Chapter 20

Open-Ended Problems

INTRODUCTION

The educational literature provides frequent references to individuals, particularly engineers and scientists, that have different learning styles; and, in order to successfully draw on these different styles, a variety of approaches can be employed. One such approach involves the use of open-ended problems.

The term "open-ended problem" has come to mean different things to different people. It basically describes an approach to the solution of a problem and/or situation for which there is usually not a unique solution. Three literature sources[(1–3)] provide sample problems that can be used when this educational tool is employed.

One of the authors of this text has applied this somewhat unique approach and has included numerous open-ended problems in several course offerings at Manhattan College. Student comments for the graduate course "Accident and Emergency Management" were recently tabulated. Student responses (unedited) to the question, "What aspects of this course were most beneficial to you?" are listed below.

1 "The open-ended questions gave engineers a creative license. We don't come across many of these opportunities."

2 "Open-ended questions allowed for candid discussions and viewpoints that the class may not have been otherwise exposed to."

3 "The open-ended questions gave us an opportunity to apply what we were learning in class with subjects we have already learned which gave us a better understanding of the course."

4 "Much of the knowledge that was learned in this course can be applied to everyday situations and in our professional lives."

5 "Open-ended problems made me sit down and research the problem to come up with ways to solve them."

6 "I thought the open-ended problems were inventive and got me to think about problems in a better way."

7 "I felt that the open-ended problems were challenging. I, like most engineers, am more comfortable with quantitative problems vs qualitative."

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The remainder of this chapter addresses a host of topics involved with open-ended problems. The remaining sections are entitled:

Developing Students' Power of Critical Thinking

Creativity

Brainstorming

Inquiring Minds

Failure, Uncertainty, Success: Are They Related?

Angels on a Pin

The chapter concludes with an Applications section containing open-ended Illustrative Examples, primarily in the mass transfer field.

DEVELOPING STUDENTS' POWER OF CRITICAL THINKING[4]

It has often been noted that we are living in the middle of an information revolution. For more than a decade, that revolution has had an effect on teaching and learning. Teachers are hard-pressed to keep up with the advances in their fields. Often their attempts to keep the students informed are limited by the difficulty of making new material available.

The basic need of both teacher and student is to have useful information readily accessible. Then comes the problem of how to use this information properly. The objectives of both teaching and studying such information are: to assure comprehension of the material and to integrate it with the basic tenets of the field it represents; and, to use comprehension of the material as a vehicle for critical thinking, reasoning, and effective argument.

Information is valueless unless it is put to use; otherwise, it becomes mere data. To use information most effectively, it should be taken as an instrument for understanding. The process of this utilization works on a number of incremental levels. Information can be: absorbed, comprehended, discussed, argued in reasoned fashion, written about, and integrated with similar and contrasting information.

The development of critical and analytical thinking is the key to the understanding and use of information. It is what allows the practicing engineer to discuss and argue points of opinion and points of fact. It is the basis for the formation of independent ideas. Once formed, these ideas can be written about and integrated with both similar and contrasting information.

CREATIVITY

Engineers bring mathematics and science to bear on practical problems, molding materials and harnessing technology for human benefit. Creativity is often a key component in this synthesis; it is the spark in motivating efforts to devise solutions to novel problems, design new products, and improve existing practices. In the competitive marketplace, it is a crucial asset in the bid to win the race to build better equipment and machines, decrease product delivery times, and anticipate the needs of future generations.[5]

Although one of the keys to the success of an engineer or a scientist is to generate fresh approaches, processes and products, they also need to be creative. Gibney[5] has detailed how some schools and institutions are attempting to use certain methods that essentially share the same objective: open students' minds to their own creative potential.

Gibney[5] provides information on "The Art of Problem Definition" developed by the Rensselaer Polytechnic Institute. To stress critical thinking, they teach a seven step methodology for creative problem development. These steps are provided below:

1 Define the problem
2 State objective
3 Establish functions
4 Develop specifications
5 Generate multiple alternatives
6 Evaluate alternatives
7 Build

In addition, Gibney[5] identified the phases of the creative process set forth by psychologists. They essentially break the process down into five basic stages:

1 Immersion
2 Incubation
3 Insight
4 Evaluation
5 Elaboration

Psychologists have ultimately described the creative process as recursive. At any one of these stages, a person can double back, revise ideas, or gain new knowledge that reshapes his or her understanding. For this reason, being creative requires patience, discipline, and hard work.

