ENVR 754 – AIR POLLUTION CONTROL
HOMEWORK PROBLEMS SPRING, 2009

Introduction to the Course

1. **Horsepower and Cost –** Calculate the horsepower requirements, kw requirements, and annual cost for each of the following control devices:

   a. A cyclone that operates 8 hr/day, weekdays only, to collect wood dust from a furniture making operation. Gas flow is 1000 cfm; pressure drop is 4.5 inches w.g.

   b. A venturi scrubber that collects fume from a basic oxygen furnace that operates for 30 minutes out of each six hour batch, 330 days per year. Gas flow is 8000 cfm; pressure drop is 80 inches w.g.

   c. A furnace filter in your house that collects dust from the return air duct. Flow is 500 cfm; pressure drop is 0.3 inches w.g. The fan operates 20% of the time, on an yearly basis.

   d. A fabric filter at a power plant that collects fly ash. Flow is 9,500,000 cfm; pressure drop is 8 inches w.g. The plant operates 24 hours a day, 345 days per year.

      Note: This flow comes from the Roxboro Steam Electric Plant, near Roxboro NC, about 50 miles from Chapel Hill, operated by Progress Energy.

   e. Suppose that after taking this course, you devise a way to reduce pressure drop through each of the above devices by 20%. After graduation, you decide to become a consultant to advise on these matters. You promise your clients that they will be able to recover the cost of your fee within six months after taking the advice you give them. Assume for the moment that taking this advice requires no new equipment; that is, your advice can be implemented for free. For each of the four cases above, how much should you charge for your fee?

2. **Size Distributions –** The following results were obtained from a Bahco analysis of fly ash, specific gravity 2.63. This device produces a cumulative size distribution by mass.

Weight % Finer Than	Aerodynamic Diameter, Micrometers
99.54	250
96.72	149
78.66	61
66.55	25.4
66.44	23.7
66.10	19.7
62.56	11.1
54.31	7.7
33.94	4.4
8.94	2.1
2.84	1.3

a. Plot the cumulative size distribution by mass for these data on log-probability paper.

b. In 750 kg of fly ash, how much will lie between 10 and 50 µm in aerodynamic diameter? How much will be less than 10 µm in aerodynamic diameter?

c. What is the mass median size?

d. Plot a frequency distribution by mass for these data.

e. Does this distribution fit any regular pattern?

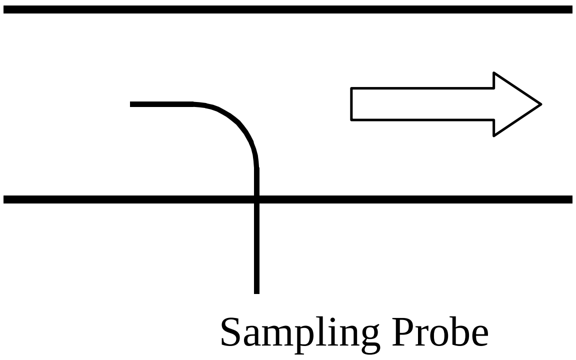
3. **Probe Design –** On your first job after graduation, you are asked to determine the size distribution and concentration of particles in a horizontal duct with an inside diameter of 10 inches. This information will be used to specify a piece of gas cleaning equipment. Before taking the sample, you find out from the plant engineer that the average gas velocity in the duct should be 3200 feet per minute.

You decide to sample isokinetically at the centerline of the duct into an Andersen cascade impactor that is designed to operate at 28.3 Lpm (1 cfm). Your probe must have a 90 degree bend as shown in the figure below. You orient the probe to be as vertical as possible to minimize collection by gravity in the probe and to lead directly into the top of the impactor. The particle-generating process is far enough upstream that you are confident that a sample taken at the centerline will be representative of the aerosol in the whole duct. Before going into the field to take the sample, you need to design a sampling probe to sample isokinetically from the duct center line.

Part a: Review the article by Pui et al. and note the method to determine particle collection in a bend; alternatively, review the article by McFarland et al. Note that Peters reports an error in the coefficients of McFarland's equation. All these articles are available on-line through the UNC library. Then specify the dimensions of your sampling probe, including inside diameter, straight length before the bend, radius of the bend, and straight length after the bend. As you do this, consider the problem of particle loss due to the bend of your sampling probe. Is it is possible to minimize collection in the bend of the probe by controlling the radius of curvature of the bend? Gas passing through a sharp bend with small radius of curvature would have a small residence time in the bend, which is good, but would also cause high radial acceleration which is bad. Use the equation you choose to determine whether the probe should have a sharp bend or a gradual, sweeping bend.

