
Lab

Control system with automatic shutdown: *Questions 41 and 42, completed objectives due by the end of day 4*

Exam

Day 4

Capstone Assessment takes the place of a mastery exam (see question 43)

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
 - Determine the effect of a component fault or condition change in a cascade-, ratio-, or feedforward-controlled process
 - Identify problem in control loop based on faceplate display and field data
 - Determine proper AI block parameters to range a Fieldbus transmitter for a given application
 - 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
 - INST241 Review: Determine suitability of different flow-measuring technologies for a given process fluid type
 - INST252 Review: Identify cause of poor loop performance from a trend graph
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Recommended daily schedule

Day 1

Theory session topic: Digital safety system security

Questions 1 through 20; answer questions 1-5 in preparation for discussion (remainder for practice)

Discuss the upcoming Capstone Assessment due by the end of the course (*Question 42*)

Day 2

Theory session topic: Overpressure protection and review for exam (site visit)

Questions 21 through 40; answer questions 21-23 in preparation for discussion at an industrial site specified by your instructor. (All remaining questions 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 3

Tour

Day 4

Exam

Day 5

Lab Clean-Up Day

Capstone Assessment: *Question 43*, **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 44 for a list of necessary tasks to complete.

Purchase PLC equipment for Summer quarter

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 purpose of any educational program, and a worthy priority in life. Every circumstance, every incident, every day here 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. To be a responsible person means you *own* the outcome of your decisions and actions.

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 in study means exercising self-discipline and persistence, 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. Diligence in work 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 closest deadline.

Communication means clearly conveying your thoughts and paying attention to what others convey, across all forms of communication (e.g. oral, written, nonverbal).

Teamwork means working constructively with your classmates to complete the job at hand. Remember that here the first job is *learning*, and so teamwork means working to maximize everyone’s learning (not just your own). The goal of learning is more important than the completion of any project or assignment.

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

Representation means your actions reflect this program and not just 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 employ.

Respect means acknowledging the intrinsic value, capabilities, and responsibilities of those around you. Respect is gained by consistent demonstration of valued behaviors, and it is 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 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 daily for important messages. Ask the instructor to clarify any assignment or exam question you find confusing, and express your work clearly.

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 if you sign the FERPA release form. You may see these records at any time, and you should track your own academic progress using the grade spreadsheet template. Extra-credit projects will be tailored to your learning needs.

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 for any of the following behaviors: false testimony (lying), cheating on any assignment or assessment, plagiarism (presenting another’s work as your own), willful violation of a safety policy, theft, harassment, sabotage, destruction of property, or intoxication. These behaviors are grounds for immediate termination in this career, and as such will not be tolerated here.

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.

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INST 263 Course Outcomes

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

- Calculate voltages, currents, and phase shifts in an AC reactive circuit. [Ref: Program Learning Outcome #4]
- Predict the response of an automatic control system to a component fault or process condition change, given a pictorial and/or schematic illustration. [Ref: Program Learning Outcome #4]
- Predict the response of a cascade, ratio, or feedforward control system to a component fault or process condition change, given a pictorial and/or schematic illustration. [Ref: Program Learning Outcome #4]
- Calculate instrument input and output values given calibrated ranges. [Ref: Program Learning Outcome #7]
- Solve for specified variables in algebraic formulae. [Ref: Program Learning Outcome #4]
- Determine the possibility of suggested faults in simple circuits given measured values (voltage, current), schematic diagrams, and reported symptoms. [Ref: Program Learning Outcome #4]
- 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 cascade-, ratio-, or feedforward-controlled process. [Ref: Program Learning Outcome #5]
- Augment an automatic control loop with safety shutdown logic. [Ref: Program Learning Outcome #5]
- Generate accurate loop diagrams compliant with ISA standards documenting your team's control systems. [Ref: Program Learning Outcome #8]
- Build a circuit using an electromechanical relay to energize an AC load, and measure current in this circuit, given a switch and relay both randomly selected by the instructor. [Ref: Program Learning Outcome #5]
- 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]
- Test the proper function of safety shutdown logic in a PID control system within a limited time, logically justifying your steps in the instructor's direct presence. [Ref: Program Learning Outcome #6]
- 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 data acquisition of a variable specified by the instructor. [Ref: Program Learning Outcomes #5 and #9]

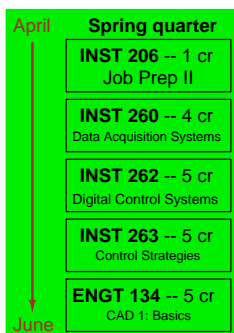
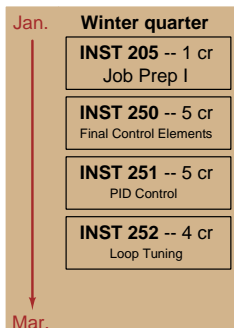
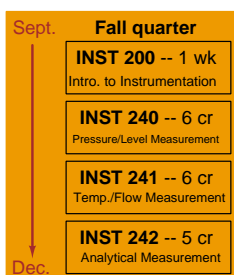
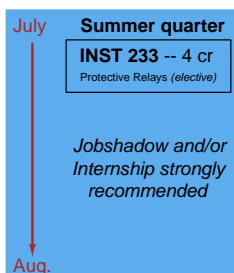
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Sequence of second-year Instrumentation courses

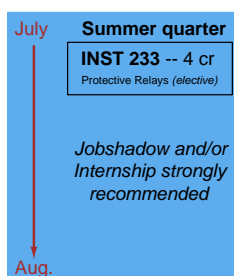
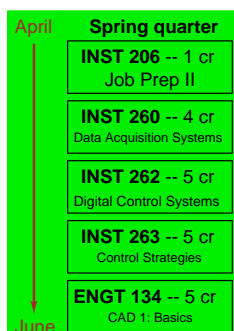
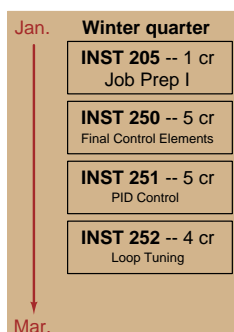
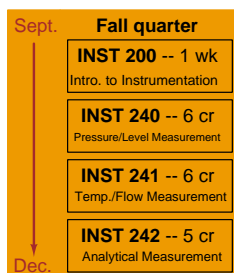


Some second-year courses are only offered in particular quarters with those quarters not having to be in sequence, while others are offered three out of the four quarters and must be taken in sequence. The following layout shows four typical course sequences for second-year Instrumentation students,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

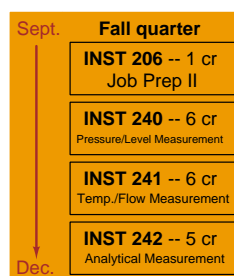
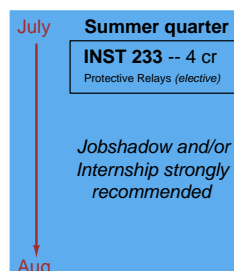
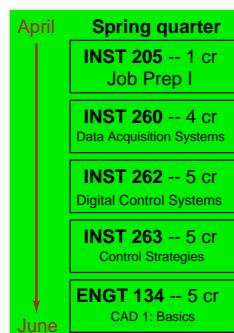
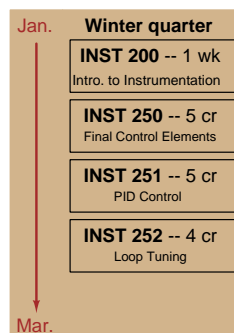
Beginning in Summer



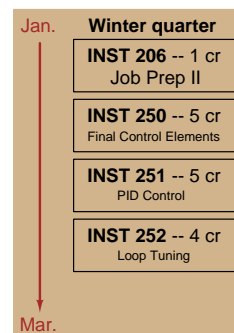
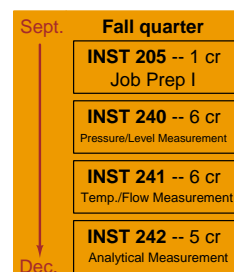
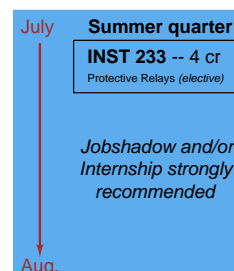
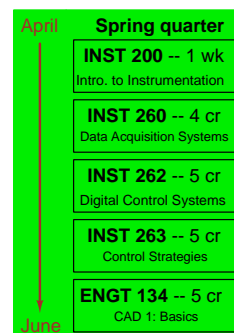
Graduation!



Graduation!



Graduation!



Graduation!

9

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 student’s 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.

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 $4^\circ\text{C} = 1000 \text{ kg}/\text{m}^3 = 1 \text{ g}/\text{cm}^3 = 1 \text{ kg}/\text{liter} = 62.428 \text{ lb}/\text{ft}^3 = 1.94 \text{ slugs}/\text{ft}^3$

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

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 $20^\circ\text{C} = 1.0019 \text{ centipoise (cp)} = 0.0010019 \text{ Pascal-seconds (Pa}\cdot\text{s)}$

Surface tension of water (in contact with air) at $18^\circ\text{C} = 73.05 \text{ dynes}/\text{cm}$

pH of pure water at $25^\circ\text{C} = 7.0$ (*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 = $0.018 \text{ centipoise (cp)} = 1.8 \times 10^{-5} \text{ Pascal-seconds (Pa}\cdot\text{s)}$

file conversion_constants

How to get the most out of academic reading:

- Outline, don't highlight! Identify every major idea presented in the text, and express these ideas in your own words. A suggested ratio is one sentence of your own thoughts per paragraph of text read.
- Articulate your thoughts as you read (i.e. “have a conversation” with the author). This will develop *metacognition*: active supervision of your own thoughts. Note points of agreement, disagreement, confusion, epiphanies, and connections between different concepts or applications.
- 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.
- Create your own questions based on what you read, as a teacher would to challenge students.

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 step 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). Remove components from a malfunctioning system to simplify it and better identify the nature and location of the problem.
- Check for exceptions – does your solution work for *all* conditions and criteria?
- 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, every single day.
- Consider the place you're in when deciding what to do. If there is project work to do and you have access to the lab, do that work and not something that could be done elsewhere (e.g. homework).
- Eliminate distractions. Kill your television and video games. Turn off your mobile phone, or just leave it at home. Study in places where you can concentrate, like the Library.
- 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, as this 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!

Checklist when reading an instructional text

“Reading maketh a full man; conference a ready man; and writing an exact man” – Francis Bacon

Francis Bacon’s advice is a blueprint for effective education: reading provides the learner with knowledge, writing focuses the learner’s thoughts, and critical dialogue equips the learner to confidently communicate and apply their learning. Independent acquisition and application of knowledge is a powerful skill, well worth the effort to cultivate. To this end, students should read these educational resources closely, write their own outline and reflections on the reading, and discuss in detail their findings with classmates and instructor(s). You should be able to do all of the following after reading any instructional text:

☒ Briefly **OUTLINE THE TEXT**, as though you were writing a detailed Table of Contents. Feel free to rearrange the order if it makes more sense that way. Prepare to articulate these points in detail and to answer questions from your classmates and instructor. Outlining is a good self-test of thorough reading because you cannot outline what you have not read or do not comprehend.

☒ Demonstrate **ACTIVE READING STRATEGIES**, including verbalizing your impressions as you read, simplifying long passages to convey the same ideas using fewer words, annotating text and illustrations with your own interpretations, working through mathematical examples shown in the text, cross-referencing passages with relevant illustrations and/or other passages, identifying problem-solving strategies applied by the author, etc. Technical reading is a special case of problem-solving, and so these strategies work precisely because they help solve any problem: paying attention to your own thoughts (metacognition), eliminating unnecessary complexities, identifying what makes sense, paying close attention to details, drawing connections between separated facts, and noting the successful strategies of others.

☒ Identify **IMPORTANT THEMES**, especially **GENERAL LAWS** and **PRINCIPLES**, expounded in the text and express them in the simplest of terms as though you were teaching an intelligent child. This emphasizes connections between related topics and develops your ability to communicate complex ideas to anyone.

☒ Form **YOUR OWN QUESTIONS** based on the reading, and then pose them to your instructor and classmates for their consideration. Anticipate both correct and incorrect answers, the incorrect answer(s) assuming one or more plausible misconceptions. This helps you view the subject from different perspectives to grasp it more fully.

☒ Devise **EXPERIMENTS** to test claims presented in the reading, or to disprove misconceptions. Predict possible outcomes of these experiments, and evaluate their meanings: what result(s) would confirm, and what would constitute disproof? Running mental simulations and evaluating results is essential to scientific and diagnostic reasoning.

☒ Specifically identify any points you found **CONFUSING**. The reason for doing this is to help diagnose misconceptions and overcome barriers to learning.

General challenges following a tutorial reading assignment

- Summarize as much of the text as you can in one paragraph of your own words. A helpful strategy is to explain ideas as you would for an intelligent child: as simple as you can without compromising too much accuracy.
- Simplify a particular section of the text, for example a paragraph or even a single sentence, so as to capture the same fundamental idea in fewer words.
- Where did the text make the most sense to you? What was it about the text's presentation that made it clear?
- Identify where it might be easy for someone to misunderstand the text, and explain why you think it could be confusing.
- Identify any new concept(s) presented in the text, and explain in your own words.
- Identify any familiar concept(s) such as physical laws or principles applied or referenced in the text.
- Devise a proof of concept experiment demonstrating an important principle, physical law, or technical innovation represented in the text.
- Devise an experiment to disprove a plausible misconception.
- Did the text reveal any misconceptions you might have harbored? If so, describe the misconception(s) and the reason(s) why you now know them to be incorrect.
- Describe any useful problem-solving strategies applied in the text.
- Devise a question of your own to challenge a reader's comprehension of the text.

