4

EXAMPLES OF PLANT PROBLEM SOLVING

4.1 INDUSTRIAL EXAMPLES

In an industrial environment where the strongest emphasis is usually placed on increased productivity, doubts about the validity of this technique will always be present. Typical questions are:

- Does this technique really work?
- On what kind of problems can it be used?
- Is it really possible in an industrial environment to use engineering calculations as opposed to intuitive problem solving?

In an attempt to answer these questions, the following examples are presented. These are all actual examples from the polymer industry. Polymer manufacturing problems are often the most difficult to solve and the author's primary experience is in this area. Two of the examples were solved successfully. The first example requires only process engineering skills and the problem solution emphasizes the need for a daily monitoring system. The second example requires minimal knowledge of statistics and mechanical engineering as well as process engineering skills. The process engineering skills required to solve these problems are covered in Chapter 5. It is likely that a process operator would require assistance when using the statistics discussed in the second example. The third example is presented to illustrate the problem of inadequate intuitive problem solving. It illustrates how a logical explanation

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

developed by an experienced engineer can be wrong due to of the engineer's not following a disciplined problem-solving approach.

4.2 POLYMERIZATION REACTOR EXAMPLE

At 0200 hours on April 2, one of the six continuous polymerization reactors in a process plant experienced a temperature runaway. That is, the reactor temperature rose exponentially from a normal temperature of 150°F to 175°F in a 30-min period. Polymerization is an exothermic reaction that generates a significant amount of heat for each pound of polymer produced. The heat of reaction is removed by circulating cooling water. Polymerization reaction rates generally double with every 20°F increase in temperature. Doubling of the polymerization rate causes the heat generated to also double. When the reactor in question reached 175°F, the reaction was terminated by injection of a quench agent. All the other reactors were operating normally.

The temperature control system on the reactor was such that an increase in temperature caused an immediate increase in the cooling water supply flow. It was known that a small increase in catalyst rate occurred right before the temperature began increasing. However, in the past, catalyst rate increases of this magnitude only resulted in a slight temperature increase. Past experience was that following this slight increase, the reactor temperature very quickly returned to normal as the cooling water control system responded. The heat exchanger that is used to remove the heat of polymerization is periodically removed for cleaning. On April 1, the exchanger seemed to be in order.

A simplified sketch of the equipment and various data is shown in Figure 4-1. At this point, the problem solver is faced with at least three questions:

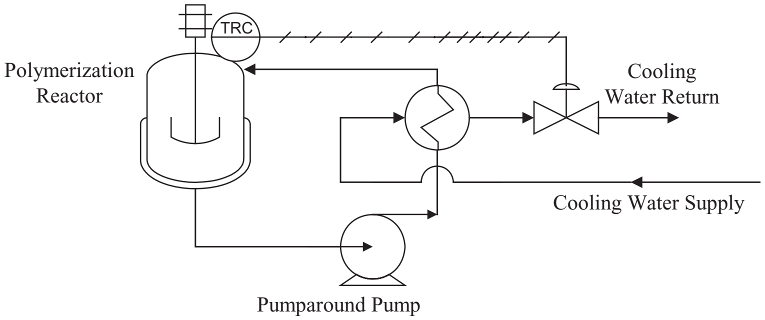
1. What should be done to return the reactor to working condition?
2. What caused the episode?
3. What can be done to prevent it from recurring in the future?

The first of these questions can be handled by a combination of good operating practices (clean out the reactor) and intuitive problem solving (the exchanger should be cleaned). However, the last two can best be approached through application of the problem-solving techniques discussed in the previous chapters.

4.3 APPLICATION OF THE DISCIPLINED PROBLEM-SOLVING APPROACH

Step 1: Verify that the problem actually occurred.

While on first glance there may not seem to be a need to perform this step, the problem solver made a cursory review of all variables to confirm that the



Data Values at Midnight

Temperatures

Cooling Water

In	90
Out	120

Pumparound Liquid

In	150
Out	142

Flow Rates, pph

Cooling Water: 195000
Reactor Slurry Pumparound: 2,000,000
The valve on the cooling water is 95 % open.

Technology Information

Reaction Heat Generated = K e ^(-11000/T)

Where K is a constant that containing monomer concentration, catalyst concentration, reactor volume and heat of reaction.

K = 3.9(10^14),
T is in Rankin

The specific heat of the reaction fluid = 0.5 BTU/lb-F.

Figure 4-1 Reactor schematic.

reaction really was terminated due to a "temperature runaway." He found that all temperature instruments indicated an increase in temperature. In addition, the pressure on the reactor also increased.

