
Lab

Multi-input control strategy: *Question 91 and 92*, **completed objectives due by the end of day 5**

Exam

Day 5 – only a simple calculator may be used! **Complete mastery of these objectives due by the next exam date**

Specific objectives for the "mastery" exam:
- Electricity Review: Calculate voltages, currents, and phase shifts in an AC reactive circuit
- Determine the effect of a component fault or condition change in a single-loop controlled process
- Determine the effect of a component fault or condition change in a cascade-, ratio-, or feedforward-controlled process
- Calculate instrument input and output values given calibrated ranges
- Solve for a specified variable in an algebraic formula (may contain exponents or logarithms)
- Determine the possibility of suggested faults in a simple circuit given measured values (voltage, current), a schematic diagram, and reported symptoms
- Motor/relay/3phase/PLC Review: Calculate voltages and currents within balanced three-phase AC electrical circuits
- INST241 Review: Calculate flow rate / pressure drop for a nonlinear flow element
- INST250 Review: Calculate split-ranged valve positions given signal value and valve calibration ranges

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Recommended daily schedule

Day 1

Theory session topic: Applications of control strategies

Questions 1 through 20; answer questions 1-9 in preparation for discussion (remainder for practice)

Discuss the upcoming Capstone Assessment due by the end of the course (*Question 93*)

Day 2

Theory session topic: Limit and Selector controls

Questions 21 through 40; answer questions 21-28 in preparation for discussion (remainder for practice)

Day 3

Theory session topic: Override controls

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

Day 4

Theory session topic: Review for exam

Questions 61 through 80; answer questions 61-68 in preparation for discussion (remainder for practice)

Feedback questions *(81 through 90)* are optional and may be submitted for review at the end of the day

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Day 5

Exam

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.

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.

file `expectations`

Program Outcomes for Instrumentation and Control Technology (BTC)

#1 | Communication

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

#2 | Time management

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

#3 | Safety

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

#4 | Analysis and Diagnosis

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

#5 | Design and Commissioning

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

#6 | System optimization

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

#7 | Calibration

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

#8 | Documentation

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

#9 | Independent learning

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

#10 | Job searching

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

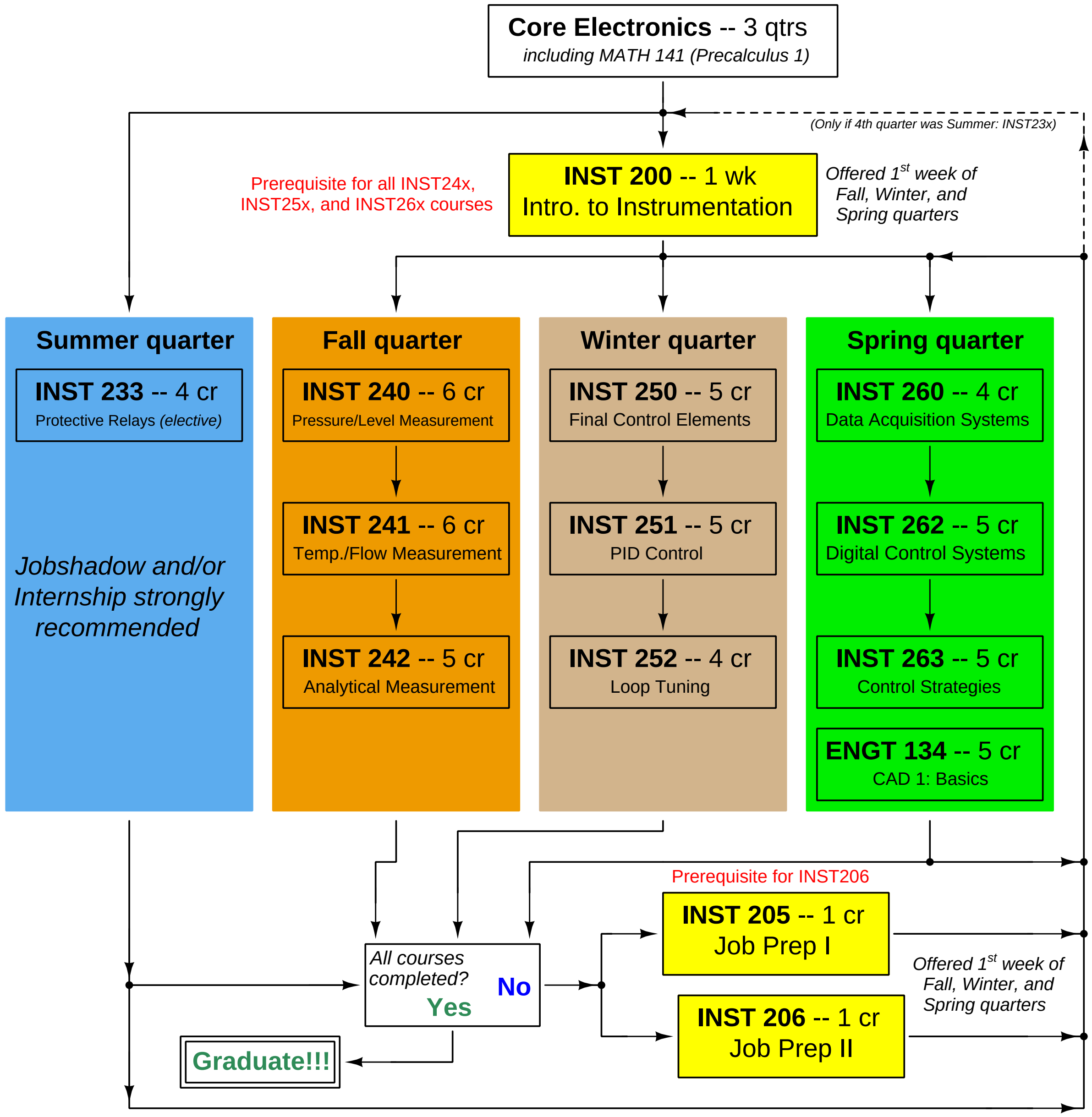
file `outcomes_program`

INST 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]

file `outcomes_INST263`


Core Electronics -- 3 qtrs
including MATH 141 (Precalculus 1)
(Only if 4th quarter was Summer: INST23x)
Prerequisite for all INST24x, INST25x, and INST26x courses
INST 200 -- 1 wk
Intro. to Instrumentation
Offered 1st week of Fall, Winter, and Spring quarters
Summer quarter
INST 233 -- 4 cr
Protective Relays (elective)
Jobshadow and/or Internship strongly recommended
Fall quarter
INST 240 -- 6 cr
Pressure/Level Measurement
INST 241 -- 6 cr
Temp./Flow Measurement
INST 242 -- 5 cr
Analytical Measurement
Winter quarter
INST 250 -- 5 cr
Final Control Elements
INST 251 -- 5 cr
PID Control
INST 252 -- 4 cr
Loop Tuning
Spring quarter
INST 260 -- 4 cr
Data Acquisition Systems
INST 262 -- 5 cr
Digital Control Systems
INST 263 -- 5 cr
Control Strategies
ENGT 134 -- 5 cr
CAD 1: Basics
Prerequisite for INST206
INST 205 -- 1 cr
Job Prep I
INST 206 -- 1 cr
Job Prep II
Offered 1st week of Fall, Winter, and Spring quarters
All courses completed?
No
Yes
Graduate!!!

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

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

file sequence

General tool and supply list

Wrenches

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

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

Pliers

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

Screwdrivers

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

Electrical

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

Safety

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

Miscellaneous

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

file `tools`

Methods of instruction

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

Inverted theory sessions

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

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

Small sessions

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

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

Large sessions

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

Correspondence

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

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.

file `instructional`

Distance delivery methods

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

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

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

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

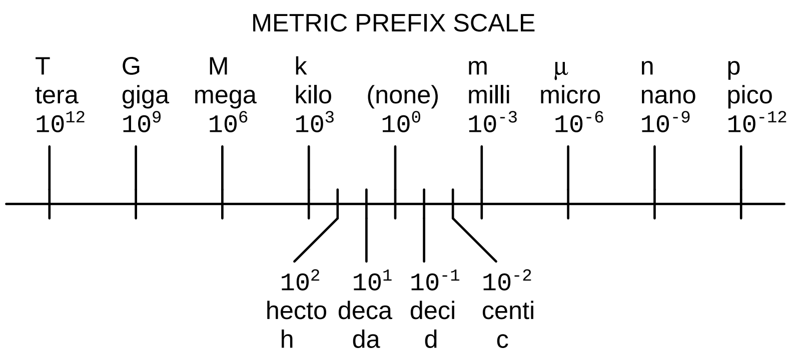
Labwork is perhaps the most difficult portion of the curriculum for a "distance" student to complete, since the equipment used in Instrumentation is typically too large and expensive to leave the school lab facility. "Distance" students must find a way to complete the required lab activities, either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

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

file `distance`

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**
- ^{o}F = (^{o}C)(9/5) + 32
- ^{o}C = (^{o}F - 32)(5/9)
- ^{o}R = ^{o}F + 459.67
- K = ^{o}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 (in^3) = 4 quarts (qt) = 8 pints (pt) = 128 fluid ounces (fl. oz.) = 3.7854 liters (l)

1 milliliter (ml) = 1 cubic centimeter (cm^3)

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 (ft^2) = 4840 square yards (yd^2) = 4046.86 square meters (m^2)

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 10^{10} 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/s^2) = 32.1740 feet per second per second (ft/s^2)

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-Kelvin^4 ($\text{W/m}^2 \cdot \text{K}^4$)

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

Properties of Water

Freezing point at sea level = 32^oF = 0^oC

Boiling point at sea level = 212^oF = 100^oC

Density of water at 4^oC = 1000 kg/m^3 = 1 g/cm^3 = 1 kg/liter = 62.428 lb/ft^3 = 1.94 slugs/ft^3

Specific heat of water at 14^oC = 1.00002 calories/g$\cdot^o$C = 1 BTU/lb$\cdot^o$F = 4.1869 Joules/g$\cdot^o$C

Specific heat of ice ≈ 0.5 calories/g$\cdot^o$C

Specific heat of steam ≈ 0.48 calories/g$\cdot^o$C

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

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

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

Properties of Dry Air at sea level

Density of dry air at 20^oC and 760 torr = 1.204 mg/cm^3 = 1.204 kg/m^3 = 0.075 lb/ft^3 = 0.00235 slugs/ft^3

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

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!

file `question0`

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:

$\boxed{\surd}$ 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.

$\boxed{\surd}$ 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.

$\boxed{\surd}$ 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.

$\boxed{\surd}$ 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.

$\boxed{\surd}$ 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.

$\boxed{\surd}$ 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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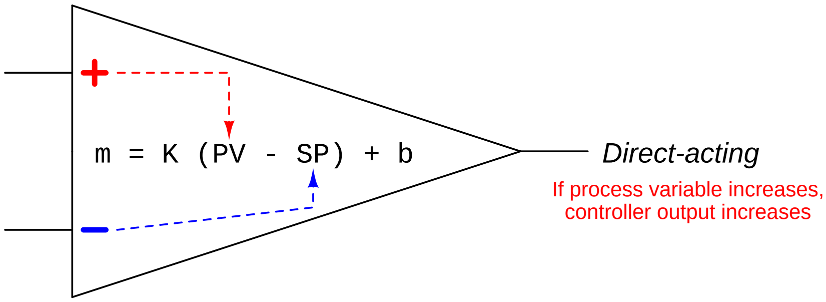
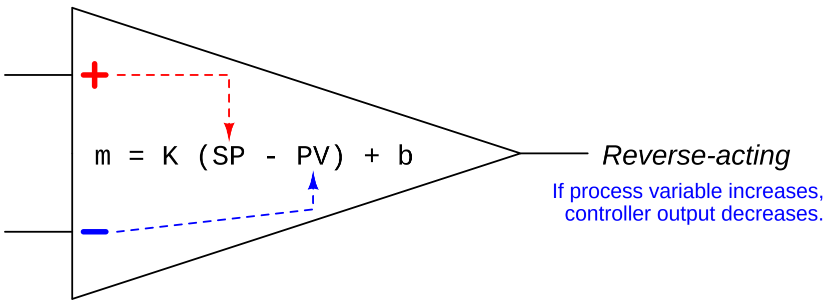
file `license`

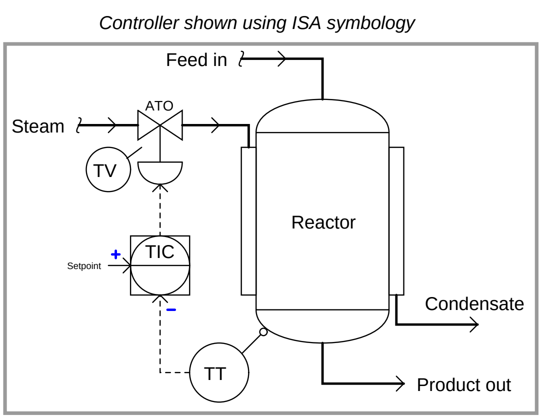
Question 1

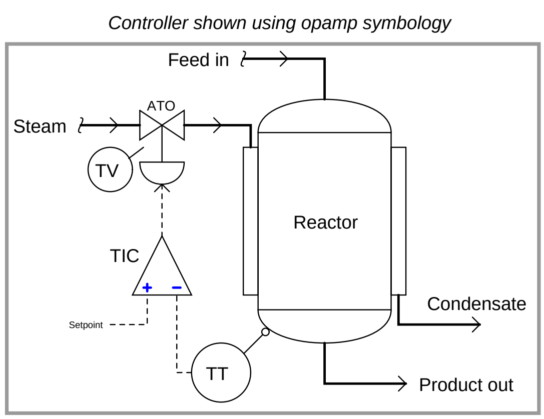
A helpful strategy for qualitatively analyzing control strategies is to mark the inputs of multi-input functions shown in those strategies with either "+" or "−" labels to denote direction of action. This is the same symbology used to mark the inputs of an operational amplifier, where "+" represents the noninverting input and "−" represents the inverting input. In fact, one might think of an operational amplifier as being a proportional controller with a really large gain (k) value:



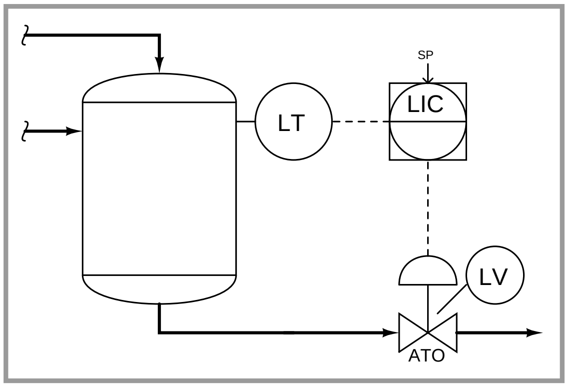


To illustrate this concept, examine these two diagrams of a single-loop control system. In the left-hand diagram, the controller is shown using standard ISA symbology. In the right-hand sketch, the controller is shown using opamp symbology instead. In both cases, the controller must be *reverse-acting* in order to stabilize the process, but the "+" and "−" symbols make it easier to distinguish the directions of action for the process variable versus the setpoint:

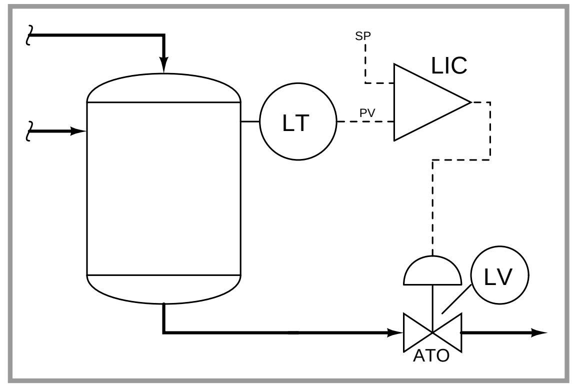


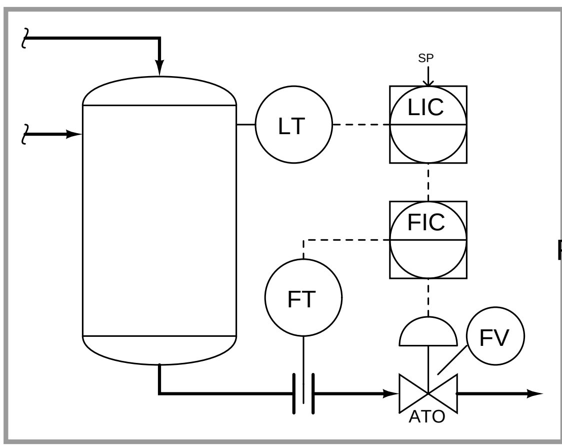


Sketch your own "+" and "−" labels at the input(s) of each controller in each of these control strategy diagrams, to denote the proper directions of action to make each system work properly. In order to help you do this, the right-hand version of each diagram uses opamp symbology for the controller rather than ISA symbology. Assume the use of direct-acting transmitters in each case, and be sure to pay close attention to each control valve's direction of action:



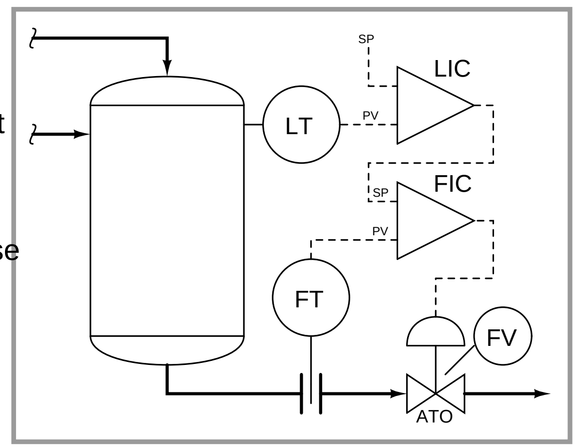
Direct





Direct

Reverse



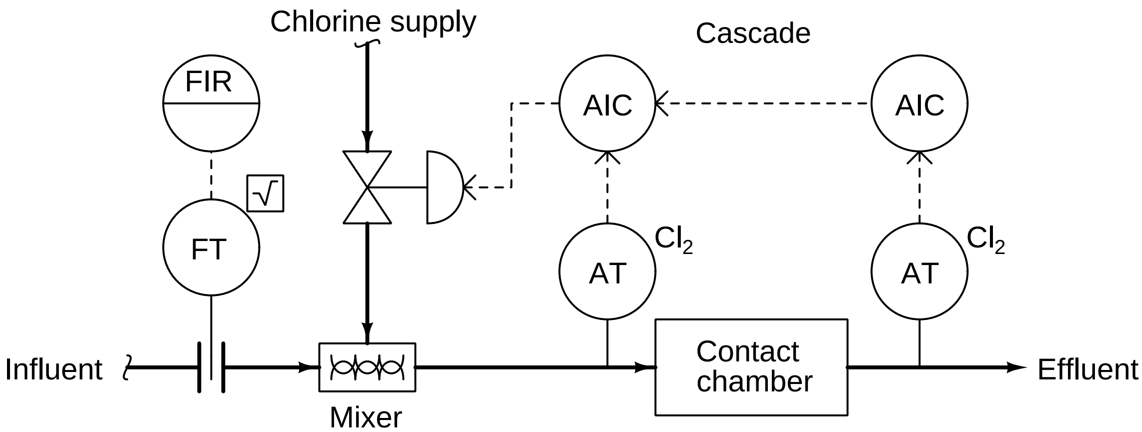
Suggestions for Socratic discussion

- Perform a series of "thought experiments" where you imagine the process variable changing value due to some change in process load, and then analyze the action taken by each controller in each control system. How do the "+" and "−" labels aid your analysis of each system?
- What do you notice about the respective actions of the master and slave controllers in the cascade systems, and how those actions must be for ATO versus ATC valves? Does this result surprise you at all?
- Explain why it only makes sense to label the *inputs* of a controller with "polarity" symbols and not the *output* of a controller.

file i01171

Question 2

Identify what sort of control strategy this is, where two chlorine analyzers are used to measure concentration of chlorine in treated wastewater prior to final discharge, and two controllers work to position the chlorine injection valve:



Note: a *contact chamber* is typically a vessel containing a labyrinth of baffles forcing water to reside inside it for a minimum length of time. In this case, the purpose of the contact chamber is to give chlorine gas sufficient time to disinfect biological contaminants in the water prior to discharge.

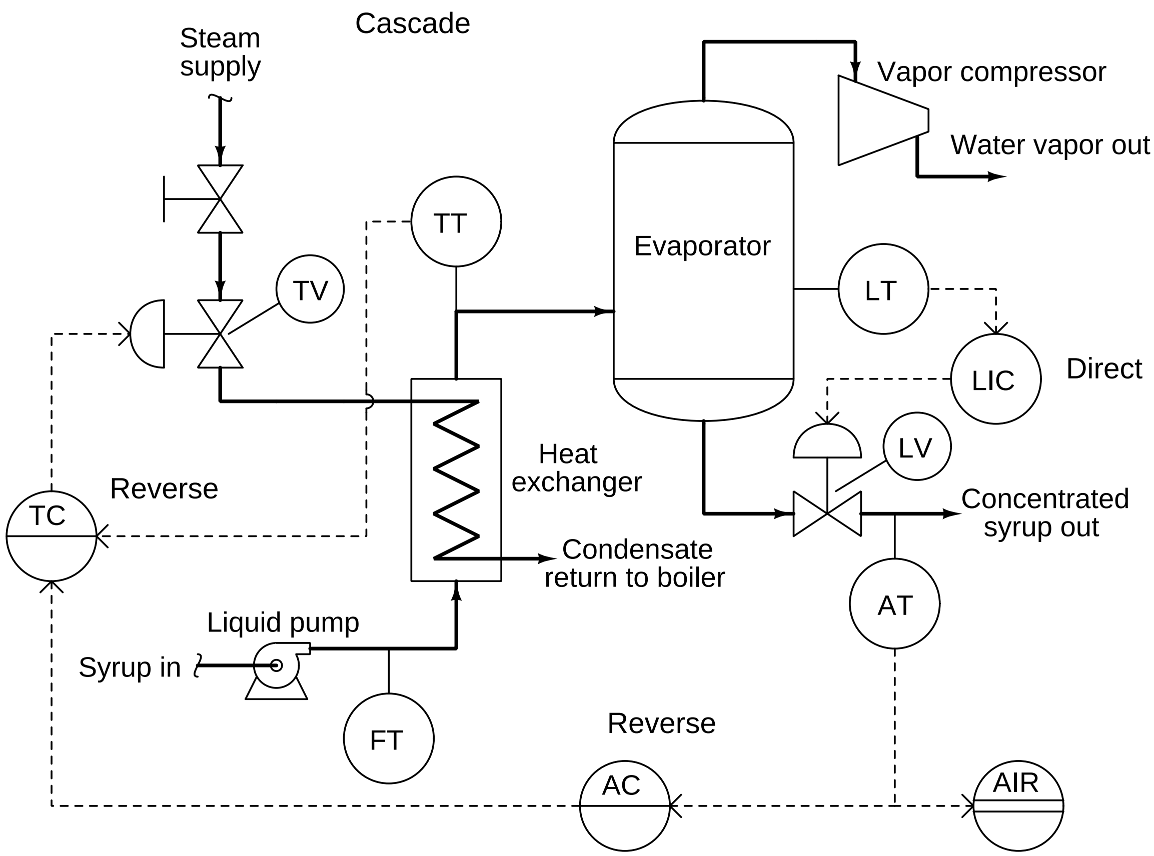
Suggestions for Socratic discussion

- A useful analytical technique for any complex control system is to annotate the diagram with "+" and "−" symbols at the instrument bubble inputs, designating "noninverting" and "inverting" characteristics, respectively. Show how this helps you track of all directions of action, making it easier to figure out how the control system responds to changes.
- For those who have studied control valves, determine the best opening characteristic for the valve trim (quick-opening, linear, or equal percent), assuming the chlorine pressure is regulated at a constant value, and the mixer operates at atmospheric pressure.
- Explain what will happen in this system if either of the chlorine transmitters fails with a low signal.
- Explain what will happen in this system if either of the chlorine transmitters fails with a high signal.
- Explain what will happen in this system if the chlorine gas supply pressure suddenly decreases.
- Explain what will happen in this system if the chlorine gas supply pressure suddenly increases.
- Identify the effect of the influent flow as a *load* on chlorine control, and incorporate a suitable feedforward control strategy to compensate.
- This process is an ideal candidate for a *adaptive gain* control strategy. Research what this is, then explain why it fits this process so well. Finally, edit the control strategy to incorporate the principle of adaptive gain.

file i01806

Question 3

Identify what sort of control strategy this is, where the analytical controller (AC) sends a signal to the temperature controller (TC) as part of a control strategy designed to enhance the concentration of sugar in maple syrup:



Identify the proper action for each controller shown in this maple syrup concentration process, assuming every control valve is signal-to-open.

Suggestions for Socratic discussion

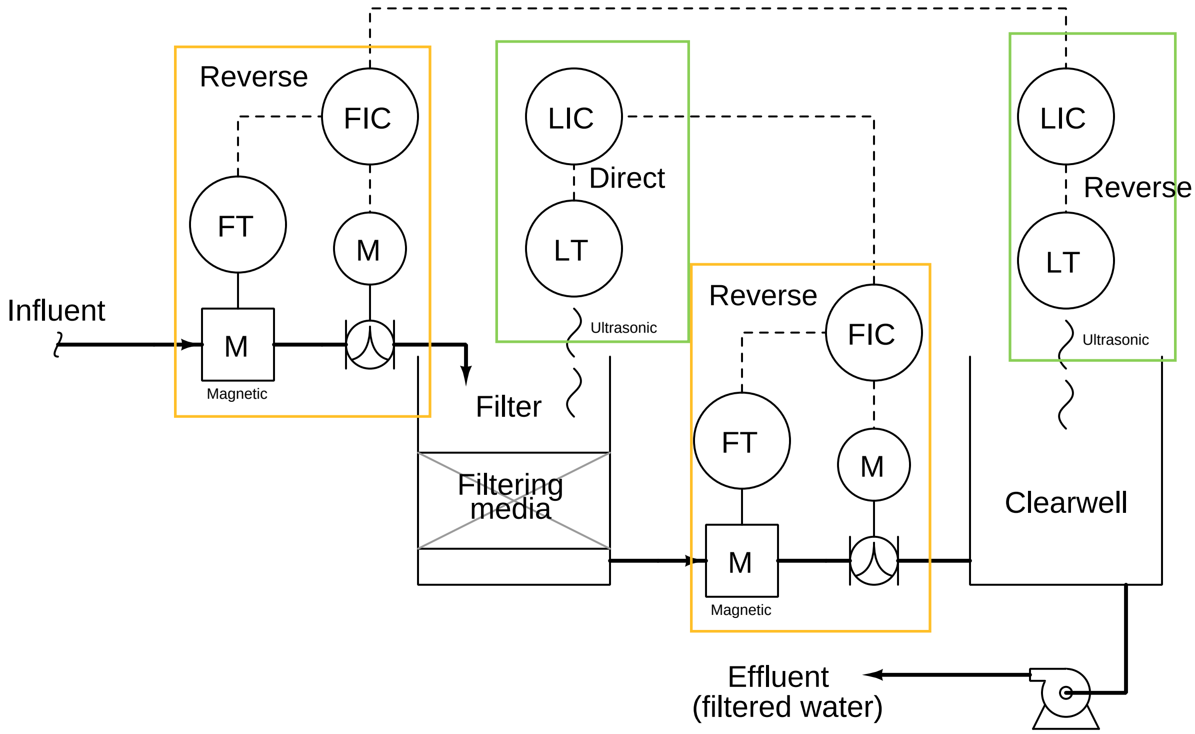
- A useful analytical technique for any complex control system is to annotate the diagram with "+" and "−" symbols at the instrument bubble inputs, designating "noninverting" and "inverting" characteristics, respectively. Show how this helps you track of all directions of action, making it easier to figure out how the control system responds to changes.
- For those who have studied control valves, determine the best opening characteristic for the steam valve trim (quick-opening, linear, or equal percent), assuming the steam header pressure is regulated at a constant value by the boiler control system, and the condensate return line operates at atmospheric pressure.
- Explain what will happen in this system if the temperature transmitter fails with a low signal.
- Explain what will happen in this system if the temperature transmitter fails with a high signal.
- Explain what will happen in this system if the analytical transmitter fails with a low signal.
- Explain what will happen in this system if the analytical transmitter fails with a high signal.
- Explain what will happen in this system if the level transmitter fails with a low signal.
- Explain what will happen in this system if the level transmitter fails with a high signal.

- Explain what will happen in this system if the heat exchanger becomes fouled.
- Explain what will happen in this system if the vapor compressor stops running.
- Explain what will happen in this system if the steam boiler shuts down.

file i02831

Question 4

Examine this water filter control system, then answer the following questions:



- Identify all primary and secondary (cascaded) loops.
- The necessary control actions (direct/reverse) for each controller, assuming direct-acting transmitters and signal-to-open control valves.
- What will happen to the filter water level if the influent supply suddenly shuts off? Hold steady
- What will happen to the clearwell reservoir water level if the influent supply suddenly shuts off? Empties

Suggestions for Socratic discussion

- A useful analytical technique for any complex control system is to annotate the diagram with "+" and "−" symbols at the instrument bubble inputs, designating "noninverting" and "inverting" characteristics, respectively. Show how this helps you track of all directions of action, making it easier to figure out how the control system responds to changes.
- For those students who have studied level measurement, what kind of transmitters are being used here and how do they function?
- For those students who have studied flow measurement, what kind of transmitters are being used here and how do they function?
- For those who have studied PID tuning, what PID tuning parameters (qualitative) would you recommend for each controller in this system?
- Explain what will happen in this system if the influent water pressure increases?
- Explain what will happen in this system if the influent water pressure decreases?
- Explain what will happen in this system if the effluent water demand (flow) increases?
- Explain what will happen in this system if the effluent water demand (flow) decreases?
- Explain what will happen in this system if the influent flow transmitter fails with a low signal.

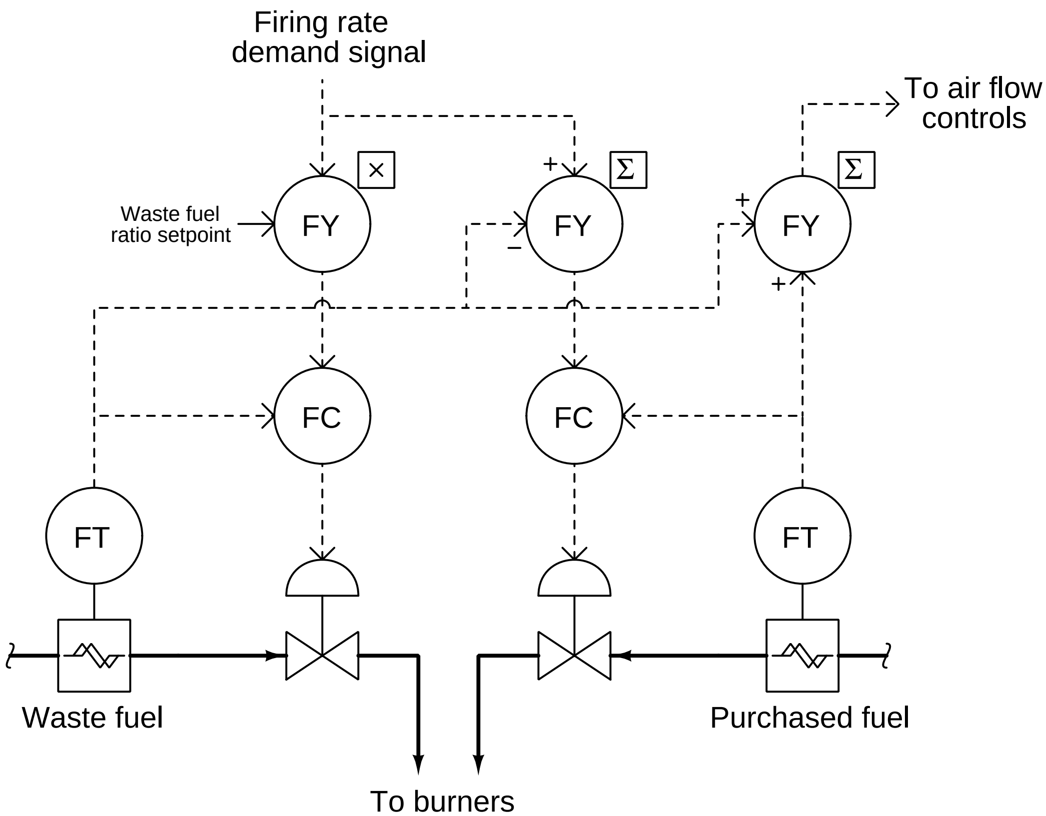
- Explain what will happen in this system if the influent flow transmitter fails with a high signal.
- Explain what will happen in this system if the filter level transmitter fails with a low signal.
- Explain what will happen in this system if the filter level transmitter fails with a high signal.
- Explain what will happen in this system if the clearwell level transmitter fails with a low signal.
- Explain what will happen in this system if the clearwell level transmitter fails with a high signal.

file i01812

Question 5

Many industries produce flammable waste products that may be used as fuel in furnaces, steam boilers, and process heaters. Obviously, if one may use a waste fuel instead of paying for natural gas or fuel oil, a double economic benefit awaits: not only do you pay less for energy, but you rid yourself of a waste product ordinarily costing money to dispose of.

Waste fuel flow, however, is often unsteady. Combustion processes usually cannot run solely on waste fuel because the supply is liable to change. For this reason, heat processes using waste fuels supplement their waste fuel sources with purchased fuels such as gas, oil, and/or coal. This requires a control system to manage the mix of waste and purchased fuel. Here is an example:



After examining this control scheme, answer the following questions:

- Which controller inputs are process variables (PVs), and which are setpoints (SPs)?
- What is the purpose of the multiplier function?
- Why would the waste fuel ratio setpoint ever be set at a value other than unity (100%)?
- What is the purpose of the subtractor function?
- What is the purpose of the summer function?
- How would the control system respond if the waste fuel source suddenly ran out, so that waste fuel flow dropped to zero?

Suggestions for Socratic discussion

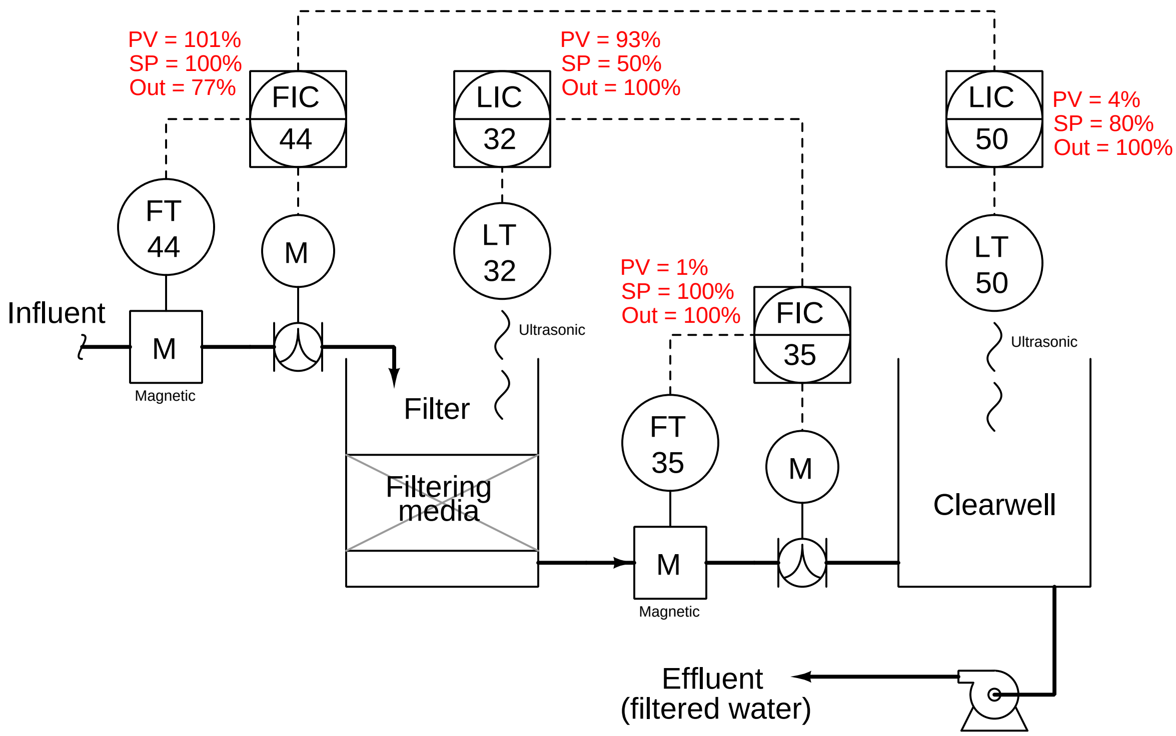
- Assuming signal-to-open control valves, determine the necessary actions of each controller in this system, and mark their PV and SP inputs accordingly with "+" and "−" symbols.

- How would the control system respond if the purchased fuel source suddenly ran out, so that purchased fuel flow dropped to zero?
- For those who have studied flowmeters, what type of flow-measuring instruments are used in this control system, and what benefit(s) do they hold over the more standard orifice plate and DP cell variety?
- Explain what will happen in this system if the waste fuel flow transmitter fails with a low signal.
- Explain what will happen in this system if the waste fuel flow transmitter fails with a high signal.
- Explain what will happen in this system if the purchased fuel flow transmitter fails with a low signal.
- Explain what will happen in this system if the purchased fuel flow transmitter fails with a high signal.

file i01832

Question 6

This water filtration system has a problem. Examine the faceplate data for all four loop controllers (shown in red text, near each controller) for evidence of the fault:



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

Fault	**Possible**	**Impossible**
Filtering media clogged		
FV-44 failed wide open		
FV-44 failed fully shut		
FV-35 failed wide open		
FV-35 failed fully shut		
FT-44 failed with high signal		
FT-35 failed with high signal		
Effluent pump shut off		

Based on what you see here, is the situation urgent or not? If you were the operator, what would be your first step in rectifying this situation?

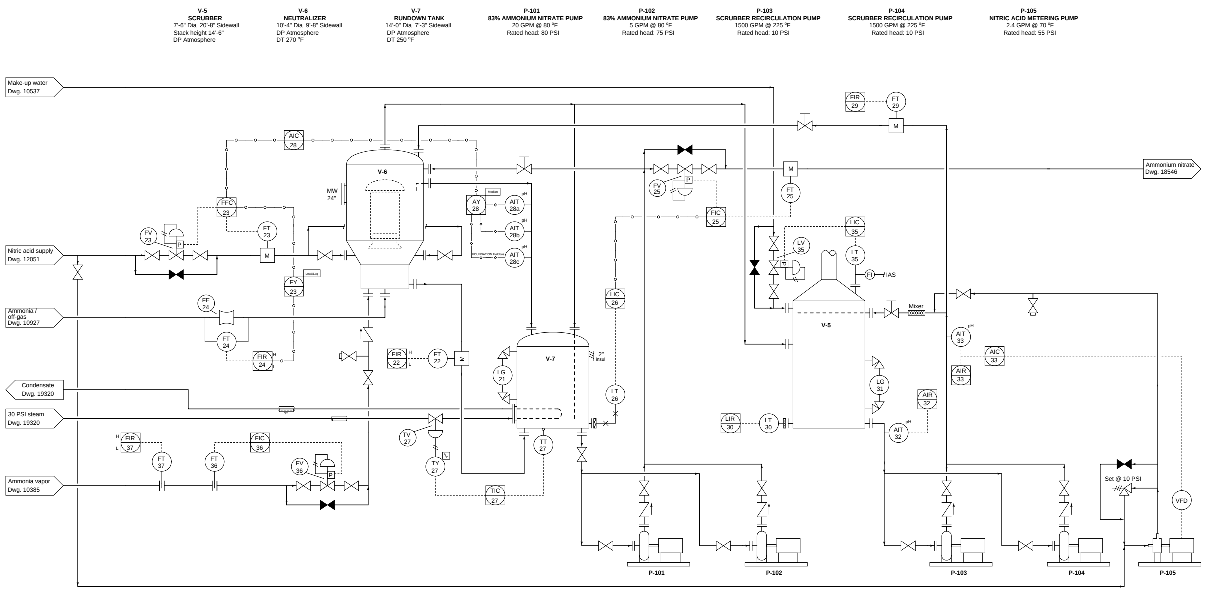
Suggestions for Socratic discussion

- Which details in this diagram were most helpful for determining the nature and location of the problem?

file i00133

Question 7

This production process manufactures *ammonium nitrate*, a principal ingredient of synthetic fertilizer, from the chemical combination of nitric acid and ammonia:



In this process, the pH of the liquid inside the scrubber vessel (V-5) is controlled by adding nitric acid which drives pH down to lower values, since ammonia vapor entering that vessel drives pH up.

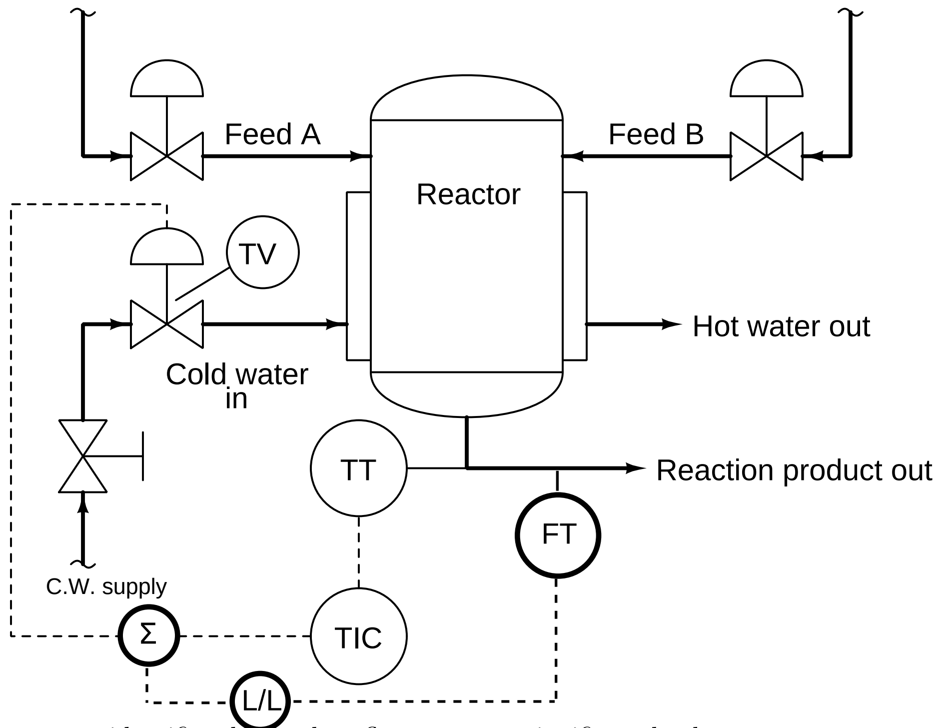
Examine the pH control system for that scrubber vessel and identify one of the loads in that control loop. After identifying the load, add a transmitter to sense that load variable, and add necessary control functions to implement a *feedforward* control strategy to the scrubber's pH control system.