General follow-up challenges for assigned problems

- Identify where any fundamental laws or principles apply to the solution of this problem, especially before applying any mathematical techniques.
- Devise a thought experiment to explore the characteristics of the problem scenario, applying known laws and principles to mentally model its behavior.
- Describe in detail your own strategy for solving this problem. How did you identify and organized the given information? Did you sketch any diagrams to help frame the problem?
- Is there more than one way to solve this problem? Which method seems best to you?
- Show the work you did in solving this problem, even if the solution is incomplete or incorrect.
- What would you say was the most challenging part of this problem, and why was it so?
- Was any important information missing from the problem which you had to research or recall?
- Was there any extraneous information presented within this problem? If so, what was it and why did it not matter?
- Examine someone else's solution to identify where they applied fundamental laws or principles.
- Simplify the problem from its given form and show how to solve this simpler version of it. Examples include eliminating certain variables or conditions, altering values to simpler (usually whole) numbers, applying a limiting case (i.e. altering a variable to some extreme or ultimate value).
- For quantitative problems, identify the real-world meaning of all intermediate calculations: their units of measurement, where they fit into the scenario at hand. Annotate any diagrams or illustrations with these calculated values.
- For quantitative problems, try approaching it qualitatively instead, thinking in terms of "increase" and "decrease" rather than definite values.
- For qualitative problems, try approaching it quantitatively instead, proposing simple numerical values for the variables.
- Were there any assumptions you made while solving this problem? Would your solution change if one of those assumptions were altered?
- Identify where it would be easy for someone to go astray in attempting to solve this problem.
- Formulate your own problem based on what you learned solving this one.

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Questions

Question 1

Read and outline the “A Primer on Uranium Enrichment” subsection of the “Stuxnet” section of the “Instrumentation Cyber-Security” chapter in your *Lessons In Industrial Instrumentation* textbook.

After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

file i00641

Question 2

Read and outline section “A” (Exploring the Attack Vector) of the report *To Kill A Centrifuge* written by Ralph Langner.

After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

The following is a helpful glossary of terms used but not well defined within the report:

- **Air gap:** a point where digital networks are separated from each other and cannot inter-communicate.
- **CERT:** Computer Emergency Response Team.
- **Data Diode:** a device or feature of other devices allowing information to only flow in one direction.
- **DDos attack:** Distributed Denial of Service attack, in which multiple demands overload a system so as to impede or prevent normal access to that system.
- **Dropper:** the portion of malware designed to deliver the rest of the malware (the “payload”) to its intended target.
- **IAEA:** International Atomic Energy Agency.
- **infosec:** Information Security – concerning the privacy of digital information.
- **ICS:** Industrial Control System.
- **IT:** Information Technology.
- **Malware:** software written with malicious intent.
- **OPSEC:** Operations Security – concerning the secrecy of the cyber-attack operation itself.
- **Payload:** the portion of malware designed to attack the target.
- **Vector:** the pathway by which malware infiltrates and inflicts damage.
- **Vulnerability:** a design weakness allowing malicious intrusion or other interference.
- **Zero-day vulnerability:** a vulnerability previously unknown to the creator(s) of that system.

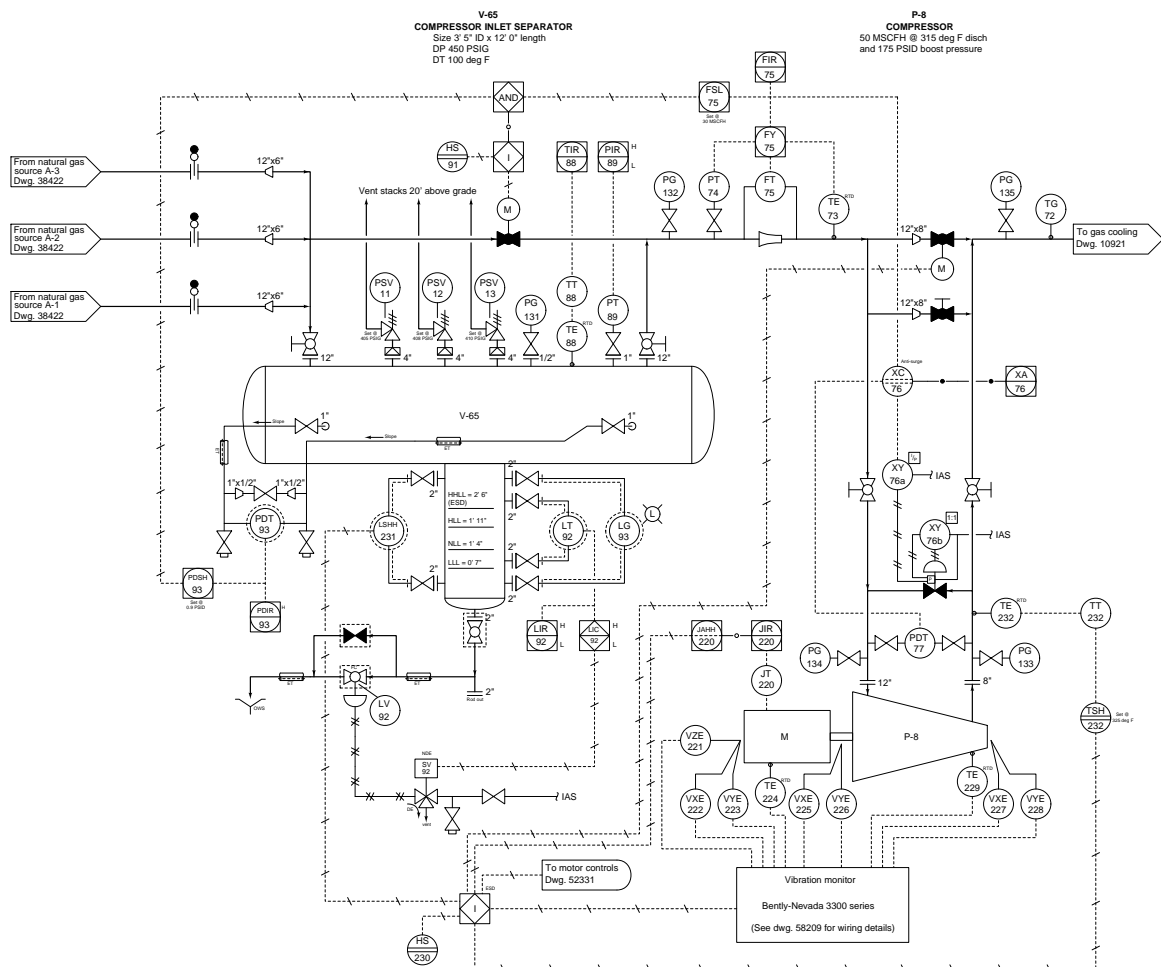
Answer the following questions after reading the report, and be prepared to discuss the points in detail:

- What is a *man-in-the-middle* cyber attack, and did Stuxnet implement this form of attack in the PLC control system?
- How exactly was the centrifuge overpressure attack designed to damage process equipment? In other words, what would have been the physical consequences of the centrifuge rotor pressures rising to abnormally high levels?
- How exactly was the rotor speed attack designed to damage process equipment? In other words, what would have been the physical consequences of the centrifuge rotor speeds varying abnormally?
- These two different attack vectors were not simultaneous, but released as updates to the Stuxnet virus. Which attack came first?
- These two different attack vectors also varied in how they were able to gain access to the PLC control system at Natanz. Contrast the different modes of infection (i.e. the “dropper” portion of these Stuxnet versions) between the two attacks.

file i00697

Question 3

A company operates a natural gas transmission pipeline, and part of their business involves boosting the pressure of the natural gas using large motor-driven compressors. This particular compressor is equipped with an “inlet separator” vessel to drop out any liquid prior to compression, since liquids are incompressible and therefore are destructive to gas compressor machinery:



Examine this diagram closely to look for any potential vulnerabilities in the instrumentation that could be exploited through a cyber-attack, and what the effects of those attacks might be on the process. Also, identify any instrumentation in this compressor system that appears immune to cyber-attack.

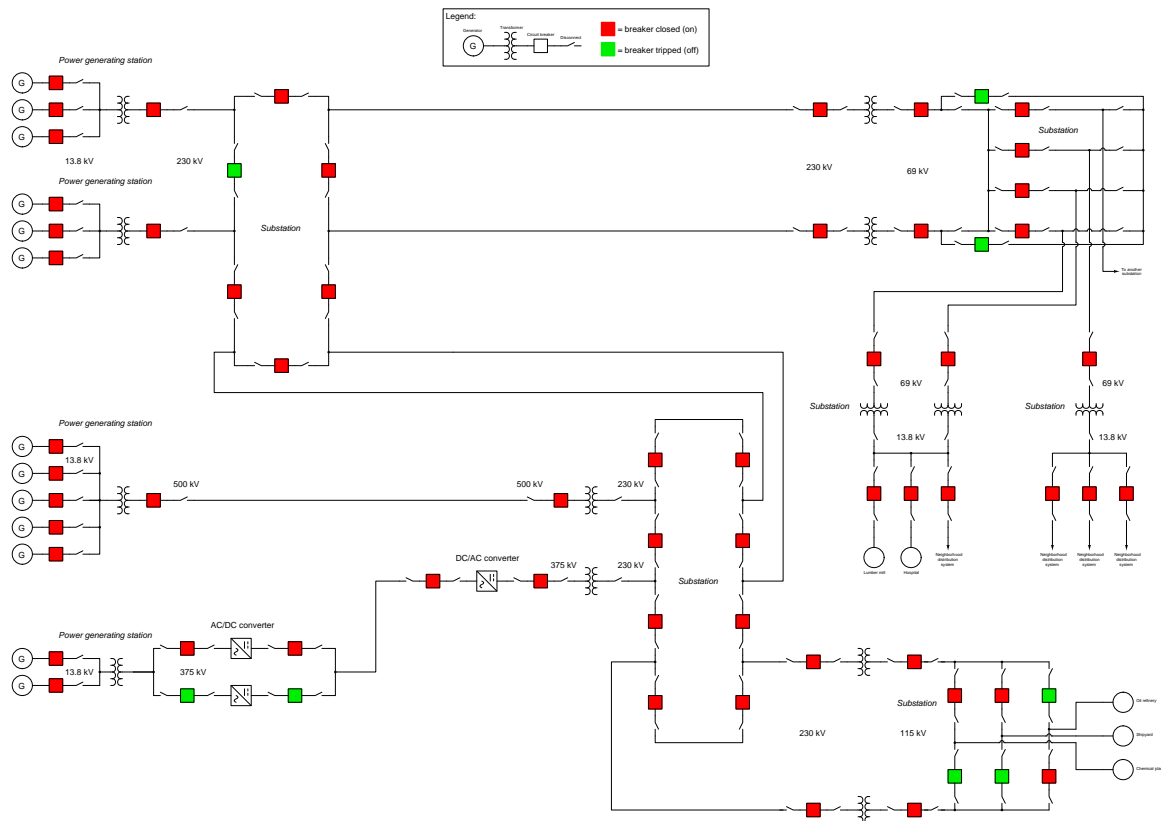
Suggestions for Socratic discussion

- How might a cyber-attacker wreak havoc in a process by introducing a *calibration error* in a digital instrument or control system?
- How might a cyber-attacker wreak havoc in a process by altering the *tuning parameters* of a PID control loop?

[file i01078](#)

Question 4

Examine the following single-line diagram of a wide-area electric power system (“grid”) and analyze it for points of vulnerability, assuming all circuit breakers in this system are equipped with digital protective relays, monitored and controlled via networked SCADA system:



Identify any “high-value targets” for cyber-attack in this system. These would be elements of the system most likely to result in extended outages and/or maximum effect from an outage of any duration.

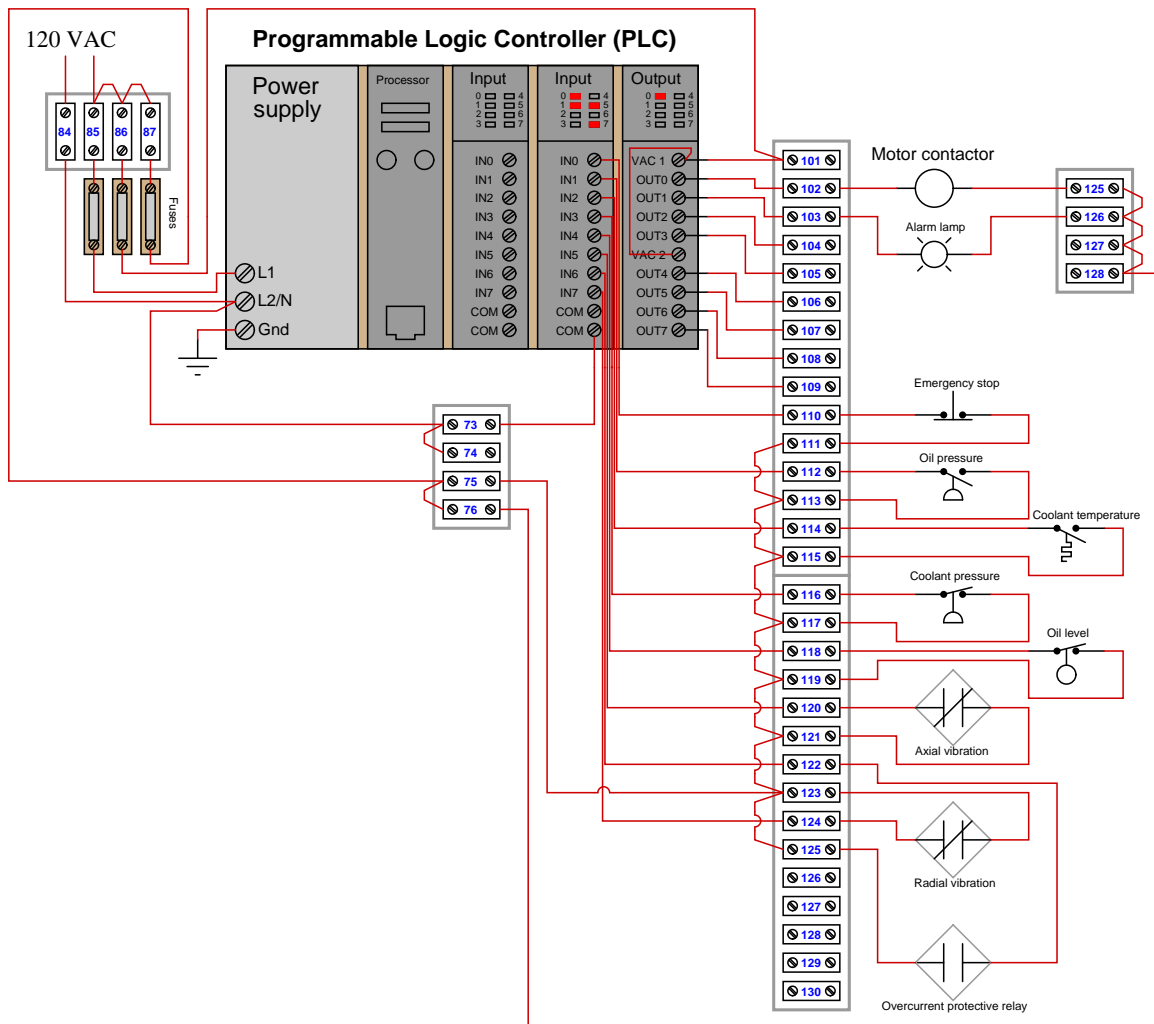
Do you see any differences in the value of these targets as viewed from different attackers’ perspectives? Consider the following categories of attackers:

- Military (i.e. a nation-state attack)
- Terrorist
- Individual hacker

[file i01185](#)

Question 5

In this safety shutdown system, a programmable logic controller (PLC) monitors inputs coming from various switches located on a large motor-driven gas compressor system, and trips the compressor off (shuts off power to the motor's contactor coil) if any of these conditions becomes dangerous.



