Reactions and Separations

Take a Hands-On Approach to Refinery Troubleshooting

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The solution to a process problem isn't found by sitting behind your desk, but by going into the plant and carrying out tests and evaluating data.

Troubleshooting is not an exact science. It begins with sound process and equipment knowledge, attention to detail, and good listening skills. From there, however, there is no blueprint or flowchart to success. Every problem is different, although specific techniques are applicable to several different types of situations. Experience can play a vital role, but only if used correctly. Do not assume that a specific problem exhibits the same set of symptoms every time, or that ones with a similar set of symptoms have the same root cause.

The one universal truth of troubleshooting is that it cannot be done successfully from behind a desk. Even when the solution is arrived at by calculation, the information needed to manipulate the numbers is obtained through field work. Personal communication with operators, direct observation of field and control-system data, and even watching operators pull samples can provide vital information for solving a problem.

This article illustrates the troubleshooting thought process and demonstrates a variety of tools, using two refinery case studies. These problems are distil-

lation related, but manifested themselves differently and required different troubleshooting approaches. In both cases, the refiners were losing a substantial amount of money because of each problem.

Troubleshooting guidelines

There is no recipe for troubleshooting. However, some general guidelines (box) are helpful to keep in mind when facing a new problem. These guidelines are useful for even experienced troubleshooters.

Troubleshooting begins with solid engineering fundamentals. Material and energy balances are as valuable as high-tech gamma scans. Finding the actual problem requires a sound understanding of the process and the specific unit in question. This includes the relevant theoretical background, and details of the process flowrates, instrumentation and control schemes, and the equipment and piping, as well as data from sampling and lab analyses. Know where temperature and pressure indicators and sample points are located. This seemingly small detail can provide tremendous insight when analyzing the data they provide.

Effective troubleshooting requires understanding the symptoms that are being presented by the system. For example, flooding is not a symptom. High-pressure drop, liquid carryover, poor fractionation, etc., are symptoms of flooding. But, they can also be symptoms of other things.

Sometimes, there may not even be a problem. Many operators and even engineers misinterpret an increase in pressure drop as the onset of flooding, even though the tower is, in fact, lightly loaded and the pressure drop is just a natural reflection of an increase in internal reflux rates. This is only one example of problems that can be misdiagnosed because of a poor understanding of the symptoms.

One of the most effective ways to prepare for troubleshooting is to know how a unit operates when it is working properly. This isn't just creating the charts that highlight the operating parameters that are deemed critical. This means watching temperature profiles in

distillation columns, preheat trains and reactors. Know what the pressure drop is and what it should be. Talk to the operators about the unit. Go on rounds with them and watch what they do. Watch them pull samples. Know what the samples look like. This way, when something changes, you know what it is and have a headstart on solving the problem.

Walk the plant

There is no substitute for spending time in the field learning about a process unit. Know where the key pieces of equipment are located. Follow the piping for major streams. Sometimes, things that do not seem out of the ordinary on paper will stand out in the field.

Use a systems-oriented approach to troubleshooting, rather than a unit-operations focus. This approach begins with the problem symptoms (*e.g.*, high-pressure drop in a column) and evaluates potential causes to determine the root cause. If the focus is too narrow, then there is a risk of a fix that masks the symptom and ignores the problem. This doesn't mean that every refinery problem can simply be traced back to a change in the crude slate. It does mean that good troubleshooters understand the potential for other refinery processes to cause or contribute to problems in any given unit.

Practice good listening skills. Not only does this allow for efficient information collection, but it also helps you to establish credibility. Never immediately challenge a diagnosis provided by another individual. Understand the observations that were made that led to the diagnosis. He or she might be right and even if not so, the observations may prove valuable.

Never underestimate the importance of the information you can get from operators. They are generally very good at describing the symptoms. Often, their knowledge goes unused because their analysis of the symptom is inaccurate and, therefore, is discarded. Learn how to ask the right questions to get to the description of the symptoms.

Occasionally, troubleshooting just happens and a solution pops up. The right piece of information clicks and the root cause is apparent. Most of the time, it is not that simple. There is either no readily apparent cause or many to choose from. When this happens, it necessary to troubleshoot by the process of elimination. Develop a hypothesis of a possible cause based on the available data. Then design an experiment to eliminate or confirm that hypothesis. Conduct the experiment and evaluate the results. If the experiment disproves the hypothesis, then eliminate it and move on.