Also, describe a test by which you could determine the necessary lead/lag settings within FY-23, which is part of an existing feedforward control strategy.

file i01278

Question 8

This P&ID shows the temperature control system for an exothermic chemical reactor, where two fluid reactants mix together and react in such a way that a significant amount of heat is produced. Cold water admitted to the vessel's cooling jacket through a control valve maintains the reactor's contents at a set temperature:

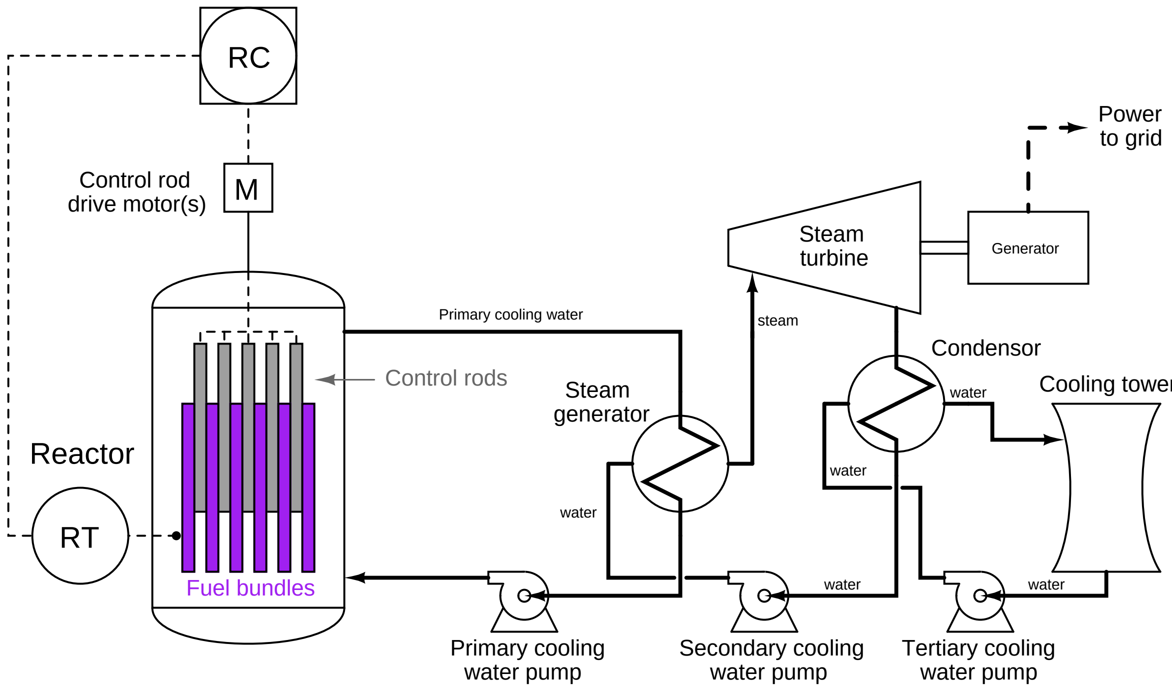


Suppose someone identifies the product flow rate as a significant load on reactor temperature, a greater flow rate representing a greater rate of heat liberated by the chemical reaction. Add all necessary components to add feedforward control to this system (including dynamic compensation), and furthermore describe a test procedure by which you will be able to tell whether the dynamic compensation needs to be configured for *lead* or *lag*.

file i02573

Question 9

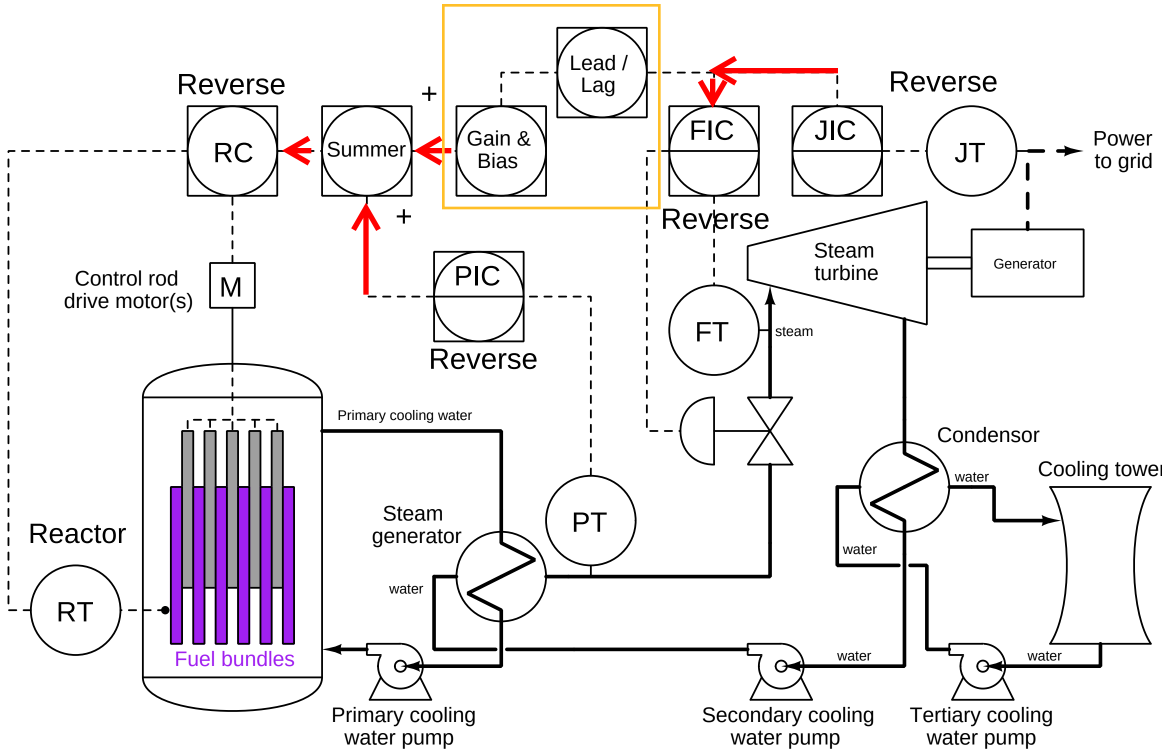
Nuclear reactors generate immense quantities of heat through a phenomenon called *nuclear fission*, whereby atoms of a particular substance "split" when struck by neutron particle radiation, releasing more neutron particles to split other atoms, and so on in a "chain reaction". Basic control of a fission reactor's power output is achieved by precisely positioning a series of special metal rods called *control rods* to absorb excess neutron radiation and thereby regulate the chain-reaction. Inserting these rods deeper into the reactor core quenches the reaction, while drawing them out of the reactor core increases the reaction. Instantaneous reactor power output is measured by a set of *neutron detectors* located in the core, sensed by a radiation transmitter (RT) and passed on to a control-rod controller (RC). A process flow diagram (PFD) shows the basic process and neutron flux control loop:



In this case, the reactor uses water as the coolant, pressurized to a level so that boiling is impossible within the reactor vessel. The heat from the reactor is transferred to a secondary "loop" of water by a heat exchanger called a *steam generator*. The secondary water is boiled there, becoming steam to turn a steam turbine to power an electrical generator. The turbine's exhaust is condensed back into water by another heat exchanger, and then that secondary water is pumped back to the steam generator to be boiled again.

In order to achieve stable and responsive power control as an electricity-generating operation, though, much more instrumentation is needed than what is shown in this PFD.

This PFD shows instrumentation as might be seen on a commercial pressurized-water nuclear power reactor:



Make this diagram even more descriptive by adding the following details:

- Label each input and output signal path for each controller (PV, SP, Out)
- Sketch arrow-heads to show the direction each control signal path sends information
- Identify the action of each controller (direct vs. reverse), assuming direct-acting transmitters and signal-to-open final control elements
- Identify the "polarity" of each input on the summer (i.e. whether each input has a "+" or a "−" symbol next to it describing its proper direction of action
- Identify which controllers have local versus remote (cascade) setpoints
- Identify the feedforward signal path in this control strategy

Explain how this control system is supposed to work by conducting at least one "thought experiment" whereby the system responds appropriately to some change.

Suppose we empirically determine (i.e. determine by actual experiment) that a step-change in control rod position has a delayed effect on secondary steam header pressure while a step-change in turbine steam flow has a much faster effect on secondary steam header pressure. Based on this knowledge, should we configure the lead/lag function for *lead* or for *lag*?

Suggestions for Socratic discussion

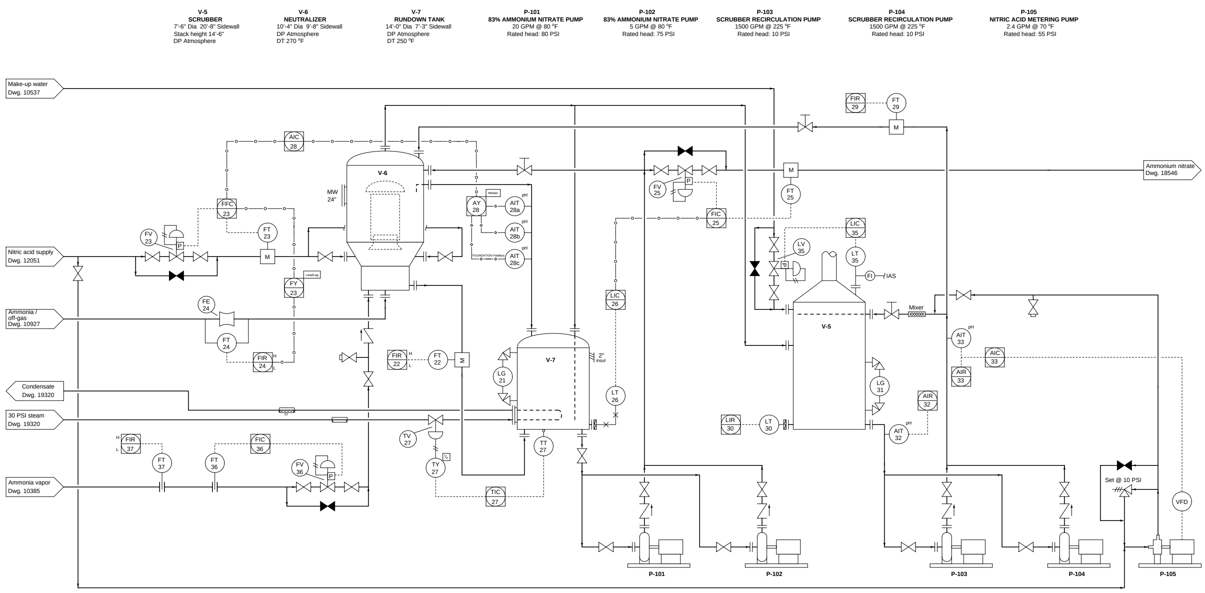
- In most feedforward control strategies, a load signal is added to the manipulated variable signal of a feedback control loop. In this system, however, we don't see this exact scheme. Does this still truly qualify as a *feedforward* control strategy? Why or why not?
- Does this control system seek to maintain mass balance, energy balance, or both?

- The primary coolant loop is pressurized by a special device not shown in either PFD, called a *pressurizer*. Research how one of these devices works (your *Lessons In Industrial Instrumentation* textbook explains this) and explain it in your own words.

  file i01752

Question 10

This production process manufactures *ammonium nitrate*, a principal ingredient of synthetic fertilizer, from the chemical combination of nitric acid and ammonia:

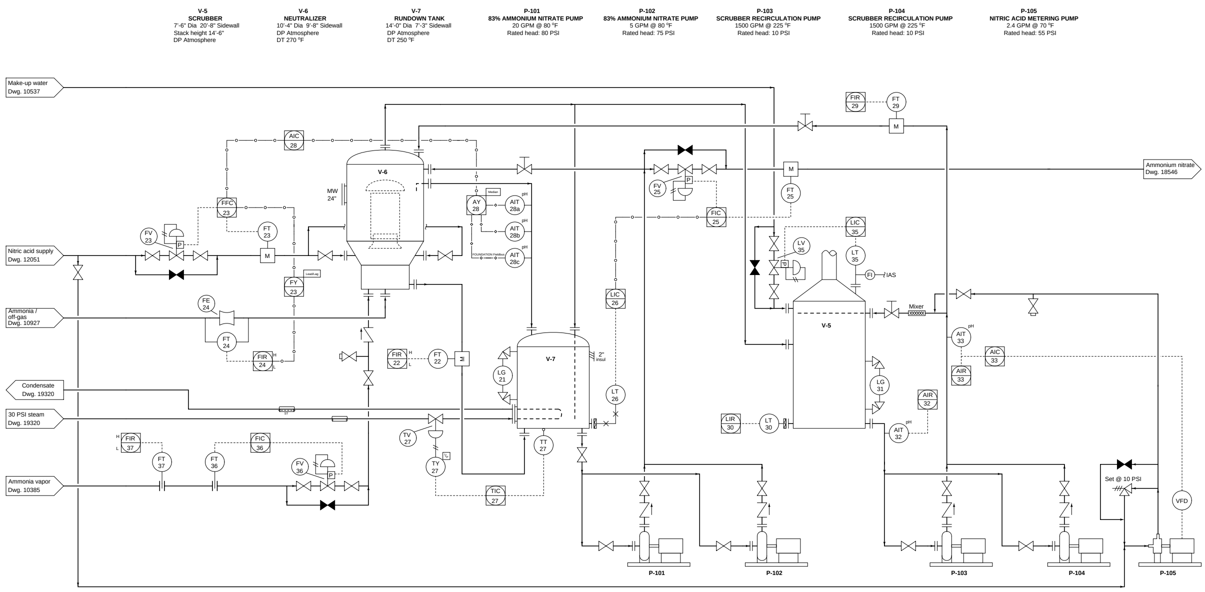


Examine the level control system for the rundown tank (V-7), and identify one of the loads in that control loop. After identifying the load, add a transmitter to sense that load variable, and add necessary control functions to implement a *feedforward* control strategy to the rundown tank's level control.

file i01276

Question 11

This production process manufactures *ammonium nitrate*, a principal ingredient of synthetic fertilizer, from the chemical combination of nitric acid and ammonia:

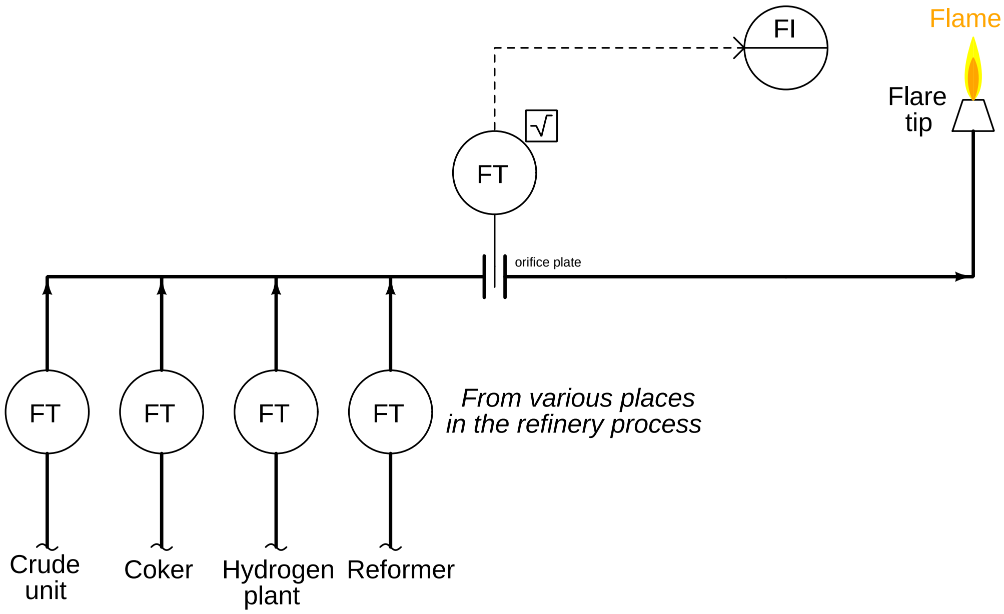


Examine the level control system for the scrubber vessel (V-5). Suppose you were informed that the make-up water header supply pressure tends to vary significantly, and that this was acting as a load in V-5's level control loop. Explain how you could add cascade control to that level control loop to better manage swings in make-up water supply pressure.

file i01277

Question 12

After installing an orifice plate in a flare-line pipe of an oil refinery, operations personnel begin to doubt the accuracy of the flow measurement it provides. The process fluid going through the flare line varies from hydrogen gas to heavy oils, and its composition continually changes. Since accurate flow measurement with an orifice plate requires a fluid of *known and constant* density, this technique of total flow measurement is doomed.



Flow measurements from the flow transmitters in each unit are far more reliable, because the flare line flow transmitter within each unit may be calibrated for the expected process fluid coming from each unit.

Determine a way for operations to obtain a reliable total flare flow measurement without having to rely on a single flowmeter in the main flare line. Hint: it can be done with a *computational relay*!

Suggestions for Socratic discussion

- For those who have already studied flowmeter technology, explain why an orifice-plate flowmeter's accuracy depends on knowing the fluid density.
- This application is an example of an *inferred* measurement: obtaining a calculated measurement of some variable that is itself difficult to measure directly. Identify ways this approach can go wrong, resulting in incorrect inferred values.

file i01784

Question 13

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

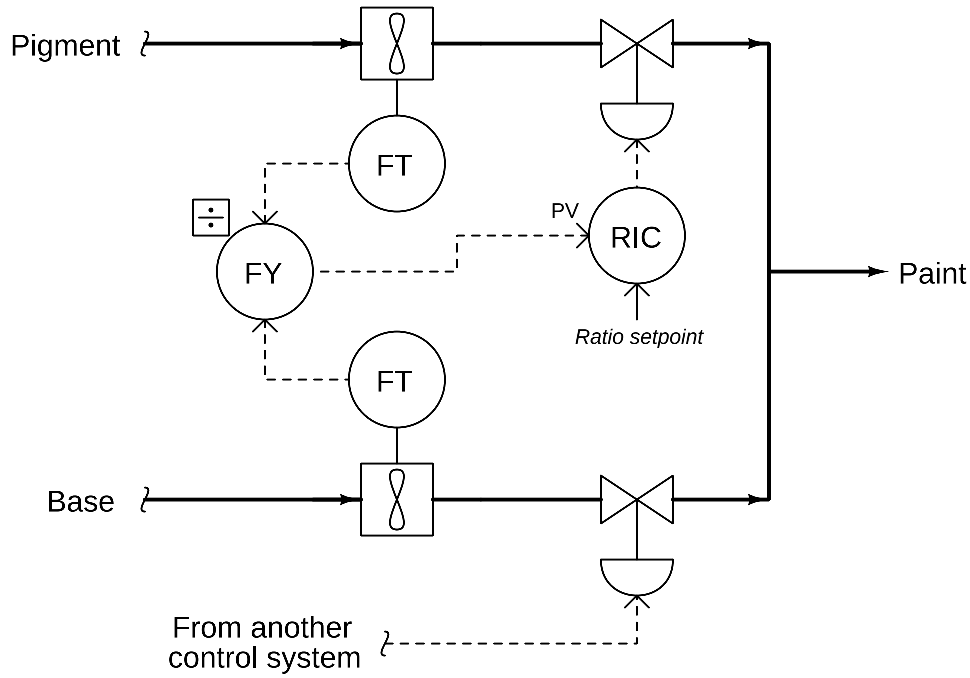
- Less heat energy lost out the exhaust (flue gases)
- Reduced NO_x emissions
- Fuel conservation

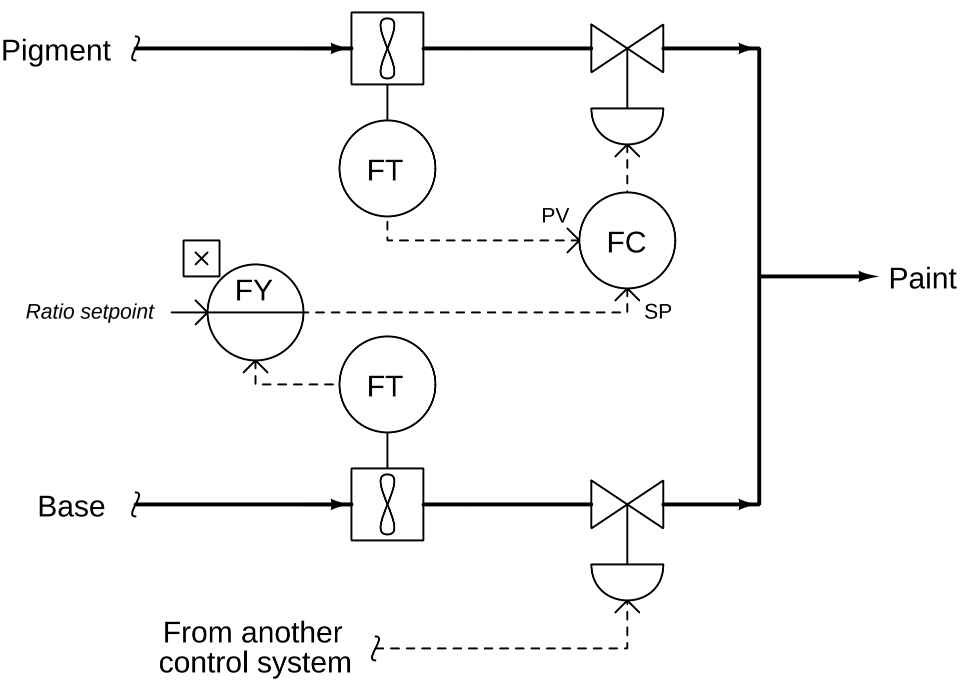
Explain *why* oxygen trim control, properly implemented, provides these advantages. Also, identify some hazards if an oxygen trim control system fails in such a way as to provide *insufficient* air to a combustion process.

file i01827

Question 14

Two engineers propose different plans for adjustable ratio control in the following paint mixing system. One of these schemes will work, but the other will prove to be unstable. Which scheme is better, and why?



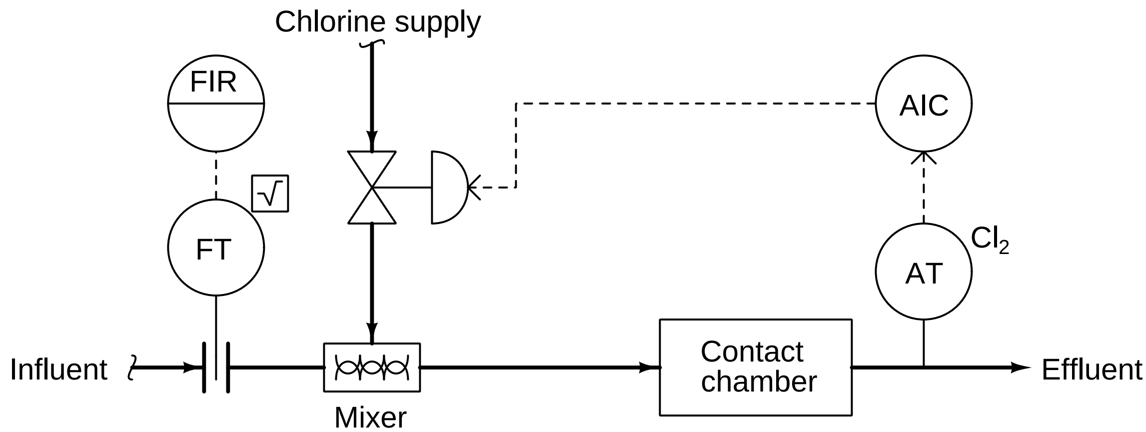


Beware: this is a deep question!
file i01730

Question 15

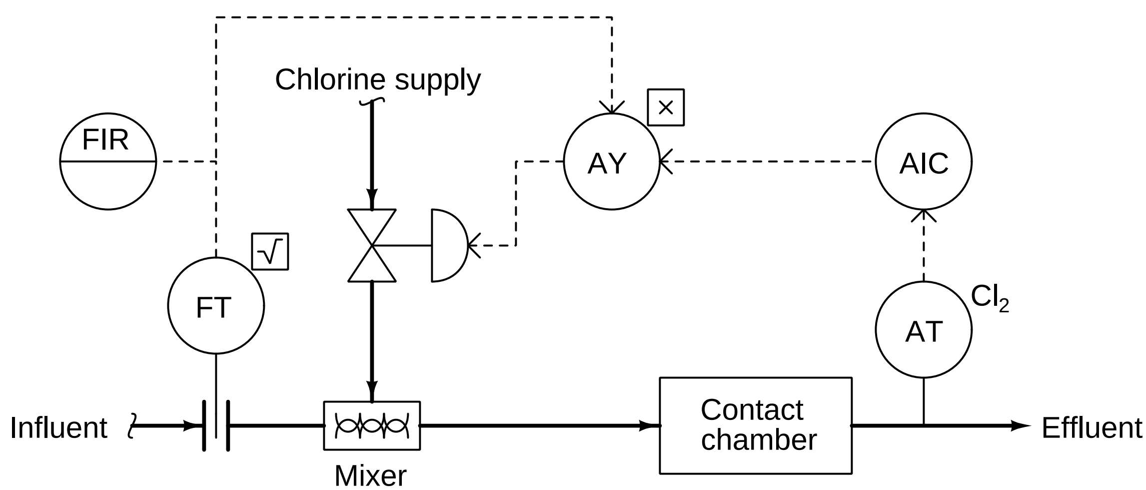
The following chlorine disinfection system (common to wastewater treatment systems) has a subtle problem the loop's stability changes with the weather. Influent in this case comes from the discharge of an open aeration lagoon, which collects rainwater during stormy weather but of course does not during dry weather.

When the influent water flow rate is low, the control system will oscillate. When the influent water flow rate is high, the system will respond sluggishly:

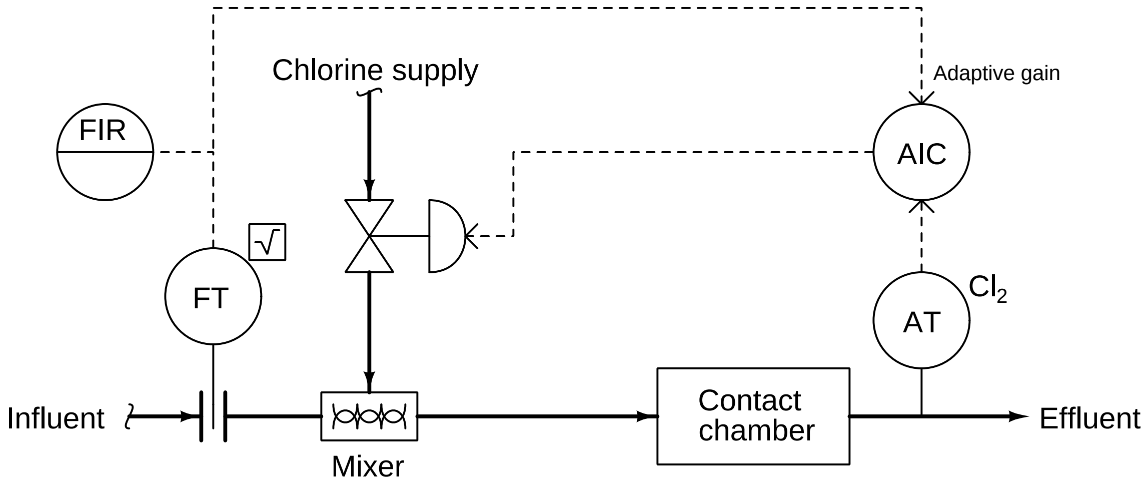


So far, instrument technicians' approach to solving this problem has been to re-adjust the PID tuning parameters seasonally. Identify how you think the controller's PID tuning parameters would need to be adjusted between the seasons and wet seasons, being as specific as you can. Explain *why* the process itself seems to control so differently based on influent flow rate.

Explain why the following modification will go a long way toward correcting this problem:



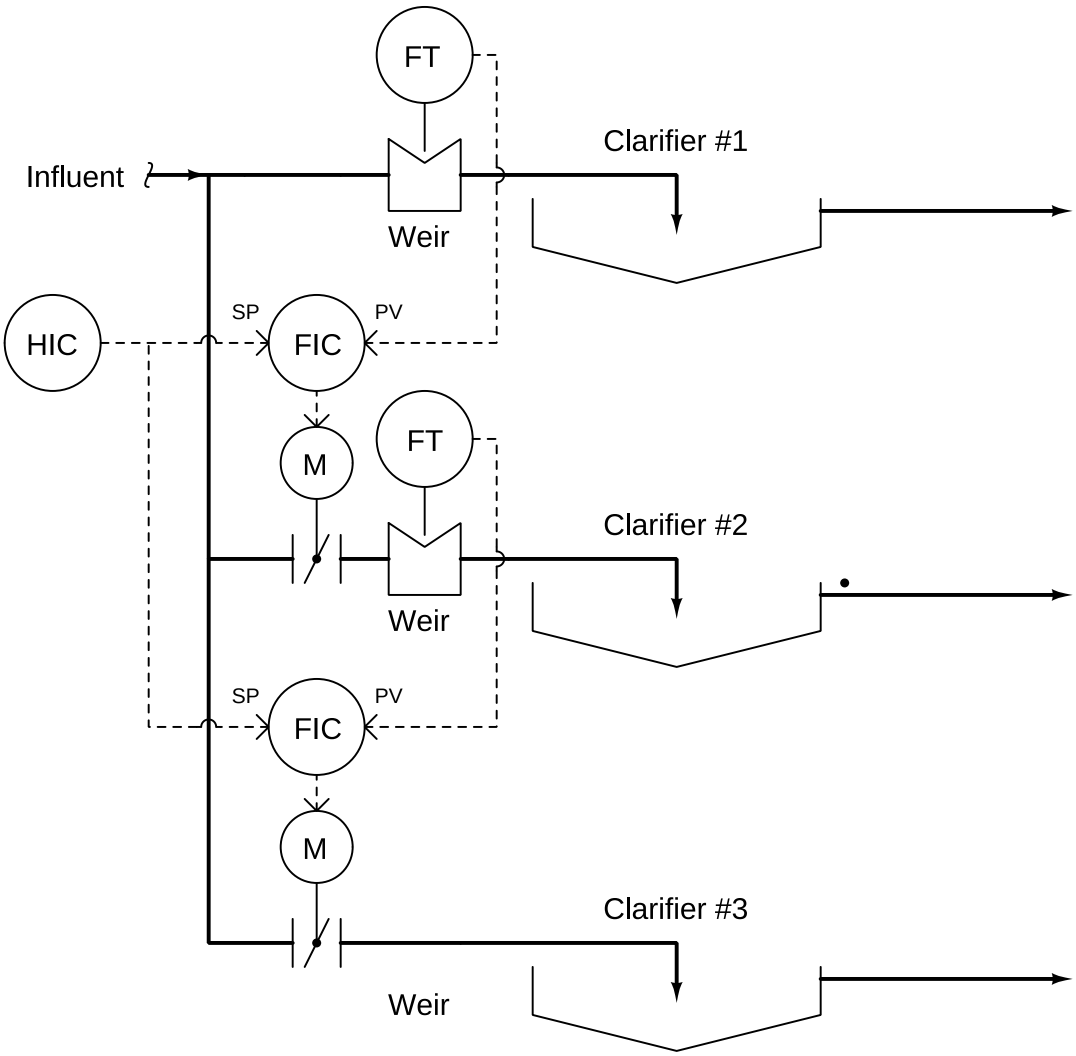
Explain why this next modification works as it does, being an alternative to the former solution:



file i01815

Question 16

The following control scheme adjusts wastewater flow though three clarifiers in a *sequenced* order:



Explain the operating philosophy of this control system. Hint: the flow controllers are *direct acting* (i.e. they each open up their respective butterfly valve as the flow transmitter indicates a greater water flow rate). Another hint: the total influent flow is not affected by the opening of the clarifier control valves. Rather, the total influent flow is a function of water usage upstream of the wastewater clarifiers.

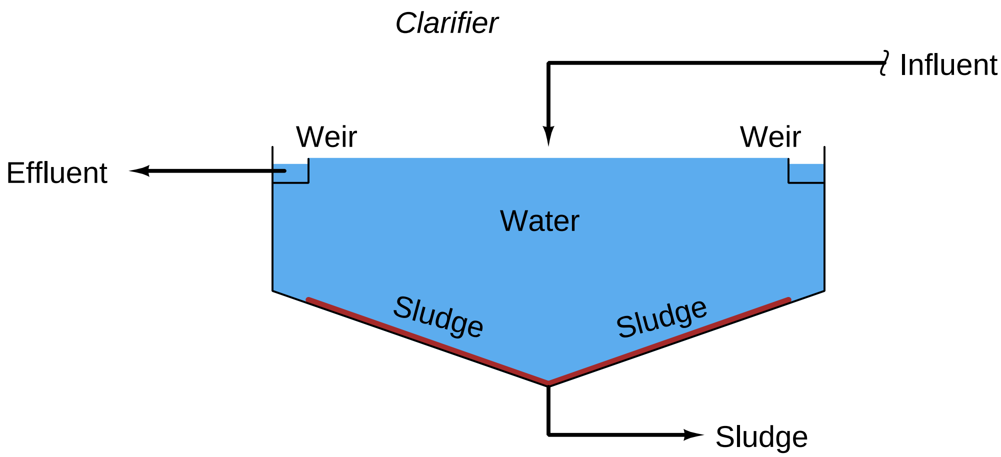
Suggestions for Socratic discussion

- A useful problem-solving strategy here is to add some numerical values to the diagram: assume a flow setpoint that is *less* than the total influent flow rate, then perform a "thought experiment" to see how the controllers would react to this.

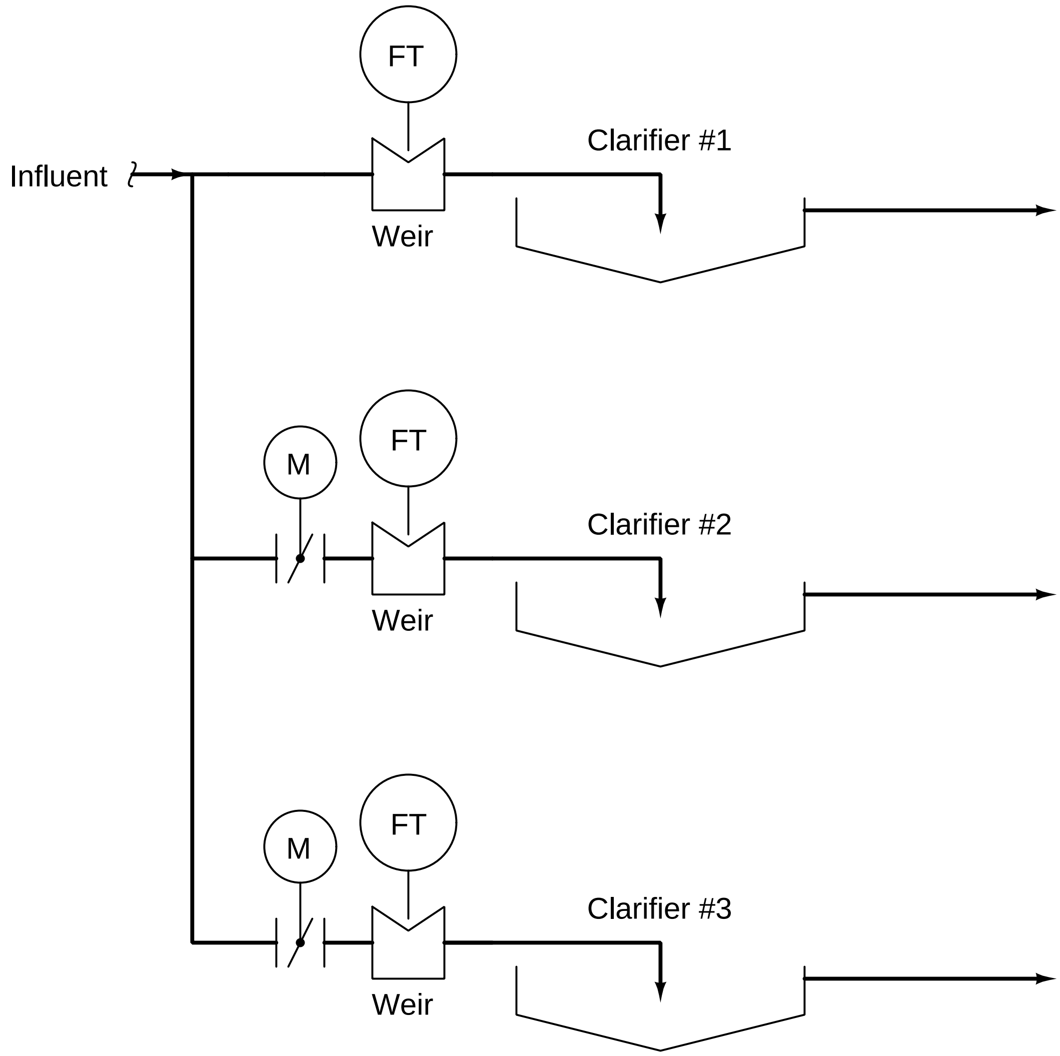
  file i01808

Question 17

One of the most basic water-treatment processes is *clarification*: letting the water move *slowly* through a large, open vessel for the purpose of allowing solids to precipitate. The resulting "clarified" water will be less turbid than the incoming water, with the precipitate being collected out the bottom of the clarifier vessel as sludge:



When multiple clarifiers are used, it is common to operate each at the same flow rate: in other words, with the influent flow equally split between the multiple clarifiers. Sketch a P&ID for a control system that will match flow through clarifiers #2 and #3 at rates equal to the flow through clarifier #1:



Suggestions for Socratic discussion

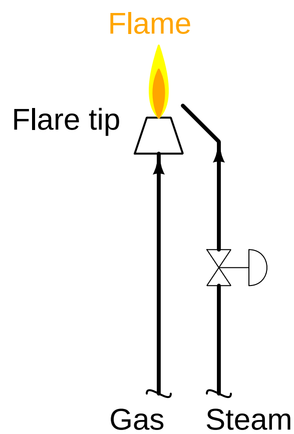
- A useful analytical technique for any complex control system is to annotate the diagram with "+" and "-" symbols at the instrument bubble inputs, designating "noninverting" and "inverting" characteristics, respectively. Show how this helps you track of all directions of action, making it easier to figure out how the control system responds to changes.
- For those who have studied flow measurement, explain what a *weir* is and how one works to measure water flow through an open channel.

file i01807

Question 18

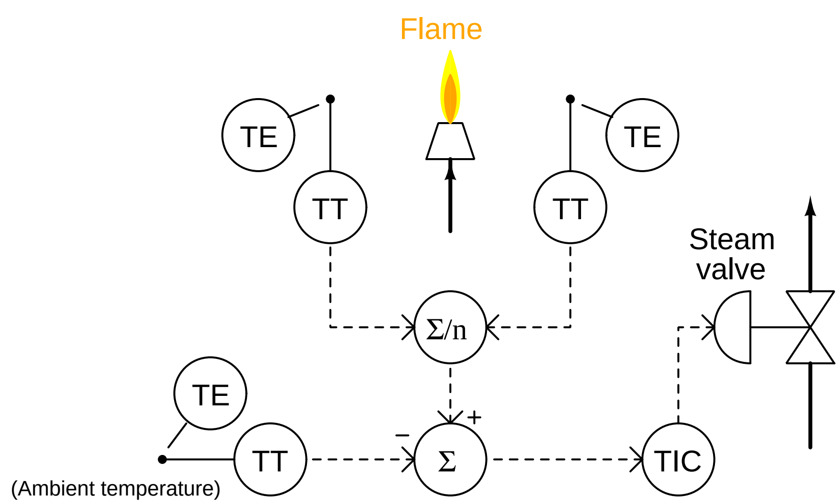
Offshore oil rigs and oil refineries often use *flare* burners to safely discharge excess product to atmosphere. Although it seems wasteful to constantly burn off petroleum compounds in a giant outdoor burner (and it is!), it is worse to not have a safe place to vent flammable compounds in the event of an emergency shutdown requiring de-pressurization of pipes and vessels.

Flares must handle a wide variety of gases for emergency combustion. Some of these gases burn clean, while others tend to burn "sooty" due to their high carbon content. It is impossible to design a single burner assembly to efficiently and cleanly burn all manner of combustible gases, so other means are necessary to control smoke. One such method is steam injection into the flame. Steam increases turbulence in the flame, which promotes better air/fuel mixing for decreased smoke:



However, steam is an expensive commodity. Leaving the steam valve wide-open all the time may ensure a smokeless flare, but it wastes steam when the flare is burning cleaner gases. An automatic control system should be used to control steam flow for optimum efficiency.

One way to indirectly measure the need for steam injection in a flare is to measure radiant heat with several thermocouples (TE) arrayed near the flare tip. Greater carbon content in a flame results in greater radiated heat, which will be sensed by the surrounding thermocouples:



The setpoint and/or bias of this controller is set such that the steam valve is fully closed when the radiant thermocouples' temperature is equal to ambient. Configured as such, it is important that this controller have no integral action, only proportional and derivative. Explain why.

file i01831

Question 19

Read and outline Case History #116 ("Poor Control Strategy: Minimum Flow Control") from Michael Brown's collection of control loop optimization tutorials.