Part b: For the probe you design, use your equation to plot the relationship between particle removal efficiency due to the bend in the probe against aerodynamic particle diameter.

Sampling Set-up



Pui, D. Y. H., F. Romay-Novas, et al. (1987). "Experimental study of particle deposition in bends of circular cross section." Aerosol Sci. and Technol. 7: 301-315.

McFarland, A. R., H. Gong, et al. (1997). "Aerosol deposition in bends with turbulent flow." Environ. Sci. Technol. 31: 3371-3377.

Peters, Thomas and David Leith (2004). "Modeling large particle deposition in bends of exhaust ventilation systems", Aerosol Sci. and Technol. 38: 1171-1177.

4. **Isokinetic Sampling –** When you get to the plant to sample, you measure the actual gas velocity at the duct centerline and find that it is only 2830 fpm instead of the 3200 fpm expected. Instead of adjusting the sample flow, which you realize would change all the cut points for the impactor, you elect to sample at 28.3 Lpm as originally planned in the hope that the aerosol particles will all be small so that the non-isokinetic sampling that results will not cause undue bias in the sample. When you return to the lab, you obtain the following data from the impactor.

Sample flow:	28.3 Lpm	Probe inlet velocity:	3200 fpm
Sample time:	50 minutes	Duct velocity:	2830 fpm

Data from Andersen Impactor Measurements

Impactor Stage	Aerodynamic Size Range, μm	milligrams collected
Pre-selector	> 10	445.2
0	9.0 to 10.0	202.4
1	5.8 to 9.0	282.1
2	4.7 to 5.8	165.8
3	3.3 to 4.7	85.2
4	2.1 to 3.3	80.9
5	1.1 to 2.1	75.2
6	0.65 to 1.1	45.5
7	0.43 to 0.65	15.1
Filter	< 0.43	10.0

Your co-worker, whose graduate work did not include a course like this one, tells you that correcting for the non-ideality in sampling is probably a waste of your time because nobody ever does it.

Correct your data for non-isokinetic sampling and for the bend in the probe. Plot the measured, uncorrected cumulative size distribution by mass and the true cumulative size distribution by mass (corrected for probe bend loss as well as for non-isokinetic sampling) on the same piece of log-probability paper. Plot the error that would result if you did not correct your size distribution data for probe loss and non-isokinetic sampling against particle diameter. Determine the measured mass concentration in the duct and the true mass concentration in the duct, in g/m^3. Was your co-worker right?

Inertial Collectors

5. **Cyclone Design –** The dust from a rock-crushing operation has the size distribution given below. The concentration of dust coming from this operation is 7 g/m^3, and the gas flow rate is 4000 cfm. The rock has a density of 2.5 g/cm^3.

Particle dia. (µm):	100	70	50	30	20	10	5	1
Mass % < stated size:	72	67	52	38	25	14	9	4

A cyclone is proposed to collect the dust from the rock crushing operation. To work this problem, use the “solver” function in Excel to optimize cyclone dimensions for given pressure drop and cut diameter.

a) Pick a cyclone diameter and cyclone height that seem appropriate.

b) Pick a cyclone pressure drop and maximize cyclone overall efficiency using equations that relate cyclone dimensions to pressure drop and cut diameter using “Solver”.

c) Repeat these steps until you develop a plot of pressure drop versus cyclone overall efficiency.

d) Plot on the figure from part (c) the point that corresponds to the overall efficiency and pressure drop of a Stairmand high efficiency cyclone of standard design.

e) If the design objective is to keep the dust concentration coming from the cyclone below 500 mg/m^3 list the dimensions and pressure drop of the cyclone required.

f) Compare your results from part (e) with the dimensions, pressure drop, and outlet dust concentration obtained using a Stairmand high efficiency cyclone for the same application.

