14

PUTTING IT ALL TOGETHER

14.1 INTRODUCTION

The previous chapters have focused on various phases of problem-solving procedures and activities as well as process engineering calculation techniques. The actual procedures and techniques applicable for any problem-solving activity have been discussed. In addition, Chapters 7–13 contain experience-based process engineering calculation techniques and guidelines. In each of these chapters, there are example problems that are directed toward the theme of the particular chapter. In real life, problems don't come packaged so neatly. For example, what is described as a problem associated with a prime mover may well be a problem associated with a reactor.

In order to see how these areas fit together, several real-life example problems are discussed in this chapter. The chapter shows how the five-step problem-solving procedure (Chapter 3) can be used, how working hypotheses can be formulated (Chapter 6), and how various process engineering calculations (Chapters 5 and 7–13) can be utilized to develop and confirm these hypotheses.

14.2 DON'T FORGET TO USE FUNDAMENTALS

Two of the most powerful tools that a process engineer (or a problem solver serving as a process engineer) can use in problem solving are heat and material

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Problem Solving for Process Operators and Specialists, First Edition. Joseph M. Bonem.

balances. These concepts were described in Chapter 5. The material balance simply states that, with the exception of atomic power, mass cannot be created or destroyed. Thus the total flow in mass units into a process or a unit operation must be equal to the total flow out. A comparable truism applies to heat balances. In addition to the need for a process to be in balance, heat and material balances can be used to determine unknowns. For example, material balance principles can be used to determine the production rate of a desirable or undesirable component. If an undesirable byproduct is being produced in a reactor and removed in a purge stream, the rate of production is simply the removal rate. Heat balances can be used to determine the boilup rate from the steam rate. A problem solver might be told that a tower is flooding because the trays are plugged. When he performs a heat balance, he might conclude that the heat input to the tower is less than the heat being removed from the tower. If he makes a closer examination, he might find that the problem really is a steam meter that is indicating a flow rate much lower than the actual flow. This is causing the tower to be flooded, due to the excessive vapor being generated in the reboiler.

As will be noted in the example problems, knowing the flow rates of process or utility streams is a requirement for successful problem solving. While this may seem very basic, it is amazing how many problem solvers will start developing intricate hypotheses even though flow instruments indicate that the amount of material coming into the unit operation does not equal the amount of material leaving. Thus one of the key ideas for a problem solver to remember is to not forget the fundamentals of their discipline.

EXAMPLE PROBLEM 14-1

Do Fundamental Processes Developed in the United States Translate to Europe?

A chloride removal unit designed and operated in the United States was an integral part of a gas-drying process that used triethylene glycol (TEG) as the circulating drying solvent. Water was removed from the gas in the absorber using a stream of TEG that had a very low water content. The properties of TEG are such that water has a very low partial pressure when dissolved in the TEG. Thus it can be readily used to dry gases of all descriptions.

In the drying process, the TEG leaving the absorber and containing the water removed in the absorber flowed to a heated, two-stage regeneration system. In this regeneration system, the dissolved water was stripped from the gas and the dry TEG was recirculated to the absorber. The initial stage of the regeneration system was a heated flash step with about 5 min of residence time. The second stage was a vacuum distillation tower. The TEG from the vacuum distillation tower flowed back to the absorber.

The gas to be dried was a chlorine derivate. Some of the gas dissolved in the circulating TEG was converted to hydrogen chloride (HCl) when the solution was heated as part of the regeneration step. The reaction of the gas to form HCl was known to be first order with respect to the concentration of the chlorine derivative in the circulating TEG. However, the exact reaction rate constant and Arrhenius constant were not known. The Arrhenius constant is a value that describes how fast the reaction increases with increasing temperature. Essentially, all of this reaction occurred in the first-stage flash drum of the two-stage regeneration system. This stage was operated at 175°F and 5 psig. The level in the drum was controlled so that the residence time was limited to 5 min. The second stage of the regeneration system consisted of a small vacuum fractionating tower. HCl generation in this stage was very limited because of the short residence time and low pressure.

The HCl formed was neutralized using a soluble amine. However, the amine could not be added continuously since the HCl-amine complex would build up in the circulating TEG to an unacceptably high level. The HCl was removed from the HCl-amine complex by passing a small stream of dry TEG through a drum filled with ion exchange resin. Ion exchange resins are complex salts supported on a synthetic resin such as polystyrene. This particular ion exchange resin had the capability of removing the Cl^- ion and replacing it with an OH^- ion. Thus the HCl-amine bond was broken and the HCl was converted to water. The ion exchange resin itself was converted from an OH^- form to a Cl^- salt. As this process continued, the bed would eventually become saturated with Cl^- ions and become ineffective. To restore the bed, operators removed it from service and regenerated it using water and a sodium hydroxide solution. This regeneration was done whenever the concentration of chlorides in the outlet increased above 50 ppm. A simplified drawing of the process is shown in Figure 14-1.

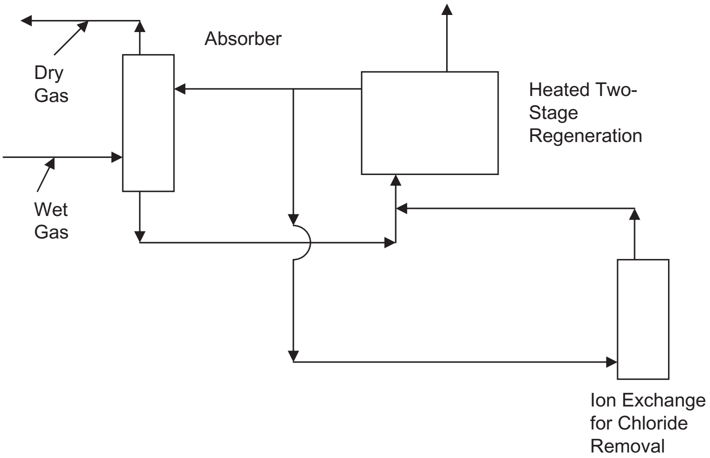

Figure 14-1 TEG system.

The process was designed and installed in a location in the United States. After initial startup problems, the operation of the process was very successful. The chlorides were controlled at a concentration of 500 ppm with a flow to the ion exchange bed of 500 lb/hr. During the initial operations, high corrosion rates where encountered when the chloride level increased to 1000 ppm.

An identical unit was installed in Europe. Flow rates, temperatures, and pressures were all the same. While the gas was successfully dried, the concentrations of chlorides in the circulating TEG rose to 1500 ppm in a month after startup. The ion exchange bed appeared to be operating well, since the outlet concentration from the bed was zero until the ion exchange resin became saturated with chlorides. However, the bed had to be regenerated more frequently than anticipated due to the heavy loading of chlorides. At the time, the plant in Europe was not using the problem-finding concepts discussed in Chapters 3 and 6. Because of the concern over corrosion, European management shut the unit down. While significant corrosion had not yet been observed, they were convinced, based on experience in the United States, that high corrosion rates would be observed soon. After some preliminary problem-solving attempts on their own, they requested help from the original designer in the United States.

When the problem solver from the United States arrived on the scene, he began a methodical problem-solving activity using the approach discussed in the previous chapters. This methodical problem-solving approach was even more important in this case since there were significant geopolitical factors involved. There was a great deal of animosity between the European affiliate and the U.S.-based technical staff. The problem solver began the five-step approach as described in Chapter 3.

Step 1: Verify that the problem actually occurred.

Since operation at high chloride concentrations had not yet resulted in observable corrosion, the first problem to be verified was that the actual concentration of chlorides was as high as 1500 ppm. The laboratory procedure was confirmed and several samples were analyzed confirming that, indeed, the chloride concentration was 1500 ppm. Since the corrosion rate had been so severe in the United States at a chloride level of 1000 ppm, it did not seem wise to continue operation and simply monitor the corrosion rate.

