Trouble Shooting in Undergraduate CAPE Education

Thomas Marlin and Donald Woods
Department of Chemical Engineering, McMaster University, Hamilton, Ontario, Canada L8S 4L7

Abstract
Trouble shooting is an application of well-known problem solving techniques to plant problems. This paper proposes that trouble shooting be included in the undergraduate program and that CAPE educators play a leading role in shaping the education. First, the six-step problem solving method is tailored to trouble shooting. Then, the tailored method is applied to a process example, which demonstrates the need for mastery of both process principles and CAPE technology. Guidance is given to instructors on how they can manage the teaching and learning to maximize benefit to the students.

1.0 Trouble shooting in CAPE Education

Trouble shooting involves continuously monitoring, diagnosing and improving process systems. It is a fundamental task performed by engineers. In this paper, we will describe how trouble shooting can be integrated into the undergraduate program in a manner that will reinforce previous education, build life-long learning skills, and be enjoyable for the students.

But first, why should CAPE educators address trouble shooting? Let’s consider some of the aspects of trouble shooting chemical processes that militate for a *systems* approach to trouble shooting: (1) sensors supply nearly all information about current behavior, (2) many corrective actions are implemented by final elements, (3) all processes are automated which affects the symptoms and introduces possible sources for faults, (4) historical data can be used as a basis for identifying and diagnosing faults, and (5) often, a fault in one unit exhibits symptoms in another unit.

A second related question is whether students need education in trouble shooting. Those instructors who have addressed the topic will certainly answer with a resounding “yes”. Most students enjoy the challenge of trouble shooting but initially apply an undisciplined approach. An important goal of education is to provide a systematic method that can be adapted and applied to many professional activities.

Finally, a third question is how do we link trouble shooting to key educational goals. The trouble-shooting educational objectives can be presented using the three categories developed by Rugarcia, Felder, Woods, Stice (2000); examples of trouble shooting goals for each category are given in the following.

- **Attitudes**: Students must learn how to solve problems when equipment never functions exactly as designed, measurements always have errors, and feed material properties are never known exactly.
- **Skills**: Students need a firm fundamental understanding of the six-step trouble shooting method along with a recognition of the emotional factors in good problem solving.
- **Knowledge**: Students need deep knowledge of engineering systems – especially control principles and equipment– to be successful troubleshooters.

2.0 A Problem-Solving Method

We agree that trouble shooting is an important CAPE topic, but can we teach it? Over the past decade, we have seen great progress in teaching engineering problem solving. Excellent documentation of approaches is available in, for example, Woods (1994) and Fogler and LeBlanc (1995), and evidence for the value of a methodology is given in Woods (2000). This paper will show how to apply the general, six-step problem-solving method to trouble shooting process systems, which helps students link process fundamentals to equipment operation.

2.1 Tailoring Problem Solving for Trouble Shooting

Problem solving can be applied to many aspects of life, and it is often introduced in first or second year of university education through simple problems like baking a cake or determining why a lamp is not working. However, higher-year students need to learn how to problem solve by applying process fundamentals (e.g., material and energy balances), equipment behavior (e.g., tray flooding), instrumentation basics (e.g., sensor accuracy), and process safety (e.g., pressure relief).

Using realistic process examples have several advantages. First, realistic process examples will reinforce prior learning. Students have typically approached chemical engineering systems as a design problem. In trouble shooting, they encounter the same systems and process fundamentals from the operations viewpoint. Second, students will learn the importance equipment behavior. The second effect is especially valuable for today's students who have received an engineering-science-based education in the transport topics. Third, students will begin to encounter unique challenges involved with being successful in a process plant, where we need to work with people and communicate clearly.

We will retain the six-step problem-solving method because it is appropriate for trouble shooting. However, students require considerable assistance in taking the big step from baking a cake to plant safety and profitability. This guidance can be provided by key questions that students should be asking at every stage of the method. A full listing of these questions is too long to include in this paper, but it is available via the WWW (Marlin, 2001). To demonstrate how to tailor the method for process trouble shooting, we present example questions for each of Steps 1 to 6. In this example, we focus on the task of identifying the cause of the "problem". The same general strategy is used to prioritize, to identify the cause, to correct the fault, and to prevent reoccurrence of the problem. Trouble shooters should cycle back and forth among the steps, not apply them serially.