Noting the status of the LEDs on the discrete input card of the PLC while the compressor is running as it should, identify what you would have to do to electrically simulate the following trip conditions (i.e. make the PLC “think” that a dangerous condition existed when in fact one did not):

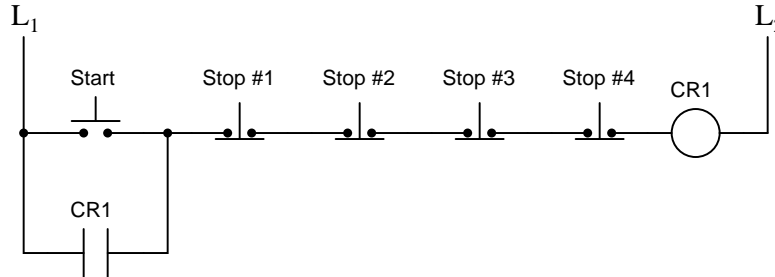
- Abnormal oil pressure
- Abnormal oil level
- Abnormal coolant temperature
- Abnormal coolant pressure
- High axial vibration
- High radial vibration
- Overcurrent condition detected

How might a hacker shut down this compressor once gaining access to the PLC via a digital network?
[file i03125](#)

Question 6

Two important concepts in control system engineering are *dependability* and *security*. Dependability refers to the probability that a safety system will shut down a potentially dangerous process when needed, while security refers to the probability of that same system allowing the process to operate when there is no dangerous condition.

For example, an emergency-stop shutdown system for a conveyor belt uses multiple emergency-stop switches which anyone can activate at multiple locations. This provides a means of stopping a running conveyor belt in more than one place:

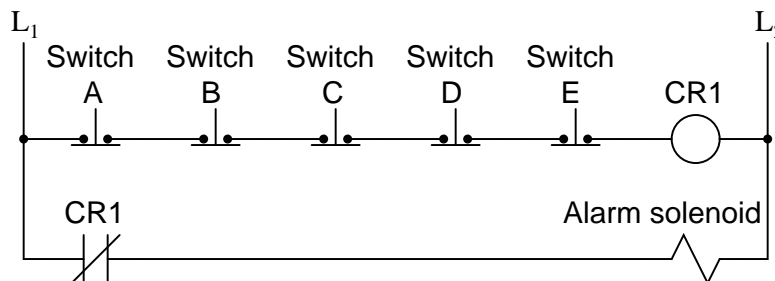


Determine the *dependability* of this safety shutdown system in terms of how many “Stop” switches would have to be actuated to halt the conveyor. Conversely, determine the *security* of this system in terms of how many “Stop” switches must be returned to their proper (running) positions in order to start the conveyor up.

[file i02488](#)

Question 7

Shown here is the ladder logic diagram for a fire alarm system, where the activation of any alarm switch opens that (normally-closed) switch contact and sounds the alarm:



Write the Boolean expression for this relay circuit, then simplify that expression using DeMorgan's Theorem and draw a new relay circuit implementing the simplified expression.

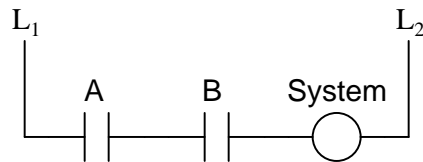
Finally, analyze the two circuits and determine which one is more practical from the perspective of fail-safe. In other words, determine which circuit will give the *safest* result in the event of a switch or wiring failure, and explain why.

[file i02478](#)

Question 8

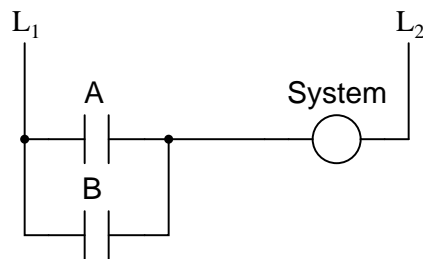
A common way of denoting the architecture of a redundant system is to express the redundancy in terms of *required* elements versus *total* elements with regard to automatic shutdowns. For example, a system using two redundant process switches to detect a dangerous process condition, where either one of the two switches tripping will guarantee a system shutdown, would be designated *1oo2*, or “One out of Two,” for dependability. However, another important measure of a redundant system is how many redundant elements need to output a “good” condition in order to guarantee the system can run. This is referred to in the electric power industry as *security*.

Examine the following ladder logic diagrams where switch contacts can either permit or inhibit the operation of a system (designated by a relay coil). Describe each one using “MooN” terminology for dependability (de-energizing the coil) as well as for security (an energized coil):



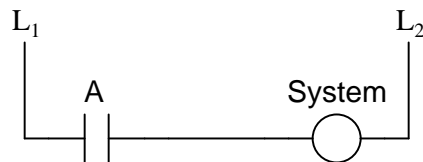
Dependability MooN = _____

Security MooN = _____



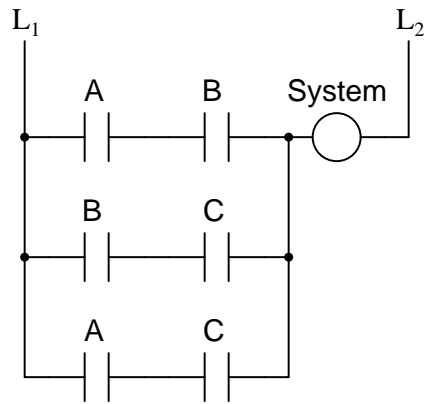
Dependability MooN = _____

Security MooN = _____



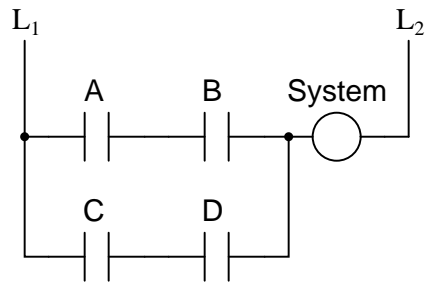
Dependability MooN = _____

Security MooN = _____



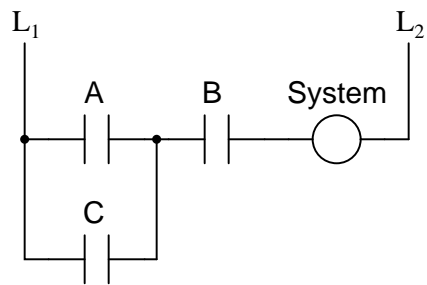
Dependability MooN = _____

Security MooN = _____



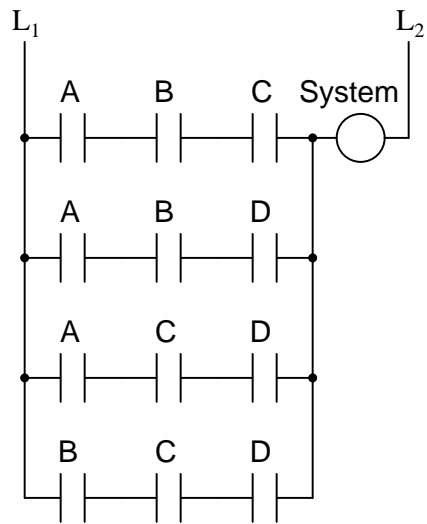
Dependability MooN = _____

Security MooN = _____



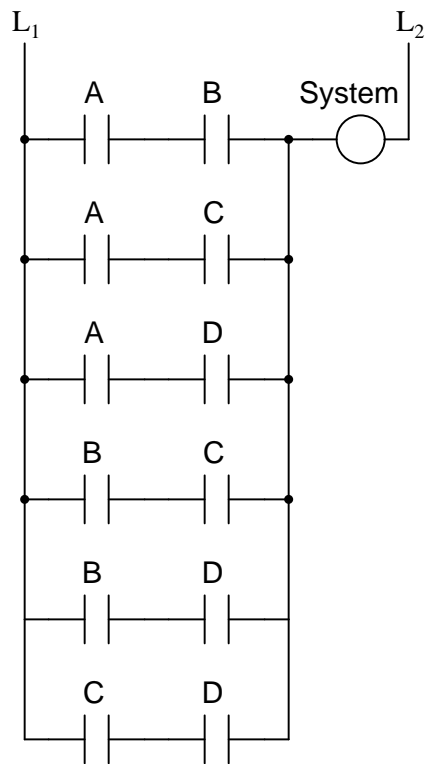
Dependability MooN = _____

Security MooN = _____



Dependability MooN = _____

Security MooN = _____



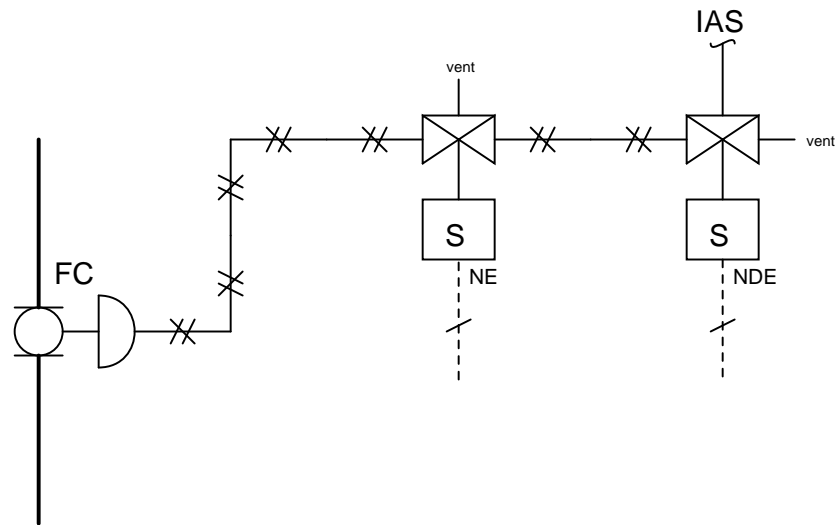
Dependability MooN = _____

Security MooN = _____

file i02490

Question 9

Sketch arrows next to each of the two solenoid valves showing the directions of air flow in the energized (E) and de-energized (D) states, assuming the process control valve is supposed to be open in regular operation and close if either of the solenoid valves “trips” (i.e. 1oo2 to trip):



file i04355

Question 10

When I was a young child, pondering the concepts of right and wrong, I noticed a friend of mine based his own ethical decisions on a simple formula: his decision to do something punishable by adults was inversely proportional to both the risk of being caught and the severity of the punishment. Thus, if the risk of getting caught was small, and/or the punishment was not severe, he would do whatever he wanted.

Despite the ethical shortcomings of my young friend's approach, there is a certain practicality to it. Risk analysis for industrial process systems follows a similar formula. Two vital factors to consider when assessing the risk posed by an industrial process is:

1. The probability of the dangerous event occurring
2. The severity of the danger

The following tables quantify probability and severity on a simple number scale:

Risk level	Description	Frequency
1	Improbable	Once per 10,000 yrs
2	Remote	Once per 1,000 yrs
3	Occasional	Once per 100 yrs
4	Probable	Once per 10 yrs
5	Frequent	Once per yr

Risk level	Description	Consequences
1	Negligible	No injuries
2	Minor	Medical treatment
3	Serious	Lost-time accident
4	Severe	Death
5	Catastrophic	Multiple deaths

Determine the most logical way to combine the two ratings to form a single numerical "risk factor" describing an industrial event.

[file i02483](#)

Question 11

Read and outline section “B” (Misconceptions about Stuxnet’s Operation and Impact) of the report *To Kill A Centrifuge* written by Ralph Langner.

After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
 - (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
 - (3) General principles, especially physical laws, referenced in the text.
 - (4) Questions of your own you would pose to another reader, to challenge their understanding.
 - (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
 - (6) Any points of confusion, and precisely why you found the text confusing.
- Briefly describe the various “Technical Security Controls” listed by the author in section “B” of this report, and explain in your own words how the Stuxnet attack bypassed all of them.
 - Imagine being employed as an instrument technician or engineer at such a facility. Identify some practical means of defending against both versions of the Stuxnet attack. Your answer may include ways to design the control system differently, as well as defensive operational protocols and engineering policies instituted after commissioning.

[file i00698](#)

Question 12

Read and outline section “C” (Inside Natanz: A Guided Tour of Plant Systems, Instrumentation, and Control) of the report *To Kill A Centrifuge* written by Ralph Langner.

After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

[file i00699](#)

Question 13

The model SEL-551 protective relay manufactured by Schweitzer Engineering Laboratories is a modern digital relay capable of overcurrent protection (both time-overcurrent and instantaneous overcurrent) as well as reclosing. Like many industrial digital devices, its internal parameters are network-accessible via the Modbus protocol.

An appendix section in the “SEL-551 Relay” protective relay manual (document PM551-01, April 2011) focuses on the relay’s Modbus capabilities. Reference this section to answer the following questions:

Identify some of the data that may be read from and written to this relay via Modbus.

Is it possible to issue a Modbus command that would force the relay’s assigned power circuit breaker to trip when it otherwise would not?

Is it possible to issue a Modbus command that would force the relay’s assigned power circuit breaker to close when it otherwise would not?

Assuming an SEL-551 relay were connected to a Modbus RTU network, what protective measures would you suggest to fortify this relay against a cyber-attack?

[file i01079](#)

Question 14

Question 15

Question 16

Question 17

Question 18

Question 19

Question 20

Question 21

Describe your recent learning experiences succinctly enough to be included as a line-item in your résumé. Identify how this learning has made you more marketable in this career field. Be as specific as you can, and feel free to include non-technical as well as technical learning in your description (e.g. project management, organization, independent research, troubleshooting, design, software applications, electric circuit analysis, control theory, etc.)!

Identify any knowledge and/or skill areas in which you would like to become stronger, and describe practical steps you can take to achieve that goal. Don't limit yourself to just technical knowledge and skills, but consider behavioral habits (e.g. patience, attention to detail, time management) and general academic abilities (e.g. reading, writing, mathematics) as well. If you find yourself struggling to achieve a goal, don't just say "I'll work harder" as your plan of action – identify something *different* you can do to achieve that goal.