Finally, Dellafemina[6] recently outlined five secrets regarding the creative process:

1 Creativity is ageless
2 You don't have to be Einstein
3 Creativity is not an eight hour job
4 Failure is the mother of all creativity
5 Dead men don't create

The reader is left with a thought from Theodore:[7] Creativity usually experiences a quick and quiet death in rooms that house large conference tables.

BRAINSTORMING

Panitz[8] has demonstrated how brainstorming strategies can help engineers generate an outpouring of ideas. Brainstorming guidelines include:

1 Carefully define the problem upfront
2 Allow individuals to consider the problem before the group tackles it
3 Create a comfortable environment
4 Record all suggestions
5 Appoint a group member to serve as a facilitator
6 Keep brainstorming groups small

A checklist for change was also provided, as detailed below:

1 Adapt
2 Modify
3 Magnify
4 Minify
5 Put to other uses
6 Substitute
7 Rearrange
8 Reverse
9 Combine

INQUIRING MINDS

In an exceptional and well-written article by Lih[9] entitled *Inquiring Minds*, Lih commented on inquiring minds saying "You can't transfer knowledge without them." His thoughts (which have been edited) on the inquiring or questioning process follow:

1 Inquiry is an attitude—a very important one when it comes to learning. It has a great deal to do with curiosity, dissatisfaction with the status quo, a desire to dig deeper, and having doubts about what one has been told.
2 Questioning often leads to believing—there is a saying that has been attributed to Confucius: "Tell me, I forget. Show me, I remember. Involve me, I understand." It might also be fair to add: "Answer me, I believe."
3 Effective inquiry requires determination to get to the bottom of things.
4 Effective inquiry requires wisdom and judgment. This is especially true for a long-range intellectual pursuit that is at the forefront of knowledge.
5 Inquiry is the key to successful life-long learning. If one masters the art of questioning, independent learning is a breeze.

6 Questioning is good for the questionee as well. It can help clarify issues, uncover holes in an argument, correct factual and/or conceptual errors, and eventually lead to a more thoughtful outcome.

7 Teachers and leaders should model the importance of inquiry. The teacher/leader must allow and encourage questions, and demonstrate a personal thirst for knowledge.

FAILURE, UNCERTAINTY, SUCCESS: ARE THEY RELATED?

After many years of uncertainty, failures, and some successes, Theodore[(7)] ultimately came to the conclusion that failure is a unifying theme of success. This experience can allow one to proceed into uncharted waters, confident in his/her decision-making and problem-solving ability.

Obviously, there are positive aspects associated with failures. Theodore[(10)] discusses this subject in his "As I See It" column entitled "On Failure." Here is an excerpt from that article.

> I am amazed at how often we as a society employ the word failure (or fail) in a negative way. Here are some recent headlines or opening sentences/statements from the media: 'local students fail to pass . . . a failure in Olympic gold effort . . . Charismatic fails to win Triple Crown . . . math scores a failure' . . . , etc.
>
> Failure is used routinely to describe an event or activity. Unfortunately, some people have now come to be frightened of not only failure and the possibility of failing but also by the word itself. This kind of mentality can obviously have a negative impact on an individual.
>
> There is a thin line separating failure from success. For me, failure is an integral and positive part of life; success is often achieved following what others would describe as failure(s).
>
> As indicated above, failures are often encountered along the path of success. I often remind my students that my undergraduate GPA was 2.4/4.0 and that I was viewed as a failure by at least one of my professors. Later as a professor myself, my first 19 proposals (approximately 100 pages each) to the National Science Foundation, U.S. Environmental Protection Agency, etc., were rejected before my first award. Those were tough times, particularly for my fragile ego, but it proved to be a real learning experience. Today, I rarely prepare and submit a proposal unless I am wired for the award. I really believe that providing numerous examples of failures to my students has significantly helped them to achieve success.
>
> In any event, when you or someone you care about fails, remember the lines from DeCervantes' Don Quixote: 'Fortune may have yet a better success in reserve for you, and they who lose today may win tomorrow.'
>
> Yep, it is okay to fail.