Don't get hung up on a preferred theory. If the data show that a hypothesis is not correct, come up with a new one. This may be difficult because of one's emotional ties to the idea. However, chasing a theory after the data reject it wastes valuable time.

Troubleshooting Guidelines

1. Apply solid engineering fundamentals.
2. Separate observations from hypotheses or conjectures.
3. Independently verify data using field measurements and observations, when possible.

4. Make rigorous comparisons with satisfactory operations.
5. Spend time in the unit making direct observations — even if you are not sure what to expect.
6. Consider the entire system related to the problem.

7. Practice good listening skills.
8. Do not reject serendipitous results.
9. Do not fall in love with a hypothesis — seek to reject, as well as to accept.

Table. Common symptoms and their potential causes.	
Symptoms	**Root Causes**
Instrument readings that do not make sense or do not agree with other observations	• Transmitter range specified incorrectly, *e.g.*, 0–100% of level does not correspond to distance between taps or to height of drum. • Range not set to specification, so full-scale flow (or measured variable) is not what it is thought to be. • Measured variable is over 100% of range, but it is not obvious on distributed-control-system (DCS) screen because it reads in engineering units. • Reported range does not include correction for static conditions in impulse lines or in vessels (*e.g.*, when measuring the pressure differential in a high-vapor-density column). • Two-phase flow through flowmeter or control valve. • Incorrectly installed or specified instruments.
Equipment suddenly begins to underperform	• Hand-operated valves in wrong position, *e.g.*, bypass opened partially or fully around heat exchanger or control valve. • Exchanger or other equipment fouled.
Inadequate flow	• Unexpected two-phase flow, creating excess pressure drop. • Fouling in piping or equipment. • Incorrect valve or valve trim installed. • Pump cavitation or other pump-related problems. • Plugged strainer.
Temperature-control problems	• Missing or damaged insulation. • Poor controller tuning. • Heat exchangers adequately sized for steady-state conditions, but not for transient state. • Unexpected heat of reaction or heat of solution effects. • Heating medium outside of expected range (*e.g.*, low steam-header pressure). • Uncertain physical property information leads to misdesign of equipment or misinterpretation of results.
Premature column flooding	• Internal damage or fouling, resulting in hydraulic restriction or loss of mass-transfer efficiency. • Off-design feed composition or thermal condition. • Unexpected entrainment, *e.g.*, at a feed point or internal transition. • Foaming problem leading to inaccurate level measurement and unexpected entrainment. • Inadequately designed chimney trays, short of vapor capacity or liquid capacity. • Unstable control system. • Level-control difficulties — maintaining high level in column sump, chimney tray or kettle reboiler. • Incorrect flow measurements of feed, product, heat medium or reflux that might conceal true operating rate. • Presence of a second liquid phase in column.
Low heater efficiency	• High combustion-air flow. • Air leaks into firebox. • High stack temperature. • Heat leaks in system (especially in the case of small systems)
Product contamination	• Leaking valves, *e.g.*, in startup or bypass lines. • Heels left in storage tanks, or dead legs in piping. • Corrosion products present. • Unexpected chemical reactions. • Deficiencies in chemical analysis, especially when mixing dissimilar streams. • Unexpected solubility effects, *e.g.*, a stored product absorbing the gas used to pad or blanket the tank.

Experimental design

It is often necessary to conduct test runs or experiments to effectively troubleshoot a process unit. If these experiments are not appropriately designed or are conducted haphazardly, they usually will not help in solving the problem. In fact, a poor experiment may actually provide misleading data, leading to inappropriate solutions. Here are guidelines for the design of effective test runs.

A successful test run begins with fundamental knowledge about the unit in question. This includes a unit material balance, process flowsheet, and equipment details. The importance of the material balance cannot be overstated. If the material balance is inaccurate, it is impossible to draw conclusions regarding equipment performance. Similarly, the process flowsheet and equipment design must be understood before a test run can be set up properly.