- **Step 1, Engage: Patiently read the problem statement, or listen to the operator describe the problem.** Manage stress. Yes, you are expected to solve the problem and you can.
- **Step 2, Define: Sort the evidence.** What is the situation? Is this startup after a shutdown? Is this the first time the process has been run? What are the facts? What is opinion? What is the source of the information? What are symptoms or initial evidence? Who are the people in the problem and affected by the problem?
- **Step 3, Explore: Create a rich understanding of the situation.** In this we specify: Who/when/where/what is and is not in the problem? We patiently gather these data, and we brainstorm *numerous* hypotheses about what could be the cause. Make many "what if?" assumptions and test these out. We are willing to take a risk, make mistakes and explore to understand what really is involved in this problem.

  What is the short term and long term desired state? In a plant, we often identify *two desired states*. One is a short-term state that quickly regains safe operation and if possible, achieves acceptable product quality. The second is a longer-term state that might require equipment changes or a process shutdown to achieve.

  We learn the key skill of checking information before using it in trouble shooting. For example, we know material balances, so we can check flow rates and component balances, and the student must consider the accuracy of the specific measurement devices in deciding whether the data is reliable.

  We look for hints in the historical data? We will explore different possible root causes if the plant (1) is being started up, (2) experiencing slow changes in performance or (3) has been in essentially unchanged operation for an extended time.

  We recall practical experience about the equipment in the system. We use existing checklists linking typical symptoms and faults with possible causes to prioritize and assess the list of hypotheses.

  Next, we use the hypotheses and evidence to develop a truth table to compare the data with the hypotheses. Since the data are seldom complete, the troubleshooter selects a sequence of *diagnostics actions* to be implemented in the plant. The sequence of the actions should provide inexpensive, rapid feedback first.
- **Step 4, Plan:** Evolve a plan to test the hypotheses and identify the root cause or perhaps to correct the fault without discovering the fault.
- **Step 5, Implement the plan.** The action must be appropriate for an operating plant. "Shutdown the plant and repair the tray" is only acceptable when other less expensive solutions are not possible. In some cases, "Lower the production rate until the next turnaround" is a better short-term solution.

- **Step 6, Evaluate: How can I continue to test/verify my hypothesis as I implement the solution?** –We look back after each step to ensure that the goal is correct and achievable. In this final step, we should monitor the response to the solution to ensure that the root cause has been identified. If not, then repeat the above process. If we think we have identified the cause, then we repeat the strategy to correct the root cause. Then we repeat the strategy to avoid this problem in the future. We should establish a program that would prevent a reoccurrence of the problem, if possible. This program might include new sensors or laboratory analyses, or it could involve equipment enhancements.

3.0 Trouble Shooting Case Studies

Students need considerable practice to understand and master the trouble-shooting method. These should begin with relatively simple cases when the students are becoming familiar with the method. The instructor should be aware of the students' knowledge of common equipment, such as heat exchangers and pumps, so that the cases are within the students' capabilities. Subsequent cases build complexity of knowledge base and analysis.

To reduce pressure on individuals, the first few cases can be performed as group exercises. After each of the six steps, a member of the group can explain their results to the class. The instructor can offer guidance and ensure that all groups are progressing well before moving to the next step. After some practice, groups can progress to trouble shooting a case without intermediate assistance.

3.1 Contents of the case study

Each case should be presented to the students as a scenario that can include the following.

- the symptoms of the current situation
- some background on the plant and recent operating experience
- data and opinions from operators.
- extraneous information ("The feed tank was switched ½ hour before the incident."), some false opinions ("The operator says that the alarm never sounded.") and inconsistent data (e.g., flows that greatly violate material balance, or inconsistent pressure and temperature of a boiling liquid).
- a drawing of the process which should have considerable detail on the process, including equipment used infrequently (bypass line and valves, spare pumps, etc.) and instrumentation; a piping and instrumentation drawing is best. Complete drawings are essential so that the troubleshooter knows what data can be collected from instrumentation and sample taps. Also, detail is required because diagnostic actions might involve checking the operation of valves, bypassing equipment or viewing the equipment (e.g., looking for a vortex in an open tank).