Ultimately, the degree to which one succeeds (or fails) is based in part on one's state of mind or attitude. As President Lincoln once said: "Most people are about as happy as they make their minds to be." William James once wrote: "The greatest discovery of my generation is that human beings can alter their lives by altering their attitude of mind." So, no matter what one does, it is in the hands of that individual to make it a meaningful, pleasurable, and positive experience. This experience can ultimately bring success.

ANGELS ON A PIN[11]

There is a tale that appeared in print many years ago that dissected the value of an open-ended approach to a particular problem. That story is presented below.

Some time ago I received a call from a colleague who asked if I would be the referee on the grading of an examination question. He was about to give a student a zero for his answer to a physics question while the student claimed he should receive a perfect score and would if the system were not set up against the student. The instructor and the student agreed to submit this to an impartial arbitrater and I was selected.

I went to my colleague's office and read the examination question: "Show how it is possible to determine the height of a tall building with the aid of a barometer."

The student had answered: "Take a barometer to the top of the building, attach a long rope to it, lower the barometer to the street and then bring it up, measuring the length of the rope. The length of the rope is the height of the building."

I pointed out that the student really had a strong case for full credit since he had answered the question completely and correctly. On the other hand, if full credit was given, it could well contribute to a high grade for the student in his physics course. A high grade is supposed to certify competence in physics but the answer did not confirm this. I suggested that the student have another try at answering the question. I was not surprised that my colleague agreed but I was surprised that the student did.

I gave the student six minutes to answer the question with the warning that the answer should show some knowledge of physics. At the end of five minutes, he had not written anything. I asked if he wished to give up but he said no. He had many answers to this problem; he was just thinking of the best one. I excused myself for interrupting him and asked him to please go on. In the next minute, he dashed off his answer which read:

"Take the barometer to the top of the building and lean over the edge of the roof. Drop that barometer, timing its fall with a stopwatch. Then using the formula $S = 1/2at^2$, calculate the height of the building."

At this point, I asked my colleague if he would give up. He conceded and I gave the student almost full credit.

In leaving my colleague's office, I recalled that the student had said he had many other answers to the problem and so I asked him what they were. "Oh yes," said the student. "There are a great many ways of getting the height of a tall building with a barometer. For example, you could take the barometer out on a sunny day and measure the height of the barometer and the length of its shadow, and the length of the shadow of the building and by the use of a simple proportion, determine the height of the building."

"Fine," I asked. "And the others?"

"Yes," said the student. "There is a very basic measurement method that you will like. In this method, you take the barometer and begin to walk up the stairs. As you climb the stairs, you mark off the length of the barometer along the wall. You then count the number of marks and this will give you the height of the building in barometer units. A very direct method."

"Of course, if you want a more sophisticated method, you can tie the barometer to the end of a string, swing it as a pendulum, and determine the value of 'g' at the street level and at the top of the building. From the difference of the two values of 'g' the height of the building can be calculated."

Finally, he concluded, there are many other ways of solving the problem. "Probably the best," he said, "is to take the barometer to the basement and knock on the superintendent's door." When the superintendent answers, you speak to him as follows: "Mr. Superintendent, here I have a fine barometer. If you tell me the height of this building, I will give you this barometer."

At this point I asked the student if he really did know the conventional answer to this question. He admitted that he did, said that he was fed up with high school and college instructors trying to teach him how to think using the "scientific method," and to explore the deep inner logic of the subject in a pedantic way, as is often done in the new mathematics, rather than teaching him the structure of the subject. With this in mind, he decided to revive scholasticism as an academic lark to challenge the Sputnik-panicked classrooms of America.

APPLICATIONS

Several of the open-ended Illustrative Examples in this chapter have been drawn from the literature[1–3] and from the class notes of Theodore,[12] keying primarily on mass transfer issues.

ILLUSTRATIVE EXAMPLE 20.1

Your boss at work wishes to speed up the process used to determine the column diameter in the design of an absorber. You have been asked to convert the flooding line from U.S. Stoneware's pressure drop correlations to equation form. You have also be asked to integrate this equation into a computer spreadsheet. The spreadsheet should calculate the diameter for the user once supplied with the appropriate system values (such as L, G, F, fraction of flooding velocity, and so on).

