
Lab

Analytical measurement loop: *Questions 61 and 62, completed objectives due by the end of day 5*

Exam

Day 6

Capstone Assessment takes the place of a mastery exam (see question 63)

Specific objectives for the optional “mastery” exam (worth +5% on the proportional exam score if passed the very first time):

- Electricity Review: Design a simple circuit to achieve a stated objective
 - Balancing a chemical reaction
 - Explain the operating principle of a specified analyzer type
 - Calculate temperatures or voltages in thermocouple and RTD circuits given access to thermocouple and RTD tables
 - Solve for a specified variable in an algebraic formula (may contain exponents or logarithms)
 - Determine the possibility of suggested faults in a 4-20 mA loop circuit given measured values (voltage, current), a schematic diagram, and reported symptoms
 - Motor/relay/3phase/PLC Review: Determine status of PLC output given input conditions and RLL program
 - INST252 Review: Identify cause of poor loop performance from a trend graph
 - INST262 Review: Use decibels to calculate power gains and losses
-

Recommended daily schedule

Day 1

Theory session topic: Optical analyses (dispersive spectroscopy, fluorescence, chemiluminescence)

Questions 1 through 20; answer questions 1-8 in preparation for discussion (remainder for practice)

Discuss the upcoming Capstone Assessment due by the end of the course (*Question 63*)

Day 2

Theory session topic: Optical analyses (NDIR)

Questions 21 through 40; answer questions 21-29 in preparation for discussion (remainder for practice)

Day 3

Theory session topic: Review for exam

Questions 41 through 60; answer questions 41-48 in preparation for discussion (remainder for practice)

Team tool locker inspection: have students inventory their team tool lockers, posting lists to the outside of the locker doors documenting what's missing.

Day 4

Tour

Day 5

Exam

Day 6

Lab Clean-Up Day

Capstone Assessment: *Question 63*, **due by the end of the last day**

The last day of the quarter is a full day, where all students are expected to attend as usual. Together, we will spend this day completing any remaining lab objectives, as well as doing general clean-up, reorganization, equipment repair, and other tasks necessary for the maintenance of our lab facility. See question 64 for a list of necessary tasks to complete.

How To . . .

Access the worksheets and textbook: go to the *Socratic Instrumentation* website located at <http://www.ibiblio.org/kuphaldt/socratic/sinst> to find worksheets for every 2nd-year course section organized by quarter, as well as both the latest “stable” and “development” versions of the *Lessons In Industrial Instrumentation* textbook. Download and save these documents to your computer.

Maximize your learning: complete all homework *before* class starts, ready to be assessed as described in the “Inverted Session Formats” pages. Use every minute of class and lab time productively. Follow all the tips outlined in “Question 0” as well as your instructor’s advice. Do not take constructive criticism personally. Make every reasonable effort to solve problems on your own before seeking help.

Identify upcoming assignments and deadlines: read the first page of each course worksheet.

Relate course days to calendar dates: reference the calendar spreadsheet file (`calendar.xlsx`), found on the BTC campus Y: network drive. A printed copy is posted in the Instrumentation classroom.

Locate industry documents assigned for reading: use the Instrumentation Reference provided by your instructor (on CD-ROM and on the BTC campus Y: network drive). There you will find a file named `00_index.OPEN.THIS.FILE.html` readable with any internet browser. Click on the “Quick-Start Links” to access assigned reading documents, organized per course, in the order they are assigned.

Study for the exams: Mastery exams assess specific skills critically important to your success, listed near the top of the front page of each course worksheet for your review. Familiarize yourself with this list and pay close attention when those topics appear in homework and practice problems. Proportional exams feature problems you haven’t seen before that are solvable using general principles learned throughout the current and previous courses, for which the only adequate preparation is independent problem-solving practice every day. Answer the “feedback questions” (practice exams) in each course section to hone your problem-solving skills, as these are similar in scope and complexity to proportional exams. Answer these feedback independently (i.e. no help from classmates) in order to most accurately assess your readiness.

Calculate course grades: download the “Course Grading Spreadsheet” (`grades_template.xlsx`) from the Socratic Instrumentation website, or from the BTC campus Y: network drive. Enter your quiz scores, test scores, lab scores, and attendance data into this Excel spreadsheet and it will calculate your course grade. You may compare your calculated grades against your instructors’ records at any time.

Identify courses to register for: read the “Sequence” page found in each worksheet.

Receive extra instructor help: ask during lab time, or during class time, or by appointment. Tony may be reached by email at tony.kuphaldt@btc.edu or by telephone at 360-752-8477.

Identify job openings: regularly monitor job-search websites. Set up informational interviews at workplaces you are interested in. Participate in jobshadows and internships. Apply to jobs long before graduation, as some employers take *months* to respond! Check your BTC email account daily for alerts.

Impress employers: sign the FERPA release form granting your instructors permission to share academic records, then make sure your performance is worth sharing. Document your project and problem-solving experiences for reference during interviews. Honor all your commitments.

Begin your career: participate in jobshadows and internships while in school to gain experience and references. Take the first Instrumentation job that pays the bills, and give that employer at least two years of good work to pay them back for the investment they have made in you. Employers look at delayed employment, as well as short employment spans, very negatively. Failure to pass a drug test is an immediate disqualifier, as is falsifying any information. Criminal records may also be a problem.

file howto

General Values, Expectations, and Standards

Success in this career requires professional integrity, resourcefulness, persistence, close attention to detail, and intellectual curiosity. If you are ever in doubt as to the values you should embody, just ask yourself what kind of a person you would prefer to hire for your own enterprise. Those same values will be upheld within this program.

Learning is the top priority in this program. Every circumstance, every incident, every day will be treated as a learning opportunity, every mistake as a “teachable moment”. Every form of positive growth, not just academic ability, will be regarded as real learning.

Responsibility means *ensuring* the desired outcome, not just *trying* to achieve the outcome. If your efforts do not yield the expected results, only you can make it right.

Integrity means being honest and forthright in all your words and actions, doing your very best every time and never taking credit for the achievement of another.

Safety means doing every job correctly and ensuring others are not endangered. Lab safety standards include wearing closed-toed shoes and safety glasses in the lab room during lab hours, wearing ear protection around loud sounds, using ladders to reach high places, using proper lock-out/tag-out procedures, no energized electrical work above 30 volts without an instructor present in the lab room, and no power tool use without an instructor present in the lab room.

Diligence means exercising self-discipline and persistence in your studies, realizing that hard work is a necessary condition for success. This means, among other things, investing the necessary time and effort in studying, reading instructions, paying attention to details, utilizing the skills and tools you already possess, and avoiding shortcuts.

Mastery means the job is not done until it is done *correctly*: all objectives achieved, all problems solved, all documentation complete, and no errors remaining.

Self-management means allocating your resources (time, equipment, labor) wisely, and not just focusing on the nearest deadline.

Communication means clearly conveying your thoughts and paying attention to what others convey. Remember that no one can read your mind, and so it is incumbent upon you to communicate any and all important information.

Teamwork means working constructively with your classmates so as to maximize their learning as well as your own.

Initiative means recognizing needs and taking action to meet those needs without encouragement or direction from others.

Representation means your actions are a reflection of this program and not just of yourself. Doors of opportunity for all BTC graduates may be opened or closed by your own conduct. Unprofessional behavior during tours, jobshadows, internships, and/or jobs reflects poorly on the program and will negatively bias employers.

Trustworthiness is the result of consistently exercising these values: people will recognize you as someone they can rely on to get the job done, and therefore someone they would want to hire.

Respect means acknowledging the intrinsic value, capabilities, and responsibilities of those around you. Respect may be gained by consistent demonstration of valued behaviors, and it may be lost through betrayal of trust.

General Values, Expectations, and Standards (continued)

Punctuality and Attendance: late arrivals are penalized at a rate of 1% grade deduction per incident. Absence is penalized at a rate of 1% per hour (rounded to the nearest hour) except when employment-related, school-related, weather-related, or required by law (e.g. court summons). Absences may be made up by directing the instructor to apply “sick hours” (12 hours of sick time available per quarter). Classmates may donate their unused sick hours. Sick hours may not be applied to unannounced absences, so be sure to alert your instructor and teammates as soon as you know you will be absent or late. Absence on an exam day will result in a zero score for that exam, unless due to a documented emergency.

Mastery: any assignment or objective labeled as “mastery” must be completed with 100% competence (with multiple opportunities to re-try). Failure to complete by the deadline date caps your grade at a C–. Failure to complete by the end of the *next* school day results in a failing (F) grade for that course.

Time Management: Use all available time wisely and productively. Work on other useful tasks (e.g. homework, feedback questions, job searching) while waiting for other activities or assessments to begin. Trips to the cafeteria for food or coffee, smoke breaks, etc. must not interfere with team participation.

Orderliness: Keep your work area clean and orderly, discarding trash, returning tools at the end of every lab session, and participating in all scheduled lab clean-up sessions. Project wiring, especially in shared areas such as junction boxes, must not be left in disarray at the end of a lab shift. Label any failed equipment with a detailed description of its symptoms.

Independent Study: the “inverted” instructional model used in this program requires independent reading and problem-solving, where every student must demonstrate their learning at the start of the class session. Question 0 of every worksheet lists practical study tips. The “Inverted Session Formats” pages found in every worksheet outline the format and grading standards for inverted class sessions.

Independent Problem-Solving: make an honest effort to solve every problem before seeking help. When working in the lab, help will not be given to you unless and until you run your own diagnostic tests.

Teamwork: inform your teammates if you need to leave the work area for any reason. Any student regularly compromising team performance through absence, tardiness, disrespect, or other disruptive behavior(s) will be removed from the team and required to complete all labwork individually. The same is true for students found inappropriately relying on teammates.

Communication: check your email account daily for important messages from your instructor. Ask the instructor to clarify any assignment or exam question you find confusing, and express your work clearly and compellingly.

Academic Progress: your instructor will record your academic achievement, as well as comments on any negative behavior, and will share all these records with employers provided you have signed the FERPA release form. You are welcome to see these records at any time, and are encouraged to track your own academic progress using the grade spreadsheet template.

Office Hours: your instructor’s office hours are by appointment, except in cases of emergency. Email is the preferred method for setting up an appointment with your instructor to discuss something in private.

Grounds for Failure: a failing (F) grade will be earned in any course if any mastery objectives are past deadline by more than one school day, or if any of the following behaviors are demonstrated: false testimony (lying) to your instructor, cheating on any assignment or assessment, plagiarism (presenting another’s work as your own), willful violation of a safety policy, theft, harassment, intoxication, or destruction of property. Such behaviors are grounds for immediate termination in this career, and as such will not be tolerated here.

file expectations

Program Outcomes for Instrumentation and Control Technology (BTC)

#1 Communication

Communicate and express concepts and ideas across a variety of media (verbal, written, graphical) using industry-standard terms.

#2 Time management

Arrives on time and prepared to work; Budgets time and meets deadlines when performing tasks and projects.

#3 Safety

Complies with national, state, local, and college safety regulations when designing and performing work on systems.

#4 Analysis and Diagnosis

Analyze, evaluate, and diagnose systems related to instrumentation and control including electrical and electronic circuits, fluid power and signaling systems, computer networks, and mechanisms; Select and apply correct mathematical techniques to these analytical and diagnostic problems; Select and correctly use appropriate test equipment to collect data.

#5 Design and Commissioning

Select, design, construct, configure, and install components necessary for the proper function of systems related to instrumentation and control, applying industry standards and verifying correct system operation when complete.

#6 System optimization

Improve technical system functions by collecting data and evaluating performance; Implement strategies to optimize the function of these systems.

#7 Calibration

Assess instrument accuracy and correct inaccuracies using appropriate calibration procedures and test equipment; Select and apply correct mathematical techniques to these calibration tasks.

#8 Documentation

Interpret and create technical documents (e.g. electronic schematics, loop diagrams, functional diagrams, P&IDs, graphs, narratives) according to industry standards.

#9 Independent learning

Select and research information sources to learn new principles, technologies, and techniques.

#10 Job searching

Develop a professional resume and research job openings in the field of industrial instrumentation.

file outcomes_program

INST 242 Course Outcomes

Each and every outcome in this course is assessed at a mastery level (i.e. 100% competence)

- Demonstrate proper use of safety equipment and application of safe procedures while using power tools, and working on live systems. [Ref: Program Learning Outcome #3]
- Communicate effectively with teammates to plan work, arrange for absences, and share responsibilities in completing all labwork. [Ref: Program Learning Outcomes #1 and #2]
- Construct and commission a working analytical loop consisting of a chemical analyzer, signal wiring, and indicator. [Ref: Program Learning Outcome #5]
- Generate an accurate loop diagram compliant with ISA standards documenting your team's analytical measurement system. [Ref: Program Learning Outcome #8]
- Calibrate analyzer to specified accuracy using industry-standard calibration equipment. [Ref: Program Learning Outcome #7]
- Design and build a circuit to fulfill a function randomly selected by the instructor (voltage divider, passive filter, capacitive time-delay, or phase shift network) and demonstrate its proper operation using a signal generator and oscilloscope. [Ref: Program Learning Outcome #5]
- Diagnose a random fault placed in another team's analytical measurement system by the instructor within a limited time using no test equipment except a multimeter, logically justifying your steps in the instructor's direct presence. [Ref: Program Learning Outcome #4]
- Construct a working control loop consisting of a pre-made process unit with transmitter and final control element, properly connected to a controller, within a limited time. Both the process and the controller are randomly selected by the instructor, with measurement range values specified by the instructor. [Ref: Program Learning Outcomes #5 and #9]

Sequence of second-year Instrumentation courses



The particular sequence of courses you take during the second year depends on when you complete all first-year courses and enter the second year. Since students enter the second year of Instrumentation at four different times (beginnings of Summer, Fall, Winter, and Spring quarters), the particular course sequence for any student will likely be different from the course sequence of classmates.

Some second-year courses are only offered in particular quarters with those quarters not having to be in sequence, while others are offered three out of the four quarters and must be taken in sequence. The following layout shows four typical course sequences for second-year Instrumentation students, depending on when they first enter the second year of the program:

Possible course schedules depending on date of entry into 2nd year



file sequence

General tool and supply list

Wrenches

- Combination (box- and open-end) wrench set, 1/4" to 3/4" – *the most important wrench sizes are 7/16", 1/2", 9/16", and 5/8"; get these immediately!*
- Adjustable wrench, 6" handle (sometimes called "Crescent" wrench)
- Hex wrench ("Allen" wrench) set, fractional – 1/16" to 3/8"
- *Optional:* Hex wrench ("Allen" wrench) set, metric – 1.5 mm to 10 mm
- *Optional:* Miniature combination wrench set, 3/32" to 1/4" (sometimes called an "ignition wrench" set)

Note: *always maximize surface engagement on a fastener's head to reduce stress on that fastener. (e.g. Using box-end wrenches instead of adjustable wrenches; using the proper size and type of screwdriver; never using any tool that mars the fastener such as pliers or vise-grips unless absolutely necessary.)*

Pliers

- Needle-nose pliers
- Diagonal wire cutters (sometimes called "dikes")

Screwdrivers

- Slotted, 1/8" and 1/4" shaft
- Phillips, #1 and #2
- Jeweler's screwdriver set
- *Optional:* Magnetic multi-bit screwdriver (e.g. Klein Tools model 70035)

Electrical

- Multimeter, Fluke model 87-IV or better
- Assortment of alligator-clip style jumper wires
- Soldering iron (10 to 40 watt) and rosin-core solder
- Resistor, potentiometer, diode assortments (from first-year lab kits)
- Package of insulated compression-style fork terminals (14 to 18 AWG wire size, #10 stud size)
- Wire strippers/terminal crimpers for 10 AWG to 18 AWG wire and insulated terminals
- *Optional:* ratcheting terminal crimp tool (e.g. Paladin 1305, Ferrules Direct FDT10011, or equivalent)

Safety

- Safety glasses or goggles (available at BTC bookstore)
- Earplugs (available at BTC bookstore)

Miscellaneous

- Simple scientific calculator (non-programmable, non-graphing, no conversions), TI-30Xa or TI-30XIIS recommended. Required for some exams!
- Portable personal computer capable of wired Ethernet connectivity, Wi-Fi connectivity, displaying PDF documents, creating text documents, creating and viewing spreadsheets, running PLC programming software (MS Windows only), and executing command-line utilities such as **ping**.
- Masking tape (for making temporary labels)
- Permanent marker pen
- Teflon pipe tape
- Utility knife
- Tape measure, 12 feet minimum
- Flashlight

file tools

Methods of instruction

This course develops self-instructional and diagnostic skills by placing students in situations where they are required to research and think independently. In all portions of the curriculum, the goal is to avoid a passive learning environment, favoring instead *active engagement* of the learner through reading, reflection, problem-solving, and experimental activities. The curriculum may be roughly divided into two portions: *theory* and *practical*. All “theory” sessions follow the *inverted* format and contain virtually no lecture.

Inverted theory sessions

The basic concept of an “inverted” learning environment is that the traditional allocations of student time are reversed: instead of students attending an instructor-led session to receive new information and then practicing the application of that information outside of the classroom in the form of homework, students in an inverted class encounter new information outside of the classroom via homework and apply that information in the classroom session under the instructor’s tutelage.

A natural question for instructors, then, is what their precise role is in an inverted classroom and how to organize that time well. Here I will list alternate formats suitable for an inverted classroom session, each of them tested and proven to work.

Small sessions

Students meet with instructors in small groups for short time periods. Groups of 4 students meeting for 30 minutes works very well, but groups as large as 8 students apiece may be used if time is limited. Each of these sessions begins with a 5 to 10 minute graded inspection of homework with individual questioning, to keep students accountable for doing the homework. The remainder of the session is a dialogue focusing on the topics of the day, the instructor challenging each student on the subject matter in Socratic fashion, and also answering students’ questions. A second grade measures each student’s comprehension of the subject matter by the end of the session.

This format also works via teleconferencing, for students unable to attend a face-to-face session on campus.

Large sessions

Students meet with instructors in a standard classroom (normal class size and period length). Each of these sessions begins with a 10 minute graded quiz (closed-book) on the homework topic(s), to keep students accountable for doing the homework. Students may leave the session as soon as they “check off” with the instructor in a Socratic dialogue as described above (instructor challenging each student to assess their comprehension, answering questions, and grading the responses). Students sign up for check-off on the whiteboard when they are ready, typically in groups of no more than 4. Alternatively, the bulk of the class session may be spent answering student questions in small groups, followed by another graded quiz at the end.

Correspondence

This format works for students unable to attend a “face-to-face” session, and who must correspond with the instructor via email or other asynchronous medium. Each student submits a thorough presentation of their completed homework, which the instructor grades for completeness and accuracy. The instructor then replies back to the student with challenge questions, and also answers questions the student may have. As with the previous formats, the student receives another grade assessing their comprehension of the subject matter by the close of the correspondence dialogue.

Methods of instruction (continued)

In all formats, students are held accountable for completion of their homework, “completion” being defined as successfully interpreting the given information from source material (e.g. accurate outlines of reading or video assignments) and constructive effort to solve given problems. It must be understood in an inverted learning environment that students *will* have legitimate questions following a homework assignment, and that it is therefore unreasonable to expect mastery of the assigned subject matter. What is reasonable to expect from each and every student is a basic outline of the source material (reading or video assignments) complete with major terms defined and major concepts identified, plus a good-faith effort to solve every problem. Question 0 (contained in every worksheet) lists multiple strategies for effective study and problem-solving.

Sample rubric for pre-assessments

- **No credit** = Any homework question unattempted (i.e. no effort shown on one or more questions); incomprehensible writing; failure to follow clear instruction(s)
- **Half credit** = Misconception(s) on any major topic explained in the assigned reading; answers shown with no supporting work; verbatim copying of text rather than written in your own words; outline missing important topic(s); unable to explain the outline or solution methods represented in written work
- **Full credit** = Every homework question answered, with any points of confusion clearly articulated; all important concepts from reading assignments accurately expressed in the outline and clearly articulated when called upon by the instructor to explain

The minimum expectation at the start of every student-instructor session is that all students have made a good-faith effort to complete 100% of their assigned homework. This does not necessarily mean all answers will be correct, or that all concepts are fully understood, because one of the purposes of the meeting between students and instructor is to correct remaining misconceptions and answer students’ questions. However, experience has shown that without accountability for the homework, a substantial number of students will not put forth their best effort and that this compromises the whole learning process. Full credit is reserved for good-faith effort, where each student thoughtfully applies the study and problem-solving recommendations given to them (see Question 0).

Sample rubric for post-assessments

- **No credit** = Failure to comprehend one or more key concepts; failure to apply logical reasoning to the solution of problem(s); no contribution to the dialogue
- **Half credit** = Some misconceptions persist by the close of the session; problem-solving is inconsistent; limited contribution to the dialogue
- **Full credit** = Socratic queries answered thoughtfully; effective reasoning applied to problems; ideas communicated clearly and accurately; responds intelligently to questions and statements made by others in the session; adds new ideas and perspectives

The minimum expectation is that each and every student engages with the instructor and with fellow students during the Socratic session: posing intelligent questions of their own, explaining their reasoning when challenged, and otherwise positively contributing to the discussion. Passive observation and listening is not an option here – every student must be an active participant, contributing something original to every dialogue. If a student is confused about any concept or solution, it is their responsibility to ask questions and seek resolution.

Methods of instruction (continued)

If a student happens to be absent for a scheduled class session and is therefore unable to be assessed on that day's study, they may schedule a time with the instructor to demonstrate their comprehension at some later date (before the end of the quarter when grades must be submitted). These same standards of performance apply equally make-up assessments: either inspection of homework or a closed-book quiz for the pre-assessment, and either a Socratic dialogue with the instructor or another closed-book quiz for the post-assessment.

Methods of instruction (continued)

Lab sessions

In the lab portion of each course, students work in teams to install, configure, document, calibrate, and troubleshoot working instrument loop systems. Each lab exercise focuses on a different type of instrument, with a limited time period typically for completion. An ordinary lab session might look like this:

- (1) Start of practical (lab) session: announcements and planning
 - (a) The instructor makes general announcements to all students
 - (b) The instructor works with team to plan that day's goals, making sure each team member has a clear idea of what they should accomplish
- (2) Teams work on lab unit completion according to recommended schedule:
 - (First day) Select and bench-test instrument(s), complete prototype sketch of project
 - (One day) Connect instrument(s) into a complete loop
 - (One day) Each team member drafts their own loop documentation, inspection done as a team (with instructor)
 - (One or two days) Each team member calibrates/configures the instrument(s)
 - (Remaining days, up to last) Each team member troubleshoots the instrument loop
- (3) End of practical (lab) session: debriefing where each team reports on their work to the whole class

Troubleshooting assessments must meet the following guidelines:

- Troubleshooting must be performed *on a system the student did not build themselves*. This forces students to rely on another team's documentation rather than their own memory of how the system was built.
- Each student must individually demonstrate proper troubleshooting technique.
- Simply finding the fault is not good enough. Each student must consistently demonstrate sound reasoning while troubleshooting.
- If a student fails to properly diagnose the system fault, they must attempt (as many times as necessary) with different scenarios until they do, reviewing any mistakes with the instructor after each failed attempt.

file instructional

Distance delivery methods

Sometimes the demands of life prevent students from attending college 6 hours per day. In such cases, there exist alternatives to the normal 8:00 AM to 3:00 PM class/lab schedule, allowing students to complete coursework in non-traditional ways, at a “distance” from the college campus proper.

For such “distance” students, the same worksheets, lab activities, exams, and academic standards still apply. Instead of working in small groups and in teams to complete theory and lab sections, though, students participating in an alternative fashion must do all the work themselves. Participation via teleconferencing, video- or audio-recorded small-group sessions, and such is encouraged and supported.

There is no recording of hours attended or tardiness for students participating in this manner. The pace of the course is likewise determined by the “distance” student. Experience has shown that it is a benefit for “distance” students to maintain the same pace as their on-campus classmates whenever possible.

In lieu of small-group activities and class discussions, comprehension of the theory portion of each course will be ensured by completing and submitting detailed answers for *all* worksheet questions, not just passing daily quizzes as is the standard for conventional students. The instructor will discuss any incomplete and/or incorrect worksheet answers with the student, and ask that those questions be re-answered by the student to correct any misunderstandings before moving on.

Labwork is perhaps the most difficult portion of the curriculum for a “distance” student to complete, since the equipment used in Instrumentation is typically too large and expensive to leave the school lab facility. “Distance” students must find a way to complete the required lab activities, either by arranging time in the school lab facility and/or completing activities on equivalent equipment outside of school (e.g. at their place of employment, if applicable). Labwork completed outside of school must be validated by a supervisor and/or documented via photograph or videorecording.

Conventional students may opt to switch to “distance” mode at any time. This has proven to be a benefit to students whose lives are disrupted by catastrophic events. Likewise, “distance” students may switch back to conventional mode if and when their schedules permit. Although the existence of alternative modes of student participation is a great benefit for students with challenging schedules, it requires a greater investment of time and a greater level of self-discipline than the traditional mode where the student attends school for 6 hours every day. No student should consider the “distance” mode of learning a way to have more free time to themselves, because they will actually spend more time engaged in the coursework than if they attend school on a regular schedule. It exists merely for the sake of those who cannot attend during regular school hours, as an alternative to course withdrawal.