The problem solver's next step in verifying that the problem actually occurred was to compare the theoretical chloride buildup to the actual chloride buildup in Europe. Since the reaction rate constant was not known, the theoretical chloride buildup was determined based on operations in the United States. Based on material balance principles, the problem solver calculated the chloride production rates in the United States. This material balance principle is as follows:

$$RC = F \times X_{\mathrm{F}} \tag{14-1}$$

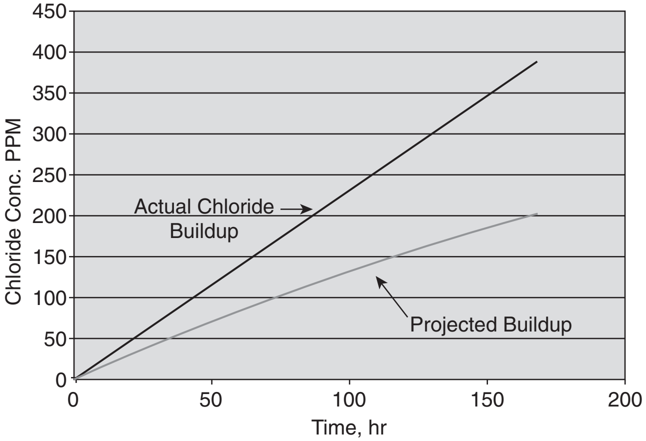

Figure 14-2 Actual and projected chloride buildup.

where

RC = rate of chloride production in the United States, lb/hr

F = flow rate to the ion exchange bed, lb/hr

X_F = concentration of chlorides in the flow to the ion exchange bed, weight fraction

Note that equation (14-1) assumes that the chloride concentration in the outlet from the ion exchange bed was zero. This was true essentially all of the time.

Knowing the rate of chloride production in the United States and assuming that it was the same in Europe, the problem solver could estimate the chloride concentration buildup rate in the European plant by knowing the TEG inventory. He then developed the relationships shown in Figure 14-2. In this figure, the projected chloride buildup based on kinetic relationships developed in the United States is shown along with the actual chloride buildup. This provides a means of comparing the theoretical and actual chloride concentration buildup rates. Obviously, there was a significant difference between the two rates.

Step 2: Write out an accurate statement of what problem you are trying to solve.

The problem solver wrote out the problem statement as follows:

> The chloride concentration in the circulating TEG in the European plant has built up to 1500 ppm instead of the anticipated level of 500 ppm. This is a major concern because experience in the United States indicated that significant corrosion would begin at levels above 1000 ppm. This high level of chlorides is being experienced in Europe at the apparent identical process conditions used in the

United States, which resulted in a chloride level of only 500 ppm. An analysis of the rate of chloride buildup indicates that the higher chloride production rate has been present since the startup of the equipment in Europe. Determine why the chloride concentration in the circulating TEG has built up to 1500 ppm instead of an anticipated level of 500 ppm. In addition to understanding what is causing the high level, changes to reduce the steady state concentration to 500 ppm should be recommended.

Step 3: Develop a theoretically sound working hypothesis that explains the problem.

The question list given in Chapter 6 was used as a guide to develop potential working hypotheses. A summary of this analysis is shown below, in Table 14-1.

Table 14-1 Questions/comments for Problem 14-1

Question	Comment
Are all operating directives and procedures being followed?	All appeared to be correct and being followed.
Are all instruments correct?	The instruments had allegedly been calibrated. However, it was observed that a venturi meter was being used in Europe where an orifice meter was used in the United States.
Are laboratory results correct?	All appeared to be correct.
Were there any errors made in original design?	The design was essentially the same as that in the United States with the exception of improvements in the regeneration section.
Were there changes in operating conditions?	No. In fact, the operating conditions of temperature and pressure were identical to those used in the United States.
Is fluid leakage occurring?	This would not explain the problem.
Has there been mechanical wear that would explain problem?	No.
Is the reaction rate as anticipated?	Higher rates of HCl formation could explain part of the problem. On the other hand, the ion exchange bed appeared to be performing as designed except for the frequent regenerations. The frequent regenerations appeared to be associated with the higher-than-anticipated rate of HCl formation.
Are there adverse reactions occurring?	There were no unusual reactions that could explain the problem.
Were there errors made in the construction of the process?	Since the unit had only recently been built, this had to be considered.

The value of using a list similar to that in Table 14-1 is that it helps to eliminate superfluous hypotheses that might be suggested and it allows problem solvers to focus on the likely areas for development of working hypotheses. For example, an examination of this table indicates that areas such as mechanical wear, fluid leakage, or changes in operating conditions are unlikely routes to pursue. In addition, the most obvious conclusion, "the ion exchange resin is not working," is shown by Table 14-1 to be highly unlikely. On the other hand, meter errors, higher-than-expected HCl production rates, and design improvements in the regeneration area appear to be valuable ideas to pursue. As is often the case in industrial problem solving, there may be more than a single item that is causing the problem. For this reason, the problem solver began looking in detail at the design improvements, the variables that might cause the reaction rate to form HCl to be higher than anticipated, and the difference between a venturi meter and orifice meter in this specific application. It was not possible to isolate the potential areas of flow meter error and higher-than-anticipated HCl production rate because the technique for calculating HCl production rate depended on the flow rate of TEG to the ion exchange bed. If this flow meter was in error, the calculated HCl production rate would be in error. Thus both possibilities had to be considered.

Since the operating conditions (temperature and pressure) were identical to those used in the plant in the United States, it would appear that the rate of HCl generation would be the same. However, as indicated earlier, the possibility of higher rates of HCl generation could not be eliminated. Since, essentially, all of the HCl was produced in the first-stage flash drum, the problem solver began an analysis of that operation. Referring back to Chapter 9, the kinetic relationship can be expressed in terms of reaction rate as shown below:

$$R^* = C \times DF \tag{14-2}$$

where

R^* = rate of change with time per unit volume of the compound under study, mols of HCl/ft^3-min that are formed

C = constant referred to as the "lumped parameter constant"

DF = driving force or incentive for reaction to occur, mols of chlorine derivative gas absorbed/ ft^3 of TEG. Since as indicated earlier essentially all of the HCl generation occurred in the flash drum that was the only area to be considered.

In this case, the constant is the reaction rate for the formation of HCl from the chlorine derivative gas. This will be a function of temperature only. As indicated, the driving force will be the concentration of the gas in the TEG in the flash drum. This will depend on temperature and pressure only. Thus the driving force and lumped parameter constant should be the same in the plants in Europe and the United States. This means that *R*, the rate of HCl formation in mols per minute per unit of volume, should be the same. Thus if the absolute value of HCl formation in mols/hour is higher, it can only be due to an increase in drum volume or residence time at a constant flow rate. This possibility by itself does not provide enough data to formulate a hypothesis. In order to determine if there is a valid working hypothesis related to increased drum volume, the following items were reviewed:

- The dimensions of the first-stage flash drum were reviewed and it was concluded that the dimensions were identical in the plants in Europe and the United States.
- While the measured liquid levels in the drums were both held at 20%, the ranges of the liquid level instruments were different. This was discovered only during a detailed review of the instrument specification sheets. The instrumentation philosophy in the United States was to only cover the planned range of operations with the liquid level instrument. This would provide a higher degree of accuracy. The range of the level instrument was 50 in. In Europe, the philosophy was to cover the entire height of the drum, 75 in in this case. The Europeans considered this to be a significant design improvement.

Thus the absolute liquid level in Europe was 15 inches versus 10 inches in the United States. Since the drums were the same diameter and the flow rates were identical, this difference would provide 50% more reaction volume in Europe than the United States. This would increase the HCl production by 50%.

In order to determine whether this hypothesis would explain all of the apparent increase in HCl production observed in Europe, an HCl material balance was developed for Europe in a similar fashion to that done for the United States. The premise of these balances was that the HCl removed was equal to the HCl produced. These balances are shown in Table 14.2:

Table 14-2 Chloride balances

Variable	U.S. (base case)	Europe
Flow rate to ion exchange, lb/hr	500	500
Chloride concentration into ion exchange, ppm	500	1500
Chloride concentration out of ion exchange, ppm	0	0
Chloride production by material balance, lb/hr	0.25	0.75
Calculated chloride production, lb/hr[a]	0.25	0.38

[a] The calculated chloride production rate was set at the material balance level for the base case (that in the United States) and was increased by 50% to allow for the increased residence time in Europe.

Thus it appeared that a working hypothesis that the increased residence time was responsible for an increased amount of chloride produced would be a valid working hypothesis. However, the calculated chloride production rate was only about half of the value obtained by material balance (0.38 lb/hr vs. 0.75 lb/hr). The failure to get a good material balance calculation check indicated that there might be other problems. Thus rather than proposing a plant test of lowering the level in the first-stage flash drum, the problem solver began considering other possible problems.