Note: your responses to these questions will not be shared in Socratic discussion with classmates without your consent. Feel free to maintain these as private notes between yourself and your instructor.

A helpful guide to traits and skills valued by employers are the "General Values, Expectations, and Standards" pages near the beginning of this worksheet. Another is the "So You Want To Be An Instrument Technician?" career guide.

file i00999

Question 22

Read and outline the “Overpressure Protection Devices” section of the “Process Safety and Instrumentation” chapter in your *Lessons In Industrial Instrumentation* textbook.

After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

In addition to reading about overpressure protection devices, locate the pressure relief valve on your home’s hot-water tank to see a practical example of one. (Even if you live in an apartment rather than a house, you should have a hot water heater located somewhere where you can inspect it.) Take a digital photograph of the pressure relief valve, noting its construction and manual test lever. Why do you think every hot water heater in America is equipped with a pressure relief valve? Can you see a lift pressure rating documented on this valve?

If you cannot locate your home’s hot water heater, open the hood of your car and locate the *radiator cap*, which also functions as a pressure relief valve. Take a digital photograph of the radiator cap, being sure to include the relief tube (where the cap vents excess pressure) in the picture. Can you see a lift pressure rating documented on this safety device?

Suggestions for Socratic discussion

- How much pressure does your car’s radiator cap lift at? How high of a water temperature does this correlate to? Hint: consult a *saturated steam table* to determine the steam pressure of boiling water at a given temperature.

[file i02986](#)

Question 23

Site visit!

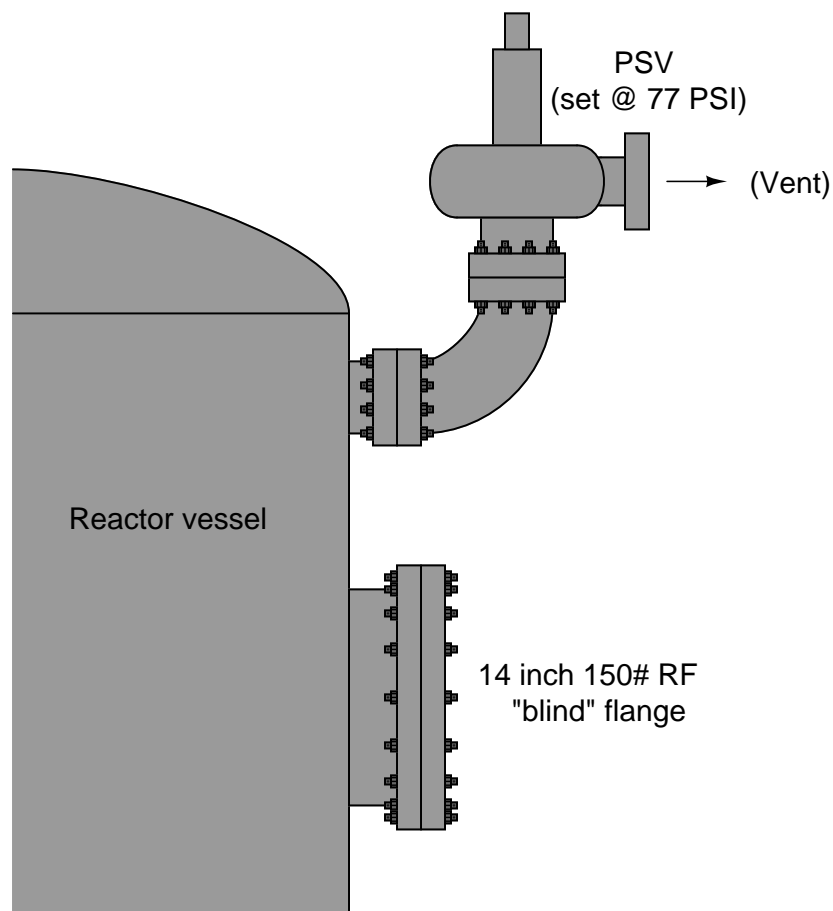
As part of today’s inverted theory session, you will meet your instructor at a site containing real processes controlled by feedback control systems, where you will evaluate those systems for safety. Prepare yourself to do the following while on site:

- Identify potential hazards of overpressure in a given process based on an inspection of the piping and vessels
- Propose safety shutdown systems to mitigate risk in a given process
- Wear safety glasses and sturdy (closed-toed) shoes

[file i01742](#)

Question 24

A safety device commonly installed on process vessels containing pressurized gases is a *Pressure Safety Valve*, or PSV. In this example, a PSV protects a reactor vessel against rupture from excessive internal gas pressure, with the PSV set to open ("lift") and vent the tank if the internal pressure exceeds 77 PSI:



Calculate the total force exerted on a 14 inch blind flange located on the side of the reactor at the PSV lift pressure, both in pounds and in tons. Use $13\frac{1}{4}$ inches as the effective diameter of the blind flange.

$$F_{total} = \underline{\hspace{2cm}} \text{ lb}$$

$$F_{total} = \underline{\hspace{2cm}} \text{ tons}$$

Suggestions for Socratic discussion

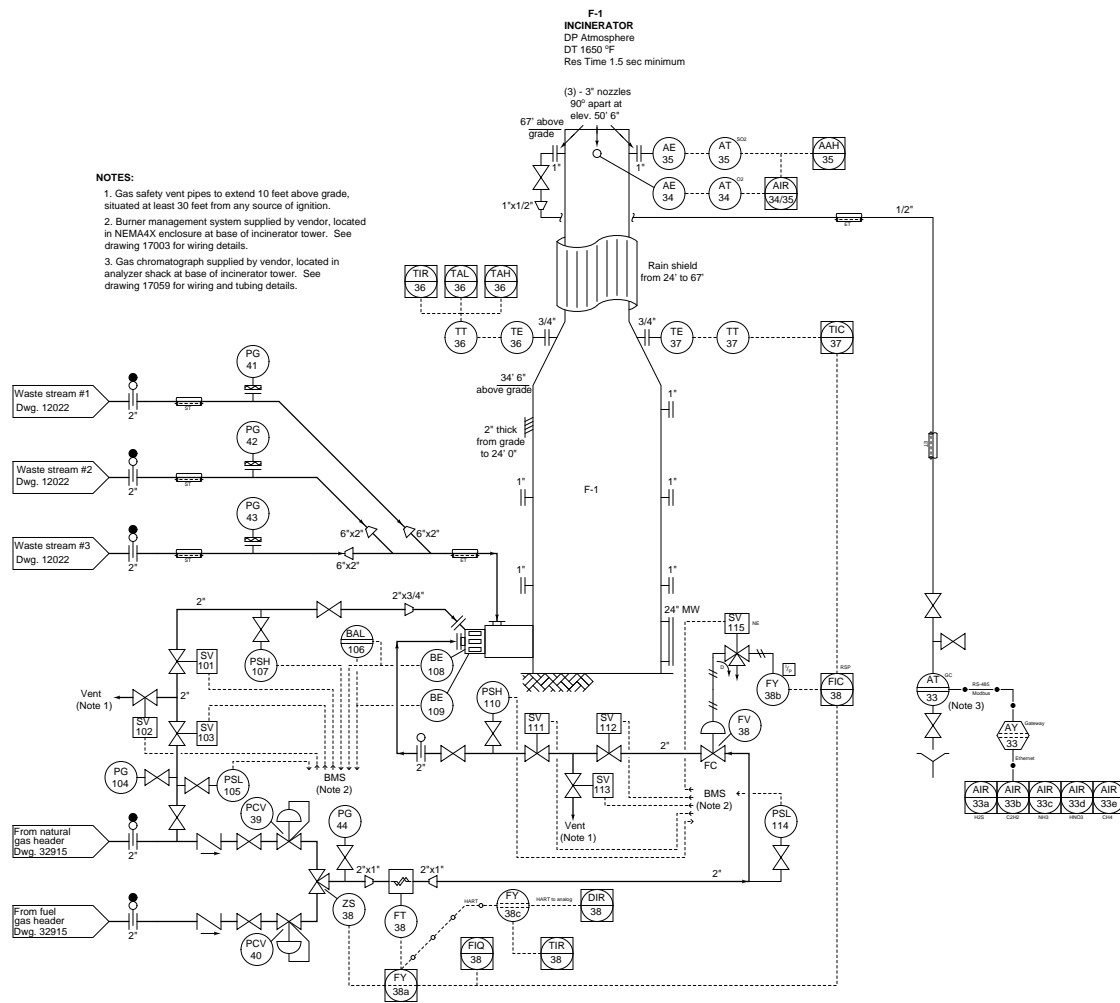
- If this reactor vessel held a liquid instead of a gas, would it affect the calculations of force applied to the flange? Why or why not?
- If this reactor vessel held a liquid instead of a gas, would it affect the proper selection of the overpressure valve? Why or why not?
- If this reactor vessel's temperature were to substantially increase, would it affect the proper overpressure valve setting? Why or why not?
- If this reactor's fluid were extremely flammable and/or toxic, what would be the safest way to plumb an overpressure valve, since direct release to the atmosphere would be itself unsafe?

- A dangerous practice unfortunately seen in some industries is called *hot-bolting* of flanges, where only half of the flange bolts (i.e. every other bolt) are tightened to hold the flange in place during unit start-ups. Explain why this practice is unsound, and also explain what factors might tempt operations personnel to try it.

file i00502

Question 25

This incinerator system is equipped with a Burner Management System (BMS), which is a particular form of Safety Instrumented System (SIS) used to maintain safe conditions in combustion processes:



Fuel pressure safety switches on a BMS are typically wired for *de-energize to trip* operation. Given this design specification, determine whether the following pressure switches should be wired as *normally-open* (NO) or *normally-closed* (NC), assuming we have the option of choosing for each switch:

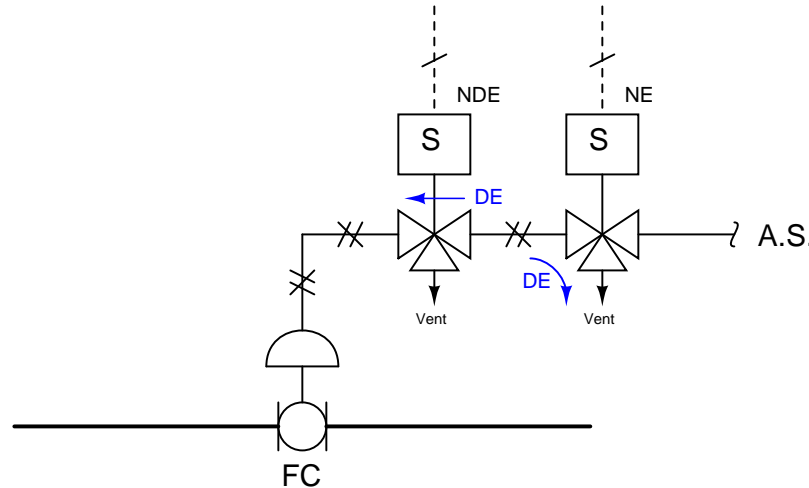
- PSL-105: should be wired *normally-open* or *normally-closed*?
- PSL-114: should be wired *normally-open* or *normally-closed*?
- PSH-107: should be wired *normally-open* or *normally-closed*?
- PSH-110: should be wired *normally-open* or *normally-closed*?

Remember that the “normal” status of any switch is the state it is in when resting (i.e. minimum stimulus).

file i02114

Question 26

Examine this P&ID and answer the following questions:



Identify the “normal” mode of operation for this system as specified by the process engineer who built it: the status of the process valve and of both solenoid valves during typical process operations.

Identify the “normal” mode of operation for each solenoid valve as specified by the solenoid manufacturer: the status of each solenoid valve when it is in a condition of rest (no stimulation).

Explain what type of electrical signal status (power applied or power removed) is required at each solenoid valve to “trip” the process valve from its regular operating position. Must both solenoids change state to trip the process valve (2oo2 to trip), or is one sufficient (1oo2 to trip)?

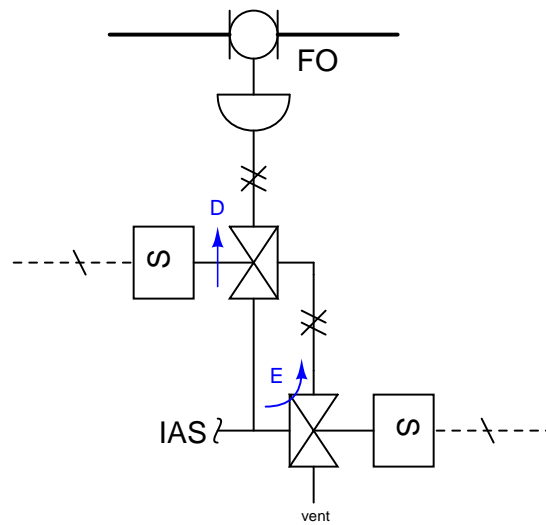
Suggestions for Socratic discussion

- The usage of the word “normal” is very different when describing a solenoid coil’s energization state versus when the same word is used to describe a spring-return valve being “normally-open” or “normally-closed.” Explain how these two meanings differ, and why this distinction – though confusing it may be – is important to understand.
- Explain the significance of the linetypes used in this diagram.
- Identify the type of process valve used in this system, from the symbol.
- Explain what *dependability* means in the context of this safety system.
- Explain what *security* means in the context of this safety system.
- If you have studied mathematical probability as it applies to system reliability, calculate the probability of the process valve shutting off when it shouldn’t (i.e. this trip system’s *unsecurity*) given the following probabilities of component failure:
 - P of first solenoid valve accidentally venting air pressure = 0.02
 - P of second solenoid valve accidentally venting air pressure = 0.01
 - P of instrument air supply failing = 0.05
- If you have studied mathematical probability as it applies to system reliability, calculate the probability of the process valve shutting off during an emergency (trip) condition (i.e. this trip system’s *dependability*) given the following component dependability figures:
 - P of first solenoid valve dependably venting air pressure = 0.99
 - P of second solenoid valve dependably venting air pressure = 0.97

[file i04197](#)

Question 27

Determine the “normal energization” states (e.g. NE or NDE) of each solenoid valve in this diagram, assuming the process valve needs to be *closed* when the process is running as it should:



Also, determine whether one or both solenoids need to “trip” in order to make the process valve go to its fail-state.