3.2 The Diagnostic Actions

As already discussed, a key aspect of trouble shooting is the selection of diagnostic actions and the correct response to this *feedback*. Students should understand that data does not prove a hypothesis, but it can *disprove a hypothesis*. The troubleshooter uses the initial data to disprove as many hypotheses as possible. Then, the troubleshooter designs actions that disprove one or more remaining hypotheses. When all but one hypothesis has been disproved, the troubleshooter can (cautiously) conclude the root cause has been identified and can focus on a solution. This viewpoint is very important and will prevent an undirected set of questions and experiments that lack focus and do not progress toward a solution.

Students can ask "Shutdown the distillation tower, open the manholes, and observe the trays". However, this is a very costly and time-consuming action and should only be performed when absolutely necessary. Remember that some equipment can be taken out of service without shutting down the entire unit - that is why block and bypass valves are provided!

3.3 Including feedback in the case

To include feedback in the case study, a person must act as the "plant". This person must understand the case and be able to respond to essentially any question, even those poorly chosen. The troubleshooter can ask diagnostic actions that involve new data, information on equipment, or other insights. These questions must be clearly stated; for example, "Check the valve" is not clear, while "Determine whether the stem indicator on valve v-103 shows a fully closed position" is clear.

Also, the action must be *possible*! Often, students ask, "Is the heat exchanger leaking?", "Is the reaction rate lower than usual?", or "Is the flow in the downcomer blocked?" These questions should *not* be answered. Students need to learn to ask for information that could be determined in the plant, for example, “What is the reading of the local pressure sensor P-42?”, “Is the block valve v-111 closed?”, or “Is the tray temperature within a few degrees of its typical value as measured by T-102?”. Also, the student can ask for a diagnostic experiment, such as placing a controller in manual and reducing its output by 10%. The principle is simple - answer questions and report results from only those experiments that could be achieved in the plant.

3.4 A Typical Case Study

Now, let’s take a look at the example of a typical chemical process in Figure 1. The scenario is given in the following, after which we provide a short synopsis of the trouble shooting method.

> *“You are working at your first job, in which you are responsible for the chemical plant in Figure 1. Good news, the market for your product has been increasing. During the morning meeting, you have asked the operator to slowly increase the feed flow rate. In the afternoon, you are visiting the control room to check on some instrumentation maintenance when the operator asks for your assistance. She shows you the trend of data in the figure. This doesn’t look usual to you, and she seems quite concerned. Fortunately, you learned trouble-shooting skills in university, which you can use in solving this problem .”*

- **Step 1** is the most important. Take a deep breath; don’t panic; don’t start guessing; and proceed with the tried-and-true, trouble-shooting method.
- In **Step 2**, we *define* the desired future state, which certainly includes returning the heater outlet temperature to its set point. Also, we note that the fuel flow has increased rapidly, and we immediately wonder about safety. We must consider the possibility of explosive conditions in the firebox, and if we uncover safety issues, we will seek a *rapid* return to a safe region of operation.
- In **Step 3**, we *explore* the process and symptoms. T3 is decreasing, and we see that the same variable is measured by T4, which is a local instrument; we can ask an outside operator to determine the sensor reading for T4 and radio the value to us. While this is being done, we can consider principles of combustion and heat transfer. We see that the feed flow is (recently) constant and the fuel rate is increasing; yet the heater effluent temperature is decreasing. If the fuel is being combusted, the temperature should be increasing rapidly. Concerning trends, we see that the feed flow has been increased, but we don’t see an immediate connection. As we explore this problem we *develop hypotheses* for the root cause that are given in Figure 1. (Many more would be possible, but these examples are sufficient to explain the principles.) To find the *root cause*, we see that the initial evidence eliminates a few hypotheses but that several remain.
- In **Step 4**, our plan might be to first check T4 and T3. Second, we check if the constant feed flow is correct by looking at the trend of the feed tank level. Third, we check if the fuel flow is increasing by looking at the pressure after the control valve. Fourth, we look at the trend of the air.
- In **Step 5**, we act and do each of the steps in turn. We might modify the next act based on the data gathered. In this example, the results are: T4 and T3 agree within 1 K. The feed tank level is decreasing at a constant slope. The pressure after the control valve is increasing also. The trend of the air has not changed! As we reapply the strategy and test hypotheses we zero in on the hypothesis that the combustion is not complete, because too little air is supplied. We think that we have identified the root cause.
- In **Step 6**, The implemented plan has verified the hypothesis and has solved the immediate problem. Now we need to repeat the strategy to correct the root cause that we have identified.