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.

Be sure to answer the following questions:

- Examine the P&ID shown in Figure 1, and explain how it is supposed to perform its dual tasks of regulating liquid level inside the vessel and maintaining a minimum amount of flow through the pump.

- What does it mean to "split-range" a pair of control valves?

- Examine the P&ID shown in Figure 3, and explain how Mr. Brown's revised control strategy performs its dual tasks of regulating liquid level and maintaining minimum pump flow.

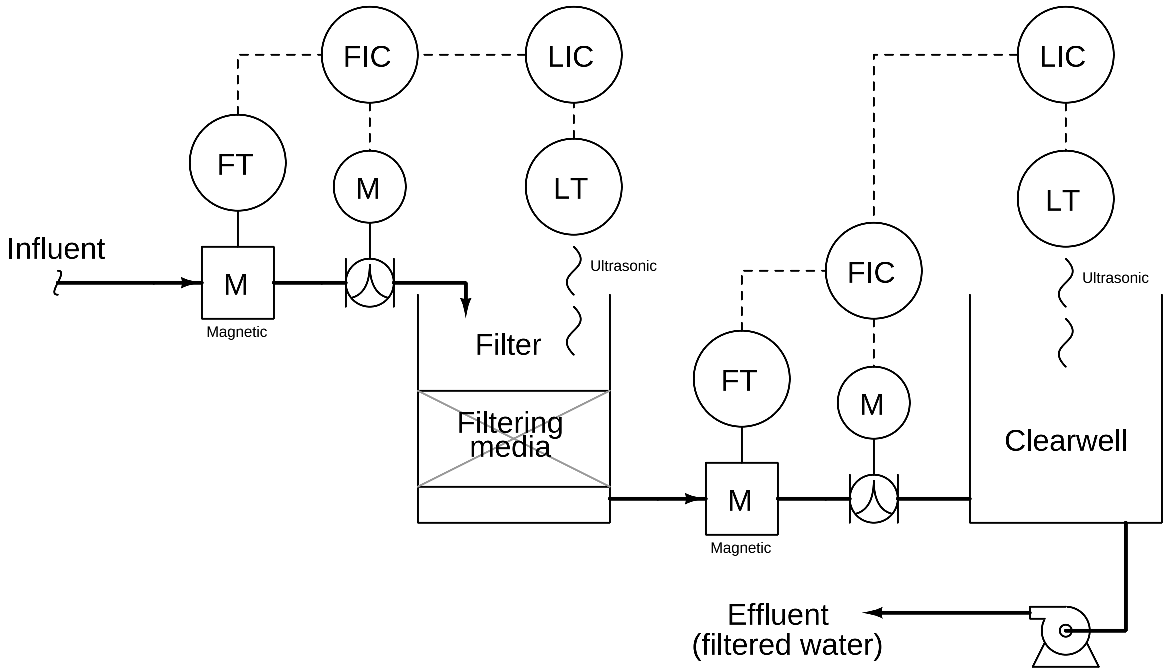
- One of the comments Mr. Brown makes in this case history is that "The [addition of another] controller would cost nothing," referring to the flow controller added to the process strategy to realize minimum flow through the pump. Explain how this "no cost" assertion can be true, knowing that loop controller hardware (and software!) can be very expensive indeed.

- As shown in the trend of Figure 2, the response of flow transmitter FT-1 was "heavily damped." What does the word "damped" mean with regard to a flow transmitter, and why might this be a problem for any control loop incorporating a damped flow transmitter?

file i00419

Question 20

Examine this water filter control system, then answer the following questions:



- Identify all primary and secondary (cascaded) loops.
- The necessary control actions (direct/reverse) for each controller, assuming direct-acting transmitters and signal-to-open valve actuators.
- What will happen to the filter water level if the influent supply suddenly shuts off?
- What will happen to the clearwell reservoir water level if the influent supply suddenly shuts off?

Suggestions for Socratic discussion

- A useful analytical technique for any complex control system is to annotate the diagram with "+" and "−" symbols at the instrument bubble inputs, designating "noninverting" and "inverting" characteristics, respectively. Show how this helps you track of all directions of action, making it easier to figure out how the control system responds to changes.
- Explain what will happen in this system if the clearwell inlet flow transmitter fails with a low signal.
- Explain what will happen in this system if the clearwell inlet flow transmitter fails with a high signal.
- Explain what will happen in this system if the clearwell level transmitter fails with a low signal.
- Explain what will happen in this system if the clearwell level transmitter fails with a high signal.
- For those who have studied PID tuning, what PID tuning parameters (qualitative) would you recommend for each controller in this system?

file i01811

Question 21

Read and outline the introduction to the "Limit, Selector, and Override Controls" section of the "Basic Process Control Strategies" 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 i02482

Question 22

Read and outline the "Limit Controls" subsection of the "Limit, Selector, and Override Controls" section of the "Basic Process Control Strategies" 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 i02468

Question 23

Read and outline the "Selector Controls" subsection of the "Limit, Selector, and Override Controls" section of the "Basic Process Control Strategies" 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.).
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(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.

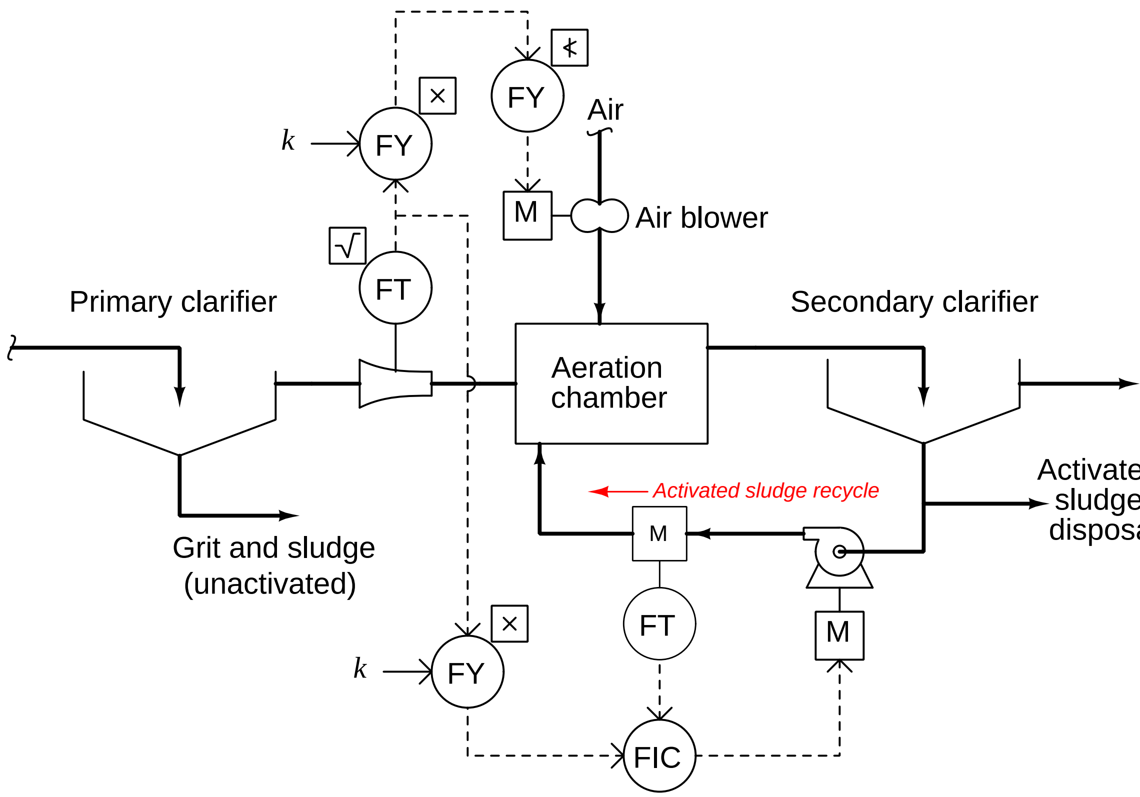
file i02469

Question 24

The *activated sludge* process exploits the natural decomposing action of bacteria to digest organic compounds dissolved and suspended in wastewater. These compounds precipitate more easily after being digested by the bacteria, and are removed from the water as sludge through clarification and settling.

In order for the activated sludge process to work well, bacteria must be supplied with an ample amount of air, and a constant stream of bacteria-laden ("activated") sludge must be re-introduced into the aeration chamber to maintain a culture capable of continually digesting incoming waste.

Examine the following P&ID, and explain how the instruments help ensure proper "care and feeding" of the bacteria for good operation:



Suggestions for Socratic discussion

- Identify whether the flow controller needs to be *direct* or *reverse* acting.
- For those who have already studied flowmeters, explain why a *magnetic* flowmeter is ideally suited for measuring sludge flow, where the sludge has the approximate consistency (and appearance!) of peanut butter.
- For those who have already studied flowmeters, identify the flowmeter type used to measure influent flow and also explain why it has a square-root symbol next to it.
- Explain what a *clarifier* vessel does, and the purposes each one serves in this process.
- Explain what will happen in this system if the venturi tube flowmeter fails with a low signal.
- Explain what will happen in this system if the venturi tube flowmeter fails with a high signal.
- Explain what will happen in this system if the magnetic flowmeter fails with a low signal.
- Explain what will happen in this system if the magnetic flowmeter fails with a high signal.

file i01809

Question 25

A computer spreadsheet program may be used as a simulator for a *median select* function, choosing the median of three values input to it.

Begin creating your own spreadsheet by following the format shown below, allowing anyone to enter three values into cells on the left-hand side of the workbook, while the spreadsheet chooses and displays the median value in a cell toward the right-hand side of the workbook. The yellow (input) and blue (output) cell shading is optional:

	1	2	3	4	5
1	Input A				
2	Input B			Median	
3	Input C				
4					
5					

Where might a median-select function be used in a process control system?

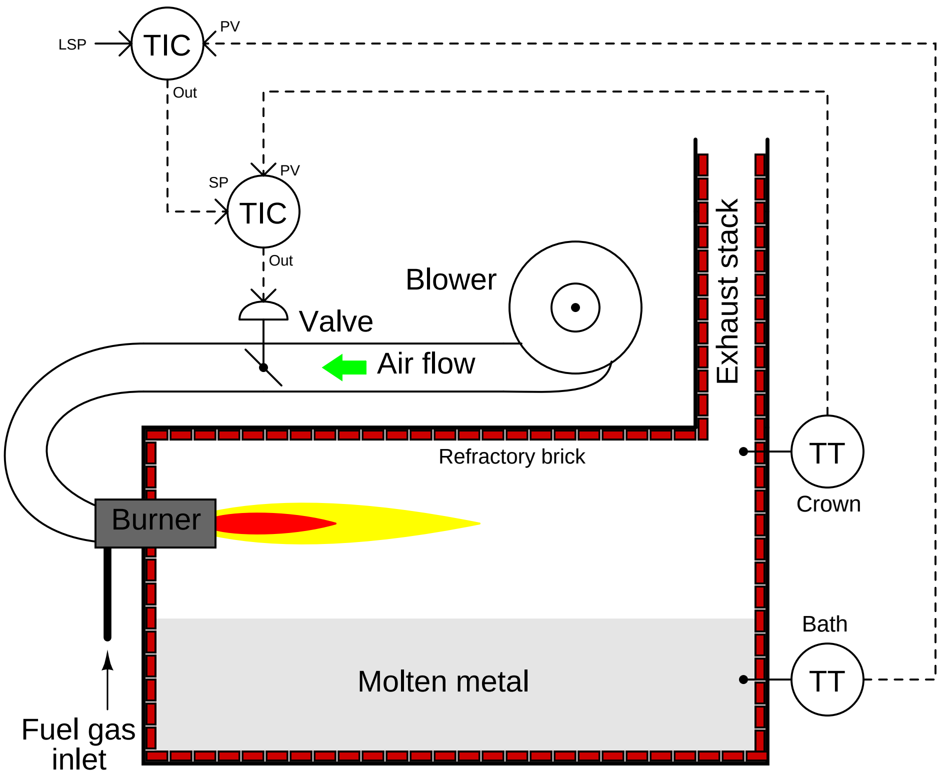
Suggestions for Socratic discussion

- There is definitely more than one way to accomplish this function using a spreadsheet program. Identify at least two of them.

file i00790

Question 26

This metal-melting furnace has a cascade control system, whereby a "bath" controller (sensing the temperature of the molten metal) acts as the primary, and a "crown" controller (sensing the temperature of the refractory wall and roof) acts as the secondary. The burner's heat output is a direct function of air flow through it; therefore, a wider-open air valve causes a more intense fire from the burner:



Sometimes a thick layer of "slag" covers the surface of the metal, impeding heat transfer from the burner flame to the molten metal bath. The bath controller, sensing low metal temperature, sends an ever-increasing setpoint to the crown controller, raising the air temperature inside the furnace to high levels, which then shortens the life of the refractory brick.

Can you think of a solution to this problem, whereby the secondary control loop won't be driven into saturation in the event of slag on the metal surface?

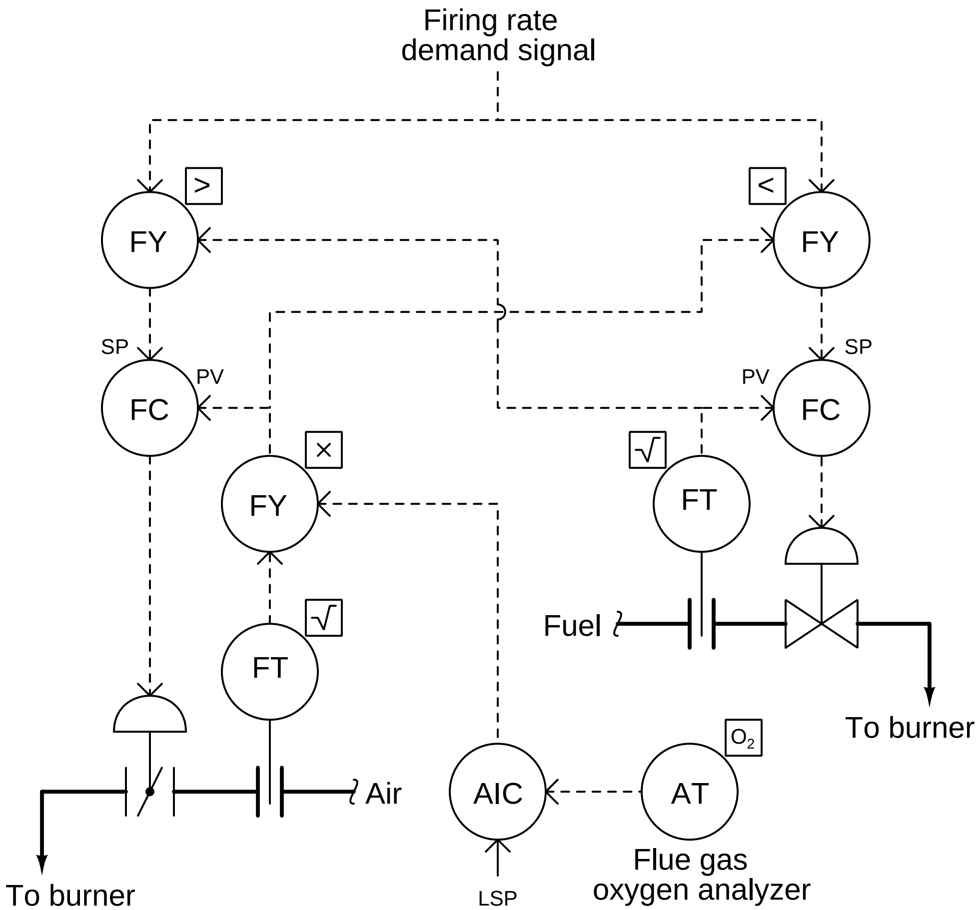
Suggestions for Socratic discussion

- Why do you suppose this furnace is equipped with a cascade control system at all? What would be wrong with just a simple single-loop PID control of metal temperature?

file i01826

Question 27

Large combustion furnaces and steam boilers optimize their energy efficiency by admitting just enough air to support complete combustion of the fuel, and no more. Excess air does nothing to a fire but carry away valuable heat out the flue (exhaust stack). In order to control the amount of air mixed with fuel in the combustion chamber, these furnaces and boilers use an *oxygen trim control system* that monitors oxygen content in the flue and adjusts the air-to-fuel ratio accordingly. The following oxygen trim control system uses cross-limiting of air and fuel flow rates for safety:



Answer the following questions about this control system:

- What is the purpose of the two select relays?
- Do the flow controllers need to be direct-acting or reverse-acting, assuming signal-to-open control valves?
- Does the oxygen controller (AIC) need to be direct-acting or reverse-acting?
- What will happen if the oxygen analyzer fails in a state with the output saturated at 100% (maximum oxygen)?

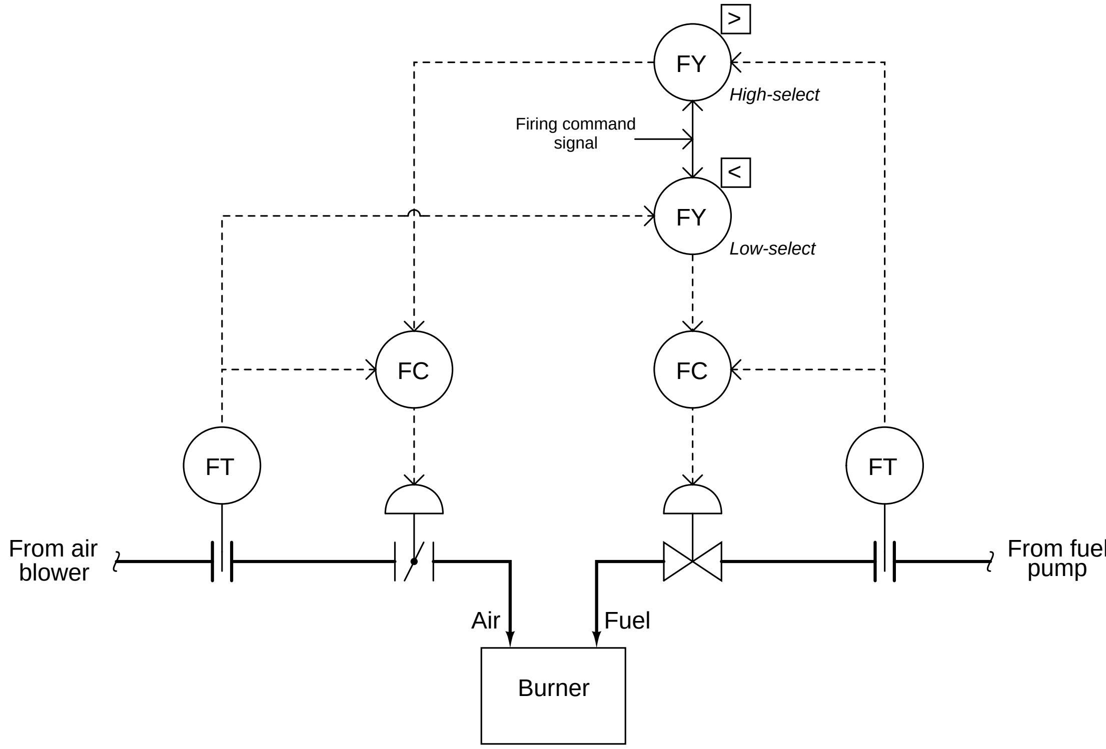
Suggestions for Socratic discussion

- It is usually a bad idea to include a multiplier relay inside a control loop, such as shown in this oxygen trim control system. Placing a multiplier function inside of a control loop changes the gain of that loop, which can lead to instability. However, it is a reasonably safe thing to do here, inside the air flow control loop. Explain why.

file i01829

Question 28

Examine this cross-limited air/fuel control system, then determine how it will respond to the following faults (assuming a constant 50% firing command signal):



- Air flow transmitter fails high
- Fuel flow transmitter fails high
- Air valve fails shut
- Fuel valve fails shut

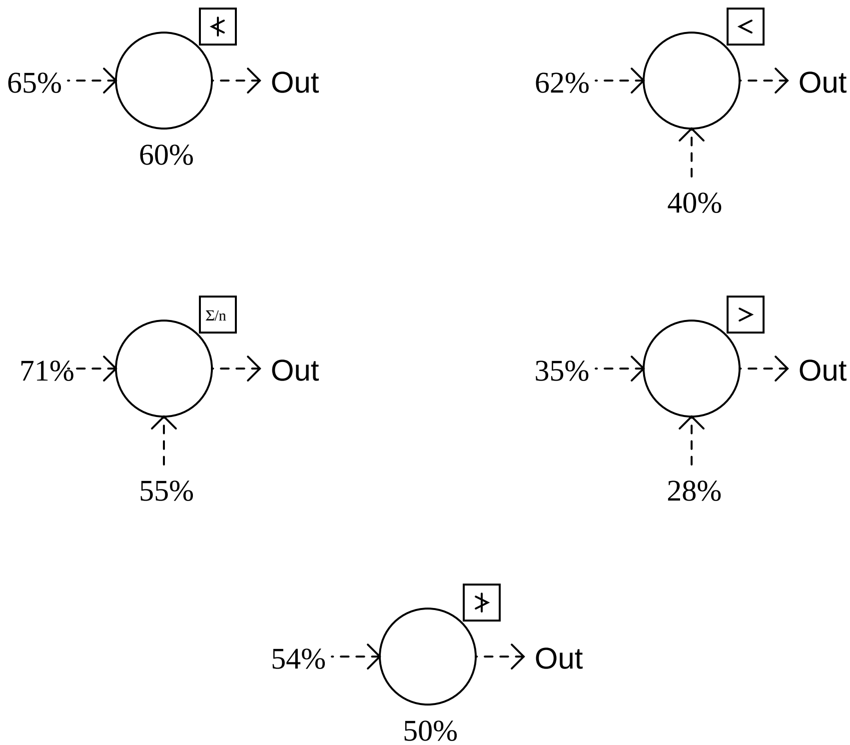
Suggestions for Socratic discussion

- Perhaps the most important question to ask yourself when analyzing the effects of these faults is *how to properly track all the signal values when performing each "thought experiment"*. Identify ways you use to keep track of all the signal values as you analyze various faults in this system.
- How will this control system's operation be affected if the fuel flow transmitter is miscalibrated so that it registers less fuel than is actually flowing through it? Will it make a difference if this calibration error is a zero shift or a span shift?
- How will this control system's operation be affected if the air valve is miscalibrated so that it is always further open than it is supposed to be? Will it make a difference if this calibration error is a zero shift or a span shift?
- Suppose you are asked to make the burner run slightly *richer* than it does right now, but without adding any function blocks to the control strategy. Identify at least two different ways to accomplish this goal.

file i01731

Question 29

Determine the output signal magnitude for each computational relay shown:



Suggestions for Socratic discussion

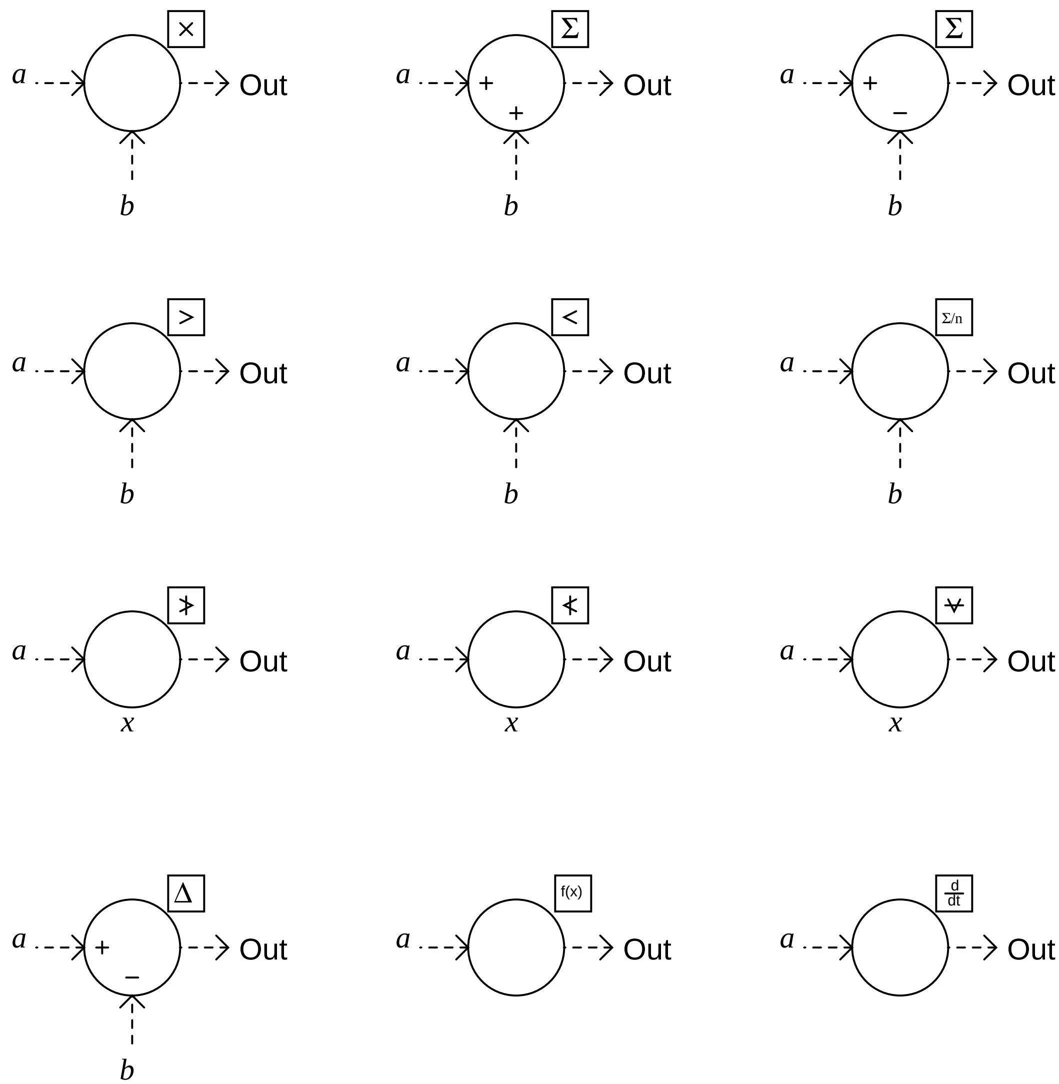
- A common problem encountered by students is mistaking the functions of *high limit* and *high select*, and also *low limit* and *low select*. Describe a way to avoid this confusion.

  file i01782

Question 30

In measurement and control systems, there is often a need to modify or select instrumentation signals. Devices designed to perform calculations on instrument signals are called *computing relays*, and digital algorithms inside control computers designed with the same tasks in mind are called *function blocks*.

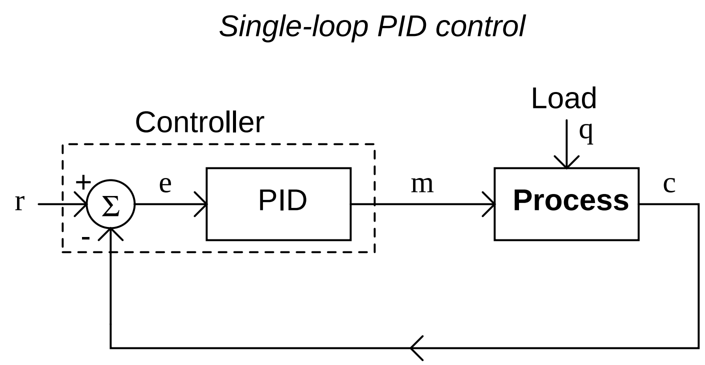
Identify the functions of each relay (or function block) shown here:



file i01781

Question 31

Process control engineers often document control strategies by using *block diagrams* to symbolize a control loop. In these diagrams, both instruments and process elements are represented by rectangular blocks, like this:

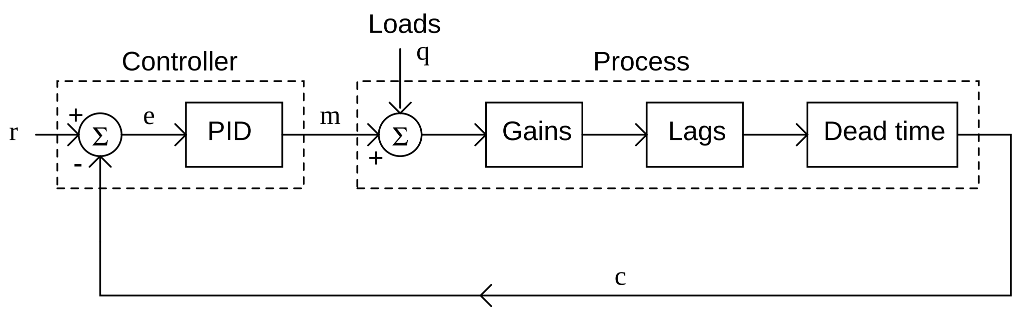


Describe what each of the variables (r, e, m, q, and c) represent in this diagram, as well as the circle with the letter "sigma" (Σ) inside of it.

file i01772

Question 32

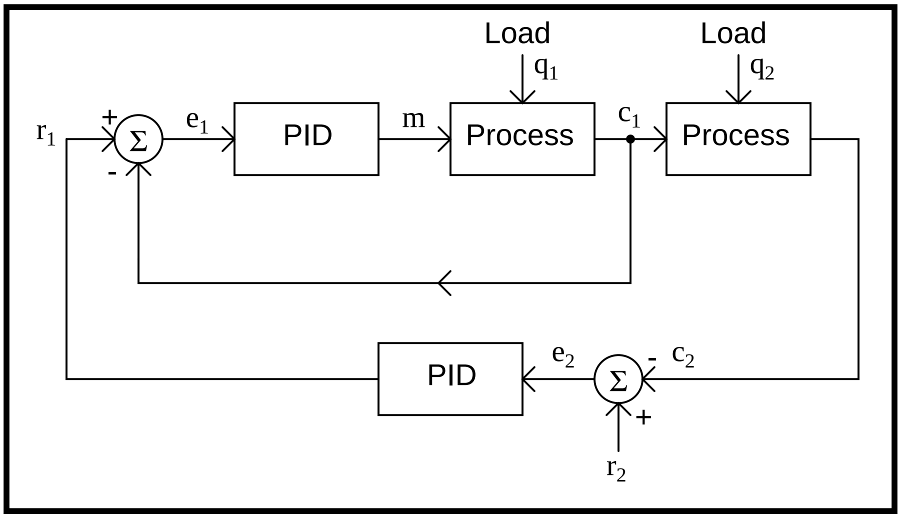
What is being represented in the following block diagram?

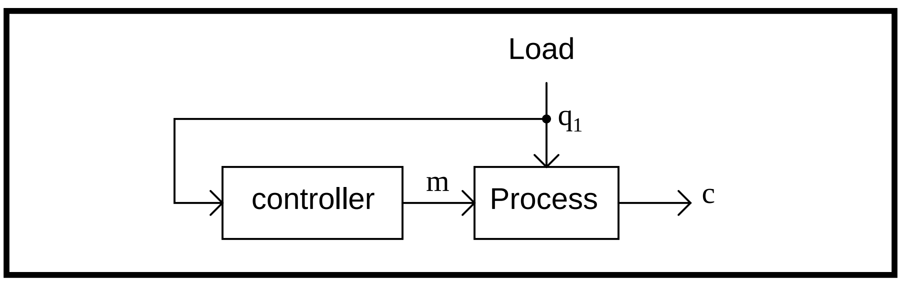


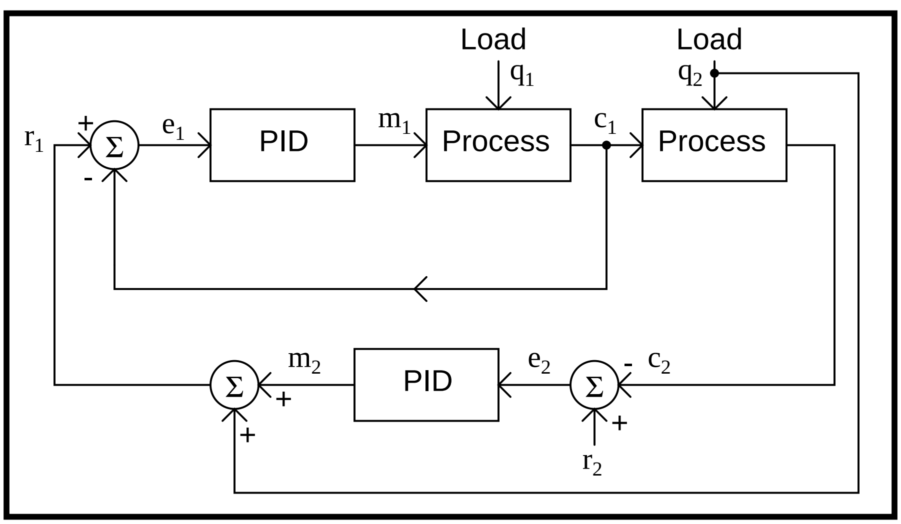
file i01774

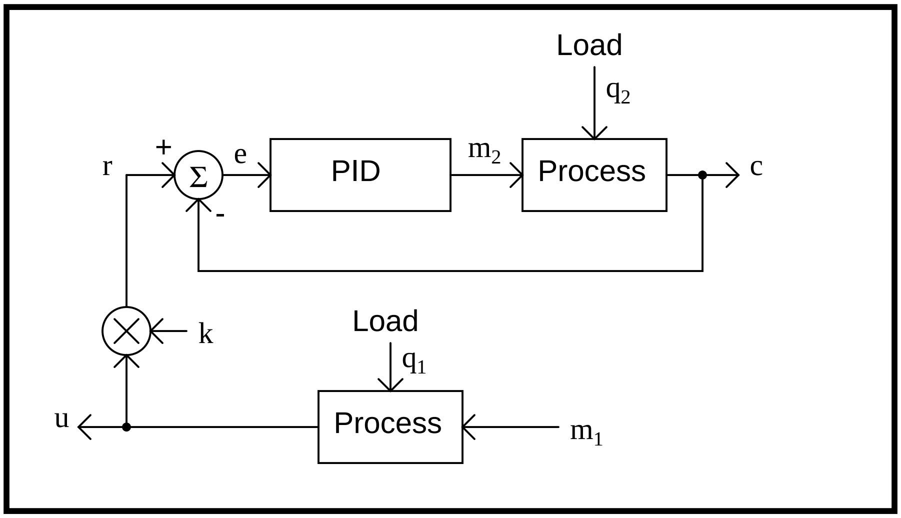
Question 33

Identify the control strategy represented in each of these block diagrams:









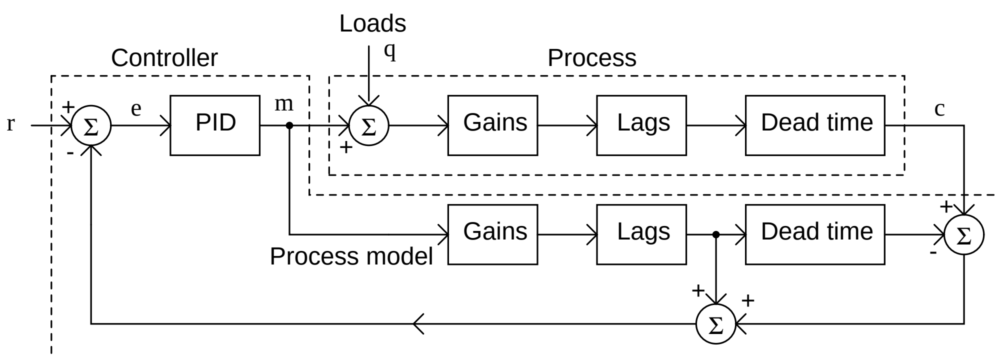
file i01773

Question 34

If the gain, lag time, and dead time of a process are known, it is possible to program a computer to mimic these dynamic elements in mathematical form. Such a program is called a *model* of the process.

Models can be very helpful for advanced control strategies. Take for instance this strategy, known as the *Smith Predictor*: its purpose is to "cancel out" dead time in a process control loop, so that setpoint changes may be made without overshoot or long response lags.

The Smith Predictor control strategy

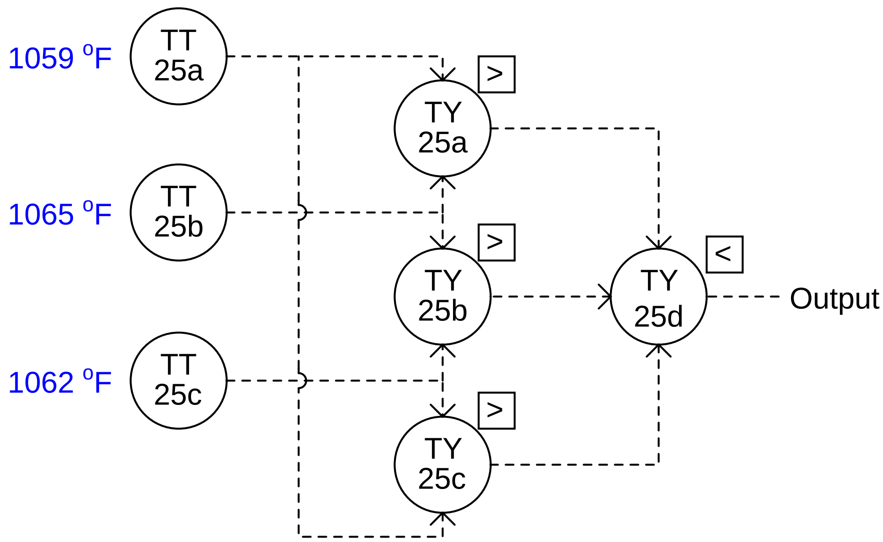


Explain how the Smith Predictor strategy would respond to a sudden increase in setpoint (r).

file i01775

Question 35

This set of high- and low-select relays outputs a single temperature measurement signal from three transmitter inputs:

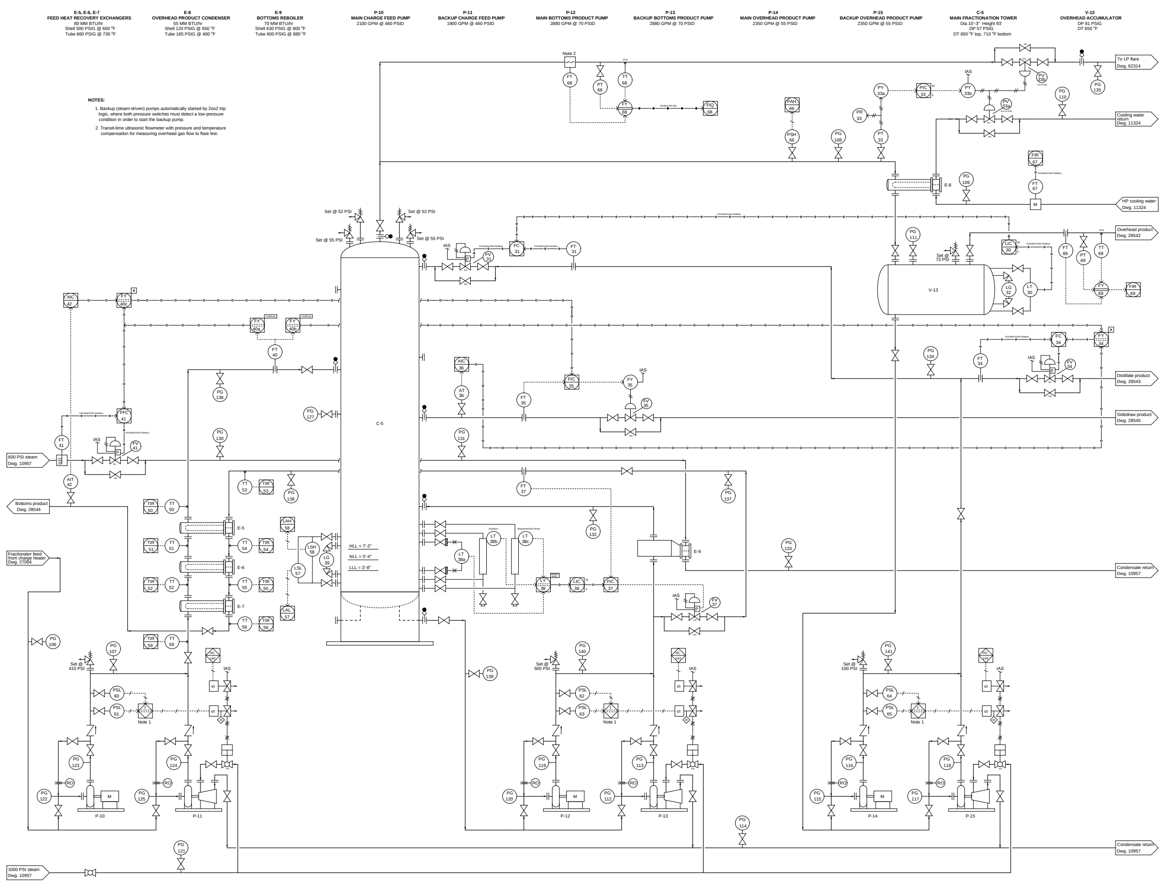


Calculate the output of this system given the temperature measurements shown in the diagram. Also, calculate the output value if the lower relay (TY-25c) fails with an output equivalent to 500 ^{o}F.

file i03850

Question 36

Examine the main fractionator level control system (at the bottom of the fractionator tower) and explain why three different types of level transmitter are used:

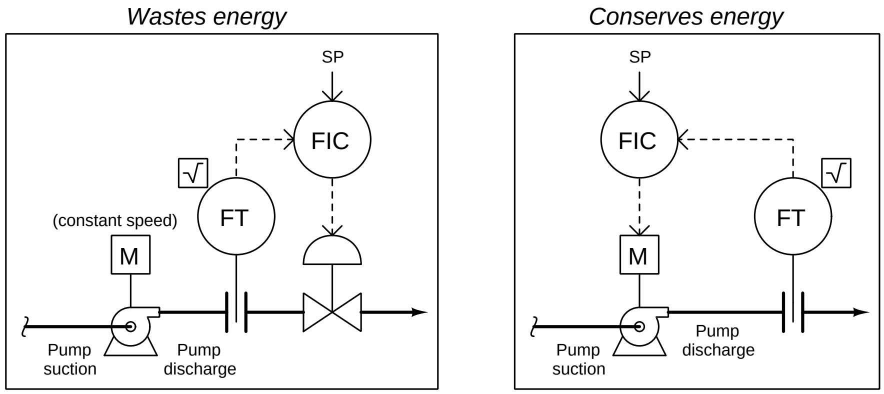


Also, if you have studied level transmitter technologies, identify how we might change *one* of those level transmitter types to achieve better reliability. As it stands right now, two of those transmitters may be "fooled" by one change in process liquid characteristics, which means there exists the potential for a "common-cause" failure in this measurement system.

