1. (10 pts) Below, I have listed six *targets* for the UN Sustainable Development Goals (SDGs). For each target listed, give the *number*, the *name*, and the *brief description* of the SDG that goes with the target. As an example, I filled in the first one for you.

Target	**SDG number**	**SDG name**	**SDG brief description**
By 2030, reduce at least by half the proportion of men, women and children of all ages living in poverty	1	No poverty	End poverty in all its forms everywhere
By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy	7	Affordable and Clean Energy	Ensure access to affordable, reliable, sustainable, + modern energy for all
Integrate climate change measures into national policies, strategies and planning	13	Climate Action	Take urgent action to combat climate change and its impacts
By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency	9	Industry, Innovation, and Infrastructure	Build resilient infrastructure, promote inclusive + sustainable industrialization
By 2030, improve water quality by reducing pollution, eliminating dumping, and minimizing release of hazardous chemicals	6	Clean water and sanitation	Ensure availability and sustainable management of water and sanitation for all
By 2030, provide access to safe, affordable, accessible, and sustainable transport systems for all	11	Sustainable cities and Communities	Make cities and human settlements inclusive, safe, resilient, and sustainable

2. (25 pts) *particle flocculation* Three witches were gathered around their cauldron, making their traditional witches' brew. They added eye of newt, toe of frog, owlet's wing – all the traditional ingredients. As they gently stirred the cauldron, one of the witches noticed something interesting: when one eye of newt collided with another in the brew, the eyes would sometimes stick together and form a clump. This witch was worried that the brew would be spoiled if all the eyes-of-newt stick together. (Witches hate clumpy brew.)

   a. (8 pts) The cauldron holds 300 L of witches' brew, and the witches initially added 600 eyes of newt to the brew. Each eye can be considered as perfectly spherical, with a diameter of 1.0 mm. Based on this, estimate Ω, the volume fraction of the eyes in the brew. In other words, of the 300 L of brew, what fraction is occupied by eyes of newt?

volume of a sphere = $\frac{4}{3}\pi r^3 = \frac{\pi}{6} d^3$

volume of an eye of newt = $\frac{\pi}{6}(1.0 \times 10^{-3}\ m)^3 = 5.236 \times 10^{-10}\ m^3$

volume of 600 eyes of newt = $(600)(5.236 \times 10^{-10}\ m^3) = 3.14 \times 10^{-7}\ m^3$

volume of brew = 300 L = $0.3\ m^3$

$$\Omega = \frac{3.14 \times 10^{-7}\ m^3}{0.3\ m^3} = \boxed{1.0 \times 10^{-6}}$$

   b. (3 pts) Which of the three ideal reactor types is the best description of the witches' cauldron? Why?

Completely mixed batch reactor ... no flows in or out, stirred gently to eliminate gradients

As the witches stir, the *number* of eyes in the brew will reduce – when two eyes collide and stick together, we go from two small eyes to one larger clump. For the purposes of this problem, we will consider that a clump of newt-eyes is also an "eye". That is, we don't distinguish between a single eye of newt and a clump of more than one eye. The witches stir the cauldron gently, so let's estimate that the velocity gradient in the cauldron is $G = 20\ s^{-1}$. For a worst-case scenario, let's also assume that when two eyes of newt collide with each other, they stick together with perfect efficiency: $\alpha = 1$.

problem 2 continues →

2. continued

c. (11 pts) Assume the witches stir the brew for 30 minutes. *Estimate/calculate how many eyes of newt you expect to find remaining in the witches' brew after they stir for 30 minutes.* Hint: the rate of eyeball flocculation is given by $R = (4/\pi)\, \alpha\, G\, \Omega\, N$, where N is the number concentration of eyes (or clumps of eyes, which we're treating as the same thing). So you know what kind of reactor it is (from part b), and you know how the rate depends on the concentration....

$R = \frac{4}{\pi} \alpha G \Omega N$ ... first-order kinetics because rate is proportional to N. It's like $R = k_1 N$ where $k_1 = \frac{4}{\pi} \alpha \Omega G$.

First-order kinetics in a batch reactor: $N = N_o e^{-k_1 t}$

$$k_1 = \left(\frac{4}{\pi}\right)(1.0)(1.05 \times 10^{-6})(20\ s^{-1}) = 2.67 \times 10^{-5}\ s^{-1} = 1.6 \times 10^{-3}\ min^{-1}$$

$$\frac{N}{N_o} = e^{-k_1 t} = \exp\left[-(1.6 \times 10^{-3}\ min^{-1})(30\ min)\right] = 0.953$$

After 30 minutes of stirring, we have 95.3 % of the number we started with.