6. Performance of the Oil Screen Collector

a) Develop from first principles (force = mass x acceleration, etc.) an equation for the relationship between aerodynamic particle diameter and collection efficiency for an “Oil-Screen” collector. The configuration and the dimensions of this collector are on the following page. The overall size of the Oil-Screen is 23.5" by 23.5". Look on the mezannine of the Baity Lab to find the Oil Screen we tested, from which you can get additional dimensions. This device is commercially sold to remove liquid mists.

b) Use your equation to predict collection efficiency for an Oil-Screen with the following characteristics. Air flow is 1000 cfm. Mist droplets are mineral oil, with a density of 0.81 g/cm^3. The Oil Screen contains two rows of collection elements in series; that is, gas passes through two rows of elements in series where each row is like that shown in “Figure 2” below. Measurements of collection efficiency for the Oil Screen made in our lab are in “Figure 7” on the second following page. Plot your predictions together with the data for measured efficiency taken from our experiments.

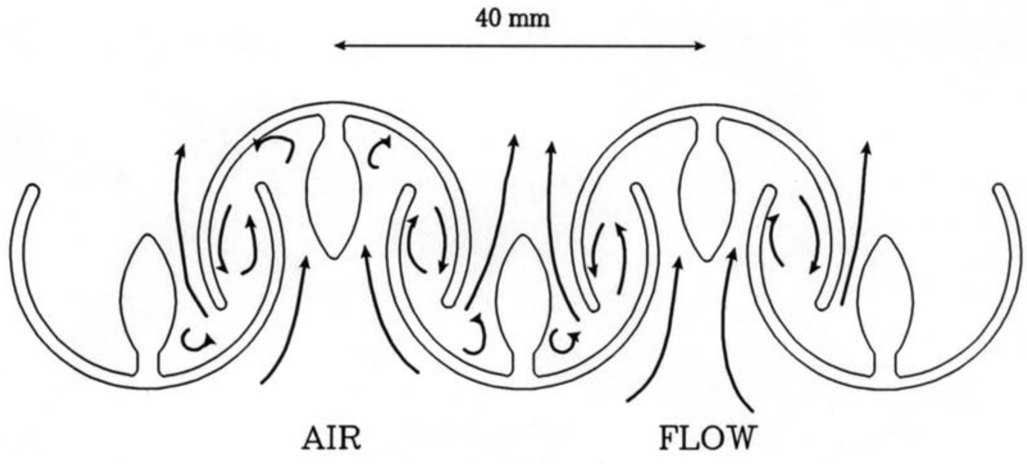


Figure 2: Oil-Screen mechanical air filters. In the top figure, air flow is from the foreground, through the semi-circular impaction elements, into the page. The bottom figure gives a schematic diagram of the impaction elements in the Oil-Screen.