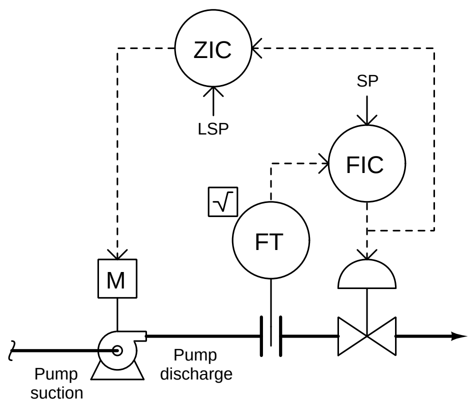
file i03364

Question 37

One way to decrease the amount of energy consumed in the pumping of liquids is to use a variable-speed electric motor to turn the pump instead of turning the pump full speed and throttling with a control valve:



A significant advantage to using a control valve to regulate liquid flow is faster speed of response. If the process requires fast flow-control response, there may be no option but to use a control valve to throttle flow, which will inevitably waste energy. We may realize the best of both worlds by using this hybrid control strategy:



The ZIC (Position Indicating Controller) varies the pump motor speed to achieve a particular stem position on the control valve. The local setpoint (LSP) for this position controller is usually set >75%. Explain how this system works to conserve energy, and also which direction of action each controller must have (direct or reverse).

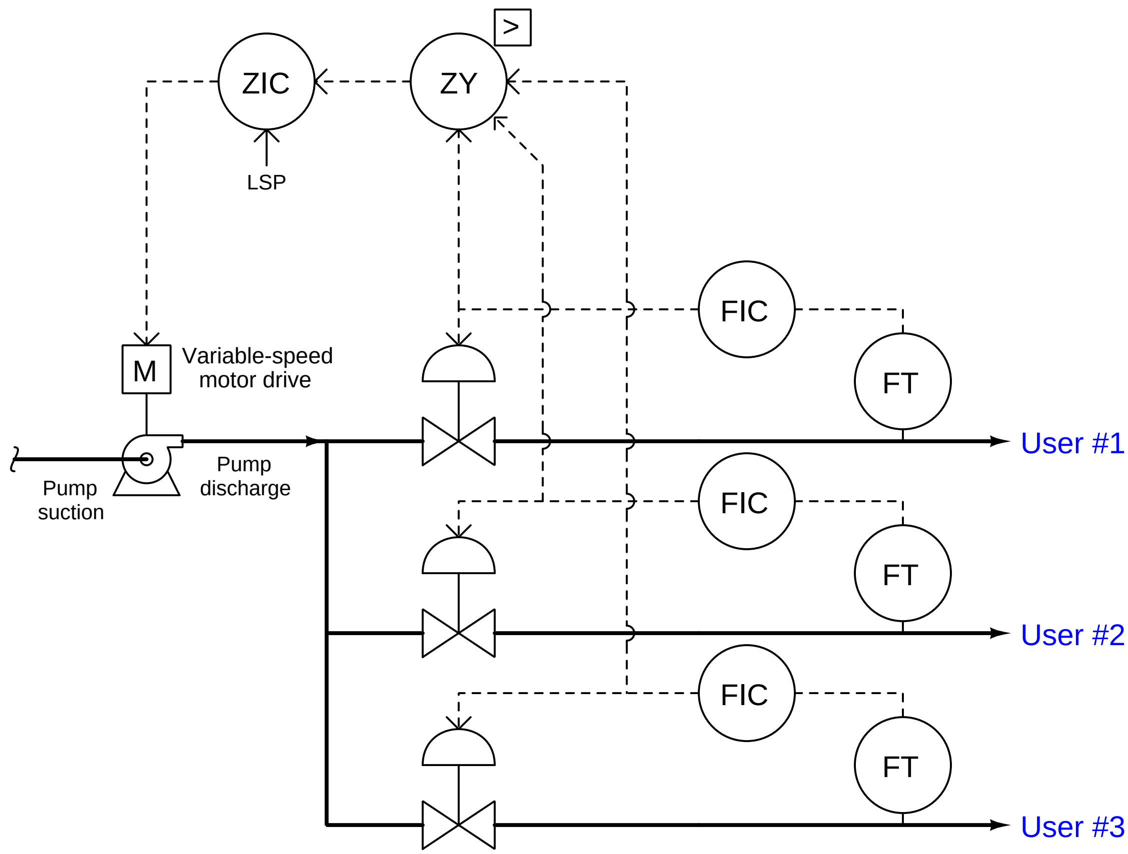
Suggestions for Socratic discussion

- A useful analytical technique for any complex control system is to annotate the diagram with "+" and "−" symbols at the instrument bubble inputs, designating "noninverting" and "inverting" characteristics, respectively. Show how this helps you track of all directions of action, making it easier to figure out how the control system responds to changes.
- For those who have studied PID control, explain why one of these two controllers (FIC or ZIC) needs to be tuned much faster than the other to avoid instability. Identify the controller which needs to be "faster," (more aggressive integral action), and explain why.

file i01783

Question 38

When multiple control valves throttle fluid flow to different points of use from the discharge of a common pump, a control system optimizing pump speed (for minimal energy consumption) needs to incorporate a computational relay, or function block, as shown here:



Explain how this control system works to minimize pumping energy, and what the specific purpose of the relay is. Also, identify the actions (direct or reverse) of each controller in this system assuming signal-to-open control valves and a signal-to-speed motor drive.

Suggestions for Socratic discussion

- A useful analytical technique for any complex control system is to annotate the diagram with "+" and "−" symbols at the instrument bubble inputs, designating "noninverting" and "inverting" characteristics, respectively. Show how this helps you track of all directions of action, making it easier to figure out how the control system responds to changes.
- Explain what would happen if one of the control valves failed in its wide-open position, despite the efforts of its flow controller to limit flow.

file i01785

Question 39

Question 40

Question 41

Read and outline the "Override Controls" subsection of the "Limit, Selector, and Override Controls" section of the "Basic Process Control Strategies" chapter in your *Lessons In Industrial Instrumentation* textbook.

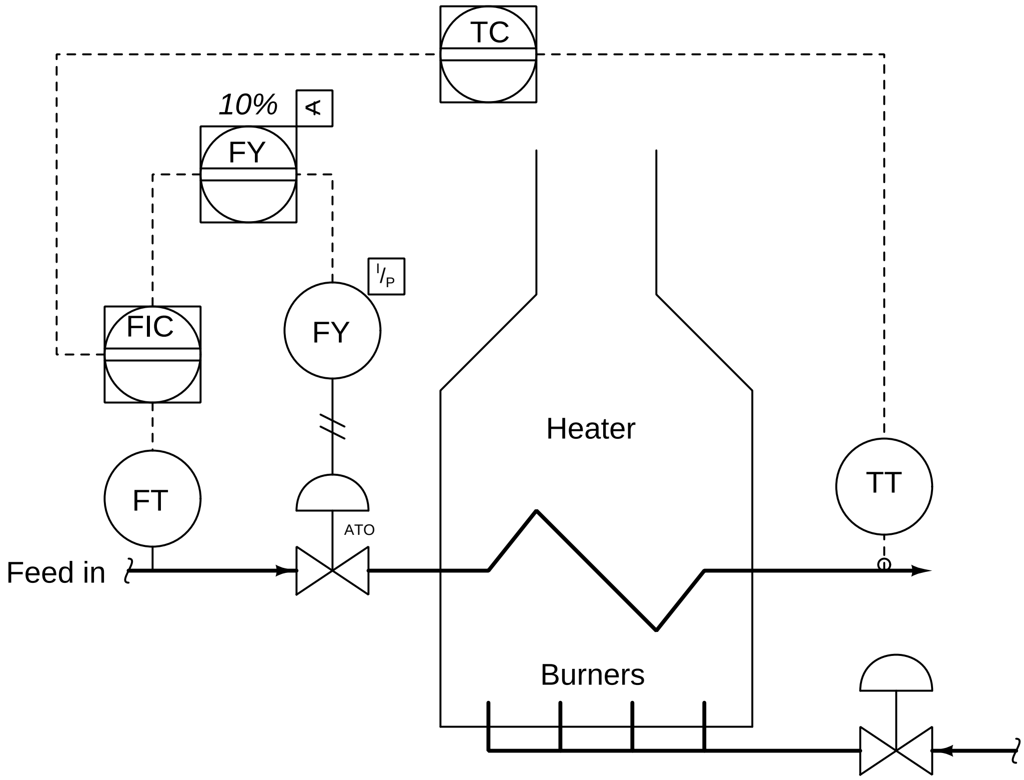
After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

(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 i02473

Question 42

Examine the P&ID for this crude oil heater – one of the first stages of crude oil distillation where the oil is split up into its constituent components – then answer the following questions:



- Explain how this control system is supposed to function, with two transmitters, two controllers, and only one control valve.
- Identify the proper action of the FIC (*direct* or *reverse*).
- The low-limit function block (FY) located between the FIC and the flow-control valve is supposed to function as a *minimum flow* override to the FIC. Explain the purpose in having such an override in this heater control system.
- How will the control system react to an operator opening up the fuel gas valve further?
- Identify at least one fault that could cause the flow control valve to shut fully despite the action of the low-limit relay.

Suggestions for Socratic discussion

- A useful analytical technique for any complex control system is to annotate the diagram with "+" and "−" symbols at the instrument bubble inputs, designating "noninverting" and "inverting" characteristics, respectively. Show how this helps you track of all directions of action, making it easier to figure out how the control system responds to changes.
- Could the low-limit function be relocated to a place between the two controllers, so as to limit the cascaded setpoint signal to some minimum value and thereby achieve the same effect? Explain why or why not.

file i02503

Question 43

Read and outline the "Determining The Design Purpose Of Override Controls" subsection of the "Techniques For Analyzing Control Strategies" section of the "Basic Process Control Strategies" chapter in your *Lessons In Industrial Instrumentation* textbook.

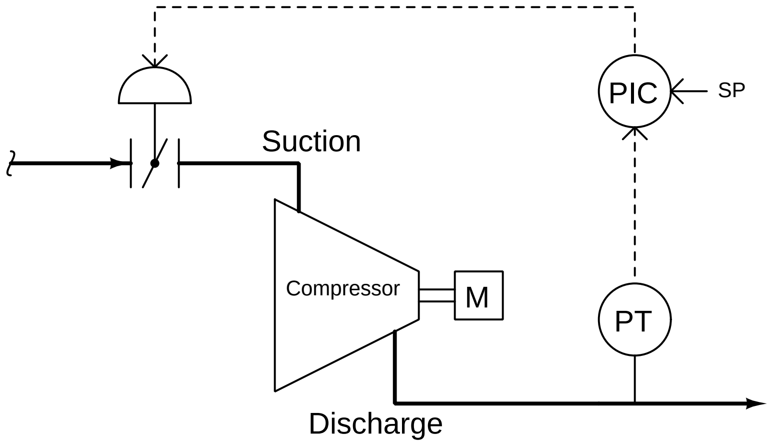
After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

(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 i02558

Question 44

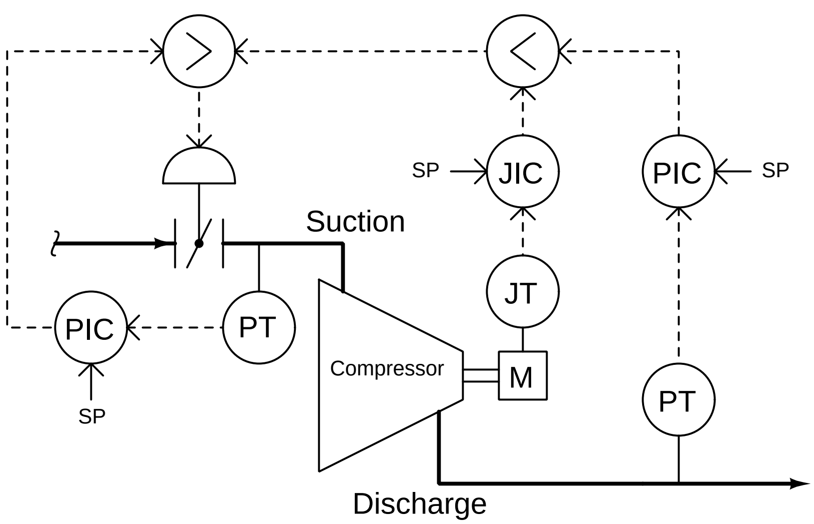
Discharge pressure for a compressor may be controlled by throttling the suction line, like this:



Limits must be placed on this pressure control system, however, to avoid damaging the compressor and/or the driving motor under certain operating conditions. In conditions where there is low discharge flow (i.e. reduced demand for compressed gas) and the pressure controller tries to keep discharge pressure from rising too high by closing off the suction valve, suction pressure may drop below atmospheric, causing "gland sealing" oil to be sucked into the compressor. This can cause damage to the compressor, so a vacuum condition on the suction line should be avoided. However, the pressure controller knows nothing of the suction line pressure, and so cannot police itself from entering this range of operation.

Conversely, when gas demand is high and the pressure controller opens up the suction valve wide to maintain adequate discharge pressure, the electric motor may become overloaded. Once again, this can cause damage, and once again the pressure controller is ignorant of motor load and so cannot prevent it from happening.

With the addition of two more controllers and a couple of select relays, though, both problems may be avoided. This is called *override control*:



Identify the proper action (direct or reverse) of each controller, and explain how this override control system functions.

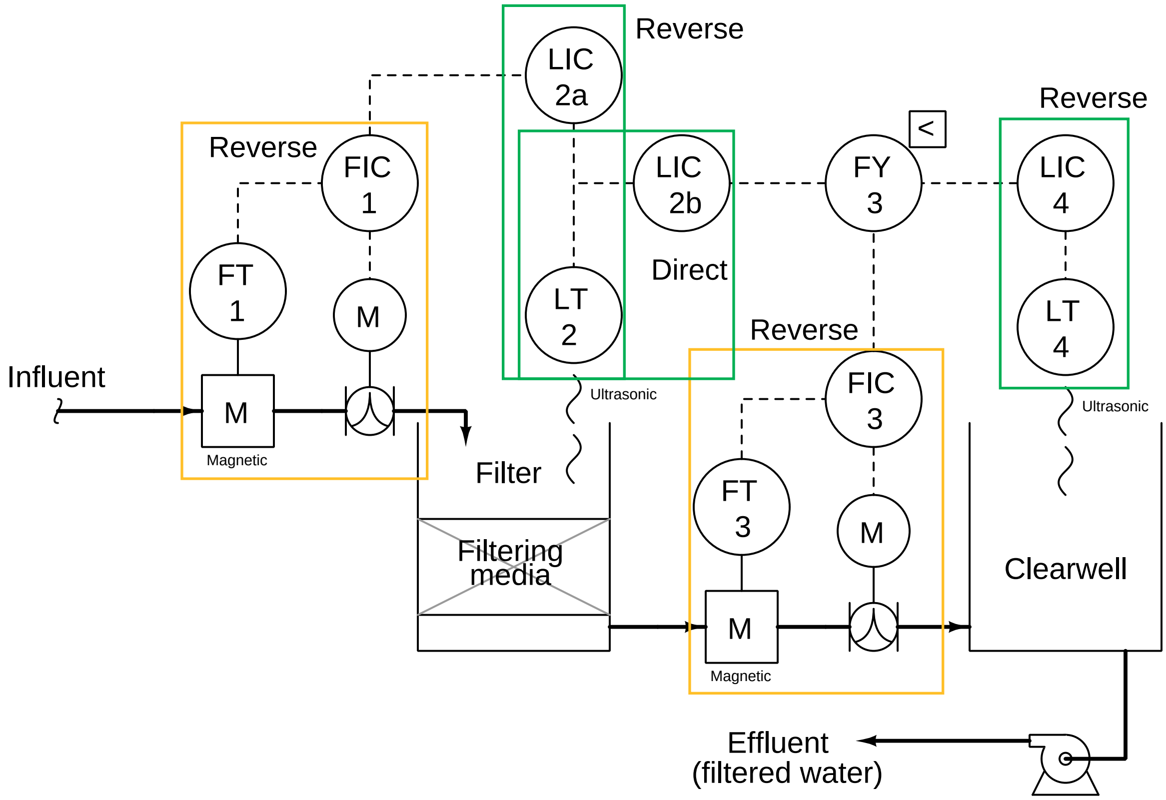
Suggestions for Socratic discussion

- Explain what will happen in this system if the suction pressure transmitter fails with a low signal (indicating maximum suction).
- Explain what will happen in this system if the power transmitter fails with a low signal (indicating an idling motor).
- Explain what will happen in this system if the discharge pressure transmitter fails with a low signal (indicating low output pressure).

file i01786

Question 45

Examine this water filter control system, then answer the following questions:



Also, determine the following:

- Identify all primary and secondary (cascaded) loops.
- The necessary control actions (direct/reverse) for each controller, assuming direct-acting transmitters and signal-to-open control valve actuators.
- What will happen to the filter water level if the influent supply suddenly shuts off?
- What will happen to the clearwell reservoir water level if the influent supply suddenly shuts off?

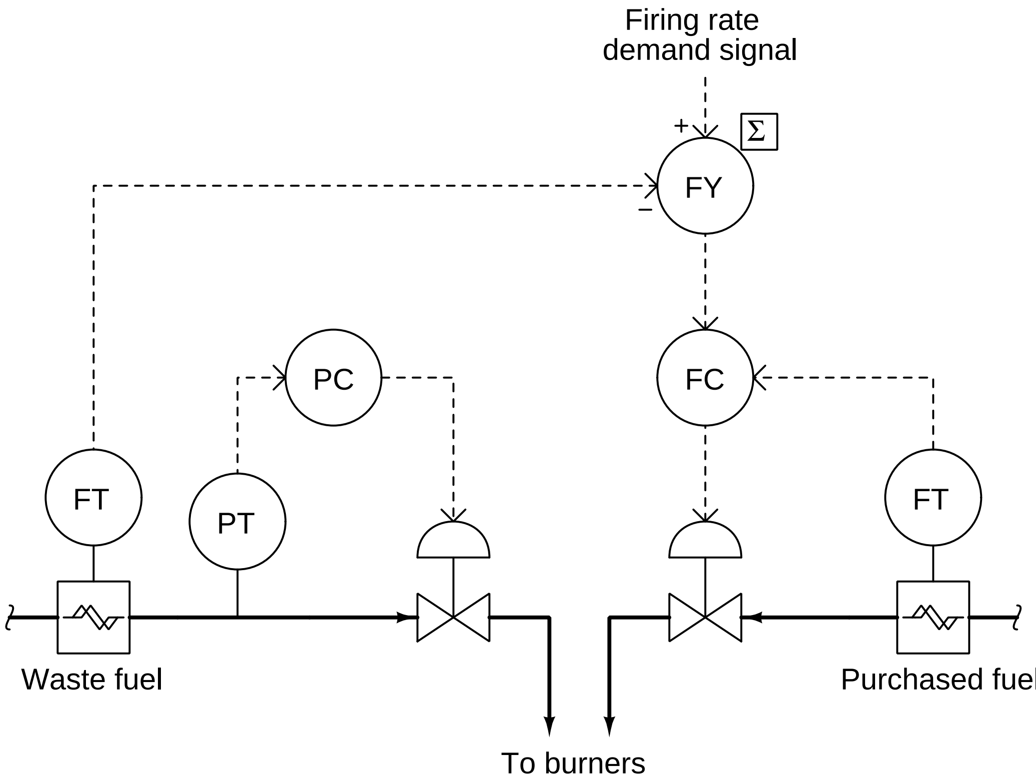
Suggestions for Socratic discussion

- What purpose is served by the override control in this system?
- Explain what will happen in this system if the filter level transmitter fails with a low signal.
- Explain what will happen in this system if the filter level transmitter fails with a high signal.
- Explain what will happen in this system if the clearwell level transmitter fails with a low signal.
- Explain what will happen in this system if the clearwell level transmitter fails with a high signal.
- For those who have studied PID tuning, what PID tuning parameters (qualitative) would you recommend for each controller in this system?

file i01813

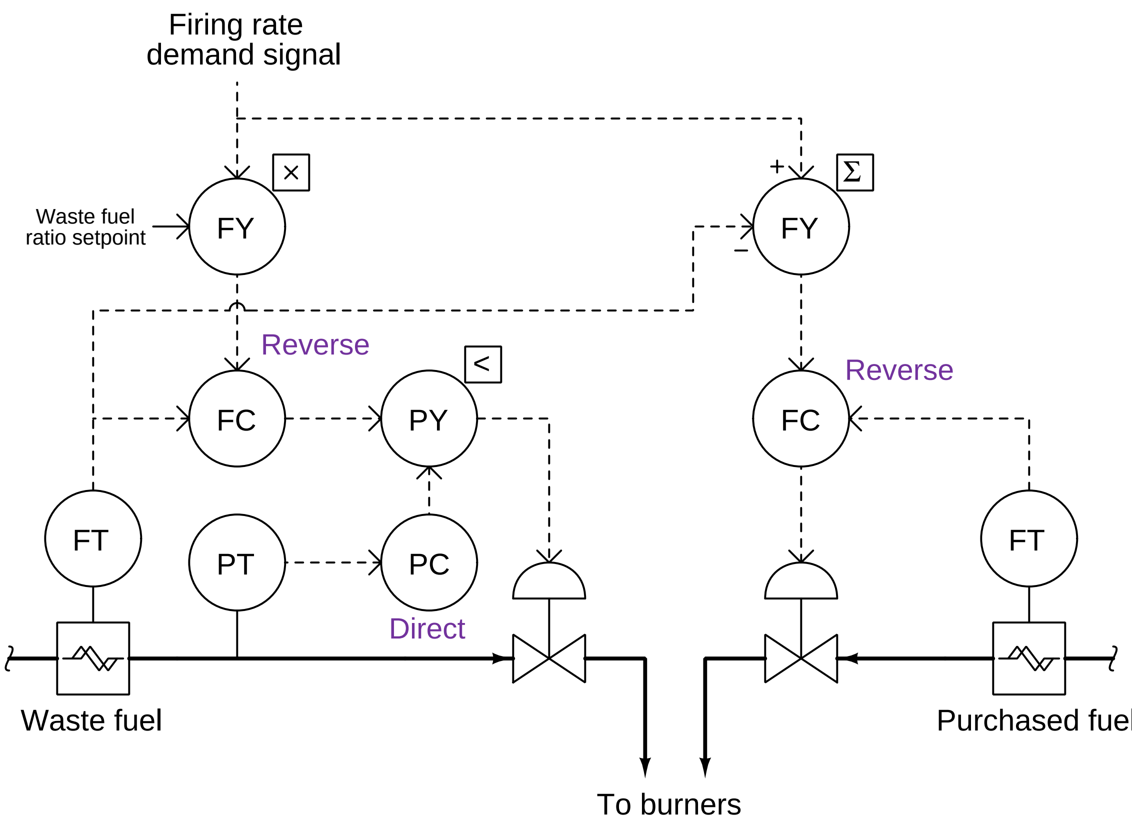
Question 46

Many industries produce flammable waste products that may be used as fuel in furnaces, steam boilers, and process heaters. This "waste fuel" enters into a common piping system called a *header*. In this system the "waste fuel" is a gas, and we control the pressure of this gas in the header by admitting it into a burner as fuel, essentially using the burner as the final component of a pressure relief system. A control system balances the flow of waste fuel with supplemental purchased fuel to meet the heating needs of the combustion process:



However, this control strategy has a problem: what happens when the waste gas header pressure happens to be excessive, and the pressure controller dumps more waste fuel to the burner than what is needed for combustion purposes? Obviously, this would overheat the process, sacrificing temperature control for waste gas header pressure control.

Since good combustion temperature control is more important than good waste gas header pressure control, the following modification is made to the control system. Explain how it works:



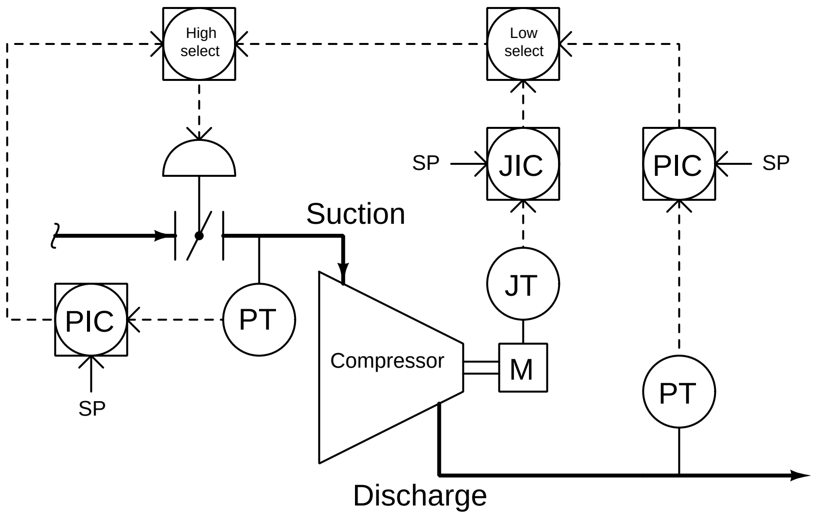
Suggestions for Socratic discussion

- A useful analytical technique for any complex control system is to annotate the diagram with "+" and "−" symbols at the instrument bubble inputs, designating "noninverting" and "inverting" characteristics, respectively. Show how this helps you track of all directions of action, making it easier to figure out how the control system responds to changes.
- Explain what will happen in this system if the waste fuel flow transmitter fails with a low signal.
- Explain what will happen in this system if the waste fuel flow transmitter fails with a high signal.
- Explain what will happen in this system if the waste fuel header pressure transmitter fails with a low signal.
- Explain what will happen in this system if the waste fuel header pressure transmitter fails with a high signal.
- Explain what will happen in this system if the purchased fuel flow transmitter fails with a low signal.
- Explain what will happen in this system if the purchased fuel flow transmitter fails with a high signal.
- Identify at least one instrument fault that would result in the burner running at an insufficient temperature.
- Identify at least one instrument fault that would result in the burner running at an excessive temperature.

file i01833

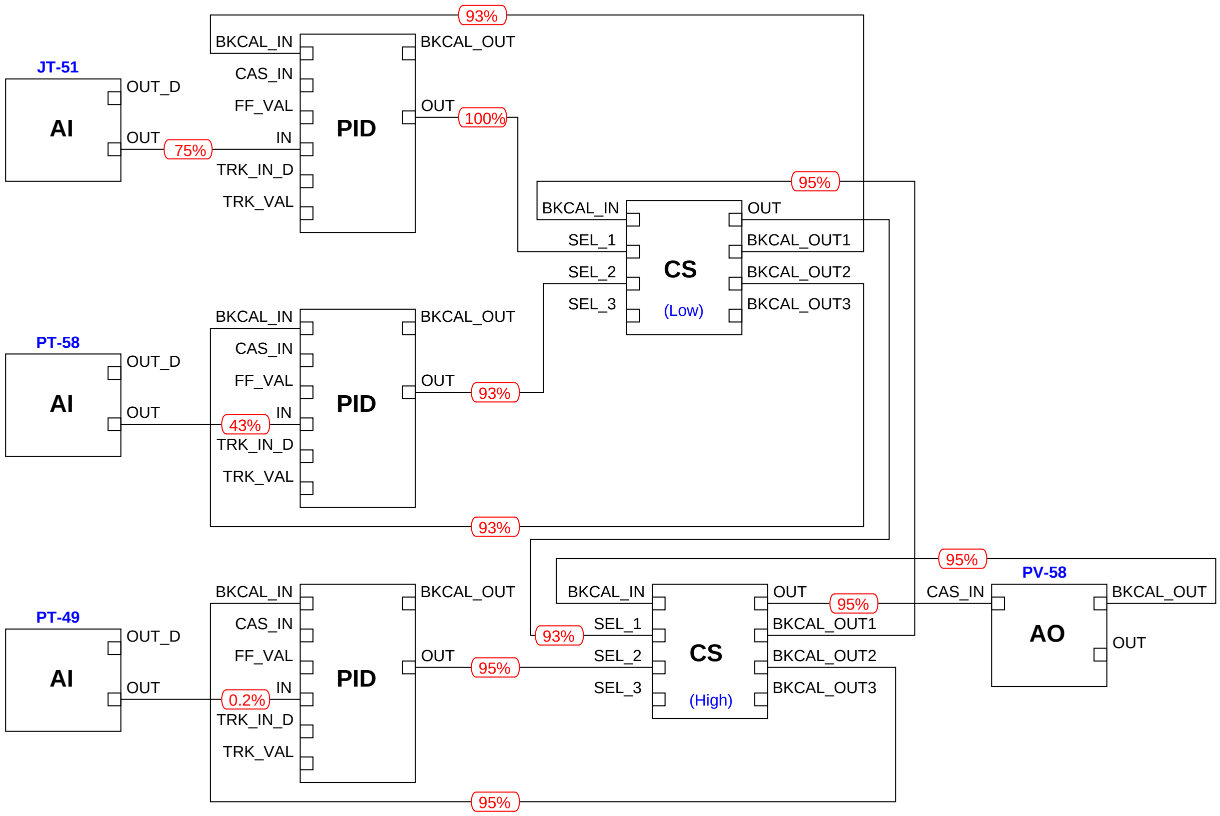
Question 47

This gas compressor is equipped with an override control system to ensure its suction line does not experience a vacuum, and that its drive motor does not become over-worked, as it attempts to maintain a constant discharge pressure:



Normally, control of the compressor's suction valve falls to the discharge pressure controller. In the event that the motor power exceeds a pre-determined setpoint, or the suction controller detects a vacuum, either one of these constraint controllers will override the discharge pressure controller to maintain safe compressor operation at the expense of desired output pressure.

The control system for this compressor is a DCS, programmed using *function blocks*. The function block diagram for this control scheme appears here, complete with "live" values showing the status of various signals at one point in time as the compressor is running:



Based on what you see here in this diagram, determine which controller is actually in control of the suction valve, and why. Also, explain why all the "back calculation" signal lines are absolutely necessary for an override control system such as this to transition smoothly between override states (i.e. switch "bumplessly" from one selected controller to another).

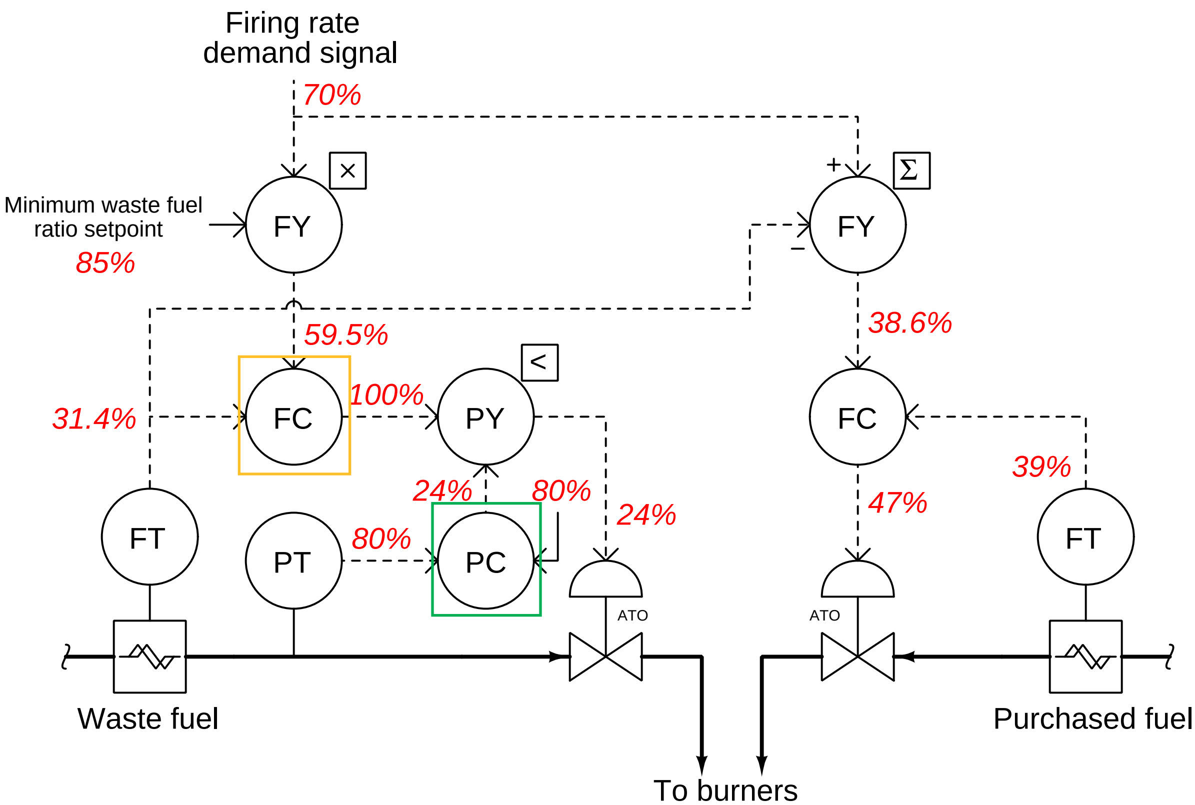
Suggestions for Socratic discussion

- Can an instrument fault in this system shut the compressor off? Why or why not?
- Explain the purpose of the BKCAL signals in this system.
- If this control strategy were implemented in FOUNDATION Fieldbus, where would you suggest locating the PID function blocks, and why?

file i02509

Question 48

This control system controls "waste" fuel gas header pressure by venting gas into the burner. It also limits the flow of "waste" gas when excessive, through the use of an override control strategy. The red-colored, italicized numbers indicate "live" signal values at one point in time:



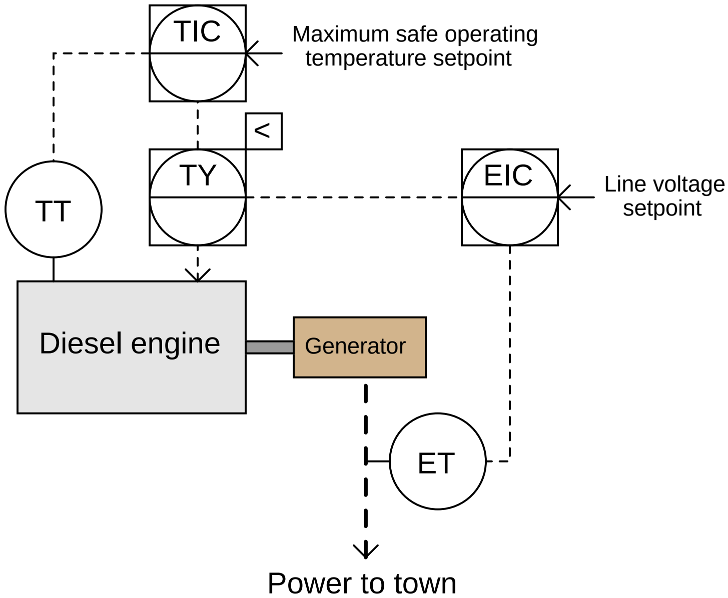
Answer the following questions, based on what you see in this diagram:

- Which waste gas controller is in control right now, and which one is being overridden?
- Does there appear to be a surplus of waste fuel gas available to this system right now, or a deficiency?
- Identify at least two changes that could take place in this process to switch control from one waste gas controller to the other.

file i02460

Question 49

This diesel engine-generator system provides electricity to power a small town during emergencies. The engine, however, is not powerful enough to supply the maximum electrical load of the town, and may overheat if pressed into continuous service under maximum-load conditions:



Examine this control system diagram, then explain in your own words how it is supposed to work. Propose a "thought experiment" where you can explore the system's operation under normal as well as overload conditions.

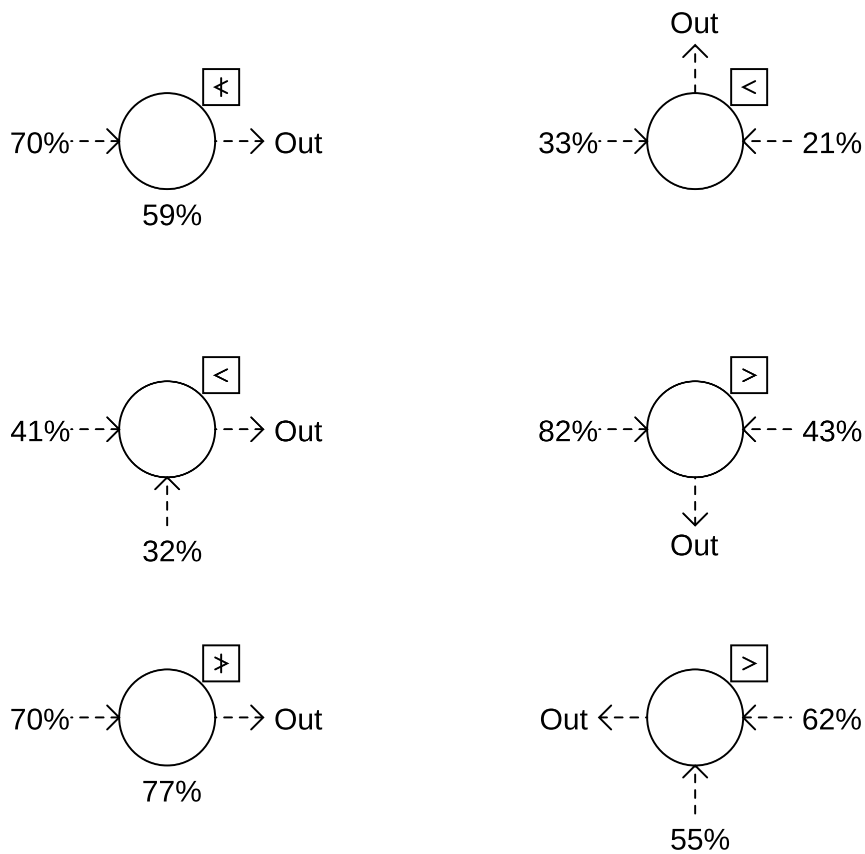
Suggestions for Socratic discussion

- A problem-solving technique useful for analyzing control systems is to mark the PV and SP inputs of all controllers with "+" and "−" symbols, rather than merely label each controller as "direct" or "reverse" action. Apply this technique to the control strategy shown here, identifying which controller input(s) should be labeled "+" and which controller input(s) should be labeled "−".
- Identify at least one instrument fault that would essentially shut the generator down, calling for zero output power from the diesel engine.

file i02427

Question 50

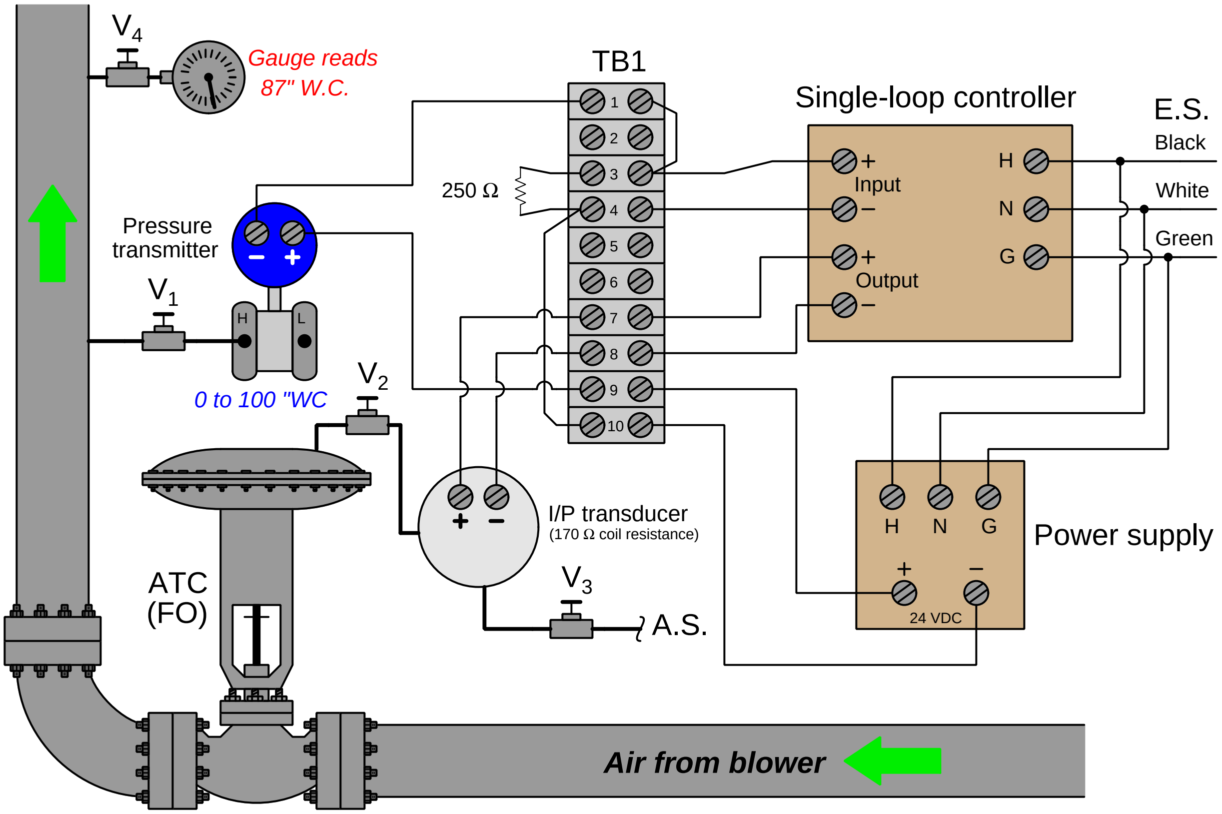
Determine the output signal magnitude for each computational relay shown:



file i03293

Question 51

This single-loop control system has a problem: the pressure indicated by the gauge is substantially greater than the setpoint value shown on the digital loop controller's display (50 inches W.C.).



