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Experimental Self-Efficacy and Troubleshooting Ability in a Chemical Engineering Laboratory

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Abstract

This research serves as a first step toward investigating how educators might evaluate (and eventually improve) students' self-efficacy and troubleshooting ability in an engineering laboratory. This study uses an established survey to assess the experimental self-efficacy (ESE) of students enrolled in a fourth-year chemical engineering laboratory course at the University of Virginia. The survey measures ESE using four factors: conceptual understanding, procedural complexity, laboratory hazards, and lack of sufficient resources. Results from the ESE survey suggest that students had higher confidence in their conceptual understanding and their ability to avoid laboratory hazards. This study also analyzes students' troubleshooting abilities using an existing chemical reactor system (a water gas shift reaction). Students were asked to use the experimental equipment to perform an activity. To succeed, students needed to identify and correct a series of challenges (e.g., closed gas valves, empty reactant reservoirs). Researchers recorded their observations about students' technical knowledge, processes, and troubleshooting strategies. Analysis of these observations suggests that students are more likely to read and follow directions or "spitball" ideas without strong use of troubleshooting strategies, though some participants successfully referenced conceptual understanding or used backtracking as troubleshooting strategies.

Introduction

Engineering laboratory courses train students in a variety of skills, many of which transfer beyond the specific equipment or theories used in a particular course. This paper considers two such skills: confidence in operating laboratory equipment (self-efficacy) and the ability to troubleshoot or "debug" equipment. The motivation for considering these two outcomes is our observation that students' troubleshooting abilities are limited and a hypothesis that students who self-report higher self-efficacy may demonstrate better troubleshooting ability. This paper takes the first step in determining how we might measure the two variables of interest: self-efficacy and troubleshooting ability.

Engineering laboratory course objectives often include the use of engineering equipment to collect data, to analyze data relative to engineering concepts, to correct for deviations in the experimental procedure, and to identify experimental problems and intervene when appropriate [1]. Assessment of these objectives often focuses on the students' ability to communicate the technical outcomes (e.g., written reports or technical presentations) and may overlook evidence for holistic development in areas such as troubleshooting abilities. Troubleshooting is a fundamental skill that instructors would like their students to gain from experience in a laboratory course, but assessing this skill can be challenging.

In this study, we tested a method to holistically test students' ability to troubleshoot a chemical engineering problem in a laboratory course. **Our research goal is to develop a baseline understanding of how to measure students' experimental self-efficacy and their troubleshooting performance.** Planned future research may then consider how these two variables relate.

Related work

The project involves measuring two desired outcomes of laboratory courses: self-efficacy and troubleshooting ability. This section reviews previous literature on these two outcomes.

The concept of **self-efficacy** states that a person with high self-efficacy, i.e., a strong belief in their ability to succeed at a task, is more likely to succeed at that task than someone with lower self-efficacy, even if the two people have the same underlying ability [2]. Increasing self-efficacy is thus a common goal of courses. Kolil et al. [3] studied students in chemistry laboratories and identified four barriers to developing ESE:

1. Lack of conceptual understanding (CU) of the underlying phenomena,
2. Fear of laboratory hazards (LH) or "messing up" expensive equipment,
3. Procedural complexity (PC), and
4. Lack of sufficient resources (SR), e.g., amount of chemicals available or time constraints.

Kolil et al. [3] developed a survey to measure ESE based on these factors and used this tool to show how interventions (e.g., a virtual laboratory) can significantly improve self-efficacy.

Troubleshooting is by nature a complex, iterative, and non-linear process. However, it can be loosely described as containing a set of four tasks [4]:

1. Formulate problem description (identify/determine problem),
2. Generate causes,
3. Test, and
4. Repair and evaluate.

Progress through these steps is often iterative. For example, after generating a list of possible causes, the troubleshooter might select one cause to test. Based on the results of that test, the troubleshooter will either conclude they found the cause of the error and proceed to repair it or decide that is not the cause and test another option. The observed themes in this study are organized according to these four basic tasks.