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

In this example, the problem that must be solved is twofold—what caused the episode? In addition, what can be done to prevent it from recurring in the future? The problem solver developed the following problem statement.

> Temperature control was lost in the polymerization operation on April 2. This loss of control occurred at about 0200, following a very small increase in the reactor temperature caused by a slight increase in catalyst flow. This loss of control occurred on only one of six reactors, all of which are operating at the same charge rate on the same feedstock. The reactor had to be removed from service and cleaned prior to restarting polymerization. There was no mechanical

Table 4-1 Hypotheses conclusions

Hypothesis	Why It Can Be Eliminated
Recirculation pump stopped	"No mechanical failure"
Pumparound exchanger plugged	"No mechanical failure"
Cooling water supply lost	"No utility failure"
Catalyst activated by feedstock	"Only occurred on one reactor"
Heat generated > heat removal capability	Not eliminated

or utility failure on the reactor in question. The weather turned slightly warmer on March 30. Once the reactor temperature began increasing it rose exponentially from 150°F to 175°F in an extended period (30 min).

Determine what caused this loss of control, and once the cause has been determined, develop recommendations to prevent this problem from recurring.

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

Several possible hypotheses can be proposed and the problem statement could eliminate all but one, as shown in Table 4-1. Thus a theoretically sound working hypothesis developed by the problem solver was: "The temperature runaway was caused by the fact that the rate at which heat generation increased with temperature was greater than the rate at which heat removal increased with temperature."

In order to use calculation procedures, this working hypothesis must be expressed mathematically. This can be done using differential calculus[1] as shown in equation (4-1).

$$dQ_g / dT > dQ_r / dT \tag{4-1}$$

where

dQ_g/dT = rate at which heat generation increases with temperature
dQ_r/dT = rate at which heat removal increases with temperature

This working hypothesis would predict a loss of temperature control since, as the temperature increased, the heat generation increased faster than the heat removal capability. In addition, since the rate of reaction increased with temperature, this hypothesis also predicts an exponential increase in temperature.

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[1] While differential calculus may not be a familiar subject to a process operator, it can be easily visualized when considering driving an automobile. Acceleration is simply the rate of increasing speed as a function of time. It is called the differential of speed relative to time and is abbreviated as dV/dT, where V is velocity and T is time.

Step 4: Provide a mechanism to test the hypothesis.

While testing a hypothesis often involves experimental work, using fundamentally correct engineering calculations can also test hypotheses. In this case, experimental work would involve the risk of another loss of reactor temperature control. Thus, the problem solver used engineering calculations as the best approach to testing the hypothesis. These calculations are shown below:

Hypothesis

$$dQ_{\mathrm{g}}/dT > dQ_{\mathrm{r}}/dT \tag{4-1}$$

Engineering calculations

$$Q_{\mathrm{g}} = K \times e^{(-11{,}000/T)} \tag{4-2}$$

where

K = a constant that depends on monomer and catalyst concentrations, reactor volume, and heat of polymerization. A typical value for this specific process and operating conditions is $3.9(10^{14})$

T = absolute temperature, °R

e = engineering constant that is equal to 2.718

A chemical engineer will recognize equation (4-2) as a typical Arrhenius equation for polymerization. The constant of 11,000 incorporates the gas constant, R. An evaluation of this equation at two different temperature levels will confirm the earlier mentioned "rule of thumb" that the rate of reaction or rate of heat generated doubles for every 20°F increase in temperature.

Equation (4-2) can be differentiated with respect to the absolute temperature, T, to yield the rate at which heat generated increases with respect to temperature as shown in equation (4-3).

$$dQ_{\mathrm{g}}/dT = (K \times 11{,}000/T^2) \times e^{(-11{,}000/T)} \tag{4-3}$$

This differentiation is performed using concepts that a process operator may not know, but that a chemical engineer would be familiar with. If differential calculus is not used, the numerical value for dQ_{g}/dT can be approximated using equation (4-2) to calculate Q_{g} at the temperature of interest (150°F) and at another temperature slightly higher. The value of dQ_{g}/dT is simply the difference between the two values of Q_{g}, divided by the difference in the temperature.