- In the next application of the strategy we search for a *short-term solution*, which must achieve a rapid return to safe operation. We have concluded that an excess of fuel exists in the firebox. First, we place the temperature controller in manual to stop any further increases in fuel flow. Next, we could achieve the proper ratio of air to fuel by either increasing the air or decreasing the fuel; the safest is to decrease the fuel, because increasing the air will provide oxidant to a fuel-rich environment. We expect to see the temperature T3 increase. (If this does not happen, you might have the wrong root cause - we would start the trouble shooting method.) When an excess of air has been achieved, the temperature controller can be switched to automatic and the process returned to normal operation. The operator must be sure to adjust the airflow rate (F5) whenever changing the feed flow (F1) or T3 set point.

- In the next application of the strategy we ensure that a *long-term solution* has been achieved. Our results are that the solution proposed does not adequately prevent a reoccurrence. Currently, we are relying on the operator to maintain a desired ratio *manually*, using only flow sensors. We would like to have this safety-related issue automated using a more direct measure of combustion performance. As a longer-term solution, the air flow should be ratioed to the fuel flow, and the air/fuel ratio should be reset in a cascade control design by a controller using a measurement of the excess oxygen in the flue gas (API, 1977). In addition, all operators should be trained on how to diagnose and solve the lack of excess air scenario.

3.5 CAPE-related Feature of Case

This example shows a situation in which the normal process operation is only mildly non-linear, i.e., the gain between fuel flow and temperature is positive and does not change excessively. However, when sufficient air is not present, incomplete combustion cools the flame and leads to a temperature decrease as fuel is increased, so that the *process gain changes sign*! The temperature control loop becomes unstable and no amount of detuning, short of tuning the controller off, will stabilize the loop. We have the opportunity to review basic feedback principles during the diagnosis. In developing the long-term solution we introduce feedforward (air/fuel ratio) and cascade (oxygen control to air/fuel ratio to air flow). Perhaps most important, we can continue to reinforce the link between process principles and process control.

4.0 Some Tips for the Instructor

The student troubleshooters are eager to proceed, so eager that they usually bypass the thorough method being taught and jump to guessing the root cause. *Guessing is not acceptable*! Also, students often suffer from tunnel vision by locking on one cause and not developing sufficient possibilities during the "explore" step. The instructor should monitor the performance and guide the student to the proper method.

To ensure that the proper thought is invested, the students should be required to complete each step on a written form. Also, diagnostic actions should be written down, so that the student and instructor can perform a post-exercise analysis of the actions for clarity, focus and appropriate sequencing.

To further encourage active learning and provide opportunity for investigation, the instructor can assign a process unit (e.g., shell and tube heat exchangers) to a group of students. Each group will develop process-specific information to aid trouble shooting, such as likely root causes, symptoms, time-dependent behaviors, and solutions. These trouble-shooting aids can be shared with the class.

5.0 Conclusions

We have presented a template for teaching students how to apply their education in process troubleshooting. The teaching method has considerable flexibility to enable instructors to integrate their special insights and approaches, and it can be adapted to many courses and levels of study. We recommend that CAPE instructors integrate this method into their courses, and they will be amazed at the enthusiastic responses by their students.