Metric prefixes and conversion constants

- **Metric prefixes**

- Yotta = 10^{24} Symbol: Y
- Zeta = 10^{21} Symbol: Z
- Exa = 10^{18} Symbol: E
- Peta = 10^{15} Symbol: P
- Tera = 10^{12} Symbol: T
- Giga = 10^9 Symbol: G
- Mega = 10^6 Symbol: M
- Kilo = 10^3 Symbol: k
- Hecto = 10^2 Symbol: h
- Deca = 10^1 Symbol: da
- Deci = 10^{-1} Symbol: d
- Centi = 10^{-2} Symbol: c
- Milli = 10^{-3} Symbol: m
- Micro = 10^{-6} Symbol: μ
- Nano = 10^{-9} Symbol: n
- Pico = 10^{-12} Symbol: p
- Femto = 10^{-15} Symbol: f
- Atto = 10^{-18} Symbol: a
- Zepto = 10^{-21} Symbol: z
- Yocto = 10^{-24} Symbol: y



- **Conversion formulae for temperature**

- $^{\circ}\text{F} = (^{\circ}\text{C})(9/5) + 32$
- $^{\circ}\text{C} = (^{\circ}\text{F} - 32)(5/9)$
- $^{\circ}\text{R} = ^{\circ}\text{F} + 459.67$
- $\text{K} = ^{\circ}\text{C} + 273.15$

Conversion equivalencies for distance

- 1 inch (in) = 2.540000 centimeter (cm)
- 1 foot (ft) = 12 inches (in)
- 1 yard (yd) = 3 feet (ft)
- 1 mile (mi) = 5280 feet (ft)

Conversion equivalencies for volume

1 gallon (gal) = 231.0 cubic inches (in³) = 4 quarts (qt) = 8 pints (pt) = 128 fluid ounces (fl. oz.) = 3.7854 liters (l)

1 milliliter (ml) = 1 cubic centimeter (cm³)

Conversion equivalencies for velocity

1 mile per hour (mi/h) = 88 feet per minute (ft/m) = 1.46667 feet per second (ft/s) = 1.60934 kilometer per hour (km/h) = 0.44704 meter per second (m/s) = 0.868976 knot (knot – international)

Conversion equivalencies for mass

1 pound (lbm) = 0.45359 kilogram (kg) = 0.031081 slugs

Conversion equivalencies for force

1 pound-force (lbf) = 4.44822 newton (N)

Conversion equivalencies for area

1 acre = 43560 square feet (ft²) = 4840 square yards (yd²) = 4046.86 square meters (m²)

Conversion equivalencies for common pressure units (either all gauge or all absolute)

1 pound per square inch (PSI) = 2.03602 inches of mercury (in. Hg) = 27.6799 inches of water (in. W.C.) = 6.894757 kilo-pascals (kPa) = 0.06894757 bar

1 bar = 100 kilo-pascals (kPa) = 14.504 pounds per square inch (PSI)

Conversion equivalencies for absolute pressure units (only)

1 atmosphere (Atm) = 14.7 pounds per square inch absolute (PSIA) = 101.325 kilo-pascals absolute (kPaA) = 1.01325 bar (bar) = 760 millimeters of mercury absolute (mmHgA) = 760 torr (torr)

Conversion equivalencies for energy or work

1 british thermal unit (Btu – “International Table”) = 251.996 calories (cal – “International Table”) = 1055.06 joules (J) = 1055.06 watt-seconds (W-s) = 0.293071 watt-hour (W-hr) = 1.05506 x 10¹⁰ ergs (erg) = 778.169 foot-pound-force (ft-lbf)

Conversion equivalencies for power

1 horsepower (hp – 550 ft-lbf/s) = 745.7 watts (W) = 2544.43 british thermal units per hour (Btu/hr) = 0.0760181 boiler horsepower (hp – boiler)

Acceleration of gravity (free fall), Earth standard

9.806650 meters per second per second (m/s²) = 32.1740 feet per second per second (ft/s²)

Physical constants

Speed of light in a vacuum (c) = 2.9979×10^8 meters per second (m/s) = 186,281 miles per second (mi/s)

Avogadro's number (N_A) = 6.022×10^{23} per mole (mol^{-1})

Electronic charge (e) = 1.602×10^{-19} Coulomb (C)

Boltzmann's constant (k) = 1.38×10^{-23} Joules per Kelvin (J/K)

Stefan-Boltzmann constant (σ) = 5.67×10^{-8} Watts per square meter-Kelvin⁴ ($\text{W}/\text{m}^2 \cdot \text{K}^4$)

Molar gas constant (R) = 8.314 Joules per mole-Kelvin (J/mol-K)

Properties of Water

Freezing point at sea level = $32^\circ\text{F} = 0^\circ\text{C}$

Boiling point at sea level = $212^\circ\text{F} = 100^\circ\text{C}$

Density of water at 4°C = $1000 \text{ kg}/\text{m}^3 = 1 \text{ g}/\text{cm}^3 = 1 \text{ kg}/\text{liter} = 62.428 \text{ lb}/\text{ft}^3 = 1.94 \text{ slugs}/\text{ft}^3$

Specific heat of water at 14°C = $1.00002 \text{ calories}/\text{g} \cdot ^\circ\text{C} = 1 \text{ BTU}/\text{lb} \cdot ^\circ\text{F} = 4.1869 \text{ Joules}/\text{g} \cdot ^\circ\text{C}$

Specific heat of ice $\approx 0.5 \text{ calories}/\text{g} \cdot ^\circ\text{C}$

Specific heat of steam $\approx 0.48 \text{ calories}/\text{g} \cdot ^\circ\text{C}$

Absolute viscosity of water at 20°C = 1.0019 centipoise (cp) = 0.0010019 Pascal-seconds (Pa·s)

Surface tension of water (in contact with air) at 18°C = 73.05 dynes/cm

pH of pure water at 25°C = 7.0 (*pH scale = 0 to 14*)

Properties of Dry Air at sea level

Density of dry air at 20°C and 760 torr = $1.204 \text{ mg}/\text{cm}^3 = 1.204 \text{ kg}/\text{m}^3 = 0.075 \text{ lb}/\text{ft}^3 = 0.00235 \text{ slugs}/\text{ft}^3$

Absolute viscosity of dry air at 20°C and 760 torr = 0.018 centipoise (cp) = 1.8×10^{-5} Pascal-seconds (Pa·s)

file conversion_constants

How to get the most out of academic reading:

- Articulate your thoughts as you read (i.e. “have a conversation” with the author). This will develop *metacognition*: active supervision of your own thoughts. Write your thoughts as you read, noting points of agreement, disagreement, confusion, epiphanies, and connections between different concepts or applications. These notes should also document important math formulae, explaining in your own words what each formula means and the proper units of measurement used.
- Outline, don’t highlight! Writing your own summary or outline is a far more effective way to comprehend a text than simply underlining and highlighting key words. A suggested ratio is one sentence of your own thoughts per paragraph of text read. Note points of disagreement or confusion to explore later.
- Work through all mathematical exercises shown within the text, to ensure you understand all the steps.
- Imagine explaining concepts you’ve just learned to someone else. Teaching forces you to distill concepts to their essence, thereby clarifying those concepts, revealing assumptions, and exposing misconceptions. Your goal is to create the simplest explanation that is still technically accurate.
- Write your own questions based on what you read, as though you are a teacher preparing to test students’ comprehension of the subject matter.

How to effectively problem-solve and troubleshoot:

- Rely on principles, not procedures. Don’t be satisfied with memorizing steps – learn *why* those steps work. Each one should make logical sense and have real-world meaning to you.
- Sketch a diagram to help visualize the problem. Sketch a graph showing how variables relate. When building a real system, always prototype it on paper and analyze its function *before* constructing it.
- Identify what it is you need to solve, identify all relevant data, identify all units of measurement, identify any general principles or formulae linking the given information to the solution, and then identify any “missing pieces” to a solution. Annotate all diagrams with this data.
- Perform “thought experiments” to explore the effects of different conditions for theoretical problems. When troubleshooting, perform *diagnostic tests* rather than just visually inspect for faults.
- Simplify the problem and solve that simplified problem to identify strategies applicable to the original problem (e.g. change quantitative to qualitative, or visa-versa; substitute easier numerical values; eliminate confusing details; add details to eliminate unknowns; consider simple limiting cases; apply an analogy). Often you can add or remove components in a malfunctioning system to simplify it as well and better identify the nature and location of the problem.
- Work “backward” from a hypothetical solution to a new set of given conditions.

How to manage your time:

- Avoid procrastination. Work now and play later, or else you will create trouble for yourself. Schedule your work appropriate to the *place* you’re in as well: e.g. don’t waste lab time doing things that could be done anywhere else, when there is work to be done that requires the lab.
- Eliminate distractions. Kill your television and video games. Study in places where you can concentrate.
- Use your “in between” time productively. Don’t leave campus for lunch. Arrive to school early. If you finish your assigned work early, begin working on the next assignment.

Above all, cultivate persistence. Persistent effort is necessary to master anything non-trivial. The keys to persistence are (1) having the desire to achieve that mastery, and (2) realizing challenges are normal and not an indication of something gone wrong. A common error is to equate *easy* with *effective*: students often believe learning should be easy if everything is done right. The truth is that mastery never comes easy!

file question0

Creative Commons License

This worksheet is licensed under the **Creative Commons Attribution 4.0 International Public License**. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/> or send a letter to Creative Commons, 171 Second Street, Suite 300, San Francisco, California 94105, USA. The terms and conditions of this license allow for free copying, distribution, and/or modification of all licensed works by the general public.

Simple explanation of Attribution License:

The licensor (Tony Kuphaldt) permits others to copy, distribute, display, and otherwise use this work. In return, licensees must give the original author(s) credit. For the full license text, please visit <http://creativecommons.org/licenses/by/4.0/> on the internet.

More detailed explanation of Attribution License:

Under the terms and conditions of the Creative Commons Attribution License, you may make freely use, make copies, and even modify these worksheets (and the individual “source” files comprising them) without having to ask me (the author and licensor) for permission. The one thing you must do is properly credit my original authorship. Basically, this protects my efforts against plagiarism without hindering the end-user as would normally be the case under full copyright protection. This gives educators a great deal of freedom in how they might adapt my learning materials to their unique needs, removing all financial and legal barriers which would normally hinder if not prevent creative use.

Nothing in the License prohibits the sale of original or adapted materials by others. You are free to copy what I have created, modify them if you please (or not), and then sell them at any price. Once again, the only catch is that you must give proper credit to myself as the original author and licensor. Given that these worksheets will be continually made available on the internet for free download, though, few people will pay for what you are selling unless you have somehow added value.

Nothing in the License prohibits the application of a more restrictive license (or no license at all) to derivative works. This means you can add your own content to that which I have made, and then exercise full copyright restriction over the new (derivative) work, choosing not to release your additions under the same free and open terms. An example of where you might wish to do this is if you are a teacher who desires to add a detailed “answer key” for your own benefit but *not* to make this answer key available to anyone else (e.g. students).

Note: the text on this page is not a license. It is simply a handy reference for understanding the Legal Code (the full license) - it is a human-readable expression of some of its key terms. Think of it as the user-friendly interface to the Legal Code beneath. This simple explanation itself has no legal value, and its contents do not appear in the actual license.

file license

Questions

Question 1

Read and outline the “Introduction to Optical Analyses” section of the “Continuous Analytical Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- Acknowledgement of previously learned concepts
- Descriptions of problem-solving strategies applied by the author

[file i04157](#)

Question 2

Read and outline the “Dispersive Spectroscopy” subsection of the “Optical Analyses” section of the “Continuous Analytical Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- Acknowledgement of previously learned concepts
- Descriptions of problem-solving strategies applied by the author

[file i04160](#)

Question 3

Suppose you take a source of *white light* and shine it through a *diffraction grating* or against a *reflection grating*. Qualitatively describe the spectrum of colors you would see as a result.

Suppose you take a source of *white light* and shine it through a transparent chamber holding a strong concentration of a gas, then shine the light exiting that chamber through a *diffraction grating* or against a *reflection grating*. Qualitatively describe the spectrum of colors you would see as a result.

Suppose you take a transparent chamber holding a strong concentration of a gas and electrically excite that gas using an arc, then shine the light exiting that chamber through a *diffraction grating* or against a *reflection grating*. Qualitatively describe the spectrum of colors you would see as a result.

Suggestions for Socratic discussion

- Comment on the relationships seen between colors in the spectrum and the chemical identity of the gas.
- Is the sun a perfect source of white light? Why or why not?
- Devise an instrument to identify the chemical composition of a gas by optical *emission*.
- Devise an instrument to identify the chemical composition of a gas by optical *absorption*.

[file i04161](#)

Question 4

Read and outline the “Fluorescence” section of the “Continuous Analytical Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative*. Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- Acknowledgement of previously learned concepts
- Descriptions of problem-solving strategies applied by the author

[file i04163](#)

Question 5

Using an ultraviolet (“black light”) LED connected to an appropriate dropping resistor and battery, demonstrate *fluorescence* in a darkened classroom with substances you bring to class (see list). Your instructor will provide the LEDs.

IMPORTANT SAFETY NOTE: ultraviolet light sources can damage your eyes, so never look directly into any UV light source!

$V_{forward} =$ _____ volts (measured using “diode test” feature of DMM)

$V_{battery} =$ _____ volts (measured using DMM)

$R_{dropping} =$ _____ ohms (calculated)

With the LED powered, test the following materials for fluorescence:

- Freshly-washed clothes
- Vitamin B-12 pill
- Club soda (tonic water, contains *quinine*)
- Postage stamps
- Chlorophyll (green, leafy plant)
- Petroleum jelly
- Agate (stone)
- Amber (resin)
- *Any others?*

Imagine you were tasked with designing an analyzer to detect the presence of any *one* of the substances listed above. Identify ways in which your analyzer could successfully ignore (“reject”) fluorescence from substances *other* than the one it is supposed to sense.

Suggestions for Socratic discussion

- Explain how we may use a digital multimeter to determine the forward voltage drop of an ultraviolet LED, for use in later resistor-sizing calculations.
- Explain how we may calculate the necessary dropping resistor value to keep the LED from burning out when powered by a battery whose voltage exceeds the maximum voltage rating for the LED.
- We know that fluorescence happens when a high-energy photon strikes a molecule and causes a lower-energy photon to be emitted. Can the reverse happen: a low-energy photon strikes a molecule and emits a higher-energy photon? Why or why not?

file i04162

Question 6

Read and outline the “Chemiluminescence” section of the “Continuous Analytical Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- Acknowledgement of previously learned concepts
- Descriptions of problem-solving strategies applied by the author

[file i04164](#)

Question 7

Read the “Continuous Emissions Monitoring (CEMS) Package With NGA 2000 Analyzers” datasheet from Rosemount (document PDS 103-101M.A01) and answer the following questions:

Identify the analytical technologies this particular CEMS instrument uses to detect the following chemical species:

- SO₂: _____
- CO: _____
- CO₂: _____
- Hydrocarbons: _____
- NO_x: _____
- O₂: _____

Explain how the “electrochemical/galvanic” cell works to sense oxygen.

Part of this analyzer system is a *sampling probe* to extract samples of gases from the exhaust stack of a combustion process (such as a large boiler or process heater). Identify some of this sampling system’s functions (i.e. what does the “sampling probe” do to the sample to ensure better analysis?).

Suggestions for Socratic discussion

- What is the purpose for analyzing stack gas composition?
- Which of the analytical sensors in this CEMS instrument contain consumable materials, and which do not?
- Suppose a combustion process was running *rich* (i.e. too much fuel per unit of air). What effects would this condition have on the relative concentrations of CO versus CO₂ gases in the exhaust?
- Do NO_x emissions increase under *lean*-burn conditions or under *rich*-burn conditions?
- Do hydrocarbon emissions increase under *lean*-burn conditions or under *rich*-burn conditions?
- How does a “paramagnetic” oxygen analyzer work?
- Is the “electrochemical/galvanic” sensor *potentiometric* (voltage-based) or *amperometric* (current-based)?

[file i04165](#)

Question 8

Calculate the molecular weight of regular air, knowing the molecular weight of nitrogen (N_2) is 28 amu, the molecular weight of oxygen (O_2) is 32 amu, the molecular weight of argon (Ar) is 40 amu, and that the percentages of each (by volume, which is practically the same as by molar concentration) are approximately as follows. Assume an air temperature of 75 degrees Fahrenheit:

- Nitrogen: 78%
- Oxygen: 21%
- Argon: 1%

Your calculation will provide a way to relate moles of air to *mass*.

Now, suppose an environmental analyzer happens to measure a concentration of sulfur dioxide (SO_2) in the air of 3 ppm (by volume). Calculate the mass of sulfur dioxide in every *pound* of air.

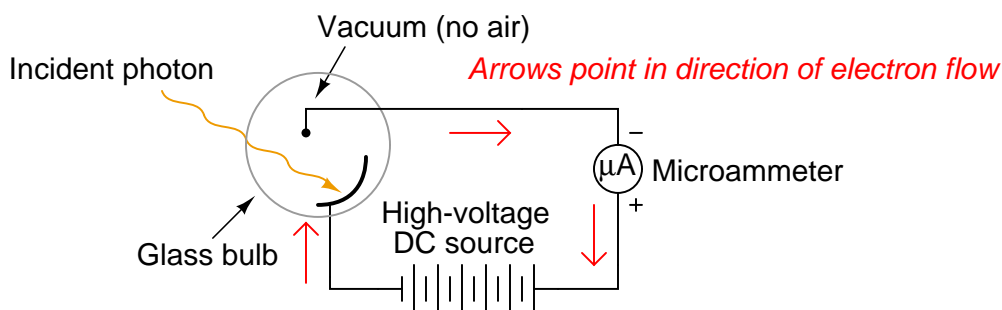
Suggestions for Socratic discussion

- Describe some of the problem-solving techniques you could (or did) apply to this question.

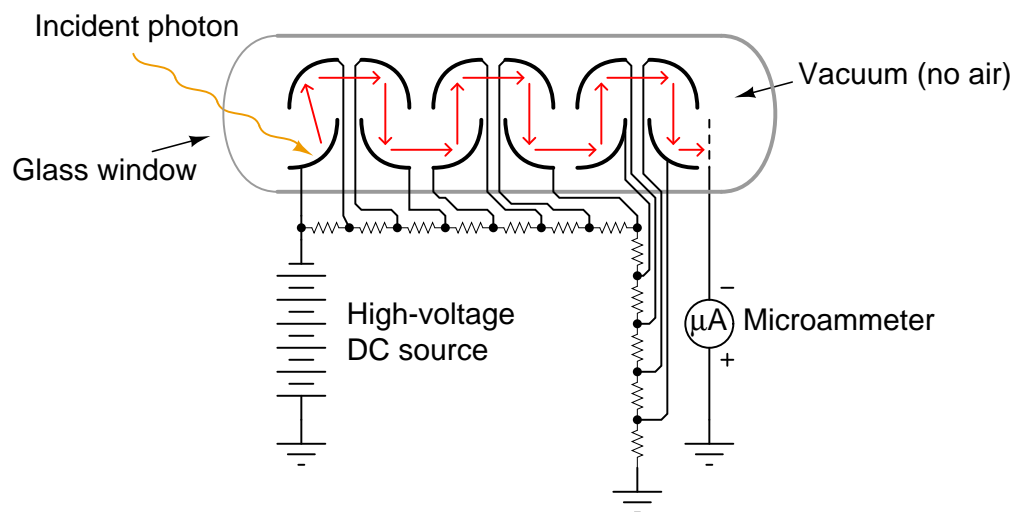
[file i04166](#)

Question 9

Many types of chemical analysis are based on the sensitive detection of light. One of the most sensitive devices available for converting a light signal into an electrical signal is a special type of electron tube known as a *photomultiplier tube*. The principle of operation for this device is something called the *photoelectric effect*, whereby electrons may be freed from a metal surface by the collision of a photon (a “particle” of light):



A true photomultiplier tube, though, has more than just two electrodes. There is the cathode (the most negative electrode in the tube) which emits electrons when struck by incident photons. The anode is the most positive electrode in the tube, collecting electrons released into the vacuum. Then, between the cathode and anode, are several other electrodes called *dynodes*, each one at a progressively more positive potential than the last:



Identify the electrodes in the above illustration, and then describe the purpose of having all those dynodes.

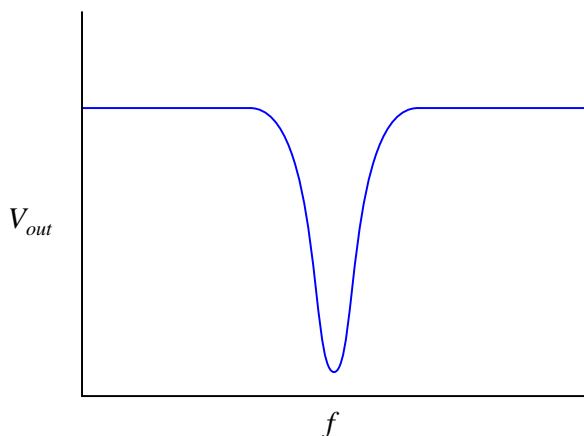
Suggestions for Socratic discussion

- What do you suppose would happen to the *gain* of a photomultiplier tube if the DC power supply voltage were to decrease? Explain your reasoning.
- What do you suppose would happen to the photomultiplier tube's performance if one of the voltage divider resistors were to fail open? Explain your reasoning.

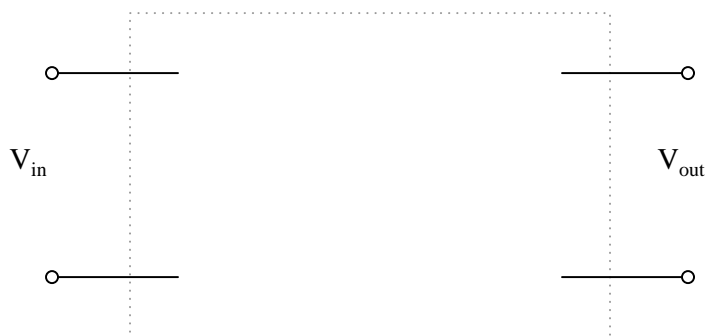
file i00658

Question 10

Identify the type of *filter circuit* (LP, HP, BP, or BS) with the following frequency response:



Now, sketch a schematic diagram for a filter circuit exhibiting this response:



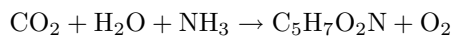
Suggestions for Socratic discussion

- Is there more than one circuit topology exhibiting this type of frequency response? If so, identify at least one other design that will respond the same way.

[file i00630](#)

Question 11

Microbes (bacteria) involved with the digestion of organic waste must form the material necessary to multiply their numbers from compounds available to them. Assuming a formulation of $C_5H_7O_2N$ for microbial cell matter, show how this compound may be formed from carbon dioxide, water, and ammonia:



In other words, *balance* this equation to show proper proportions of all compounds. Also, elaborate on whether you think this reaction is *exothermic* or *endothermic*.

[file i03705](#)

Question 12

A *Lambert-Beer* law relates the absorption of light by a substance to the path length of the light beam and the concentration of the absorbing substance:

$$A = abc$$

Where,

A = Absorbance

a = Extinction coefficient (a constant for any given substance and wavelength of light)

b = Path length of light traveling through the substance

c = Concentration of substance

Furthermore, the Lambert-Beer Law relates this quantity of “absorbance” to the measured intensities of light entering and exiting the absorbing sample:

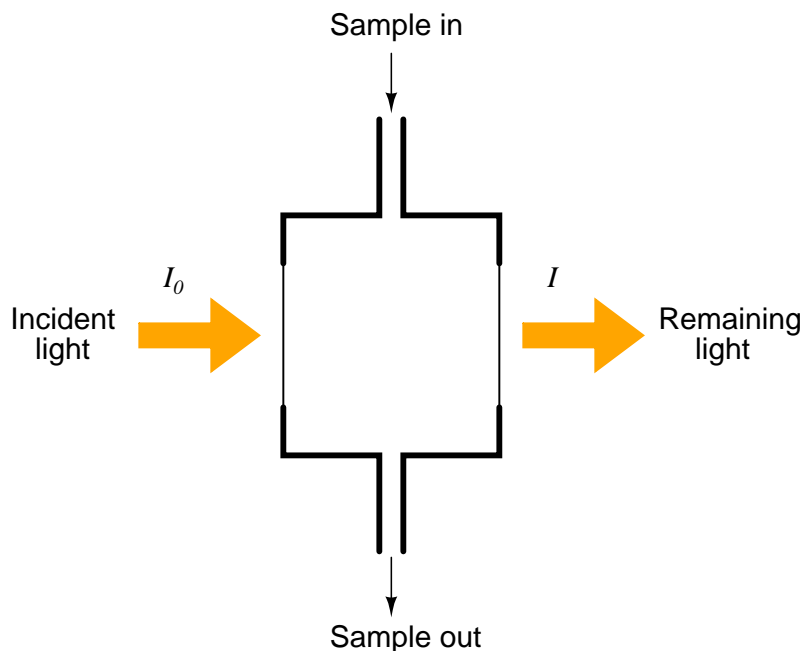
$$A = \log \left(\frac{I_0}{I} \right)$$

Where,

A = Absorbance

I_0 = Intensity of incoming (“incident”) light

I = Intensity of light leaving the sample



Based on either one or both of these equations, determine whether “absorbance” is directly related to a substance’s ability to attenuate a light beam, or if it is inversely related. In other words, does a strongly-attenuating substance have a small absorbance or a large absorbance?

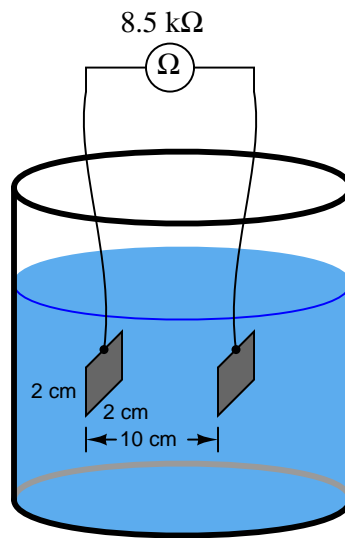
Next, combine these equations and use algebra to solve for the concentration of a substance (c) given the measured light intensities entering and exiting a sample.

If we wish to measure the concentration of a gas by optical absorption, and we know that the gas in question is a very weak absorber of light, how may we optimize the sensitivity of the instrument?