The rate at which heat is removed from the reactor can be represented by a typical heat removal equation shown in equation (4-4). Heat balance concepts are explained in more detail in Chapter 5.

$$Q_r = U \times A \times \ln\Delta T \tag{4-4}$$

where

U = exchanger heat transfer coefficient

A = exchanger surface area

$\ln\Delta T$ = log temperature difference between the polymerization slurry side and the cooling water side

As noted in Figure 4-1, the cooling water flow is almost at a maximum (valve is 95% open), so the average water temperature will not decrease. Therefore as a first approximation:

$$\ln\Delta T = (T - T_w) \tag{4-5}$$

$$Q_r = U \times A \times (T - T_w) \tag{4-6}$$

where

$(T - T_w)$ = difference between the average reactor temperature and the average cooling water temperature

In the initial few minutes, the average cooling water temperature will remain constant. Thus differentiation of equation (4-6) gives equation (4-7). This is based on the concepts of differential calculus which state that the differential of a constant (T_w) is equal to zero.

$$dQ_r = U \times A \times dT \quad \text{or} \quad dQ_r / dT = U \times A \tag{4-7}$$

As pointed out earlier, the same numerical results can be developed by simply using two different reactor temperatures and a constant cooling water temperature. These temperatures can be used to calculate Q_r at the different temperatures and dQ_r/dT determined by dividing the difference in the Q_r values by the difference in temperatures.

By substituting actual values into equation (4-3), equations (4-8) and (4-9) can be developed.

$$dQ_g / dT = 3.9(10^{14}) \times (11{,}000/(610)^2) \times (e^{(-11{,}000/610)}) \tag{4-8}$$

$$dQ_g / dT = 170{,}000 \text{ BTU/hr-°R} = 170{,}000 \text{ BTU/hr-°F} \qquad \text{(4-9)}^1$$

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[1] The equality between °R and °F is valid for this expression since the temperature difference is what is being considered rather than an absolute temperature.

$U \times A$ can be estimated from the midnight values shown in Figure 4-1 using equation (4-10).

$$U \times A = Q_r / \ln \Delta T \tag{4-10}$$

where

$Q_r = 5.75(10^6)$ BTU/hr
$\ln\Delta T = 40$

therefore

$$dQ_r / dT = U \times A = 144{,}000 \text{ BTU/hr-°F} \tag{4-11}$$

As indicated earlier, the hypothesis was that "The temperature runaway was caused by the fact that the rate at which heat generation increased with temperature was greater than the rate at which heat removal increased with temperature," or, mathematically, $dQ_g/dT > dQ_r/dT$. Since the calculated value of dQ_g/dT (170,000 BTU/hr-°F) exceeds the calculated value of dQ_r/dT (144,000 BTU/hr-°F), the hypothesis was proved with calculations.

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

The required remedial action developed by the problem solver consisted of providing operating procedures to ensure that the rate of heat removal always increases faster than the rate of heat generated. Mathematically this can be expressed as follows:

$$dQ_r / dT > dQ_g / dT \tag{4-1}$$

To be conservative, a 10 to 20% safety factor should be included. Thus:

$$dQ_r / dT > 1.1 \times dQ_g / dT \tag{4-12}$$

From equation (4-9), $dQ_g/dT = 170{,}000$ BTU/hr-°F. Thus:

$$dQ_r / dT > 187{,}000 \text{ BTU/hr-°F} \tag{4-13}$$

$$\text{or } UA > 187{,}000 \text{ BTU/hr-°F} \tag{4-14}$$

Therefore, to prevent future occurrences, he specified that the exchanger should be removed from service whenever the "*UA*" drops below 187,000 BTU/hr-°F.

Since UA could be easily calculated (see equation (4-10)), it became one of the key variables that was plotted and monitored on a daily basis. This could be done using the plant process control computer or by hand plotting.

Some may question the need to actually calculate a *UA* value since the narrative indicates that the cooling water was close to a maximum flow rate. While this fact should have been a red flag warning to both operations and technical personnel, there is value in being as precise as possible.

It should also be noted that the calculated value of dQ_g/dT depends on both reaction rate and reaction temperature. If the reaction rate increases (larger value of K) or the reactor temperature decreases (larger slope in the rate vs. temperature relationship), the value of dQ_g/dT will increase. This will cause the minimum value of *UA* to increase.

A potential problem analysis might reveal that the main potential problem was the degree of conservativeness used to evaluate the heat removal capacity required. A study of the variability of the rate of reaction would reveal whether 10 to 20% above the dQ_g/dT factor was sufficient. The proposed solution is certainly a simple solution. However, follow-up will be difficult because it involves requiring that operations remove a "perfectly good" exchanger from service for cleaning to avoid future episodes of temperature runaways.