In two studies from an undergraduate electronics lab, Dounas-Frazer et al. [5] and Van De Bogart et al. [6] promote the ability to troubleshoot as a fundamental skill. There is a lack of methods to assess troubleshooting. Van De Bogart et al. [6] addressed this by designing a troubleshooting exercise in which pairs of students had to identify and correct two faults in an electric circuit and 'think aloud' as they did so. By having the students work in pairs, the authors observed social troubleshooting behaviors. They found that students use distinct types of knowledge while troubleshooting: knowledge of theories and principles, knowledge of the specific circuit or system, and knowledge of troubleshooting strategies.

There are many examples of researchers developing and testing interventions to improve self-efficacy or troubleshooting skills. In addition to [3], Mataka and Kowalske [7] designed a laboratory course to increase self-efficacy, in this case using a problem-based learning laboratory. One example for improving troubleshooting ability is Adams et al. [8]. The authors developed an inquiry-guided laboratory manual that encouraged students to take a more independent role in laboratory experiments. Anticipating students might be afraid of making a mistake or failing to execute an experiment correctly, the facilitators allowed students to report lessons learned for grading purposes if they did not complete the lab. Part of the authors' goal in taking this approach was to normalize mistakes and help students to prepare for the true iterative nature of design (and troubleshooting) in industry.

We are unaware of any studies explicitly testing a link between troubleshooting and ESE, but Estrada and Atwood [9] suggest there may be an interaction between these variables. The authors surveyed students in an introductory physics course and found that the most common source of student frustration centered around equipment and equipment troubleshooting. Students commonly attributed problems to faulty equipment when their misunderstanding of how the equipment worked was the true cause. Further, the authors found an inverse relationship between student frustrations with equipment and their confidence in technical aspects of the course.

Methods

This study used an exploratory and primarily qualitative analysis. To measure ESE, students (n=26) in a chemical engineering laboratory course at the University of Virginia took an adapted version of the ESE survey from Kolil et al. [3]. To measure troubleshooting ability, we used qualitative observations (n=12) of students troubleshooting a laboratory experiment set-up of the water gas shift reaction. The sections below describe the course setting, water gas shift laboratory experiment, the survey, and the observation methodology in turn.

Course Setting and Participants

The fourth-year chemical engineering laboratory course in this study teaches students the basics of experimentation and experimental design, teamwork, technical communication, and safety by having students complete three four-week experimental studies focused on chemical and biological reaction systems. Students choose which chemical engineering systems they want to study (out of four possible options), spending four hours each week in the laboratory and one hour each week in lab-lecture. Each experiment involves multiple unit operations, which leads to some variation in the student experience due to division of team responsibilities.

Student assessment comprises a variety of reports and activities with 45% of the final grade derived from individual work. This includes a 60-minute final exam used to assess an individual's understanding about each experiment emphasizing conceptual understanding with a few questions on lab procedures and interpretation of results.

All students enrolled in the course were invited to participate in the study. There was no incentive for students to consent to the research nor to complete the ESE survey, but students were offered a small amount of extra credit for completing the troubleshooting exercise. In total, 26/42 students completed the survey and signed the consent form. Of those students, six pairs completed the troubleshooting exercise. Of this group, only one pair of students had no prior experience using the reactor equipment.

Lab experiment

We designed an authentic chemical engineering problem inspired by the approach taken by Van De Bogard et al. [6]. In their work, [6] provided electrical engineering students with a bounded troubleshooting problem that required students to troubleshoot a breadboarded circuit with two pre-set problems. Like this work, we adapted an experiment used as part of the Chemical Engineering Lab II course to assess students troubleshooting ability. The experiment involved the operation of a chemical reactor to create a product (hydrogen). Within the experimental procedure, we integrated three challenges that students needed to troubleshoot.