[file i00634](#)

Question 13

An ohmmeter registers a resistance of $8.5\text{ k}\Omega$ when connected between two metal plates immersed in a sample of water. The metal plates each measure 2 centimeters by 2 centimeters, and are separated by a distance of 10 centimeters:



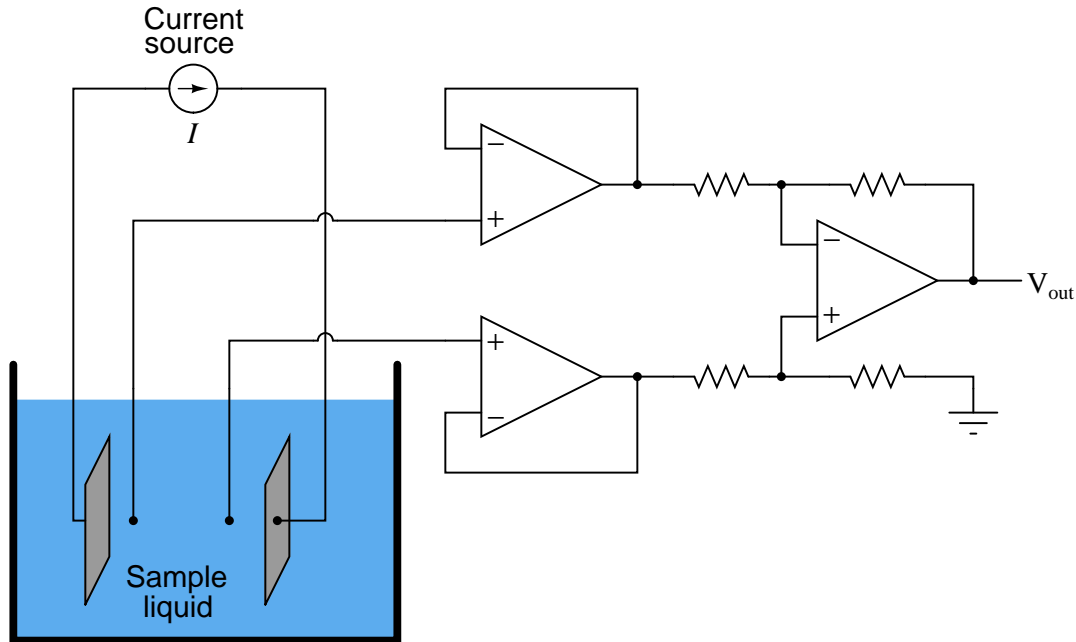
Calculate the specific conductivity of this water, expressed in units of microsiemens per centimeter ($\mu\text{S}/\text{cm}$):

Specific conductivity = _____ $\mu\text{S}/\text{cm}$

file i00907

Question 14

Examine the following four-electrode conductivity analyzer circuit, then answer the questions that follow:



- If the current source's output were to increase, would V_{out} *increase, decrease, or stay the same*?
- If the conductivity of the liquid were to increase, would V_{out} *increase, decrease, or stay the same*?
- If the two outer electrodes (connected to the current source) were to become plated with minerals or some other non-conducting coating, would V_{out} *increase, decrease, or stay the same*?
- If the sampled liquid is tap water, identify something you could do to the water to increase its conductivity.

[file i00910](#)

Question 15

Large combustion systems benefit greatly from *oxygen trim control*, keeping the ratio of air to fuel at just the right amount so that there is sufficient oxygen for complete combustion, and little (or no) more. In such systems, an oxygen analyzer samples flue gas for oxygen content and reports the concentration of exhaust oxygen to the air/fuel ratio control system, which then adjusts ("trims") the air/fuel ratio accordingly. By controlling air/fuel ratio as such, several advantages are realized:

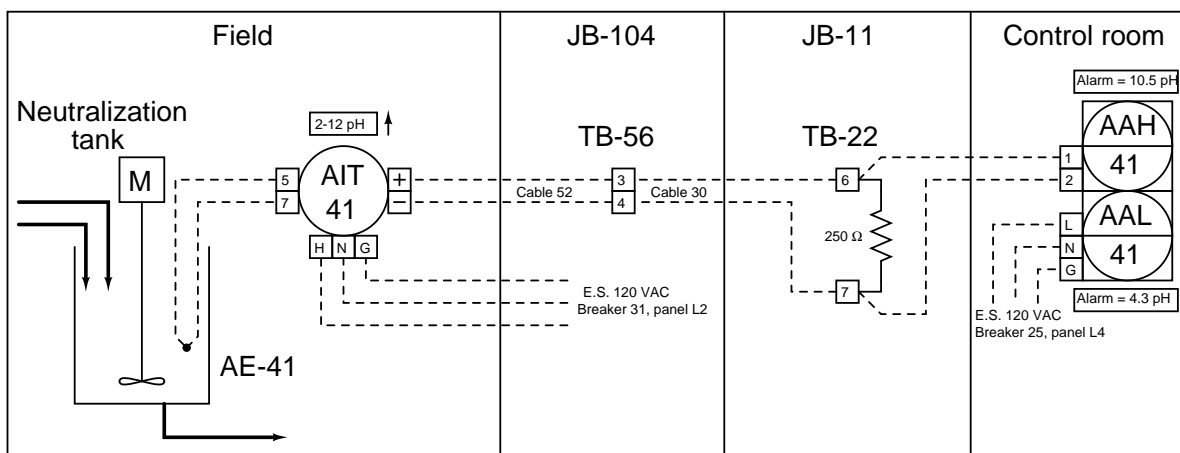
- Less heat energy lost out the exhaust (flue gases)
- Reduced NO_x emissions
- Fuel conservation

Explain *why* oxygen trim control, properly implemented, provides these advantages. Also, identify some hazards if an oxygen trim control system fails in such a way as to provide *insufficient* air to a combustion process.

[file i01827](#)

Question 16

This pH monitoring system triggers an alarm if the pH value of the process water in the neutralization tank drifts past either of two threshold (trip) values:



Answer the following questions about this pH alarm system:

- If a wire breaks loose at TB56-4, creating an “open” fault in the loop circuit, determine what will happen at the alarm unit (AAH, AAL-41) and also where you would expect to measure voltage in the loop circuit and where you would expect to measure *no* voltage in the loop circuit.
- If breaker #25 in panel L4 suddenly trips, what will happen in this system? Will an operator still be able to read the pH value of the water in the neutralization tank?
- If a fire breaks out near the conduit through which cable 52 runs, causing the plastic insulation around the conductors of cable 52 to melt and consequently causing those conductors to *short* together, what will happen in this system? Where would you expect to measure voltage in the loop circuit, and where would you expect to measure *no* voltage in the loop circuit? Where would you expect to measure current in the loop circuit, and where would you expect to measure *no* current in the loop circuit?
- Calculate the loop current value when the pH measures 6.8 inside the neutralization tank.

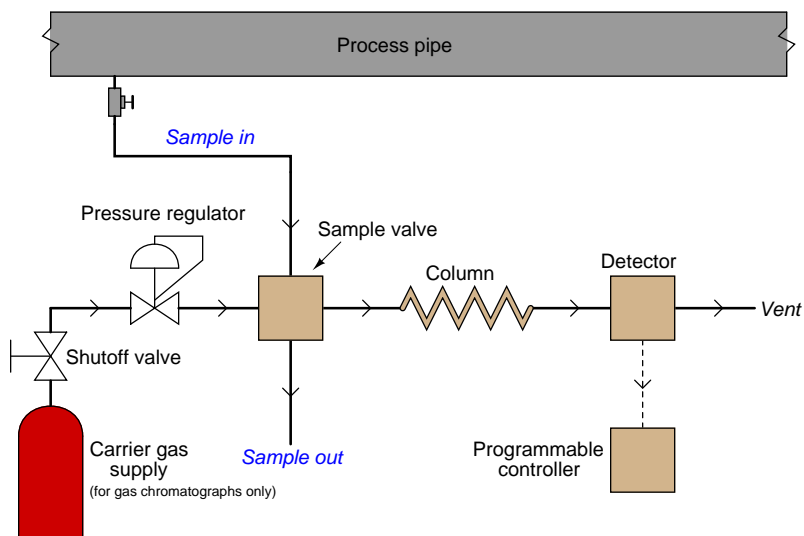
Suggestions for Socratic discussion

- For those who have studied pH measurement, explain why pH “neutralization” is an important control process in industry.
- How can we tell from this diagram whether the 4-20 mA output of transmitter AIT-41 is *active* or *passive* (i.e. *sourcing* or *sinking*)?

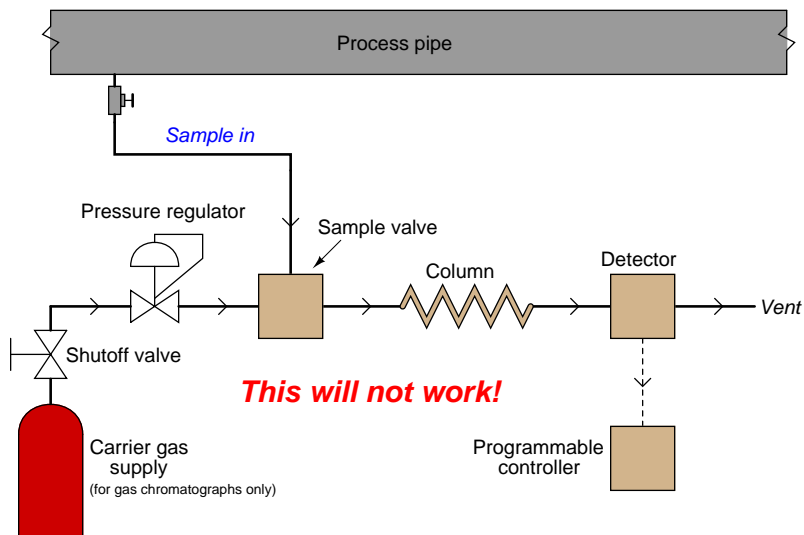
[file i00239](#)

Question 17

It is important for a process chromatograph that the sample injection valve have a continuously flowing source of sample fluid, as well as a continuous exit point for that flowing sample (i.e. a *sample supply* and a *sample waste* tube leading in and out of the sample injection valve):



If we only provided the sample valve with a single (entry) tube for the sample fluid, the chromatograph's operation would be seriously impaired:

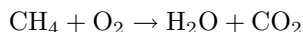


Explain why we need the sample to continuously flow *through* the sample valve when it is not injecting sample into the column.

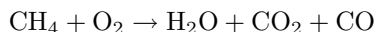
file i00676

Question 18

When a hydrocarbon such as methane (CH_4) is burned with oxygen (O_2), the *ideal* reaction products are simply water vapor (H_2O) and carbon dioxide gas (CO_2):

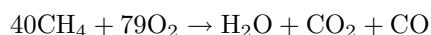
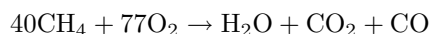


However, in practice we often find some carbon monoxide gas (CO) formed in addition to carbon dioxide gas (CO_2):



If you try to find a single set of proportions to “balance” the above equation, you will find the task impossible. Explain why.

Now, try balancing the following two equations, each one supplied with definite proportions of methane to oxygen:



Explain why these chemical equations are easier to balance. Also, identify whether it is a *rich* fuel/air mixture or a *lean* fuel/air mixture that produces more dangerous carbon monoxide in the exhaust of an engine burning natural gas.

[file i00667](#)

Question 19

When benzene (C_6H_6) is burned with oxygen (O_2) under ideal conditions, the products are water vapor (H_2O) and carbon dioxide (CO_2). Write a balanced equation showing all reactants and all reaction products in the proper proportions.

Suggestions for Socratic discussion

- Suppose benzene were burned in a “rich” environment (too little oxygen). What other combustion products might form then?

[file i00899](#)

Question 20

A relatively new technology for measuring the concentration of oxygen gas dissolved in water is called *dynamic luminescence quenching*. This is an optical technology, relying on the fluorescent properties of a substance containing “lumiphore” molecules. The basic concept is this: the lumiphore molecules readily fluoresce when exposed to a particular wavelength of light, but this fluorescence is affected by the presence of oxygen molecules. Oxygen near the lumiphore molecules tends to “quench” the excited state of those molecules after being exposed to the incident light, thereby prohibiting fluorescence. By repeatedly exciting the lumiphore molecules with pulses of light and measuring the fluorescent light returned by those molecules, the concentration of dissolved oxygen may be inferred.

Different colors of light are used by this type of analyzer: one color injected into the lumiphore molecules by a light source, and a different color of light emitted by the lumiphore molecules to be detected by a light sensor. One of these colors is *blue* and the other is *red*.

Based on what you know about the interaction of light with molecules, identify which color is emitted by the light source and which color is emitted by the lumiphore molecules. Also, determine whether the intensity of the light emitted by the lumiphore molecules is *directly proportional* to or *inversely proportional* to the concentration of dissolved oxygen in the liquid sample.

[file i00635](#)

Question 21

Read and outline the introduction and the “Single-Beam Analyzer” subsection of the “Non-Dispersive Light Detector Spectroscopy” section of the “Continuous Analytical Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative*. Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- Acknowledgement of previously learned concepts
- Descriptions of problem-solving strategies applied by the author

[file i04167](#)

Question 22

Read and outline the “Dual-Beam Analyzer” subsection of the “Non-Dispersive Luft Detector Spectroscopy” section of the “Continuous Analytical Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative*. Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- Acknowledgement of previously learned concepts
- Descriptions of problem-solving strategies applied by the author

[file i04168](#)

Question 23

Read and outline the “Luft Detectors” subsection of the “Non-Dispersive Luft Detector Spectroscopy” section of the “Continuous Analytical Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative*. Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- Acknowledgement of previously learned concepts
- Descriptions of problem-solving strategies applied by the author

[file i04171](#)

Question 24

Read and outline the “Filter Cells” subsection of the “Non-Dispersive Luft Detector Spectroscopy” section of the “Continuous Analytical Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

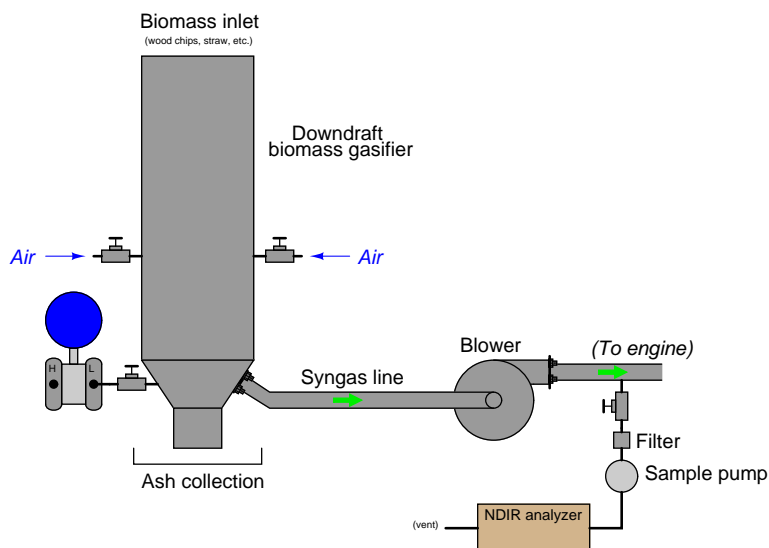
The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- Acknowledgement of previously learned concepts
- Descriptions of problem-solving strategies applied by the author

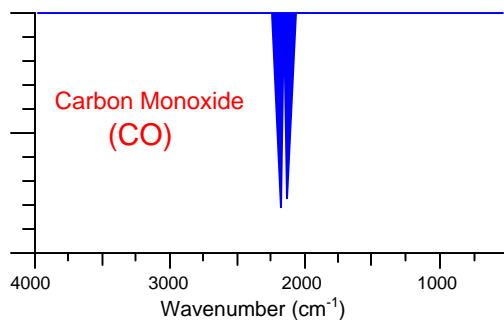
[file i04172](#)

Question 25

An NDIR gas analyzer is going to be used to measure the concentration of carbon monoxide (CO) in “synthesis gas” produced by a biomass gasification process. This process converts dry organic matter into a flammable gas stream which may be used to run an internal combustion engine:



Other gases known to be in this stream in large quantity include nitrogen (N_2) and hydrogen (H_2). The infrared absorption characteristics of carbon monoxide are shown in the following plot. Neither nitrogen nor hydrogen gas absorbs infrared light to any appreciable degree:



Identify which gases the “reference cell” and “detector” chambers of the NDIR analyzer should be filled with, and whether or not this analyzer will require filter cells. If filter cells are required, identify the gas(es) they should be filled with as well.

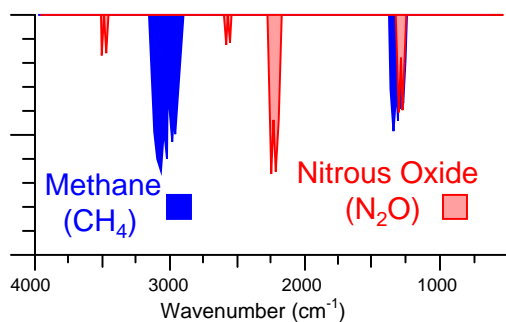
Suggestions for Socratic discussion

- Explain why the differential pressure transmitter has its *low-pressure* port connected to the gasifier (with the high-pressure port vented), rather than the other way around.
- A gasifier’s operation should be such that the production of flammable gases such as H_2 and CO are maximized. Explain how too much air admitted into the gasifier would cause a decrease in production of these fuel gases.

file i04173

Question 26

An NDIR gas analyzer is going to be used to measure the concentration of nitrous oxide (N_2O) in the presence of methane (CH_4). The infrared absorption characteristics for these gases are shown in the following plot (methane in blue; nitrous oxide in red):



Identify which gases the “reference cell” and “detector” chambers should be filled with, and whether or not this analyzer will require filter cells. If filter cells are required, identify the gas(es) they should be filled with as well.

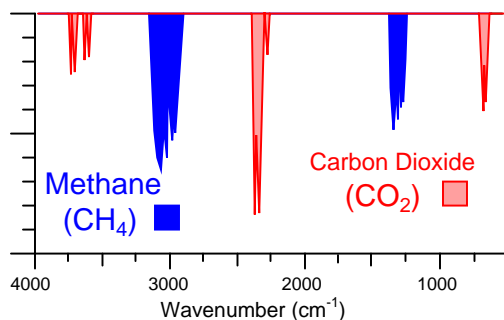
Suggestions for Socratic discussion

- Is there any reason the analyzer cannot be configured to measure the concentration of methane, with nitrous oxide as the interferent?
- Supposing CH_4 and N_2O are the only gases present in this process stream to any significant degree, are there alternative analyzer technologies you might suggest for the application?

[file i04174](#)

Question 27

An NDIR gas analyzer is going to be used to measure the concentration of carbon dioxide (CO_2) gas in a process stream composed mostly of methane (CH_4) gas. The infrared absorption characteristics of both gases are shown in the following plot (methane in blue; carbon dioxide in red):



Identify which gases the “reference cell” and “detector” chambers should be filled with, and whether or not this analyzer will require filter cells. If filter cells are required, identify the gas(es) they should be filled with as well.

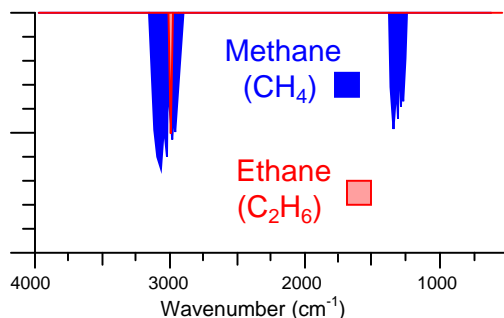
Suggestions for Socratic discussion

- Is there any reason the analyzer cannot be configured to measure the concentration of methane, with carbon dioxide oxide as the interferent?
- Supposing CH_4 and CO_2 are the only gases present in this process stream to any significant degree, are there alternative analyzer technologies you might suggest for the application?

[file i04175](#)

Question 28

An NDIR gas analyzer is going to be used to measure the percentage balance between methane (CH_4) gas and ethane (C_2H_6) gas in a process stream where *only* these two hydrocarbon gases exist, and the mixture is approximately half-and-half. The infrared absorption characteristics of both gases are shown in the following plot (methane in blue; ethane in red):



Identify which gases the “reference cell” and “detector” chambers should be filled with, and whether or not this analyzer will require filter cells. If filter cells are required, identify the gas(es) they should be filled with as well.

Also, identify whether it matters which of these two gases the analyzer is “sensitized” to, since the percentage balance between methane and ethane in this process stream is nearly 50%-50%.

Suggestions for Socratic discussion

- If this sample stream were analyzed by a gas chromatograph, which compound peak would appear *first* on the chromatogram, methane or ethane?
- Describe a full calibration procedure for this analyzer, by which you may check its LRV, URV, and also check to see that the interfering gas has negligible effect.

[file i04176](#)

Question 29

Read and outline the “Analyzer Sample Systems” section of the “Continuous Analytical Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- Acknowledgement of previously learned concepts
- Descriptions of problem-solving strategies applied by the author

[file i03728](#)

Question 30

With NDIR analyzers, the “fill” gas used inside the detector is supposed to sensitize the instrument to that same gas in the sample. For example, an NDIR analyzer having its detector chambers filled completely with CO₂ gas should exhibit a stronger response to CO₂ in the sample than to any other infrared light-absorbing gas in the sample.

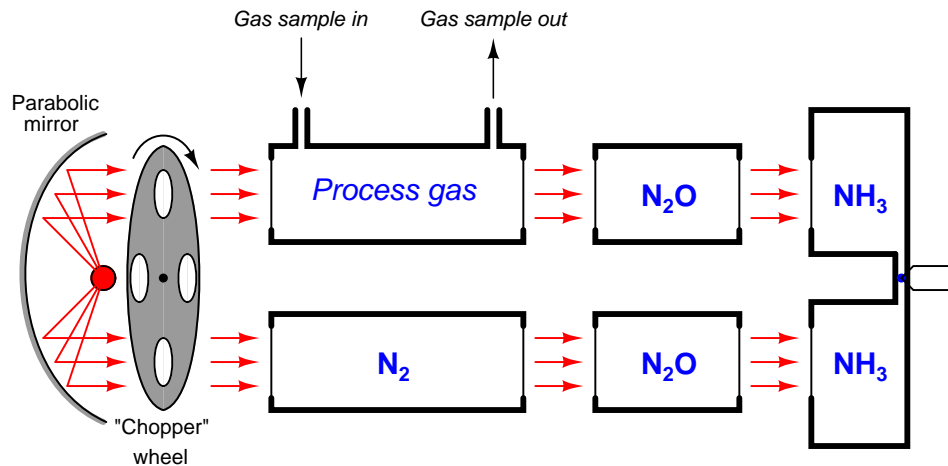
First, explain why this is so. What is it, exactly, about the fill gas inside an NDIR detector that makes it respond more strongly to that gas species than to other gas species in the sample?

Second, devise a “thought experiment” whereby you could prove that an NDIR instrument was sensitized to one particular gas species.

file i04169

Question 31

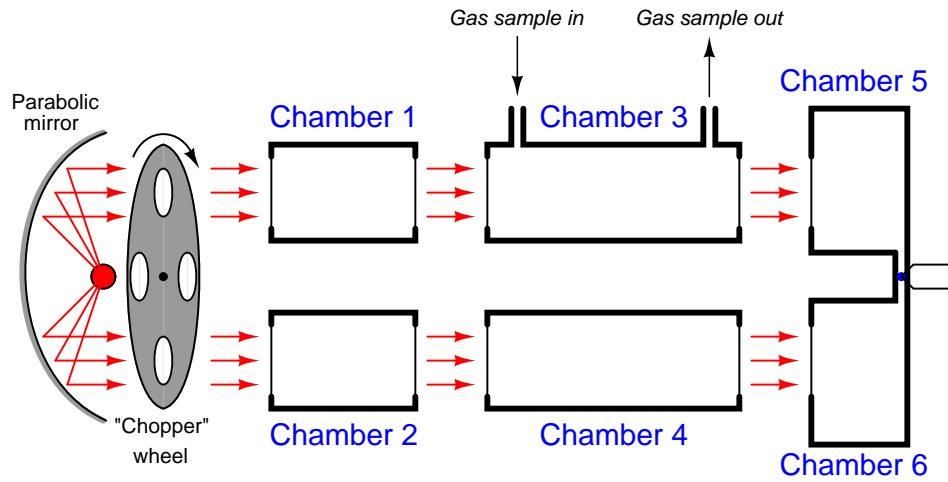
Identify which gas this NDIR analyzer is configured to measure, and which gas (if any) it has been *de-sensitized* to:



file i00132

Question 32

Determine the effect(s) of each fault – considered one at a time – on the operation of this nondispersive infrared (NDIR) analyzer:

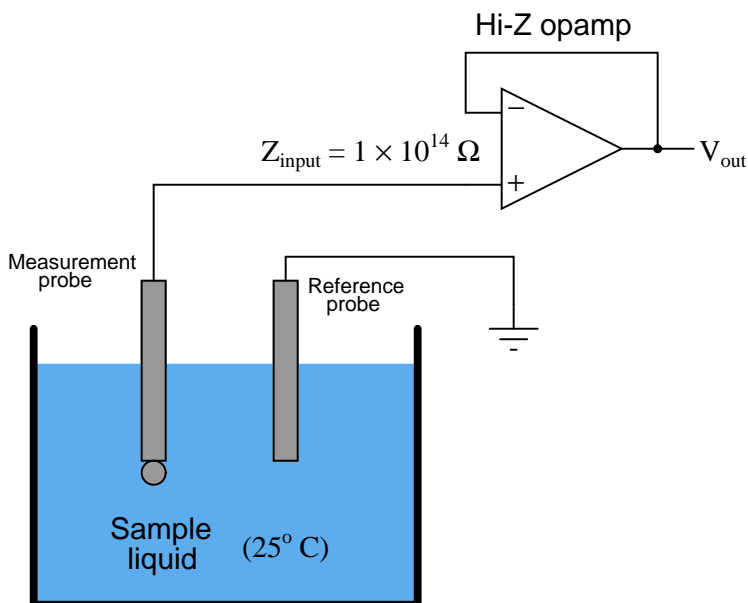


- Chopper wheel stops spinning
- Leak develops in chamber 2
- Leak develops in chamber 4
- Parabolic mirror cracks

file i00758

Question 33

Examine the following pH measurement circuit, then answer the questions that follow:



- Calculate the ideal output voltage of the two pH measurement probes if the solution's hydrogen ion molarity is 0.0056 M. $V_{\text{probe}} = \underline{\hspace{2cm}}$ volts
- Will the output voltage *increase*, *decrease*, or *stay the same* as what you just calculated if a very small amount of caustic substance is added to the liquid?
- Will the output voltage *increase*, *decrease*, or *stay the same* if the resistance of the measurement probe increases greatly due to coating?
- Calculate the actual output voltage of the opamp if the measurement electrode's resistance is 5.9×10^{12} ohms and the probes are generating a voltage of 103 mV. Assume that the reference probe's resistance is low enough to be ignored. $V_{\text{output}} = \underline{\hspace{2cm}}$ volts

[file i00911](#)

Question 34

Suppose we need to measure the concentration of substance X in a process gas stream. If we know that X happens to generate ions when burned, does this mean we can connect the output of a flame ionization detector (FID) to an indicator and have a guaranteed indication of substance X 's concentration? Why or why not?