4.4 LESSONS LEARNED

The value of being as quantitative as possible is actually twofold. The daily monitoring of a numerical value allows engineers to plan an exchanger downtime for cleaning as opposed to an unplanned cleaning, which will almost always occur at an inopportune time. If the heat transfer capability were followed on a daily basis in a numerical fashion, the exchanger could be removed from service for cleaning during periods of line downtimes for other mechanical reasons, or during downtimes associated with a reduction in sales volumes. In addition, the subjective observation that the cooling water flow was close to a maximum may depend on climatic conditions. These can change rapidly. Therefore, what appeared to be a situation where the exchanger had plenty of capacity changed quickly as the ambient temperature changed. If the value of the heat transfer coefficient or a comparable value had been calculated, there would be minimal affect of climatic conditions.

In situations like this, the problem solver who is under time pressures will often participate in doing whatever is necessary to get the equipment back into service. The question of what should be done to prevent the same or a similar problem from happening in the future is not considered. In this particular case, as the problem solver investigated the problem in detail, he uncovered a new area and a new technique that would prevent future temperature runaways.

While the approach that the problem solver used solved the problem and developed a system to prevent future problems, it would have been better to have a more methodical approach to developing a theoretically correct working hypothesis (step 3). The approach to developing this working hypothesis can be enhanced by a list of questions that will stimulate theoretically correct, creative thinking. This list of questions will be given in Chapter 6.

4.5 MULTIPLE ENGINEERING DISCIPLINES EXAMPLE

This example illustrates the value of a disciplined problem-solving approach when dealing with people or organizations who appear to have fixed positions based on sound logic, but inadequate data. In addition, it also illustrates the advantages of making simple changes to test hypotheses.

A process plant using a rotary filter (shown in Fig. 4-2) was plagued by excessive downtimes caused by tears of the screen cloth. A slurry of solids and liquid enters the filter at the bottom of the case. The internal drum rotates through the slurry and differential pressure forces liquid through the fine mesh screen cloth covering the rotating metal drum into the drum internal. From there the liquid and gas are removed to the filtrate handling section. The solids caught on the screen cloth are held in place by sweep gas which flows through the screen cloth into the filtrate handling section. The solids are blown off the screen by "blowback gas" as the rotating drum has gone about 270° of the total rotation. The screen cloth momentarily blows away from the rotating drum as the gas passes through the cloth. The screen cloth is held in place against the metal drum by tension rods. These retainers, while holding the cloth in place, create stress on the cloth during the blowback step. The solids that are blown off the screen are segregated from the initial slurry by a longitudinal baffle and are conveyed to the next processing step by a scroll conveyer.

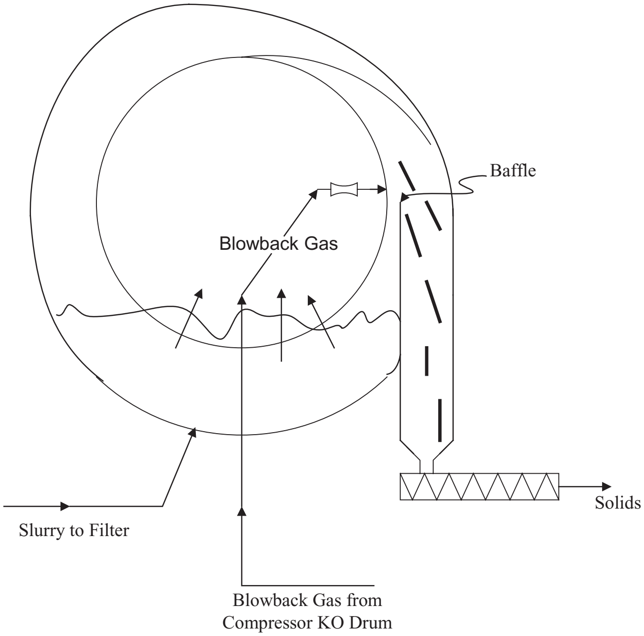

Figure 4-2 Rotary filter schematic.

The excessive screen cloth-related downtimes occurred on only one out of three rotary filters. These filters were thought to be operating under essentially the same conditions as judged by operations and technical personnel. Whenever the screen cloth would tear, solids would enter the filtrate stream, causing a shutdown of critical equipment and a resulting shutdown of the plant. After each screen cloth tear, the screen cloth and rotating metal filter drum were carefully examined. The examinations showed that the metal drum would be scratched. There was no apparent reason for the scratches, that is, there was no residual that could have caused the scratches. Solids would be present between the cloth and the drum. This was not surprising since the cloth was torn and it was known that solids had passed into the filtrate. The cloth would be torn in a circumferential manner, with most of the tears and drum scratches occurring in the middle 60 to 70% of the rotating drum.