***SOLUTION*:** Below is one equation that relates the liquid and gaseous flow rates in the tower with the column cross-sectional area at the flooding point[13]

$$Y = -3.84 - 1.06X - 0.119X^2 \tag{20.1}$$

Where $Y = \ln\left[\dfrac{w_G^2 F \psi \mu_L^{0.2}}{\rho_G \rho_L g_c A_f^2}\right]$

$$X = \ln\left[\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}\right]$$

w_G = gas flow rate, lb/h

L = liquid superficial mass velocity at the bottom of packing, $lb/h \cdot ft^2$

G = gas superficial mass velocity at the bottom of packing, $lb/h \cdot ft^2$

ρ_L = liquid density, lb/ft^3

ρ_G = gas density, lb/ft^3

F = packing factor, dimensionless

A_f = cross-sectional area of the column, ft^2

μ_L = liquid viscosity, cP

ψ = ratio, density of water/liquid density, dimensionless

g_c = constant = 4.173×108 $lb \cdot ft/lb_f \cdot h$

This equation is applicable in the range $0.01 < e^X < 10$ or $-4.6 < X < 2.3$. ■

ILLUSTRATIVE EXAMPLE 20.2

A twenty-four-year-old perforated plate distillation column is no longer delivering the degree of separation required for the process. Rather than replace the unit, you have been asked to recommend what other possible steps can be taken to the existing unit to get it back "on line." Unfortunately, it is not currently possible to completely replace the column. Some other solutions need to be found.

***SOLUTION*:** The issue with the current operation is its inability to perform the separation at its designed level.

The first thing that needs to be investigated is what is the current state of the column? How was it originally designed? Were safety margins included in the design that allow for some "tweaking" of the actual structure of the column? How much change in pressure (drop) is allowed? What will the materials stand up to?

A possibility for the column is changing the flow rate of gas through the column. If the gas is made to pass through the column at a higher velocity, it should result in more foaming of the liquid on the trays. This will increase the mass transfer area. This will also help to separate the products. Unfortunately, this could create new problems with flooding and entrainment. This needs to be examined very closely before it is implemented.

It also might be possible to change the reboiler and condenser conditions. It is possible after 24 years of service that these two devices are not working at their optimum settings. An examination should be made of their contribution to the failure to separate the products. Is the column failing because these devices are no longer functioning? If so, then they need to be replaced with newer models.

The composition and conditions of the feed stream also need to be examined. Is it the same as what the column was originally designed to separate? Has the process been altered upstream in such a way that the separation is no longer feasible? Perhaps it has changed through the years in such a manner that the column is no longer designed to deal with the stream. This stream could be altered to adhere to the original conditions to make the column operate correctly again. Also, the feed tray (location) could be changed; the inlet stream quality (defined as q in Chapter 9) might also be changed.

Adding trays is the most difficult thing to implement but would probably have the largest impact. The trays could be added near the top of the column if a safety margin of headspace had been designed into the column. A possibility would be the complete removal of all the trays and reinstalling them with smaller tray spacing between them. If that is done, the company should consider replacing the trays with a better tray design. Significant work has gone into tray design in the past 24 years. Improvements have been made to their efficiency and capabilities.

Finally, it is possible that the column needs cleaning and that could increase the column's efficiency. ■

ILLUSTRATIVE EXAMPLE 20.3[14]

Consider a chemical plant that uses two liquid feeds of different densities as provided in Table 20.1. It produces four different liquid chemical products of varying density following chemical reaction and separation, see Table 20.2. The plant storage requirements call for maintaining 4–5 weeks supply of each feed, 4–6 weeks supply of products A, B, and C, and 1–2 weeks supply of product D. The plant operates year round but each tank must be emptied once a year for a week for maintenance. Tanks are normally dedicated to one feed or product and one or two could be used as "swing" tanks; however, one day of cleaning is required between uses with different liquids.

Specify a set of tanks from the "standard" sizes given in Table 20.3 to minimize this plant's needs.