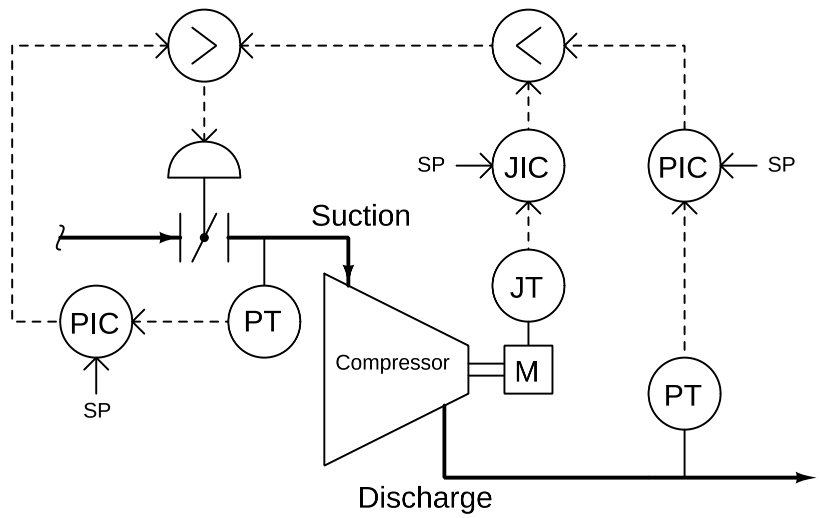
Determine the diagnostic value of each of the following tests. Assume only one fault in the system, including any single component or any single wire/cable/tube connecting components together. If a proposed test could provide new information to help you identify the location and/or nature of the one fault, mark "yes." Otherwise, if a proposed test would not reveal anything relevant to identifying the fault (already discernible from the measurements and symptoms given so far), mark "no."

Diagnostic test	Yes	No
Measure AC line voltage		
Measure DC power supply output voltage		
Inspect PID tuning parameters in controller		
Check pressure transmitter calibration		
Measure transmitter current signal		
Put controller into manual mode and move valve		
Measure DC voltage between TB1-3 and TB1-4		
Measure DC voltage between TB1-7 and TB1-8		

file i02461

Question 52

This compressor control system uses a pressure transmitter and controller to regulate the discharge pressure to a constant setpoint, allowing either a power controller (JIC) or a suction pressure controller (PIC) to override. The power controller overrides the discharge pressure controller under conditions of high load, throttling back the suction valve to limit power. The suction pressure controller overrides them all under conditions of high inlet vacuum, opening the suction valve in order to ensure the compressor's gland seals are not ruined by excessive vacuum:

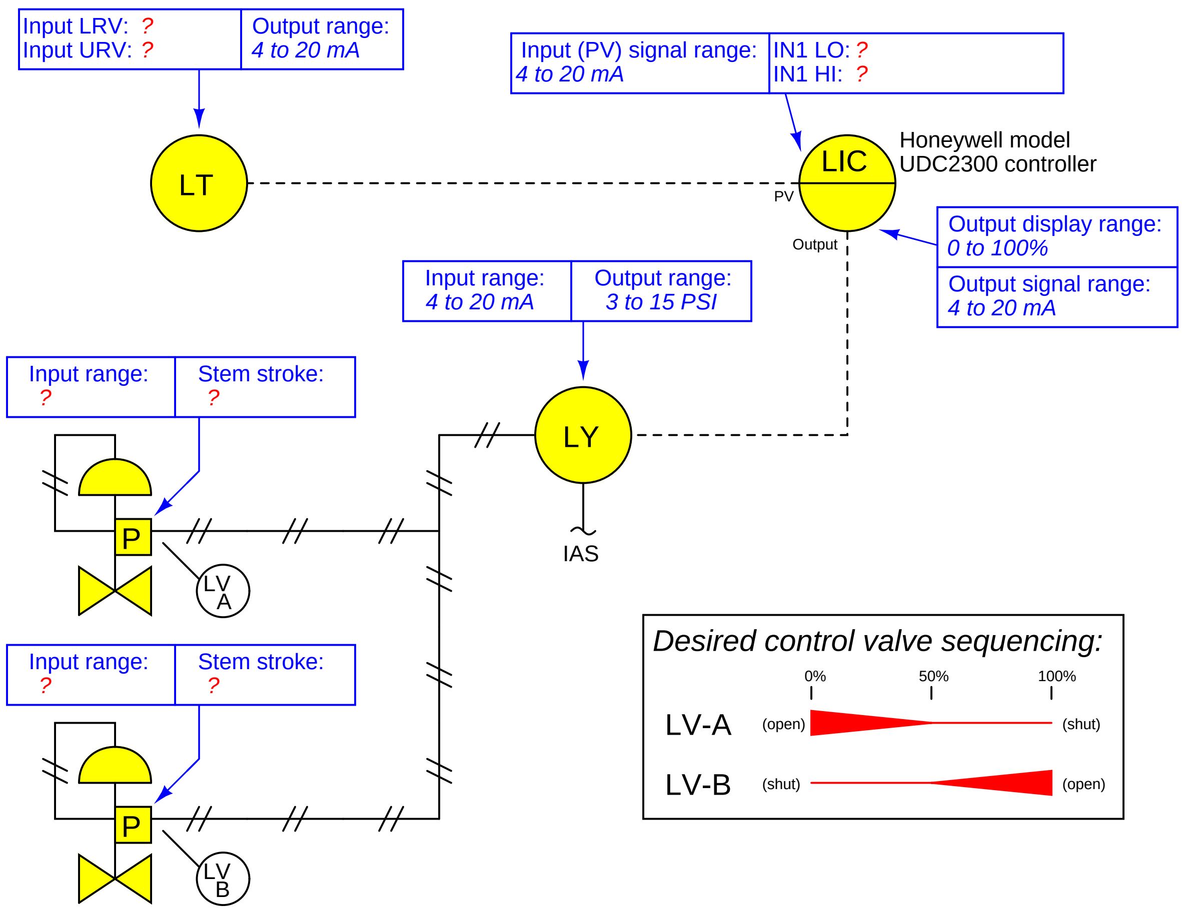


In the event of a high inlet vacuum condition simultaneous with a high load condition, the suction pressure controller will "win" by overriding the power controller. Alter this system so that the override priority is vice-versa: the power controller is able to override the suction pressure controller, yet the suction controller is still able to override the discharge controller.

file i00179

Question 53

Suppose you are asked to configure the instruments in this level control loop to sense and display process level over a range of 15 to 30 inches, with the loop controller actuating two split-ranged control valves in an exclusive sequence:



Write the proper range values inside the boxes near each instrument, showing the proper configuration for each instrument needed to achieve the desired result.

Suggestions for Socratic discussion

- Suppose the controller displayed a level of 21 when the actual process level was 24 inches. First, identify *two* possible locations in this loop for a calibration error that would account for this discrepancy. Then, assuming only one fault, explain how you could positively determine the location of this calibration error with a single diagnostic test.
- Suppose valve LV-A was 0% open and LV-B was 47% open when the controller output displayed 75%. First, identify *three* possible locations in this loop for a calibration error that would account for this discrepancy. Then, assuming only one fault, explain how you could positively determine the location of this calibration error with no more than two diagnostic tests.

file i02093

Question 54

Question 55

Question 56

Question 57

Question 58

Question 59

Question 60

Question 61

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.

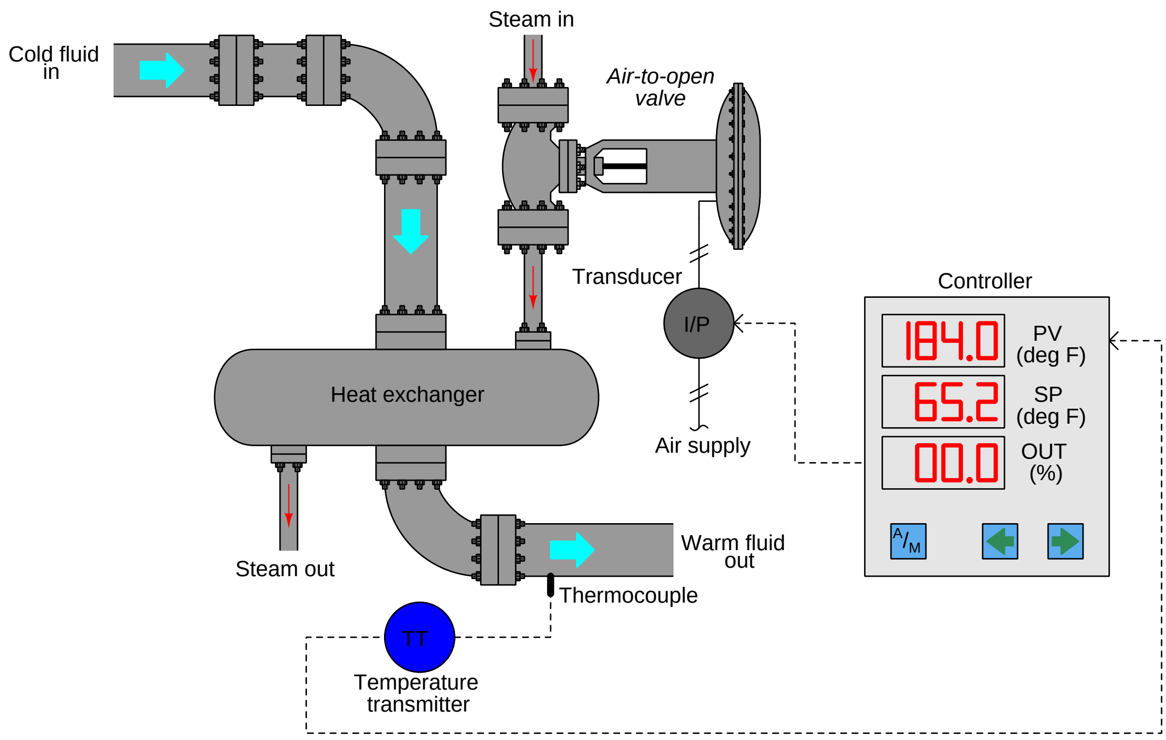
Note: your responses to these questions will not be shared in Socratic discussion with classmates without your consent. Feel free to maintain these as private notes between yourself and your instructor.

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 62

The following process has a problem, as evidenced by its controller faceplate display. The controller's PV display has been far above the SP value for quite some time:

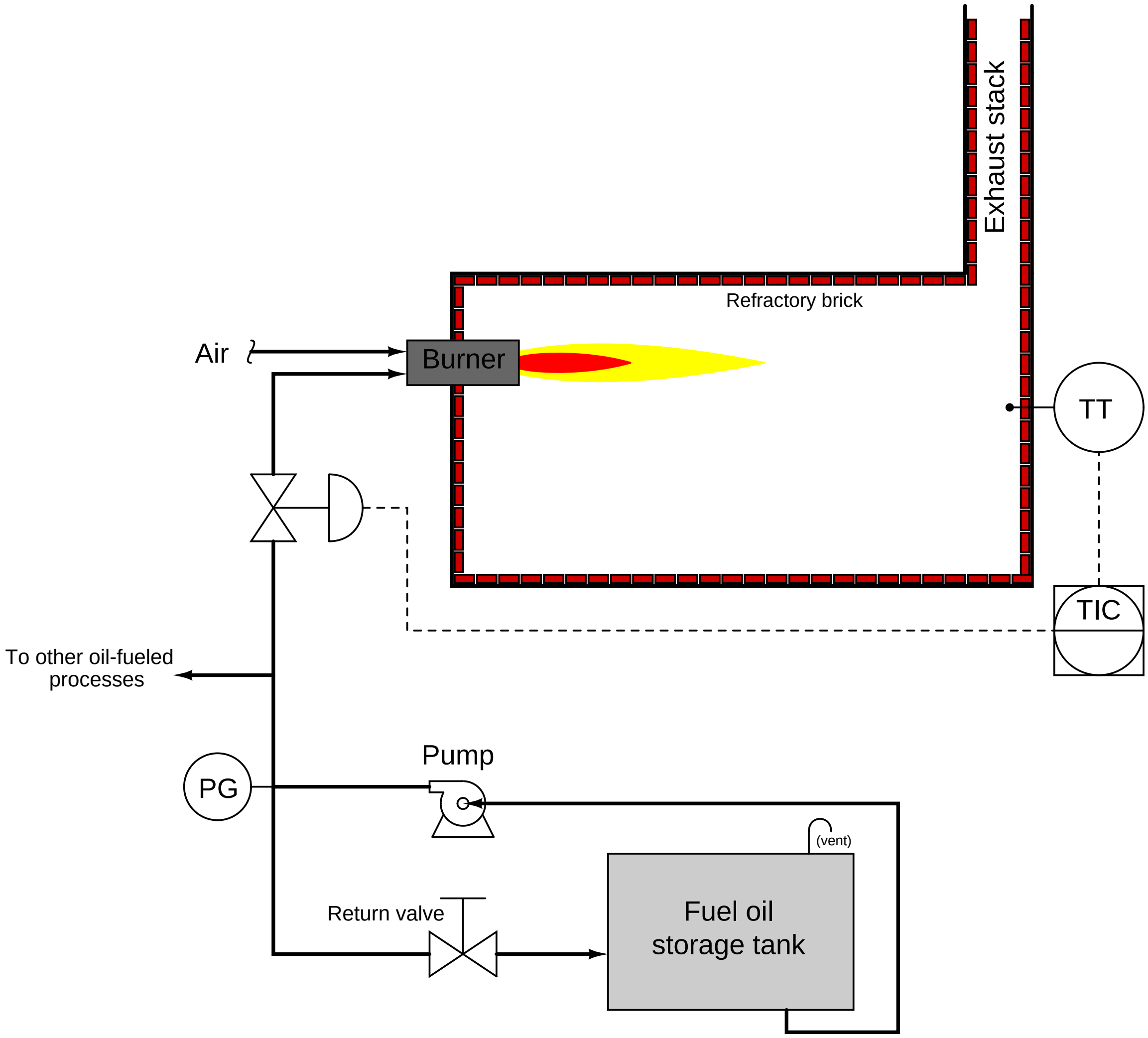


Determine the nature and location of the fault as best you can. If there are multiple possible problems, list them and then identify diagnostic tests you could use to eliminate possibilities from that list.

file i01186

Question 63

This furnace temperature control system does not work as well as operations personnel would like. The temperature drifts around, unable to hold steady at setpoint, despite many attempts to adjust the "tuning" parameters in the TIC (proportional, integral, and derivative):



Finally a fellow instrument technician happens to notice the pressure gauge (PG) at the fuel oil pump discharge indicate an unsteady pressure. Rather than hold constant at some value, the fuel oil pressure seems to rise and fall seemingly at random.

Design a solution for this temperature-stability problem using a *cascade* control strategy, explaining the reasoning behind your solution.

Suggestions for Socratic discussion

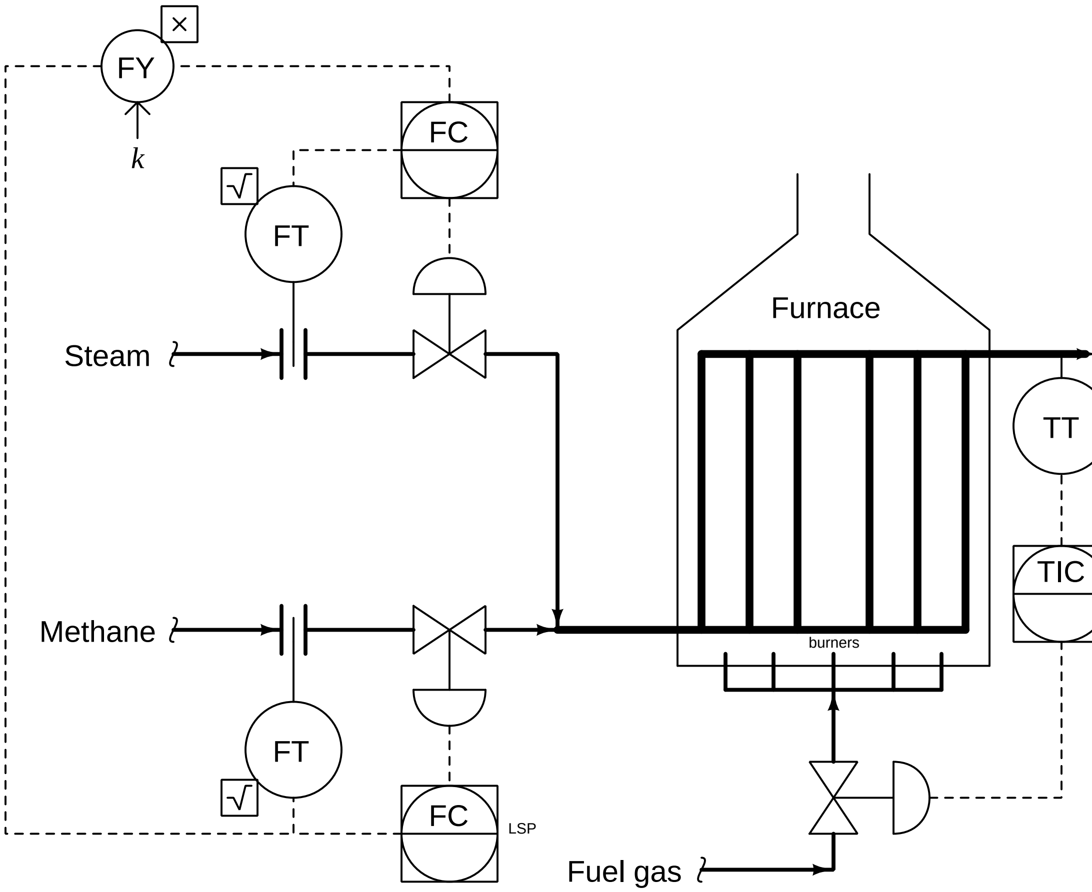
- Can you think of any solutions to this control dilemma other than cascade?
- Why do you suppose there is a return valve in the fuel oil plumbing?
- Explain what will happen in this system if someone suddenly shuts off the return valve, from its normal position.

- Explain what will happen in this system if someone suddenly opens up the return valve, from its normal position.

  file i00714

Question 64

Reforming furnaces are special process furnaces used to generate pure hydrogen gas from a hydrocarbon feed gas, such as methane. Methane gas (CH_4) added to steam (H_2O) at high temperatures forms hydrogen gas (H_2) and carbon monoxide gas (CO), the latter converted into CO_2 and more hydrogen gas in subsequent reactions. The chemical reaction is highly *endothermic*, meaning that it requires energy input rather than liberating energy (as what happens in an *exothermic* process such as combustion). This required heat comes from a set of gas burners at the bottom of the reaction furnace:



The rate of hydrocarbon feed greatly "loads" the control of temperature inside the reaction furnace, making it more challenging to maintain setpoint temperature as the feed rate varies. Design a solution for this temperature-stability problem using a *feedforward* control strategy, explaining the reasoning behind your solution.

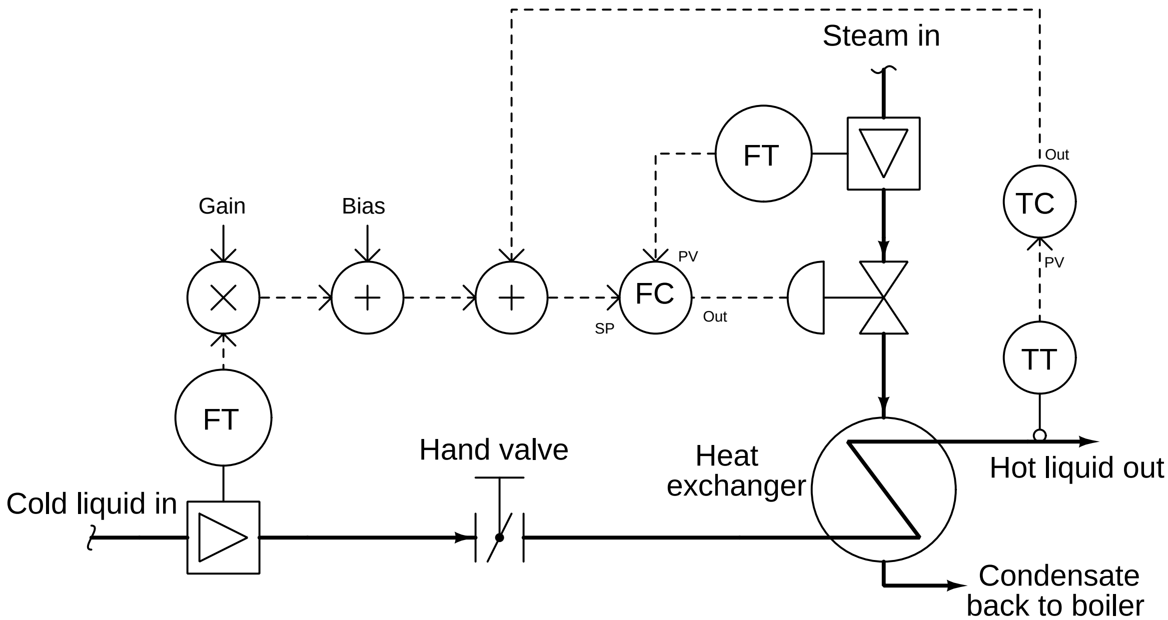
Suggestions for Socratic discussion

- How would your design solution be affected if the chemical reaction inside the furnace were mildly *exothermic* rather than endothermic?
- Predict the effects resulting from one of the transmitters in this system failing with either a *high* or a *low* signal.
- Predict the effects resulting from an operator increasing the steam-to-methane ratio value (k).
- Devise a test by which you could determine whether *dynamic compensation* is needed in your proposed feedforward control strategy. Be specific, identifying how you can tell whether you will need to incorporate *lead* or *lag* into the feedforward loop to optimize its performance.

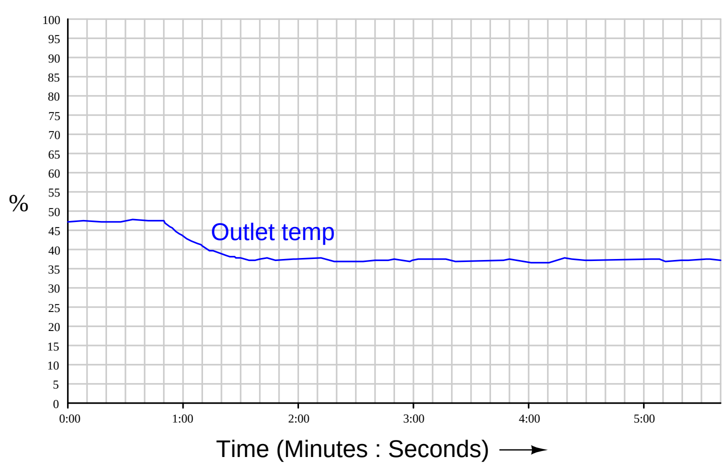
file i02504

Question 65

Suppose this feedforward control system was just recently installed on a heat exchanger, complete with "gain" and "bias" functions to allow the feedforward action to be adjusted:



After tuning the flow and temperature controllers (in that order), the instrument technician's next step is to place the temperature controller in manual mode, then slightly close the hand valve leading into the heat exchanger in order to introduce a load change. The result is this trend of outlet temperature:



What should be adjusted in the feedforward system in order to achieve better load compensation? Why was it important for the technician to first place the temperature controller in manual mode before attempting the load change test? Would it have been equivalent to place the flow controller in manual mode instead?

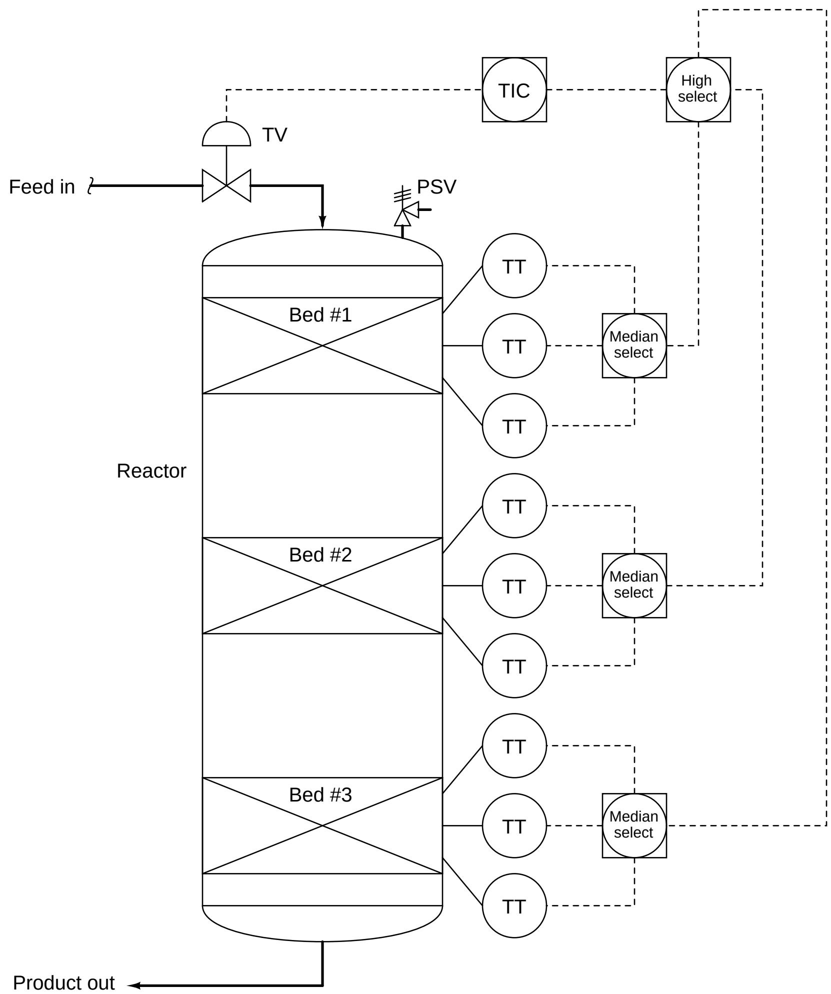
Suggestions for Socratic discussion

- Predict the effects resulting from one of the transmitters in this system failing with either a *high* or a *low* signal.
- Can we tell from the results of this test whether the feedforward system requires *lead* or *lag* dynamic compensation? If so, which form of dynamic compensation do you think this system requires?

file i02462

Question 66

Temperature control in this multi-bed chemical reactor is quite critical. The chemical reaction happening inside of it is *exothermic*, which means it gives off heat. If any of the catalyst beds inside the reactor gets too hot, the reaction could "run away" and destroy the catalyst:



Explain how the selector functions improve the safety and reliability of the control system for this reactor. In particular, explain why *median-select* functions are used at each of the catalyst beds, and why a *high-select* function is used before the temperature controller.

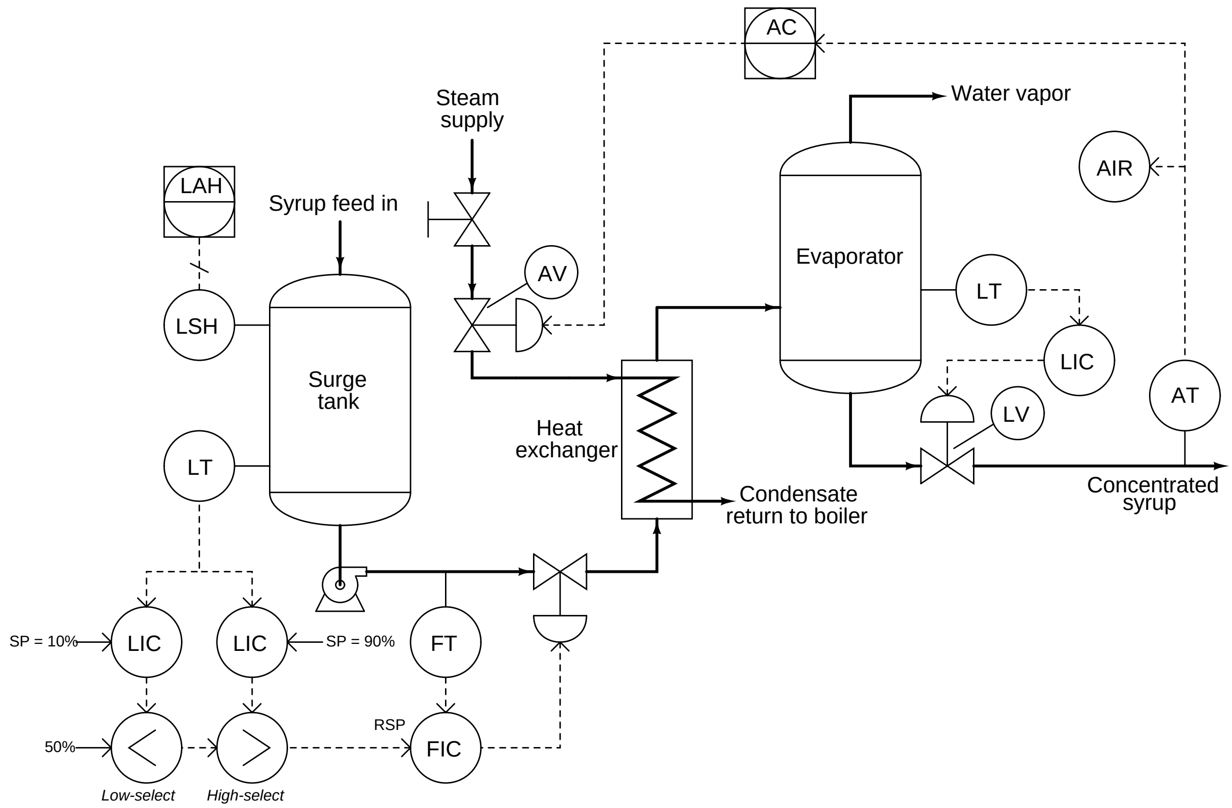
Suggestions for Socratic discussion

- For those who have studied chemistry, what is a *catalyst* used for in chemical reaction engineering?
- What is a *PSV*, and what is one doing in this process?
- Predict the effects resulting from one of the transmitters in this system failing with either a *high* or a *low* signal.
- Modify the control strategy (and the piping if necessary) to permit individual temperature control of each catalyst bed inside the reactor.
- Suppose someone were to swap the selectors' functions, so that each bed had a high-select function and the controller received its PV signal through a median-select function. Would this strategy fulfill the same design purpose as the system shown here? Why or why not?

file i02467

Question 67

In this process, raw maple syrup is heated by steam to evaporate water and make it more concentrated. The control of sugar concentration is much better when the feed flow rate is stable, and so a "surge tank" has been added to the front of the process to allow the raw syrup feed rate to vary over time without forcing the evaporator feed rate to fluctuate. In fact, the surge tank even allows operators to add raw syrup in discrete batches while the system maintains a steady flow rate to the evaporator:



Examine this control strategy, and then explain how it works, using a series of "thought experiments" to demonstrate its action for multiple process conditions.

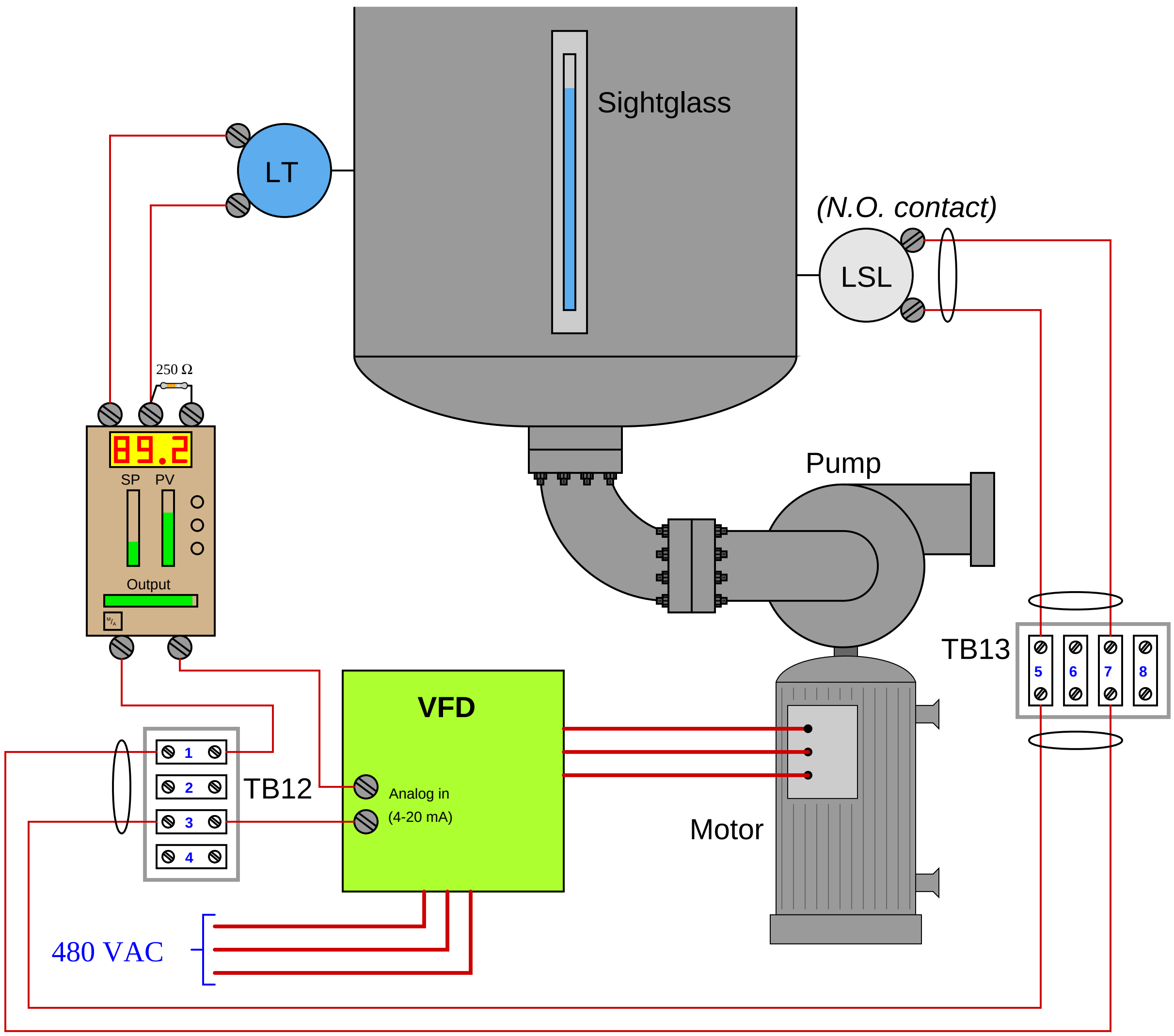
Suggestions for Socratic discussion

- For those who have studied PID tuning, explain why the two level controllers on the surge tank *must* have absolutely no integral action in them, but rather need to be proportional-only with moderate gain values and fixed bias values of 50%.
- Predict the effects from one of the transmitters in this system failing with either a high or a low signal.

file i00425

Question 68

A level control system uses a variable-frequency motor drive (VFD) to control the speed of a pump drawing liquid out of the vessel. The greater the liquid level, the faster the pump spins, drawing liquid out at a faster rate. A low-level cutoff switch is also part of this control system, forcing the pump to a full stop to protect it from running dry if ever a low-level condition is sensed by the switch:



Unfortunately, this system seems to have a problem. The pump refuses to start even though the liquid level is greater than the controller's setpoint (as indicated by both the controller and the sightglass). It was running just fine yesterday, and no technician has touched any of the components since then.

A fellow instrument technician helping you troubleshoot this problem decides to perform a simple test: he uses his multimeter (configured to measure DC current) as a "jumper" wire to momentarily short together terminals 5 and 7 on terminal strip TB13. Still, the motor remains off and does not start up as it should.

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

Fault	**Possible**	**Impossible**
No AC power to VFD		
Controller has dead 4-20 mA output		
Level transmitter out of calibration		
Level switch contacts failed shorted		
Level switch contacts failed open		
250 ohm resistor failed open		
Cable between TB12 and TB13 failed open		
Cable between TB13 and LSL failed open		

Also, explain why the "jumper test" was a very good first step to take.

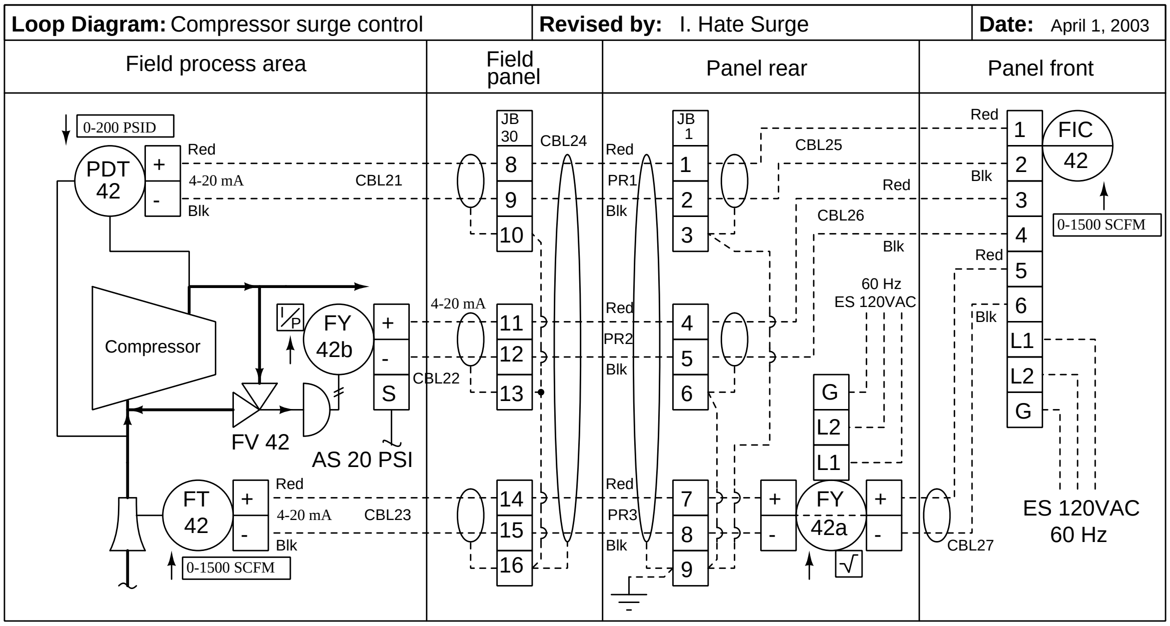
Suggestions for Socratic discussion

- Propose a "next test" to perform on this system to further isolate where the fault is located.
- Is this an example of a *soft-constraint* override system or a *hard-constraint* override system?
- Predict the effects resulting from various wiring faults in this system (e.g. *opens* or *shorts*).
- What does the label *normally open* (NO) mean for a switch such as the one sensing liquid level here?
- For those who have studied PID tuning, how should the level controller be tuned: mostly using proportional action, integral action, or derivative action to control the liquid level?

file i03235

Question 69

The following loop diagram shows a compressor surge control system. When the flow controller (FIC 42) detects a condition of high differential pressure across the compressor and a simultaneous condition of low flow through the compressor, it responds by opening the surge control valve (FV 42), bypassing flow from the outlet of the compressor directly back to the input of the compressor:



If the screw on terminal JB1-4 were to come loose, breaking the connection between the two wires joined at that point, what would this surge control valve do, and what effect do you think that would have on the compressor?

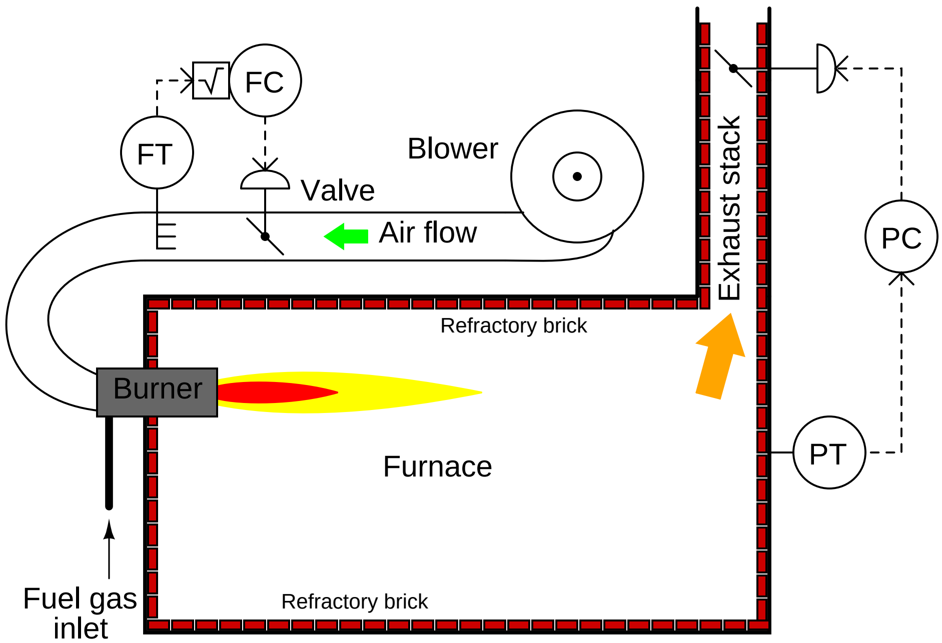
Suggestions for Socratic discussion

- Identify whether FV-42 is *fail-open* (FO) or *fail-closed* (FC).
- What do the short arrows represent (located next to the individual instrument bubbles) in this loop diagram?

file i00134

Question 70

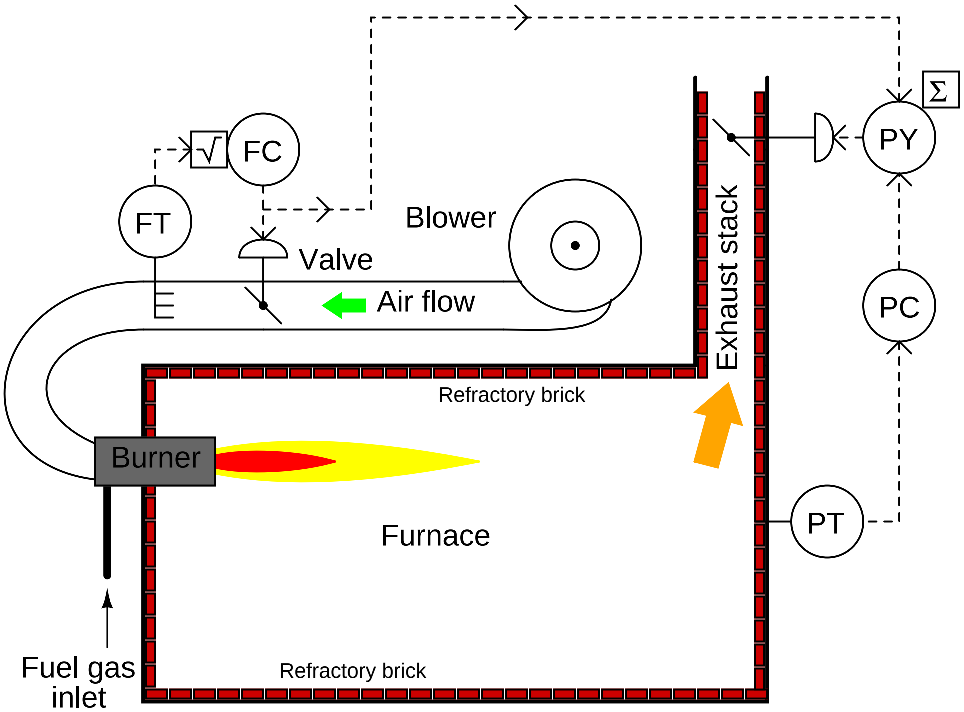
Sometimes two or more separate control loops interact with one another by way of the process being controlled. When this happens, the loops are said to be *coupled*. An example of this is air flow and air pressure control on a large combustion furnace:



The flow controller (FC) works to maintain a set air flow into the furnace for combustion, in order to precisely control the firing rate of the burner. The pressure controller (PC) works to maintain a constant furnace box pressure, to ensure minimal leakage of cold air into the furnace, or hot air out of the furnace.