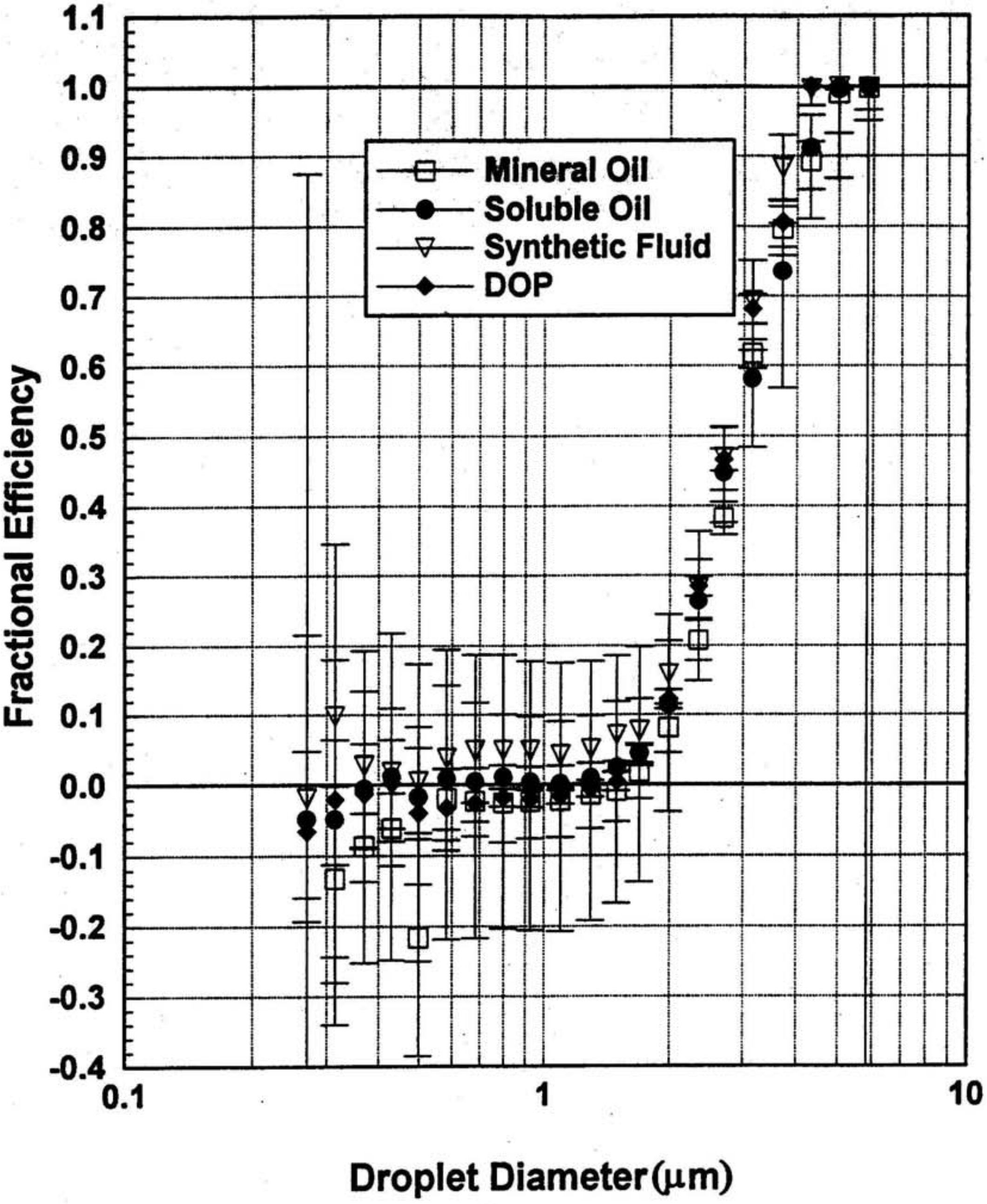


Figure 7: Efficiency vs. droplet diameter for the Oil-Screens alone. For the three cutting fluids only measurements made with high concentration mist are included. Air flow was 1000 cfm. Error bars represent 95% confidence intervals.

Filters

7. **Design of Filter for Diesel Car –** You have been asked to determine whether a fiber filter is practical to collect "smoke" from the exhaust of diesel cars. The concern is that particles in diesel exhaust contain PAH compounds that may be carcinogenic; therefore, these particles should be controlled if possible. Objectives in your design are:

   i. The filter should be small, not to exceed the size of a typical muffler, 1 meter x 30 cm x 15 cm.

   ii. The filter should have high efficiency for small particles.

   iii. The filter should have a reasonable pressure drop; that is, energy consumption of the filter should not affect gas mileage to an appreciable extent.

   iv. The filter should have a reasonable lifetime. The filter may be replaced as often as an oil filter or an air filter in a car is replaced.

Assume that glass fibers are available with diameters between 0.5 and 100 micrometers (you can specify fiber diameter in your design). Also, assume that the exhaust flow is 100 cfm at 50 °C, the mass concentration of smoke from the car is 0.1 g/m^3, and the smoke particles have a density of 1 g/cm^3. The size distribution of the smoke is given below.

Determine:

   a. The layout for the filter, i.e., gas passages in and out, location of filter media within the filter housing, etc. Be creative here. The layout need not be with gas flow along the axis of a long, cylindrical tube. Consider the pros and cons of alternative layouts in terms of efficiency, pressure drop, and filter life.

   b. The fractional efficiency curve for the filter layout you select at the design flow,

   c. The overall efficiency for the filter,

   d. The filter lifetime in operating hours and in days, assuming the car is operated one hour per day.

   e. The pressure drop across the filter when new and at the end of its lifetime.

   f. The cost of using this filter, expressed in reduction of miles per gallon of fuel used.

Based on your results, decide whether such a filter is practical for use on diesel automobiles. In working this problem, you will have to make some assumptions. List and justify the assumptions you make.