A review of the question guidelines and answers in Table 14-1 indicated that there was likely some mistake in construction or the revised design. Several possible additional hypotheses were developed. Most of them tended to point to the flow measurement of the stream going to the ion exchange bed. If the flow rate was significantly less than that indicated, chlorides would still be removed, but the concentration would build up to a higher level than was anticipated. For example, if the flow was actually 250 lb/hr, the amount of chloride removed in the ion exchange unit would be equivalent to that calculated based on the increased residence in the first-stage flash drum. The problem solver began developing a hypothesis associated with the flow meter by selecting the simplest explanation possible. A review of the venturi meter calculations used for the flow to the ion exchange bed indicated that it was selected to minimize pressure drop. The venturi meter discharge coefficient was assumed to be one which would have been true for a low-viscosity fluid. However, the TEG has a viscosity much higher than that of a typical hydrocarbon. While it appeared to the problem solver that a standard orifice meter would have provided a much more accurate installation, he refrained from indicating this to the Europeans.

The problem solver now developed the following hypothesis that actually contained two possible theoretically correct working hypotheses.

> It is believed that the increased absolute level in the flash drum (15 in vs. 10 in) is causing the chloride production to be 50% higher in Europe than in the United States. The level hypothesis does not explain that the concentration of chlorides in the TEG is three times that anticipated based on results in the United States. Thus another problem must be present. It is believed that the measurement of flow to the ion exchange bed is in error.

It should be noted that this problem illustrates that in industrial problem solving, there is often more than one valid hypothesis. Using basic chemical engineering principles can often confirm whether one hypothesis can explain the entire problem.

Step 4: Provide a mechanism to test the hypothesis.

Two separate plant tests were developed to test both of these hypotheses. The tests were conducted concurrently since, as hypothesized, there was no interaction between the two tests. In the first test, the level was reduced in the first-stage flash drum so that the residence time was reduced to 5 min. In the second test, the flow to the ion exchange bed was diverted into a 5-gallon bucket and the actual flow rate was measured. The five gallon bucket required about 11 min to fill, as opposed to the 6 min that it would have required if the flow rate was really 500 lb/hr. In order to confirm that the problem was truly solved, the plant test on the flash drum was continued. That is, the operating directive for the level was set so that the residence time continued at 5 min. In addition, the flow rate to the ion exchange bed was increased to a measured value of 1000 lb/hr. It was anticipated that a measured flow of 1000 lb/hr would give an actual flow of 500 lb/hr. The flow was again measured using the 5-gallon bucket to confirm that a flow rate of about 500 lb/hr was achieved. After a few days at these conditions, the chloride concentration decreased to 500 ppm, the concentration experienced in the United States.

Step 5: Recommend remedial action to eliminate the problem without creating another problem.

The remedial action was relatively simple and consisted in only slight modifications to the changes made to conduct the plant test. These changes were designed to ensure that, at a future time, comparisons made between the two plants did not cause changes in operations which would recreate the startup problems. The changes were as follows:

- The level instrument on the first-stage flash drum was re-ranged from 75 in to 50 in. This would allow both flash drums in the United States and Europe to operate at the same apparent level (20%). This would also give the same absolute level of 10 in. If the level instrument had not been re-ranged, it would have been necessary to maintain the level in Europe at about 13%. There was a concern that this discrepancy between the conditions of the plants in the United States and Europe might lead the European affiliate to raise the flash drum level at some point to be consistent with the level in the United States.
- The discharge coefficient for the European venturi flow meter was changed to a value that was based on the actual viscosity, rather than an assumed value of unity.

A detailed potential problem analysis did not reveal any significant new problems if these changes were made.

Lessons Learned If the problem-solving concepts discussed earlier had been applied, the European technical staff might have elected to predict the chloride buildup rate based on data from the United States. If they had been using this potential problem analysis concept, they would have been able to spot the problem much sooner than a month after startup. As can be seen from

Figure 14-2, it was readily apparent after 2 to 3 days that the chloride level was increasing much faster than would have, based on experience in the United States. The advantage of comparing the actual to projected chloride buildup is that problem-solving activity could have started 3 weeks earlier than it actually had.

This problem illustrates the validity of calculations. There will always be a tendency to treat the first discovery as the root cause of the problem. Many industrial problems have more than a single root cause. For example, the discovery that the flash drum in Europe had more residence time than the comparable drum in the United States might have been considered to be the single root cause of the problem. If the problem solver had not concluded, based on calculations, that there must be another cause, the flash drum changes would have been made, but the problem of high chlorides would have continued. In the case described, it was especially desirable to ensure that the problem solutions were complete since the problem solver had only a limited amount of time in Europe.

In our advanced age of electronic equipment, we often forget the more basic measurement techniques. The use of a 5-gallon bucket to measure the low flow rate of a low toxicity and non volatile material is probably one of the best techniques available.

Any design change, regardless of how small (use of venturi meter and change in range of a level instrument), should receive a careful review, including a potential problem analysis.

EXAMPLE PROBLEM 14-2

An Embarrassing Moment

A high vacuum system was designed as part of a new process. The vacuum system was required to achieve an absolute pressure of 15 mm of Hg. In order to do this, a three-stage steam ejector was selected. A schematic of the vacuum system is shown in Figure 14-3.

The construction was relatively straightforward, except for obtaining a steam supply for the ejector. In order to furnish steam and avoid a shutdown of the 200 psig steam supply line, it was necessary to "hot tap" the steam line. Hot tapping is a procedure in which a valve with a flange is welded to the line. When the valve is fully secured and the welding is inspected, a cutting instrument is connected to the open end of the flanged valve. The valve is opened and the cutting instrument is lowered into the valve opening until it touches the pipe. A small pilot drill is first used to cut a small (1/4 to 3/8 in) hole. Following that, a full-size hole is cut. The tool used to cut the full-size hole is then used to pull the piece of the pipe that has been cut out back through the valve. The valve is closed as the tool is removed. The new steam piping to the

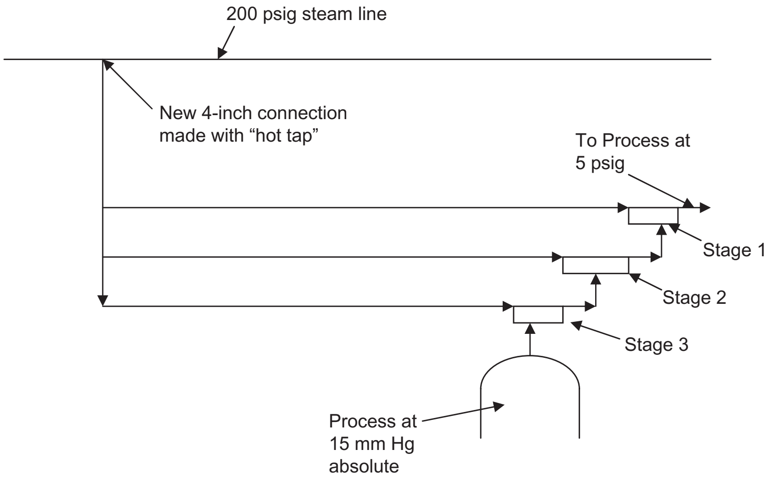

Figure 14-3 Schematic of three-stage steam ejector.

process is then connected to the valve. The valve is then opened at the appropriate point in the startup procedure. The hot tap crew will often save the section of pipe cut from the main line as proof that the hot tap really has been made.

The startup procedure for the three-stage ejector system called for starting the stages in the order shown on the schematic drawing. This allowed the lowest steam demand stages to be started first. The steam jet manufacturer's guaranteed steam consumptions were as follows:

Stage 1	300 lb/hr
Stage 2	500 lb/hr
Stage 3	1700 lb/hr

The startup procedure seemed to go well, as the first- and second-stage jets were placed into service. The steam pressure, as measured by a gage in the new 4-in steam line, remained relatively constant at about 200 psig, and the pressure in the vacuum drum decreased to the level anticipated with only two stages in service. However, when steam flow was started to the third stage, the measured steam pressure on the 4-in line decreased rapidly to 105 psig, and the pressure on the vacuum drum increased as the first- and second-stage jets were no longer able to perform at the reduced steam pressure. The initial reaction of the problem solver was that there was obviously something wrong with the third-stage jet. After all, the system performed perfectly when only two stages were used. He called the sales representative and strongly suggested that maybe an orifice had been left out of the third-stage jet. The problem solver believed that this would cause a huge increase in steam flow and result in a large pressure drop in the 4-in line. As time passed, the problem solver began a more methodical approach to analyzing the problem. He used the five-step approach, as follows.