So $(0.953)(600) =$ **572 eyes of newt remaining**

d. (3 pts) Does the witch need to worry about the brew being spoiled by flocculation of the eyes-of-newt? Explain very briefly (one sentence).

No need to worry. Ω is very low, so there is not much flocculation occurring. We still have 95% of what we started with.

e. EXTRA CREDIT. In what play do the witches brew a concoction with eye of newt and toe of frog? +1 for naming the play, +1 for naming the act and scene in which it occurs, and +1 for naming any of the other ingredients that I didn't already list in this problem.

MacBeth, Act IV, scene I.

Eye of newt, toe of frog, wool of bat, tongue of dog, adder's fork, blind-worm's sting, lizard's leg, owlet's wing.

3. (25 pts) Two demons in the Land of the Dead were comparing notes on the horrible, atrocious things they did while they were alive.

The first one said "When I was alive, I had a co-worker whom I hated. She was a little thing, but she sure was mean to me. I noticed that she drank a big mug of coffee every day, so I started putting arsenic in it. When she wasn't looking, I'd put 1 mg of arsenic into her mug. I did it every work day for 5 years before I got caught and sent to prison."

The second demon was not impressed. "Hmph. Arsenic in the coffee. How unoriginal. When *I* was alive, I couldn't stand my husband. He was a very large man and he snored terribly. It got so bad that I had to sleep in a separate wing of our mansion. So I started pumping chloroform gas into his bedroom while he was sleeping. I could get the concentration of chloroform up to about 10 mg/m^3 while he was getting his eight hours of sleep. I did it every night for 10 years before I got caught and sent to prison."

Which of these vile, despicable demons created a higher risk of contracting cancer for his/her victim? Show your calculations to support your answer. You must show your work to get credit!

Demon #1 ... assume victim is 50 kg, takes 4 weeks vacation per year

$$CDI = \frac{1 \text{ mg arsenic/d}}{50 \text{ kg}} \cdot \frac{5 \text{ d}}{7 \text{ d}} \cdot \frac{48 \text{ wks}}{52 \text{ wks}} \cdot \frac{5 \text{ years}}{70 \text{ years}} = 9.42 \times 10^{-4} \frac{\text{mg}}{\text{kg} \cdot \text{d}}$$

$$\text{Slope factor} = 1.5 \frac{\text{kg} \cdot \text{d}}{\text{mg}} \quad \text{from table}$$

$$\text{Cancer risk} = \left(9.42 \times 10^{-4} \frac{\text{mg}}{\text{kg} \cdot \text{d}}\right)\left(1.5 \frac{\text{kg} \cdot \text{d}}{\text{mg}}\right) = \underline{1.4 \times 10^{-3}}$$

pretty high

problem 3 continues →

3. continued

additional space for your answer

Demon #2 ... assume victim is 100 kg, sleeps there 350 nights per year.

Probably we should assume that a person only absorbs ~75% of what they inhale, but we didn't discuss that in ENV 4001, so most students will probably assume 100% absorption. Thus:

$$CDI = \frac{(20\ m^3\ air/d)(10\ mg/m^3)}{100\ kg} \cdot \frac{8\ hrs}{24\ hrs} \cdot \frac{350\ d}{365\ d} \cdot \frac{10\ yrs}{70\ yrs} = 0.0913\ \frac{mg}{kg \cdot d}$$

slope factor $= 0.08\ \frac{kg \cdot d}{mg}$ from table

cancer risk $= \left(0.0913\ \frac{mg}{kg \cdot d}\right)\left(0.08\ \frac{kg \cdot d}{mg}\right) = \underline{7.3 \times 10^{-3}}$ also pretty high

Demon #2 caused a higher cancer risk.

The only good news is that there is still a 99% chance that the dastardly plan <u>failed</u> in each case (risk < 0.01).

4. (25 pts) Trixie Treete operates Trixie's Trout Farm along the Ygor River. She grows her trout in cages that are submerged in the river. Trixie and her trout are happy because the Ygor River is pretty clean. Unfortunately for Trixie and her business, the Sickly Sweet Candy Company is thinking about building a new candy factory along the river, upstream of her trout farm. The proposed factory would discharge its waste, full of organic compounds (which exert oxygen demand), into the river. Trixie is worried because her trout need at least 6.0 mg/L of dissolved oxygen in the river to stay healthy. They haven't yet decided exactly where they will build the candy factory, but it would be somewhere 15–85 km upstream of Trixie's Trout Farm.