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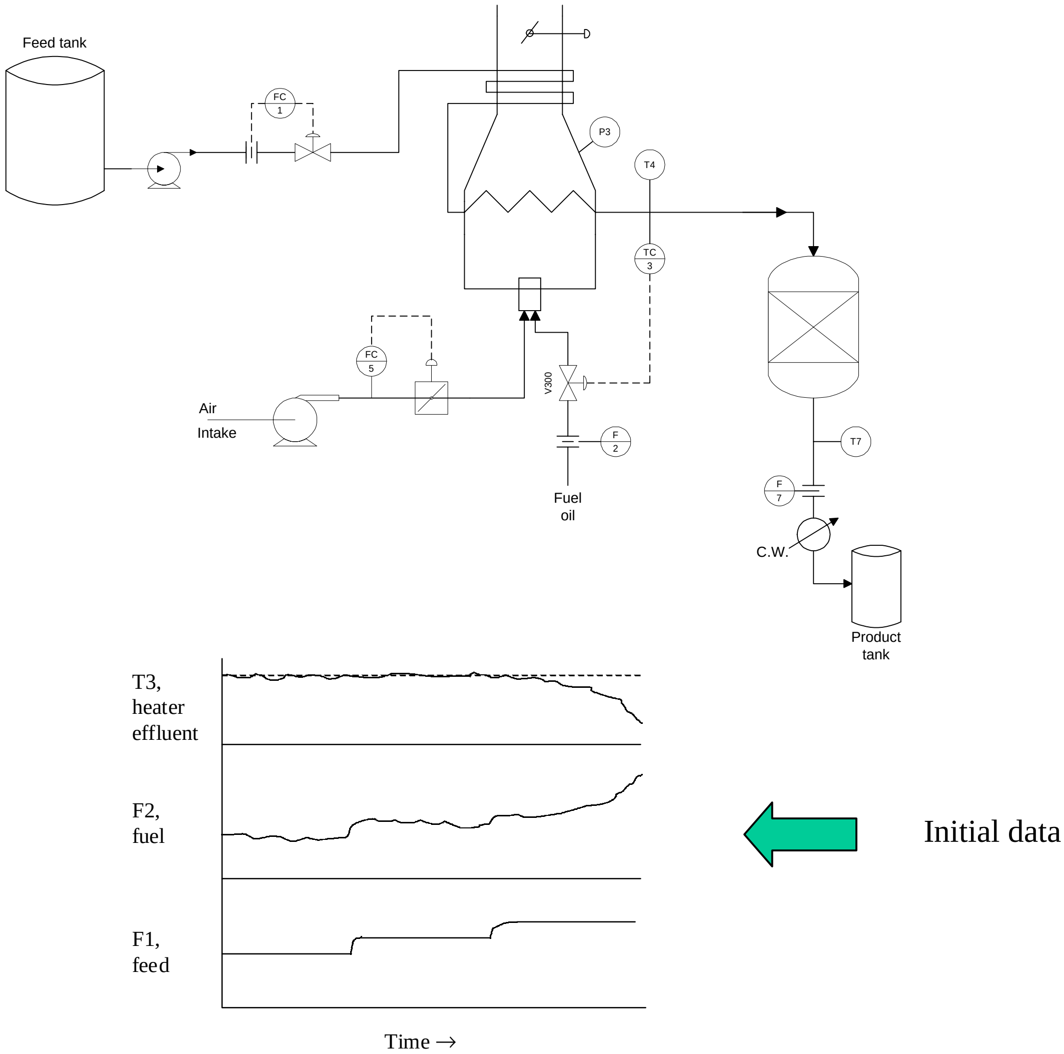

WORKING HYPOTHESES	INITIAL EVIDENCE (**S**upport, **D**isprove, **N**eutral)					DIAGNOSTIC ACTIONS (**S**upport, **D**isprove, **N**eutral)			
	a	b	c	d	e	A	B	C	D
T3 in error	S	N							
Controller tuning poor	D	N							
Fuel valve fails open	N	N							
Heat transfer efficiency inc.	N	N							
Feed flow rate is decreasing	S	N							
Combustion incomplete	S	S							

Disprove all but one hypothesis

Figure 1. Fired heater example trouble shooting case study, with abbreviated table of hypotheses.