Suppose the ball valve refused to shut off when it should. Identify at least two possible faults that could cause this to happen.

Suggestions for Socratic discussion

- Suppose the probability of each solenoid valve “sticking” in its regular operating position instead of tripping when commanded is 6.2×10^{-3} . Calculate the probability of the process valve refusing to trip when commanded as a result of this type of failure.
- Suppose the probability of each solenoid valve “sticking” in its tripped position instead of going to its regular operating position when commanded is 7.7×10^{-3} . Calculate the probability of the process valve refusing to go to its regular operating position when commanded as a result of this type of failure.
- Suppose the probability of each solenoid valve accidentally tripping during regular operation is 8.1×10^{-4} . Calculate the probability of the process valve tripping accidentally as a result of this type of failure.

[file i04359](#)

Question 28

Read selected sections of the US Chemical Safety and Hazard Investigation Board's report (2008-3-I-FL) of the 2008 chemical reactor explosion at T2 Laboratories in Jacksonville, Florida, and answer the following questions.

Explain in your own words what the CSB's "only credible cause" was for the chemical reactor vessel to violently explode.

Page 20 shows a simple diagram of the reactor vessel and associated apparatus. Identify in this diagram the single over-pressure protection device, and explain how it is supposed to function in the event of an emergency.

Page 25 describes some chemical tests the CSB performed in the wake of this accident, and one of their recommendations is that the over-pressure relief limit should have been set much lower than it was. Explain the rationale for this recommendation.

On page 24, it says "*Interviews with employees indicated that T2 ran cooling system components to failure . . .*". Explain what this phrase means, in your own words, and how this policy adversely affects the probability of failure on demand (PFD) for any safety-related control system.

Page 24 lists several potential single-point failures in the reactor's cooling system. Brainstorm specific design changes which could have been made to this process in order to mitigate each one of these potential failures.

Pages 29 and 30 describe a rather sad state of affairs in American chemical engineering curricula. Describe what the Mary Kay O'Connor Process Safety Center discovered in their 2006 survey of 180 chemical engineering departments at universities around the United States.

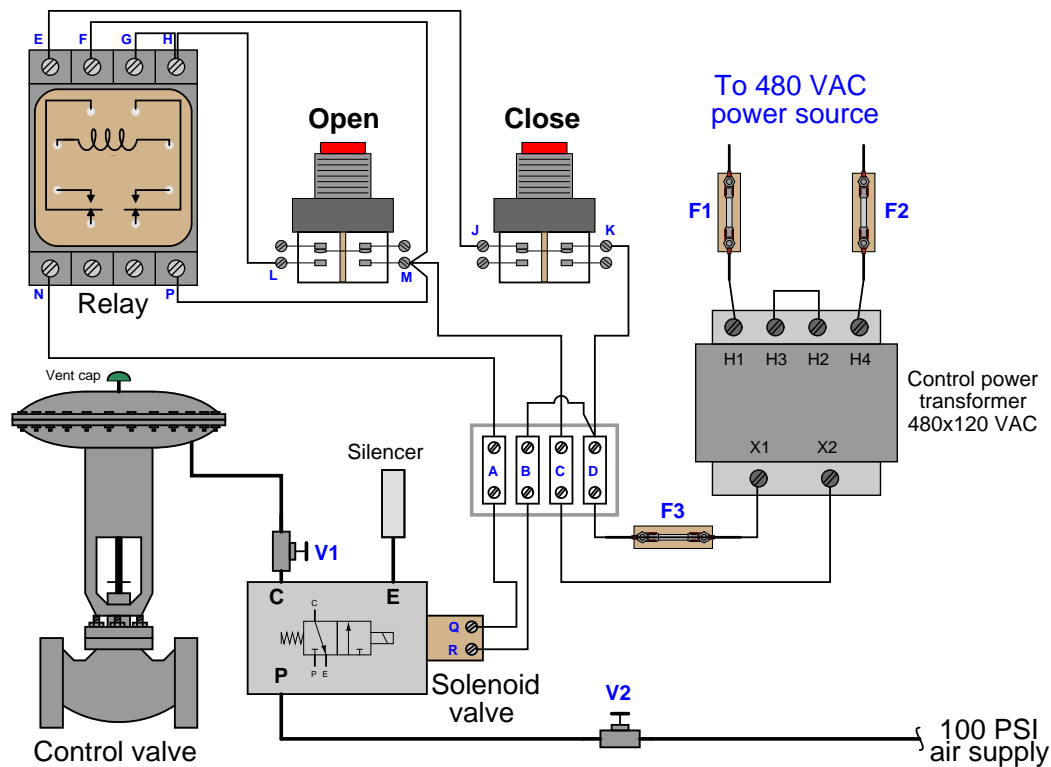
Suggestions for Socratic discussion

- When combining the probability value of a single-point failure (such as any listed on page 24) with other PFD values for other components in a system to arrive at a total system PFD, do we use the AND function or the OR function? Explain your answer.

[file i03290](#)

Question 29

Suppose this solenoid-controlled valve refuses to open when the operator pushes the “open” switch:



You measure 0 volts AC between terminals **C** and **D** on the terminal strip, and then switching your multimeter to “resistance” you read a few ohms of resistance between the same two terminals.

A fellow technician hypothesizes that fuse **F3** is blown (explaining the lack of AC voltage) *and* that the “open” pushbutton is failed-short (thus accounting for the low resistance measurement). After some thought, you disagree. You say it is more likely that either fuse **F1** *or* **F2** has blown.

Explain why the latter hypothesis is more probable than the former, based on what you know about probability and how it relates to component failures.

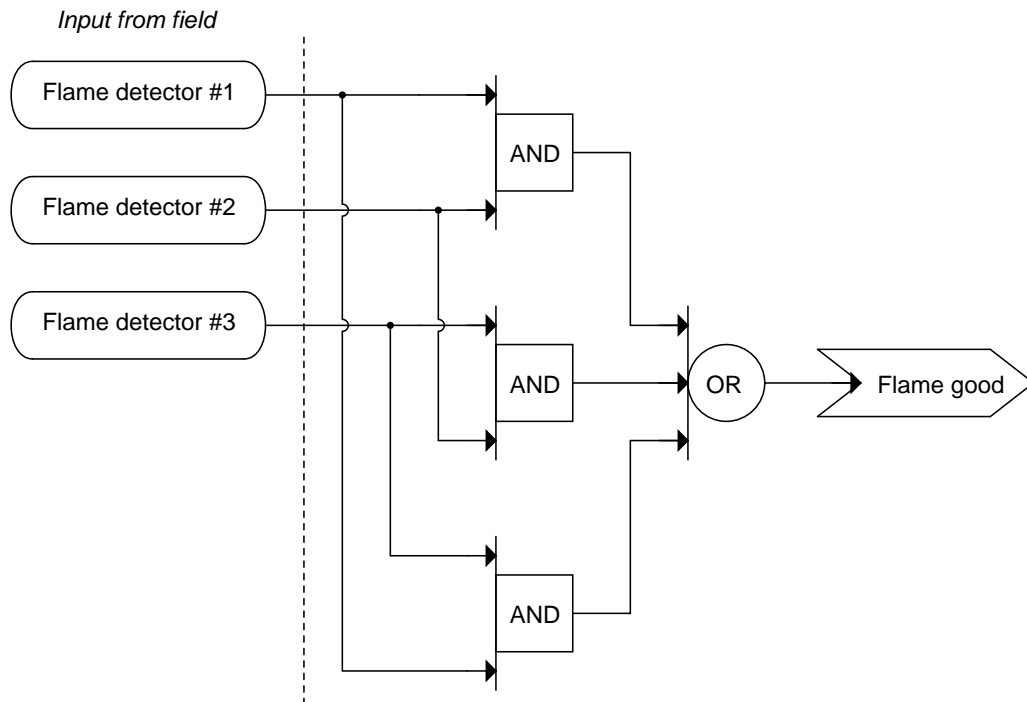
Suggestions for Socratic discussion

- Normally one should never attempt a resistance measurement in a “live” electric circuit. Explain why this is, and also why it was okay to do it here.
- Suppose the failure probabilities of **F1** (open), **F2** (open), **F3** (open), and the “open” pushbutton (short) are each 0.1. Calculate the probability of either **F1** or **F2** failing, versus **F3** and the pushbutton failing.

[file i03236](#)

Question 30

The following binary logic diagram shows a two-out-of-three detector scheme for a flame safety system:



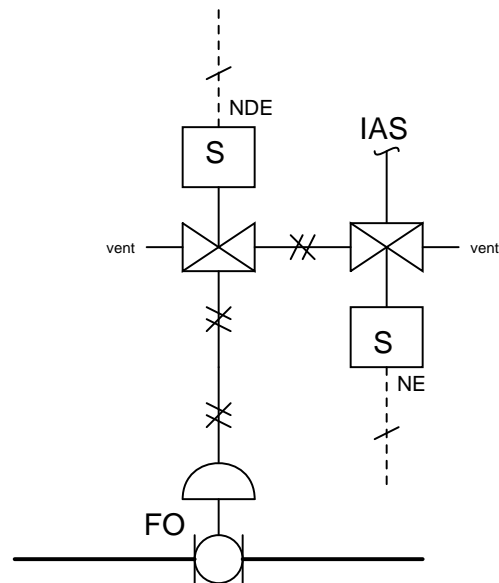
The purpose of this logic system is to indicate whether or not at least *two* flame detectors are showing the presence of flame in a burner system. Here, flame is good, and no flame is bad. Explain how this logic system works, and relate the symbols contained within to traditional logic symbols such as these shown below:



file i02331

Question 31

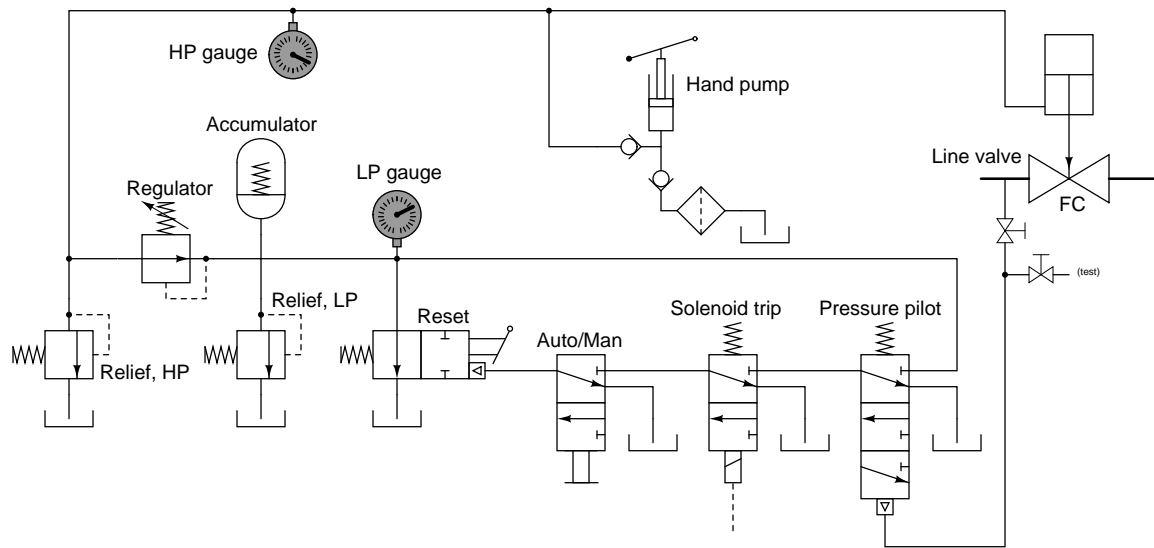
Sketch arrows next to each of the two solenoid valves showing the directions of air flow in the energized (E) and de-energized (D) states, assuming the process control valve is supposed to be open in regular operation and close if both of the solenoid valves “trip” (i.e. 2oo2 to trip):



file i04356

Question 32

This fluid diagram shows the components and connections of a Bettis self-contained hydraulic module used to automatically shut off a “line valve” on a natural gas pipeline in the event of the pipeline pressure going outside of its limits (either falling below the low-pressure limit or rising above the high-pressure limit):

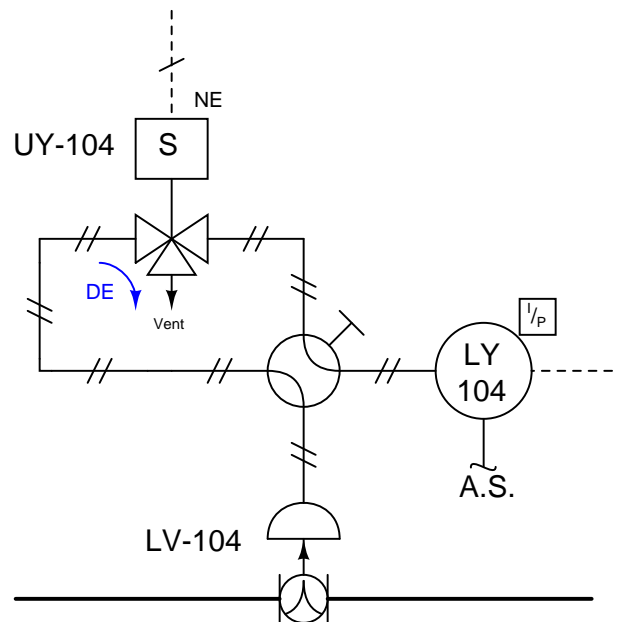


Identify all spool valve positions, and also trace the direction of oil flow, following a solenoid “trip” event.