Here is what we know about the river and the proposed wastewater stream:

- Currently, the Ygor River flows with a volumetric flow rate of 15 m^3/s, has a concentration of dissolved oxygen equal to 9.2 mg/L, and has a low concentration of dissolved organic carbon -- $BOD_5 = 4.0$ mg/L.
- The river and the proposed waste discharge stream both have a temperature of 17 °C.
- The proposed wastewater stream will enter the river at a rate of 0.5 m^3/s and has a high concentration of dissolved organic carbon -- $BOD_3 = 180$ mg/L. It contains no dissolved oxygen.
- Stream hydrologists have estimated that, if the waste is discharged into the river, the river depth will be 2.0 m and the river velocity will be 0.25 m/s.
- The deoxygenation rate coefficient for both the river and the proposed waste stream is 0.25 d^{-1}. The reaeration rate coefficient for the river, based on the expected depth and velocity, is estimated to be 0.70 d^{-1}.

Ms Treete has hired you as a technical consultant to help her figure out what legal action she should take about the siting of the proposed factory.

(a) (15 pts) From your client's point of view, where would be the *worst* place to put the proposed factory? Show the calculations that support your answer.

The worst-case scenario is that Trixie's Trout Farm would be located at the critical point in the river, where concentration of dissolved oxygen is lowest. So let's find t_{crit}.

$$L_0^{river} = BOD_5 \div [1 - e^{-kt}] = (4.0 \tfrac{mg}{L}) \div \{1 - \exp[-(0.25 d^{-1})(5 d)]\} = 5.6 \tfrac{mg}{L}$$

$$L_0^{waste} = BOD_3 \div [1 - e^{-kt}] = (180 \tfrac{mg}{L}) \div \{1 - \exp[-(0.25 d^{-1})(3 d)]\} = 341 \ mg/L$$

problem 4 continues →

4. continued

additional space for your answer – write on the back of this page if necessary

$$L_o^{mix} = \frac{(15\ m^3/s)(5.6\ mg/L) + (0.5\ m^3/s)(341\ mg/L)}{15.5\ m^3/s} = 16.4\ mg/L$$

$$[O_2]^{mix} = \frac{(15\ m^3/s)(9.2\ mg/L) + (0.5\ m^3/s)(0)}{15.5\ mg/L} = 8.90\ mg/L$$

$$D_o = \underbrace{9.74\ mg/L}_{\text{from table on p. 2}} - 8.90\ mg/L = 0.84\ mg/L$$

$$t_{crit} = \frac{1}{k_2 - k_1} \ln\left\{\frac{k_2}{k_1}\left[1 - \frac{D_o(k_2-k_1)}{k_1 L_o}\right]\right\} = 2.073\ d$$

... This is the travel time from the factory to the trout farm under worst-case conditions

worst location $= (2.073\ d)(0.25\ m/s)(86400\ s/d)(1\ km/1000\ m) =$ **45 km upstream**

b. (10 pts) Assume that the worst-case scenario comes to pass, and they build the factory at exactly the spot that you said would be worst. Are Trixie's trout in trouble, or should she stop worrying? Show the calculations to support your answer to Trixie.

deficit $D = \frac{k_1 L_o}{k_2 - k_1}\left[e^{-k_1 t} - e^{-k_2 t}\right] + D_o e^{-k_2 t}$

So if they put the factory 2.073 d upstream of Trixie's Trout Farm, then at her farm the deficit will be

$$D = \frac{(0.25\ d^{-1})(16.4\ mg/L)}{(0.70\ d^{-1} - 0.25\ d^{-1})}\left\{\exp[-(0.25\ d^{-1})(2.073\ d)] - \exp[-(0.70\ d^{-1})(2.073\ d)]\right\}$$

$$+ (0.84\ \tfrac{mg}{L})\exp[-(0.70\ d^{-1})(2.073\ d)] = 3.49\ mg/L$$

$$[O_2]_{crit} = 9.74\ mg/L - 3.49\ mg/L = 6.25\ mg/L$$

Trixie's trout will just barely be OK if the factory goes in at the worst location.

END OF TEST