Once the basics have been covered, review the reported symptoms with operations personnel. Clarify what has been observed and what is conjecture. Compare the observed behavior with what is expected,

based on the design and current material balance. Collect process data from periods when the symptoms were observed and when the unit was operating normally. Compare the data for any obvious differences.

It may be helpful at this point to construct a process simulation for the unit. Generally, this is the case for large or highly complex processes. The simulation should be limited to obtaining the information necessary to study the problem. Otherwise, it may become unwieldy and confusing. Remember, the purpose of the simulation is to simplify the process so that changes can be studied in isolation.

Review the process to determine the candidate causes for what was observed. This is where experience and sound engineering fundamentals come into play. The table lists some common problems and their potential root causes, based upon these two factors. However, no article or book can enumerate all possible process problems and their causes.

Since this step requires independent judgment based on experience or first-principles analysis, brainstorming can be helpful in generating ideas. However, it is also possible to involve too many people, resulting in a list of probable causes that is impractical to pursue. Multiple possibilities should be considered and ranked based on their likelihood of occurrence and ease of elimination.

The next step is the actual design of the experiment. Determine which process variables might cause the reported symptoms and which of these can be manipulated. Design the test run to hold constant as many variables as possible. Although this simplifies the analysis of the results, it does not address the situation when the problem is caused by the interaction between two variables. The process must be examined carefully to determine where these interactions may exist, and then design the experiment appropriately. When large numbers of variables must be included, consider using a statistical experimental design method. These methods enable examination of large numbers of variables with relatively few experiments.

When designing an experiment, know what to expect from the proposed process changes. If necessary, use process simulations to predict the response. Also, remember it is often easier to disprove a hypothesis than to prove it.

Close supervision is essential when conducting the experiment to ensure that its design is followed. Deviations must be evaluated and the experiment repeated, if necessary. Verify critical data using field measurements, when possible.

Data analysis is an important part of troubleshooting. Examine the data to ensure that they are consistent and that no unexpected interactions have occurred. If data are inconsistent or inconclusive, then repeat the experiment.

Maintain objectivity during the analysis. It is easy to twist the data to support a theory for which there is an emotional tie. Even the most experienced troubleshooters must maintain a constant vigil against this pitfall. Now, we will present two examples to illustrate how we have used this method.

Increased FCCU fuel gas production

The fluid catalytic cracking unit (FCCU) in a North American refinery experienced a gradual increase in the production of fuel gas, a low-value byproduct of the catalytic reaction that converts high-molecular-weight gas oils into motor fuels. This unit processes a mixture of virgin and coker gas oils, which are hydrotreated to remove sulfur and other impurities, and to saturate the aromatics.

The initial investigation found that the nickel and vanadium concentrations on the FCCU catalyst had increased in correspondence with the increased production of fuel gas. These metals act as a dehydrogenation catalyst in the FCCU reactor, resulting in the increase in fuel gas production. The increase in metals on the catalyst could be due to:

1. Reduced FCCU catalyst addition rate
2. Reduced metals removal in the upstream hydrotreater
3. Increased concentration of the metals in the hydrotreater feed.

The FCCU catalyst addition rate is a key operating parameter and is monitored frequently. The catalyst addition logs were reviewed and compared with catalyst receipts. This comparison did not indicate a reduced addition rate. Further, other catalyst parameters, such as surface area, indicated that the addition rate had been constant over the period in question. Thus, reduced catalyst addition was ruled out as a cause.

The FCCU feed was periodically monitored for both nickel and vanadium. Neither had increased above the 0.5 ppm detection limit of the test method over the time that the concentration increased on the FCCU catalyst. A metals balance on the FCCU quickly demonstrated, however, that the amount of nickel and vanadium required to reach the existing concentration on the catalyst were below the detection limit of the test method. It was not possible to completely rule out a reduction in hydrotreater demetallization performance as the root cause. However, no other hydrotreater performance measure (sulfur and nitrogen removal, Conradson carbon-residue-reduction or hydrogen addition) showed signs of significant degradation. Therefore, hydrotreater performance was ruled out for the time being as the root cause.