[file i04357](#)

Question 33

Suppose this valve control system has a problem. The control valve (LV-104) does not move to the full-open position as it should when the solenoid is de-energized, although it will move when the 4-20 mA current signal to the I/P transducer is varied while the solenoid is energized:



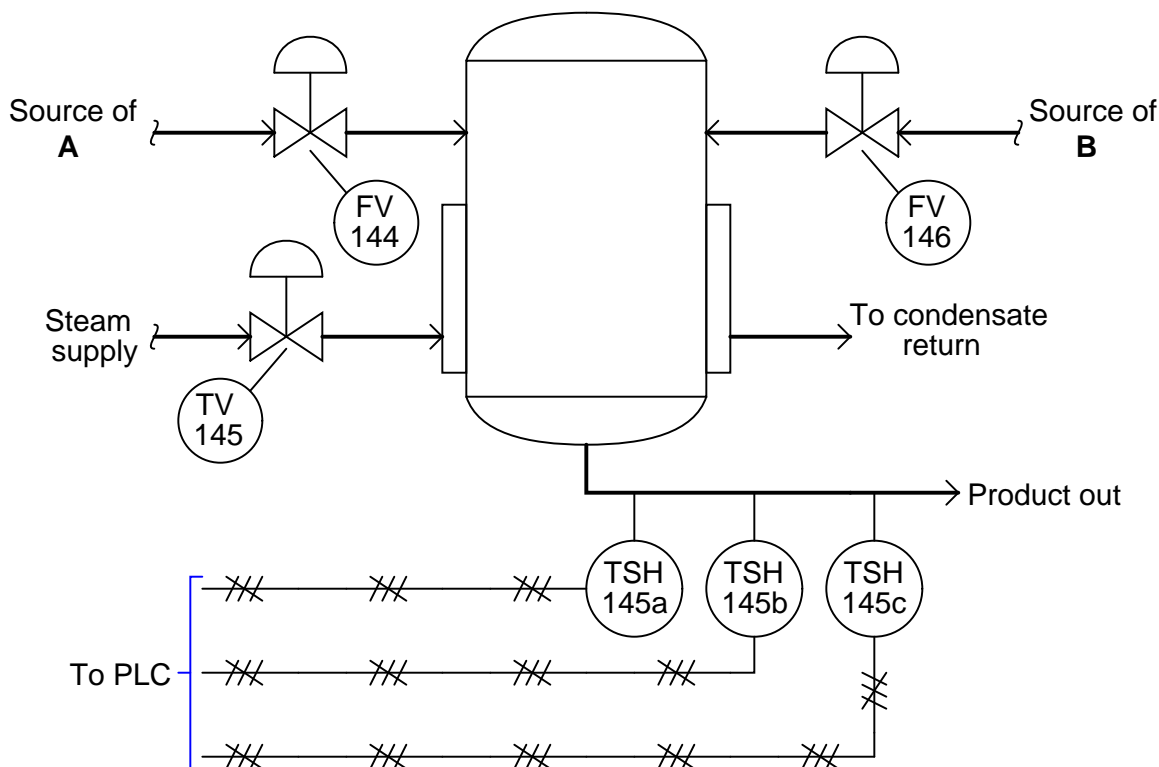
Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

Fault	Possible	Impossible
Manual valve in "bypass" position		
Solenoid coil failed open		
Solenoid coil failed shorted		
Solenoid valve (UY-104) spool stuck		
Solenoid valve (UY-104) vent plugged		
Air supply to LY-104 failed		
4-20 mA signal wiring to LY-104 failed open		
4-20 mA signal wiring to LY-104 failed shorted		
Control valve (LV-104) stuck		

file i04692

Question 34

This chemical reaction process combines two reactants, chemical **A** and chemical **B**, in a reactor vessel where they combine endothermically. A constant flow of hot steam through a “jacket” surrounding the reactor vessel adds heat to prevent the chemical mix from solidifying into a frozen mass:



Three temperature switches connect to a PLC, triggering an automatic shutdown of the process if at least two of the three switches register too-cold temperatures (2oo3 shutdown).

Determine the best fail-safe status for each of the three control valves shown in this P&ID, as well as the best contact status (*normally open* or *normally closed*) for the temperature switches, assuming the goal is to avoid a low-temperature condition at any cost. Also assume that the most likely kind of cable or switch contact failure is an electrical *open* rather than a short, and that such electrical faults in the switch circuits should result in the system shutting down just to be safe..

- Chemical **A** control valve: (*fail-open* or *fail-shut*)
- Chemical **B** control valve: (*fail-open* or *fail-shut*)
- Steam control valve: (*fail-open* or *fail-shut*)
- Temperature switch status: (*normally-open* or *normally-closed*)

file i03585

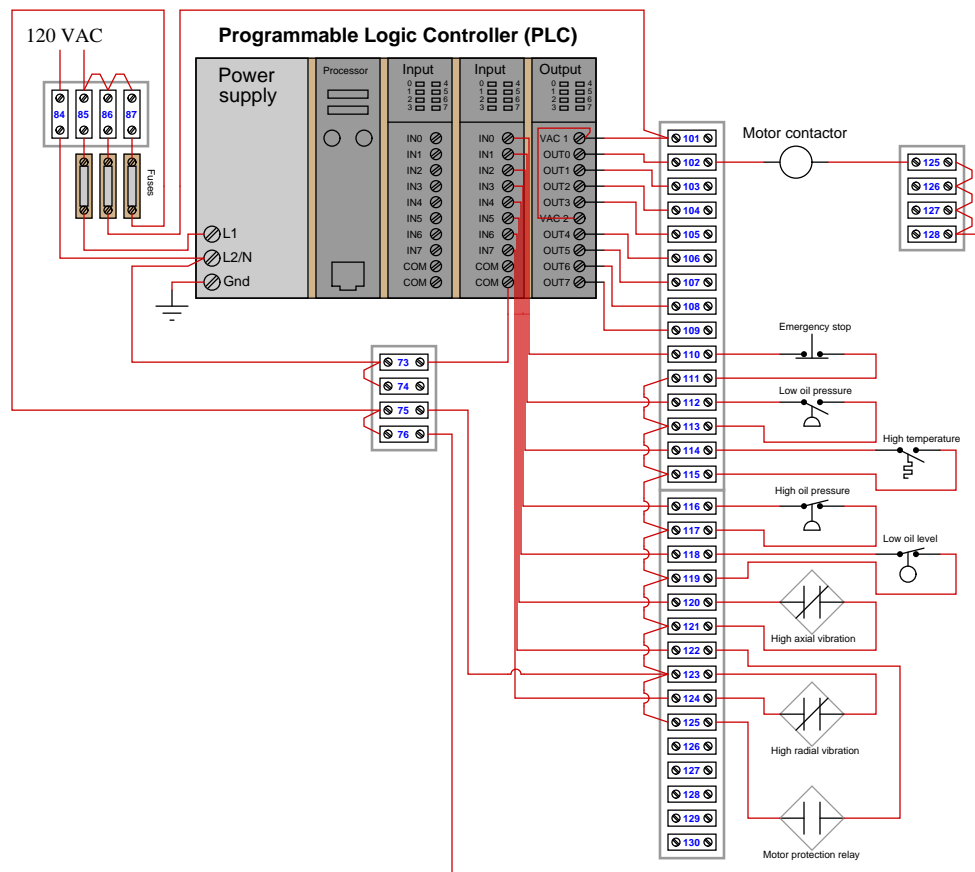
Question 35

It is customary when using a rupture disk in conjunction with a pressure safety valve to locate the disk between the PSV and the process vessel. Explain the purpose for locating the rupture disk there, and why it might be a very bad idea to locate the PSV between the rupture disk and the vessel.

file i00196

Question 36

In this safety shutdown system, a programmable logic controller (PLC) monitors inputs coming from various switches located on a large motor-driven gas compressor system, and trips the compressor off (shuts off power to the motor's contactor coil) if any of these conditions becomes dangerous.



Identify the “trip state” for each of the PLC inputs (sensing switches): whether each input must *energize* or *de-energize* to trip the compressor. Note that the PLC input channels are not drawn here showing operating conditions (i.e. there are no LED lights shown in an illuminated state to help you determine switch status).

- Emergency stop = *Energize to trip* or *De-energize to trip*
- Low oil pressure = *Energize to trip* or *De-energize to trip*
- High temperature = *Energize to trip* or *De-energize to trip*
- High oil pressure = *Energize to trip* or *De-energize to trip*
- Low oil level = *Energize to trip* or *De-energize to trip*
- High axial vibration = *Energize to trip* or *De-energize to trip*
- High radial vibration = *Energize to trip* or *De-energize to trip*
- Motor protection relay = *Energize to trip* or *De-energize to trip*

Hint: remember that the “normal” status of a switch (i.e. the way a switch is always drawn in a schematic diagram) is its *resting* or *minimum-stimulus* state.

Suggestions for Socratic discussion
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- A common mistake is to assume the normal status of the switch is the only piece of information you need to determine whether it will be “energize to trip” versus “de-energize to trip”. Explain why it is a bit more complicated than that.

file i02100

Question 37

Question 38

Question 39

Question 40

Lab Exercise – introduction

Your team’s task is to construct and test a safety “shutdown” system designed to bring some process to an idle condition if one or more variables drift beyond acceptable parameters. This may take the form of an additional layer of sensors and controls incorporated into your existing process control loop (e.g. a high-pressure shutdown system on an air pressure control loop), or it may be entirely separate (e.g. a protective relay system designed to trip a circuit breaker on excessive load current).

If implemented as an additional layer of controls to a functioning process loop, the shutdown function must bring the process to a “safe” condition (power off, vessels drained/vented, etc.) independent of any action on the part of the loop PID controller. In other words, the safety function must work *no matter what the loop controller is trying to do*. This shutdown condition must “latch” and be re-settable only from a manual pushbutton, also independent of the loop PID controller. You may use either a hard-wired relay, a PLC, or a dedicated safety controller to implement the latching safety shutdown function. The safety control element must be a solenoid valve if the process final control element is pneumatically actuated!

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	mastery	–	–	–	–	
Circuit design challenge	mastery					– – – –
Final loop diagram and system inspection	mastery					– – – –
Demonstration of working system	mastery	–	–	–	–	
Safety “trip” testing	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 testing 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

Read the lab exercise documentation and discuss with your teammates the objectives to be achieved and the time allotted to do so. Formulate a plan to achieve these objectives and draft a prototype design for the system you intend to build. Then, meet with your instructor to present your team's action plan and prototype design. *This prototype sketch should be annotated with all expected physical parameters (e.g. voltage polarities, current directions, fluid pressures, etc.).* Be prepared to answer all manner of questions about your team's goals, planned schedule of work, available resources, and prototype design, including analysis of the design for specific faults and condition changes. Do not begin construction until your design has been analyzed and approved! Note that multiple meetings may be required if the instructor's assistance is needed to select components influencing your design.

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.

Demonstration of working system

Show that the safety shutdown system overrides the control system when the measured variable crosses the trip threshold value. The instructor will randomly select a trip threshold at the time of demonstration, and all team members must be able to demonstrate how to accurately set that value for the safety shutdown system.

Safety “trip” testing

Test the function of a safety shutdown system 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, formulating a plan to complete the lab project in the allotted time, 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 during the school day* 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.

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.

Your first design step needs to be deciding what process variable condition might be deemed dangerous in a full-scale process, and what the automated shutdown action(s) should be to limit that process variable’s value. The variable to monitor may or may not be the process variable (PV) being regulated by the loop controller. Whatever action the shutdown system automatically takes, however, should completely override the action of the loop controller in a shutdown condition.

Once you have defined the shutdown variable and action(s), the next step is to design an independent control system to add to your working process. This SIS (Safety Instrumented System) needs to be based on a *latch*: the SIS will “trip” whenever a shutdown condition is detected, and will not “reset” (even after the condition clears) until an operator manually presses a reset pushbutton. A typical SIS for the scope of a lab project such as this usually consists of these components:

- Sensor for detecting shutdown condition (separate from PV sensor used in the PID control system)
- Threshold detection relay (outputs a discrete signal to trip the latch)
- Latching system (e.g. electromechanical relay, PLC, or dedicated SIS controller)
- FCE override (e.g. solenoid valve forcing the control valve to its “fail-safe” position)

Your instructor will verify that your team’s SIS design is practical. Note that the SIS need not be complex: in fact, simpler is better here. A system consisting of a process switch, and an ice-cube relay to latch on as well as energize or de-energize a “dump” solenoid when tripped, is sufficient for many student-built processes. If your SIS sensor is a 4-20 mA analog transmitter, you will need some “alarm” module or relay to trigger the latch. A PLC with an analog input works well for this purpose, as does a stand-alone alarm module such as the Moore Industries DDA or SPA units.

If your team plans to build a protective relay system, you will need to first select a suitable relay to use. Modern digital relays such as the SEL model 501 are highly recommended. Due to the fact your electrical load won’t be drawing much current, you will need to use a CT (current transformer) with multiple turns of wire run through its core in order to achieve a workable load:relay current ratio. I rule of thumb here is

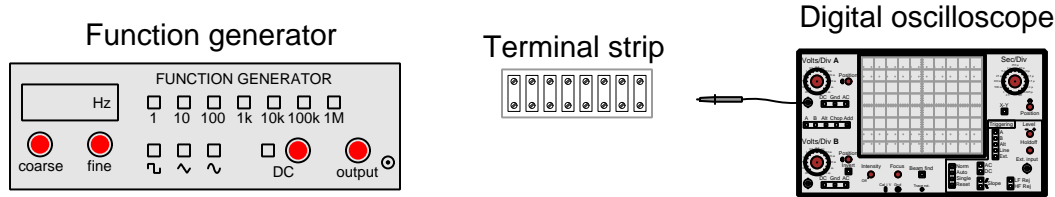
to not wrap more than 4 turns of wire through the core of the small CT you will be given, in order to avoid saturation and inaccurate performance.

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 solderless breadboards, 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/modifying the system

After getting your prototype sketch approved by the instructor, you are cleared to begin building your system. Instruments attach to 2-inch pipes using special brackets and U-bolts. These brackets and U-bolts are located in the instrument storage area.

You may install your SIS control hardware inside the nearest field junction box. The installation should be neat and professional, like the rest of the control system. Instruments should attach to 2-inch pipes using special brackets and U-bolts, located in the instrument storage area. Liquid-tight flexible conduits should be used to route signal cable between the instrument(s) and the junction box.

Finally, your SIS needs to have a loop number, so all instruments may be properly labeled. This loop number needs to be unique, not only from other SIS installations in the lab but also different from the instruments used for regulatory control in the process (i.e. the PID controller, transmitter, FCE).

If your choice of shutdown systems is a protective relay and circuit breaker, there will be no 2-inch-pipe-mount devices such as pressure transmitters. Neither will there be ISA-standard loop numbers, as protective relays are labeled according their specific function rather than according to the general process. You may choose to set up such a system entirely inside an electrical enclosure, or perhaps between two different enclosures (e.g. one for the circuit breaker and load, the other for the relay). An “open” design such as on an enclosure subpanel is also acceptable, so long as all electrical terminals are “touch-safe” (recessed) so as to present little shock hazard and the system is locked and tagged out when not in use.

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!

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 – safety “trip” testing

Instead of troubleshooting a fault in the system as is customary for lab exercises, your task in this lab is to test a SIS (Safety Instrumented System) to ensure its proper operation with the process running. The goal is to validate the correct operation of one SIF (Safety Instrumented Function) to ensure its readiness to act when needed. All “trip” testing is done on an individual basis (no team credit!), and must be done *on a system you did not help build*, so that you must rely on schematic diagrams to find your way around the system and to determine how to do the test instead of from your own memory of building it.