The experiment used a small bench-top plug-flow reactor to carry out the water gas shift reaction (see Figure 1). To achieve a successful reaction, participants combined two reactants, water and carbon monoxide, over a catalyst at high temperature to produce hydrogen (product) and carbon dioxide (side product). We controlled the experiment by maintaining the initial conditions (e.g., reactor temperature maintained at 250^{o}C and helium (He) flowrate of 75mL/min to maintain safe conditions).

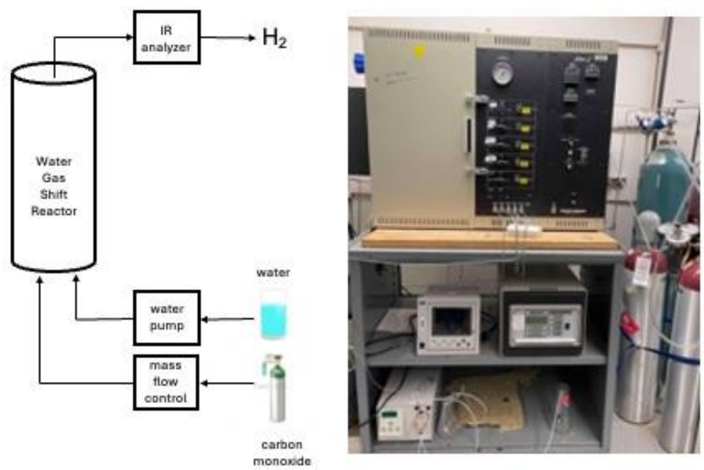

Figure 1. Overview of the experimental setup and an image of the actual setup used by participants in the laboratory.

Participants completed the exercise in teams of two. Participants entered the lab and put on appropriate safety equipment (i.e., safety glasses). Next, a Teaching Assistant (TA) greeted participants, provided a written procedure (see instruction sheet in appendix), and began timing the fifteen-minute exercise. The TA ensured adherence to safety protocols and responded only to safety related questions. A researcher recorded observations about participant performance.

We designed three authentic and realistic challenges that we expected the students to be capable of addressing, ordered here by expected difficulty.

1. **3-way valve**: Located on the front panel of the reactor, the 3-way valve enables gas to enter the reaction chamber. The valve has three settings: closed, vent (to the atmosphere), and system. All 3-way valves were initially set to vent. One step of the instructions was to “Turn the CO 3-way valve to system,” which would introduce CO to the reactor. To complete this challenge, participants had to identify the appropriate 3-way valve that controlled CO flow, recognize its incorrect position, and turn the valve to “system” to enable gas to enter the reactor.

2. **Carbon monoxide flow**: A regulated gas cylinder with a sufficient volume of gas supplied CO to the system. The main valve of the gas cylinder was initially closed. Gas flow was controlled by a mass flow controller and participants were asked to set the "CO flow through the mass flow controller to 50 ml/min." To successfully complete this challenge, participants had to identify the correct gas cylinder, open its main valve, and set the mass flow controller. The instructions asked participants to confirm the flow of CO using the Infrared gas analyzer (IR Analyzer), which measured both CO and carbon dioxide (CO2) in the effluent stream.
3. **Water flow**: A reservoir that comprised a 250mL Erlenmeyer flask supplied liquid water to the reactor via a pump. The water reservoir was intentionally empty. To successfully complete this challenge, participants had to identify the empty water reservoir and set the pump to a flowrate of 0.15mL/min. The instructions asked participants to confirm the flow of water into the reactor by measuring the presence of CO_2 in the effluent using the Infrared gas analyzer (IR Analyzer). Production of H_2 is confirmed by measurement of CO_2, because hydrogen and CO_2 are produced in a 1:1 mole ratio.

Survey

To measure experimental self-efficacy, we modified a version of the ESE survey taken from [3]. Table 1 presents the survey items. All questions used a 5-point Likert scale and responses ranged from strongly disagree (1) to strongly agree (5). Scores were averaged across all questions in a factor to calculate the descriptive statistics in the results section.