Step 1: Verify that the problem actually occurred.

There was little doubt that the problem occurred. The drop in steam pressure and the loss of vacuum was also accompanied by loud noises inside the drum as material flowed backwards through the ejectors. However, to satisfy the need to verify the problem and get a maximum amount of data, the startup was repeated. The same results were observed. However, the increased attention to the steam pressure gage on the 4-in line indicated that the steam pressure actually dropped slightly when the first- and second-stage ejectors were placed into service.

Step 2: Write out an accurate statement of what problem you are trying to solve.

The problem solver developed a problem statement as follows:

> During startup of the steam jet system, the steam pressure on the 4-in steam supply line decreased rapidly to 105 psig when the third-stage ejector was placed into service. The operation of the three-stage steam jet is impossible at pressure conditions this low. Very small pressure drops were also observed as the first- and second-stage ejectors were placed into service. The same results occurred during both instances when the ejector system was being placed into service. The pressure on the 200 psig steam pressure header was normal during both trials. There are no steam meters available to measure the actual steam flow to the ejector system. Determine why the steam pressure on the 4-in steam supply line decreased rapidly to 105 psig when the third-stage ejector was placed into service. Recommendations for modifications to allow operating the steam ejector system are also to be provided.

The actual measured pressures from the second trial are shown in Table 14-3.

Step 3: Develop a theoretically sound working hypothesis that explains the problem.

The question list given in Chapter 6 was used as a guide to develop potential working hypotheses. A summary of this analysis is shown in Table 14-4.

Table 14-3 Steam pressure measurements

Ejectors in Service	Steam Pressure, psig
0	200
1	198.5
2	190.3
3	105

Table 14-4 Questions/comments for Problem 14-2

Question	Comment
Are all operating directives and procedures being followed?	The vendor provided startup procedure was being followed exactly.
Are all instruments correct?	The pressure gage that was initially used was replaced with a new gage before the second test.
Are laboratory results correct?	Not applicable in this case.
Were there any errors made in original design?	The 4-in steam line could be too small.
Were there changes in operating conditions?	No. The process was being operated exactly as specified on the duty specification for the steam ejector.
Is fluid leakage occurring?	Not applicable.
Has there been mechanical wear that would explain problem?	Not applicable.
Is the reaction rate as anticipated?	Not applicable.
Are there adverse reactions occurring?	Not applicable.
Were there errors made in the construction of the process?	Since the unit had only recently been built, this had to be considered.

The approach of using the guidelines provided by Chapter 6 may seem trivial for this example, but they helped to isolate the development of a hypothesis to two areas. The areas that the problem solver decided to investigate further were the sizing of the 4-in steam supply line and some sort of construction error. The hypothesis of a construction error would also include the possibility of an error in the manufacturing of the steam ejector. Three potential working hypotheses were proposed, as described below:

1. The process designer had made a mistake in the sizing of the 4-in steam supply line.
2. There was an error made in the construction of the third-stage steam jet.
3. The hot tap crew had made an error and did not completely cut and remove the 4-in piece of the line.

Initially, the hot tap crew was contacted to ascertain that that they did pull a piece of pipe from their cut to determine that the hot tap had indeed been completed. Unfortunately, this was many weeks after the cut had been made and the problem solver was told that all cuts made during that time frame had been discarded.

In order to narrow down the number of working hypotheses to a minimum, the following actions were taken and the indicated results obtained:

- The steam supply line was resized and it was concluded that the 4-in line was more than adequate. The pressure drop should be less than 2 psi even if the steam rates were double the rates guaranteed by the steam jet manufacturer.
- The third-stage jet was removed and inspected and its dimensions were compared to the factory issued drawings. The dimensions of the ejector were as specified in the drawings.

The only remaining hypothesis was that the hot tap had not been completely cut through and that all of the steam was flowing through the pilot drill hole or another restriction in the piping.

Step 4: Provide a mechanism to test the hypothesis.

While the hypothesis could have been tested by insisting that the hot tap crew return and redo their hot tap, the problem solver decided to test the hypothesis using calculations. He proceeded to consider the data shown in Table 14-5.

If the hot tap had not been cut completely, the pressure drop across the pilot drill hole should be proportional to the steam flow rate squared. This is a standard concept of chemical engineering as discussed in Chapter 5. Thus he decided to plot the pressure drop versus the flow rate squared. The resulting plot is shown in Figure 14-4.

The resulting plot had a slope of 0.0000152 and an intercept of zero. Thus it could be specified by the following relationship:

$$\Delta P = 0.0000152 \times F^2 \tag{14-3}$$

where

ΔP = pressure drop across the restriction, psi
F = steam rate, lb/hr

Table 14-5 Steam flow and pressure drops

Stages in Service	Steam Flow, lb/hr[a]	Pressure Drop, psi
1	300	2
2	800	10
3	2500	95

[a] The steam flows were taken from the steam jet manufacturer's specification sheet.

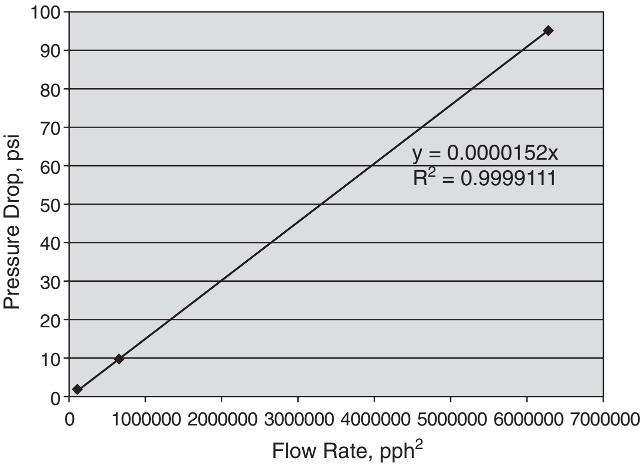

Figure 14-4 Pressure drop vs. flow rate squared.

The intercept of zero was as expected. That is, at no flow there should be no pressure drop. The slope of 0.0000152 was used to approximate the size of the opening that steam was flowing through. To do this, the problem solver used the following relationship for fluid flowing through a restriction. This equation was originally given as equation (5-26) in Chapter 5.

$$\Delta P = 0.5 \times S \times U^2/148.2 \tag{14-4}$$

where

S = density of the flowing fluid relative to water

U = velocity of the flowing fluid through the orifice, fps; the constants represent conversion factors and the orifice discharge coefficient

Since there was now an experimental relationship between the flow rate and the pressure drop, as well as a similar theoretical relationship, these two equations could be used to estimate the diameter of the restriction. To make this estimate, the right hand side (RHS) of equations (14-3) and (14-4) were set equal to each other since they were both equal to the pressure drop in the restriction.

$$0.0000152 \times R^2 = 0.5 \times S \times U^2/148.2 \tag{14-5}$$

knowing

$$U = R/(3600 \times A \times \rho) \tag{14-6}$$

$$S = \rho/62.4 \tag{14-7}$$

where

A = area of restriction, ft^2
ρ = fluid density, lb/ft^3

Solving these two relationships for the area of the restriction and then calculating the resulting diameter gave a value of 3/8 in. This was likely the diameter of the pilot drill used for the hot tap of the steam line.

It appeared likely that the hot tap had not been cut all the way through and that steam was only flowing through the opening that was cut for the pilot drill. When the hot tap crew was contacted, they agreed to return to recut the hot tap only after considerable discussion. When they did recut the hole, they were surprised to find that the piece of material that they removed was exactly as calculated by the problem solver. That is, it was a 4-in piece of metal with a 3/8-in hole in it.

Step 5: Recommend remedial action to eliminate the problem without creating another problem.

No additional actions appeared to be required after the hot tap was recut. The steam ejector system was started up successfully and the steam pressure on the 4-in supply header remained constant at 200 psig throughout the startup and operation.