Even after this careful observation of the filter, no consensus conclusions were reached concerning the failure. In fact, several heated arguments developed, with several fixed positions being taken. The mechanical engineers believed that the hard solid polymer particles were cutting the cloth. They believed that these polymer particles were so small, they leaked through the cloth and around the cloth-retaining facilities. The process engineer believed that some hard, metallic part of the filter was rubbing against the cloth and the metal drum. This would cause the cutting and failure of the screen cloth, letting large amounts of solids into the filtrate to scratch the metal drum. He thought that the baffle which isolated the solids from the filtrate might be the part of the filter that was rubbing against the cloth and drum. However, he had no explanation for how this might happen, since there was acceptable clearance between the baffle and rotating drum.

Since there were people in the research organization who were experienced in this process, they were also called for assistance. They believed that there was liquid in the blowback gas and that this liquid was cutting the cloth. This would allow solids to enter the filtrate and also to scratch the rotating metal drum.

Faced with such a diversity of opinions and minimal data, the problem solver approached the problem using the five-step approach discussed earlier. He made a decision to obtain as much data as possible from all sources.

4.6 APPLICATION OF DISCIPLINED PROBLEM-SOLVING APPROACH

Step 1: Verify that the problem actually occurred.

In this example, there was no doubt that the problem actually occurred. However, there was question as to whether the problem was worse than it had been in previous years. That is, problem verification consisted of considering if there had there been a change in the frequency of screen cloth tears.

Table 4-2 Mechanical history

Time Period	Mean Time between Failures (days)	Type of Tear
Past data	43	Horizontal along the tension rods that held cloth in place
Current data (all runs)	16	Circumferential
Current data excluding the very short runs	25	Circumferential

A review of mechanical records indicated the following, as shown in Table 4-2.

Obviously, a problem existed. It should be noted that without detailed mechanical records (daily monitoring), quantifying the extent of the problem would have been impossible.

A further review of what changed between the past and current data revealed that the filtration temperature on this filter was increased from 130°F to 170°F. This higher temperature was not originally considered to be a problem, as the mean times between failures on the first few runs at the higher temperature were essentially the same as they had been prior to the increase in temperature. There was a significant advantage to operating at the higher filtration temperature, so returning to the previous process conditions was not a satisfactory solution to the problem.

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

The following problem statement was written by the problem solver: “There has been a significant increase in the screen tearing frequency that occurred on only one of three filters. This increase appeared to occur at the same time the filtration temperature was raised. In addition, to a reduction in mean time between screen failures (increased frequency), the nature of the screen failure changed. Previous failures were fatigue failures caused by the cloth being weakened during flexing while being held in place by the tension rods. The current failure is a catastrophic circumferential failure. The current failure is also characterized by scratch marks on the metal drum. Determine the cause for the significant change in screen-tearing frequency. In addition, recommendations should be made for what changes are necessary to eliminate this problem.”

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

Since the new failure mode appears to be related to the increase in filtration temperature, the following three hypotheses were developed.

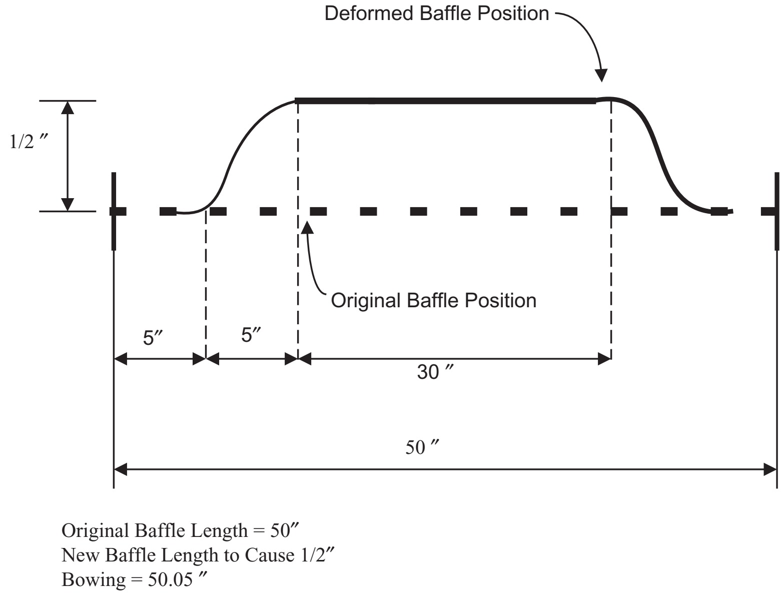

Figure 4-3 Hypothetical baffle deformation, top view.