Table 1. ESE questionnaire, adapted from Kolil et al. [3] and the mean and standard deviation of responses. The crossed-out words were removed from the original survey and replaced with the underlined words to better reflect the specific course setting. The last three questions from the original survey on sufficient resources were condensed into a single question about limited lab time.

Factor	Item	Question	μ ± σ
Conceptual understanding	1	I believe I have a sound grasp of the theory behind laboratory experiments before performing experiments	3.8 ± 0.7
	2	Experimental concepts become clearer to me as I perform the experiment	4.8 ± 0.4
	3	I am confident that I can understand the underlying ~~chemical~~ <u>engineering</u> phenomena in the experiment	4.2 ± 0.5
Laboratory hazards	4	I can usually handle the ~~glass apparatus~~ <u>equipment</u> in the laboratory on my own without any fear of breakage and injury	4.2 ± 0.9
	5	I am confident of working in the laboratory without ~~chemical spillage~~ <u>major incident.</u>	4.6 ± 0.5
	6	I am always alert in the laboratory and have minimal accidents	4.5 ± 0.9
Procedural complexity	7	After an experiment, I have no difficulty figuring out how my calculation procedures and errors affected my results	3.3 ± 1.0
	8	When presented with laboratory results, I know how to interpret them and draw relevant conclusions from them	4.1 ± 0.6
	9	I do not struggle with processing information in background articles and relating them to my own laboratory procedures and results.	3.8 ± 0.9
Sufficient resources	10	I find it easy to complete the exercise in the laboratory even though there is limited time to perform experiments	3.2 ± 0.8

Lab observations

In the last week of the class, students had the option to participate in the troubleshooting laboratory exercise described above. In addition to the pair of students, one TA and one of the non-instructor researchers were present. During the exercise, the researcher took notes on students' actions and statements; the exercise was not audio or video recorded, so these notes were the primary source for data analysis. The researchers aimed to minimize interactions with participants during the exercise and to follow the general guidelines for think-aloud interviews outlined in [10]. As is standard in a classroom laboratory, students had some interaction with the TA to ensure safety. For most groups, this interaction was limited to instructions at the start of the exercise, but the results section of this paper explains how some groups interacted more with the TA than others. After 15 minutes, the TA stopped the exercise if students were still working.

Following Van de Bogard et al. [6], we planned to analyze the observations by splitting them into "episodes," where the episodes would be defined by transitions between the different challenges. We could then look for themes and patterns within and across episodes. However, our data did not naturally fall into episodes, with participants either working on different tasks at the same time or suggesting ideas without clear follow-up. Instead, we analyzed the data by coding it then looking for themes within an interview (across codes) and within a theme (across interviews).

We used the ESE survey as a guide to develop the initial codebook then created additional *in vivo* codes while reading the observation notes. Our codes included students asking and answering questions; referencing concepts, previous experiences, mathematical calculations, or other coursework; affective responses (e.g., fear or confidence) relating to their understanding or the chance of an accident; and comments about time pressure. We also coded expected actions and results such as following directions, reading directions, proposing or taking a debugging step, interpreting results, or reaching understanding. The added *in vivo* codes captured discussions about helium, measurement units, and meta comments about the exercise.

Results

Experimental Self-efficacy

Table 1 presents the mean and standard deviation for each item on the ESE questionnaire. Overall, students reported being relatively confident in their ability to avoid laboratory hazards (4.4 ± 0.5) and in their conceptual understanding of experiments (4.3 ± 0.3). These results align with the instructor's expectations for two reasons. First, laboratory safety is prioritized, and students receive conceptual and hands-on safety education, which likely led to a high ESE score for laboratory hazards. Second, the laboratory experiments are designed based on content from core engineering courses, therefore students have been exposed to the engineering concepts before they enter the laboratory.