Lessons Learned This problem illustrates how jumping to conclusions can often lead to embarrassing moments. Rather than immediately confronting the sales representative, the problem solver should have made a careful study of the available data. A careful study of the data would have revealed that the steam supply pressure did not stay constant even when the smaller first- and second-stage jets were placed into service. The problem also illustrates the value of doing calculations to attempt to pinpoint the problem source. After the designer had rechecked the sizing calculations for the 4-in steam line, the calculations described in Step 4 should have been done. If these additional calculations had been done, there would have been no reason to open and check the dimensions in the third-stage jet. The removal of this third-stage jet was a major effort since it was located three levels up in the structure and had large pipes connected to it.

The calculations described in Step 4 would have been sufficient to point out that the hot tap was likely done incorrectly, and thus would have eliminated the need to remove and inspect the third-stage jet. These calculations also provided a strong argument for redoing the hot tap, as opposed to providing simply a suspicion that it was not done correctly.

EXAMPLE PROBLEM 14-3

Prime Mover Problems Are Not Always What They Appear to Be

An ethylene refrigeration system was expanded by increasing the capacity of a blower. Prior to the expansion, this blower was used to boost the pressure on the system from 10 in of vacuum to 8 psig. The system was expanded by increasing the blower discharge pressure (also the compressor suction pressure) to 10 psig. The increase in pressure to 10 psig was to provide an increase in capacity of about 10%. No other changes were required in the ethylene compression or condensation system. The increased capacity of the blower was to be obtained by replacing the existing impeller with a larger impeller. This increase in impeller size would allow an increased flow rate and an increase in discharge pressure to 10 psig. A short shutdown was required in order to install the new impeller. A schematic drawing of the process is shown in Figure 14-5.

Ethylene liquid flows from the compression and condensation block to provide refrigeration for a low-temperature process operating at approximately –150°F. The ethylene liquid is vaporized at 10 in of mercury vacuum and flows as vapor to the ethylene blower. Prior to the blower, a series of economizers (heat exchangers) raise the temperature of the ethylene from about –156°F to –40°F. The blower boosts the pressure from 10 in vacuum to 10 psig. The ethylene gas at 10 psig flows to the reciprocating compression system where it is compressed to approximately 350 psig and condensed in heat exchangers that are cooled by vaporizing propane. The refrigeration load is not constant. The rate of vapors flowing to the ethylene blower and

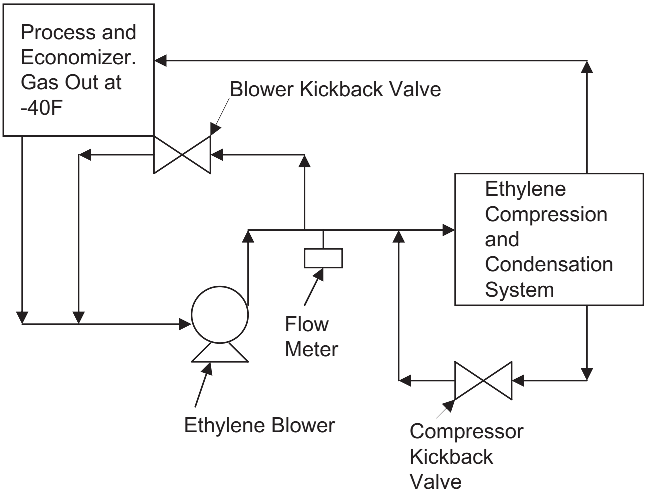

Figure 14-5 Ethylene refrigeration schematic.

compressors varies significantly. To maintain the suction pressure of the blower and compressor, constant "kickback valves" are provided. As the refrigeration load decreases, the kickback valves open, keeping the suction pressures constant.

The operation of the expanded blower was disappointing. While it appeared that additional ethylene flow had been obtained, the pressure was well below the required discharge pressure of 10 psig. Since ethylene flowed from the blower discharge to the compressor suction, this lower discharge pressure also resulted in a lower compressor suction pressure. The lower suction pressure caused both a reduction in compressor capacity and an increase in the compression ratio. Operations personnel requested problem-solving help because, in their words, "This new impeller is not as good as the one that we took out! We never had this kind of trouble before and that kickback valve was always open at least 10%." The problem solver used the five-step approach to assess the situation.

Step 1: Verify that the problem actually occurred.

Verification that there was a problem was relatively easy. When attempts were made to increase the unit production and, hence, the refrigeration load, above that possible before the new impeller was installed, the blower kickback valve would close all the way and the blower suction pressure would increase above the operating value of 10 in of vacuum. Since operating at 10 in of vacuum was necessary in order to maintain the process temperatures, the blower discharge pressure was reduced, causing the reciprocating compressors to have less than the desired capacity.

Step 2: Write out an accurate statement of what problem you are trying to solve.

Prior to attempting to write out an accurate problem statement, the problem solver decided to look at the blower manufacturer's supplied compressor curve for the new impeller. As part of the preparation for this assessment of comparing the theoretical blower curve to actual performance, he had all the key meters checked, so he knew that the blower suction pressure, discharge pressure, and flow rate variables were as accurate as possible. In order to assess the blower performance, it was necessary to maintain the kickback valve in the closed position during the test. This was because the flow meter was located outside the kickback valve line, as shown in Figure 14-5. The problem statement that he developed was as follows:

> The performance of the ethylene blower seems to be worse than anticipated with the new impeller. Rather than obtaining a 10–12% improvement in the plant capacity, operations since the startup of the revised facilities have resulted in a capacity only slightly above the previous capacity. While no test data exists for

performance with the old impeller, operations personnel believe that the performance was adequate when the old impeller was being utilized. They also indicate that the kickback valve was normally open at least 10%. Currently, the valve is closed whenever the system is fully loaded. The ethylene compressors are operating as predicted. The problem is not related to instrumentation, since all the meters have been checked. Determine the following:

- "Is the blower operating as specified by the manufacturer's supplied blower curve?
- "If it is not, determine why.
- "Recommend changes to correct the problem or operating conditions that will allow operation at full capacity."

As indicated in Chapter 3, time is always an important component of a problem statement. In this problem, while no data was available from past operations, the problem solver still noted that performance seemed adequate with the old impeller. In addition, he indicated that the problem seemed to have been present since the startup of the expanded facilities. This helps to focus on the time period after the facilities were expanded. In parallel with developing working hypotheses, the problem solver decided to run a series of plant tests to assess the actual blower performance. A summary of these plant tests is shown in Table 14-6. In addition, the results are shown graphically in Figure 14-6.

Also note in the problem specification that the problem solver takes into account the operator's observations that, prior to the expansion, the perfor-

Table 14-6 Blower capacity tests

Variable	Design	Test 1	Test 2
Molecular weight	28	28	28
Specific heat ratio	1.25	1.25	1.25
Gas compressibility	1	1	1
Polytropic efficiency, %	70	TBD	TBD
Suction pressure, Hg	10	7.5	8.7
Discharge pressure, psig	10	10	10
Gas density at suction, lb/ft^3	0.0609	0.0670	0.0633
Flow rate, lb/hr	35000	42590	36560
ACFM	9580	10590	9630
Temperatures			
Out economizer, °F	–40	–40	–40
Blower suction, °F	–40	–30.5	–29.3
Blower discharge, °F	87	81	91
Blower speed, RPM	10000	10000	10000
Calculated polytropic head, ft	24560	21525	23250
Projected polytropic head, ft		23200	24500
Performance deficiency, %		7.2	5.1

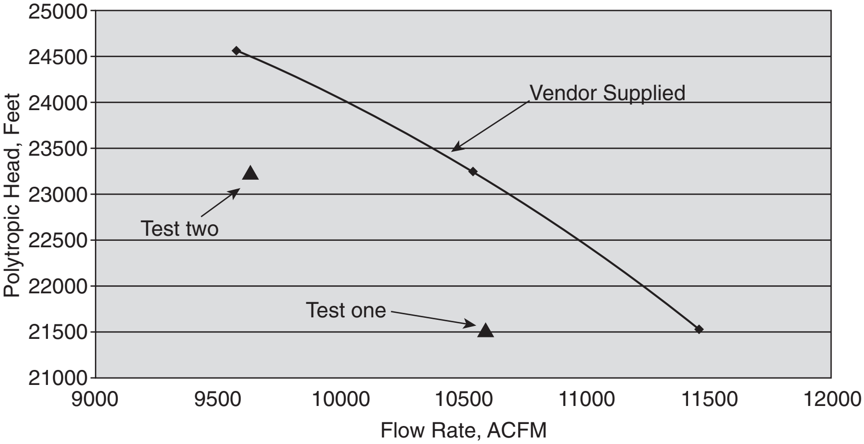

Figure 14-6 Blower capacity curve.

mance was adequate and that the kickback valve was open at least 10%, essentially all of the time. However, the problem statement did not include their conclusion that the blower was performing better with the old impeller.

