not making this up!) Food scraps are, by mass, 72.5% water. The food scraps go into the device at 25°C. Once the device is closed, it heats up enough to evaporate all the water to steam at 100°C. A typical person generates about 2 kg of food waste per week. How much thermal energy (in kWh) would this device require **per year** in a household of **4 people** to operate? You may ignore the specific heat capacity of the non-water portion of the food and assume the device is 100% efficient.

Solution: First we need to figure out how much water we are evaporating:

$$\mathrm{m}_{water} = 2\text{ kg/week/person (52 weeks/yr)(0.725)(4 people)} = 302\text{ kg/yr}$$

$$\Delta\mathrm{T} = 100°\mathrm{C} - 25°\mathrm{C} = 75°\mathrm{C}$$

$$\text{Energy} = \mathrm{m}_{water}(\Delta\mathrm{Tc}_{water} + \Delta\mathrm{H}_{vap})$$

$$\text{Energy} = 302\text{ kg/yr}(75°\mathrm{C}\ (4.18\text{kJ kg}^{-1}°\mathrm{C}^{-1}) + 2257\text{ kJ kg}^{-1})$$

$$\text{Energy} = 776291\text{ kJ/yr}$$

Convert from kJ to kWh...

$$1\text{ kWh} = 1\text{ kJ-h/s (3600s/h)} = 3600\text{ kJ}$$

$$776291\text{ kJ/yr}\ (\frac{1\text{ kWh}}{3600\text{ kJ}}) = 216\text{ kWh/yr for a household of 4}$$

Sig Fig note: we announced in class that you should use 3 sig figs for this answer because the question was ambiguous.

$\boxed{15}$ 3. **Population Growth:** Suppose you have a small island nation with a current annual population growth rate of 2.2% per year. The carrying capacity is 3.4 million people and the current population is 1.3 million. How long (in years) until the population doubles relative to its current value?

Solution: We know that $k_0 = 0.022$ and $P_0 = 1.3 \times 10^6$ and $K = 3.4 \times 10^6$

$$k_0 = k(1 - \frac{P_0}{K})$$

$$k = \frac{0.022}{(1 - \frac{1.3\times 10^6}{3.4\times 10^6})} = 0.035619$$

Now we need to find t where $P = 2(1.3 \times 10^6) = 2.6 \times 10^6$.

$$P = \frac{K}{1 + Ae^{-kt}} \text{where} A = \frac{K - P_0}{P_0}$$

$$A = \frac{3.4 \times 10^6 - 1.3 \times 10^6}{1.3 \times 10^6} = 1.615$$

$$2.6 \times 10^6 = \frac{3.4 \times 10^6}{1 + 1.615e^{-0.035619t}}$$
$$2.6 \times 10^6 + 4199000.0e^{-.0.035619t} = 3.4 \times 10^6$$
$$e^{-.0.035619t} = 0.19052$$
$$t = 47 \text{ years}$$

15 4. **Combustion:** You have an engine running on ethanol (C_2H_5OH) as a fuel with a stoichiometric air/fuel ratio. Now, suppose you replace that ethanol fuel with an equivalent mass of gasoline (approximate gasoline as C_8H_{18}) and you do not alter the air/fuel ratio (mass basis). What is λ for the gasoline combustion process (λ = actual air/fuel ratio divided by stoichiometric air/fuel ratio)? Is it fuel rich, fuel lean, or stoichiometric (explain how you know)?

Helpful info: Assume combustion air contains 4 moles of nitrogen gas for every mole of oxygen gas.

Solution: Sig fig note: We will accept any number of sig figs for this answer.
First, we need to write out the stoichiometry of ethanol combustion:
$C_2H_6O + n[O_2 + 4\ N_2] \rightarrow a\ CO_2 + b\ H_2O + 4n\ N_2$

Then we should balance the equation.

$$a = 2$$
$$b = 6/2 = 3$$
$$1 + 2n = 2a + b$$
$$1 + 2n = 2(2) + 3$$
$$n = 3$$
$$\text{air-to-fuel ratio} = \frac{m_{air}}{m_{fuel}}$$
$$m_{air} = 3[2(15.999) + 4(2)(14.007)] = 432.16 \text{ g}$$
$$m_{fuel} = 2(12.011) + 6(1.008) + 15.999 = 46.069 \text{ g}$$
$$\frac{m_{air}}{m_{fuel}} = 9.3808$$

Now we need to calculate the stoichiometric air/fuel ratio for C_8H_{18}:
$C_8H_{18} + n[O_2 + 4\ N_2] \rightarrow a\ CO_2 + b\ H_2O + 4n\ N_2$

$$a = 8$$
$$b = 18/2 = 9$$
$$2n = 2a + b$$
$$2n = 2(8) + 9$$

$$n = 12.5$$

$$\text{stoichiometric air-to-fuel ratio } = \frac{m_{air}}{m_{fuel}}$$

$$m_{air} = 12.5[2(15.999) + 4(2)(14.007)] = 1800.7$$

$$m_{fuel} = 8(12.011) + 18(1.008) = 114.23$$

$$\frac{m_{air}}{m_{fuel}} = 15.764$$

So now we just divide the actual air to fuel ratio by the stoichiometric air to fuel ratio for gasoline to get λ

$$\lambda = \frac{9.3808}{15.764} = 0.59508$$

$\lambda < 1$ means this is fuel rich combustion.