Table 20.1 Feed Data

Feed 1	110,000 lb/day	$\rho = 49\ \text{lb/ft}^3$
Feed 2	50,000 lb/day	$\rho = 68\ \text{lb/ft}^3$

Table 20.2 Product Data

Product A	40,000 lb/day	$\rho = 52\ \text{lb/ft}^3$
Product B	25,000 lb/day	$\rho = 62\ \text{lb/ft}^3$
Product C	10,000 lb/day	$\rho = 52\ \text{lb/ft}^3$
Product D	95,000 lb/day	$\rho = 47\ \text{lb/ft}^3$

Table 20.3 Tank Data

Standard Tank Sizes (gallons):			
2800	11,200	56,100	561,000
5600	16,800	140,000	1,123,000
8400	28,100	281,000	

Table 20.4 Storage Requirements

Material	lb/day	Gal/day	Days	Gals storage required
Feed 1	110,000	16,800	28–35	470,200–587,800
Feed 2	50,000	5500	28–35	154,000–192,500
Product A	40,000	5750	28–42	161,100–241,700
Product B	25,000	3020	28–42	84,500–126,700
Product C	10,000	1440	28–42	40,300–60,400
Product D	95,000	15,120	7–14	105,800–211,700

***SOLUTION*:** There is no single, simple method for determining the optimum mix of stage tanks for a chemical plant. Most often, estimates are made of the minimum and maximum amounts of feeds, intermediates, and products that must be kept on hand. Then some additional allowance is made to permit periodic cleaning and maintenance of the tanks. The minimum number of tanks may not always be optimum if the tanks are extremely large. Several smaller tanks may cost somewhat more initially but they offer more flexibility in use. One solution and some calculational details follow.

Determine the maximum and minimum amounts of each material to be stored (see Table 20.4). The conversion to gallons requires dividing the rate in lb/day by the density in lb/ft^3, then multiplying by 7.481 gal/ft^3.

For each material, select a set of tanks:

Feed 1:	Use 2	281,000 gallon tanks
Feed 2:	Use 4	56,100 gallon tanks
Product A:	Use 2	140,000 gallon tanks
Product B:	Use 2	56,100 gallon tanks
Product C:	Use 1	56,100 gallon tanks
Product D:	Use 2	140,000 gallon tanks

This set is 5% short on the maximum of Feed 1, 11% short on Product B, and 7% short on Product C. For most situations, this would be acceptable.

Select spare and/or "swing" tanks to provide for maintenance:

Feed 1:	Use an additional 281,000 gallon tank
Feed 2 and all products:	Use one 56,100 gallon "swing" tank

This combination provides adequate auxiliary storage for maintenance periods:

Total tanks required:	3	281,000 gallons
	4	140,000 gallons
	8	56,100 gallons

The number of tanks required will be quite large in this application. If market forces such as fluctuating demand require this much storage, they may all be necessary. More modern commercial operations such as "just-in-time" manufacturing, call for reducing in-plant inventory to the absolute minimum possible. ■

ILLUSTRATIVE EXAMPLE 20.4

Consider the absorber system shown in Figure 20.1. It is designed to operate with a maximum discharge concentration of 50 ppm. Once the unit is installed and running, the unit operates with a discharge of 60 ppm. Rather than purchase a new unit, what options are available to bring the unit into compliance with the specified design concentration?

***SOLUTION*:**

1 Use a smaller packing size. A different size may produce a better packing factor.

2 Use a different type of packing. A different packing type may produce a better packing factor.

3 Make sure there is no channeling inside the column. The packing should be randomly distributed and there should be no open spots where water will accumulate.

4 Increase the water flow entering the column. If the water flow is increased, there will be a greater mass transfer between the liquid and gas phase and the efficiency of the column will increase. In effect, the slope of the operating line will increase and provide a greater driving force for mass transfer.

5 Use a liquid other than water to scrub the gas. Another liquid may cause better mass transfer between the gas and liquid phase.