The polytropic head is calculated using the following equation, given in Chapter 7:

$$H = 1545 \times T_S \times Z \times (R^{\sigma} - 1)/M\sigma \tag{7-6}$$

where

H = polytropic or adiabatic head, ft
T_S = suction temperature, °R
Z = average (suction and discharge) compressibility
R = compression ratio
M = gas molecular weight
σ = polytropic or adiabatic compression exponent

The projected polytropic head is taken from the blower manufacturer's supplied head curve shown in Figure 14-6. The performance deficiency is simply the deviation from the projected head curve, expressed as a percentage.

Figure 14-6 clearly indicates that the blower does not appear to be performing as predicted by the performance curve. However, this data does not by itself provide a working hypothesis. For example, if one simply presents a working hypothesis that says, "The blower is not performing as predicted by the blower manufacturer's supplied capacity curve," does this mean that the blower should be shutdown for maintenance, or is there another problem that

Table 14-7 Questions/comments for Problem 14-3

Question	Comment
Are all operating directives and procedures being followed?	Operating directives were being followed exactly.
Are all instruments correct?	All instruments were checked.
Are laboratory results correct?	Not applicable in this case.
Were there any errors made in original design?	There could be errors in the compressor impeller design calculations.
Were there changes in operating conditions?	Yes. The blower discharge pressure was increased as part of the revised design.
Is fluid leakage occurring?	Fluid leakage could be occurring through the kickback valve or through blower internals.
Has there been mechanical wear that would explain problem?	Blower wear rings are a potential problem.
Is the reaction rate as anticipated?	Not applicable.
Are there adverse reactions occurring?	Not applicable.
Were there errors made in the construction of the process?	Since the unit had only recently been expanded, this had to be considered.

is causing the blower to appear to be operating differently than predicted by the performance curve?

Step 3: Develop a theoretically sound working hypothesis that explains the problem.

The question list given in Chapter 6 was used as a guide to develop potential working hypotheses. A summary of this analysis is shown in Table 14-7. Using these questions from Chapter 6, several hypotheses were developed, as follows:

- There could have been errors in the design calculations for the new compressor impeller. These could consist of either errors in the data supplied to the manufacturer or errors made by the manufacturer.
- An impeller of the wrong size could have been installed.
- The increase in the blower discharge pressure could result in more leakage through wear rings.
- The increase in the blower discharge pressure could cause more leakage through the blower kickback valve.
- The poor insulation on the line between the economizer and the blower suction could cause the ethylene to warm up and thus cause a loss in capacity. As shown in Table 14-6, the gas temperature is increasing from –40°F to about –30°F.

All of these are possible hypotheses. The problem solver thought that with additional data and/or calculations that he could eliminate some of them. So he reviewed the original physical properties and design bases and confirmed that they were correct. He then reviewed the purchase order and blower manufacturer's specification for the new impeller and compared them to the bases for the upgraded blower. He found that these were consistent. Of course this does not eliminate the possibility that the wrong impeller was shipped from the supplier. He also compared the old blower curve to the new blower curve and found that they were consistent. That is, when extrapolating from the old blower curve to the new blower curve using the appropriate diameter scaling factors, the extrapolated blower curve was essentially the same as the one supplied by the blower manufacturer. Based on this work, he believed that he had done all that he could do except recommend a blower shut down to eliminate hypothesis 1. Before recommending that the blower be shut down to inspect the impeller to confirm that it was the correct diameter, he decided to consider the other hypotheses.

If there was internal leakage due to excessive clearance inside the blower, the internal gas recirculation would cause a decrease in the polytropic efficiency. This could be determined by the blower suction and discharge temperatures. The following equations from Chapter 7 were used to estimate the efficiency for the two tests. The results are shown in Table 14-8.

$$\sigma = (k-1)\times 100/(k\times E) \tag{7-7}$$

where

E = either adiabatic or polytropic compression efficiency, percent
k = ratio of specific heats, C_p/C_v

$$T_D = T_S \times R^{\sigma} \tag{7-8}$$

where

T_D = absolute discharge temperature
T_S = absolute suction temperature

Table 14-8 Calculated efficiencies for test runs

	Test one	Test two
Suction temperature, °R	429.5	430.8
Discharge temperature, °R	541.0	551.1
Compression ratio	2.24	2.37
Compression exponent	0.286	0.285
Polytropic efficiency, %	70	70.2

Based on the test runs, there does not appear to be any indication of internal leakage, since the calculated efficiencies from the suction and discharge temperatures appear to be essentially the same as the design. Thus hypothesis 3 was eliminated.

As indicated earlier, one hypothesis was that the poor insulation was allowing a 10°F increase in temperature between the economizer and the blower suction. This increased suction temperature would cause an increase in polytropic head. To determine if this was a theoretically sound working hypothesis, the problem solver calculated the blower head, assuming that the gas temperature stayed at –40°F. He obtained the results shown in Table 14-9.

If the gas temperature stayed at –40°F, the required head would have been reduced slightly. The reduced head would decrease the horsepower requirements. However, the system does not appear to be limited by power requirements. As indicated in Table 14-6, the steam turbine driving the compressor remained at the design speed of 10,000 RPM throughout the tests. Thus it appeared that the probability that this hypothesis was correct was very low.

The elimination of these hypotheses left only the alternative hypothesis that there was excessive leakage across the kickback valve. If leakage was occurring through this valve when it was in the closed position, that would explain both the increase in temperature between the economizer and the blower suction, as well as the poor performance of the blower relative to the manufacturer's supplied curve. Rather than immediately recommending a shutdown to inspect the valve, the problem solver reviewed the specifications for the 14 in kickback valve. When he reviewed the specifications, he found that the valve was not specified as a tight shutoff valve. In addition, a review of the drawings indicated that the butterfly valve had a peripheral clearance of 0.05 in. That is, there was a clearance of 0.05 in between the flap of the butterfly valve and the wall of the valve. He then estimated the leakage that could occur across the valve when it was completely closed. The flow rate through this small opening will be at sonic velocity (sonic velocity was described in Chapter 5). The calculations required to estimate the leakage through the valve are as follows:

$$\begin{aligned} A &= \pi \times (D_1^2 - D_2^2)/4 = \pi \times (14^2 - 13.9^2) = 2.19\ \text{in}^2 \\ &= 0.0152\ \text{ft}^2 \end{aligned} \tag{14-8}$$

$$P = 0.55 \times (14.7 + 10) = 13.58\text{psia} \tag{14-9}$$

Table 14-9 Calculation results

	Test one	Test two
Gas rate, ACFM	10590	9630
Polytropic head at suction temperature, ft	21525	23250
Calculated polytropic head at –40°F	21050	22700

$$VS = (P \times g \times k/\rho))^{0.5}(13.58 \times 144 \times 32.2 \times 1.25/0.065)^{0.5}$$
$$= 1100 \text{ ft/sec} \tag{14-10}$$

$$F = \rho \times VS \times A = 0.065 \times 0.0152 \times 1100 \times 3600$$
$$= 3910 \text{ lb/hr} \tag{14-11}$$

$$ES = F/(60 \times \rho) = 3910/(60 \times 0.065) = 1000 \text{ ft}^3\text{/min} \tag{14-12}$$

where

A = peripheral area with a clearance of 0.05 in
D_1 = approximate diameter of valve, in
D_2 = approximate diameter of the butterfly wafer, in
P = pressure at restriction, psia
VS = sonic flow velocity, fps
g = gravity factor, fps^2
k = specific heat ratio
ρ = gas density, lb/ft^3
F = flow rate through peripheral area, lb/hr
ES = approximate volumetric flow, ft^3 /min

A brief review of the sonic flow conditions modeled by equations (14-9) to (14-11) may be appropriate. Essentially all chemical engineering text books discuss this phenomenon in more detail than is possible in this book. Chapter 5 includes a brief discussion of this phenomenon. The velocity across the peripheral opening will be at sonic flow velocity. This is because the pressure after the valve is only about 40% of the pressure before the valve. For a gas with a specific heat ratio (k) of 1.25, sonic flow properties occur if the pressure after a restriction is less than 55% of the pressure before the restriction. If sonic flow conditions are encountered, the maximum flow rate (sonic velocity) that will occur across any size opening with any amount of pressure drop is that which occurs when the outlet pressure is 55% of the inlet pressure. Thus the actual flow rate across the peripheral opening is evaluated at 55% of the absolute inlet pressure (equation 14-9) and at the sonic velocity and density at these conditions (equations 14-10 and 14-11).