[file i00927](#)

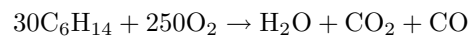
Question 35

Determine the proper number of ethanol molecules and oxygen molecules to combine for complete combustion (the only products being water and carbon dioxide). Express your answer in the form of a balanced chemical equation.

[file i00573](#)

Question 36

Balance this chemical reaction, showing the combustion of hexane (C_6H_{14}) to produce water vapor, carbon dioxide, and carbon monoxide. Note the quantities of hexane and oxygen already specified in the equation:



Next, calculate the proportions of fuel (hexane) to oxygen which will result in *no* carbon monoxide being formed.

Suggestions for Socratic discussion

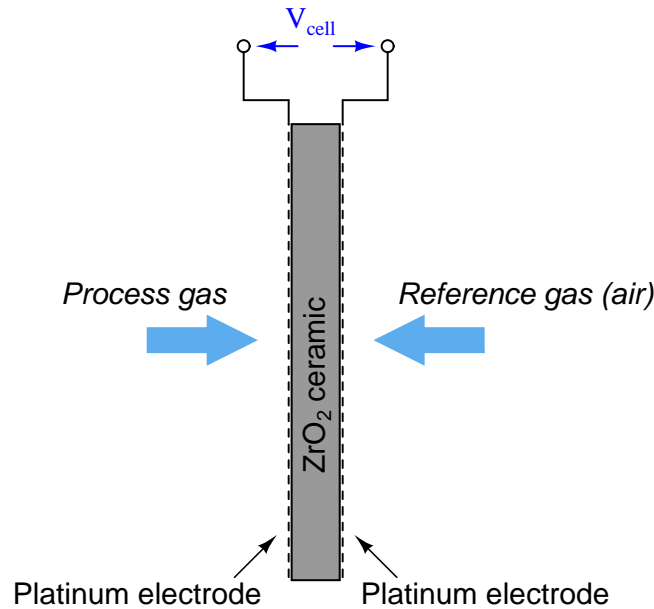
- Is carbon monoxide gas (a very *poisonous* substance) produced under *rich* burning conditions or *lean* burning conditions?

file i00456

Question 37

The measurement of oxygen content in the exhaust of a combustion heater (or boiler) is very important both for maximizing fuel efficiency and for minimizing pollution (specifically, the production of NO_x molecules). Ideally, a burner's exhaust gas will contain no oxygen, having consumed it all in the process of combustion with a perfect stoichiometric mix of fuel and air. In practice, the exhaust gas of an efficiently-controlled burner will be somewhere near 2%, as opposed to the normal 21% of ambient air.

One way to measure the oxygen content of hot exhaust is to use a *high-temperature zirconium oxide* detector. This detector is made of a “sandwich” of platinum electrodes on either side of a solid zirconium oxide electrolyte. One side of this electrochemical cell is exposed to the exhaust gas (process), while the other side is exposed to heated air which serves as a reference:



Voltage output by the cell is predicted by the Nernst equation:

$$V = \frac{RT}{nF} \ln \left(\frac{C_1}{C_2} \right)$$

Where,

V = Voltage produced across membrane due to ion exchange, in volts (V)

R = Universal gas constant (8.315 J/mol·K)

T = Absolute temperature, in Kelvin (K)

n = Number of electrons transferred per ion exchanged (unitless)

F = Faraday constant, in coulombs per mole (96,485 C/mol e^-)

C_1 = Concentration of measured solution, in moles per liter of solution (M)

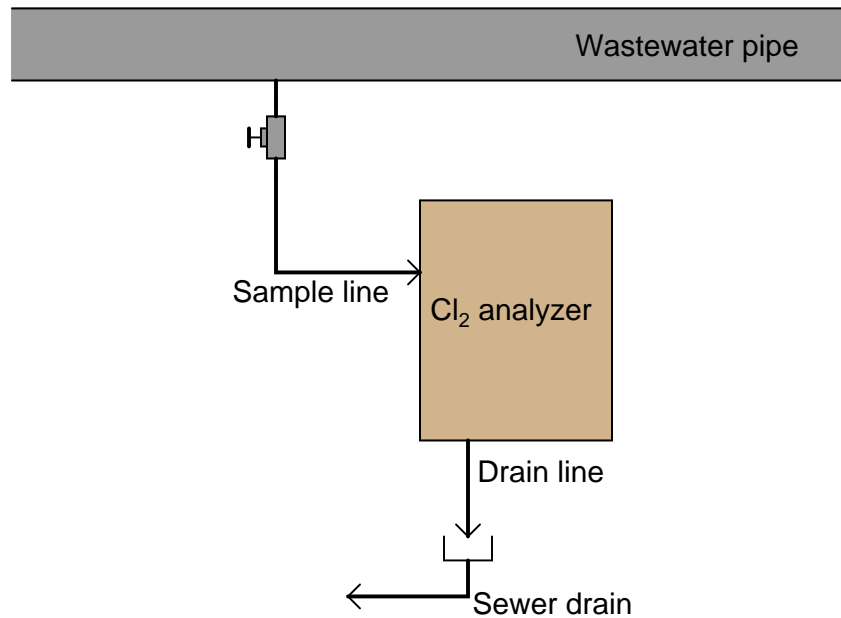
C_2 = Concentration of reference solution (on other side of membrane), in moles per liter of solution (M)

In order for the cell to function properly, it must be maintained at a high temperature (approximately 800° C). Accurate measurement and/or control of cell temperature is vital to accurate measurement of oxygen.

Explain why temperature is such a critical factor to the function of this sensor technology, and also characterize the relationship between measured oxygen content and cell output voltage (i.e. is voltage directly or inversely related to oxygen content?).

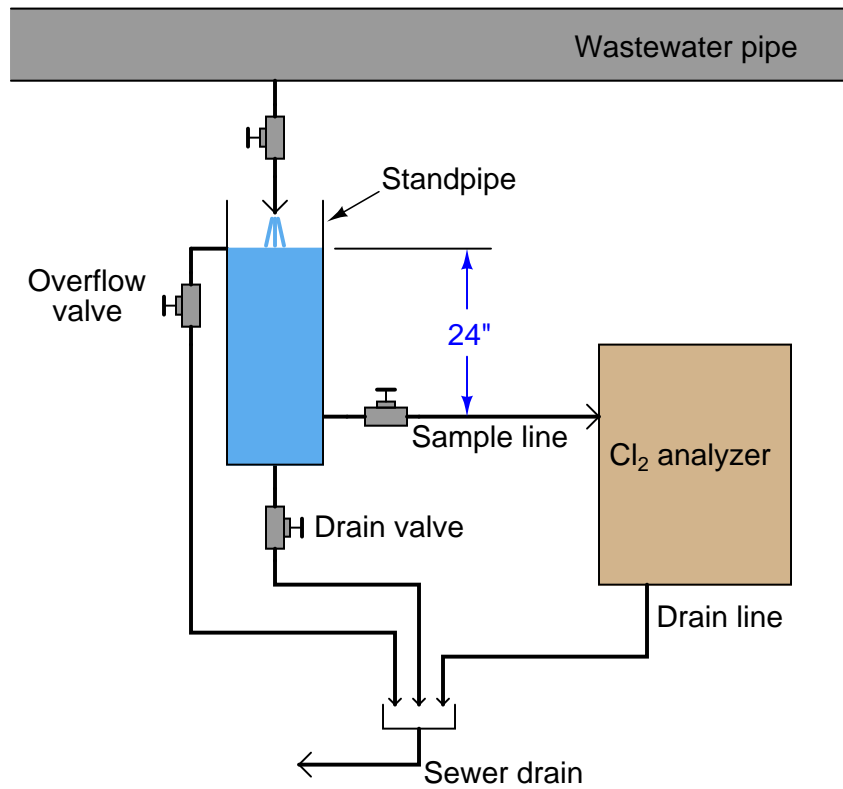
Question 38

A chlorine analyzer measures the chlorine concentration in wastewater, to determine whether or not there is sufficient chlorine dissolved in the wastewater to properly disinfect it prior to discharging into a natural body of water such as a river or bay:



There is a problem with this system, though: the valves and hoses inside the chlorine analyzer keep bursting because the sample pressure is too great. The analyzer is designed for a maximum sample water pressure of 1 PSI, and the pipe is pressurized to 10 PSI.

An instrument technician figures out a solution to this dilemma. His solution involves installing an open-top “standpipe” where water from the main wastewater pipe enters before flowing into the analyzer:

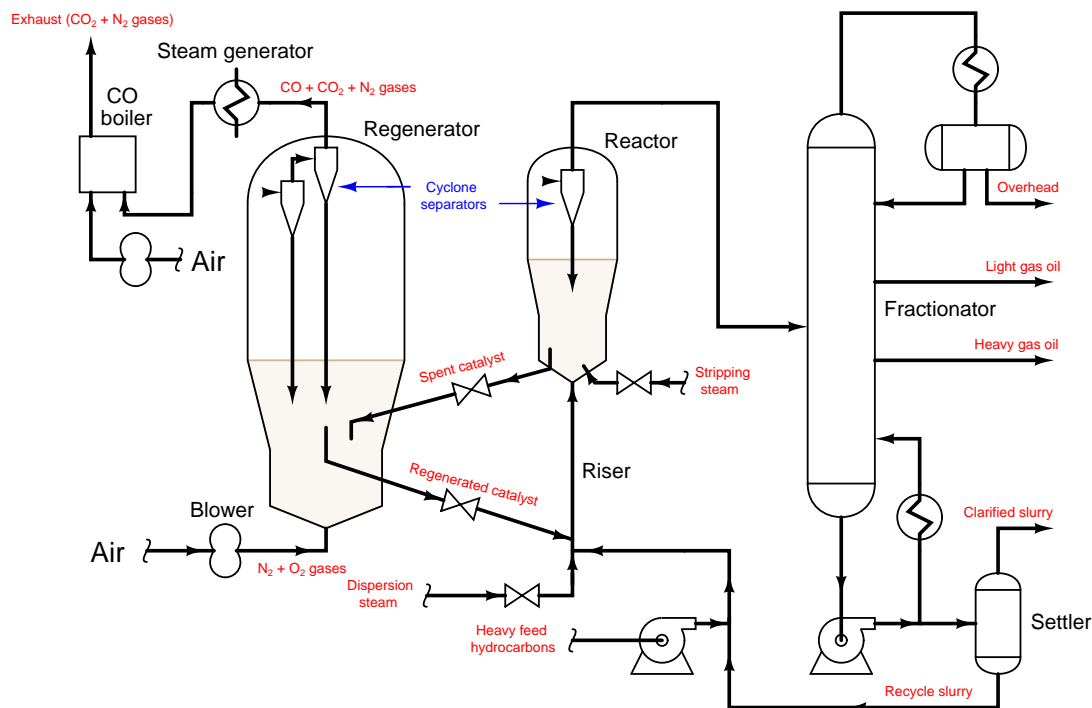


Describe how the technician's solution avoids the overpressure problem.

[file i00679](#)

Question 39

This simplified PFD shows the *fluid catalytic cracking* or *FCC* process, used extensively in American oil refineries. FCC processes employ finely-powdered catalyst to accelerate chemical reactions where heavy liquid hydrocarbon molecules are split (“cracked”) into lighter molecules, producing petroleum liquids with greater market value. This is not unlike the chemical process of *biomass gasification*, where solid fuel materials are broken down by intense heat into simpler, flammable gases with more flexible application as fuels:



The cracking reactions begin in the riser and continue in the reactor, with the catalyst powder carried along by the steam and hydrocarbon fluids. These reactions leave much of the catalyst powder covered with coke (solid carbon deposits) which limits its effectiveness as a catalyst. This “spent” catalyst falls by gravity into the regenerator, where it encounters a blast of air entering the bottom of the vessel, converting the carbon deposits into CO and CO_2 gases and “fluidizing” the catalyst powder once again so it flows freely back to the riser. The hot gases leaving the regenerator pass through a heat exchanger to boil water into useful steam, then pass to a burner where more air is introduced to convert the CO gas into CO_2 gas and generate more steam with the heat. Vapors leaving the top of the reactor vessel are distilled into their constituent compounds in the fractionator vessel, with the heaviest of them recycled back to the reactor for re-processing.

Identify appropriate instrumentation technologies for each of the following measurement points:

- Hydrocarbon feed flow
- Stripping steam flow measurement
- Regenerator air flow
- Regenerated catalyst flow
- Recycle slurry flow
- CO concentration to steam generator
- Oxygen concentration inside regenerator
- NO_x emissions from CO boiler

file i01120

Question 40

Question 41

Identify any general principles applicable to the topics within this course, and describe where you applied some of these principles. Examples include:

- Conservation of Energy
- Conservation of Mass
- Negative feedback
- Electrical principles:
- Unit conversion and dimensional analysis
 - Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL)
 - Ohm's Law
 - Properties of series and parallel networks
 - Capacitance and Inductance
 - Transformers
 - Filtering networks
 - Semiconductor switching

Next, identify any problem-solving strategies applicable to the problems you faced in this course, and describe where you applied them. Examples include:

- Performing “thought experiments”
- Re-drawing a complex diagram in simpler form
- Annotating a diagram to show relevant quantities
- Simplifying the problem, and solving that simpler version first
- Collecting data and analyzing for patterns

Suggestions for Socratic discussion

- One useful strategy is to maintain a *journal* of all you've learned in a course of study. Explore ways you could take the work you're already doing to prepare for homework (daily discussions with your instructor) and turn this into a journal or even a weblog (“blog”) for your own reflection and eventual use as a portfolio to showcase your capabilities to employers.
- Where exactly are the practice problem worksheets located on the *Socratic Instrumentation* website?
- Peruse the “feedback questions” for this (and/or past) course sections to identify any questions related to areas you would like to strengthen.

[file i00999](#)

Question 42

Explain why water (H_2O) will not ignite, despite the fact that it is comprised of hydrogen which is known to be extremely flammable and oxygen which is known to greatly accelerate combustion. With these two substances embedded within each water molecule, why isn't water explosive?

Suggestions for Socratic discussion

- Write a balanced chemical equation showing the electrolysis of water into hydrogen and oxygen gas. Identify whether the ΔH value for this equation will be a positive or a negative quantity, and what this quantity means.
- Relate your answer here to the case of carbon dioxide (CO_2), comprised of carbon (C – a flammable element) and oxygen (O – a combustion accelerant).

[file i01199](#)

Question 43

When hydrogen sulfide gas (H_2S) is burned with oxygen (O_2) under ideal conditions, the products are water vapor (H_2O) and sulfur dioxide (SO_2). Write a balanced equation showing all reactants and all reaction products in the proper proportions.

Also, determine how many moles of oxygen gas will be required to completely combust 15 moles of hydrogen sulfide gas.

[file i00898](#)

Question 44

If a hydrocarbon fuel is completely mixed with just the right amount of air and thoroughly burned, the only products of combustion will be carbon dioxide (CO_2) and water vapor (H_2O). If the mixing ratio is not stoichiometrically perfect, however, one or the other of the unburned reactants (either fuel or oxygen) will remain after combustion and be detectable in the exhaust gas stream.

Suppose a furnace operates with pure pentane (C_5H_{12}) as the fuel, and the balance of pentane to oxygen in the mix is as follows:



First, determine whether or not this mix is too rich (excessive fuel) or too lean (excessive oxygen). Then, determine what the output signal of an oxygen transmitter located in the exhaust pipe of this furnace will do (*increase, decrease, or remain the same*) if the mix changes to this:



Assume the oxygen transmitter is *direct-acting* (i.e. outputs a greater milliamp signal with greater oxygen concentration).

Suggestions for Socratic discussion

- A common product of high-temperature combustion is NO_x emissions (NO , NO_2 , etc.). Explain where the nitrogen comes from to form NO_x compounds, since pentane fuel contains no nitrogen.
- Will NO_x emissions (NO , NO_2 , etc.) in this combustion process increase, decrease, or remain at the same concentration level with the change in air/fuel ratio? Explain why.
- A common method for mitigating NO_x emissions (NO , NO_2 , etc.) is to react the exhaust gases with ammonia (NH_3). Identify the harmless byproducts of a complete NO_x -ammonia reaction.

[file i03638](#)

Question 45

Calculate the pH of the following aqueous solutions and the voltage (ideally) generated by a pH electrode pair, given the hydrogen ion molarity of each solution. Assume a solution temperature of 25°C :

$[\text{H}^+]$	pH	V_{probe}
0.001995 M		
6.309×10^{-7} M		
7.943×10^{-13} M		
3.881×10^{-5} M		
1.452×10^{-11} M		

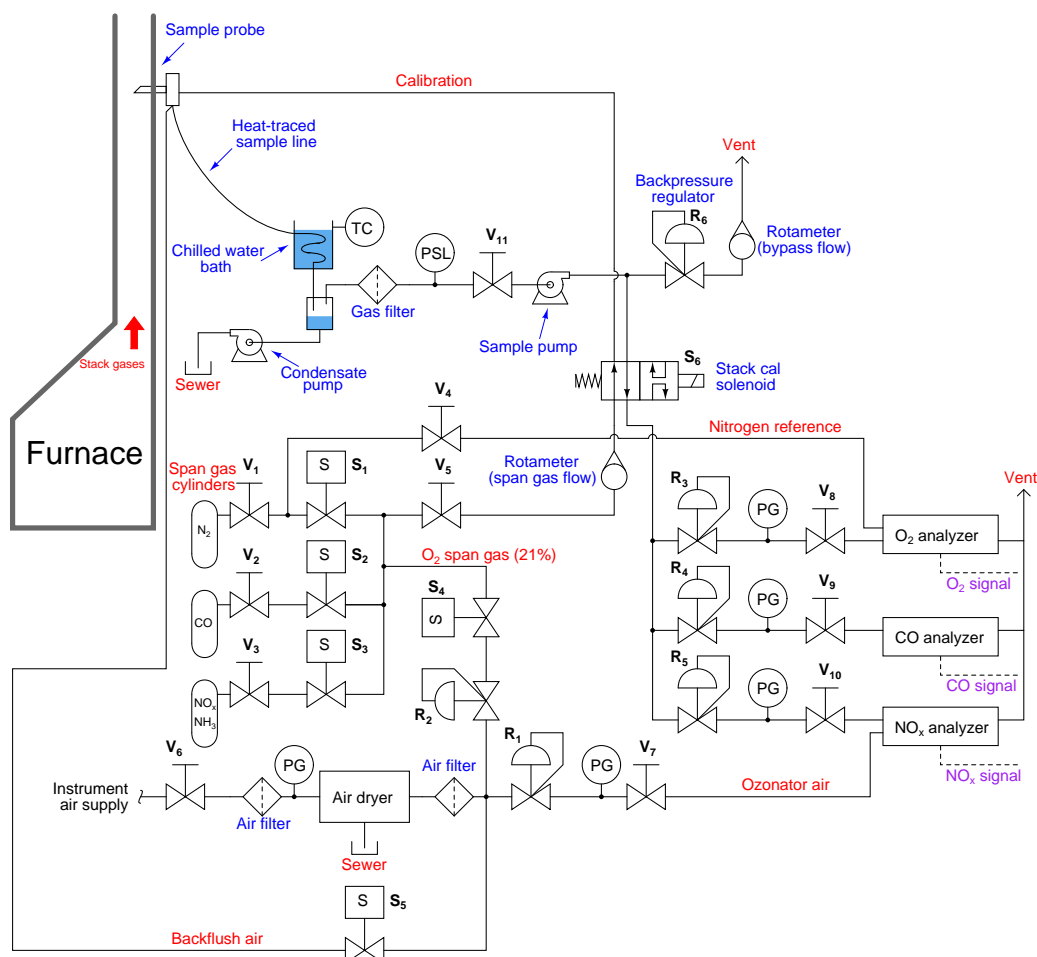
Suggestions for Socratic discussion

- How does a pH instrument tell the difference between a pH value above 7 versus one below 7?
- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

[file i03006](#)

Question 46

This CEMS has a problem, and you are called to diagnose it. The NO_x analyzer is reading nearly zero, while all other analyzers are registering normal quantities:



The first thing you check are the rotameters. The bypass flow registers a normal amount, while the span gas flow rate registers zero.

Identify the likelihood of each specified fault for this sample system. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this system.

Fault	Possible	Impossible
Valve V_1 shut		
Valve V_7 shut		
Valve V_8 shut		
Regulator R_1 failed low pressure		
Regulator R_6 failed low pressure		
Solenoid valve S_4 stuck open		
Solenoid valve S_6 stuck "on"		

Finally, identify the *next* diagnostic test or measurement you would make on this system. Explain how the result(s) of this next test or measurement help further identify the location and/or nature of the fault.

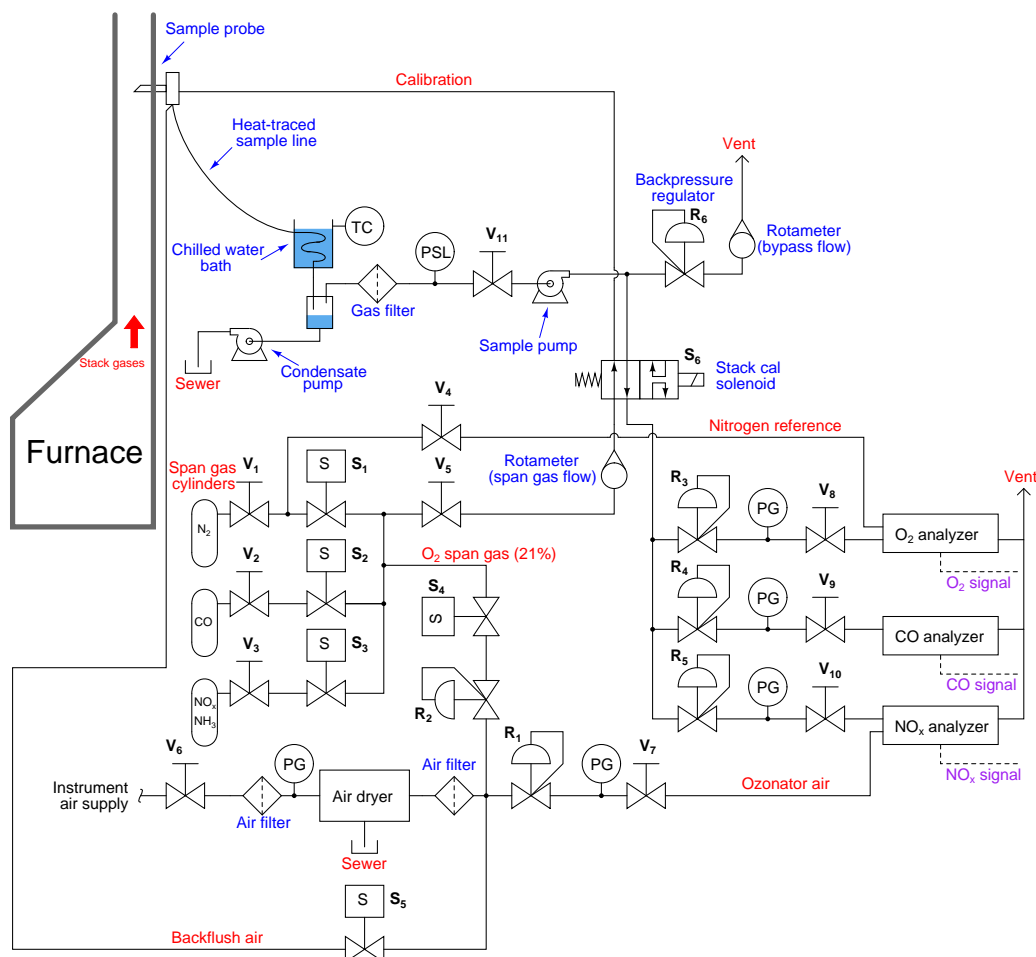
Suggestions for Socratic discussion

- What significance is there in the fact that the bypass flow rate is normal? In other words, what faults are ruled out by this fact, and what faults might still be possible in light of this fact?
- Explain the purpose of the *chilled water bath* in this sample system.
- Explain how this CEMS analyzer array is set up to be *self-calibrating*.
- Can you identify any other possible faults not listed in the table which could account for all we're seeing?

file i02338

Question 47

This CEMS has a problem, and you are called to diagnose it. The CO and NO_x analyzers are reading too low, and the O₂ analyzer is registering too high (nearly 14%, where its typical reading is 3% or less):



The first thing you check are the rotameters. The bypass flow registers a normal amount, while the span gas flow rate registers about half-scale. You wait for 15 minutes to see if anything changes, but both rotameters keep reading the same steady flow rates.

Identify the likelihood of each specified fault for this sample system. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this system.

Fault	Possible	Impossible
Valve V_1 shut		
Valve V_7 shut		
Valve V_8 shut		
Regulator R_1 failed high pressure		
Regulator R_6 failed low pressure		
Solenoid valve S_4 stuck open		
Solenoid valve S_6 stuck "on"		

Finally, identify the *next* diagnostic test or measurement you would make on this system. Explain how the result(s) of this next test or measurement help further identify the location and/or nature of the fault.

Suggestions for Socratic discussion

- What significance is there in the fact that the bypass flow rate is normal? In other words, what faults are ruled out by this fact, and what faults might still be possible in light of this fact?
- Explain the purpose of the *chilled water bath* in this sample system.
- Explain how this CEMS analyzer array is set up to be *self-calibrating*.
- Can you identify any other possible faults not listed in the table which could account for all we're seeing?