The instructor will choose the SIF for you to test, as well as the instrument(s) within that SIF to be tested. This may be a process constructed by another student team, or it may be one of the permanently constructed processes in the lab (e.g. the turbocompressor system, the protective relay demonstration system, one of the protective relays in the lab’s miniature AC power grid system). Your procedure will need to adequately test the system as specified by the instructor in the following check-box format:

Safety Instrumented Function (SIF) to test: _____
(e.g. high vessel pressure, high turbine speed)

Instrument(s) to test:
(may select more than one)

☐

Sensor

☐

Logic (controller)

☐

Final control element

Process status:
(select only one option)

☐

Maintain regular operation

☐

Test to shutdown

For example, if the instructor writes “low oil pressure” in the SIF line and checks the “Logic” and “Maintain regular operation” boxes, it means you will need to electrically simulate a low-oil pressure condition to the input of the SIS logic solver and verify that the logic produces the proper output response, while ensuring the process does not actually shut down (i.e. you will need to somehow simulate a “good” output condition from the logic to ensure the final control element will not shut down the process). As another example, if the instructor checks the “Final control element” and “Test to shutdown” boxes for the same SIF (“low oil pressure”), it means you will simulate the same shut-down signal as would be generated by a low oil pressure condition to the input of the final control element and let it actually shut down the process. If multiple boxes are checked in the Instrument(s) section, it means your one procedure will need to verify all of the selected SIS elements at once. Note that it *is* possible to test the final control element of an SIS without shutting down the process, if the test is done quickly enough!

A common point of confusion for many students is to test the wrong instrument(s). A helpful hint is to identify both the *input* and *output* of the instrument your instructor has assigned you to test, and to be sure your test is based on those specific signals or process states. For example, if your instructor has assigned you to test SIS *sensor*, this means you must stimulate the sensor at its input (pressure, temperature, etc.) and measure the sensor’s output signal. An example of an incorrect test for this application would be to use a loop calibrator to simulate a signal from the sensor: this would not actually test the sensor itself!

Each student is given 5 minutes to plan their test after having been given the conditions by the instructor. The student must then describe their test in step-by-step detail to the instructor. If the test as described is safe to perform and meets all the specified criteria, the student will then be allowed to execute the test. All testing activities will take place under direct instructor supervision to ensure students are working independently and efficiently.

Failure to formulate a safe and effective test strategy at the end of the 5-minute time period, or failure to execute the planned test, will disqualify the effort in which case the student must re-try with a different set of conditions (perhaps on a different system as well).

A standard multimeter and signal source (e.g. loop calibrator or protective relay test set) are the only pieces of test equipment allowed during the time limit. If the SIS makes use of a PLC as the logic solver,

a computer with PLC programming software *may* be provided to aid in planning and executing the test (e.g. using this software to force bits in the PLC as part of the test). If an electrical “jumper” connection is necessary to perform the test, it is expected that you will use your multimeter (test leads plugged into the “Amp” jacks) as the jumper, so that your jumper will be fused to protect against personal hazard if it is incorrectly applied.

Common mistakes:

- Testing the wrong portion of the SIS (i.e. not carefully identifying the necessary stimulus and measurement points to encompass just specified portion(s) of the SIS)
- Making or breaking electrical connections in such a way that causes the system to trip before the test is supposed to begin
- Neglecting to confirm the system’s status with a multimeter before proceeding
- 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!

Even though this exercise is not called “troubleshooting,” it is every bit as analytical as diagnostic work, and may require some amount of creativity to execute. This takes a lot of lab time, usually at least two 3-hour lab sessions for everyone in a full class to successfully pass. Be sure your team budgets 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 trip-test, to better learn this art.

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.

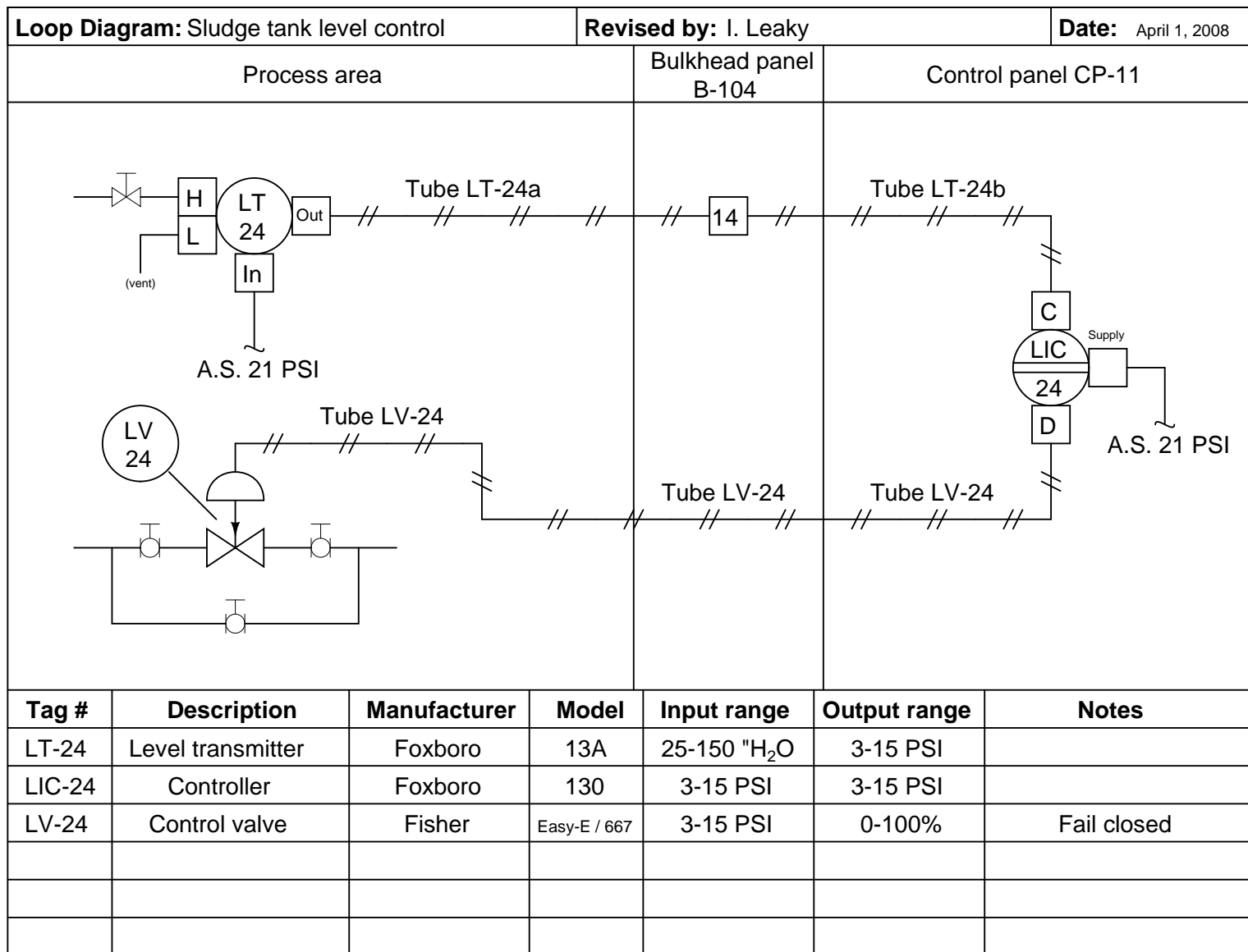
First, the locker will be entirely emptied. Next, the instructor will inspect each tool before placing it in the locker, following the order of the inventory list taped to the inside of the locker door. The team is responsible for finding or replacing any missing items. Any items not on the inventory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

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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.*

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- 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.
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- 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:

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- 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!*
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- Forgetting to note all wire colors.
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- 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: _____

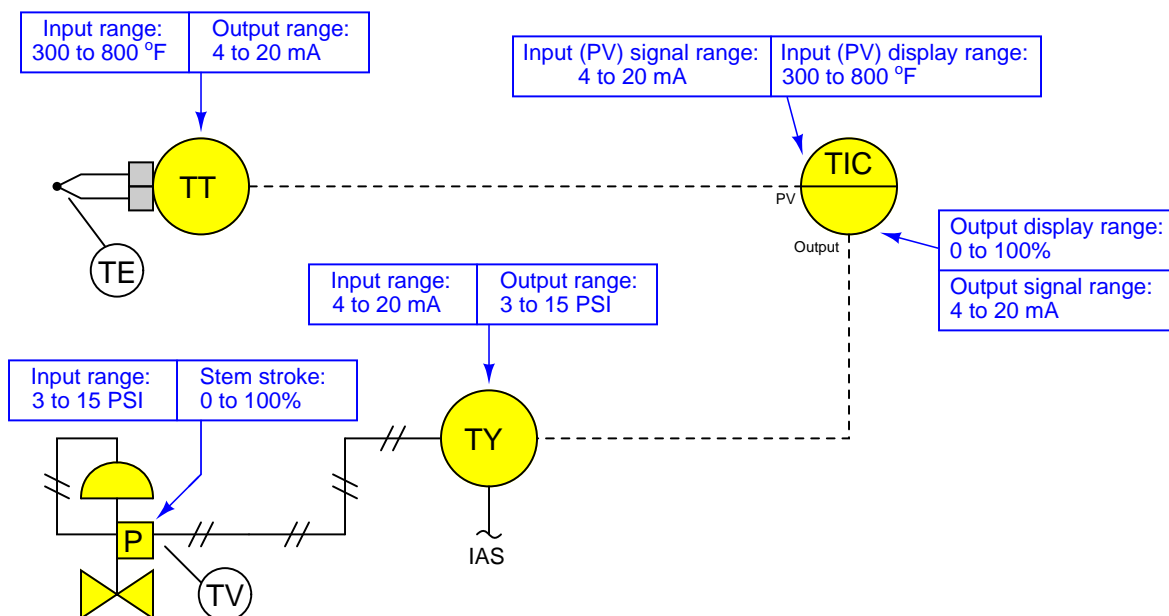
Criterion	(Instructor verifies)
Instructor verifies all signal wires/tubes disconnected	
Instructor verifies controller reset to original configuration	
Instructor verifies DAQ is returned to team tool locker	
Instructor collects your diagrams	

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

Partial answer:

If the hacker gains access to PLC programming software, he or she may be able to *force* bits in the PLC's memory to simulate various trip conditions.

Answer 6

Any one of the four “Stop” switches is capable of shutting the conveyor off (**1004** dependability).

All four “Stop” switches must be returned to their normal positions in order to start the conveyor (**4004** security).

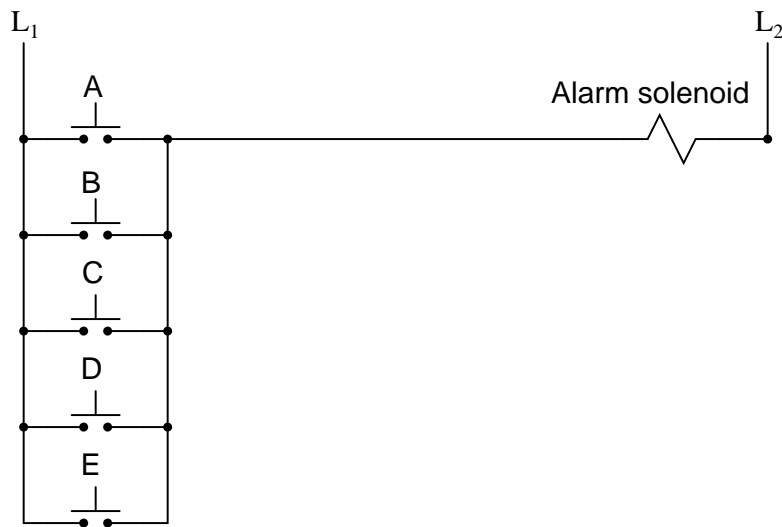
Answer 7

Original circuit expression:

$$\overline{\overline{A} \overline{B} \overline{C} \overline{D} \overline{E}}$$

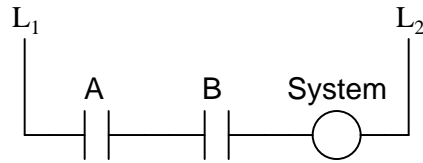
Simplified expression and circuit:

$$A + B + C + D + E$$



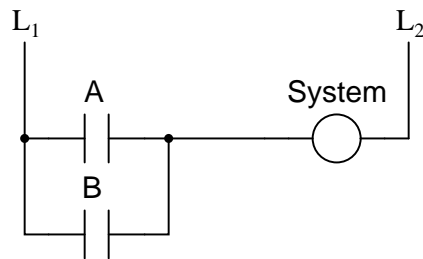
I'll let you determine (and explain) which circuit is safest.

The rule-of-thumb to use when determining dependability MooN redundancy is, “how many inputs must trip to *guarantee* the coil will de-energize, versus how many inputs total?” Similarly, the rule-of-thumb for determining security MooN redundancy is, “how many inputs must be good in order to *guarantee* the coil will energize, versus how many inputs total?”