As shown above, the estimated leakage through the butterfly valve could account for a capacity loss of approximately 1000 ft^3/min. Referring to Figure 14-6, this difference in suction flow rate could explain the deficiency in performance of the blower.

Step 5: Recommend remedial action to eliminate the problem without creating another problem.

The problem solver was faced with no other reasonable recommendation to make except to shutdown the system and replace the kickback valve with one that had a tight shutoff rating. The potential problems that had to be considered were:

- Was the replacement valve really a tight shutoff valve? Would it be possible to find a 14-in valve that would fit into the space available and not have a peripheral opening similar to that of the existing valve?
- Would the new valve fit without a need for significant piping modifications? Could it be installed with a minimal amount of effort?
- Was there anything else that should be considered prior to a recommended shutdown? For example, should the efficiency of the steam turbine be determined to ensure that it is performing as designed?

Lessons Learned This example problem indicates the value of doing a thorough problem analysis rather than just jumping to the conclusion that the blower is not performing as it was designed. If a complete analysis had not been done, the blower might have been shut down for an inspection or additional insulation might have been added to the blower suction lines in hope that this would improve the performance. Either of these solutions which, on the surface, seemed to make sense, would have delayed finding the leakage in the kickback valve. If the blower had been shut down for an inspection and/or replacement of wear rings without knowledge that the kickback valve was leaking, another shutdown would have been required to replace the kickback valve. The analysis conducted here illustrates the value of doing calculations to prove or disprove hypotheses.

As indicated in Chapter 3, a component of successful plant problem solving is a daily monitoring system that allows for the early detection of problems. This early detection will provide an earlier initiation of problem-solving activities than would occur if the problem were allowed to continue to develop. If such a system had been in place in this example, a plot of “head curve deviation” as defined in Table 14-6 would have likely provided an early signal that there was a performance deficiency. An even better approach to the evaluation of a critical piece of revised equipment is to conduct a performance test as soon after startup as possible.

The problem with the leaking kickback valve could have been detected even earlier than the startup of the expanded facilities. If a plant test had been run prior to the shutdown to expand the plant or if the blower performance had been monitored on a daily basis, the problem with the valve could have been detected prior to the expansion. This would have eliminated the downtime required to replace the valve after the facilities startup.

A conservative approach of inspecting the blower during the recommended shutdown to replace the kickback valve could have been taken. However, this would have required major mechanical work and extended the time of the shutdown. Since the calculated polytropic efficiency was very close to the design value of 70%, it is highly unlikely that this would have been a value-added exercise.

EXAMPLE PROBLEM 14-4

The Value of a Potential Problem Analysis

While the utilization of a potential problem analysis was not emphasized in the previous problems, it would have been of great value in this example problem.

A new fractionation process was designed to minimize cost by eliminating a reboiler, minimizing instrumentation, and maximizing heat integration. The fractionation tower products were a high-purity overhead and a high-purity bottoms stream.

A simplified sketch of the process is shown in Figure 14-7. In the figure, the feed to the tower is fractioned into a high-purity overhead methanol product and a high-purity xylene bottoms product. The heat integration is such that the heat input to the tower consists of a controlled vapor flow of xylene from a furnace. This vapor is the same material as the high purity bottoms product, so that no reboiler is required. That is, the vapors from the furnace are fed directly to the tower to provide heat input. The tower reflux is controlled to maintain a tower temperature profile. In addition to the controlled vapor flow to the bottom of the tower, the vapor output from the furnace is also used to heat the tower feed in exchangers. The xylene vapors condensed in the exchangers then flow to the accumulator as shown in Figure 14-7. The design of the exchangers was such that at full capacity and at the design heat transfer coefficient of the exchanger, the outlet material from the exchanger would be condensed xylene at the boiling point and pressure of the accumulator. That

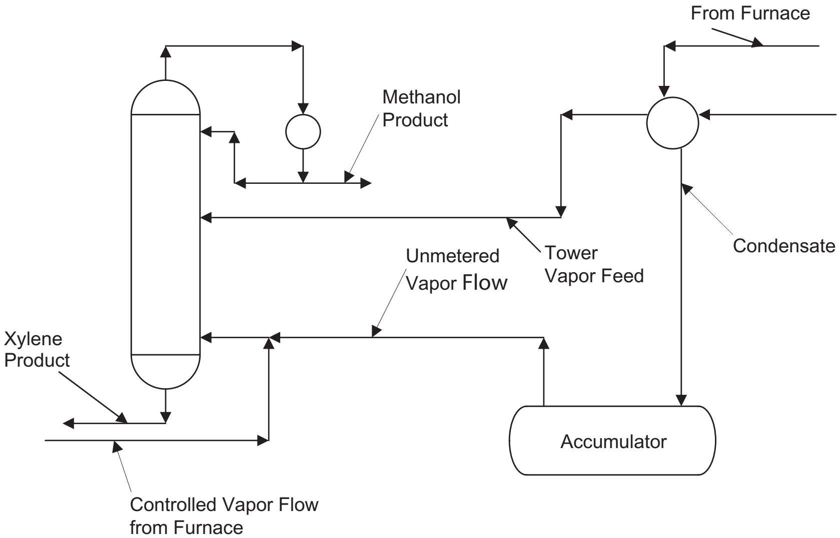

Figure 14-7 Simplified sketch of fractionation system.

is, there would be no significant vapor flow from the accumulator to the tower. The fact that there was no meter on this flow back to the tower did not seem like a significant problem, since there would normally be no flow in the line. However, the designer recognized that there might be times when the conditions were such that the material leaving the exchanger would not be totally condensed and might contain vapor flowing into the accumulator, so he provided a vent line to allow uncondensed vapors from the accumulator to flow to the tower. The designer believed that in cases in which the vapor did vent out of the accumulator in an uncontrolled fashion, the control system would "take care of things" by adding more reflux to the tower.

As often happens, processes that are designed for steady state are rarely operated at steady state. The heat content of the material flowing into the accumulator was constantly changing. At times, there would be two phases (vapor and liquid) entering the drum. In this case, vapor would vent out of the drum into the tower. At other times, the xylene being condensed in the exchanger would be cooled to the point at which the material entering the accumulator would be below the boiling point at accumulator pressure. If this occurred, vapor would flow back out of the tower. The predominant situation was the unsteady state cycling of no vapor being vented back to the tower, transitioning to one where there were two phases in the flow to the accumulator. In this case, where there were two phases present in the flow to the accumulator, vapor would flow uncontrollably to the tower, creating an increase in the heat flow to the tower. The control system would respond after the temperature profile was disturbed and cause more reflux to be added to the tower. During this transient condition, the purity of the overhead product stream would be less than desired, since the increased vapor rate would cause more low-volatility material to be carried overhead until the control system responded and increased the reflux rate. If the reflux rate had to be increased too much to compensate for the vapor venting out of the accumulator, it was possible that the tower would flood. As this situation transitioned to one in which there was no vapor vent from the accumulator, the temperature profile in the tower would again be upset since there was now excessive reflux going to the tower. Again the control system would correct the reflux rate, but only after the bottoms product was off specification.

When the converse situation occurred, the vapor flowed back out of the tower due to the low pressure in the accumulator. In this case, the temperature profile would again be disturbed and the control system would again respond after the disturbance occurred. In this case, it was generally the bottoms stream that would be below specification during the transient.

The problem solver used the five-step procedure discussed earlier to begin solving the problem.

Step 1: Verify that the problem actually occurred.

The initial description of the problem was only that something was causing an upset in the tower and the operations people believed that it was somehow associated with the accumulator. They often tried to compensate for these upsets by trying to adjust the controlled vapor rate. However, this was largely guess work and often made things worse. The problem solver verified that upsets in the tower were being caused by changes (increases or decreases) in the fraction of vapor in the condensate flowing to the accumulator.

Step 2: Write out an accurate statement of what problem you are trying to solve.