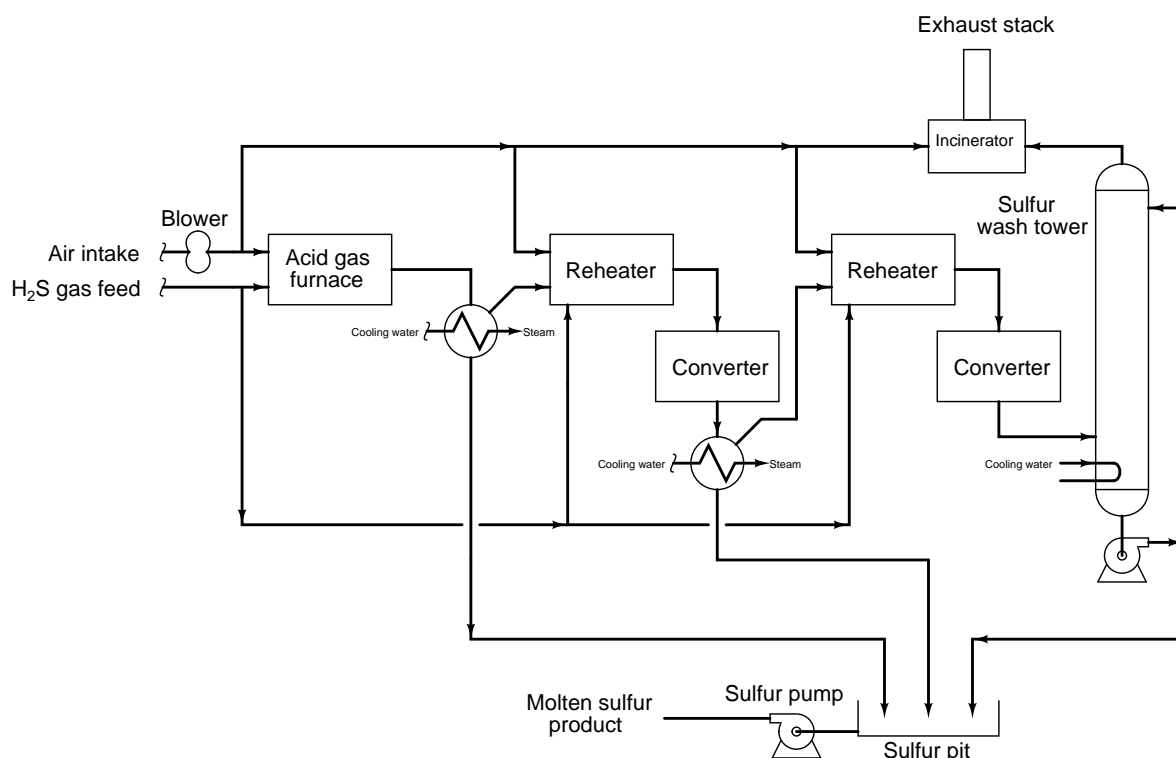
file i03729

Question 48

The so-called *Claus process* is widely used to convert hydrogen sulfide gas (H_2S) into elemental sulfur (S), turning a waste product of oil refining into a valuable feedstock for chemical processes. The conversion takes place in two steps, shown by these (unbalanced) chemical reactions:



A simplified PFD of the Claus process appears here:



Determine the following:

- Where each of the two chemical reactions occurs in the PFD.
- The meaning of the ΔH values stated next to each equation.
- Which of the two heat exchangers transfers more heat energy than the other.
- The principal danger of H_2S gas as it relates to human health.
- The probable types and locations of analytical transmitters in this process, and how their measurements might be used for control.
- Potential pollutants emitted by this process into the atmosphere.

Suggestions for Socratic discussion

- Identify suitable flowmeter technologies for each of the process flows shown in this PFD. Note that molten sulfur is hot (about 240 °F), viscous, and solidifies quickly when cooled to ambient temperature.

- Identify pipes carrying fluids into and out of various vessels in this process, and identify whether the temperature of the incoming or outgoing flow will be greater. Explain why, in each case.

[file i03726](#)

Question 49

An inventor claims to have built an automobile that runs on water. Opening the hood of this car, he points to a device he calls an “electrolyzer,” which uses electricity from the car’s battery to split ordinary water into hydrogen and oxygen gas. These gases are then fed into the car’s internal combustion engine as fuel and oxidizer, respectively. The car’s engine turns a generator which replenishes the battery powering the electrolyzer. His claim is that the only consumable is the water itself, and points to the fact that the electrolyzer must be periodically refilled with water after driving the car.

Explain how we can tell this is a fraudulent claim, based on what you know of chemistry and physics.
[file i03002](#)

Question 50

A sample of “table” salt has a mass of 1 kg. How many moles of salt is this equal to?

Now, suppose this exact quantity of salt were completely dissolved in water, resulting in a saltwater solution of 850 liters’ volume. Calculate the *molarity* of this saltwater solution.

Suggestions for Socratic discussion

- Identify a particular analyzer technology that might readily estimate the molarity of a salt-water solution, and identify different versions of this technology.

[file i00568](#)

Question 51

Match the appropriate analytical technologies to the following measurement applications. Note that more than one analytical technology may be applicable to any given application!

- _____ Measuring the concentration of oxygen in air
- _____ Measuring the concentration of specific complex aromatic hydrocarbons in air (no other compounds present)
- _____ Measuring the concentration of SO₂ gas in a process stream predominantly composed of CO₂
- _____ Measuring balance of argon and CO₂ in a welding shield gas supply system
- _____ Measuring concentration of NO gas, excluding NO₂ and NO₃
- _____ Measuring the heating value of a mixed fuel gas (a wide range of hydrocarbons)
- _____ Detecting flammable gases (of any kind) in air
- _____ Measuring the strength of a concentrated acid (no other compounds present but water)
- _____ Measuring balance of CO to CO₂ in synthesis gas (from a biomass gasifier), with hydrogen and nitrogen gases also present
- _____ Detecting the presence of crude oil in sea water
- _____ Detecting hydrogen sulfide gas (H₂S) in air with no other compounds present

A: Non-dispersive infrared (NDIR)

B: Gas chromatography (GC)

C: Conductivity

D: pH (glass probe)

E: Chemiluminescence

F: Fluorescence

G: Flame Ionization (FID)

H: Electrochemical (other than pH)

I: Paramagnetic

Suggestions for Socratic discussion

- As always, the most important point to discuss in questions such as this is *why*. Discuss the rationale for selecting each analyzer type for the given applications, and any caveats associated with those selections.
- Write a one-sentence explanation for each of these analyzer types, explaining how each one functions.

[file i03707](#)

Question 52

When ethane (C₂H₆) is burned with oxygen (O₂) under ideal conditions, the products are water vapor (H₂O) and carbon dioxide (CO₂). Write a balanced equation showing all reactants and all reaction products in the proper proportions.

[file i00900](#)

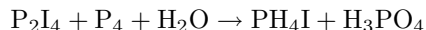
Question 53

When butane (C_4H_{10}) is burned with oxygen (O_2) under ideal conditions, the products are water vapor (H_2O) and carbon dioxide (CO_2). Write a balanced equation showing all reactants and all reaction products in the proper proportions.

[file i00904](#)

Question 54

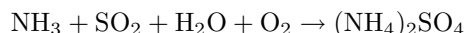
Balance the following chemical reaction:



[file i04304](#)

Question 55

Ammonium sulfate, having the chemical formula $(\text{NH}_4)_2\text{SO}_4$, may be produced from ammonia (NH_3), sulfur dioxide (SO_2), water (H_2O), and oxygen (O_2) by the following (unbalanced) chemical reaction:



Balance this chemical reaction, showing all the reactants and reaction products in their proper proportions.

[file i00111](#)

Question 56

One of the byproducts of high-temperature combustion using atmospheric air as the oxidizer is collectively referred to as NO_x : oxides of nitrogen. Nitrogen gas, which comprises the vast majority of the air we breathe, reacts with oxygen at high temperatures to form the following compounds:

- NO
- NO_2
- N_2O_4
- N_2O_5

These oxides of nitrogen can later form nitric acid in the atmosphere, and are a critical component of *smog*. Thus, reducing NO_x emissions in combustion processes is a significant environmental concern.

Oxygen trim control, which minimizes the amount of air drawn in to a combustion process, helps to minimize NO_x production: the less air brought into a fire, the less free nitrogen available, and the less oxygen left after combustion to combine with nitrogen to form NO_x . However, there are combustion processes where oxygen trim is not practical. Diesel and gas turbine engines are two such processes, because their air intake must be unrestricted for maximum thermodynamic efficiency (conversion of heat into mechanical energy).

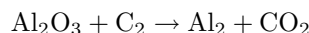
Another method of NO_x mitigation is *ammonia injection*, sometimes in the form of pure (anhydrous) ammonia gas, other times in the form of *urea* (liquid). In either case, ammonia is sprayed into the exhaust stream of the engine prior to a catalyst, and the resulting chemical reaction reduces NO_x molecules to harmless byproducts.

Determine this chemical reaction between ammonia (NH_3) and NO_x , and identify the harmless byproducts produced by it. Then, determine what sort of control system might control the flow of ammonia into the exhaust of an engine. In a vehicle engine control system, where a NO_x sensor installed in the exhaust pipe might be cost-prohibitive, determine what other variables might predict (feedforward) the amount of ammonia flow necessary to neutralize all the exhaust NO_x .

[file i01828](#)

Question 57

The *Hall* process for converting alumina (Al_2O_3) into metallic aluminum (Al) involves electrolysis with carbon electrodes. A powerful electric current forces carbon to join with the oxygen atoms in the alumina, forming carbon dioxide (CO_2) gas. The chemical equation describing this reaction is shown here:

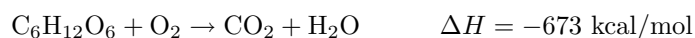


Balance this equation so that all molecules appear in their proper proportions. Also, determine how many pounds of carbon electrode must be consumed in this process to yield three tons (6000 pounds) of metallic aluminum, assuming perfect conversion efficiency.

[file i02353](#)

Question 58

Certain types of microbes (bacteria) facilitate the decomposition of organic matter in such a way that energy may be extracted. One way is *aerobic*, which means the bacteria are supplied with ample amounts of oxygen to metabolize the matter. The basic chemical reaction may be modeled by the oxidation of glucose ($\text{C}_6\text{H}_{12}\text{O}_6$), since this sugar is the base of the starches and cellulose found in plant matter. When glucose is oxidized (aerobic decomposition), the general (unbalanced) reaction is as follows:



Balance this chemical reaction to show the proper proportions of carbon dioxide and water vapor to glucose, and identify whether it is endothermic or exothermic.

A different way microbes may “digest” organic matter is in the absence of oxygen. This is called *anaerobic* decomposition, and the following (unbalanced) reaction shows glucose being converted into carbon dioxide and methane gases:



Balance this chemical reaction as well to show the proper proportions of carbon dioxide and methane to glucose, and identify whether it is endothermic or exothermic. Then, comment on which of these two reaction products is useful as a fuel (to be burned with oxygen).

Suggestions for Socratic discussion

- Explain why the negative ΔH values make sense in light of the fact that both of these reactions are facilitated by *bacteria* in dark environments.

[file i03897](#)

Question 59

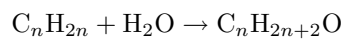
Balance each of the two following chemical reactions, depicting the *incomplete* combustion of methane gas with oxygen:



[file i03706](#)

Question 60

Dow Chemical patented a process for converting olefinic hydrocarbons (molecules having the general formula C_nH_{2n}) into alcohols by combination with water:



Re-write this chemical reaction showing the conversion of ethylene to ethanol, then once again showing the conversion of propylene to isopropanol.

Lab Exercise – introduction

Your task is to build, document, and troubleshoot an analytical measurement system consisting of a digital electronic analytical transmitter connected to an electronic indicator or recorder (I recommend something other than an indicating controller, just to make this system different). Process variable options include pH measurement, conductivity measurement, or any other analyzer available in the lab's collection.

The following table of objectives show what you and your team must complete within the scheduled time for this lab exercise. Note how some of these objectives are individual, while others are for the team as a whole:

Objective completion table:

Performance objective	Grading	1	2	3	4	Team
Team meeting and prototype sketch (do <i>first!</i>)	mastery	–	–	–	–	
Circuit design challenge	mastery					– – – –
Final loop diagram and system inspection	mastery					– – – –
Calibration (using chemical standard)	mastery	–	–	–	–	
Loop ranging ($\pm 1\%$ of span accuracy)	mastery					– – – –
Troubleshooting	mastery					– – – –
<i>Safety and professionalism</i>	deduction					
<i>Lab percentage score</i>	proportional					– – – –
Decommission and lab clean-up	(ungraded)	–	–	–	–	
Team tool locker inspection	(ungraded)	–	–	–	–	

The “proportional” score for this activity is based on the number of attempts require to master each objective. Every failed attempt is marked by a 0, and every pass by a 1. The total number of 1 marks divided by the total number of marks (both 1's and 0's) yields a percentage value. Team objectives count as part of every team member's individual score. The *Safety and professionalism* deduction is a flat –10% per instance, levied on occasions of unprofessional or unsafe conduct.

It is essential that your team plans ahead what to accomplish each day. A short (10 minute) team meeting at the beginning of each lab session is a good way to do this, reviewing what's already been done, what's left to do, and what assessments you should be ready for. There is a lot of work involved with building, documenting, and troubleshooting these working instrument systems!

As you and your team work on this system, you will invariably encounter problems. You should always attempt to solve these problems as a team before requesting instructor assistance. If you still require instructor assistance, write your team's color on the lab whiteboard with a brief description of what you need help on. The instructor will meet with each team in order they appear on the whiteboard to address these problems.

Lab Exercise – objectives and expectations

Each objective is assessed at the *mastery* level, which means it is not complete until it meets *all* expectations. Re-tries are allowed, but failed attempts will be recorded and factored into your score for this lab exercise.

Team meeting and prototype sketch

Meet with your instructor prior to any project construction, presenting the design as a prototype sketch. *Analyze the circuit represented in your prototype sketch, being sure to annotate the diagram with all expected voltages and currents, and identifying all electrical sources and loads. Be prepared to identify the effects of specific faults your instructor may propose in this circuit, applying principles such as series and parallel network properties, Kirchhoff's Laws, and Ohm's Law.* Read the lab exercise documentation in its entirety and discuss with your teammates prior to this meeting, where you may ask questions and clarify expectations with the instructor. Be prepared to answer questions from your instructor about this lab exercise, especially regarding any unique safety or procedural details described in the documentation.

Circuit design challenge

Design, build, and demonstrate the operation of a simple circuit based on random selections by the instructor, using a digital oscilloscope as the test instrument.

Final loop diagram and system inspection

Create a complete loop diagram of your team's completed system according to the ISA 5.1 standard, then show that the constructed system meets or exceeds all standards described in the lab exercise documentation.

Instrument calibration

Calibrate an analytical transmitter against a trusted chemical standard, using a trusted test instrument for verifying signal current values. Complete both As-Found and As-Left calibration tables, and tag when complete.

Loop ranging

Set the lower- and upper-range values (LRV and URV) in both the transmitter and indicator as randomly selected by the instructor, demonstrating accurate measurement of the process variable to within $\pm 1\%$ of span.

Troubleshooting

Logically diagnose the nature and location of a fault placed in a working system that your team did not build. This will be limited in time, with each student passing or failing individually.

Lab Exercise – objectives and expectations (continued)

Lab percentage score

Successful completion of the lab exercise requires demonstrated mastery of all objectives. A percentage value is based on the number of attempts required to achieve mastery on these objectives: the number of objectives divided by the number of total attempts equals the percentage. Thus, a perfect lab percentage score is possible only by completing all objectives on the first attempt. Marks given for team objectives factor into each individual's score. If one or more members of a team repeatedly compromise team performance, they may be removed from the team and required to complete remaining lab exercises alone.

Deductions from this percentage value will be levied for instances of unsafe or unprofessional conduct (see below), the final result being the lab percentage score.

Safety and professionalism (deduction)

In addition to completing the specified learning objectives in each lab exercise, each student is responsible for abiding by all lab safety standards and generally conducting themselves as working professionals (see the *General Values, Expectations, and Standards* page near the beginning of every worksheet for more detail). Expectations include maintaining an orderly work environment and returning all tools and test equipment by the end of every school day (team), as well as following clear instructions (e.g. instructions given in equipment manuals, lab documentation, verbally by the instructor), communicating with teammates, and productively managing time. As with the other objectives, chronic patterns of poor performance in this domain may result in the offending student being removed from the team. Deductions to the lab percentage score will *not* be made for performance already graded such as tardiness and attendance.

General format and philosophy

This lab exercise is *project-based*: the instructor serves as the project engineer, while each student's role is to implement the standards set for the project while budgeting time and resources to complete it by the deadline date. Students perform real work as part of the lab exercise, managing their work day and functioning much the same as they will on the job. The tools and equipment and materials used are all industry-standard, and the problems encountered are realistic. This instructional design is intentional, as it is proven effective in teaching project management skills and independent working habits.

When you require the instructor's assistance to answer a question or to check off an objective, write your name (or your team's name) on the lab room whiteboard. Questions take priority over checkoffs, so please distinguish questions from other requests (e.g. writing a question-mark symbol “?” after your name makes this clear). **There will be times when you must wait for extended periods** while the instructor is busy elsewhere – instant service is an impossibility. Adequate time does exist to complete the lab exercise if you follow all instructions, communicate well, and work productively. Use all “down time” wisely: filling it with tasks not requiring the instructor's assistance such as other lab objectives, homework, feedback questions, and job searches.

Remember that the lab facility is available to you at all hours of the school day. Students may perform non-hazardous work (e.g. circuit work at less than 30 volts, documentation, low air pressures, general construction not requiring power tools) at any time without the instructor's presence so long as that work does not disturb the learning environment for other students.

DO NOT TAKE SHORTCUTS when completing tasks! Learning requires focused attention and time on task, which means that most “shortcuts” actually circumvent the learning process. Read the lab exercise instructions, follow all instructions documented in equipment manuals, and follow all advice given to you by your instructor. Make a good-faith effort to solve all problems on your own *before* seeking the help of others. Always remember that this lab exercise is just a means to an end: no one *needs* you to build this project; it is an activity designed to develop marketable knowledge, skills, and self-discipline. In the end it is your *professional development* that matters most, not the finished project!

Lab Exercise – team meeting, prototype sketch, and instrument selection

An important first step in completing this lab exercise is to **meet with your instructor** as a team to discuss safety concerns, team performance, and specific roles for team members. If you would like to emphasize exposure to certain equipment (e.g. use a particular type of control system, certain power tools), techniques (e.g. fabrication), or tasks to improve your skill set, this is the time to make requests of your team so that your learning during this project will be maximized.

An absolutely essential step in completing this lab exercise is to work together as a team to **sketch a prototype diagram** showing what you intend to build. This usually takes the form of a simple electrical schematic and/or loop diagram showing all electrical connections between components, as well as any tubing or piping for fluids. This prototype sketch need not be exhaustive in detail, but it does need to show enough detail for the instructor to determine if all components will be correctly connected for their safe function.

For example, if you intend to connect field devices to a PLC (Programmable Logic Controller), your prototype sketch must show how those devices will connect to typical input/output terminals on the PLC, where electrical power will be supplied, etc. Prototype sketches need not show all intermediary connections between components, such as terminal blocks in junction boxes between the field device and the controller.

You should practice good problem-solving techniques when creating your prototype sketch, such as consulting equipment manuals for information on component functions and marking directions of electric current, voltage polarities, and identifying electrical sources/loads. Use this task as an opportunity to strengthen your analytical skills! Remember that you will be challenged in this program to do all of this on your own (during “capstone” assessments), so do not make the mistake of relying on your teammates to figure this out for you – instead, treat this as a problem *you* must solve and compare your results with those of your teammates.

Your team’s prototype sketch is so important that the instructor will demand you provide this plan before any construction on your team’s working system begins. *Any team found constructing their system without a verified plan will be ordered to cease construction and not resume until a prototype plan has been drafted and approved!* Similarly, you should not deviate from the prototype design without instructor approval, to ensure nothing will be done to harm equipment by way of incorrect connections. Each member on the team should have ready access to this plan (ideally possessing their own copy of the plan) throughout the construction process. Prototype design sketching is a skill and a habit you should cultivate in school and take with you in your new career.

When selecting field instruments for this lab exercise, choose a *process analyzer* (a pH analyzer is recommended) with electronic (4-20 mA) signal output. Many analyzer types, pH included, use remotely-mounted sensing elements along with the transmitter unit. Be sure to locate the appropriate sensing elements for your analyzer. For a pH analyzer, this takes the form of a *combination electrode* stored with its glass sensing bulb immersed in a liquid to prevent dehydration.

Consult documentation from the manufacturer’s website to identify how to properly wire, power, and calibrate the transmitter. Your instructor will check to see you have located and are familiar with the equipment manual(s).

After locating a suitable instrument and its associated documentation, you should qualitatively test it prior to installing it in your system. For a pH transmitter, this entails inserting the sensing electrode in a cup of tap water to see that it registers a pH value somewhere near 7.0 (it may be as low as 5.0 or as high as 8.0, depending on the water quality and the condition of the sensing electrode). If the transmitter fails to respond properly, consult the instructor for assistance before tagging it with a label explaining what it does (or what it fails to do). Be sure not to let the pH electrode become dry, as dehydration will very quickly ruin it!

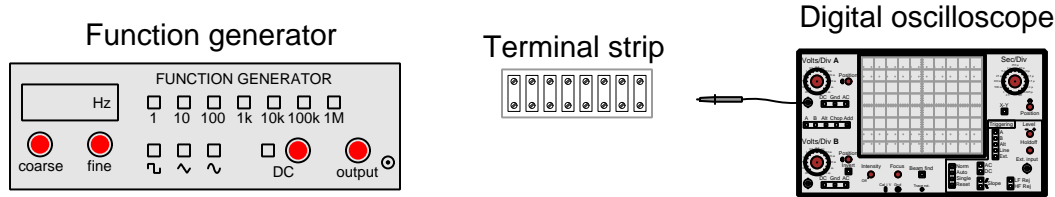
Bear in mind that analyzers powered by their own (non-loop) power source typically behave as current *sources*, and must be connected to the indicating instrument differently than a loop-powered device! Consult the manufacturer’s documentation for wiring details.

Planning a functioning system should take no more than an hour if the team is working efficiently, and will save you hours of frustration (and possible component destruction!).

Lab Exercise – circuit design challenge

Design, build, and test a circuit to fulfill one of the functions listed below (randomly selected by your instructor). All electrical connections must be made using a terminal strip (no twisted wires, crimp splices, wire nuts, spring clips, or “alligator” clips permitted). The only electrical source allowed in this circuit will be the function generator.

This exercise tests your ability to apply basic electrical principles to the design, construction, and proving (testing) of a simple passive circuit intended to fulfill a specific function, as well as your ability to use a digital oscilloscope and function generator.



The following components and materials will be available to you: **terminal strips** ; lengths of **hook-up wire** ; digital **oscilloscope** ; and **function generator**. You must provide all electronic components, tools, and digital multimeter (DMM) as well as a copy of this page for your instructor to mark objectives.

SEQUENCE: (1) Instructor chooses criteria; (2) You build and test circuit without any power sources at all; (3) Instructor observes you energizing the circuit for the first time; (4) You demonstrate to the instructor that the circuit fulfills its intended function.

Circuit function (randomly selected by the instructor):

- Voltage divider with total resistance between _____ and _____ ohms, with a division ratio of _____ : _____
- Low-pass filter with total impedance between _____ and _____ ohms, with a cutoff frequency of _____ Hz
- High-pass filter with total impedance between _____ and _____ ohms, with a cutoff frequency of _____ Hz
- Time-delay *charging* where the voltage rises to a value of _____ percent of the final (maximum) in _____ seconds
- Time-delay *discharging* where the voltage falls to a value of _____ percent of the initial (maximum) in _____ seconds
- Phase-shifter with total impedance between _____ and _____ ohms, where the output voltage lags the input voltage by _____ degrees
- Phase-shifter with total impedance between _____ and _____ ohms, where the output voltage leads the input voltage by _____ degrees

Study references: all your textbooks and lessons from the first year of the program. Also, specific modules contained in the *Modular Electronics Learning Project* which is found online at <http://www.ibiblio.org/kuphaldt/socratic/model/index.html>.

Lab Exercise – building the system

The Instrumentation lab is set up to facilitate the construction of working instrument “loops,” with over a dozen junction boxes, pre-pulled signal cables, and “racks” set up with 2-inch vertical pipes for mounting instruments. The only wires you should need to install to build a working system are those connecting the field instrument to the nearest junction box, and then small “jumper” cables connecting different pre-installed cables together within intermediate junction boxes.

After getting your prototype sketch approved by the instructor, you are cleared to begin building your system. Many analyzers are designed to be panel-mounted rather than field-mounted (attached to 2-inch pipes using special brackets and U-bolts). Feel free to set your panel-mount analyzer on a table or shelf in lieu of mounting it in an actual panel.

Select a specific loop controller or indicator to act as a display for the measured chemical concentration. Your instructor may choose the indicator for your team.

Finally, your analyzer system needs to have a loop number, so all instruments may be properly labeled. This loop number needs to be unique, so that another team does not label their instruments and cables the same as yours. One way to make your loop number unique is to use the equivalent resistor color-code value for your team’s color in the loop number. For example, if you are the “Red” team, your loop number could be “2”.

Common mistakes:

- Neglecting to consult the manufacturer’s documentation for field instruments (e.g. how to wire them, how to calibrate them).
- Mounting the field instrument(s) in awkward positions, making it difficult to reach connection terminals or to remove covers when installed.
- Failing to tug on each and every wire where it terminates to ensure a mechanically sound connection.
- Students working on portions of the system in isolation, not sharing with their teammates what they did and how. It is important that the whole team learns all aspects of their system!

Building a functioning system should take no more than one full lab session (3 hours) if all components are readily available and the team is working efficiently!