The self-reported responses for both the procedural complexity (3.7 ± 0.6) and sufficiency of resources (3.2 ± 0.8) factor were on average lower. While completing the experiments, students work in teams and rotate the job of experimenting, interpreting results, and writing about the different experimental operations. This design is intended to provide students with an opportunity to interpret results and connect them to theory across the entirety of the experiment. A final exam is administered to assess how well each student can connect conceptual understanding across each complex experiment. We find that the average scores for laboratory reports (90%) are consistently higher than the scores on individual final exams (77%), providing evidence to support the lower ESE score for procedural complexity. Future work will seek to interview students to learn how their survey responses align with their perceptions of the assessments and course objectives. A low ESE score for procedural complexity might suggest an opportunity for more targeted training about how to deal with procedural complexity.

Troubleshooting ability

Of the six pairs of students included in this study, all correctly identified and resolved the 3-way valve settings, one correctly resolved the valve on the CO cylinder, and one identified the empty water reservoir.

For the **3-way valve**, all pairs correctly identified the 3-way CO valve, recognized its position, and opened it to allow flow into the system. Most pairs did so immediately after reading the instruction suggesting a procedural rather than troubleshooting action.

In contrast, **opening the CO valve (cylinder)** required multiple troubleshooting steps. First, participants had to identify the lack of CO as a problem and then remedy this by opening the CO valve (cylinder) and setting the flow rate on the mass flow controller. All groups understood how to measure CO flow (using the IR analyzer). However, for four of the groups, residual CO remained in the system–a limitation of our design–and these groups set the mass flow controller and observed CO flow into the reactor despite not having opened the CO tank. Although these groups completed the task successfully, we reason that they did not fully identify the complexity of the problem. Only one pair was successful in troubleshooting this issue as intended. This pair successfully opened the valve on the CO gas cylinder and did so by first asking where the CO flow was originating before realizing they had never opened the cylinder to begin with.

The most difficult challenge for the students to fix was the **empty water reservoir**, with only one pair identifying and resolving the missing water. This pair had no previous experience using the equipment. Like the pair that was successful in identifying and opening the valve on the CO cylinder, this pair asked the question of where the water was originating from before they traced the water tubing system back to the empty reservoir. Two additional pairs identified the lack of water as the source of the issue, but they did not identify the source of the error within the allotted time limit.

To understand how participants approached the troubleshooting problem, we separated our data according to the four basic tasks included in the troubleshooting model outlined in [4].

Step 1: Formulate problem description

Participants were generally successful at **identifying the problem** (a lack of CO and/or water). However, they were sometimes distracted at this first step by inconsequential details. For example, half of the groups discussed helium (He) flow through the system, despite He not being part of the instructions, an unreactive species, and otherwise unimportant to the achievement of project goals. Most comments about He related to prior experience, and only one of the groups demonstrated understanding of the purpose of the He in the system (e.g., safety). One group expressed concern about the risk of manipulating He flow despite it being an inert gas. Groups were similarly focused on the use of ice (used to chill cooling water) which had no effect on the system or the achievement of project goals. Some pairs also became side-tracked by conversations about units of measurement. We attribute this distraction to participants' prior experiences where they might have had questions or challenges with these issues from previous labs and an overall lack of conceptual understanding of what factors impacted the experiment.

Step 2: Generate Causes
We noted several strategies for brainstorming explanations employed during the exercise to varying degrees: backtracking, using conceptual understanding, reading the instructions, and spit-balling. The pairs that were successful at opening the CO tank valve and finding the empty water reservoir both demonstrated a version of a "**backtracking**" strategy; they identified the problem was a missing reactant and followed up with questions about the source of that reactant.