The problem solver wrote out the following problem description:

> Fractionation tower upsets are being caused by changes in an unmetered flow going to the bottom of the tower. These changes in the unmetered flow cause an increase or decrease in heat input to the bottom of the tower, the temperature profile in the tower to be upset, and the purity of the distillate and bottom products to be off specification. Determine how to eliminate the fractionation tower upsets caused by changes in the unmetered flow going to the bottom of the tower.

Step 3: Develop a theoretically sound working hypothesis that explains the problem.

In this example, a start of the working hypothesis that explains the problem was included as part of the problem statement. However, it was not obvious how to solve the problem until the hypothesis was more fully developed. The questions given in Chapter 6 were used to fully develop a working hypothesis for obtaining a solution to the problem, as shown in Table 14-10.

Table 14-10 Questions/comments for Problem 14-4

Question	Comment
Are all operating directives and procedures being followed?	All operating directives and procedures were being followed. New ones were considered, but would not solve the problem.
Are all instruments correct?	Yes.
Are laboratory results correct?	Not applicable in this case.
Were there any errors made in original design?	The assumption of steady state was not valid.
Were there changes in operating conditions?	No.
Is fluid leakage occurring?	Not applicable.
Has there been mechanical wear that would explain problem?	No.
Is the reaction rate as anticipated?	Not applicable.
Are there adverse reactions occurring?	Not applicable.
Were there errors made in the construction of the process?	Since the unit had only recently been built, this had to be considered.

The only two reasonable hypotheses were that the assumption of steady state operations was not valid and the possibility that a construction error had been made. No specific hypothesis was developed that would tie construction errors to the symptoms being observed. While it was possible that an error in the tray design, fabrication, or installation might be possible for fractionation upsets at the extreme conditions of high rates of uncontrolled vapors to the tower, it seemed unlikely that these tray errors would not show up at other times. Exploring the construction error hypothesis would likely require elaborate test equipment and/or a tower shutdown. It was decided to first consider the possibility that the original assumption of steady state operation was the primary cause of the problem. It was clear that if the temperature of the condensate returning to the drum was not at the boiling point at the pressure in the drum, there would be an unmetered flow either to or from the tower. Developing the simplest solution for the problem, as pointed out in Chapter 3, is always the best approach.

Thus the problem solver developed the following hypothesis:

> It is believed that the problems associated with the control of the tower are due to the fact that the heat content of the stream leaving the exchangers is not constant. At times, there are large amounts of vapor in this stream which then vent to the tower as an uncontrolled heat input. At other times, the stream leaving the exchangers is subcooled, which causes vapors to flow from the tower to the accumulator. Tower control will be greatly improved if the vent or back flow from the accumulator can be measured.

Step 4: Provide a mechanism to test the hypothesis.

As what was thought to be a permanent solution to the problem, a venturi meter was installed in the vapor line. The venturi meter was selected because it would have a low pressure drop and because it had the inherent capability to measure flow in both directions. If the enthalpy of the flow to the accumulator was such that some flashing occurred in the accumulator, the venturi would measure flow from the accumulator into the tower and the controlled vapor rate from the furnace would be reduced to compensate for this vapor flow from the accumulator. Thus the vapor rate in the tower would remain constant. Conversely, if the enthalpy of the flow into the accumulator was such that the liquid in the accumulator was subcooled, creating back flow from the tower, the controlled vapor rate would be increased to compensate for this back flow. It was believed that the installation of the venturi meter would maintain the vapor flow in the tower constant and thus avoid tower upsets. The control algorithm for the system is described as shown below:

$$F = V - Y + ZF \tag{14-13}$$

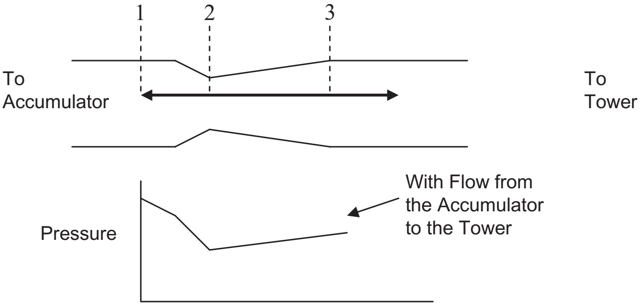

Figure 14-8 Venturi sketch.

where

V = tower internal vapor rate, which should be held constant
F = controlled vapor rate from the furnace
Y = flow rate from the accumulator to the tower
ZF = flow rate from the tower to the accumulator

A simplified sketch of the venturi meter design is shown in Figure 14-8. A typical venturi pressure profile is also shown for the case where there is flow from the accumulator to the tower. It was recognized that the accuracy of the flow from the accumulator to the tower (measured by the pressure drop from points 1 to 2) would be more accurate than the backflow from the tower to the accumulator (measured by the pressure drop from points 3 to 2).

Unfortunately, no potential problem analysis (as suggested in Chapter 3) for this problem solution was done. The fact that there is pressure recovery with any type of meter was not considered. This pressure recovery is represented in the sketch as the pressure increase from point 2 to point 3, when flow is from the accumulator to the tower. Since the pressure at point 3 is greater than the pressure at point 2, the control system would assume that this was backflow from the tower. The control system would then have values for both *Y* and *ZF*. Of course, when flow was from the accumulator to the tower, the actual value of *ZF* was zero. However, the pressure recovery made the control system think that *ZF* had a nonzero value. A potential problem analysis that included a detailed understanding of the venturi meter would have discovered this problem and allowed an engineering solution well before startup of the revised facilities.

Step 5: Recommend remedial action to eliminate the problem without creating another problem.

After the initial startup difficulties discussed above, a selector switch was installed to allow the control scheme to select the greater value of *Y* or *ZF* and set the other variable to zero. The system performed flawlessly after that minor modification.

Lessons Learned There are several lessons that can be learned from this problem. While process design involves the assumption of steady state, consideration should always be given to the question of "How does unsteady state impact the design?" If the process designer had considered unsteady state, it is likely that he would have provided flow measuring devices as part of the original design. The problem solver can also use the question of "How does unsteady state impact things?" as a problem-solving tool by questioning the validity of the steady state assumption.

There is great value in both understanding the equipment involved in a problem solution and in performing a potential problem analysis prior to making a recommendation. In the example given here, the fact that pressure recovery would impact the results was blatantly obvious to anyone with a minimal knowledge of flow instruments. However, in the rush to get the facilities designed and installed, it was overlooked. The discipline to conduct a potential problem analysis would have pinpointed this problem before the venturi meter was installed. Potential problem analyses are often not done except if they are required as part of a disciplined procedure.

NOMENCLATURE

A	Area. In this chapter it is used to represent the area of a restriction or a peripheral area with a clearance of 0.05 in. The value is in ft^2.
C	A constant referred to as the "lumped parameter constant"
D_1	Approximate diameter of valve, in
D_2	Approximate diameter of the butterfly wafer, in
DF	Driving force or incentive for reaction to occur, mols of chlorine derivative gas absorbed/ft^3 of TEG
E	Either the adiabatic or polytropic compression efficiency, %
ES	Approximate volumetric flow, ft^3/min
F	Flow rate. In this chapter, it is used to represent the ion exchange bed feed rate, flow rate through a peripheral area, the flow of steam through the restriction, or the controlled vapor rate from the furnace, all in lb/hr.
g	Gravity factor, fps^2
H	Polytropic or adiabatic head, ft
k	Ratio of specific heats, C_p/C_v
M	Gas molecular weight
P	Pressure at restriction, psia
R	Compression ratio
R^*	Rate of change with time per unit volume of the compound under study, mol of HCl/ft^3-min that are formed

RC	Rate of chloride production in the United States, lb/hr
S	Density of the flowing fluid, relative to water
T_{D}	Absolute discharge temperature
T_{S}	The suction temperature, °R
U	Velocity of the flowing fluid through the orifice, fps
V	Tower internal vapor rate which should be held constant
VS	Sonic flow velocity, fps
X_{F}	Concentration of chlorides in the flow to the ion exchange bed, weight fraction
Y	Flow rate from the accumulator to the tower
Z	Average (suction and discharge) compressibility
ZF	Flow rate from the tower to the accumulator
ΔP	Pressure drop across the restriction, psi
ρ	Fluid density, lb/ft^3
Σ	Polytropic or adiabatic compression exponent