Lab Exercise – loop diagram and system inspection

Each team's system will undergo an inspection simultaneous with inspection of each team member's loop diagram. Team members will exchange diagrams with each other and then verify from those diagrams what the instructor sees when inspecting each and every panel and connection. *Please note that the "Lessons In Industrial Instrumentation" textbook describes good practices for construction and documentation.*

Construction Standards

- All construction must be *safe* (i.e. must not pose any unnecessary hazard to students or visitors). This includes electrical, chemical, thermal, pressure, and general safety hazards (e.g. trip hazards, cut hazards). *Unsafe construction will be dismantled upon discovery.*
- All electrical sources greater than 30 volts must be overcurrent-protected and all related wire connections must be guarded against accidental contact (e.g. use recessed terminals with no exposed metal).
- Proper use of colors for electrical power source wiring (e.g. red and black for DC + and –, black and white for AC "hot" and "neutral", green for earth ground).
- All metallic electrical enclosures must be bonded to earth ground for safety.
- Proper wire types and attachment to terminals (e.g. appropriate wire gauge for the expected current, use of stranded wire wherever possible, correct terminals crimped to ends of wires, no stray wire strands at any point).
- Attached wires must withstand being lightly pulled with fingers.
- Wire insulation must be intact (i.e. no bare wires anywhere).
- Panel wiring must be neat in appearance (e.g. all cables run directly from terminal block to nearest wire duct, with all excess wire length tucked inside wire duct).
- Wiring outside of panels should be run through conduit wherever possible.
- Correct tools must be used at all times. This includes the use of fixed-size wrenches rather than adjustable wrenches whenever possible, box-end over open-end wrenches whenever possible, and the correct type and size of screwdriver used to turn screw heads.
- All electrical components must be located to avoid exposure to liquids.
- All tube and pipe connections must be properly made (e.g. correct "swaging" of tube ends, no over- or under-tightened fittings, Teflon tape or pipe sealant used on all NPT threads).
- All manual controls (e.g. buttons, handles, knobs) must be accessible and function without undue effort.

Documentation Standards

- Loop diagrams must be drawn in accordance with ISA standard 5.1.
- Each instrument must have an appropriate ISA-standard tag name, and this tag name must be visible on the actual instrument (e.g. written on masking tape and attached to the instrument).
- Each signal cable and each signal tube must have an identifying label documented and attached. Long cables must be labeled at each end, as close to the termination points as practical.
- Each team must have its own unique loop number.
- Each instrument's (final) calibrated range must be shown.
- Each control valve's fail mode (e.g. fail-open, fail-closed) or action must be shown.
- All writing must be legible (i.e. easy for anyone to read). *Hint: large-format paper helps!*
- All instrument symbols must be appropriate to the device, function, and location. The large white-colored control panel and the DCS operator stations constitute the *main control room*. All electrical enclosures in the lab room are *auxiliary* locations, and everything else is considered a *field* location.
- Instrument functions shared within a common device must be represented by the "shared" symbol on the diagram (e.g. a controller that is part of a multi-loop control system such as a DCS). Shared controllers must have their identifying loop noted on the diagram (e.g. DCS South Loop #23).
- Any controller I/O cards must be labeled with slot number and channel number in addition to terminal numbers.

- Each location (e.g. field, junction box, control room) must be clearly delineated with vertical separation lines on the diagram.
- Each diagram must be sufficiently detailed so that no other student will have difficulty locating components (e.g. “Where is the controller for this loop?”) or determining important configuration parameters (e.g. range settings).

Sample diagrams are provided in this worksheet (immediately following the lab exercise documentation), and each student is urged to use these sample diagrams as references when drafting their own. The “Lessons In Industrial Instrumentation” textbook also describes ISA-standard documentation practices.

Common mistakes:

- Incorrect tag name format, using letters that do not conform to the ISA 5.1 standard (e.g. including “PLC” or “DCS” in a controller’s tag name).
- Forgetting that every instrument’s tag name in a loop must begin with the same letter, and that this first letter represents the process variable being measured/controlled.
- Forgetting to label all field instruments with their own tag names (e.g. AT-83).
- Failing to label termination points (e.g. terminal block screws) *exactly* as they are labeled in real life.
- Poor use of space on the diagram paper, causing some portions of the diagram to become “crowded” rather than all components being evenly spaced. *Hint: begin your diagram by sketching the field instrument at the far left of the paper and the control room instrument at the far right of the paper, then draw all other instruments and connections in between!*
- Forgetting to label all signal wires (see example loop diagrams).
- Forgetting to note all wire colors.
- Forgetting to put your name on the loop diagram!
- Leaving junction box cables outside of wire duct, looking messy.
- Leaving wire duct covers off.
- Basing your diagram off of a team-mate’s diagram, rather than closely inspecting the system for yourself.
- Not placing loop sheet instruments in the correct orientation (field instruments on the left, control room instruments on the right).

Creating and inspecting accurate loop diagrams should take no more than one full lab session (3 hours) if the team is working efficiently!

Lab Exercise – instrument calibration

Each team must calibrate the transmitter to ensure it interprets chemical composition accurately and outputs an accurate current. Then, each team member must configure the transmitter for a unique range (set the LRV and URV parameters) and scale the indicator to register in the proper engineering units (e.g. a pH analyzer ranged for 4 to 12 pH should actually register 4 to 12 pH back at the control room display). The accuracy of this ranging will be checked by the instructor stimulating the analyzer with a random sample while each student verifies the indicator display.

As in all cases where an instrument must be calibrated, you will need to check the instrument's response against one or more *standards*. In this case, the ideal standard to use for an analyzer is a chemical solution of precisely known composition. For pH instruments, this takes the form of *pH buffer solutions*, easily mixed from distilled water and pH buffer powder. For gas analyzers, this takes the form of either ambient air (21% oxygen content) or more likely bottled *calibration gases*. Chemical calibration standards will be made available by the instructor, and should be used sparingly as they tend to be expensive.

Document the accuracy of your transmitter's measurement at two (minimum) different points throughout its sensing range using these two tables:

As-Found calibration table

Applied concentration	Output signal (actual)	Output signal (ideal)	Error (% of span)

As-Left calibration table

Applied concentration	Output signal (actual)	Output signal (ideal)	Error (% of span)

$$\text{Error as \% of span} = \left(\frac{\text{Actual} - \text{Ideal}}{\text{Span}} \right) (100\%)$$

When finished calibrating your team's transmitter, be sure to place a calibration tag on it showing the range and the date it was calibrated. A set of calibration tags are shown here which you may cut out and tape to the transmitter after completing your calibration:

Cut out tag(s) with scissors, then affix to instrument(s) using transparent tape to show calibration:

CALIBRATED

By: _____ Date: _____

Range: _____

CALIBRATED

By: _____ Date: _____

Range: _____

CALIBRATED

By: _____ Date: _____

Range: _____

CALIBRATED

By: _____ Date: _____

Range: _____

Each student, however, must individually re-range the transmitter and the receiving instrument (indicator, controller, and/or recorder). Re-ranging an analyzer is usually done using a keypad and display on the transmitter unit, following the manufacturer's instructions. Each student's ranging is confirmed by the instructor by applying a random chemical concentration to the sensing element and verifying that the indicating controller reads the same (to within $\pm 1\%$ of span).

Common mistakes:

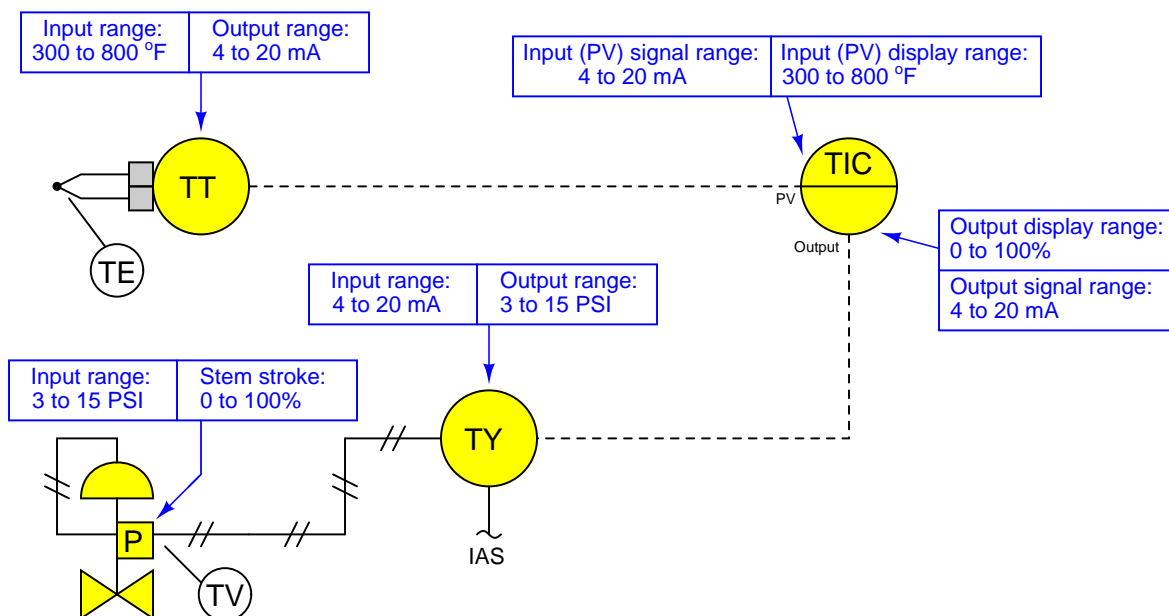
- Choosing a calibration ("trim") range that is substantially less than the final range of measurement when installed. As a general rule, you should trim the sensor of the transmitter to cover the broadest range of measurement possible with your calibration equipment.
- Neglecting to place a calibration tag on the transmitter after "trimming" it.

Trimming and individually ranging your transmitter should take no more than one full lab session (3 hours) if the team is working efficiently!

Notes on instrument ranging

An important configuration parameter for any practical measurement or control system is *process variable ranging*. This entails setting both the transmitter and indicator/controller to a specified measurement range, with the controller indicating the process variable in real “engineering units” (e.g. PSI or degrees F rather than just percent). The following tutorial describes how this works and which configuration parameters to modify in a variety of different control systems found in the Instrumentation lab room.

The reason this is an issue at all is because loop controllers operating on 4-20 mA analog signals don’t “know” what those signals are supposed to represent unless someone configures the controller with the proper range reflecting real-world conditions. For example, if a student is assigned a temperature transmitter with a range of 300 to 800 degrees Fahrenheit, not only does the transmitter have to output 4 mA when sensing 300 °F and output 20 mA when sensing 800 °F, but the controller must display an indication of 300 °F when it receives a 4 mA signal from the transmitter, and display an indication of 800 °F when it receives a 20 mA signal from the transmitter. None of this happens on its own – the student must range the transmitter for 300-800 °F input (and 4-20 mA output) as well as range the controller to display 300-800 °F over its 4-20 mA input scale. A typical loop is shown here with all instrument ranges displayed:



Analog (non-“smart”) transmitters, I/P transducers, and valve positioners are ranged using “zero” and “span” adjustments, typically screws or nuts. The ranging of analog instruments is discussed in the “Instrument Calibration” chapter of the *Lessons In Industrial Instrumentation* textbook.

Digital (“smart”) transmitters and valve positioners are ranged by setting LRV and URV parameters using a “communicator” device or a personal computer equipped with the appropriate interface and software. This too is discussed in the “Instrument Calibration” chapter of the *Lessons In Industrial Instrumentation* textbook.

Digital electronic loop controllers contain parameters specifying the process variable (PV) ranges. The following page lists examples of PV range configuration parameters for several different makes and models of loop controllers.

Notes on instrument ranging (continued)

- Siemens/Moore 352 controller: process variable range parameters are located in the “Operator’s Display” function block (FB15):
 - $LRV = Process\ Lo$
 - $URV = Process\ Hi$
- Siemens/Moore 352P and 353 controller: process variable range parameters are located in the “Analog Input” function block (AIN):
 - $LRV = Minscale$
 - $URV = Maxscale$
- Emerson DeltaV DCS: process variable range parameters are located in the “Analog Input” function block (AI) and “PID” function block (PID):
 - (AI block) = the *OUT_SCALE* parameter contains both high and low range limits, engineering units (e.g. deg F), and decimal point position. The *L_Type* parameter needs to be set to “indirect” to allow scaling to occur (“direct” mode prohibits scaling), and the *XD_Scale* parameter needs to be ranged 0 to 100%. Note that the “direct” and “indirect” options for *L_Type* have absolutely nothing to do with “direct” and “reverse” PID controller action, which is configured elsewhere.
 - (PID block) = the *PV_SCALE* parameter contains both high and low range limits, engineering units (e.g. deg F), and decimal point position. Note: the PID block’s *PV_SCALE* range must exactly match the *OUT_SCALE* range of the AI block!
- Honeywell UDC 2500 controller: process variable input #1 range parameters are located in the “Input 1” set-up group of parameters:
 - $LRV = IN1\ LO$
 - $URV = IN1\ HI$
- Automation Direct “SOLO” controller: process variable range parameters are located in the following registers:
 - $LRV = P3-4\ Input\ Range\ Low$
 - $URV = P3-3\ Input\ Range\ High$
- Allen-Bradley PLC5, SLC500, and MicroLogix controllers: process variable scaling parameters are typically located either in a “Scale” instruction (SCL) or a “Scale with Parameters” instruction (SCP). In either case, the instruction takes the raw count value from the input channel’s analog-to-digital converter and scales it into the desired process variable display range. A YouTube video on our BTCInstrumentation channel shows how to do this for the networked MicroLogix PLCs in the lab using the SCP instruction. *Note: SCP instruction parameters may be edited online. For this reason, downloading edits is not necessary for the MicroLogix PLCs in our lab. In fact, it is very important that you not save or download the PLC program, because doing so may alter the PLC’s network address and lead to communication problems. Just make the changes while the PLC is in “Run” mode and then exit the program:*
 - (SCL instruction) = *Rate* and *Offset* values scale the signal according to the slope-intercept formula $y = mx + b$, where *Rate* is $10000m$ and *Offset* is b
 - (SCP instruction LRV) = *Scaled Min.*
 - (SCP instruction URV) = *Scaled Max.*
- Allen-Bradley Logix5000 controller: process variable scaling parameters are located in the “PID” instruction (PID):
 - $LRV = .MINS$
 - $URV = .MAXS$

- caSCADA “pid” control program: process variable scaling parameters are located in one of the source code files which must be modified using a text editor program, then recompiling the pid program so the new parameters may take effect. This control program may be initiated from the Linux command line by typing `./pid` and pressing the Enter key, after which a set of instructions will appear on the screen showing the default LRV and URV range values, and which file to find these parameters within. After editing and saving this file, you will need to type `make` at the Linux command line and press Enter to recompile the program. Finally, type `./pid` and press Enter to initiate the recompiled program.
 - $LRV = pid[0].LRV$
 - $URV = pid[0].URV$

Lab Exercise – troubleshooting

The most important aspect of this lab exercise is *troubleshooting*, where you demonstrate your ability to logically isolate a problem in the system. All troubleshooting must be done on a system you did not help build, so that you must rely on others' documentation to find your way around the system instead of from your own memory of building it. Each student is given a limited amount of time to identify both the location and nature of the fault. All troubleshooting activities must be proctored by the instructor to assess proper diagnostic reasoning and technique.

The standard procedure involves a group of no more than four students troubleshooting the same faulted system, with the builders of that system playing the role of operators. All troubleshooters are given a two-minute period to individually identify a plausible fault based on observable symptoms and submit it in writing to the instructor for assessment. Those students whose faults are indeed plausible advance to the next round, where each one takes turns making diagnostic tests on the system. One minute is given to each student for devising this test, but no time limit is placed on the execution of that test. Whenever someone decides enough data has been collected to pinpoint the location and nature of the fault, they declare to have reached a conclusion and submit to the instructor in writing for assessment.

Individual troubleshooting with a five-minute time limit is also an acceptable format, but this generally only works with small class sizes.

Failure to correctly identify both the general location and nature of the fault within the allotted time, and/or failing to demonstrate rational diagnostic procedure to the supervising instructor will disqualify the effort, in which case the student must re-try with a different fault. Multiple re-tries are permitted with no reduction in grade.

A standard multimeter is the only test equipment allowed during the time limit. No diagnostic circuit breaks are allowed except by instructor permission, and then only after correctly explaining what trouble this could cause in a real system.

The instructor will review each troubleshooting effort after completion, highlighting good and bad points for the purpose of learning. Troubleshooting is a skill born of practice and failure, so do not be disappointed in yourself if you must make multiple attempts to pass! One of the important life-lessons embedded in this activity is how to deal with failure, because it *will* eventually happen to you on the job! There is no dishonor in failing to properly diagnose a fault after doing your level best. The only dishonor is in taking shortcuts or in giving up.

Common mistakes:

- Attempting to *visually* locate the fault.
- Neglecting to take measurements with your multimeter.
- Neglecting to check other measurements in the system (e.g. pressure gauge readings).
- Incorrectly interpreting the loop diagram (e.g. thinking you're at the wrong place in the system when taking measurements).
- Incorrect multimeter usage (e.g. AC rather than DC, wrong range, wrong test lead placement). This is especially true when a student comes to lab unprepared and must borrow someone else's meter that is different from theirs!

The purpose of every troubleshooting exercise is to foster and assess your ability to intelligently diagnose a complex system. Finding the fault by luck, or by trial-and-error inspection, is no demonstration of skill. Competence is only revealed by your demonstrated ability to logically analyze and isolate the problem, correctly explaining all your steps!

Troubleshooting takes a lot of lab time, usually at least two 3-hour lab sessions for everyone in a full class to successfully pass. Budget for this amount of time as you plan your work, and also be sure to take advantage of your freedom to observe others as they troubleshoot.

Lab Exercise – decommissioning and clean-up

The final step of this lab exercise is to decommission your team's entire system and re-stock certain components back to their proper storage locations, the purpose of which being to prepare the lab for the next lab exercise. Remove your system documentation (e.g. loop diagram) from the common holding area, either discarding it or keeping it for your own records. Also, remove instrument tag labels (e.g. FT-101) from instruments and from cables. Perform general clean-up of your lab space, disposing of all trash, placing all tools back in their proper storage locations, sweeping up bits of wire off the floor and out of junction boxes, etc.

Leave the following components in place, mounted on the racks:

- Large control valves and positioners
- I/P transducers
- Large electric motors
- Large variable-frequency drive (VFD) units
- Cables inside conduit interconnecting junction boxes together
- Pipe and tube fittings (do not unscrew pipe threads)
- Supply air pressure regulators

Return the following components to their proper storage locations:

- Sensing elements (e.g. thermocouples, pH probes, etc.)
- Process transmitters
- “Jumper” cables used to connect terminal blocks within a single junction box
- Plastic tubing and tube fittings (disconnect compression-style tube fittings)
- Power cables and extension cords
- Adjustment (loading station) air pressure regulators

Finally, you shall return any control system components to their original (factory default) configurations. This includes controller PID settings, function block programs, input signal ranges, etc.

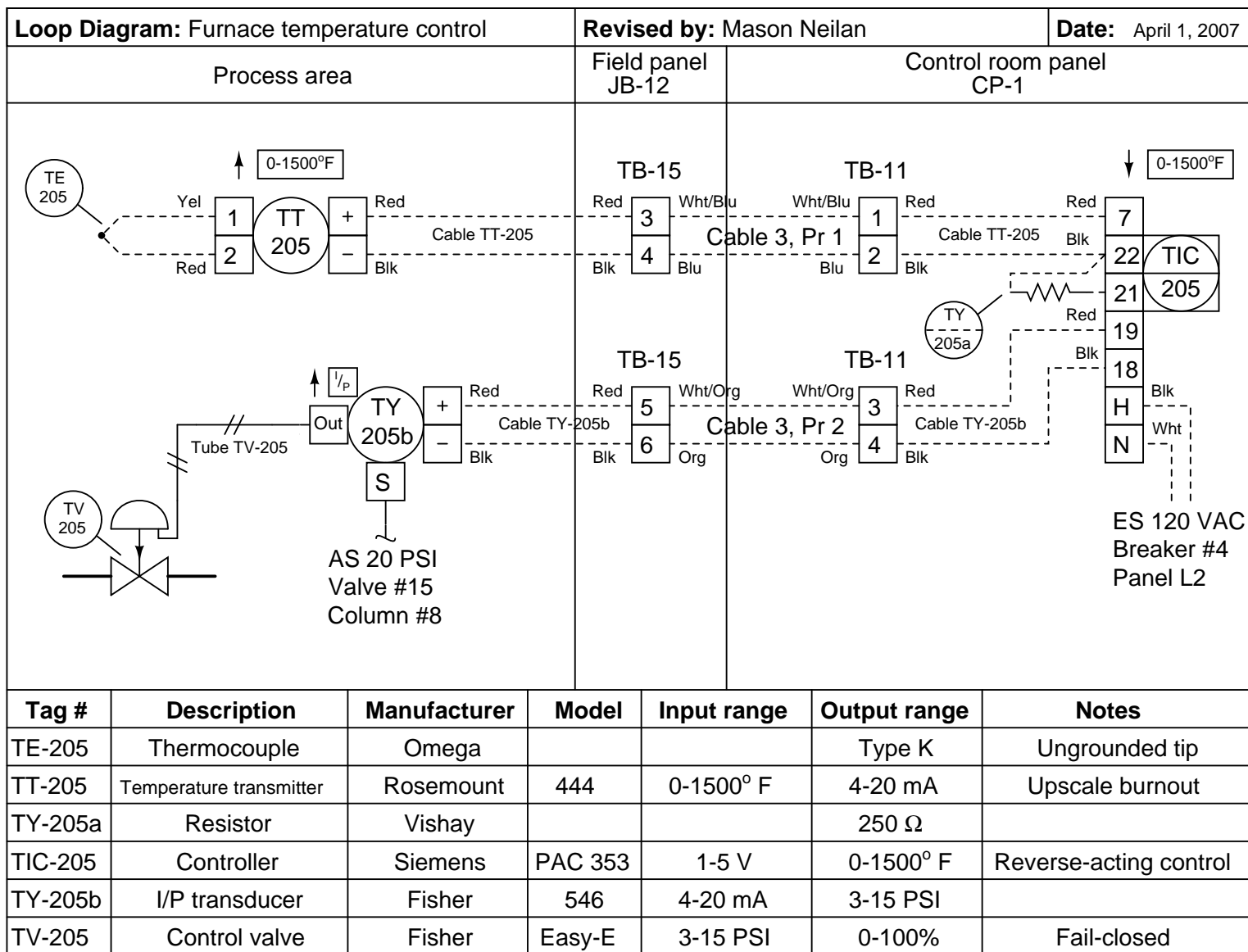
Lab Exercise – team tool locker inspection

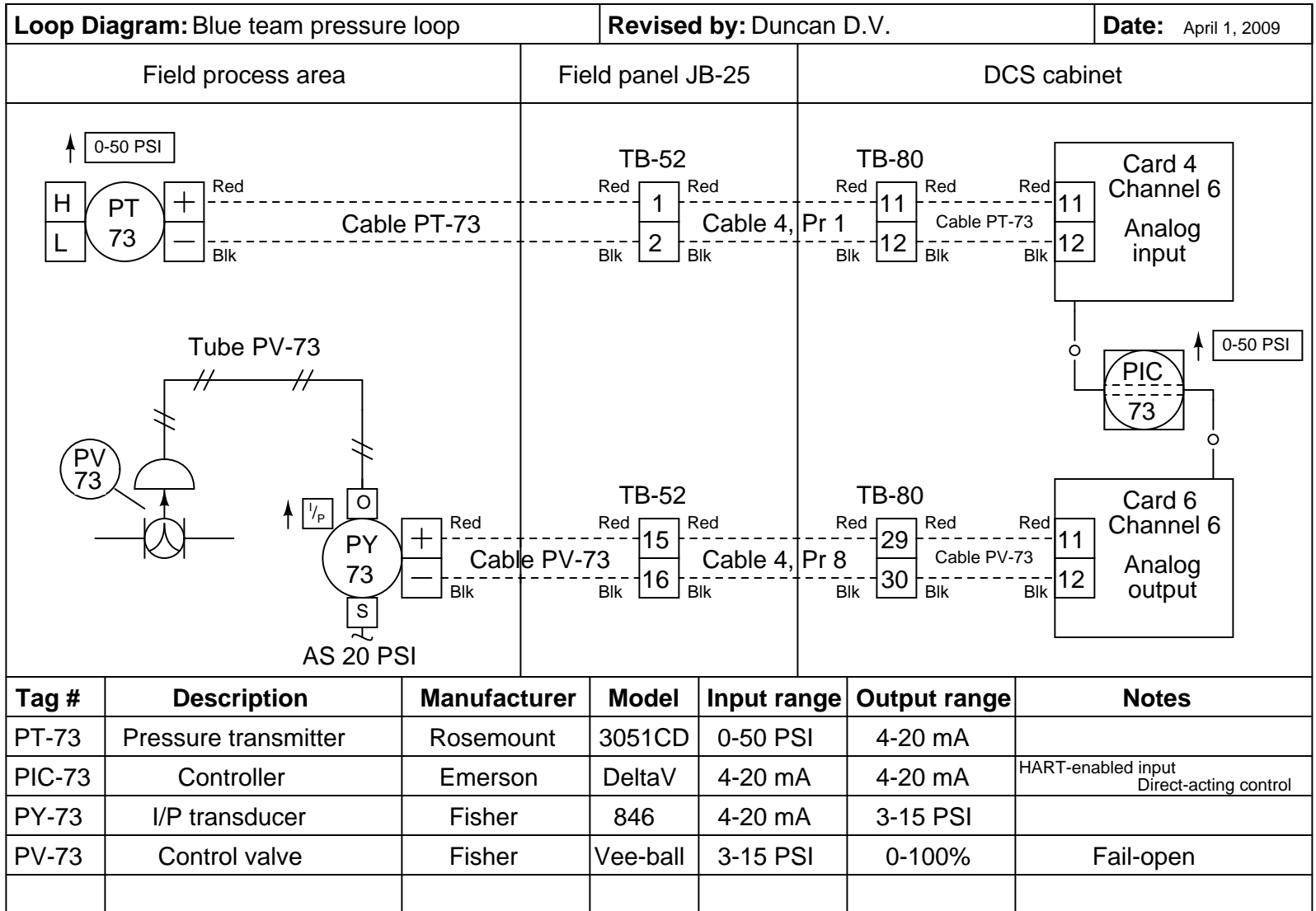
The instructor will work with each team to inspect their tool locker for all required items, and also to ensure nothing else is being stored there.