A simple "thought experiment" illustrates the problem of coupling: suppose the setpoint to the flow controller is suddenly increased, calling for more air (to fuel a larger fire). What happens to furnace pressure as the inlet air flow damper opens up? What does the pressure controller tell the exhaust stack damper to do in order to maintain constant furnace pressure? How does the stack damper's motion consequently affect the air flow into the furnace? Unless one of these controllers is tuned much faster than the other, the two control systems will tend to "fight" one another through coupling.

A solution to this control problem is *decoupling*, illustrated in the next diagram:

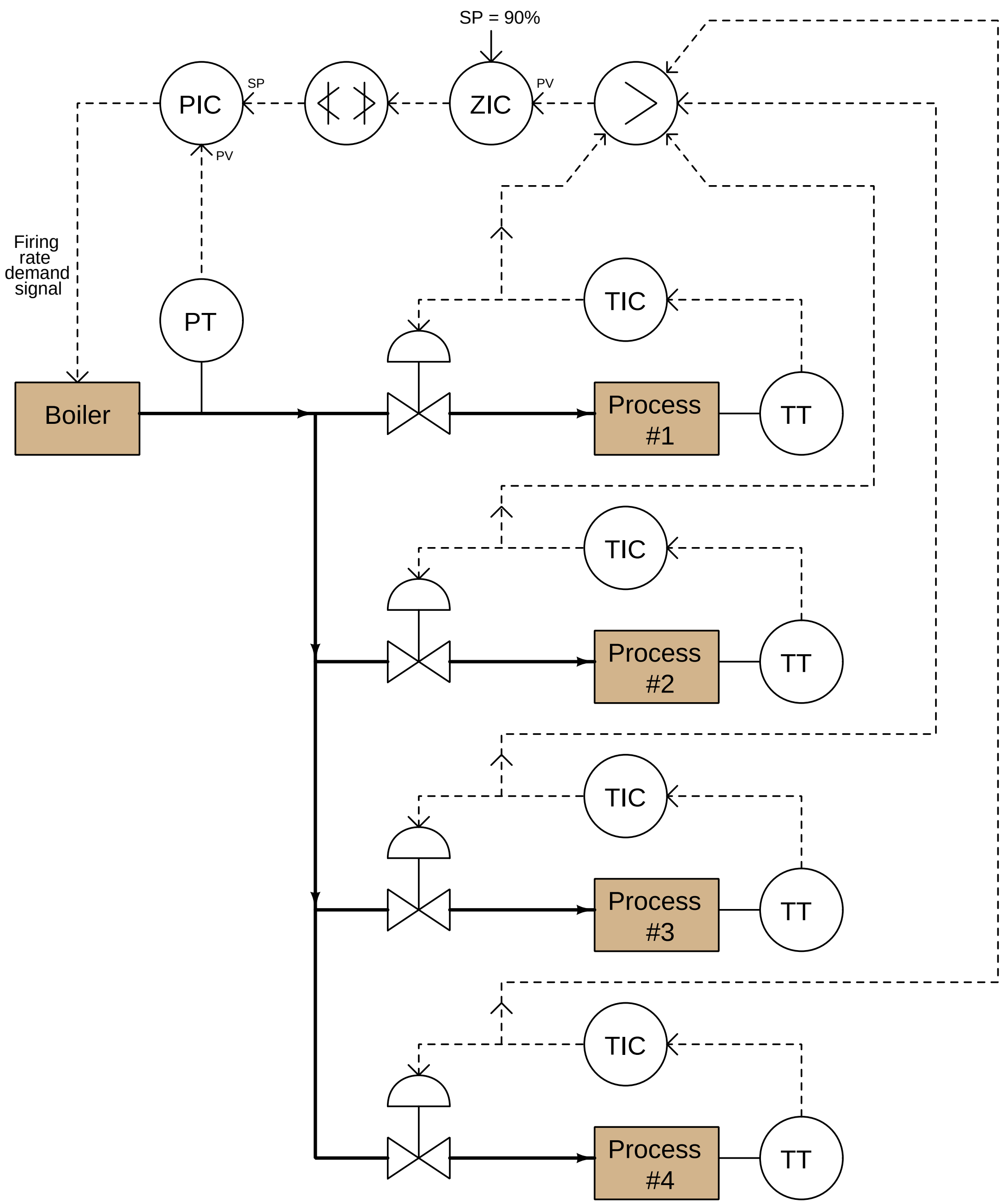


Explain how this control system modification solves the problem of coupling, and also explain how it is similar to *feedforward control* in its design.

file i01771

Question 71

A valve that is throttling (less than fully open) wastes energy, and so one way to minimize energy usage is to create less upstream pressure so that the control valve operates at a greater opening position. When the valve in question is a steam valve throttling steam to a load, this means varying the boiler output pressure to keep the throttling valves nearly full open.



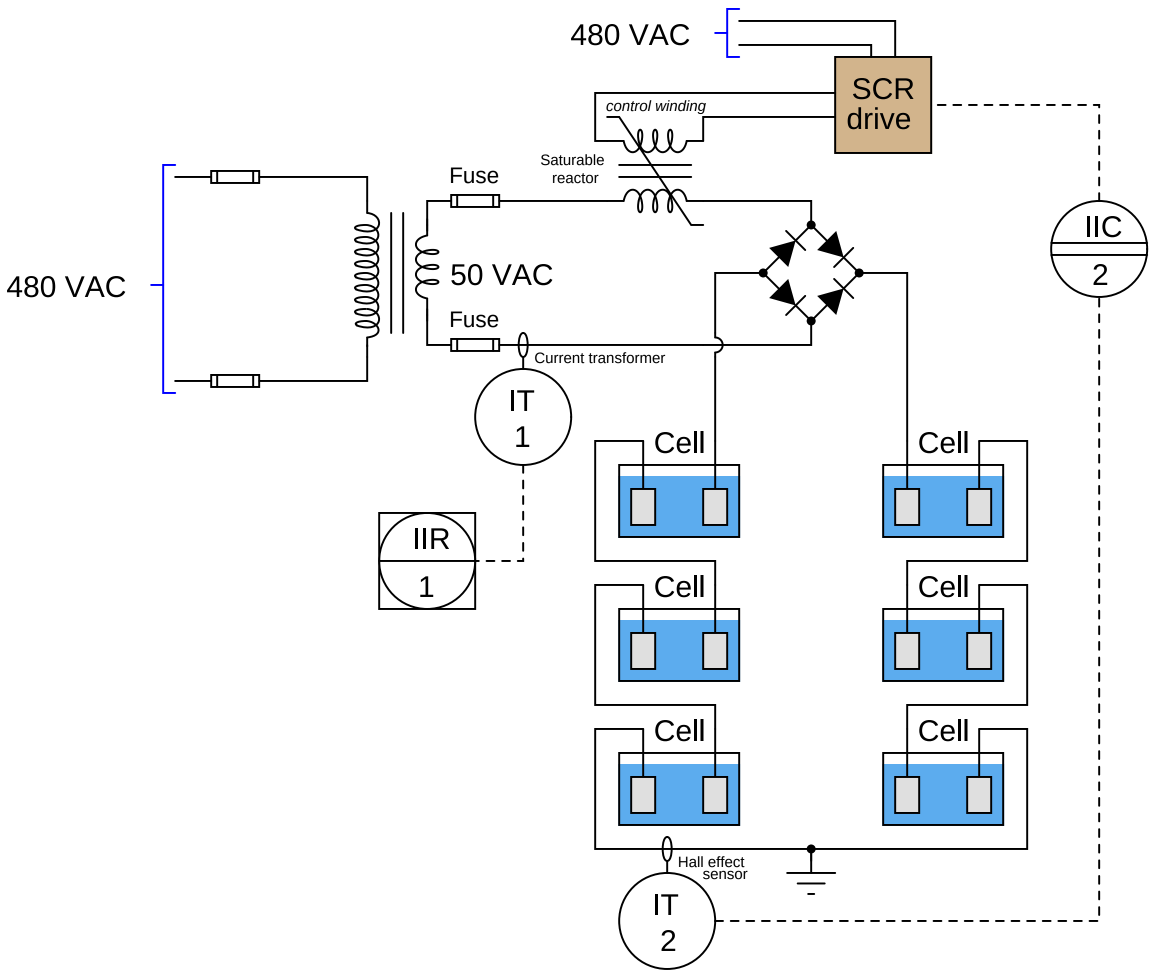
Explain how this control system works to maximize energy efficiency, including the role each instrument plays in achieving this goal.

file i01802

Question 72

Electrolytic cells are used in a variety of process industries (aluminum smelting, electroplating, chlorine production) to drive certain endothermic (energy-absorbing) chemical reactions. The basic concept is to pass large amounts of direct current (DC) through liquid electrolyte solutions, where the electricity will force the desired chemical reaction to take place.

In this system, six electrolytic cells are connected in series, the amount of current through them regulated by a control system. The "final control element" in this electrical system is a device known as a *saturable reactor*: an electrical component constructed much like a transformer, designed to impose different amounts of inductive reactance (X_L) in an AC circuit with varying amounts of DC control current injected through a "control winding." The greater the DC control current through the control winding, the less inductive reactance in the AC circuit (and therefore more current in the AC circuit). In this system, a solid-state SCR drive outputs the necessary DC control current to the saturable reactor, at the command of a 4-20 mA signal from the current indicating controller (IIC):



Unfortunately, this control system seems to have a problem. The indicating recorder (IIR) in the main control room where you are at shows the cells' current to be unstable, slowly varying up and down over time with no predictable pattern. You are called to investigate the problem, and your first diagnostic test is to have a field operator place the controller (IIC) into *manual* mode.

After doing this, you notice that the recorded current is still erratic, showing no sign of stabilizing.

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

Fault	**Possible**	**Impossible**
Poor controller tuning		
Rectifying diode failed open		
Rectifying diode failed shorted		
SCR drive output unstable		
Chemical problems in one or more cells		
High-resistance earth ground connection		
IT-1 faulty		
IT-2 faulty		

Also, trace the direction of electric current through all the cells as well as the voltage drop polarity across each.

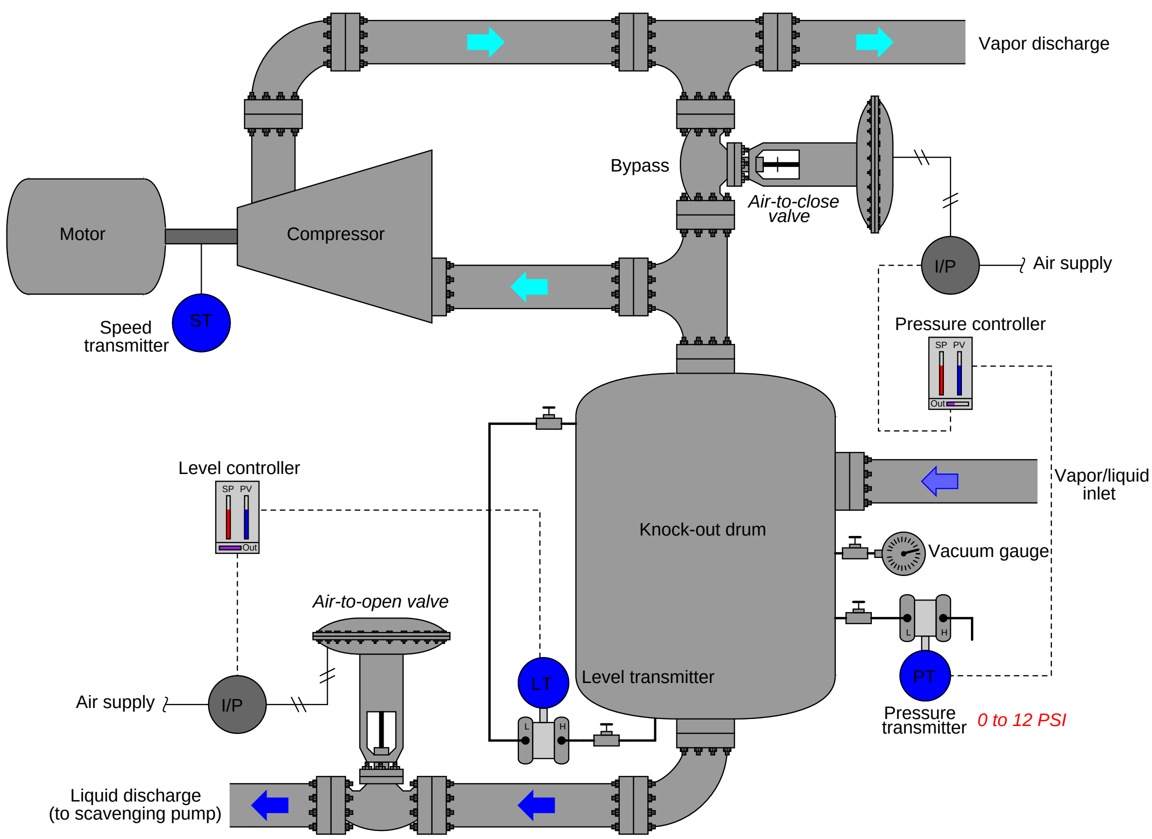
Suggestions for Socratic discussion

- What kinds of current sensors are used in this control system to monitor electrolytic cell current? Why are two different sensor types used?
- Should there normally be any electrical current flowing into or out of the earth ground at the mid-point of the series cell circuit? Explain why or why not.

file i02510

Question 73

This amount of vacuum (negative pressure) in this knock-out drum is controlled by varying the compressor's bypass valve:



An operator tells you there is a problem with this system, though: the vacuum gauge near the pressure transmitter registers −6.9 PSI, even though the controller faceplate registers −8.0 PSI which is the same as the setpoint. The same operator notes that the control valve position is approximately 30% open, with the controller's output bargraph registering 31.4% open.

Another instrument technician happens to be with you, and recommends the operator place the pressure controller in manual mode to "stroke-test" the control valve. Explain why this test would be a waste of time, and propose a better test for helping to pinpoint the location of the fault.

Suggestions for Socratic discussion

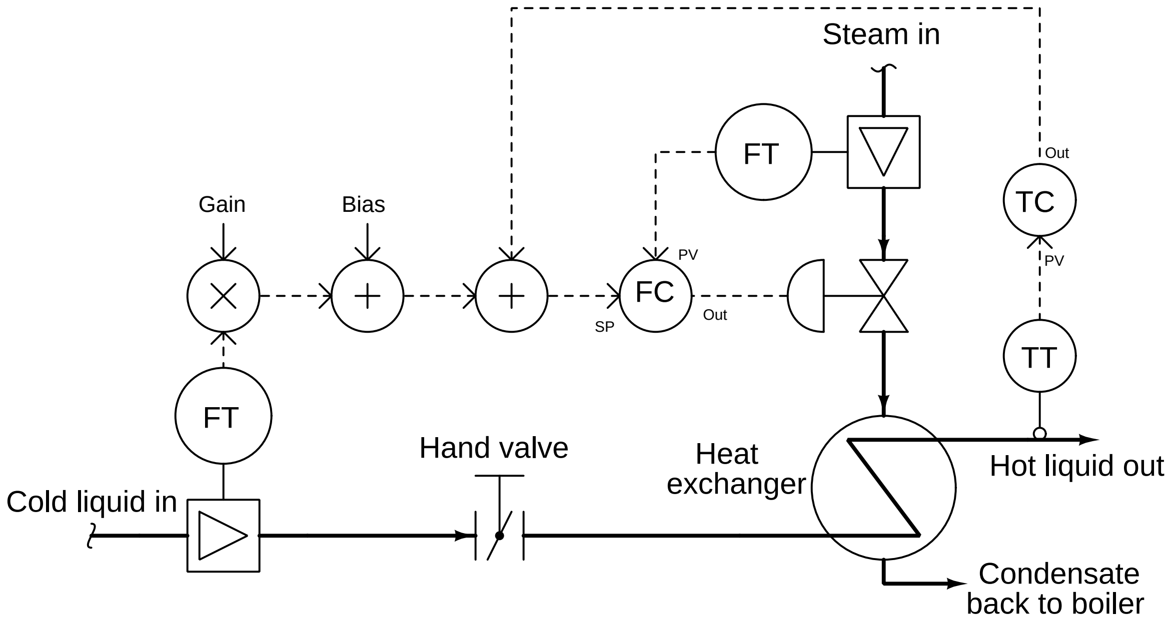
- A valuable principle to apply in a diagnostic scenario such as this is *correspondence*: identifying which field variables correspond with their respective controller faceplate displays, and which do not. Apply this comparative test to the scenario described, and use it to explain why the technician's proposed test was probably not the best first step.
- A problem-solving technique useful for analyzing control systems is to mark the PV and SP inputs of all controllers with "+" and "−" symbols, rather than merely label each controller as "direct" or "reverse" action. Apply this technique to the control strategy shown here, identifying which controller input(s) should be labeled "+" and which controller input(s) should be labeled "−".
- Predict the effects resulting from one of the transmitters in this system failing with either a *high* or a *low* signal.

- For those who have studied level measurement, explain how the level transmitter (which is nothing more than a DP transmitter) senses liquid level inside the knock-out drum.

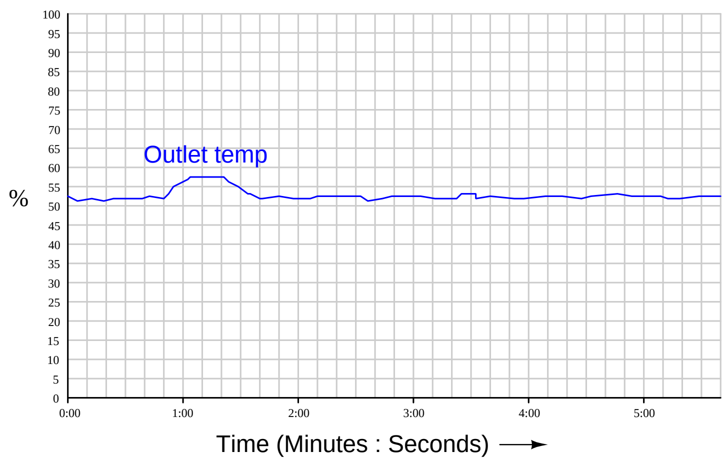
file i02489

Question 74

Suppose this feedforward control system was just recently installed on a heat exchanger, complete with "gain" and "bias" functions to allow the feedforward action to be adjusted:



After tuning the flow and temperature controllers (in that order), the instrument technician's next step is to place the temperature controller in manual mode, then slightly close the hand valve leading into the heat exchanger in order to introduce a load change. The result is this trend of outlet temperature:



What should be altered in the feedforward system in order to achieve better load compensation?

file i00445

Question 75

Question 76

Question 77

Question 78

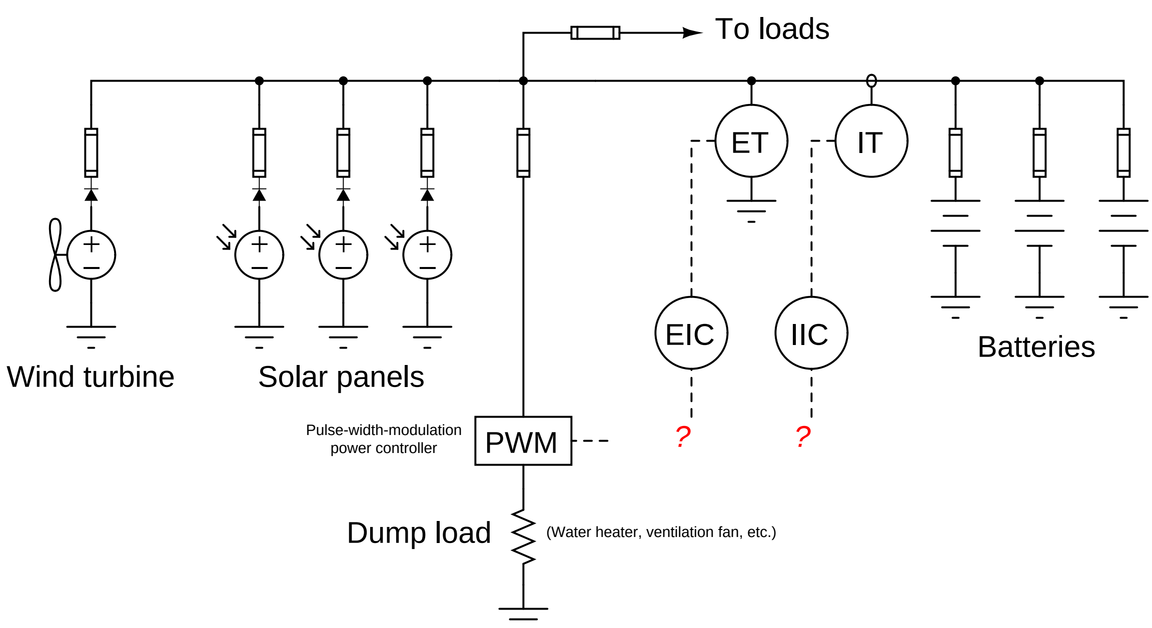
Question 79

Question 80

Question 81

"Off-grid" electric power systems using solar panels (photovoltaic), wind turbines, and other ambient-energy generators to charge battery banks often enter states where more power is being generated than is needed by loads or to charge the batteries. It would be a shame to let this unwanted power go to waste, and so these systems are often equipped with *dump loads* which may be activated to put the excess power to productive use. The best "dump loads" are those which perform some useful task such as water heating, UV water disinfection, etc.

In this system, a voltage transmitter (ET) senses the DC bus voltage of the power system and reports that to a voltage indicating controller (EIC) with a setpoint of 30 volts. A current transmitter (IT) senses charging current to the battery bank and reports that to a current indicating controller (IIC) with a setpoint of 28 amps. A pulse-width modulation (PWM) power controller sends DC power to the dump load at the command of a 4-20 mA signal (the greater the 4-20 mA signal, the higher the duty cycle on the PWM power controller, sending more power to the dump load):

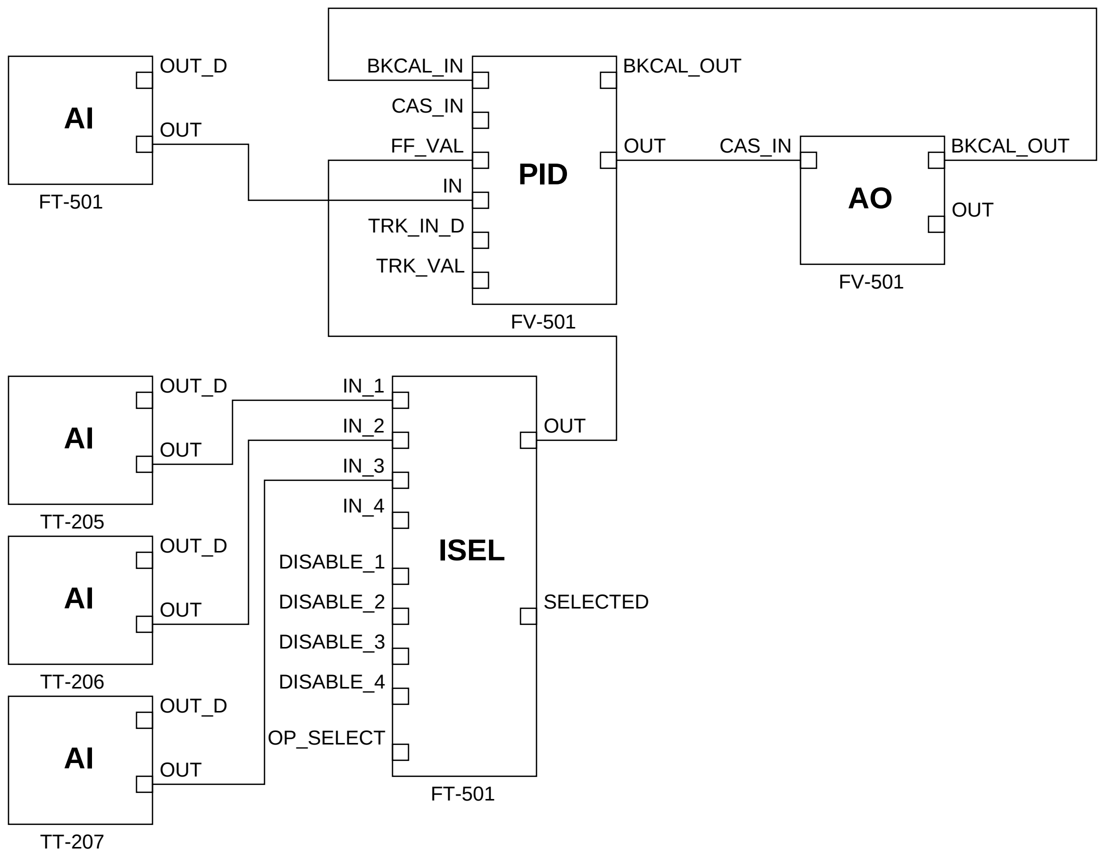


The question is how to arrange these two controllers (EIC and IIC) in some sort of control strategy to prevent over-charging of the battery bank?

file i04599

Question 82

Examine this function block diagram for a control strategy:

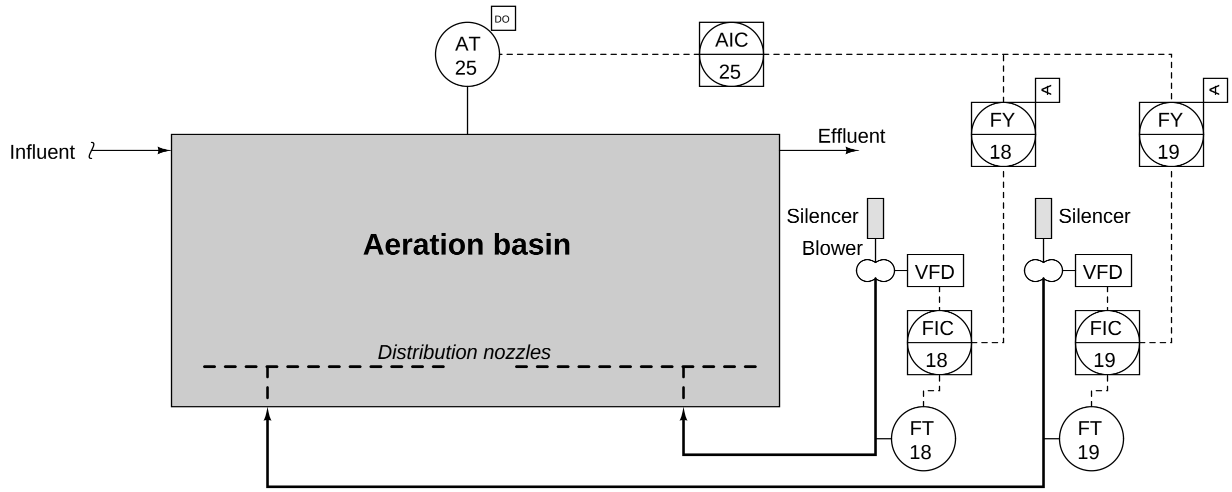


Explain what sort of control strategy this is, based on what you can discern from this function block diagram. Be as specific as you can in your answer!

file i03280

Question 83

One of the major processes used to treat municipal wastewater is *aeration*, where the dissolved oxygen concentration of the wastewater is enhanced by bubbling air through the water in an *aeration basin*. A dissolved oxygen ("DO") analyzer measures the oxygen concentration in the wastewater, and a controller varies the speeds of blowers pumping air into the basins using AC motors powered through variable-frequency drives (VFDs):

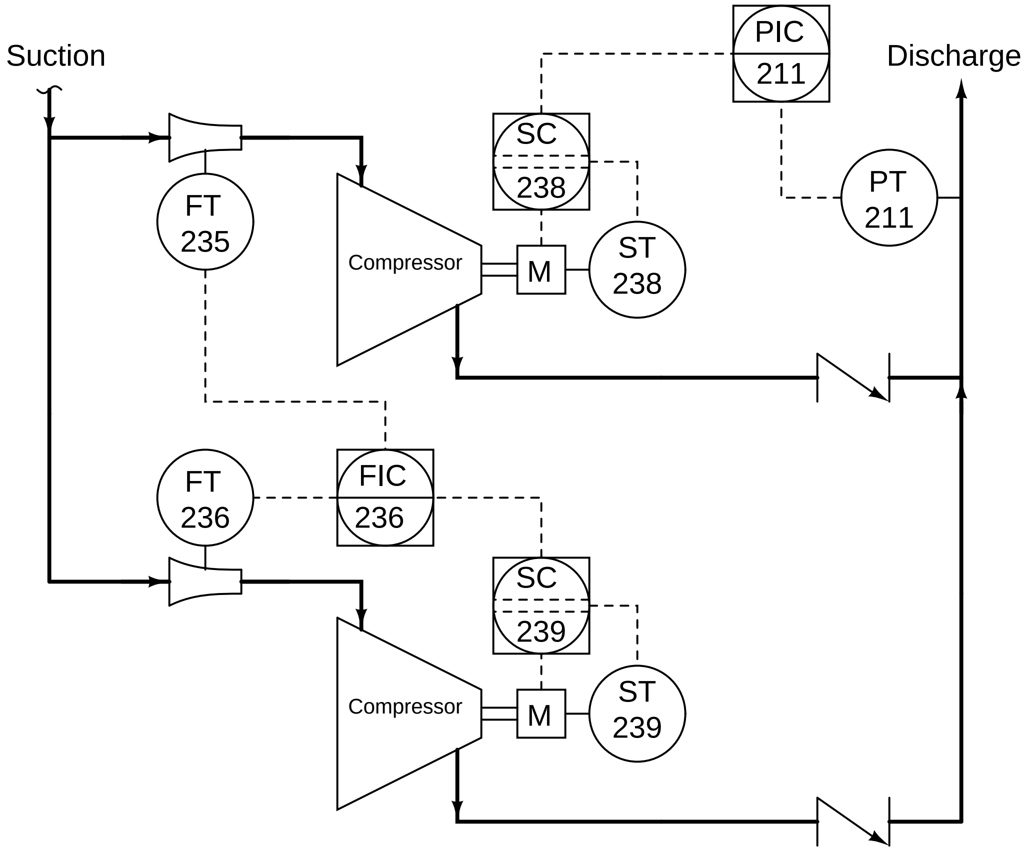


Suppose flow transmitter FT-19 fails with a high-flow signal. Determine the effect this will have on the other two controllers in the system, and on the actual dissolved oxygen content of the wastewater over time.

file i04598

Question 84

A pair of motor-driven compressors work in tandem to compress gas at an industrial ammonia production facility:



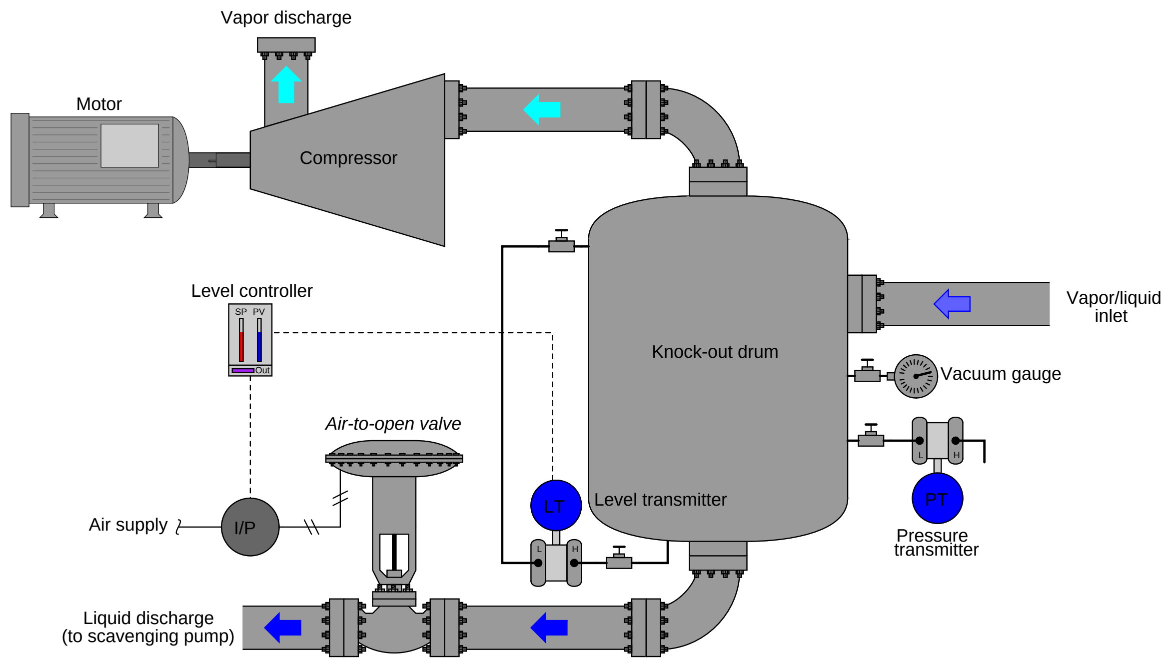
Explain how this control system attempts to evenly match the load between the two compressors, so that one is never working harder than the other, yet at the same time the two machines work together to maintain a common goal.

Additionally, explain what will happen if flowmeter FT-235 fails with a low signal.

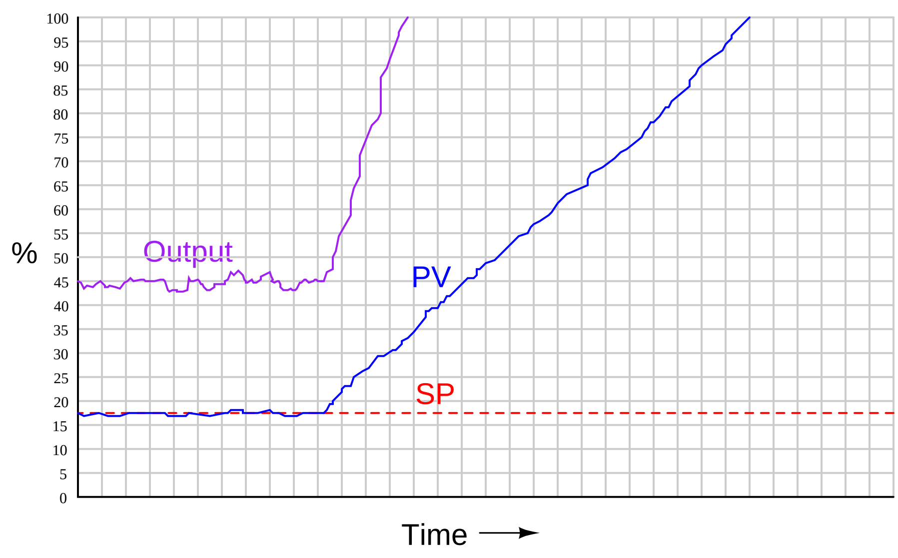
file i00700

Question 85

This level-control system is supposed to maintain a constant liquid level inside the knockout drum, preventing liquid from entering the compressor as well as gas from entering the scavenging pump. Yet, for some reason liquid did manage to enter the compressor, causing the compressor to violently fail:



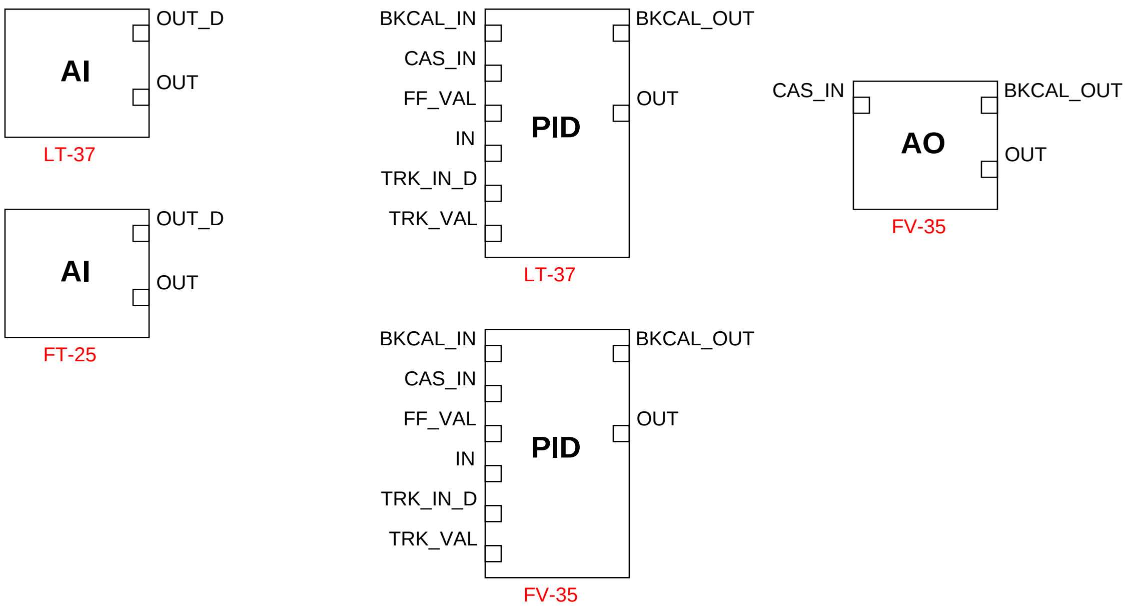
A trend recording of liquid level and control valve position captured before the explosion holds the only clue as to why this happened. Examine it to see if you can determine the source of the trouble:



file i00701

Question 86

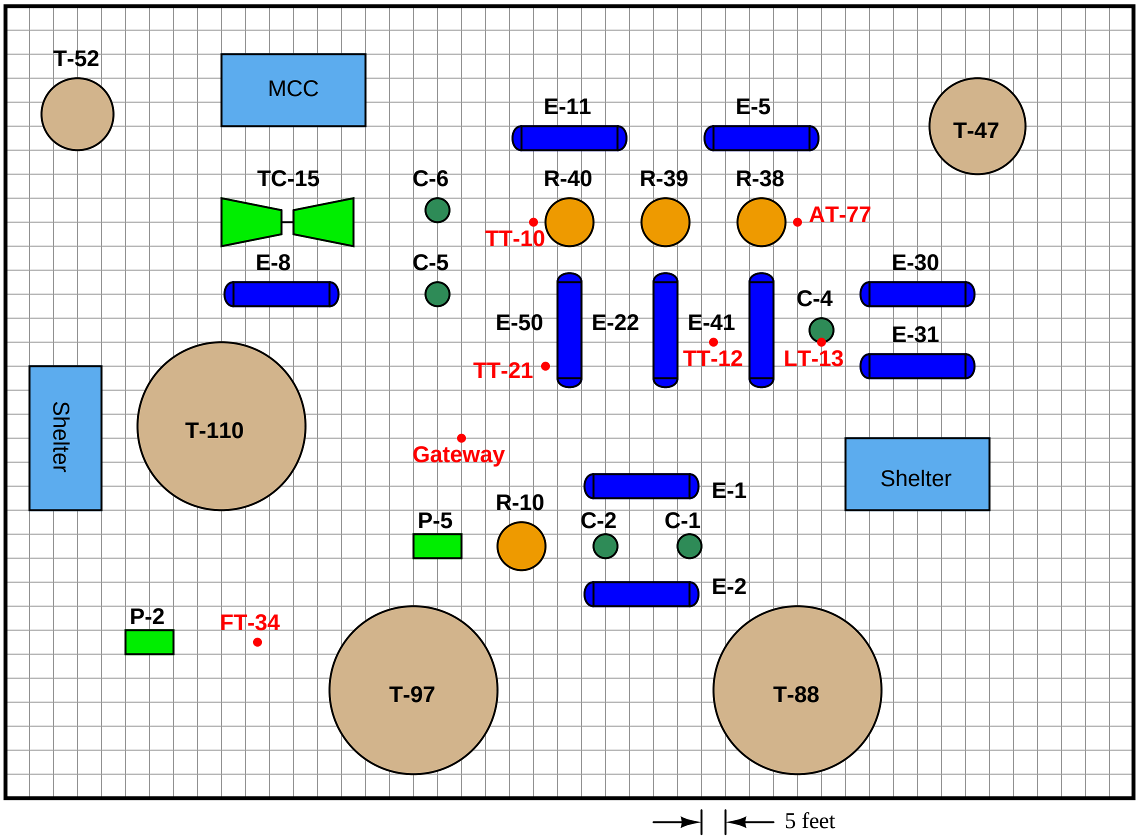
Sketch the necessary connections between FOUNDATION Fieldbus function blocks to form a working cascade control system:



file i04597

Question 87

Calculate the line-of-sight distance between these *Wireless*HART instruments, based on locations shown on this plot plan of an industrial processing unit. Each division on the map is equivalent to a distance of 5 feet:

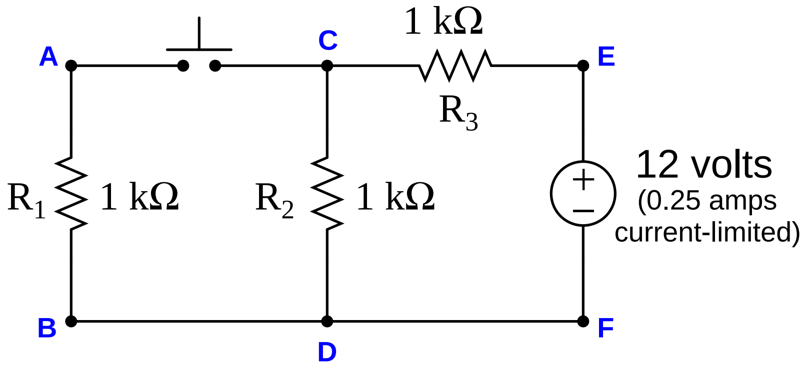


- Distance from Gateway to FT-34 =
- Distance from TT-10 to FT-34 =
- Distance from Gateway to LT-13 =
- Distance from TT-10 to AT-77 =

file i00930

Question 88

Suppose a voltmeter registers 6 volts between test points **C** and **D** while the pushbutton is released (not pressed), and also 6 volts between the same test points while the pushbutton is pressed:



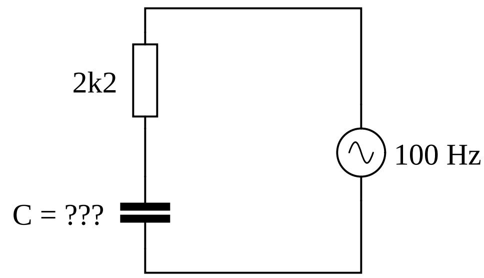
Determine the diagnostic value of each of the following tests. Assume only one fault in the system, including any single component or any single wire/cable/tube connecting components together. If a proposed test could provide new information to help you identify the location and/or nature of the one fault, mark "yes." Otherwise, if a proposed test would not reveal anything relevant to identifying the fault (already discernible from the measurements and symptoms given so far), mark "no."