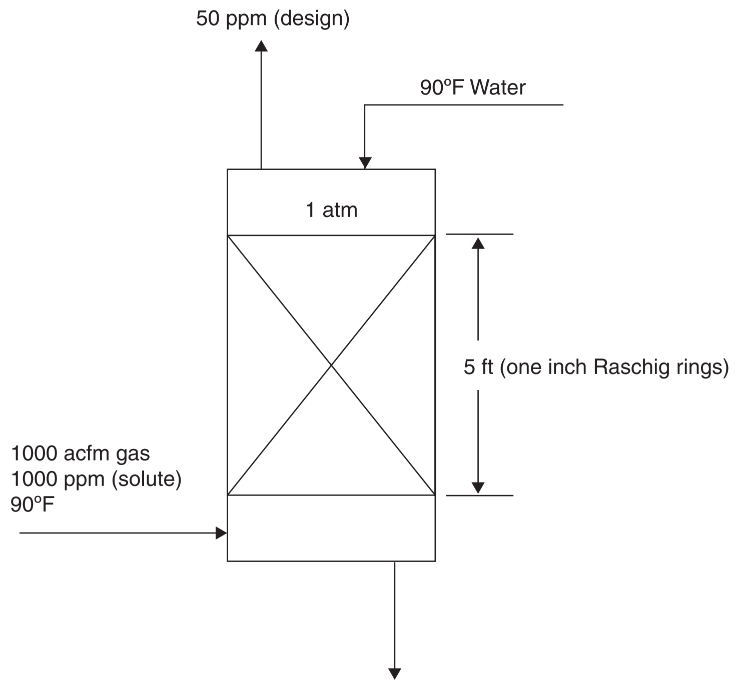

Figure 20.1 Faulty design?

6 Check to see if flooding is occurring. If the column is near the flooding point, there will not be much mass transfer. The water will be pushed up the column by the gas rather than the water coming down the column.
7 Lower the initial concentration in the carrier gas (if possible).
8 Increase the height of the bed. This will provide more surface area for mixing and more time in the absorber.
9 Increase the pressure. This will reduce the slope of the operating line and lead to a greater driving force.
10 Decrease the temperature. This will reduce the slope of the operating line and lead to a greater driving force.
11 Increase the pressure and decrease the temperature.
12 Additional packing height could be added at the top of the column. This would increase the amount of the solute removed from the gaseous phase.
13 Add sprays at the bottom of the column.
14 Modify the process producing the problem. Since the details of this process are not included in the problem statement, no specific recommendations can be mentioned in this discussion.
15 Finally, before considering changes to the system, one should undertake a thorough inspection of the unit and surrounding components. The emission monitoring system should be recalibrated. All valves, fittings, and pipes should be checked for plugging or leaks. The liquid distributor should be checked to make sure it is functioning properly. The distribution of the packing should be inspected to make sure it is as uniform as possible. Any problems encountered during this inspection should be corrected immediately. Following the maintenance check, the performance of the unit should be re-evaluated.

The reader should note that some of the recommendations above could lead to higher pressure drops and potential problems with the flow. An example of this problem would be the implementation of suggestion 1. The reader is left the exercise of determining what other steps could lead to flow/pressure drop problems. *Hint*: There are at least six suggestions that fall into this category, including firing the engineer who designed the absorber. ■

ILLUSTRATIVE EXAMPLE 20.5

Refer to Illustrative Example 20.4. A similar situation exists with a *gaseous* adsorption unit. Rather than purchase a new unit, what options are available to bring the unit into compliance with the specified design concentration? *Note*: The packing is activated carbon and there is now no liquid flow.

***SOLUTION*:**

1 Check/increase the depth of the adsorption bed. Make up any adsorbent lost to carryover (as necessary). Increasing the depth of the bed will increase the removal capacity of the column.
2 Change the adsorbent type or size. Use an adsorbent with a higher saturation capacity.
3 Reducing the flow will increase the residence time and may allow for more adsorption.
4 Decrease the inlet temperature. This will favor the adsorption equilibrium process.
5 Increase the system pressure. This will favor the adsorption equilibrium process.

6 Regenerate the adsorbent for a longer period.
7 Replace the adsorbent.
8 Consider changing the flow direction.

Again, pressure drop considerations should be included in the analysis. ■

ILLUSTRATIVE EXAMPLE 20.6

Refer to Illustrative Example 20.5. A similar situation exists with a *liquid* adsorption unit. Rather than purchase a new unit, what options are available to bring the unit into compliance with the specified design concentration?

***SOLUTION*:** The solution to this problem, in many respects is similar to that presented in Illustrative Examples 20.4 and 20.5. ■

ILLUSTRATIVE EXAMPLE 20.7

Comment on the various techniques available for the treatment of solid wastes.