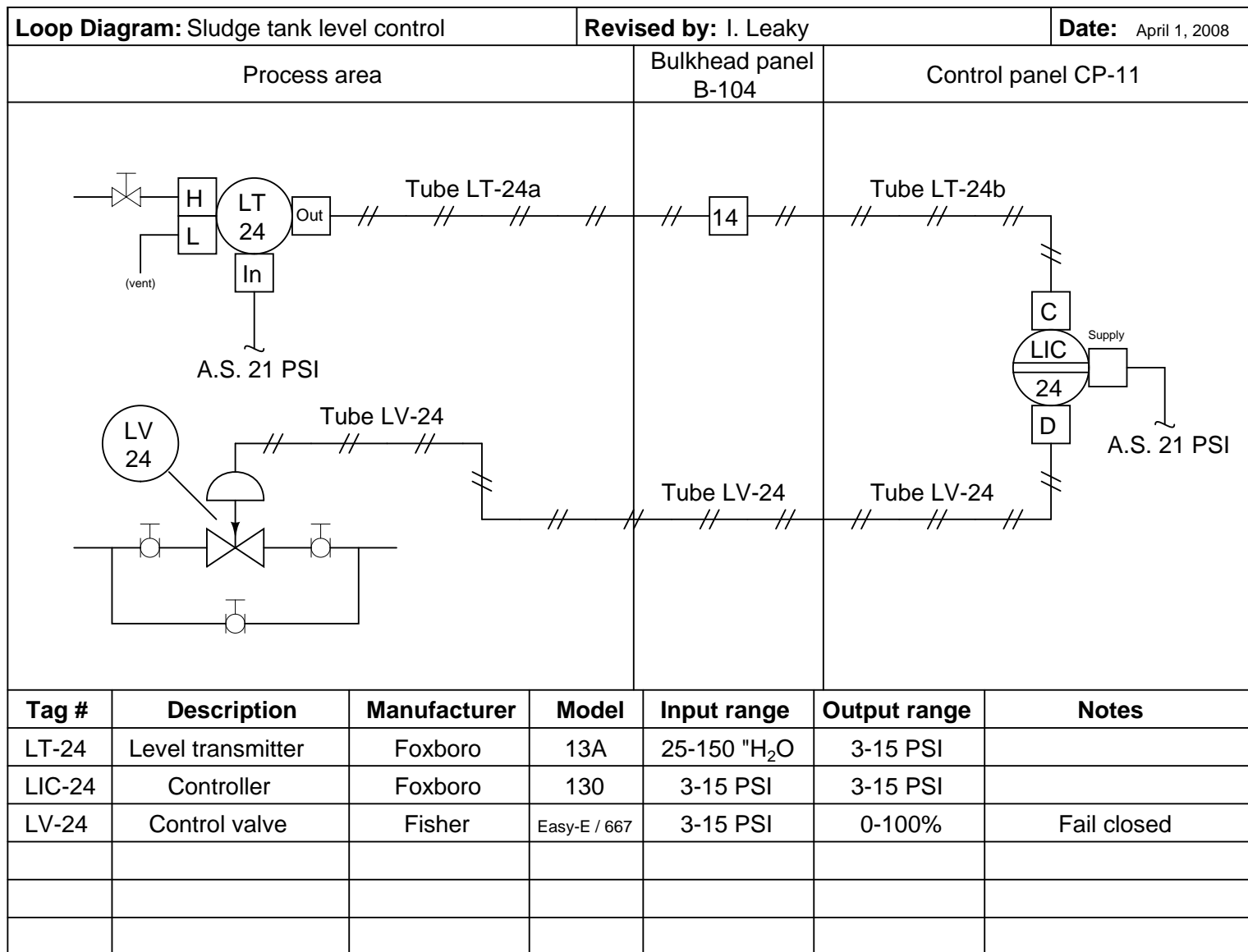
First, the locker will be entirely emptied. Next, the instructor will inspect each tool before placing it in the locker, following the order of the inventory list taped to the inside of the locker door. The team is responsible for finding or replacing any missing items. Any items not on the inventory list will be left out of the locker.

Any damaged or worn components will be replaced. Inexpensive items such as drill bits and taps will be replaced at student expense. More expensive items will be replaced at the school's expense, with students doing research to identify the replacement cost of the item(s) in question.

file i01294







Lab Exercise – loop diagram and system inspection

Each team's system will undergo an inspection simultaneous with inspection of each team member's loop diagram. Team members will exchange diagrams with each other and then verify from those diagrams what the instructor sees when inspecting each and every panel and connection. *Please note that the "Lessons In Industrial Instrumentation" textbook describes good practices for construction and documentation.*

Construction Standards

- All construction must be *safe* (i.e. must not pose any unnecessary hazard to students or visitors). This includes electrical, chemical, thermal, pressure, and general safety hazards (e.g. trip hazards, cut hazards). *Unsafe construction will be dismantled upon discovery.*
- All electrical sources greater than 30 volts must be overcurrent-protected and all related wire connections must be guarded against accidental contact (e.g. use recessed terminals with no exposed metal).
- Proper use of colors for electrical power source wiring (e.g. red and black for DC + and –, black and white for AC "hot" and "neutral", green for earth ground).
- All metallic electrical enclosures must be bonded to earth ground for safety.
- Proper wire types and attachment to terminals (e.g. appropriate wire gauge for the expected current, use of stranded wire wherever possible, correct terminals crimped to ends of wires, no stray wire strands at any point).
- Attached wires must withstand being lightly pulled with fingers.
- Wire insulation must be intact (i.e. no bare wires anywhere).
- Panel wiring must be neat in appearance (e.g. all cables run directly from terminal block to nearest wire duct, with all excess wire length tucked inside wire duct).
- Wiring outside of panels should be run through conduit wherever possible.
- Correct tools must be used at all times. This includes the use of fixed-size wrenches rather than adjustable wrenches whenever possible, box-end over open-end wrenches whenever possible, and the correct type and size of screwdriver used to turn screw heads.
- All electrical components must be located to avoid exposure to liquids.
- All tube and pipe connections must be properly made (e.g. correct "swaging" of tube ends, no over- or under-tightened fittings, Teflon tape or pipe sealant used on all NPT threads).
- All manual controls (e.g. buttons, handles, knobs) must be accessible and function without undue effort.

Documentation Standards

- Loop diagrams must be drawn in accordance with ISA standard 5.1.
- Each instrument must have an appropriate ISA-standard tag name, and this tag name must be visible on the actual instrument (e.g. written on masking tape and attached to the instrument).
- Each signal cable and each signal tube must have an identifying label documented and attached. Long cables must be labeled at each end, as close to the termination points as practical.
- Each team must have its own unique loop number.
- Each instrument's (final) calibrated range must be shown.
- Each control valve's fail mode (e.g. fail-open, fail-closed) or action must be shown.
- All writing must be legible (i.e. easy for anyone to read). *Hint: large-format paper helps!*
- All instrument symbols must be appropriate to the device, function, and location. The large white-colored control panel and the DCS operator stations constitute the *main control room*. All electrical enclosures in the lab room are *auxiliary* locations, and everything else is considered a *field* location.
- Instrument functions shared within a common device must be represented by the "shared" symbol on the diagram (e.g. a controller that is part of a multi-loop control system such as a DCS). Shared controllers must have their identifying loop noted on the diagram (e.g. DCS South Loop #23).
- Any controller I/O cards must be labeled with slot number and channel number in addition to terminal numbers.

- Each location (e.g. field, junction box, control room) must be clearly delineated with vertical separation lines on the diagram.
- Each diagram must be sufficiently detailed so that no other student will have difficulty locating components (e.g. “Where is the controller for this loop?”) or determining important configuration parameters (e.g. range settings).

Sample diagrams are provided in this worksheet (immediately following the lab exercise documentation), and each student is urged to use these sample diagrams as references when drafting their own. The “Lessons In Industrial Instrumentation” textbook also describes ISA-standard documentation practices.

Common mistakes:

- Incorrect tag name format, using letters that do not conform to the ISA 5.1 standard (e.g. including “PLC” or “DCS” in a controller’s tag name).
- Forgetting that every instrument’s tag name in a loop must begin with the same letter, and that this first letter represents the process variable being measured/controlled.
- Forgetting to label all field instruments with their own tag names (e.g. AT-83).
- Failing to label termination points (e.g. terminal block screws) *exactly* as they are labeled in real life.
- Poor use of space on the diagram paper, causing some portions of the diagram to become “crowded” rather than all components being evenly spaced. *Hint: begin your diagram by sketching the field instrument at the far left of the paper and the control room instrument at the far right of the paper, then draw all other instruments and connections in between!*
- Forgetting to label all signal wires (see example loop diagrams).
- Forgetting to note all wire colors.
- Forgetting to put your name on the loop diagram!
- Leaving junction box cables outside of wire duct, looking messy.
- Leaving wire duct covers off.
- Basing your diagram off of a team-mate’s diagram, rather than closely inspecting the system for yourself.
- Not placing loop sheet instruments in the correct orientation (field instruments on the left, control room instruments on the right).

Creating and inspecting accurate loop diagrams should take no more than one full lab session (3 hours) if the team is working efficiently!

[file i00654](#)

Capstone Assessment (end of quarter)

This performance assessment tests your mastery of many important instrumentation concepts. You are to automate a pre-built process based on prototype diagrams you sketch of all instrument connections, and demonstrate the automatic control of this process. All this must be done individually with no assistance from anyone else, within one continuous time block not to exceed three hours. You may refer to manufacturer documentation and/or textbooks, but not to personal notes, while building your loop.

You are entirely responsible for figuring out how the process works and what you must do to control it, based on your inspection of it after it has been selected for you. This includes identifying the process variable, the final control element, any loads, instrument model numbers, and locating manufacturer's documentation for the instrumentation.

You may perform the assessment activity at any time in the quarter. Successful completion counts as the "mastery" portion of the course exam(s). There will be no grade penalty for repeated attempts, however successful completion of this activity is required to pass the course.

In addition to exhibiting a steady-state control in automatic mode (i.e. the process variable follows changes made to the setpoint and settles at or near the setpoint value without oscillation after some time), the process must also meet the following criteria based on courses you have completed:

- If you have passed or are currently taking the *INST241* course, your transmitter and controller must be properly configured to register the process variable (in engineering units, not percent) over a range specified by the instructor. Note: if the transmitter is analog rather than "smart," the instructor will have you determine its "As-Found" range and direct you to range the loop controller to match the transmitter rather than calibrate the analog transmitter to a specified range.
- If you have passed or are currently taking the *INST252* course, the controller must be tuned for robust response to perturbations (changes) in either setpoint or load as selected by the instructor at or near a setpoint value also specified by the instructor. "Robust" control is defined here as the controller compensating for perturbations as quickly as possible without creating any process variable oscillations (i.e. a *critically damped* response). It will be your decision to use P, I, D, or any combination thereof in the controller's tuning.
- If you have passed or are currently taking the *INST260* course, you must connect a data acquisition unit (DAQ) to record a variable in the process selected by the instructor and display a trend graph and/or a scaled representation of the measured variable on a personal computer networked to the DAQ. For example, if you are instructed to display the controller's output value using the DAQ, the display should register on a scale of 0% to 100% just like the controller's output is ranged from 0% to 100%. If the DAQ needs to show the process variable, it must register that variable in the same range as the transmitter. If your DAQ provides a trend graph, the vertical scale markings of that trend graph must be similarly ranged.

Given the time constraint of this assessment, you will not be required to cut and fit flexible conduit to the field instruments. All other wiring must be neatly installed so as to avoid creating safety hazards (tripping, etc.) and confusion for other students assembling their loops.

Limited availability of components and physical space in the lab means that only a few students will be able to work on this assessment at once, so plan on attempting this *well before* the final due date!

Bring a printed copy of this check-list with you when beginning the capstone assessment! Remember that you must work independently once the instructor assigns you a vest to wear. Any consultation with classmates, use of personal notes, or deviation from your approved diagram(s) will result in immediate disqualification, which means you must take everything apart and re-try the capstone assessment on a different process. Any damage done to the process or instrumentation will similarly result in disqualification, and you must repair the damage prior to re-trying the capstone assessment. You are allowed to use manufacturer documentation, as well as any documentation provided by the instructor (e.g. textbooks).

No teamwork is allowed while wearing the vest!

Selection	(Instructor writes/checks)
Instructor assigns a vest for you to wear	
Instructor selects a process for you to automate	
Instructor selects process variable range (<i>INST241 only</i>)	
Instructor selects setpoint/load & SP value (<i>INST252 only</i>)	@ SP =
Instructor selects DAQ variable to measure (<i>INST260 only</i>)	
Instructor selects controller – label with your name!	
Instructor verifies no wiring connected to the process	

The time clock starts now!

Start time: _____

Criterion	(Instructor verifies)
You sketch basic loop diagram – instructor verifies correctness	
You sketch DAQ connection diagram – instructor verifies correctness	

Now you may begin wiring and configuring the components

Criterion	(Instructor verifies)
Steady-state control in automatic mode	
Controller correctly registers the process variable (<i>INST241 only</i>)	
Controller responds robustly to perturbations (<i>INST252 only</i>)	
DAQ measurement correctly scaled and/or graphed (<i>INST260 only</i>)	

The time clock stops now!

Stop time: _____

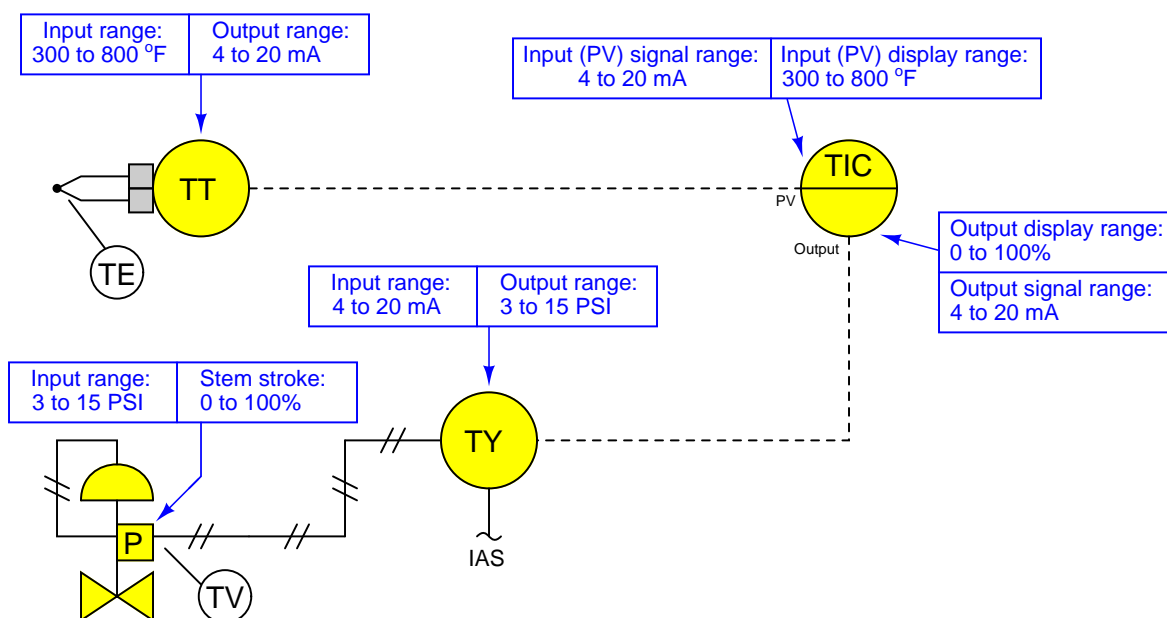
Criterion	(Instructor verifies)
Instructor verifies all signal wires/tubes disconnected	
Instructor verifies controller reset to original configuration	
Instructor verifies DAQ is returned to team tool locker	
Instructor collects your diagrams	

Your mastery score will not be recorded until all steps are complete!

Notes on instrument ranging

An important configuration parameter for any practical measurement or control system is *process variable ranging*. This entails setting both the transmitter and indicator/controller to a specified measurement range, with the controller indicating the process variable in real “engineering units” (e.g. PSI or degrees F rather than just percent). The following tutorial describes how this works and which configuration parameters to modify in a variety of different control systems found in the Instrumentation lab room.

The reason this is an issue at all is because loop controllers operating on 4-20 mA analog signals don’t “know” what those signals are supposed to represent unless someone configures the controller with the proper range reflecting real-world conditions. For example, if a student is assigned a temperature transmitter with a range of 300 to 800 degrees Fahrenheit, not only does the transmitter have to output 4 mA when sensing 300 °F and output 20 mA when sensing 800 °F, but the controller must display an indication of 300 °F when it receives a 4 mA signal from the transmitter, and display an indication of 800 °F when it receives a 20 mA signal from the transmitter. None of this happens on its own – the student must range the transmitter for 300-800 °F input (and 4-20 mA output) as well as range the controller to display 300-800 °F over its 4-20 mA input scale. A typical loop is shown here with all instrument ranges displayed:



Analog (non-“smart”) transmitters, I/P transducers, and valve positioners are ranged using “zero” and “span” adjustments, typically screws or nuts. The ranging of analog instruments is discussed in the “Instrument Calibration” chapter of the *Lessons In Industrial Instrumentation* textbook.

Digital (“smart”) transmitters and valve positioners are ranged by setting LRV and URV parameters using a “communicator” device or a personal computer equipped with the appropriate interface and software. This too is discussed in the “Instrument Calibration” chapter of the *Lessons In Industrial Instrumentation* textbook.

Digital electronic loop controllers contain parameters specifying the process variable (PV) ranges. The following page lists examples of PV range configuration parameters for several different makes and models of loop controllers.

Notes on instrument ranging (continued)

- Siemens/Moore 352 controller: process variable range parameters are located in the “Operator’s Display” function block (FB15):
 - LRV = *Process Lo*
 - URV = *Process Hi*
- Siemens/Moore 352P and 353 controller: process variable range parameters are located in the “Analog Input” function block (AIN):
 - LRV = *Minscale*
 - URV = *Maxscale*
- Emerson DeltaV DCS: process variable range parameters are located in the “Analog Input” function block (AI) and “PID” function block (PID):
 - (AI block) = the *OUT_SCALE* parameter contains both high and low range limits, engineering units (e.g. deg F), and decimal point position. The *L_Type* parameter needs to be set to “indirect” to allow scaling to occur (“direct” mode prohibits scaling), and the *XD_Scale* parameter needs to be ranged 0 to 100%. Note that the “direct” and “indirect” options for *L_Type* have absolutely nothing to do with “direct” and “reverse” PID controller action, which is configured elsewhere.
 - (PID block) = the *PV_SCALE* parameter contains both high and low range limits, engineering units (e.g. deg F), and decimal point position. Note: the PID block’s *PV_SCALE* range must exactly match the *OUT_SCALE* range of the AI block!
- Honeywell UDC 2500 controller: process variable input #1 range parameters are located in the “Input 1” set-up group of parameters:
 - LRV = *IN1 LO*
 - URV = *IN1 HI*
- Automation Direct “SOLO” controller: process variable range parameters are located in the following registers:
 - LRV = *P3-4 Input Range Low*
 - URV = *P3-3 Input Range High*
- Allen-Bradley PLC5, SLC500, and MicroLogix controllers: process variable scaling parameters are typically located either in a “Scale” instruction (SCL) or a “Scale with Parameters” instruction (SCP). In either case, the instruction takes the raw count value from the input channel’s analog-to-digital converter and scales it into the desired process variable display range. A YouTube video on our BTCInstrumentation channel shows how to do this for the networked MicroLogix PLCs in the lab using the SCP instruction. *Note: SCP instruction parameters may be edited online. For this reason, downloading edits is not necessary for the MicroLogix PLCs in our lab. In fact, it is very important that you not save or download the PLC program, because doing so may alter the PLC’s network address and lead to communication problems. Just make the changes while the PLC is in “Run” mode and then exit the program:*
 - (SCL instruction) = *Rate* and *Offset* values scale the signal according to the slope-intercept formula $y = mx + b$, where *Rate* is $10000m$ and *Offset* is b
 - (SCP instruction LRV) = *Scaled Min.*
 - (SCP instruction URV) = *Scaled Max.*
- Allen-Bradley Logix5000 controller: process variable scaling parameters are located in the “PID” instruction (PID):
 - LRV = *.MINS*
 - URV = *.MAXS*

- caSCADA “pid” control program: process variable scaling parameters are located in one of the source code files which must be modified using a text editor program, then recompiling the pid program so the new parameters may take effect. This control program may be initiated from the Linux command line by typing `./pid` and pressing the Enter key, after which a set of instructions will appear on the screen showing the default LRV and URV range values, and which file to find these parameters within. After editing and saving this file, you will need to type `make` at the Linux command line and press Enter to recompile the program. Finally, type `./pid` and press Enter to initiate the recompiled program.
 - $LRV = pid[0].LRV$
 - $URV = pid[0].URV$

Notes on controller action

An important set of configuration parameters for any control system are *controller action* and *PID tuning*. Proper controller action means that the control system reacts to setpoint changes and process variable disturbances in the correct direction (e.g. a temperature control system that acts to reduce heat input when the process variable is above setpoint). Proper PID tuning means that the control system reacts to setpoint changes and process variable disturbances to an appropriate degree over time (e.g. a temperature control system that applies the right amount of additional heat input when the process variable goes below setpoint). A controller with the wrong action will cause a process to “run away” to one extreme value or the other. A controller with poor PID tuning will fail to achieve setpoint, and/or oscillate needlessly. The following is a list of configuration parameters to modify in a variety of different control systems found in the Instrumentation lab room.

If the controller happens to be programmed using function blocks, these important parameters will be found in the “PID” function block. For other controller models, there will be a menu option with action (direct/reverse) and tuning (P/I/D) parameters. Note that some controllers provide a quick-access feature to edit the PID tuning parameters, but generally not for changing the direction of action. Here are some examples:

- Siemens/Moore 352 controller: control action parameters are located in the “PID” function block (FB13). Note that the P, I, and D tuning parameters may be quickly accessed by pressing the “Tune” button rather than by entering the PID function block edit menu:
 - Direction (Direct/Reverse) = *SA1*
 - Proportional (P) = *SPG1* as a unitless gain value
 - Integral (I) = *STI1* in units of minutes per repeat
 - Derivative (D) = *STD1* in units of minutes
- Siemens/Moore 352P and 353 controller: control action parameters are located in the “PID” function block (PID). Note that the P, I, and D tuning parameters may be quickly accessed by pressing the “Tune” button rather than by entering the PID function block edit menu:
 - Direction (Direct/Reverse) = *DIR ACT*
 - Proportional (P) = *PG* as a unitless gain value
 - Integral (I) = *TI* in units of minutes per repeat
 - Derivative (D) = *TD* in units of minutes
- Emerson DeltaV DCS: control action parameters are located in the “PID” function block (PID) conforming to the FOUNDATION Fieldbus standard:
 - Direction (Direct/Reverse) = Found in the *CONTROL_OPTS* set of parameters as a “check-box” where a checked box sets direct action and an unchecked box sets reverse action.
 - Proportional (P) = *GAIN* as a unitless gain value
 - Integral (I) = *RESET* in units of seconds per repeat
 - Derivative (D) = *RATE* in units of seconds
- Honeywell UDC 2500 controller: control direction is located in the “CONTRL” set-up group of parameters, while the PID tuning coefficients are located in the “TUNING” set-up group of parameters:
 - Direction (Direct/Reverse) = *Action*
 - Proportional (P) = *PB* or *Gain* as a proportional band percentage or as a unitless gain value, respectively
 - Integral (I) = *I Min* or *I RPM* in units of minutes or repeats per minute, respectively
 - Derivative (D) = *Rate T* in units of minutes

Notes on controller action (continued)

- Automation Direct “SOLO” controller: process variable range parameters are located in the following registers:
 - Direction (Direct/Reverse)= *P3-7 Heating/Cooling*
 - Proportional (P) = *P1-4 Proportional band* as a proportional band percentage
 - Integral (I) = *P1-5 Integral time* in units of seconds
 - Derivative (D) = *P1-6 Derivative time* in units of seconds
- Allen-Bradley PLC5, SLC500, and MicroLogix controllers: control action parameters are located in the “PID” instruction. A YouTube video on our BTCInstrumentation channel shows how to do this for the networked MicroLogix PLCs in the lab (reading the PV on the first analog input and sending the output to the first analog output of the I/O card):
 - Direction (Direct/Reverse)= Found in the *Control Mode* field where $E = PV - SP$ represents direct action and $E = SP - PV$ represents reverse action.
 - Proportional (P) = *Controller Gain K_c* as a unitless gain value
 - Integral (I) = *Reset T_i* in units of minutes per repeat
 - Derivative (D) = *Rate T_d* in units of minutes
- Allen-Bradley Logix5000 controller: control action parameters are located in the “PID” instruction (PID):
 - Direction (Direct/Reverse)= *E* where $PV - SP$ represents direct action and $SP - PV$ represents reverse action.
 - Proportional (P) = K_p or K_c as a unitless gain value
 - Integral (I) = K_i in units of seconds per repeat
 - Derivative (D) = K_d in units of minutes
- caSCADA “pid” control program: control action parameters are located on the operator interface screen, above the trend graph. This control program may be initiated from the Linux command line by typing `./pid` and pressing the Enter key. Once the `pid` control program is running (reading the PV on analog input AIN0 and sending the output to analog output DAC0 of the LabJack DAQ), each parameter may be selected by pressing the **S** key as often as needed, and the parameter values changed by pressing the arrow and page up/down keys. Note that the control direction may only be switched while the controller is in manual mode. Tuning parameters may be altered in either manual or automatic modes.
 - Direction (Direct/Reverse)= will either show “**Direct-acting**” or “**Reverse-acting**”
 - Proportional (P) = K_P as a unitless gain value
 - Integral (I) = K_I in units of repeats per minute
 - Derivative (D) = K_D in units of seconds

Notes on controller tuning

For those who have never tuned a controller before but need to set the PID parameters for basic loop stability in automatic mode, here are some tips for setting the P, I, and D parameter values. Every PID controller provides means to alter the tuning coefficients named *proportional* (also called *gain*), *integral* (also called *reset*), and *derivative* (also called *rate or pre-act*). Settings which are virtually assured to yield stable control are as follows:

- **P** – a “gain” value of less than one (i.e. a “proportional band” value of at least 100%).
- **I** – a “reset” value of zero repeats per minute, or the largest value possible for minutes per repeat.
- **D** – a “rate” value of zero.