The crude unit heavy vacuum gas-oil (HVGO) product was periodically monitored for both nickel and vanadium. It showed an increase in both, but these were not consistently high over the period in

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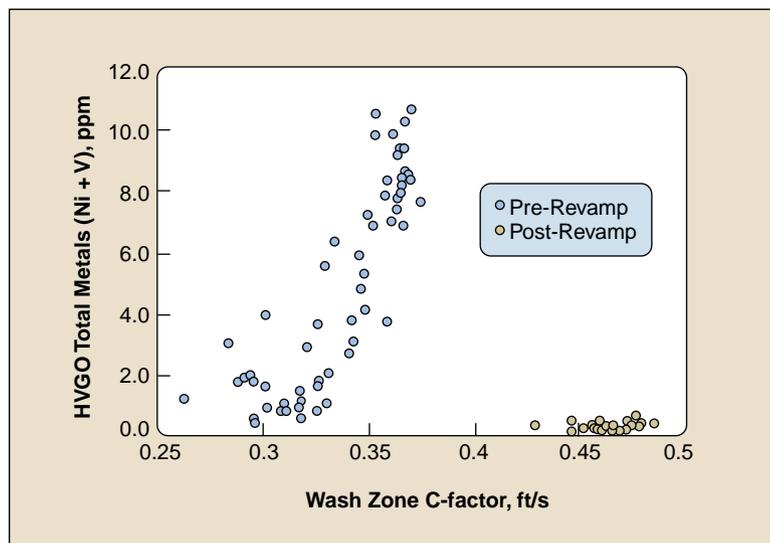
■ Figure 1. The revamp reduced the metals concentration and decreased fuel-gas production in the fluid catalytic cracking unit.

question. Also, the concentrations were not consistently high enough to expect the type of increase exhibited on the FCCU catalyst. However, the samples were only pulled for metals analysis a few times per month. No metals concentration data were available for the majority of the operation. Further investigation was necessary.

Vacuum-gas-oil metals concentration is affected by volatile organometallic compounds and entrainment of resid into the gas oil. The volatile metals concentration is a function of either the crude slate or of contaminants. Crude assays showed no expected increase in volatile metals over the period in question. Entrainment is a function of column C-factor:

$$C_s = u \sqrt{\frac{\rho_v}{\rho_l - \rho_v}} \qquad (1)$$

where: u = column superficial vapor velocity, ft/s; ρ_v = vapor density, lb/ft^3; and ρ_l = liquid density, lb/ft^3.

It is possible to estimate the C-factor by measuring vacuum-tower product-rates and flash-zone conditions. The C-factor was correlated vs. gas-oil metals concentration for the days when data were available (Figure 1). Above a C-factor of about 0.32, the metals concentration increases exponentially. A re-

view of operating data showed that an increase in average vacuum-tower C-factor correlated closely with the increase in FCCU catalyst metals.

Other factors beside the C-factor that affect entrainment in a vacuum tower include the wash-zone design, feed distiubutor type and design, and the design of the transfer-line from the vacuum furnace to the tower. All three were found to be deficient in this vacuum tower. However, the next unit turnaround was only months away, so attention focused on improvements in the wash zone as having the highest probability of success on a short time-line.