***SOLUTION*:** There are many ways to manage solid waste. A few methods are discussed below. One option in solid waste treatment is incineration. There are two major types of incinerators: stoker types and fluidized bed types. Stokers have the capability to stabilize the combustion for many types of materials, including infectious materials. The advantage of the fluidized bed incinerator is its ability to achieve nearly isothermal conditions within the bed. The high mass and heat transfer rates lower the temperature necessary to achieve the required removal/destruction efficiency. Fluidized bed incineration is used mainly for hazardous waste. There may be direct energy recovery.

Plasma membranes are an efficient way of disposing of wastes, including infectious materials. This process decomposes complex organic molecules into hydrogen, carbon dioxide, coke and hydrogen chloride. The waste is broken into elemental atoms in plasma. The gases are cooled and sprayed with caustic to remove particulates and acid gases. This method is used for the complete destruction of PCBs and dioxins.

Instead of complete disposal, there are alternatives such as recycling. There are several applications of recycling. The first is direct onsite reuse where the site/plant reuses the waste it generated. Offsite recovery can be utilized when the refuse generated by the site is too little to warrant an onsite recovery unit. Another option in recycling is the sale of refuse offsite. In this option, the plant sells the waste from their plant for use as raw materials in another plant.

Yet another way to dispose of solid waste is landfilling. This solution partially appeases the aesthetic problem waste brings to a society. In this solution, the waste is buried and out of sight. Burying the waste also aids in the ultimate disposal of it. The organic parts of the waste can decompose and hopefully, once again become part of the Earth. ■

ILLUSTRATIVE EXAMPLE 20.8

A certain petrochemical company plans on installing an adsorption unit to remove a specific volatile organic compound (VOC). Rather than rely on existing design methods and procedures entirely, the company wishes to conduct a pilot scale test to aid in the design. You have been asked to plan this test. Discuss how you will do this. How will you simulate actual conditions at the pilot scale? What measurements need to be taken?

***SOLUTION*:** This study would obviously require a detailed plan of action. A summary of the key steps are provided below.

1. Prepare a bench scale unit for testing.
2. Prepare a small pilot scale unit for testing.
3. Use the results of steps (2) and (3) above for scale up purposes.
4. During testing, measure inlet and outlet concentrations, and pressure drop for a variety of operating conditions.
5. Consider another mass transfer option. ■

ILLUSTRATIVE EXAMPLE 20.9

You are an engineer at an Aquafina plant. As stated on a bottle of Aquafina water, it is purified using reverse osmosis (RO). One of the RO units at your plant is no longer operating to the required "separation" efficiency. What steps should be taken to avoid purchasing a new purification unit?

***SOLUTION*:**

1. Check the membrane to see if it needs to be replaced.
2. If the membrane is satisfactory, check the concentration of the feed stream to the unit. The feed stream may be more concentrated due to a problem before the RO unit.
3. Check that the appropriate pressure is being applied in order to overcome the osmotic pressure (i.e., check the pumps).
4. Check that none of the other components of the system have been damaged by the membrane. ■

ILLUSTRATIVE EXAMPLE 20.10

List some advantages and disadvantages of employing distillation vs liquid–liquid extraction to separate a two-component liquid stream.

***SOLUTION*:** Distillation is normally employed for large-scale processing and where there is a need for a high degree of separation. Maintenance costs are usually lower. It almost always is the preferred choice. Liquid–liquid extraction is less expensive to operate and there are no heat transfer requirements. It is usually employed for small-scale operations. Some specific comments are provided below.

Distillation:

1. A separation technique that is based on difference in boiling points/volatilities of the individual components.
2. The feed flows down the column to the reboiler where it is heated; the vapor is allowed to flow up the column and the liquid product is removed in the reboiler. The vapor product is condensed and removed from the top of the column as the distillate.

Liquid–liquid extraction:

1 A separation process that is based on the relative solubilities of solutes in immiscible solvents.

2 The solution containing the desired solute is contacted with another solvent that is immiscible with the solution.

3 The solvent is chosen so that the solute in the solution has more affinity for the added solvent. Mass transfer of the solute from the solution to the solvent occurs.

4 The solvent containing the extracted solute leaves the top of the column and is referred to as the extract stream. The solution exits the bottom of the column containing only small amounts of solute and is called the raffinate.

Refer to Chapters 9 and 12 for additional details. ■

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