$\boxed{15}$ 5. **Resource Depletion:** The total known recoverable lithium on Earth totals 65 million metric tons (this includes material already extracted, and material not yet recovered). In the year 2020, lithium mines produced a total of 82,500 metric tons. Assume lithium production will grow 15.1% annually. How many years of supply remain before all lithium reserves have been depleted?

Solution: This essentially the same problem as one in the practice problems. We know from the information in the question that $Q_\infty = 65 \times 10^6$ metric tonnes. We also know that $P_0 = 8.25 \times 10^4$ metric tonnes/yr. We know that the production rate will grow each year with $r = 0.151 \frac{1}{\text{year}}$, we use an exponential model:

$$P(t) = P_0 e^{rt}$$

Integrating the production function P(t) over time gives us:

$$Q_\infty = \int_0^{t_F} P(t)dt$$

where t_F is the time until all resources have been used up. Carrying out the integration and solving for t_F gives us:

$$Q_\infty = \int_0^{t_F} P(t)dt$$

$$Q_\infty = \frac{P_0}{r} e^{rt}|_0^{t_F} = \frac{P_0}{r}[e^{rt_F} - 1]$$

$$e^{rt_F} = \frac{rQ_\infty}{P_0} + 1$$

$$t_F = \frac{1}{r} \ln(\frac{rQ_\infty}{P_0} + 1)$$

Then we just plug in our values and get the answer:

$$t_F = \frac{1}{0.151 \frac{1}{\text{yr}}} \ln(\frac{0.151 \frac{1}{\text{yr}} \times 65 \times 10^6 \text{ metric tons}}{8.25 \times 10^4 \text{ metric tons/yr}} + 1) = 32 \text{ years}$$

$\boxed{5}$ 6. **Greenhouse Gases & the Carbon Cycle:** Which of these emissions *will* contribute to net radiative forcing (and thus, climate change) on Earth? Select any/all that apply. Hint: recall our discussion of contemporary vs. fossil carbon and different types of greenhouse gases.

a. CO_2 emitted from combustion of gasoline
b. CO_2 emitted from a wood burning fire
c. CO_2 emitted from combustion of coal
d. CO_2 exhaled by a human
e. CH_4 emitted from a manure storage lagoon
f. HFC-143a leaked from refrigeration equipment
g. CO_2 emitted during combustion of corn-based ethanol
h. N_2O emitted from agricultural activities
i. CH_4 leaked from a natural gas pipeline
j. CH_4 emitted from a natural wetland

Solution: Note that the letters are different in version A vs. version B of the exam.
The following items contribute to net radiative forcing on Earth: a, c, e, f, h, i, j

$\boxed{5}$ 7. **Nuclear Power:** Based on the neutron cross-sections shown in the table below, identify the most likely use for each of these made-up isotopes would be in a nuclear reactor based on the following 3 options: 1) moderators, 2) absorbers, 3) fuels. All cross sections are listed in barns.

	Thermal Neutron			Fast Neutron		
Isotope Identifier	Scattering	Capture	Fission	Scattering	Capture	Fission
a	200	1,500,000	-	5	0.0008	-
b	5	0.003	-	3	0.00001	-
c	18	90	685	4	0.09	1
d	2	150	-	2	0.4	-
e	10	122	678	4	0.07	0.3

Solution: Note that the letters are different in version A vs. version B of the exam.
Moderators: b
Absorbers: a, d
Fuels: c, e

$\boxed{3}$ 8. **Grid:** What strategies are employed on the U.S. electric grid for the purpose of minimizing line losses on the grid (while maintaining safety)? Select any/all that apply.

a. Using inverters to step voltage up/down
b. Using DC power

c. Using AC power
d. Maintaining high current, low voltage on transmission lines
e. Maintaining low current, high voltage on transmission lines
f. Using transformers to step voltage up/down

Solution: Note that the letters are different in version A vs. version B of the exam.
Answer: c, e, f
Rationale: Maintaining high voltage and low current is key because $P_{drop}=I^2R_{line}$.
Because $P = IV$, we can either choose to have high current (I) or high voltage (V). Stepping voltage up and down also allows us to minimize line losses while avoiding the hazards of running high voltage power lines near population centers. The grid uses AC power because it allows for voltage to be easily stepped up/down. Inverters do not step voltage up/down (they convert between DC and AC power).

Potentially useful constants and conversion factors:

Constants Other Useful Values:
Stefan-Boltzmann constant: $\sigma = 5.67 \times 10^{-8}$ W/(m^{2}K^4)
Radius of the Earth: $R_E = 6.3781 \times 10^6$ m
Heat capacity of water = 4.18 kJ kg^{-1}°C^{-1}
Enthalpy of vaporization for water = 2257 kJ kg^{-1}
Lower Heating Value of Coal = 29.0 MJ/kg
Lower Heating Value of Natural Gas = 47.1 MJ/kg
1 barn = 1.0×10^{-28} m^2
Atomic masses (in g/mol) are:
C = 12.011
H = 1.008
O = 15.999
N = 14.007
Ar = 39.948
Useful unit conversion factors:
1 ton = 0.907185 metric tons
Remember: ton = short ton
Remember: tonne = metric ton
Temperature in Kelvin = °C + 273.15