Another somewhat successful strategy was referencing **conceptual understanding** of the system and the water gas shift reaction. Five of the groups used this strategy, but all did so only at the end of the exercise and two used only incomplete concepts. We did not observe participants using conceptual understanding to successfully initiate troubleshooting. More commonly, students simply **read and followed the instructions**. All students started the exercise this way, with most following the instructions one step at a time. Throughout the exercise, they continued to be more focused on the procedural steps involved in completing the exercise, only stepping back to understand the entirety of the system toward the end. One quote that is indicative of this approach/attitude was "if we keep pushing enter [on mass flow controller], something will happen." This quote was said in jest (with the students making fun of themselves), but still matches many of the pair's actions.

A common theme in the observations was students suggesting an action without any resolution to the suggestion. In almost half of the examples where students would propose a debugging step, there was no resulting action nor a response from the partner – the pair simply moved on to something else. We consider these examples of "**spit-balling**," with students suggesting ideas without any follow-up. There are many possible explanations for this tactic, e.g., a lack of individual confidence, that silence from a partner was an implicit lack of support for the idea, that participants were hoping for (potentially silent) feedback on the idea from the TA, that the participants simply had a better idea, or that the participants had no viable starting point. Other quotes from the students support that they were seeking affirmation, e.g., asking the TA whether it is okay to turn the helium to zero. Understanding why participants did not follow up on these ideas would be an interesting avenue for future work.

Step 3: Test
We observed a few instances of students testing generated causes before moving on to carry out and validate a repair. For example, students used the IR analyzer to confirm the presence (or lack of) CO_2 in the off gas, an indicator of H_2 production. Though most groups understood the implications of the outputs from the gas analyzer, no group linked that information to the suggested repair. It is not clear from our observations whether students did not know to test their

causes, actively avoided testing due to time constraints, or if the experiment did not permit testing opportunities. When students did identify a cause, they preferred to initiate a repair and observe any change rather than test the validity of that cause.

Step 4: Repair and evaluate

Like their ability to initially identify the lack of CO and/or water as a problem, students generally did well at **evaluating repairs** by noting whether there was any change in the measured flow of these reactants. However, considering the small number of students that solved the challenges in the designed experiment, our data for this step is limited.

Reflections on the Experiment Set-up and Observation Process

Part of our research goal was to develop and evaluate a troubleshoot activity as an assessment tool for improving laboratory outcomes. This section evaluates and provides suggestions for future iterations on troubleshooting assessments.

Overall, the experiment provided a good first iteration at assessing the first two steps in the troubleshooting process (formulate problem description and generate causes). Following the procedure of Van de Bogart et al. [6], we found the consistent set-up and identical challenges between groups (ignoring the issue of residual CO flow) made analyzing our data straightforward. The 15-minute time limit also worked well, as most groups had either completed the exercise or were becoming frustrated and ready to give up. Finally, the decision to do observations rather than record the exercises worked in our specific laboratory environment due to loud machinery that would have made it difficult to hear recordings.

The experimental set-up was not as good at testing the latter two steps in troubleshooting process (testing and making/evaluating repairs) because there were few incidents where we could look at students testing hypotheses. To gather more observations on this step, future designs should consider different challenges that have more possible explanations so that students must test and evaluate various hypotheses. Our hope was the CO flow would provide this data, however, the biggest obstacle we faced was that many groups saw residual CO flow from a previous group having opened the gas cylinder valve. With indication that the CO was not flowing into the system, participants did not continue their investigation. This lack of control between experiments limited our analysis and in future we will manage these time-dependent issues.

Another challenge we faced was inconsistent TA behavior. Although all TAs were asked to only answer questions about safety, the interactions between students and the TAs varied, suggesting the existing (and differing) personal relationship between the students and the TAs impacted our results. Having a single TA for all groups would be preferred.

Our main goal in designing the experimental activity was to assess students' ability to troubleshoot. For instructors who may wish to use a similar activity to measure ESE or fear of laboratory equipment, we note that there was minimal evidence of students being afraid of breaking the equipment or hurting something/someone. It is possible our participant pool simply had a high ESE, but we think it more likely that the set-up was not optimized to observe that component of ESE.