Diagnostic test	Yes	No
Measure V_{AB} with switch pressed		
Measure V_{AC} with switch pressed		
Measure current through wire connecting **B** to **D** with switch pressed		
Measure V_{AB} with switch unpressed		
Measure V_{AC} with switch unpressed		
Measure R_{EF} with switch pressed and source disconnected from **E**		
Measure R_{EF} with switch unpressed and source disconnected from **E**		

file i01861

Question 89

Calculate the necessary size of the capacitor to give this circuit a total impedance (Z_{total}) of 4 kΩ, at a power supply frequency of 100 Hz:



Also calculate the following phase shift angles (θ) between voltage and current for each component in this series circuit:

Phase shift between resistor voltage drop and resistor current = __________ degrees

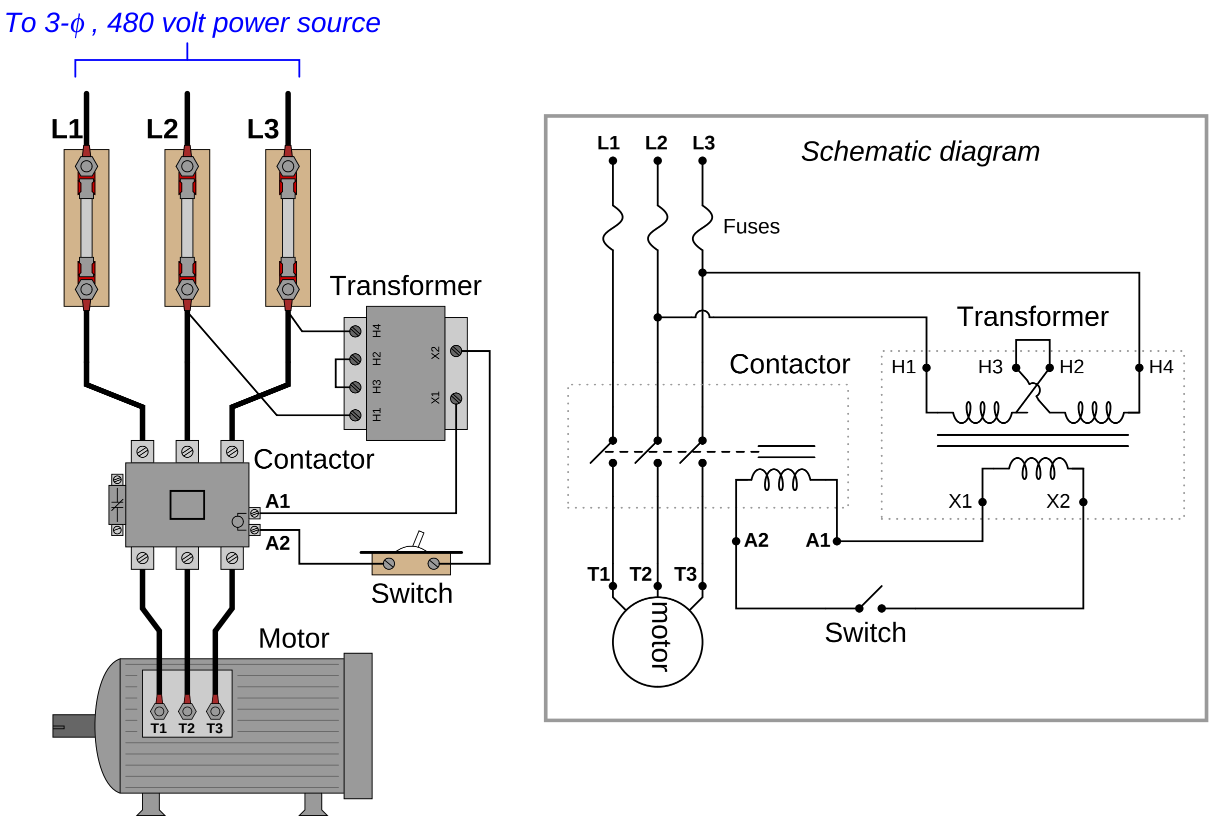
Phase shift between capacitor voltage drop and capacitor current = __________ degrees

Phase shift between source voltage and source current = __________ degrees

file i01035

Question 90

In this 480 volt AC induction motor control circuit (sometimes referred to as a "bucket"), a three-pole relay (typically called a *contactor*) is used to switch power on and off to the motor. The contactor itself is controlled by a smaller switch, which receives 120 volts AC from a step-down transformer to energize the contactor's magnetic coil. Although this motor control circuit used to work just fine, today the motor refuses to start.



Using your AC voltmeter, you measure 480 volts AC between L1 and L2, 479 volts AC between L2 and L3, and 483 volts AC between L1 and L3. With the switch in the "on" position, you measure 119 volts AC between terminals A1 and A2 on the contactor. From this information, identify the following:

- Two components or wires in the circuit that you know cannot be failed either open or shorted, besides the 480 volt AC source which is obviously operational.

- Two different component or wire failures in the circuit, either one of which could account for the problem and all measured values, and the types of failures they would be (either open or shorted).

file i04449

Question 91

Lab Exercise – introduction

Your task is to add cascade, ratio, or feedforward action to your working process control system. This will require the addition of another process transmitter as well as additional programming inside the controller.

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					– – – –
P&ID showing control strategy	mastery					– – – –
Demonstration of working system	mastery	–	–	–	–	
Safety and professionalism	deduction					
Lab percentage score	proportional					– – – –

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

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

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

Lab Exercise – objectives and expectations

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

Team meeting and prototype sketch

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. <u>Do not begin construction until your design has been analyzed and approved!</u> Note that multiple meetings may be required if the instructor's assistance is needed to select components influencing your design.

Circuit design challenge

Wire an electromechanical relay to switch power to a 120 VAC load, controlled by a low-voltage pushbutton circuit (either *on* when pressed or *off* when pressed, as chosen by the instructor).

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 exceed all standards described in the lab exercise documentation.

P&ID showing control strategy

Sketch a simple P&D showing interconnections of process vessels and the control strategy used to regulate the process variable. The control strategy must be unambiguous: cascade master/slave controllers drawn separately; feedforward summer drawn separately.

Demonstration of working system

Show that the control strategy functions as intended, providing regulatory control superior to that of simple feedback (PID) alone.

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.

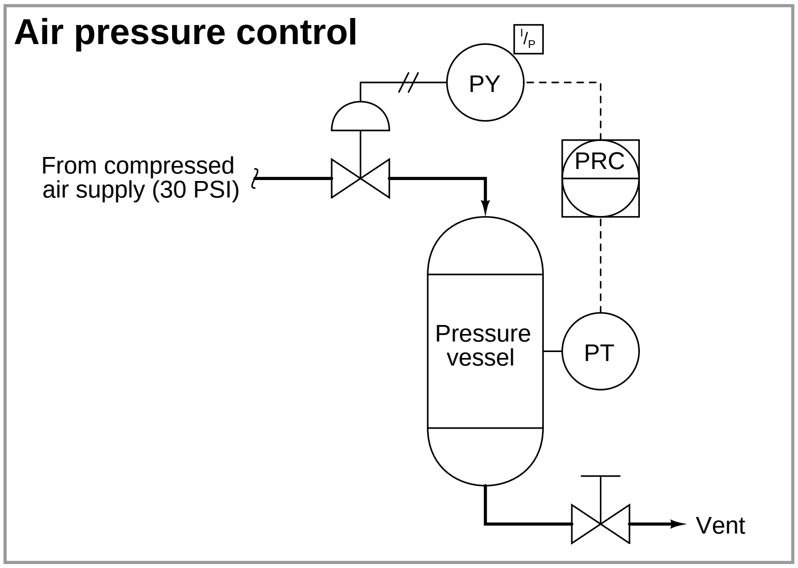
Remember that the lab facility is available to you at all hours of the school day. Students may perform non-hazardous work (e.g. circuit work at less than 30 volts, documentation, low air pressures, general construction not requiring power tools) at *any time during the school day* without the instructor's 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!

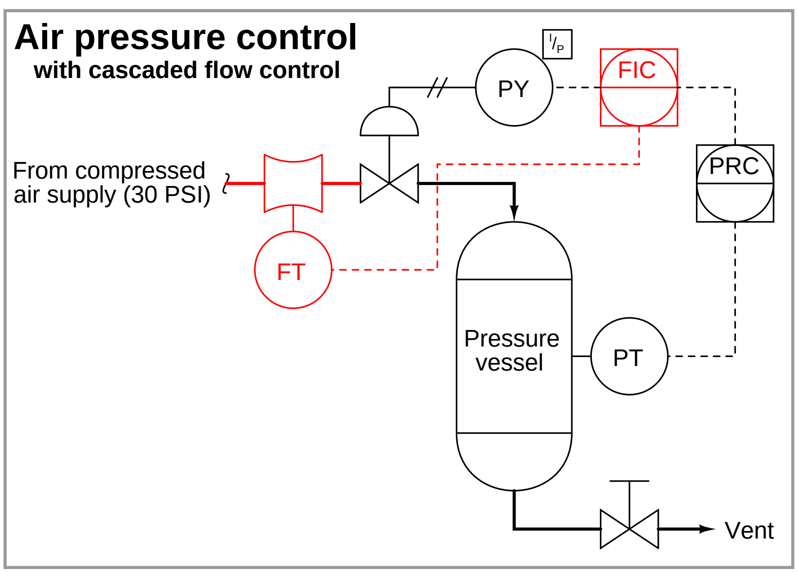
Notes on process control strategies

Your first step needs to be deciding what kind of multi-input control strategy to implement. Both cascade and feedforward strategies work to minimize the influence of loads in a process, while ratio works to match one process variable to another. Ratio control is often the simplest strategy to implement, but not always applicable to student-built processes. Cascade control is generally applied to flow through the control valve, which can be challenging to measure given the instruments on hand in the lab. Feedforward is quite easy to find applications for, but can be challenging to "tune" in such a way that it takes the proper degree of stabilizing action. My own recommendation is to go with feedforward: chances are, you'll learn the most doing this strategy!

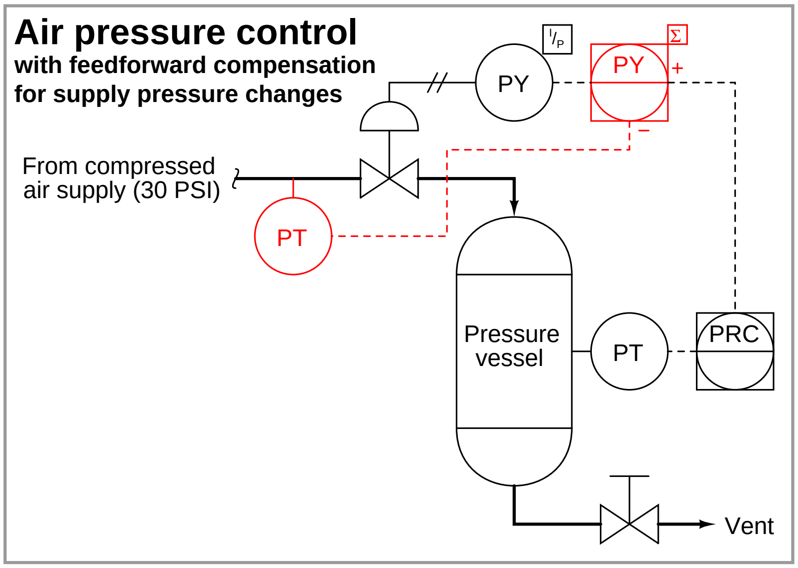
For example, here is a simple air pressure control system using a loop controller:



Next, we see this system modified for cascade control (additional control elements shown in red):



In the following example we see the same basic air pressure control system modified for feedforward control (additional control elements shown in red):



Other options include:

- **Cascade speed/flow control on air-powered turbine**: master controller senses turbine speed, while slave controller senses air pressure upstream of the nozzle. The nozzle functions as an orifice for flow measurement, so configuring the pressure transmitter for square-root characterization yields air flow measurement to the turbine.
- **Feedforward control on electric heater temperature**: heater temperature is the process variable, while the controller drives a fan's speed to cool the heater. A Variac adjusts AC line power to the heater element, and serves as the load variable. This AC line voltage is converted into a 4-20 mA feedforward signal by means of a step-down transformer, rectifier, low-pass filter, and voltage divider circuit feeding a millivolt signal into an electronic temperature transmitter.

After deciding on a control strategy, your next step should be selecting the appropriate sensing instrument to measure the additional variable, drafting a prototype diagram to show how the instrument will be included in your existing system, and then installing this new instrument in the process. As usual, 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 modifying their system's control strategy without a verified plan will be ordered to cease construction and not resume until a prototype plan has been drafted and approved!* 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.

The installation should follow the same general standards as the construction of the original system: all wiring in conduit (where possible), all tubing neatly arranged, all instruments and cables labeled with appropriate ISA-standard tag names. After installation, you should test the new transmitter by ensuring it measures the variable as anticipated. The controller's indication of this new variable should be properly scaled (in engineering units) rather than register in percent.

If the transmitter senses the variable properly, it is now time to design the controller program that will make sense of this new process data and use it to stabilize control of the (original) process variable. The details of this are too varied to give a general explanation here. Your *Lessons In Industrial Instrumentation* textbook describes each of the alternative strategies (cascade, ratio, feedforward) in some detail. Your instructor can also help you design a strategy that is practical.

Each of the control systems available within the BTC Instrumentation lab is able to implement control strategies beyond simple single-loop PID, but some strategies are easier to implement on some control systems than others. Here is a list of some of the control systems available in the lab and how easy or difficult it is to implement various control strategies on each one:

- **Panel-mount controllers**: The Siemens 352/353 controllers are easily capable of implementing cascade or ratio control, each of these being a pre-defined Factory Configured Option (FCO). Feedforward is possible to implement by doing some of your own function block programming, but it is not intuitive. Dynamic compensation (lead/lag) is available for feedforward as its own function block. Other controllers such as the Honeywell UDC series are much more limited and cannot do anything but single-loop PID control.

- **Allen-Bradley MicroLogix PLCs**: These are set up to do single-loop PID control, but may be reprogrammed to do either feedforward, ratio, or cascade. In any case, you will need to revise the ladder-logic code to implement the control strategy. Dynamic compensation (lead/lag) for feedforward is not available.

- **Emerson DeltaV DCS**: This system very easily does ratio or feedforward control with the addition of just one function block and some parameter adjustments. Dynamic compensation (lead/lag) is available for feedforward as its own function block. However, cascade control requires the setup of two function-block control modules linked together using "output connector" objects, as well as modifications to the DeltaV Operate screen, which requires much more work.

- **caSCADA**: This system has feedforward built in as a standard feature to its normal single-loop PID control, but no dynamic compensation (lead/lag). Cascade and ratio are not offered as options yet (as of version 3.2). If you choose to modify the C-language code yourself to add another strategy, ratio would be much easier to do than cascade.

The "Proportioning Feedforward Action" section of your *Lessons In Industrial Instrumentation* textbook contains some information on function-block programming for feedforward control strategies, as well as tips on how to "tune" feedforward action to provide the appropriate degree of control.

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.
- Improper pipe/tube fitting installation (e.g. trying to thread tube fittings into pipe fittings and vice-versa).
- 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 – 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.

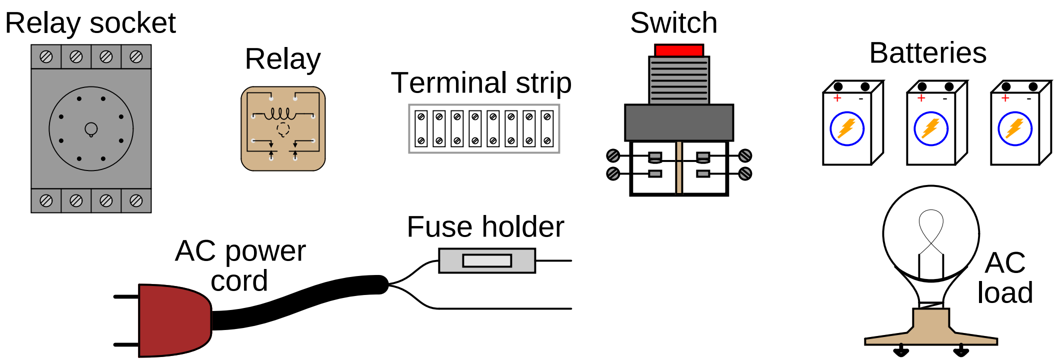
Your team's prototype sketch is so important that the instructor will demand you provide this plan before any construction on your team's working system begins. *Any team found constructing their system without a verified plan will be ordered to cease construction and not resume until a prototype plan 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.

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

Connect an "ice-cube" relay to a low-voltage DC source as well as 120 volts AC so that a hand-operated switch will control the energization of a 120 VAC load. Use a digital multimeter to either measure relay coil current or measure AC load current, as selected by the instructor. All electrical connections must be made using a terminal strip (no twisted wires, crimp splices, wire nuts, spring clips, etc.) "Alligator" clips permitted for making connections to battery terminals only. The 120 VAC portion of the circuit must be fused for overcurrent protection.

This exercise tests your ability to properly interpret the "pinout" of an electromechanical relay, properly wire a switch to control a relay's coil, properly wire a load to the contacts of a relay, properly select NO/NC contacts on both the switch and the relay, properly use a multimeter to measure current, and use a terminal strip to organize all electrical connections.



The following components and materials will be available to you: assorted "ice cube" **relays** with DC-rated coils and matching **sockets** ; assorted pushbutton **switches** ; **terminal strips** ; lengths of **hook-up wire** ; **batteries** ; 120 VAC **power cord** with **fuse assembly** ; 120 VAC **lamp or other suitable load**. You must provide your own 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 provides batteries and observes you energizing the circuit for the very first time; (4) You demonstrate to the instructor that the circuit fulfills its intended function. (5) You connect your DMM into the circuit and demonstrate the correct current being measured.

Load/switch status (instructor chooses): ____ On when pressed *or* ____ Off when pressed

Current measurement (instructor chooses): ____ Relay coil *or* ____ AC load

Study reference: the "Control Relays" section of *Lessons In Industrial Instrumentation*.

Lab Exercise – loop diagram and system inspection

Each team's system will undergo an inspection simulaneous 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 seperation 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!

Notes on control strategy tuning

Ratio control strategies are the easiest to tune, because they merely consist of switching the original loop controller's setpoint from "local" to "remote" with perhaps the addition of a ratio function block to scale the wild variable to the captive (setpoint). If the base loop controller was well-tuned to begin with, that PID tuning will probably not have to be changed at all to accommodate the new ratio strategy.

Cascade control strategies involve the addition of another PID control function (usually inside the same controller hardware as the original PID function). This "slave" controller must be tuned before the "master" controller may be successfully tuned. Note that the original PID function (which now serves as the master controller) may have to be re-tuned following the change from single-loop control to cascade control, as cascade often changes the dynamics of the process presented to the master controller. For example, a liquid level-control system using the vessel drain as the manipulated variable, after installing a "slave" flow-control loop on that drain line, will now become a *pure integrating* process as opposed to the self-regulating process it used to be. This necessitates re-tuning of the master (level) PID function block. Simply place the master controller in manual while tuning the slave controller, then proceed with tuning the master controller (only) after the slave controller has been tuned for quick and accurate response.

Feedforward control strategies are by far the most challenging to adjust, especially if they incorporate dynamic compensation. Since the fundamental concept of feedforward control is to take pre-emptive action upon sensing a load change so that the basic feedback controller doesn't have to perform any corrective (after-the-fact) action, the way you assess a feedforward loop is by disabling feedback control (by setting PID gain at or very near zero) so that it *cannot* perform any corrective action, then introduce a load change. If the feedforward system functions are properly scaled and proportioned, the load change will have little or no effect on the process variable even with the PID feedback algorithm disabled. If you see that load changes still have major effects on the process variable with PID disabled, it means the feedforward system is not taking appropriate action.

Bear in mind that pure feedforward action cannot be expected to maintain fidelity to setpoint: since feedforward is completely unaware of the PID controller's setpoint, it cannot be expected to maintain the PV at that value. At best, all pure feedforward action will do is minimize how far the PV *changes* following a load change.

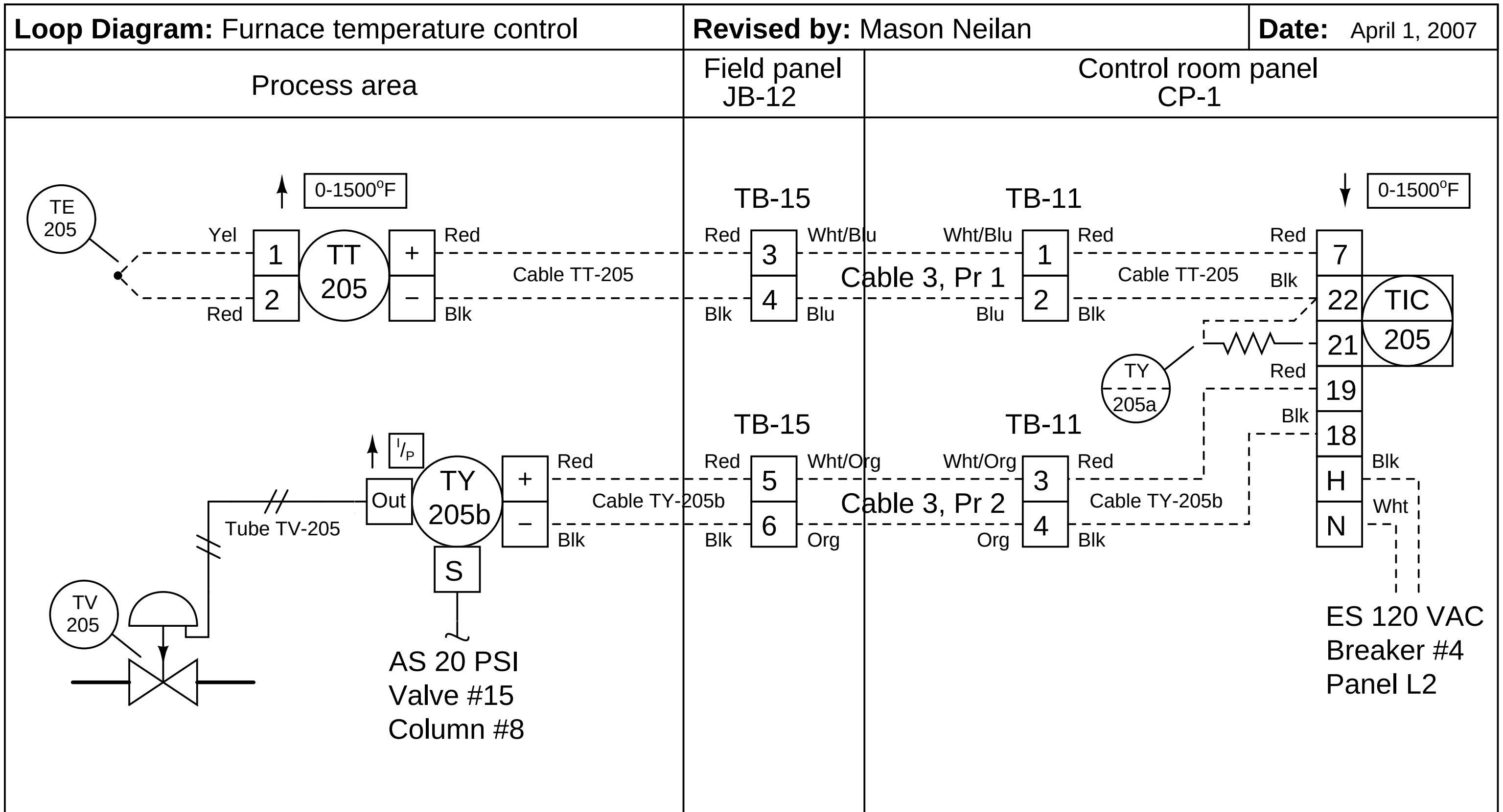
Since the effect of a load variable on the PV tends to be nonlinear over the entire range of the PV, it is advisable to make modest adjustments to the load when tuning feedforward control strategies. Find a load value and setpoint setting where the process gives reasonably good feedback control behavior, and then make load adjustments on the order of $\pm$ 5% at that setpoint. It is recommended that you begin this tuning process by making such load adjustments with all automatic control in *manual mode*, in order to document the uncompensated effects of that load on the PV. This "baseline" response may then be used as a guide to tell whether feedforward action is appropriately compensating.

A feedforward system that is too aggressive will *over-compensate* for load changes, resulting in an effect on the PV that is opposite what you would expect the load change to do. A feedforward system that is not aggressive enough will still see load changes having predictable effects on the PV. The basic "aggressiveness" of a feedforward loop is set by a *gain* adjustment in a gain/bias function block placed between the feedforward sensor's analog input function block and the summer block where the feedforward signal gets combined with the PID controller's output (going to the final control element).

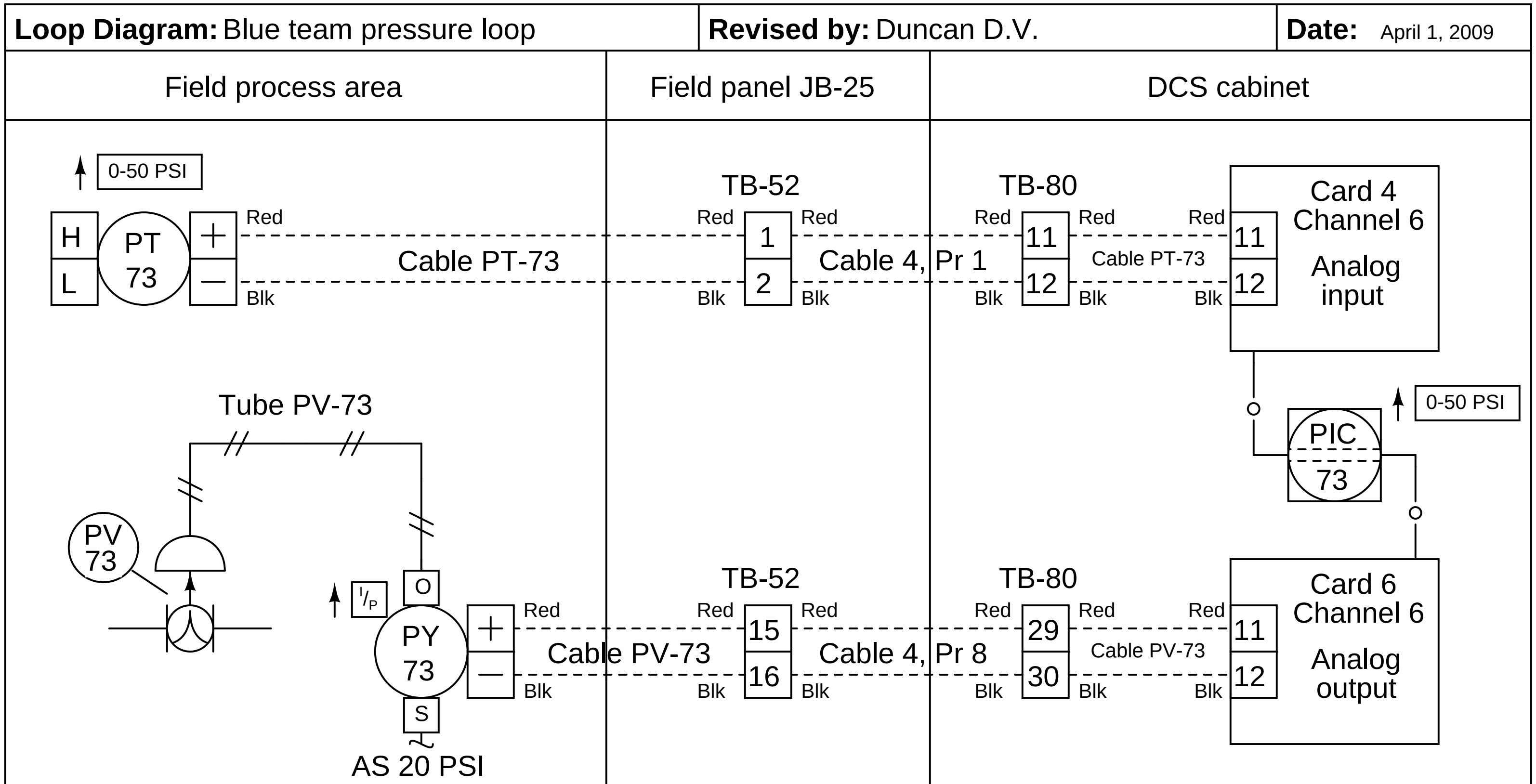
If you find that the feedforward action *eventually* cancels out the effects of load changes, but still exhibits effects on the PV for a short while before things settle out, it is a good indication you need to add *dynamic compensation* to the feedforward loop. This will take the form of a *lead/lag* function block, or possibly a *dead time* function block. Adjustments to the parameters of these functions should only be attempted after the basic gain/bias function in the feedforward loop has been properly "tuned" for good steady-state control. If you find that the feedforward action is initially "too much," then you need to delay its effects by adding lag time (or dead time) to the feedforward signal. If you find that the feedforward action is initially lagging (too late to completely cancel the load change), then you need to add lead time to the feedforward signal.

file i00921

Sample Loop Diagram (using a single-loop controller)

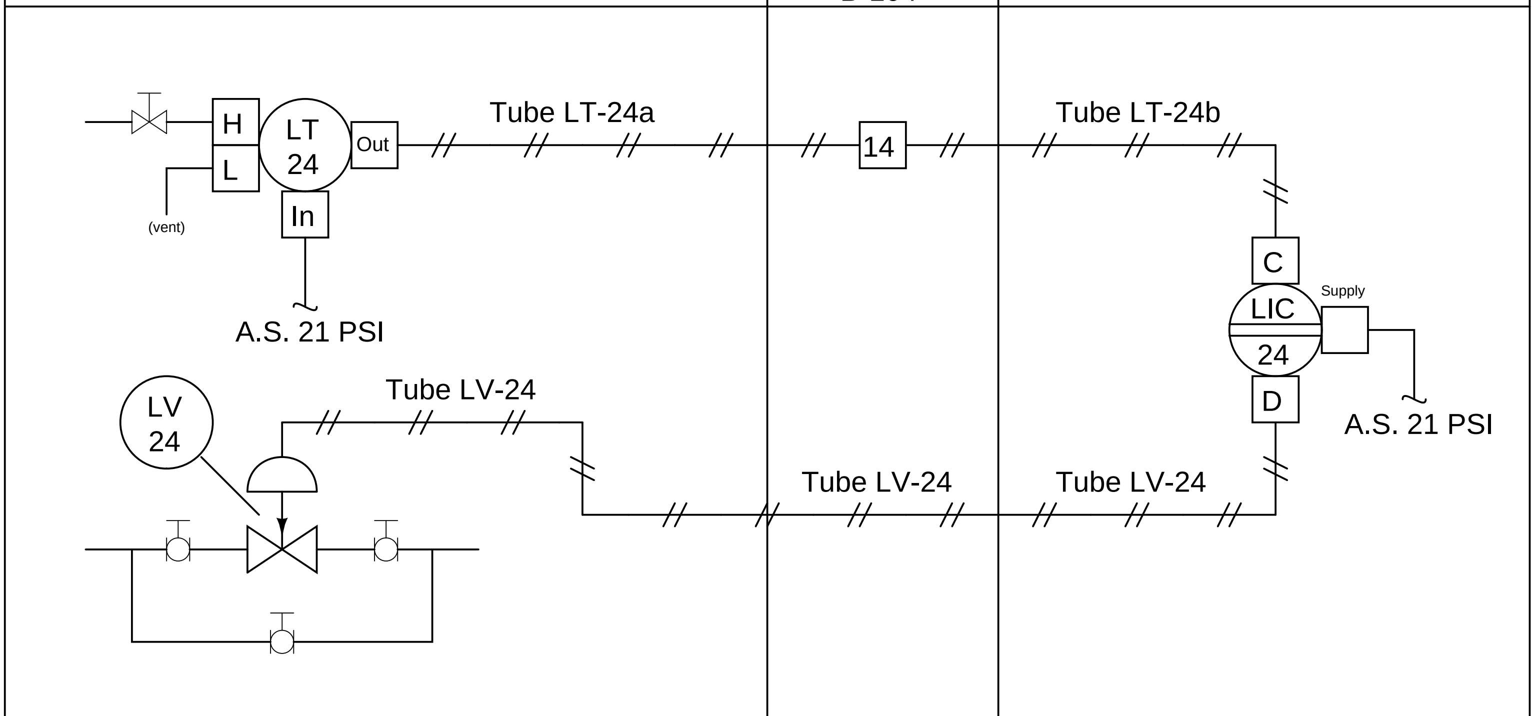


Tag #	Description	Manufacturer	Model	Input range	Output range	Notes
TE-205	Thermocouple	Omega			Type K	Ungrounded tip
TT-205	Temperature transmitter	Rosemount	444	0-1500° F	4-20 mA	Upscale burnout
TY-205a	Resistor	Vishay			250 Ω	
TIC-205	Controller	Siemens	PAC 353	1-5 V	0-1500° F	Reverse-acting control
TY-205b	I/P transducer	Fisher	546	4-20 mA	3-15 PSI	
TV-205	Control valve	Fisher	Easy-E	3-15 PSI	0-100%	Fail-closed



Tag #	Description	Manufacturer	Model	Input range	Output range	Notes
PT-73	Pressure transmitter	Rosemount	3051CD	0-50 PSI	4-20 mA	
PIC-73	Controller	Emerson	DeltaV	4-20 mA	4-20 mA	HART-enabled input Direct-acting control
PY-73	I/P transducer	Fisher	846	4-20 mA	3-15 PSI	
PV-73	Control valve	Fisher	Vee-ball	3-15 PSI	0-100%	Fail-open

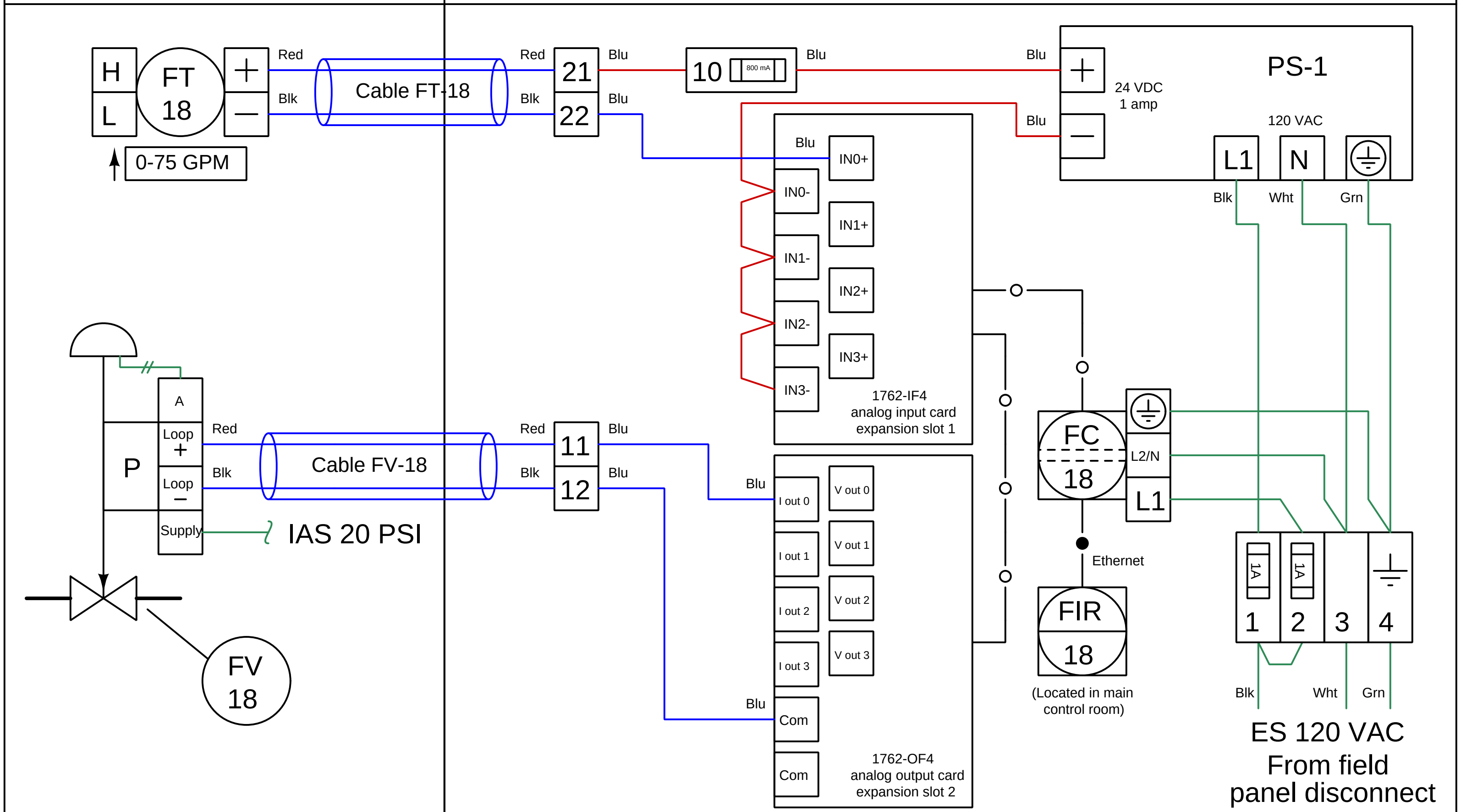
Loop Diagram: Sludge tank level control	**Revised by:** I. Leaky	**Date:** April 1, 2008
Process area	Bulkhead panel B-104	Control panel CP-11



Tag #	Description	Manufacturer	Model	Input range	Output range	Notes
LT-24	Level transmitter	Foxboro	13A	25-150 "H_2O	3-15 PSI	
LIC-24	Controller	Foxboro	130	3-15 PSI	3-15 PSI	
LV-24	Control valve	Fisher	Easy-E / 667	3-15 PSI	0-100%	Fail closed

Loop Diagram: Unit feed flow control	**Revised by:** A. Bradley	**Date:** April 1, 2013

Process area	Field panel FP-25



Tag number	Description	Manufacturer	Model	Calibration	Notes
FT-18	Flow transmitter	Rosemount	3051S	0-100" WC input 4-20 mA output	Square-root characterization
FC-18	PLC	Allen-Bradley	ML1100	1762-IF4 input 4-20 mA 1762-OF4 output 4-20 mA	IP = 169.254.10.9 Mask = 255.255.0.0
FIR-18	HMI touch-panel	AutomationDirect	C-More		
FV-18	Flow valve with positioner	Fisher	ED / 667 DVC6010	4 mA = fully closed 20 mA = fully open	Fail-closed

Lab Exercise – loop diagram and system inspection

Each team's system will undergo an inspection simulaneous 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.*
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- 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.
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- 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 seperation lines on the diagram.
- Each diagram must be sufficiently detailed so that no other student will have difficulty locating components (e.g. *"Where is the controller for this loop?"*) or determining important configuration parameters (e.g. range settings).

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

Common mistakes:

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

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

file i00654

Question 93

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!