1. The screen cloth is decomposing at the higher temperatures.
2. The baffle (see Fig. 4-2) is expanding due to thermal growth and bowing into the filter cloth and metal drum.
3. The rotating drum is deforming at the higher temperatures, causing poor distribution of blowback gas. The poor distribution causes an increase in blowback gas in the middle of the drum, which then blows the filter cloth into the baffle, causing the cloth to tear.

Of these hypotheses, only the single hypothesis of baffle expansion could account for both the screen cloth tears and the scratches on the metal drum. The baffle position required to cause the observed failures is shown in Figure 4-3.

Step 4: Provide a mechanism to test the hypothesis.

This hypothesis was tested by calculations of thermal growth of the baffle. These calculations assume that the drum case will remain at the ambient temperature. The baffle, since it is immersed in the slurry, will approach the slurry temperature and experience thermal growth. The magnitude of this thermal growth will depend on the difference between ambient and filtration temperature as well as the coefficient of linear expansion. The coefficient of linear expansion for the specific metal can be found in any reference source (either handbooks or on the Internet).The growth calculations are shown below:

Given:

Original baffle length = 50 in
Original distance between baffle and rotary drum = 0.5 in
Coefficient of linear expansion = 0.000011 in/in-°F

A typical relationship relating length to temperature is as follows:

$$l_t - l_o = l_o \times 0.000011 \times dt \tag{4-15}$$

where

l_t = the baffle length at the new temperature
l_o = the original baffle length
dt = the change in temperature, °F

Considering the baffle shape shown in Figure 4-3, the baffle would only have to grow 0.05 in to cause it to bow into the rotating drum. Thus the new baffle length would be 50.05 in. The increase in temperature that would cause this amount of growth was calculated using equation (4-15) as shown below in equation (4-16).

$$dt = 0.05/(50 \times 0.000011) = 90°\text{F} \tag{4-16}$$

As these calculations indicated, the baffle would be expected to grow sufficiently to expand into the metal drum and screen if the differences between the filtration temperature and ambient temperature exceeded 90°F. Thus, an increase in filtration temperature from 130°F to 170°F significantly increased the probability of the baffle bowing into the drum. The fact that the baffle could also bow away from the drum without any particular consequences explained why failures did not always occur when the temperature difference approached 90°F.

Two alternatives were available to further test this hypothesis. The filtration temperature could be reduced to the level at which it had been during previous operations. A second possibility was that a mechanical constraint could be provided to cause the baffle to always bow away from the drum.

Since hot filtration was desirable for the process, reducing the filtration temperature would only be permissible for testing. In addition, the testing period would have to provide a high degree of confidence that the problem was caused by the higher filtration temperature, while taking place over a minimum amount of time.

An analysis was made to determine the minimum amount of time required to give a 90% confidence level that returning to the lower filtration

Table 4-3 Statistical data

Period	Mean Time between Failures (days)	Runs
Before hot filtration	43 ± 26	31
After hot filtration	16 ± 10	26

temperature could eliminate the problem. The basic statistical data developed for this analysis is shown in Table 4-3. In addition, the statistical approach used by the problem solver to determine how to proceed with step 4 is defined in the following paragraphs. While it is recognized that the process operator or specialist will not normally have sufficient knowledge to proceed with this statistical calculation, the calculation is shown here to illustrate the value of using statistics to determine the requirements for determining whether a process change really improved operations.

If the filtration temperature is returned to the lower value, the mean time between failures will increase to the previous value (43 ± 26). We will assume that the values of the mean and standard deviation will be the same as they were before hot filtration. The experimental test of returning to the lower filtration temperature needs to be accomplished in the minimum amount of time (i.e., with the minimum number of experimental runs). The high values of the standard deviation (26 and 10) means that more than a single test run will be required. Thus, the minimum number of runs required to prove that there has been a significant statistical improvement from hot filtration at the 90% confidence level needs to be determined. The minimum number of runs can be determined using a statistical comparison of the means of hot filtration and the results after the process is returned to the lower temperature filtration. When statistics are used to compare two values of means, a two-sided test is involved. This comparison of means will produce a numeric value such as $A \pm B$, where A is the difference in the means and B depends on the standard deviations and the actual number of runs to be used in the statistical test. To conclude that there is a real difference between hot filtration and cold filtration in the experiment, both possible values of the term $A \pm B$ must be positive. For both possible values of the algebraic manipulation to be positive, B must be less than A. Since the value of B decreases as the number of experimental runs increases, the minimum number of experimental runs will be the number that produces a positive value for both sides of the statistical test. An iterative procedure is required to develop the final answer. The final iteration is shown below:

Assumed number of runs at reduced temperature = 5

$$\text{SE} = (s_1^2/n_1 + s_2^2/n_2)^{1/2} = (100/26 + 676/5)^{1/2} = 11.79 \qquad (4\text{-}17)$$

$$1/\varphi = (1/\varphi_1)\times(s_1^2/n_1/(s_1^2/n_1 + s_2^2/n_2))^2 + (1/\varphi_2)\times(s_2^2/n_2/(s_1^2/n_1 + s_2^2/n_2))^2 \quad (4\text{-}18)$$

$$1/\varphi = (1/26)\times(3.85/139)^2 + (1/5)\times(135.2/139)^2 \approx 5 \quad (4\text{-}19)$$

where

SE = standard error for comparing the two means
s = standard deviation of the two samples
n = the number of runs in each sample
φ = the degrees of freedom in each sample (number of runs)

From statistical tables for t distribution (two-sided at 90% confidence level)

$$\mu = 2.01$$

$$\therefore \text{Difference in mean time between failures} = 43 - 16 \pm 2.01\times 11.79 = 3 \text{ to } 50 \text{ days} \quad (4\text{-}20)$$

When only four runs at the lower temperature are assumed, the calculated difference in mean time between failures is –1 to 55. Therefore, four runs are not sufficient to provide conclusively significant data. However, when assuming that five runs are conducted at the lower temperature, both sides of the statistical test (3 and 50) are positive. This represents the minimum number of runs that are required. At this point, the problem solver could say with 90% confidence that returning to the lower temperature filtration would lower the frequency of screen tears. However, it would be difficult to accurately define the anticipated advantage for returning to the lower temperature due to the large standard deviation. More experimental runs would be required to narrow the range of anticipated benefits.

An estimated period of time for these five runs would be 5 × 43 or 215 days. Therefore, after 215 days at the lower temperature filtration (90% confidence level), the problem solver could say that returning to the previous temperature conditions will return the average screen cloth life to 43 days. However, this does not conclusively prove or disprove the working hypothesis. It only proves or disproves the effect of filtration temperature on the average screen cloth life. There might be another potential hypothesis that explains the problem. In addition, the test does not yield any acceptable problem solution, since it was desirable to operate at hot filtration.

The other alternative testing procedure (adding a mechanical constraint to ensure that the baffle always bows away from the drum) was easy to perform and provided a good mechanism to test the “baffle bowing” hypothesis while allowing continued operation at higher filtration temperatures. However, it involved political risks, since the addition of the mechanical constraint had “never been done this way before.”

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

Selecting the remedial action in this example was a strong function of how the hypothesis was tested. If the process conditions were modified to allow the system to return to the lower temperature filtration for 215 days, there would be a tendency to recommend staying at the lower temperature operation as a problem solution. Note that since this was undesirable in terms of process considerations, it would not be an acceptable recommendation.

The alternative technique of mechanically constraining the baffle so that it always bows away from the drum would provide both a testing procedure and a permanent solution. Thus, after 215 days, steps 4 and 5 could both be considered to be complete. This was the alternative that the problem solver recommended for the test and for the permanent solution. The potential problem analysis focused on how to make sure that sufficient tension would be applied to the mechanical constraint to ensure that the baffle bows away from the filter.

4.7 LESSONS LEARNED

As indicated in the problem description, the initial assumption was that all of the filters were operating at essentially the same conditions. Assumptions of this kind are almost always present in any problem-solving activity. It is only when one dedicates sufficient time to analyze data that it will be found that the initial statement of "essentially at the same conditions," or, "no process changes were made," is found to be incorrect.

Often, minor mechanical changes (such as adding a baffle brace) will provide simple solutions to complex problems. However, in this case, the potential problem analysis of the proposed remedial action missed the possibility that the mechanical constraint might fall off the baffle due to corrosion, vibration, or metal fatigue. If this happened, the device would likely go with the polymer. This did happen, causing failure of downstream equipment and some contamination of the polymer with metal. If this problem had been uncovered in a potential problem analysis, preventative action could have been taken, consisting of using a backup nut on the constraining device and/or insuring that the bolt and clamp were made out of corrosion-resistant materials. This illustrates the importance of potential problem analyses. Often, the problem solver is so intent on moving into the execution phase of a problem solution that he does not give adequate consideration to potential problem analysis. This phase deserves as much attention as does developing a problem solution.