Size Distribution for Diesel Exhaust Smoke

Size Range, micrometers	Fraction of Mass in this Size Range
0.0 - 0.2	0.043
0.2 - 0.3	0.058
0.3 - 0.4	0.085
0.4 - 0.6	0.180
0.6 - 0.8	0.261
0.8 - 1.0	0.196
1.0 - 1.5	0.082
1.5 - 3.0	0.052
> 3.0	0.043

8. **Specific Resistance of Dust Deposit** – For coal fly ash collected on fabric filters, the book by Calvert and Englund (see table in your notes) lists a value for K_2 of 1.17 to 2.51 N min/(g m). The same reference gives the density of fly ash as 2.3 g/cm^3. Assume the porosity of a dust deposit is between 0.75 and 0.85. The size distribution for fly ash from a pulverized-coal boiler is:

Upper bound size	% by mass < stated size
3 μm	15
5	25
10	42
20	65
40	81

a. Compare this handbook value for K_2 with values calculated from the Kozeny-Carman equation and the Rudnick-Happel equation.

b. Can disagreement between your calculated K_2 values and the tabulated value be due to uncertainties in the particle size distribution of the dust or the porosity of the dust deposit? Explain, using examples if appropriate.

9. **Pulse Jet Filter Performance** – A pulse-jet filter collects rock dust with bulk density of 145 lb/ft^3. The filter now operates at a pressure drop of 7 inches of water. It has 200 bags made from untreated polyester fabric; each bag is 4-1/2 inches in diameter and 8 feet long. The filter handles 10,000 cfm of gas. Each bag is cleaned once every three minutes with compressed air at 100 psi. The inlet dust concentration is 1.5 g/m^3.

Ventilation air from a new process must also be controlled. Your boss suggests that this new air can also be passed through the existing pulse-jet filter. The new process will provide 2000 cfm of *additional* air, and contain rock dust in concentration of 0.5 g/m^3; this dust will probably be coarser than the dust from the existing process. The dust concentration *of the new process* may occasionally rise to 5 g/m^3 and the flow *from the new process* may sometimes be as high as 3000 cfm.

a. Determine K_2/K_3 for the filter as it operates now.

b. Determine the gas flow and dust concentration in the gas after the flow streams are combined.

c. Using the K_2/K_3 value from (a), determine whether the filter can be operated after combining the flows without pressure drop exceeding 7 inches of water. Consider changes in filter operating conditions if necessary.

d. Do you agree with your boss that the air flows can be combined? Explain.

Scrubbers for Particle Collection

10. **Venturi Scrubber Design –** The size distribution by mass of dust emitted from a rotary rock dryer without control is given below.

Size	by mass < Size
0.1 µm	0.01
0.2	0.05
0.5	0.2
1	1
2	5
3	40
5	95
7	99.9
8	99.99

The particles have a density of 2.7 g/cm^3 and the temperature of the gas is 200 C. 8,000 cfm of gas are to be cleaned. The diameter of the duct leading to the venturi is 22 inches. An efficiency of 99% is required, on an overall mass basis. Remember that some of the water supplied to the venturi will cool and saturate the gas stream. Only after the gas is saturated will water be available to collect dust particles.

Design a venturi scrubber that will achieve the required efficiency. You should specify:

- a) the water flow necessary to cool and saturate the gas stream in gallons per minute, and the temperature of the gas after saturation occurs,
- b) the diameter and throat length of the venturi,
- c) the venturi throat velocity in feet per minute,
- d) the total water rate to the venturi in gallons per minute,
- e) the pressure drop required,
- f) the efficiency achieved.

Try using Excel's "Solver" to explore the effect of different venturi operating conditions on pressure drop for the given efficiency requirement.

11. **A Practical Problem –** The bus stop directly across the street from the Public Health School is closed due to construction. As a result, you must walk or run in the rain from the front door of the School of Public Health to the bus stop across from the Carolina Inn, a distance of 400 meters. You have forgotten your umbrella.

Assume the raindrops are 0.8 mm diameter water drops that fall vertically at the rate of 2 cm water accumulation per hour. After a program of vigorous weight-training, your body closely resembles a solid rectangle 1.5 m tall, 450 mm wide and 180 mm thick. You wish to evaluate alternative strategies for reaching the bus stop.