Mind you, these parameters will not yield *good* control, but merely *stable* control. In other words, these tuning parameter values will make the controller fairly unresponsive, but at least it won’t oscillate out of control. Also bear in mind that having an integral (reset) value set for minimum action (i.e. zero repeats per minute, or very high minutes per repeat) will result in a controller that never quite makes the process variable value reach setpoint – instead, there will be a persistent “offset” between PV and SP with integral action essentially turned off.

The maintenance of a working lab facility is extensive, especially for a program such as Instrumentation, where most of the equipment comes in the form of donations which must be pieced together, and where many of the systems are custom-built for the purpose. Every student bears a responsibility for helping maintain the lab facility, because every student benefits from its provisions.

On the last day of every quarter, time is allocated to the clean-up and re-organization of the lab facility. This is a full work day, with attendance enforced as per usual. In order to help students focus on the tasks that need to be done, the following list documents some of the work necessary to make the lab ready for next quarter. Tasks preceded by a blank line will be assigned to lab teams for completion.

Lab tasks

- Check to see that all small items bearing BTC inventory tags are painted a bright color to make them easy to spot for each year's inventory check.
- _____ Sweep all lab floor areas, recycling or discarding any waste material.
- _____ Sweep all storage room floor areas, recycling or discarding any waste material. Place items found on floor back on shelves where they belong.
- _____ Collect all copper tube segments and place them in the copper/brass recycling receptacle.
- _____ Collect all aluminum, stainless steel, brass, and copper wire scrap (pieces shorter than 1 foot) in the scrap metal buckets near the north-west exit door.
- _____ Haul recyclable metals to a local scrap dealer, and return with cash to buy pizza for today's lunch.
- _____ Organize storage bins for danger tags and masking tape. Collect any unused danger tags from around the lab room and place them in that bin.
- _____ Help search for any missing Team Tool Locker items.
- _____ Clean all workbench and table surfaces.
- _____ Remove items from the compressor room, sweep the floor, and make sure there is no junk being stored there.
- _____ Collect lengths of cable longer than 1 foot and place in the storage bins inside the DCS cabinets for future use.
- _____ Re-organize wire spool storage area: remove any empty spools from the rack, ensure all boxes and unmounted spools are neatly stacked on the floor.
- _____ Collect all plastic tubes and return them to the appropriate storage bin.
- _____ Re-organize tube fitting drawers (north-west corner of lab room), ensuring no pipe fittings are mixed in, that all fittings are found in the proper drawers, and that all drawers are properly labeled (these drawers should have sample fittings attached to the fronts).
- _____ Re-organize pipe fitting drawers (north-west corner of lab room), ensuring no tube fittings are mixed in.
- _____ Re-organize hose fitting drawers (north-west corner of lab room).
- _____ Re-organize terminal block and ice-cube relay drawers (north end of lab room).
- _____ Drain condensed water out of air compressor tank (in the compressor room).
- _____ Return all books and manuals to bookshelves.
- _____ Inspect each and every control panel in the lab, removing all wiring except for those which should be permanently installed (120 VAC power, signal cables between junction boxes). Ensure that each junction box's power cords are securely fastened and grounded.
- _____ Inspect each and every signal wiring junction box in the lab, removing all wiring except for those which should be permanently installed (e.g. 120 VAC power, signal cables between junction boxes.). Ensure that each junction box's power cords are securely fastened and grounded.
- _____ Check condition of labels on all junction boxes and control panels, making new labels if the old labels are missing, damaged, or otherwise hard to read.
- _____ Check condition of labels on all permanently-installed cables (e.g. between junction boxes), making new labels if the old labels are missing, damaged, or otherwise hard to read.

- _____ Check condition of labels on all terminal blocks inside control panels and junction boxes, making new labels if the old labels are missing or otherwise hard to read.
- _____ Remove all debris left in control panels and junction boxes throughout the lab room, using a vacuum cleaner if necessary.
- _____ Clean up deadweight testers (they tend to leak oil). *Hint: WD-40 works nicely as a solvent to help clean up any leaked oil.*
- _____ Maintenance on turbocompressor system: (safety tag-out, check oil level, repair any oil leaks, repair any poor wire connections, clean debris out of control cabinet, re-tighten all power terminal connections).
- _____ Return all shared tools (e.g. power drills, saws) to the proper storage locations (hand tools to the tool drawer in the north-east corner of the lab room, and power tools to the tool shelf in the upstairs storage area).
- _____ Remove items from all storage cabinets on the north end of the lab room, cleaning all shelves of junk (e.g. pH probes that have been left dry) and returning all items to their proper places. Install covers on all transmitters missing them, especially on pneumatic transmitters which are vulnerable to damage without their covers attached.
- _____ Visually inspect all general-purpose pressure regulators stored in the north storage shelves for missing adjustment bolts, missing tube connectors, damaged port threads, etc. Make repairs as necessary.
- _____ Test all pressure transmitters not labeled “good” to see if they are indeed defective. Repair if possible, salvage parts and discard if not. Check for stripped screw heads and replace screws if necessary. *Do not discard any instrument with a BTC inventory tag!*
- _____ Test all temperature transmitters not labeled “good” to see if they are indeed defective. Repair if possible, salvage parts and discard if not. Check for stripped screw heads and replace screws if necessary. *Do not discard any instrument with a BTC inventory tag!*
- _____ Test all I/P converters not labeled “good” to see if they are indeed defective. Repair if possible, salvage parts and discard if not. Check for stripped screw heads and replace screws if necessary. *Do not discard any instrument with a BTC inventory tag!*
- _____ Test all precision pressure gauges not labeled “good” to see if they are indeed defective. Repair if possible, salvage parts and discard if not. *Do not discard any instrument with a BTC inventory tag!*
- _____ Test all precision pressure regulators not labeled “good” to see if they are indeed defective. Repair if possible, salvage parts and discard if not. *Do not discard any instrument with a BTC inventory tag!*
- _____ Test all hand air pumps used for pressure calibration work. If a pump leaks, disassemble the pump to clean and inspect its internal parts. Repair if possible, salvage parts and discard if not. *Do not discard any instrument with a BTC inventory tag!*
- _____ Return all field instruments (e.g. transmitters) and miscellaneous devices (e.g. pressure gauges and regulators) to their proper storage locations. *Note that I/P transducers and valve positioners should remain near their respective control valves rather than be put away in storage!*
- _____ Store all 2×2 foot plywood process boards in secure locations, ensuring each one is ready to use next quarter.
- _____ Ensure that each and every control valve mounted on the racks in the lab room has an I/P transducer mounted nearby, complete with Swagelok tube connectors in good condition for connecting compressed air supply and signal to the valve.
- _____ Check to make sure that each valve is securely mounted to the rack, and if there is a positioner attached that the feedback arm is properly connected to the valve stem (e.g. no missing tension springs, bent linkages, obvious misalignments).
- _____ Remove all items from the flammables cabinet, wipe all shelves of liquid and residue, then re-stock in a neat and safe manner.
- _____ Clean all bar-be-que grills of residue left over from lunches and fundraisers. *Note: you may need to take the grill racks and grease drip trays to a car wash station and use the engine degreaser solution to clean them thoroughly enough!*

- _____ Re-set all function block parameters in the DCS “Generic Loops” to their default settings. See the documentation on the main BTC_PPlus workstation for instructions on parameter values.
- _____ Check manometers on the calibration bench, ensuring those filled with red fluid are at their fluid levels and that all the others (normally filled with distilled water) are completely drained.
- _____ Turn on compressed air to the calibration bench, checking for leaks and ensuring every pressure regulator is functioning as it should.
- _____ Clean refrigerators, throwing away any food items remaining within.
- _____ Thoroughly clean all food ovens and any other cooking tools.
- _____ Return all shelf boards to their appropriate places on the racks.
- _____ Clean and re-organize all shelves in classroom DMC 130 storing components for the hands-on mastery assessments. Throw away any damaged jumper wires, battery clips, etc. Discard any batteries whose terminal voltages are less than 80% of their rating (e.g. less than 7.2 volts for a 9-volt battery).
- _____ Shut off power to all control systems except for the DCS.
- _____ Store any donated components in the proper locations.
- _____ Clean all whiteboards using Windex, so they actually look white again!

• *Instructors may add items to this list as necessary:*

- _____
- _____
- _____
- _____
- _____
- _____
- _____

Personal tasks

- Apply “sick hours” to missed time this quarter (remember, this is *not* automatically done for you!).
- Donate unused “sick hours” to classmates in need.
- Take any quizzes missed due to classroom absence this quarter (remember, a quiz not taken will be counted as a failed quiz!).

file i01229

Answers

Answer 1

Answer 2

Answer 3

Answer 4

Answer 5

Answer 6

Answer 7

Answer 8

Partial answer:

0.00000663 pounds of sulfur dioxide in every pound of air (6.63×10^{-6} lb of SO₂ in each lb of air).

Answer 9

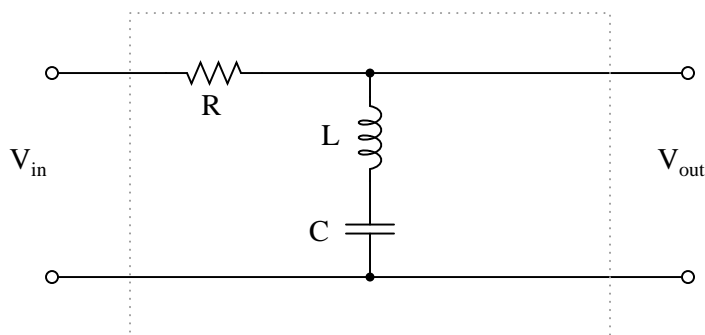
The dynodes exhibit an effect called *secondary emission*, which “multiplies” the number of emitted electrons from the cathode. The more dynodes, the more multiplication, which may range upward of 10^8 .

Answer 10

Partial answer:

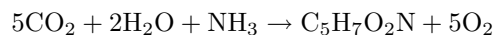
This filter is also known as a *notch* filter. I’ll let you figure out which of the four abbreviated filter types is a synonym for “notch filter.”

Here is one possible schematic diagram for a notch filter circuit:



Follow-up question: how would you calculate the notch frequency of this filter circuit?

Answer 11



This is definitely an *endothermic* reaction, because both CO₂ and H₂O are highly stable (i.e. low-energy) molecules requiring much energy input to split apart, which is what must happen in order to form the compound necessary to build microbes.

Answer 12

We may optimize the instrument's sensitivity by maximizing the path length (b).

$$c = \frac{\log\left(\frac{I_0}{I}\right)}{ab}$$

Answer 13

Specific conductivity = **294.12** $\mu\text{S}/\text{cm}$

Answer 14

- If the current source's output were to increase, V_{out} would **increase**.
- If the conductivity of the liquid were to increase, V_{out} would **decrease**.
- If the two outer electrodes (connected to the current source) were to become plated with minerals or some other non-conducting coating, V_{out} would **stay the same**.
- You could add salt or some other ionic compound to the water to increase its conductivity. You could also heat the water to a greater temperature.

Answer 15

I will not give away the answer(s) here, but I will propose a “thought experiment” to help: imagine a combustion process where the flow rate of air into a burner system grossly exceeded the amount needed to burn the fuel. Supposing the flame was not blown out by all this excess air, what would all that extra air do flowing through the furnace/boiler/firebox on its way out the exhaust stack?

Insufficient air flow to a burner system is quite dangerous: it may result in an explosion!

Answer 16

Partial answer:

- If a wire breaks loose at TB56-4, creating an “open” fault in the loop circuit, determine what will happen at the alarm unit (AAH, AAL-41) and also where you would expect to measure voltage in the loop circuit and where you would expect to measure *no* voltage in the loop circuit. *The AAL would trip (but not the AAH), and we would expect to measure voltage between the wires of cable 52 but not between the wires of cable 30.*
- If a fire breaks out near the conduit through which cable 52 runs, causing the conductors inside cable 52 to *short* together, what will happen in this system? Where would you expect to measure voltage in the loop circuit, and where would you expect to measure *no* voltage in the loop circuit? Where would you expect to measure current in the loop circuit, and where would you expect to measure *no* current in the loop circuit? *The AAL would trip (but not the AAH), and we would expect to measure no voltage anywhere in the loop circuit. However, we would still have current at the terminals of the AIT-41 transmitter (although no current to the right of the short).*

Answer 17

Process chromatographs only require *very* small volumes of sample injected for proper operation. This is especially true for chromatographs using *capillary tubes* for their columns. Since the volume of injected sample is so incredibly small, a chromatograph with no “sample out” flow would take *days* to draw a new sample through the volume of the tube connecting the chromatograph to the process pipe.

A continuously flowing sample provides a way for the chromatograph to obtain a “fresh” sample at each and every analysis cycle.

Answer 18

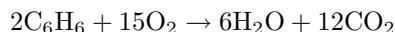
The first equation has an infinite number of balanced solutions. Mathematically, there are more unknowns (variables) than we have linear equations to write. In practical terms, this means the combustion of methane may produce *any* ratio of CO₂:CO depending on how rich or lean the flame burns. This tells us that air/fuel mixture is a critical parameter for ensuring complete combustion (minimal remaining CO gas).

The two equations with given fuel/air ratios are balanced as such:



Having been given a fixed ratio between methane to oxygen, we only have three unknowns (variables) to solve for, and three linear equations to write (one for carbon, one for hydrogen, and one for oxygen), making it a solvable linear system of equations. As you can see, a leaner fuel/air mixture results in less carbon monoxide being produced.

Answer 19



Answer 20

The light source outputs blue light, while the lumiphore molecules fluoresce red light. We know this because in all cases of fluorescence the incident wavelength is shorter (higher-frequency) than the fluoresced wavelength. Blue light has a shorter wavelength (higher frequency) than red light, and therefore it must be the blue color that is emitted by the light source and the red color that is returned by the lumiphore molecules as they fluoresce.

The proportionality between the intensity of this fluoresced light and the concentration of dissolved oxygen is *inverse* based on the description given of dynamic luminescence quenching at the start of this question. The more dissolved oxygen in the presence of the lumiphore molecules, the more their fluorescence will be quenched, and therefore the less red light they will emit when excited by the blue light coming from the light source.

Answer 21

Answer 22

Answer 23

Answer 24

Answer 25

Answer 26

Partial answer:

Filter cells *are required* for this NDIR analyzer!

Answer 27

Partial answer:

Filter cells are not required for this NDIR analyzer.

Answer 28

Partial answer:

Filter cells *are required* for this NDIR analyzer, and they *must* be filled with ethane gas!

Answer 29

Answer 30

The detector in an NDIR analyzer works on pressure: infrared light not absorbed by the sample gas heats gas molecules inside the detector's chambers, exerting pressure in a way that can be converted into an electronic signal. With Dr. Luft's original design, the gas pressure was sensed by a very thin "microphone" diaphragm. In more modern detectors, the gas pressure causes a flow of gas through a tiny channel which is sensed by a thermal sensor.

The key to understanding NDIR detector sensitivity is to recognize that the gas contained within will only be heated by those specific frequencies of light its molecules absorb. That is to say, the detector's fill gas will generate pressure only when exposed to wavelengths of light specific to the absorption spectrum of that fill gas type, and not to light of any other wavelengths.

In the given example where our detector was filled completely with CO₂, pressure would be generated inside the detector only by infrared light wavelengths specific to the absorption patterns of CO₂ gas. If any *other* light-absorbing gas happened to enter the instrument's sample chamber, the light wavelengths absorbed by that other gas will not heat the CO₂ gas inside the detector, to the same degree (or even at all!). Therefore, the detector will be maximally responsive to CO₂ in the sample, and minimally responsive to any other light-absorbing gases in the sample.

As for the thought experiment, it does us no good to imagine what will happen if CO₂ enters the sample chamber. We *already* know what that will do, Luft detector or no! If the goal is to prove that filling the Luft detector *sensitizes* the instrument to one particular gas, we must perform a thought experiment where we imagine *some different light-absorbing gas* entering the sample chamber, and see for ourselves that this other gas causes little or no response from the Luft detector.

Answer 31

This analyzer is sensitized to ammonia (NH₃) and de-sensitized to nitrous oxide (N₂O).

Answer 32

- Chopper wheel stops spinning: *the analyzer's output will go to zero for all gas concentrations.*
- Leak develops in chamber 2: *a "zero" shift will develop.*
- Leak develops in chamber 4: *there may be no effect, unless the ambient air carries a significant concentration of interferent gas.*
- Parabolic mirror cracks: *zero shift, depending on the location and severity of the crack.*

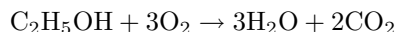
Answer 33

- Calculate the ideal output voltage of the two pH measurement probes if the solution's hydrogen ion molarity is 0.0056 M. $V_{probe} = \mathbf{280.9\ mV}$
- The output voltage will **decrease** if a very small amount of caustic substance is added to the liquid.
- The output voltage will **decrease** slightly if the resistance of the measurement probe increases greatly due to coating. However, an answer of **stay the same** is also okay because generally the amount of decrease is negligible.
- $V_{output} = \mathbf{97.262\ mV}$

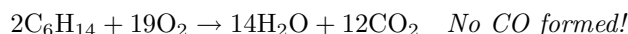
Answer 34

No, because we don't know what *other* substances in the process stream also generate ions when burned, and therefore the measurement we get may not necessarily reflect the concentration of *X* in the process. We can, however, use an FID to measure this substance if it serves as the detector at the end of a *chromatograph*, where substance *X* is expected to emerge from the column at some definite time. Here, the non-specific detection capability of the FID is made specific by the selective delay of the chromatograph column.

Answer 35



Answer 36



Answer 37

The reason why temperature is so critical should be obvious upon inspection of the Nernst equation. As for oxygen/voltage characterization, let's just say this: the cell output will be zero (0) if the process gas contains just as much oxygen as the reference (air).

Answer 38

With the standpipe installed, wastewater flows to the analyzer by gravity (hydrostatic pressure) alone. The main wastewater pipe pressure is completely isolated from the analyzer.

Answer 39

The following suggestions are not necessarily the *only* possible choices for each application:

- Hydrocarbon feed flow: *orifice plate*
- Stripping steam flow measurement: *vortex flowmeter*
- Regenerator air flow: *pitot tube*
- Regenerated catalyst flow: *Doppler ultrasonic*
- Recycle slurry flow: *Segmental wedge*
- CO concentration to steam generator: *NDIR (with filter cells!)*
- Oxygen concentration inside regenerator: *paramagnetic*
- NO_x emissions from CO boiler: *chemiluminescence*

Answer 40

Answer 41

Answer 42

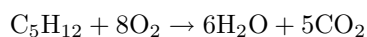
The answer to this question is rooted in an understanding of what combustion is, and how energy gets released in a chemical reaction such as combustion between hydrogen (H) and oxygen (O).

Answer 43

22.5 moles of oxygen (O₂) are necessary to completely combust 15 moles of hydrogen sulfide (H₂S).

Answer 44

This mixture is **too lean**. The ideal (stoichiometric) pentane-to-oxygen mix is:



If the oxygen content is reduced, the mixture will be closer to ideal, but still too lean. Thus, the oxygen transmitter signal will **decrease** (become closer to 4 mA).

Answer 45

[H ⁺]	pH	V _{probe}
0.001995 M	2.7 pH	254.4 mV
6.309×10^{-7} M	6.2 pH	47.32 mV
7.943×10^{-13} M	12.1 pH	-301.7 mV
3.881×10^{-5} M	4.41 pH	153.2 mV
1.452×10^{-11} M	10.84 pH	-227.1 mV

Answer 46

Answer 47

Answer 48

The inventor's real claim is not that he made a car run on water, but that he found a way to (magically) amplify the energy contained in the battery to not only fully replenish the battery's reserves but also to propel the car. This is really a claim of perpetual motion: getting more energy out of a system than what is put in.

Some will argue we cannot dismiss the inventor's claim simply because it contradicts well-established laws of physics. Science does not yield absolute knowledge, and so there must always be some room for open-mindedness, right? The problem with this argument is that it ignores scale. The Law of Energy Conservation is *so well established*, on *so many levels*, and in *so many different fields* of research, that it stands as one of the most well-substantiated principles ever discovered in science. On the other hand, we all know full well the temptation for people to lie and deceive (even themselves) when there is a vested interest at hand (e.g. fame, fortune, and/or strong emotional satisfaction). The odds are literally millions to one that this claim is false, and that the inventor is either knowingly perpetrating a fraud or terribly self-deceived. The plea for open-mindedness comes at the expense of ignoring overwhelming odds. True, there is always a *chance* that someone will discover an exception to a physical Law, but we need to recognize just how slim that chance is when the Law in question is the Conservation of Energy (or Conservation of Mass, for that matter). And, if the claim is indeed true, there is a prize waiting in Stockholm for anyone able to overthrow one of the best-established laws in all of science.

The argument that oil companies actively suppress this technology is laughable on several fronts:

- Oil companies are not just *oil* companies. If they were that small-minded, they would have gone out of business long ago. Oil companies are in fact *energy* companies. This is why many of them support solar energy divisions and other renewable research efforts. They can see the inevitability of oil shortage as well as anyone else, and they have no desire to be caught off guard when it happens.
- If the inventor wished, he could easily build his own stationary power plant using this technology and power his home for (virtually) free. These power plants could then be marketed to anyone and everyone with little capital investment, forming a brand-new market that would not compete with existing oil companies' markets.
- The military (of any country) would be *extremely* interested in finding ways to power their trucks, tanks, airplanes, ships, and submarines with nothing but water. The tactical advantage of water-fueled machines would be so great that no attempted interference by private industry would stop a major military power (such as the United States of America, China, or Russia) from exploiting it to the fullest. Those who may claim that the military is controlled by oil interests and therefore forbidden to pursue alternatives conveniently ignore the fact that the major world militaries are the biggest users of *nuclear power*, having abandoned oil as the fuel of choice for aircraft carriers and submarines long ago for precisely the same reasons they would be willing to embrace "water power" if it existed.

“Table” salt is sodium chloride (NaCl), with 1 atom of sodium bound to 1 atom of chlorine. Together, the number of atomic mass units (amu) for each sodium chloride molecule is the sum of the individual atoms’ atomic masses:

- *Each molecule of NaCl contains:*
- 1 atom of Na at 22.99 amu each
- 1 atom of Cl at 35.45 amu each

$$[(1 \text{ atom})(22.99 \text{ amu/atom}) + (1 \text{ atom})(35.45 \text{ amu/atom})] = 58.44 \text{ g per mole of NaCl}$$

Since we now know the number of grams per mole for NaCl, we may calculate the number of moles needed to make 1 kg (1000 g) of salt:

$$\left(\frac{1000 \text{ g}}{1}\right) \left(\frac{1 \text{ mol NaCl}}{58.44 \text{ g}}\right) = 17.11 \text{ mol NaCl}$$

Therefore, 1 kg of “table” salt is equal to 17.11 moles.

Molarity, or *molar concentration*, is the number of moles of solute per liter of solution. Given 17.11 moles of solute and 850 liters of solution, the molarity will be equal to:

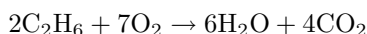
$$\frac{17.11 \text{ mol NaCl}}{850 \text{ L}} = 0.0201M$$

Molarity for a substance is usually represented by placing the chemical symbol for that substance inside square brackets. Molarity as a unit of measurement is expressed as an italicized *M*. Therefore, in this question, $[\text{NaCl}] = 0.0201 \text{ } M$.

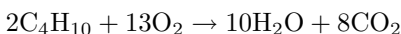
Answer 51

- B, H, I Measuring the concentration of oxygen in air
- A, B, F, G, H Measuring the concentration of specific complex aromatic hydrocarbons in air (no other compounds present)
- A, B, F Measuring the concentration of SO₂ gas in a process stream predominantly composed of CO₂
- A, B Measuring balance of argon and CO₂ in a welding shield gas supply system
- A, B, E Measuring concentration of NO gas, excluding NO₂ and NO₃
- B, G? Measuring the heating value of a mixed fuel gas (a wide range of hydrocarbons)
- B, H Detecting flammable gases (of any kind) in air
- C, D Measuring the strength of a concentrated acid (no other compounds present but water)
- A, B Measuring balance of CO to CO₂ in synthesis gas (from a biomass gasifier), with hydrogen and nitrogen gases also present
- C Detecting the presence of crude oil in sea water
- A, B, H Detecting hydrogen sulfide gas (H₂S) in air with no other compounds present

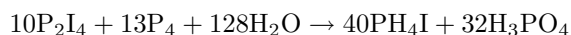
Answer 52



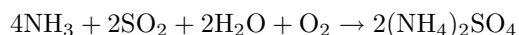
Answer 53



Answer 54



Answer 55

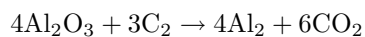


Answer 56

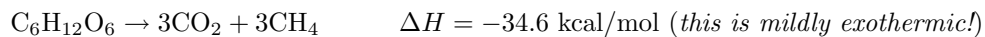
Harmless byproducts: free nitrogen and water vapor.

Follow-up question: write a stoichiometrically balanced chemical reaction for NH₃ and NO₂, showing how the only byproducts will be nitrogen (N₂) and water vapor (H₂O).

Answer 57

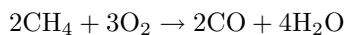


Answer 58



Answer 59

Note that the first equation was a bit of a trick: there are *no* molecules of CO_2 produced at this ratio of methane to oxygen!

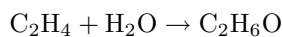


In the second reaction, we have both CO and CO_2 produced, along with water vapor:

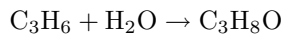


Answer 60

Ethylene to ethanol:



Propylene to isopropanol:



Answer 61

Answer 62

Your loop diagram will be validated when the instructor inspects the loop with you and the rest of your team.

Answer 63

The only “answer” to this question is a properly documented and functioning instrument loop!

Answer 64