Besides the engineering advantage of using the disciplined problem-solving approach in this example, there is also a psychological advantage. Once a person takes a fixed position on any subject, it is almost impossible to change his or her mind without sound data. Often, it takes more sound data to change a person's opinion than it would have taken to form the person's opinion if the data had been obtained prior to the development of a working hypothesis. Any of the initial positions described by the different engineering disciplines within this example could be partially supported with logic. However, it was only after the problem solver uncovered as much data as possible and developed a hypothesis based on this data that a theoretically correct working hypothesis emerged. Normally, the application of the proposed approach will significantly narrow the hypotheses down to one or two, which can then be tested in step 4 of the five-step procedure.

4.8 A LOGICAL, INTUITIVE APPROACH FAILS

A customer complaint was received at the manufacturing location of a highly regarded supplier of a baled elastomer (12 in × 28 in × 7 in). The customer alleged that he had received some green bales of the product in a recent shipment. The bales were normally a yellow color. The process for manufacturing the elastomer was about 10 years old and a similar problem had never been encountered. When confronted with this complaint, the Operating Department Head used problem-solving techniques and developed the following problem statement:

> The customer complaint has been investigated. We have not made any significant changes in our operation in 10 years except for the use of "magic markers." Our operators have started carrying "magic markers" to mark equipment that requires maintenance at the next downtime. We believe that one of these markers must have fallen from one of their pockets into the extruder. The subsequent fracture and dispersion of the material caused several bales to have a green appearance.

This intuitive, logical approach overlooked several details that a more structured procedure would have uncovered. There was no verification that the problem really occurred. It would have been valuable for the customer to send a sample of the material that he received. The problem definition was incomplete. Consideration of other questions, such as the following, would have been helpful in forming a better problem statement.

- On what shift did the problem occur?
- Did other customers notice the problem?
- How many bales were green?
- Did the problem occur on all lines?
- Did laboratory-retained samples on the problem date, previous dates, or subsequent dates show a green color?
- Were there really no operational changes?
- Were the bales green when they were boxed?

In addition to problem definition failures, the hypothesis was not tested against any type of theory. For example, how much of a green magic marker would be required to turn a single yellow bale to a green color? There was no way to estimate the concentration of green magic marker in the bale since there was no knowledge of the number of green bales. No mechanism was provided to test the hypothesis; though the hypothesis could have easily been tested by dropping a green magic marker into the extruder. This would only provide a one-sided test. If the bales did not turn green, the test would be successful in that it would prove that the hypothesis was incorrect. However, if the bales did turn green, it would be necessary to consider the hypothesis in more detail. For example, the following questions should be considered:

- How many bales turned green from a single magic marker?
- Did this number correspond to the number of green bales that the customer observed?

After the manufacturing manager wrote the customer a letter of apology for a magic marker falling into the extruder, several other complaints on the same subject were received from different customers. The continued customer complaints led to the formation of a multidiscipline problem-solving team that determined, after a lengthy investigation, that the green color was associated with an obscure change in the makeup water used for the polymer-water slurry system.

4.9 LESSONS LEARNED

This example illustrates how a failure to adequately develop a problem statement can lead to an embarrassing and faulty problem solution. If the problem statement had been fully developed, using some of the questions shown above, it is likely that the problem would have been recognized as systemic rather than as an individual isolated accident. The failure to adequately define the problem then led to the point at which only a simplified, logical approach to problem solving was used. If the problem had been recognized as a systemic problem initially, the problem-solving team would have been formed at a much earlier point in time.

This example also illustrates how what appears to be an operation to which plant operators have not made any changes can be impacted by subtle and obscure changes in utilities. The assumption that "water is water" was not true in this case.

NOMENCLATURE

A	Exchanger surface area
dQ_g/dt	Rate that heat generation increases with temperature

dQ_r/dT	Rate that heat removal increases with temperature
dt	Change in temperature, °F
K	A constant that depends on monomer and catalyst concentrations, reactor volume, and heat of polymerization
$\ln\Delta T$	Log temperature difference between the polymerization slurry side and the cooling water side
l_o	Original baffle length
l_t	Baffle length at the new temperature
n	Number of runs in each sample
s	Standard deviation of the two samples
SE	Standard error for comparing the two means
T	Absolute temperature, °R
$(T - T_w)$	Difference between the average reactor temperature and the average cooling water temperature
U	Exchanger heat transfer coefficient
φ	Degrees of freedom in each sample (number of runs)