The existing wash zone consisted of 5 ft of Flexigrid grid-style structured packing. This packing is effective for de-entrainment for C-factors up to approximately 0.3. Above that, structured packing is recommended. The wash zone was re-designed using a combination bed of structured packing and Flexigrid. In addition to providing better de-entrainment, this design was more efficient, resulting in greater wash-oil vaporization. This required replacing the wash-oil spray-header to provide sufficient wash oil to prevent coking the bed.
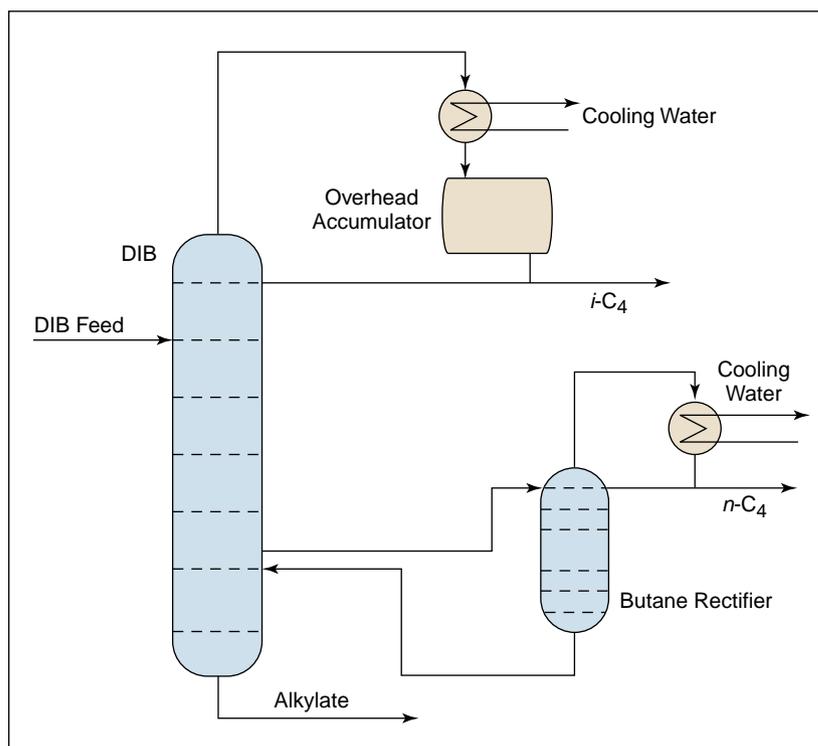
■ Figure 2. Proper troubleshooting solved problems in the deisobutanizer (DIB).

The wash-zone revamp was completed along with other unit modifications that allowed the unit to increase its charge rate. Wash-bed performance was greatly enhanced, resulting in reduced metals in the HVGO at *C*-factors approaching 0.5, as shown in Figure 1.

Premature DIB flooding

A deisobutanizer (DIB) in a sulfuric acid alkylation unit separates excess *i*-butane from *n*-butane and alkylate product for recycle to the alkylation reactors. Isobutane purity is a key variable since impurities take up space in the alkylation reactors and increase the heat load on the refrigeration system. The alkylation unit in one refinery was unable to achieve the desired overhead purity due to flooding of the DIB. However, an evaluation of the DIB trays based on a simulation of the column indicated that they were operating at about 70% of flood. Capacity should not have been the issue.

A closer comparison of the simulation with the process data showed a significant difference between the calculated and actual DIB reboiler duties. The data revealed a higher heat requirement than the simulation calculated. Further evaluation was required.

This DIB column is equipped with a vapor side-draw that feeds a butane rectification column (Figure 2). Liquid from the bottom of the butane rectifier returns to the DIB by gravity flow through a seal loop. Discussions with the plant operators revealed that they frequently had to drain water from the bottom of this loop to maintain flow. Water was not accounted for in the original simulation. Because the entire process of draining was executed manually, there was no way for the engineer to know that it was an issue without speaking to the operators.

The DIB and butane rectifier were re-simulated with water in the feed. It quickly became clear that no significant amount of water could accumulate in the butane column, assuming that it was removed from the DIB overhead accumulator as it was produced. However, the existing overhead accumulator was not designed for proper water removal. The accumulator's hydrocarbon drawoff nozzle was equipped with a 2-in. internal projection. The accumulator also had a water "boot" consisting of a 4-in. dia. × 3-ft long pipe on the bottom of the vessel. The operators drained this on their rounds every 2 h. Rough estimates of the expected water feedrate to the tower indicated that this arrangement was insufficient.

During a routine round, the time to drain the water from the overhead-accumulator water boot was measured. After a 15 min wait, the experiment was repeated with no significant change in the draining time. Clearly, the existing water boot was being filled in less than 15 min. Once the boot was full, any additional

water left the overhead accumulator with the hydrocarbon draw and was either refluxed to the DIB or recycled to the alkylation reactors. Water refluxed to the DIB resulted in an excess load on the trays and the reboilers. Water recycled to the reactors could contribute to excess acid consumption, if not removed.

The DIB overhead accumulator was redesigned with a larger water-removal boot and a coalescer to improve water removal efficiency. The projection at the hydrocarbon drawoff nozzle was extended to 6 in. In addition, the boot was equipped with a level controller to draw off the water continuously.

The modifications were implemented and DIB performance was improved notably. The *n*-butane concentration in the *i*-butane product dropped by nearly 2% and the tower no longer flooded. Tray efficiency also improved substantially. **CEP**

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