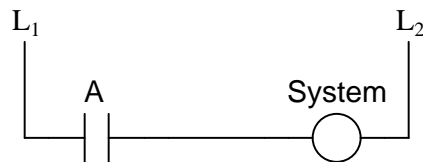
Dependability MooN = 1oo2

Security MooN = 2oo2



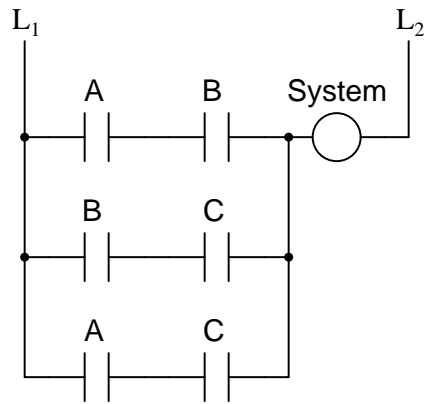
Dependability MooN = 2oo2

Security MooN = 1oo2



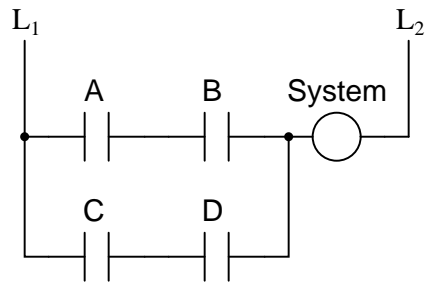
Dependability MooN = 1oo1

Security MooN = 1oo1



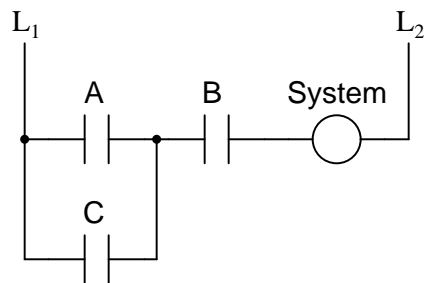
Dependability MooN = 2003

Security MooN = 2003



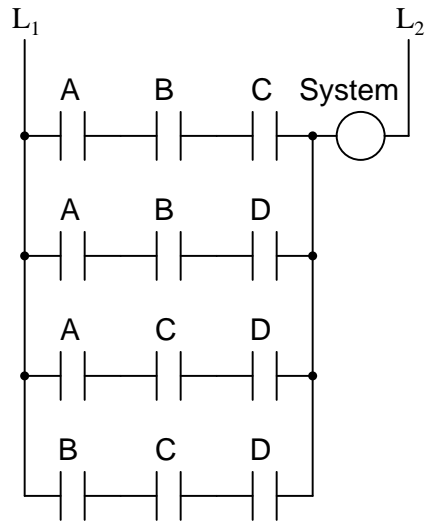
Dependability MooN = 3004

Security MooN = 3004



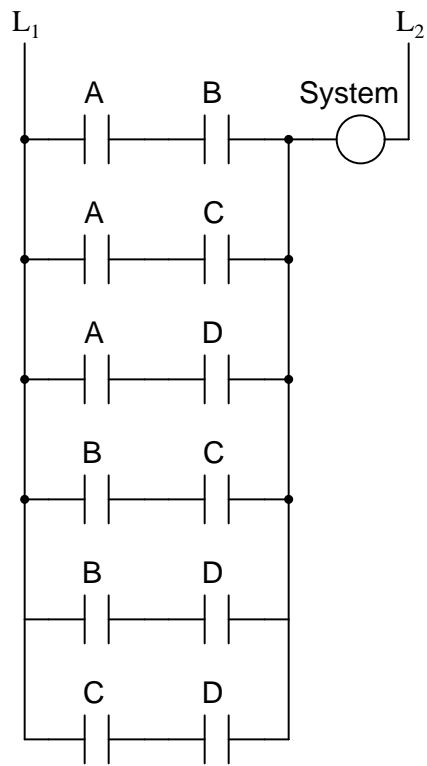
Dependability MooN = 2003

Security MooN = 3003



Dependability MooN = 2004

Security MooN = 3004



Dependability MooN = 3004

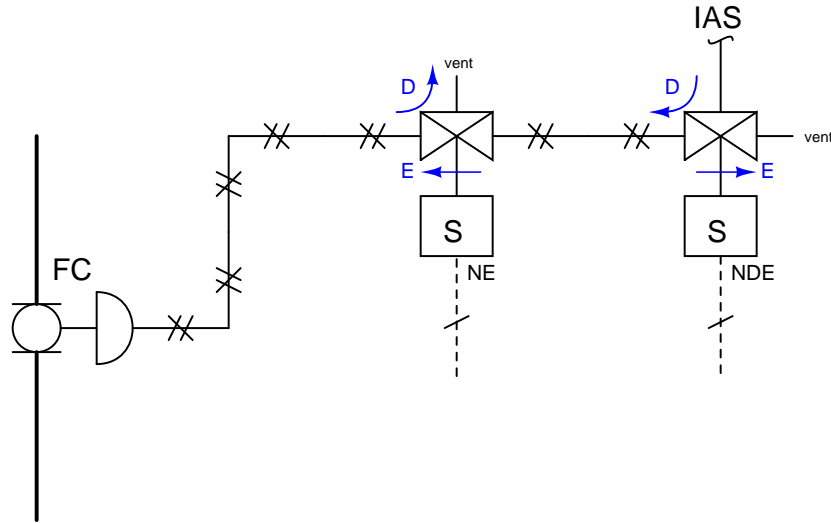
Security MooN = 2004

According to a document published by Honeywell (“2oo4D: A New Design Concept for Next-Generation Safety Instrumented Systems”),

As defined in ANSI/ISA S84.01-96, an MooN voting system requires at least M of the channels to be in agreement before the SIS can take action (M out of N). The following voting principles are most commonly used:

- 1oo1 (One out of One)
- 1oo2 (One out of Two)
- 2oo2 (Two out of Two)
- 2oo3 (Two out of Three)
- 1oo2D (One out of Two with diagnostics)
- 2oo4D (Two out of Four with diagnostics)

Answer 9



Answer 10

Multiplication makes the most sense, resulting in a number ranging between 1 and 25. Some might think addition is the proper way to mathematically combine the two risk figures, but multiplication makes more sense especially when you note the exponential scale of frequency. Now, addition *would* be most appropriate if the result was taken to mean a power of ten!

The Emerson (Fisher/Rosemount) corporation gives the following suggestions for relating SIL level requirements with risk product:

- SIL 1 = risk product between 1 and 6
- SIL 2 = risk product between 6 and 15
- SIL 3 = risk product between 15 or greater

Answer 11

Answer 12

Answer 13

Table G.18 in Appendix G is a complete Modbus Register Map for the SEL-551 relay. The table lists a great many parameters that may be either read or written via Modbus.

Table G.15 shows three different Modbus registers in the device (0090h, 0091h, and 0092h) that may be used to force the relay to do different functions (those functions listed in table G.16 on page G.11). This includes:

- **Force the circuit breaker to trip:** *send command code 01 to register 0090h*
- **Force the circuit breaker to close:** *send command code 02 to register 0090h*
- **Pulse any of the four OUT contacts:** *send command codes 05, 06, 07, or 08 to register 0090h*
- **Switch the serial communications mode from Modbus RTU to plain ASCII, for a denial-of-service attack:** *send command code 10 to register 0090h*

Since there is no password protection with Modbus commands, and the Modbus messages themselves are not encrypted, fortification consists of protecting access to the relay's Modbus channel. One could disable Modbus control altogether by not connecting any cable to the relay's serial port (i.e. form an *air gap*). If Modbus control is absolutely required, one could use an encryption device such as the Serial Shield to make sure no one lacking a properly connected Shield device could read or write serial data with that relay.

Answer 14

Answer 15

Answer 16

Answer 17

Answer 18

Answer 19

Answer 20

Answer 21

Answer 22

Answer 23

$$F = PA$$

$$F = P\pi r^2$$

$$F_{total} = (77 \text{ PSI})\pi(13.25 \text{ in}/2)^2$$

$$F_{total} = (77 \text{ PSI})\pi(6.625 \text{ in})^2$$

$$F_{total} = (77 \text{ PSI})(137.89 \text{ in}^2)$$

$$F_{total} = 10,617 \text{ lb} = 5.309 \text{ tons}$$

Answer 25

All low-pressure switches will be in their “normal” statuses when the fuel pressure becomes abnormally low. Therefore, given the design criterion of de-energize to trip, we should wire PSL-105 and PSL-114 as *normally-open*.

All high-pressure switches will be in their “normal” statuses when the fuel pressure is good, and will actuate if the fuel pressure becomes abnormally high. Therefore, given the design criterion of de-energize to trip, we should wire PSH-107 and PSH-110 as *normally-closed*.

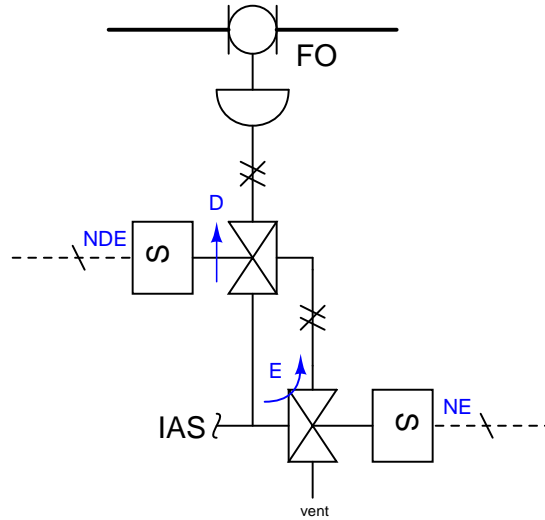
Answer 26

The design engineer made it so that air will pass to the process valve actuator during typical (good) operating conditions, holding the process valve open.

This is a 1oo2 to trip system, because the process valve will go to its “fail” position if either of the two solenoid valves trip (go to their abnormal operating states).

Answer 27

Both solenoid valves must trip to “fail” the process valve (i.e. 2oo2 to trip):



Possible faults:

- Instrument air supply dead
- Break in tubing between upper solenoid valve and ball valve actuator
- Large leak in ball valve actuator

Answer 28

Answer 29

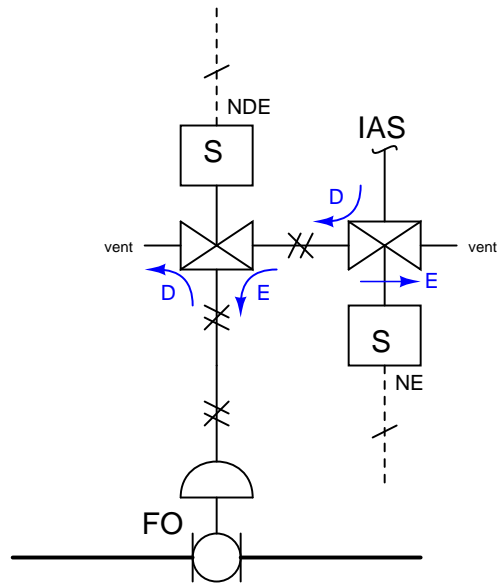
This is a good example of *Occam's Razor*: that the best hypothesis is the one making the fewest (or the greatest-probability) assumptions. If we assume equal PFD for each fuse, then the hypothesis more likely to be true is the one where all symptoms are explained by a single fuse blowing, rather than a fuse blowing *and* some other (unrelated) fault occurring.

Answer 30

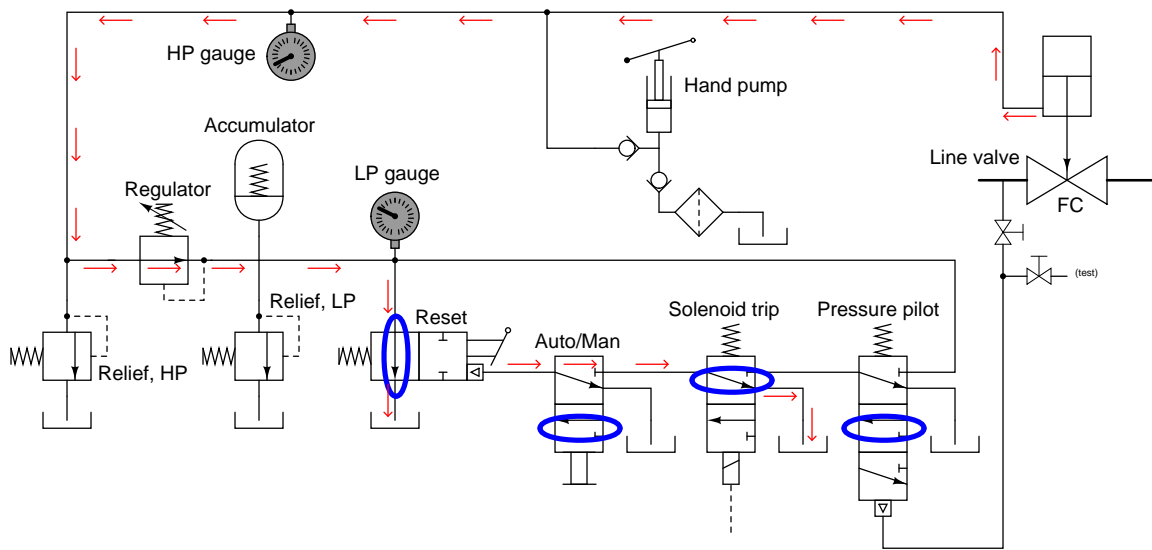
Other than the AND and OR symbols looking a bit different, there is little else in the binary logic diagram that should cause confusion to someone already familiar with the rounded logic gate symbols.

Follow-up question: what do you think might be suggested by the oval bubbles versus the pointed box, showing inputs and outputs in this diagram, respectively? I'll give you a hint: the different shapes do *not* simply spell the difference between input and output!

Answer 31



Answer 32



Answer 33

Fault	Possible	Impossible
Manual valve in “bypass” position	✓	
Solenoid coil failed open		✓
Solenoid coil failed shorted		✓
Solenoid valve (UY-104) spool stuck	✓	
Solenoid valve (UY-104) vent plugged	✓	
Air supply to LY-104 failed		✓
4-20 mA signal wiring to LY-104 failed open		✓
4-20 mA signal wiring to LY-104 failed shorted		✓
Control valve (LV-104) stuck		✓

Answer 34

- Chemical **A** control valve: (**fail-shut**)
- Chemical **B** control valve: (**fail-shut**)
- Steam control valve: (**fail-open**)
- Temperature switch status: (**normally-open**)

Answer 35

Rupture disks are sometimes inserted between the PSV and the process vessel in order to stop fugitive emissions (because all valves will leak some finite amount during normal operation, whereas an intact rupture disk cannot leak). This same leaking problem explains why one should never place a rupture disk on the outlet of a pressure safety valve.

To illustrate the problem, imagine a PSV set to lift at 800 PSI, and a rupture disk with the same burst pressure rating placed at the outlet of the PSV. Now imagine that PSV leaking a bit over time, slowly pressurizing the pipe between the PSV and the rupture disk until that enclosed space holds 500 PSI of vapor. Now, how much process pressure will it take to lift the PSV? Remember that PSVs, as self-actuated devices, respond to the pressure *difference* between inlet and outlet!

Answer 36

- Emergency stop = **De-energize to trip**
- Low oil pressure = **De-energize to trip**
- High temperature = **Energize to trip**
- High oil pressure = **De-energize to trip**
- Low oil level = **Energize to trip**
- High axial vibration = **De-energize to trip**
- High radial vibration = **De-energize to trip**
- Motor protection relay = **Energize to trip**

Answer 37

Answer 38

Answer 39

Answer 40

Answer 41

Answer 42

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

Answer 43

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

Answer 44