- a) Plot the volume of water your body collects against speed with which you run. Distinguish between top (head) hits and front (body) hits.
- b) How fast should you run to the bus stop?
- c) The bus will not arrive until 20 minutes after you leave the School, regardless of how fast you run. The bus shelter is already filled with people so you must stand out in the rain the whole time you are there. Does this change your opinion about how fast you should run to the bus stop?
- d) How would your answers to b) or c) change if you had remembered your umbrella?

Electrostatic Precipitators

12. **Precipitator Design –** The fly ash from a pulverized coal fired furnace has a mass median diameter of 10 µm and a geometric standard deviation of 3.5. Particle density is 2.5 g/cm^3. This fly ash is emitted at the rate of 170 lb/ton of coal fired in a flue gas stream (molecular weight of 28.1) of 14.7 x 10^6 ft^3/min at 350 F.

A collection system must be designed and used to meet the EPA emission regulation of 0.10 lb/million BTU. The coal used has a heating value of 12,800 BTU/lb, and is fired at the rate of 35 tons/hour. Consider the use of an electrostatic precipitator with or without a primary collector such as a cyclone ahead of it for this purpose. For the precipitator,

a. Estimate the minimum collecting surface required in square meters.

b. Propose an arrangement for the plates: number in parallel, spacing, height, length, and number of compartments. The overall arrangement of plates and the overall configuration of the precipitator must be practical and as close to cubic as is reasonably feasible to save space and to minimize the cost of insulation. The maximum height of the plates is 10 meters.

13. **Two-Stage Precipitator Optimization –** For a two-stage precipitator, consider the trade-off between the length of the charging section and the length of the collection section. What fraction of the total precipitator length should be devoted to the charging section.

Hint: You could approach it in one of several ways. One way would be to use a rigorous analytical procedure in which, for example, you take the derivative of efficiency with respect to fraction as charging section. Then set the derivative equal to zero and identify the location of the efficiency maximum (make sure it's not a minimum!). Another way would be to set up the equations in Excel and either use Solver or a trial-and-error approach to locate the efficiency maximum for you.

Control of Gases and Vapors

14. **Air Condition the Superdome –** One of the larger carbon adsorption systems is the air conditioning system for the Louisiana Superdome in New Orleans.

http://www.superdome.com/site1.php

The purpose of this system is to remove odors from the air inside this structure. Specifications for the building are:

Building area	13 acres
Building height	27 stories
Capacity	70,000 people for football
Use Rate	8 hours/day; 100 days/year

You determine from a literature search that a person generates one mg of odorous compounds per hour, and that in a "stressful" game, this rate increases to 5 mg/hour. However, the literature is ambiguous on generation rate; the references you find give values that range from 0.02 to 10 mg/hr generated per person.

Specifications for the carbon used in the air handling system are:

Bed porosity	0.5 (disregarding interior pores)
Granule diameter	2 mm

a) What air flow is required if the concentration of pollutants is to be below the odor threshold?

You must decide how big a bed to specify and how often it will be regenerated.

b) Specify the design (height, width, thickness) of an activated carbon bed adequate to remove these pollutants.

c) Specify how often this bed will have to be regenerated.

Extra Credit Estimate bed pressure drop using the theory we developed for flow through dust deposits. Remember that our model assumes flow through the deposit is laminar. Is this a correct application of this equation? If not, would actual pressure drop be higher or lower than that calculated?

15. **Carbon Bed Optimization –** You are to evaluate a carbon adsorption bed for control of CCl_4. The system from which the CCl_4 comes operates 10 hours per day and six days per week. According to the manufacturer, the carbon bed can be regenerated 100 times before it must be replaced. In addition, you know that:

CCl_4 costs $6.50/gallon
Effluent flow is 1000 cfm
CCl_4 concentration is 2500 ppm
Activated carbon costs $1.25/pound
Cost of an adsorption system is $25,000 + $10 per pound of carbon installed
Operating costs are $4000/yr for maintenance and $50 each time the bed is regenerated

Design a carbon bed system to collect this pollutant. You must consider how large a bed to use, and how often the bed should be regenerated. Specify:

a) Amount of carbon to be used

b) How often the bed should be regenerated,

c) Bed configuration (height, width, depth),

d) Annual operating cost for your design,

e) Time until initial cost is repaid.

In preparing your answer, determine the bed size that is economically "optimum"; that is, the bed size that results in lowest annual cost