Future Work and Conclusion

Two of the many goals of laboratory courses are to build students' self-efficacy in working with laboratory equipment and to teach transferable skills, such as how to troubleshoot. Assessing these goals is challenging and many courses do not explicitly grade students based on these outcomes. This paper piloted using an existing ESE survey and a troubleshooting exercise to measure how well students in a fourth-year, lab-based chemical engineering course achieved these goals near the end of the semester.

Our hope is to eventually test whether these two variables are related and to relate them to course grades. As an initial reflection on how the sources of data may relate, we note that the results from the ESE survey show students rated their conceptual understanding of laboratory experiments as relatively high (along with their confidence in avoiding laboratory hazard). However, we found little use of conceptual understanding during the troubleshooting exercise. Whether this seeming contradiction is a result of the different measurement devices, a misalignment in students' perceptions of their abilities, or students not recognizing the relevance of conceptual understanding to the troubleshooting exercise would be yet another interesting avenue for future work. We also did a preliminary correlation between the ESE factor scores and the final exam grades in the course. Given the small data size for this study, it is unsurprising that we found no significant correlation.

While designing our experiment, we expected students to solve the CO and water reservoir challenges by backtracking the problem. The observational data suggests that students were much more likely to read and follow directions without strong use of troubleshooting strategies, though they did show evidence of referring to the theory of the reaction (conceptual understanding) and some good engineering practices (verifying flow rates). An interesting variation of the experiment would be to ask students to first draw the reaction ahead of the exercise, potentially priming the students to apply concepts during the troubleshooting exercise. If this approach made students more successful, it would beg the question of how we encourage students to complete this step without prompting.

Finally, while analyzing these data, we realized that debugging strategies are not something that we explicitly teach. This experience has caused us to articulate our goals for students, think about how to assess these goals, and then reflect on how we can better teach to reach these goals. For example, a possible future teaching strategy might be to demonstrate a backtracking strategy using CO and then ask the students to use the same approach to address the water challenge. Thus, the framing of the lesson would shift from procedure and experimental set-up to understanding these same elements via use of a troubleshooting method.

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Appendix: Handout for Troubleshooting Exercise

Prompt:

1. **Your goal**: Use the BTRS-Jr reactor to produce hydrogen.
2. **Time**: You have 15 minutes to complete this exercise.
3. **Talk through your process:** Please verbalize your decision process to the TA. The TA's role is to ensure your safety. A researcher will observe your approach.

Water Gas Shift Reaction (WGS): We can produce hydrogen (and carbon dioxide) by reacting carbon monoxide (CO) and water vapor (H2O) over a copper/aluminum-based catalyst at moderate temperatures according to the following relationship:

$$CO + H_2O \leftrightarrow H_2 + CO_2$$

Your reactor is located inside the BTRS-Jr, contained within the fume hood. We have pre-set experimental conditions for this reaction at:

- Reactor temperature: 250^{o}C
- Oven temperature: 100^{o}C
- Helium flow: 75mL/min

The reactor will be running when you arrive, operating at a constant temperature and flowrate of helium.

1. Open the back pressure regulator by turning the large blue valve counterclockwise until fully open.
2. Check that the water to the condenser (green valve located on side of fume hood) is turned on and that a moderate flow of water is passing through the tubing.
3. Release any water in the condenser by opening the liquid outlet valve located on the side of the reactor.
4. Confirm that the reactor is turned on and that temperatures are within 10% of pre-set conditions.
5. Set the CO flow through the mass flow controller to 50 ml/min.
6. Turn the CO 3-way valve to system.
7. Monitor gas flow through the reactor using the IR analyzer and confirm flow to the TA before proceeding.
8. Set the water flow through the HPLC pump to the desired value (0.15 ml/min). Start the HPLC pump.
9. Monitor and record time to produce hydrogen (less than 2 minutes) to the TA.