Capstone assessment check-list (listed in sequential order) Name: ________________

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 (*INST241 only*)	
Instructor selects setpoint/load & SP value (*INST252 only*)	@ SP =
Instructor selects DAQ variable to measure (*INST260 only*)	
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 (*INST241 only*)	
Controller responds robustly to perturbations (*INST252 only*)	
DAQ measurement correctly scaled and/or graphed (*INST260 only*)	

The time clock stops now! **Stop time:** ________________

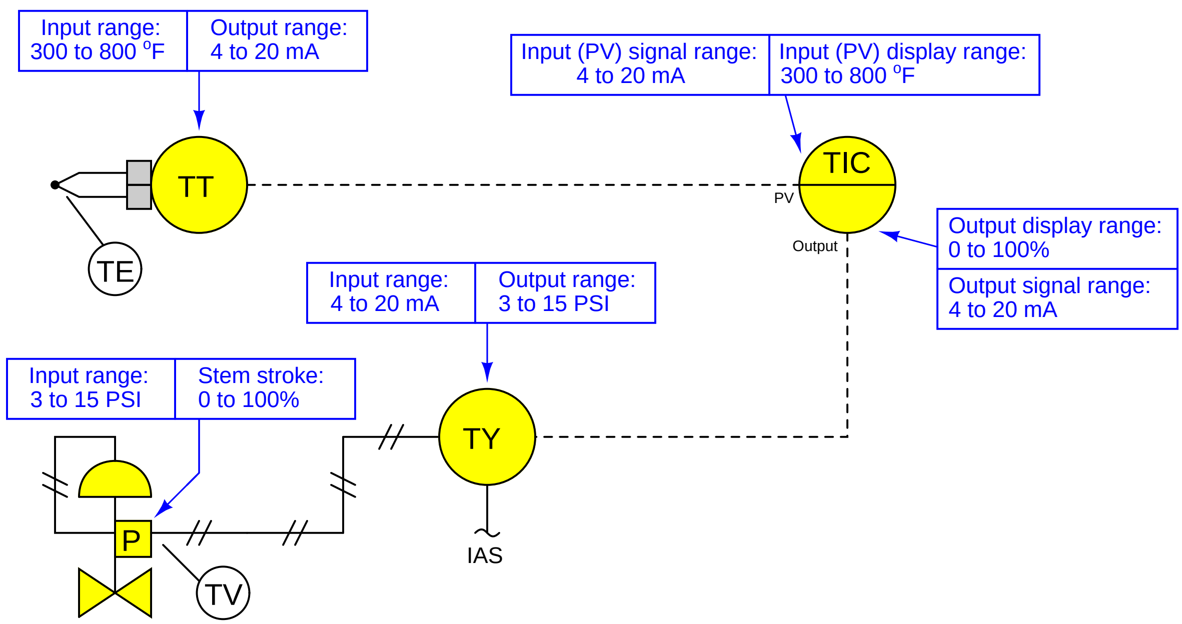
Criterion	**(Instructor verifies)**
Instructor verifies all signal wires/tubes disconnected	
Instructor verifies controller reset to original configuration	
Instructor verifies DAQ is returned to team tool locker	
Instructor collects your diagrams	

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 ^{o}F and output 20 mA when sensing 800 ^{o}F, but the controller must display an indication of 300 ^{o}F when it receives a 4 mA signal from the transmitter, and display an indication of 800 ^{o}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 ^{o}F input (and 4-20 mA output) as well as range the controller to display 300-800 ^{o}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.

- 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*

file `ranging`

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

- 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:

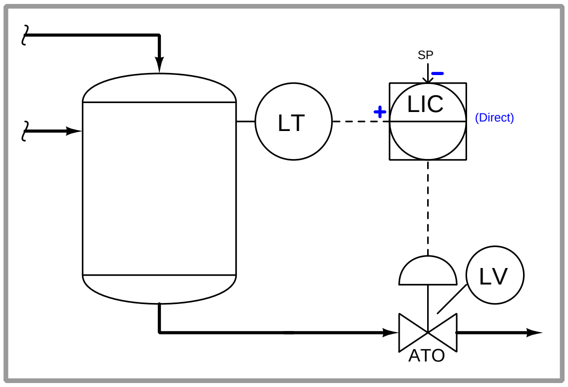
- **P** – a "gain" value of less than one (i.e. a "proportional band" value of at least 100%).
- **I** – a "reset" value of zero repeats per minute, or the largest value possible for minutes per repeat.
- **D** – a "rate" value of zero.

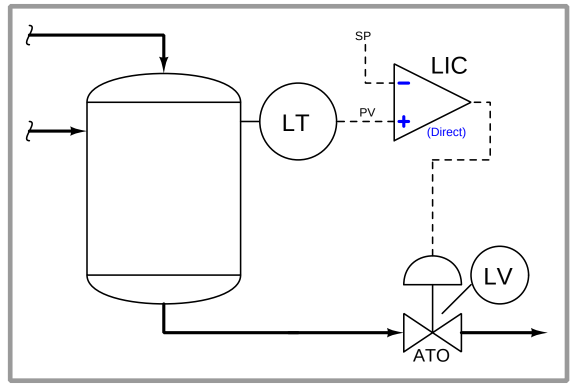
Mind you, these parameters will not yield *good* control, but merely *stable* control. In other words, these tuning parameter values will make the controller fairly unresponsive, but at least it won't oscillate out of control. Also bear in mind that having an integral (reset) value set for minimum action (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.

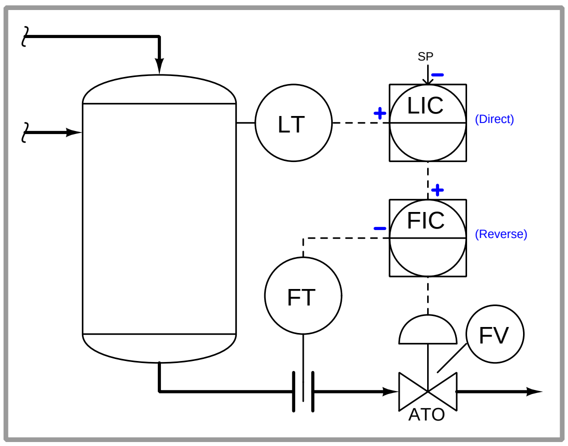
file `control`

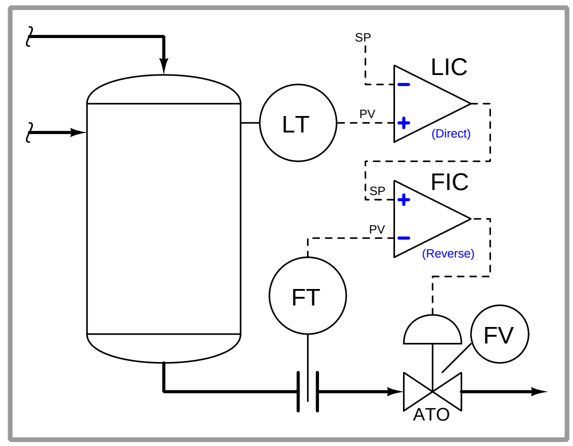
file i00998

Answer 1









Note that the words "direct" and "reverse" are redundant to the "+" and "–" labels. A controller with a "+" label at its PV input is by definition direct-acting; a controller with a "–" label at its PV input is by definition reverse-acting.

Answer 2

Answer 3

Answer 4

Partial answer:

Both flow controllers must be *reverse-acting*. The filter level controller must be *direct-acting*, while the clearwell reservoir level controller must be *reverse-acting*. In the event of a water supply failure, the clearwell will fail low (become empty).

Answer 5

Partial answer:

- What is the purpose of the multiplier function? *To establish a target value for percentage of fuel that is waste fuel.*

- Why would the waste fuel ratio setpoint ever be set at a value other than unity (100%)? *Perhaps the waste fuel does not burn clean, and 100% usage would create emissions problems, so it must be "diluted" at a prescribed ratio with clean, purchased fuel.*

- How would the control system respond if the waste fuel source suddenly ran out, so that waste fuel flow dropped to zero? *The purchased fuel valve would open as necessary to maintain the same total fuel flow as directed by the firing rate demand signal.*

Answer 6

Partial answer:

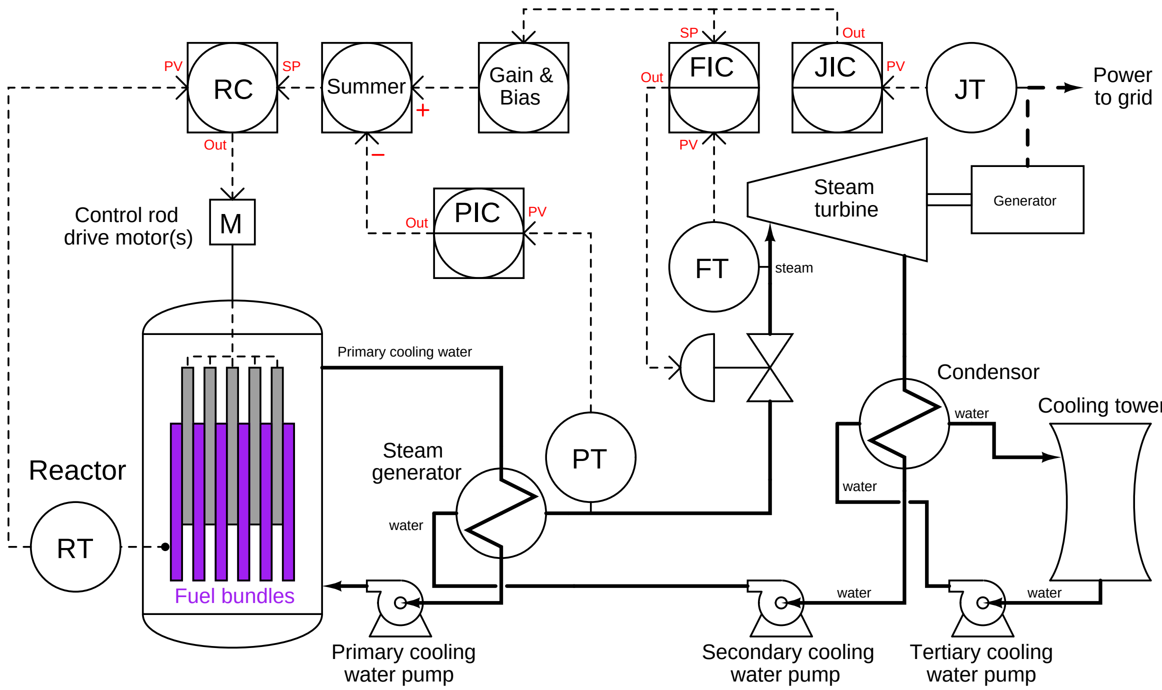
Fault	**Possible**	**Impossible**
Filtering media clogged		
FV-44 failed wide open		√
FV-44 failed fully shut		
FV-35 failed wide open		
FV-35 failed fully shut	√	
FT-44 failed with high signal		
FT-35 failed with high signal		
Effluent pump shut off		

Answer 7

Partial answer:

Perhaps the most significant load on the scrubber vessel's pH control loop is the incoming ammonia vapor flow rate from the top of the neutralizer vessel (V-6), since any changes in this flow rate will alter the rate at which ammonia vapor reacts to raise the pH of the scrubber's water.

Answer 8



- RC = reverse action
- PIC = direct action (assuming its output goes to the "−" input on the summer; reverse action would be appropriate if both summer inputs were "+")
- FIC = reverse action
- JIC = reverse action

The power controller (JIC) and steam pressure controller (PIC) both have local setpoint values. The neutron flux controller (RC) and flow controller (FIC) are cascade slave units.

The feedforward signal path is from the power controller (JIC) output to the lead/lag function, and then to the gain/bias function. When the power controller calls for more power, it not only cascades an increased setpoint value to the steam flow controller, but it also feeds that information to the neutron flux controller to call for a greater reactor power output.

Since we know that a sudden change in steam flow has a faster effect on steam header pressure than a sudden change in control rod position, the lead/lag function must be configured to *lead* in order to give the control rods a "head start" on preempting the effect of steam flow rate changes on steam pressure. This will improve the reactor's response to changes in power demand.

Answer 10

Perhaps the most significant load on the rundown tank's level control loop is the incoming flow rate from the neutralizer vessel (V-6) through the line with the three pH transmitters, since any changes in this flow rate will cause the level controller (LIC-26) to take corrective action to maintain level at setpoint.

The feedforward transmitter for this load, of course, will be a flow transmitter added to the line carrying ammonium nitrate from V-6 to V-7. This transmitter's signal will pass through a gain/bias function and then (possibly) through a lead/lag function before entering a summer function placed between LIC-26 and FIC-25. This way, the proportioned feedforward signal will be added to the cascaded setpoint of FIC-25 calling for more or less discharge flow from V-7 in accordance with the amount of flow entering V-7 from V-6.

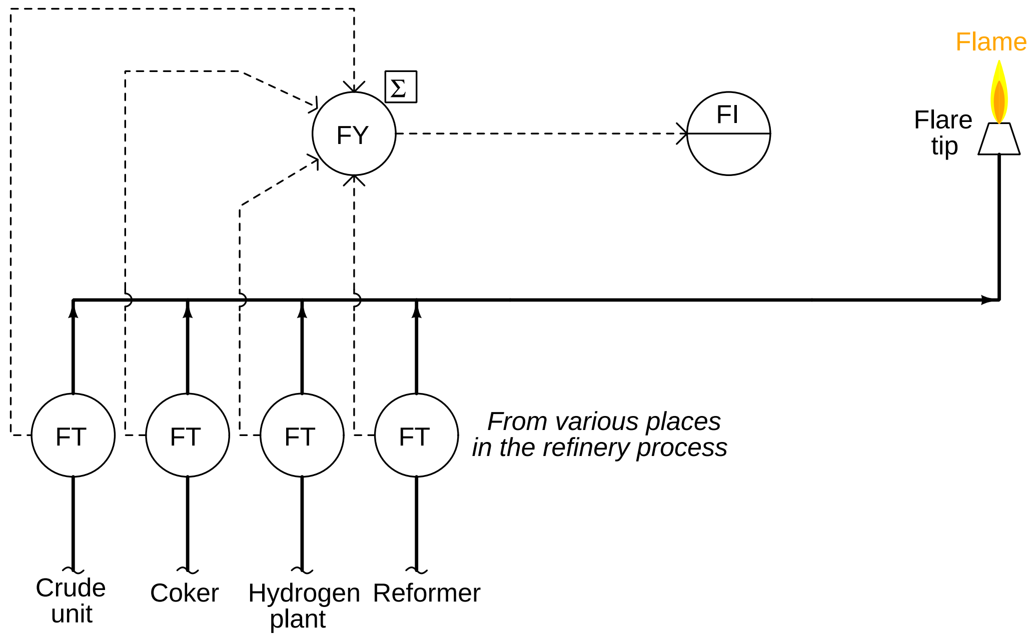
Answer 11

Cascade control works by adding another controller before the final control element, taking setpoint orders from the original loop controller to ensure the manipulated variable holds to that value. In this application level controller LIC-35 directly controls valve LV-35 to admit make-up water to the scrubber as needed to maintain a constant level in that scrubber. Water supply pressure is a load to level control because changes in water supply pressure will directly affect flow rate into V-5 for any given valve position, forcing level controller LIC-35 to compensate as it sees liquid level drift off of setpoint.

To add cascade control to this application, we would first need to add a flowmeter to the make-up water line so that we could monitor the rate of water flow into V-5. Then, we would add a flow controller (FIC) to the loop, sensing flow from the new transmitter and taking the output of LIC-35 as a remote setpoint. The control valve (LV-35) would now be driven by the output of the flow controller rather than by the output of the level controller.

Assuming signal-to-open action for LV-35, the new flow controller would need to be configured for *reverse action* (i.e. commanding LV-35 to close down if flow exceeds the setpoint given by LIC-35).

Answer 12



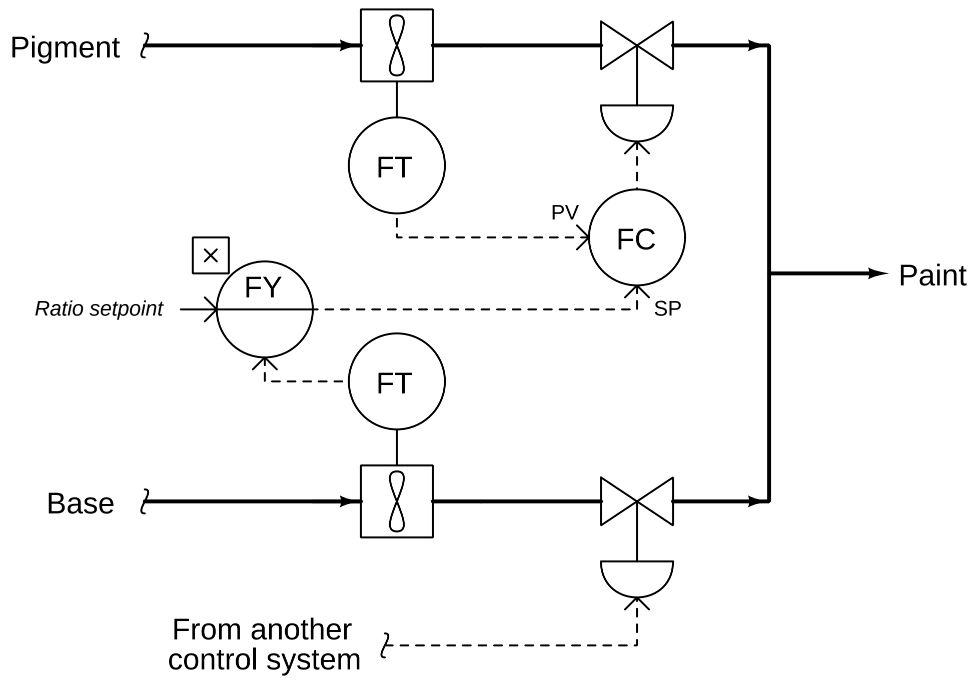
Answer 13

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

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

Answer 14

This is the more stable control system of the two:



The other control system was unstable because the gain of the flow control loop varied with the "wild" flow, as well as with the ratio setpoint. If this is not immediately apparent (which it usually isn't to most), imagine a case where we were trying to maintain a 1:1 ratio with 50 GPM of pigment and 50 GPM of base, both flowmeters being ranged for 0-100 GPM. A 1% change in pigment flow would equate to a 2% change in ratio (51 GPM base / 50 GPM pigment = 1.02 pigment:base ratio):

Answer 15

The fundamental problem here is that the *process gain* varies inversely to flow rate. During the rainy seasons when the lagoon captures rainwater and the influent flow rate is high, it takes a big change in valve position to make a significant difference in chlorine concentration. When the weather is dry and the influent flow rate is low, even small moves in valve stem position generate large changes in chlorine concentration.

The multiplication relay (or adaptive gain controller) attempts to keep the overall *loop gain* constant despite changes in process gain.

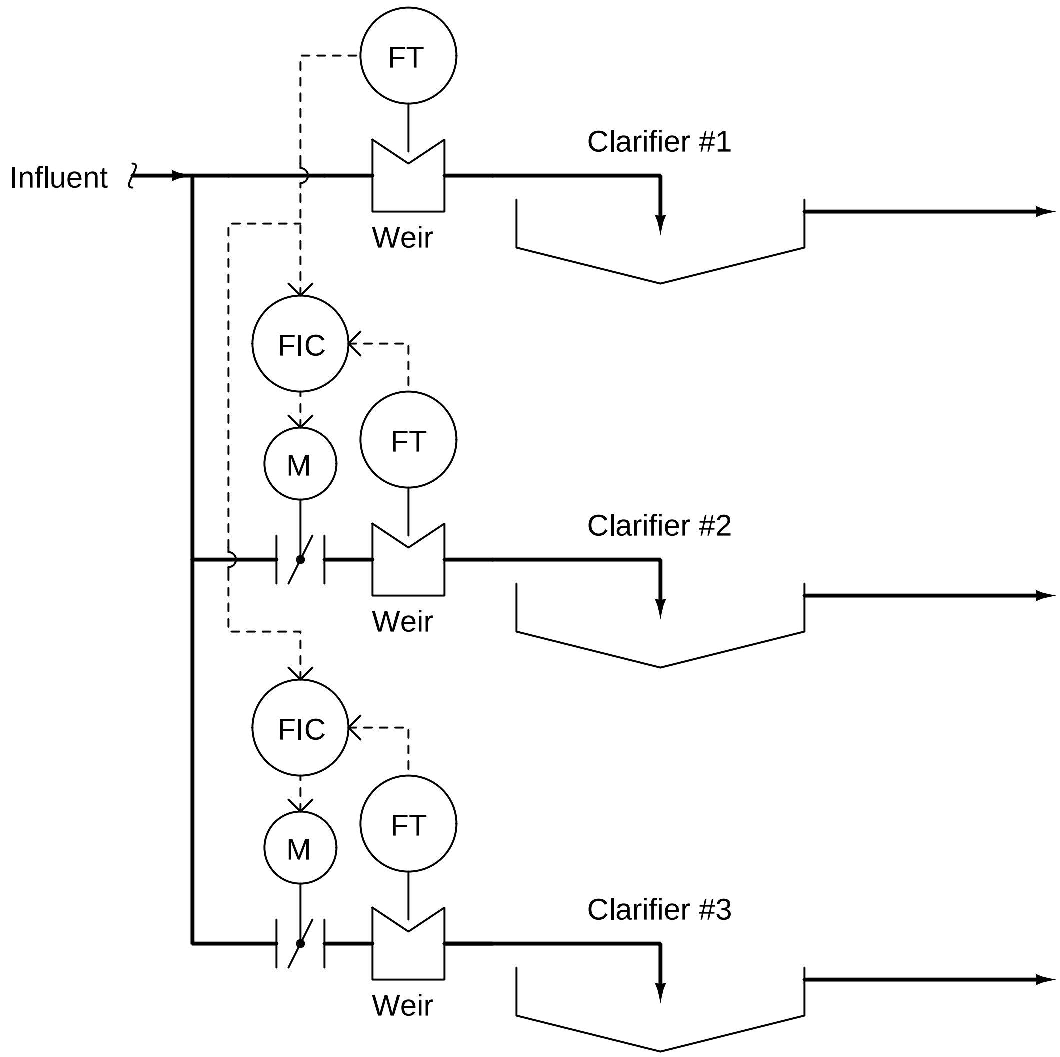
Answer 16

This control scheme tries to minimize the water flow rate through one clarifier while running the other clarifier(s) at a maximum flow rate value set by the HIC.

The secret to understanding how this scheme works is to realize the total influent flow rate is fixed (coming from customers sending wastewater to be treated). Opening up any one valve "steals away" water from the other clarifiers, such that each valve has an influence over *all* clarifier flow rates!

Answer 17

Here is a simple solution, using 1:1 ratio control to make the bottom and middle clarifiers match flow with the top clarifier:



Answer 18

The controller should be configured for direct action, since we wish to have more steam flow for greater differential temperature.

Note: derivative control action helps overcome lag in the thermocouple sensing elements and in the steam response by acting as a *lead* element.

Since no amount of steam injection can reduce the radiant thermocouples' sensed temperature down to ambient, a controller with integral would experience reset *windup* under most conditions.

Answer 19

The control strategy as found attempts to regulate level and maintain minimum flow using a weird split-range sequence between two control valves. The valve letting liquid away from the vessel works over a 32% to 100% signal range, while the recirculating valve works over a 0% to 75% signal range.

This is what split-ranging means: to have more than one valve operate off of one controller signal, usually each valve operating on a different portion of that signal's range.

Mr. Brown's revised control strategy makes far more sense: the level controller operates one valve over its full range, while a separate flow controller monitors pump flow and ensures minimum flow by opening the recirculating valve when needed to supplement the out-going flow rate.

If the control system used to implement the original strategy is a PLC or DCS, there probably exist some unused analog I/O points which may be pressed into service for a control loop. The actual control algorithm is merely software running in the PLC or DCS, and so costs nothing to add.

A "heavily damped" transmitter is one with a large filter time entered into it. This is a problem in any feedback control loop because the damping adds phase shift, which makes oscillation more likely.

Answer 20

Partial answer:

Both flow controllers must be *reverse-acting*. Both level controllers must also be *reverse-acting*. In the event of a water supply failure, both levels will fail low (become empty).

Answer 21

Answer 22

Answer 23

Answer 24

Both air and activated sludge flow rates to the aerator are controlled in accordance with the flow rate of the incoming wastewater (discharged from the primary clarifier). A low limit relay maintains a minimum flow rate of air into the aerator to maintain an aerobic bacterial culture and to prevent sludge from compacting at the bottom during periods of low wastewater flow.

Answer 25

Answer 26

Answer 27

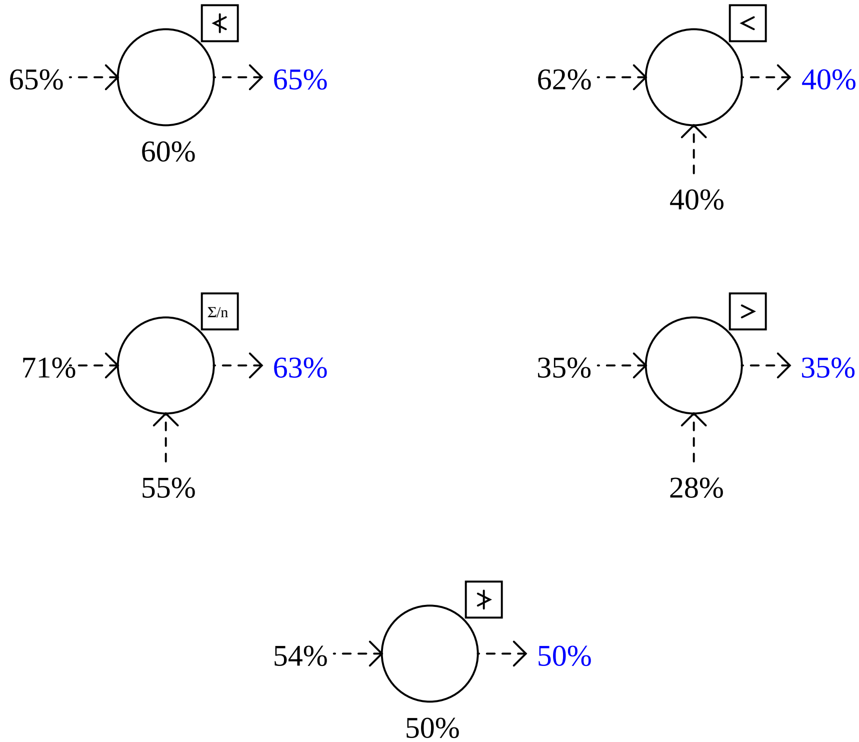
The two "select" relays ensure the air/fuel ratio will always err on the side of too lean (instead of too rich) during quick changes in firing rate demand.

Both flow controllers need to be *reverse* acting.

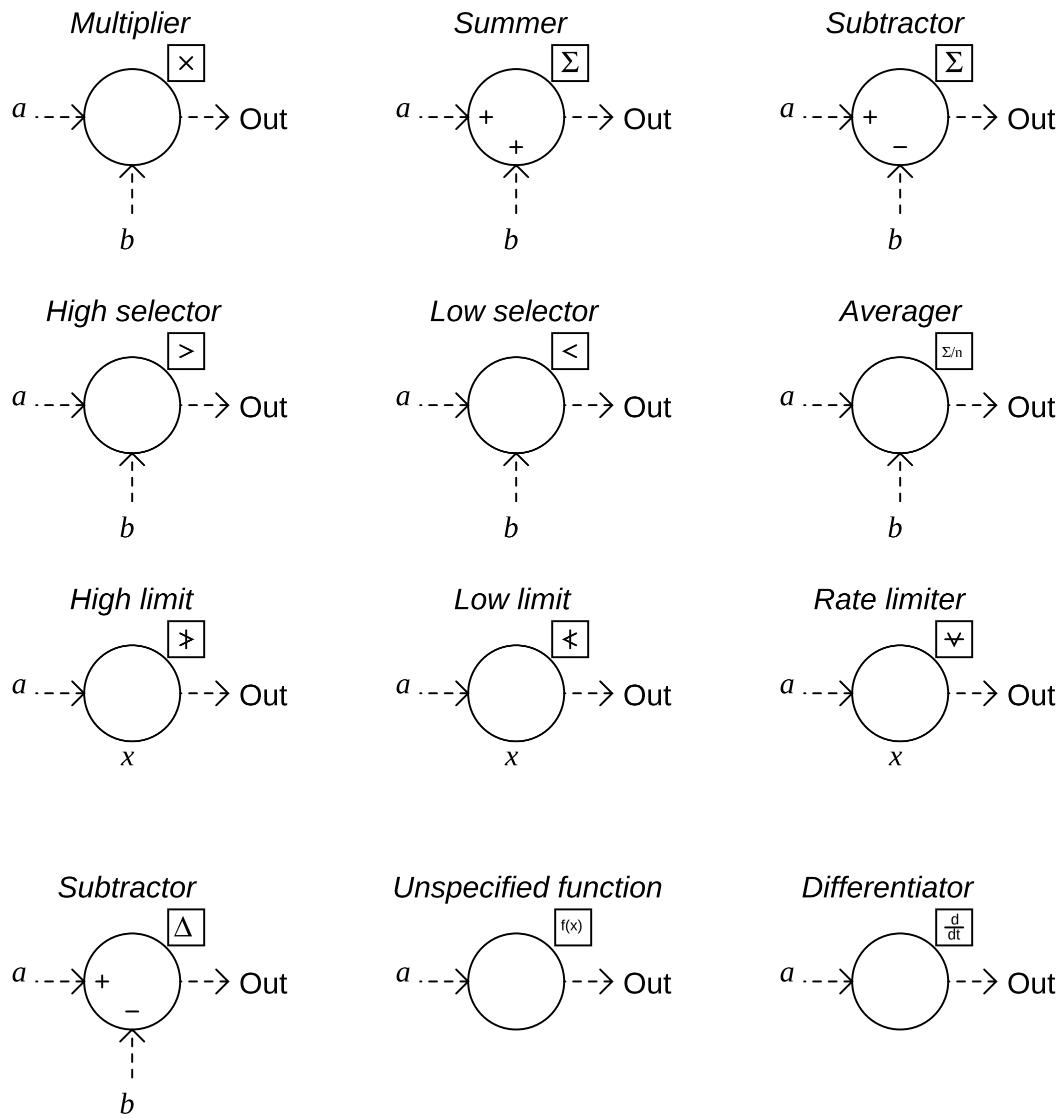
The oxygen controller needs to be *direct* acting.

Answer 28

Answer 29



Answer 30



Answer 31

- r = Setpoint (*Reference*)
- e = Error (SP − PV)
- m = Controller output (*Manipulated* variable)
- c = Process variable (*Controlled* variable)
- q = Load

The circle with the Σ symbol in it represents the portion of the PID controller where error (e = SP − PV) is calculated. The actual PID algorithm is symbolized by the box with "PID" written inside it.

Answer 32

This diagram shows the dynamic elements of a process (gain, lag, and dead time) represented as separate blocks, for more convenient analysis within a simple feedback control loop.

Answer 33

In order from first to last:

- Cascade
- (Pure) feedforward
- Feedforward with trim
- Ratio

Answer 34

If the setpoint (r) increases, the PID control block will output an increased manipulated variable signal (m). This increased controller output will affect the process, (eventually) increasing the process variable (c). The model, internal to the controller, also responds to the increased PID output. The gain and lag time portions of the controller's model respond immediately to the change in output, feeding back that information to the error summer so that the PID block may begin to control a "virtual" representation of the process without any dead time. Meanwhile, the process response delayed by dead time is still propagating through the dead time block of the model, and the dead time of the real process.

When the response finally propagates through the dead time of process and model, the result should be the same (if the model is accurate). These equal changes in process response cancel each other out at the subtraction block at the far right of the diagram, so that all the PID block "sees" is the gain and lag time of the process.

Answer 35

Normal output = 1062 ^{o}F

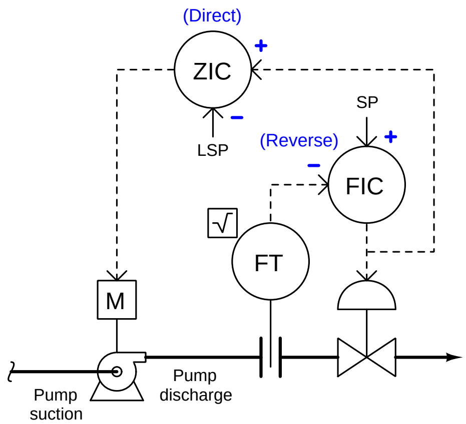
Output with failed TY-25c = 500 ^{o}F

Answer 36

The three level transmitters (LT-38a, LT-38b, and LT-38c) are supposed to be *redundant* to each other: all sensing the exact same liquid level inside the fractionator tower, but using different technologies. The selector function used between these three transmitters is a *median-select*, choosing the middle value of the three. This essentially functions as a "best-2-out-of-3" selector because if any one transmitter gives a reading significantly different from the other two it will be de-selected by LY-38.

The problem with the instrument choices in this application is that of the differential pressure (DP) based transmitter LT-38a and the displacer (buoyancy) based transmitter LT-38b. Both of these instruments' calibrations are affected in the exact same way by changes in liquid density. Therefore, if the density of the liquid in the bottom of the fractionator tower were to change significantly for some reason, as can happen during start-up, shut-down, or "upset" conditions, those two transmitters will output the same erroneous results. With two out of the three transmitters agreeing with each other, the selector function LY-38 will choose the wrong level measurement signal and reject the signal given by the float-type transmitter LT-38c even though that transmitter will not be affected by the change in liquid density and will be reporting the correct level value.

Answer 37

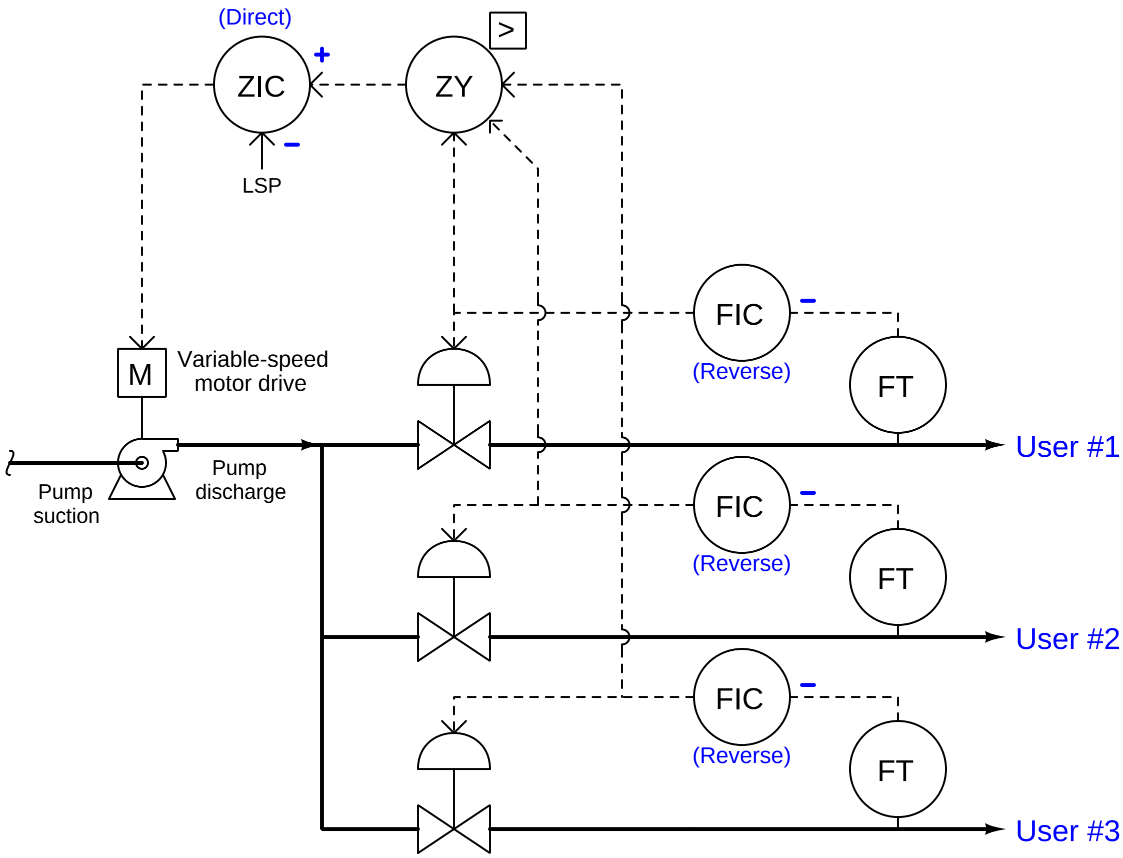


If the flow rate suddenly increases due to some load, the control valve will immediately pinch down to bring the flow back to setpoint. However, the position controller will notice the new (lower) valve position and slowly turn down the pump's speed to allow the control valve to open back up to its former position where it is less restrictive and therefore wastes less pumping energy.

If the flow rate suddenly decreases due to some load, the control valve will immediately open up to bring the flow back to setpoint. However, the position controller will notice the new (higher) valve position and slowly turn up the pump's speed to allow the control valve to close back down to its former position where it has more freedom of motion to control flow.

It is bad to configure a controller for a faster response than its final control element is able to respond. Since the electric motor is slower-responding than the control valve, the valve's controller must be tuned "faster."

Answer 38



Here, the pump speed is controlled according to the position of the *furthest-open* control valve.

Answer 39

Answer 40

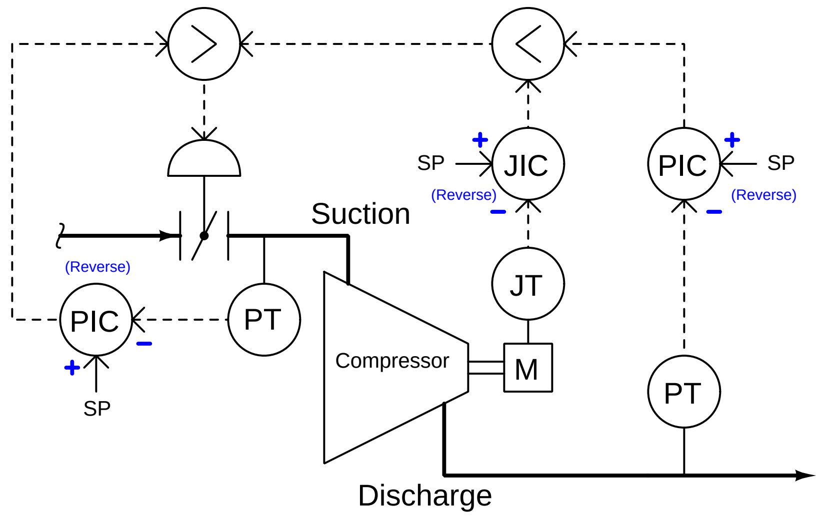
Answer 41

Answer 42

Answer 43

Answer 44

The power controller (JIC) ensures the suction valve can never open up far enough to overload the motor, while the suction pressure controller ensures the suction valve can never close off far enough to draw sealing oil into the compressor.



Answer 45

Partial answer:

Both flow controllers must be *reverse-acting*. Level controller LIC-2a must be *reverse-acting*. Level controller LIC-2b must be *direct-acting*. Level controller LIC-4 must be *reverse-acting*. In the event of a water supply failure, the clearwell will fail low (become empty) while the filter retains (almost) all its water.

Answer 46

This is an example of an *override* control scheme: where one controller "takes priority" over another controller under certain process conditions.

Answer 47

Back-calculation signal lines are essential for letting the non-selected function block(s) "know" what is going on "downstream" in the function block signal path. Without these back-calculation lines in place, the de-selected control blocks would be completely unaware they were being de-selected, and would keep trying to control the process even though they had no control.

Answer 48

Partial answer:

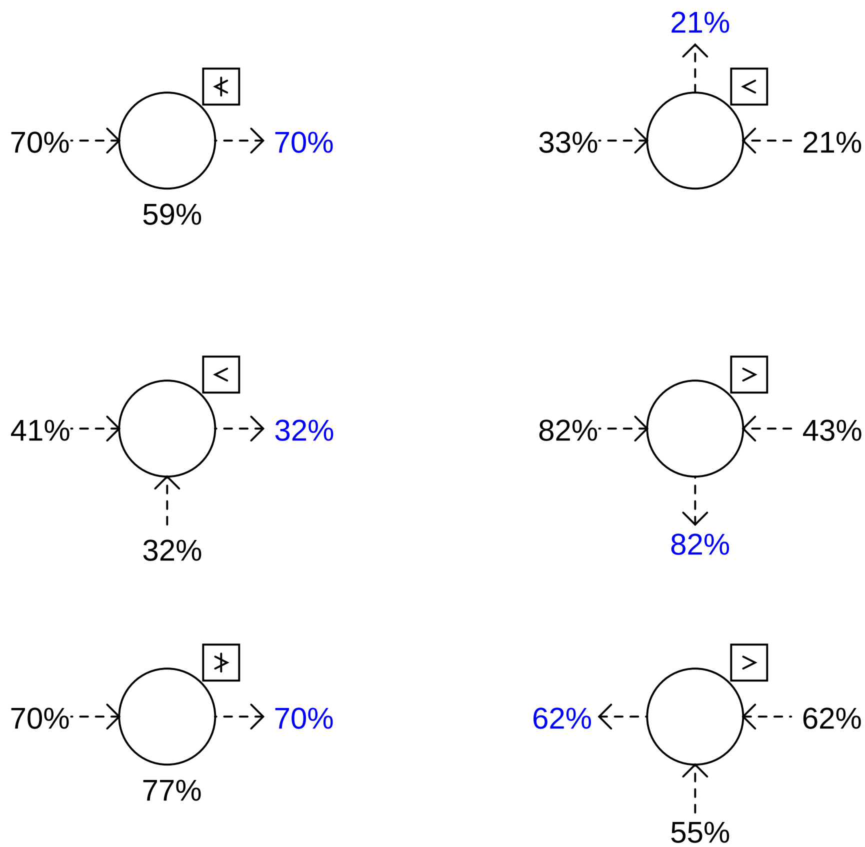
The PC is currently in control, overriding the FC.

Answer 49

Under normal conditions, the engine's power output is regulated by the voltage controller (EIC). However, if engine temperature ever exceeds the safe operating setpoint, the temperature controller (TIC) overrides the voltage controller by calling for reduced engine power. The low-select function selects which ever controller is calling for the *least* amount of engine power.

Either a failed-high temperature transmitter or a failed-high voltage transmitter would call for zero power output by the engine.

Answer 50

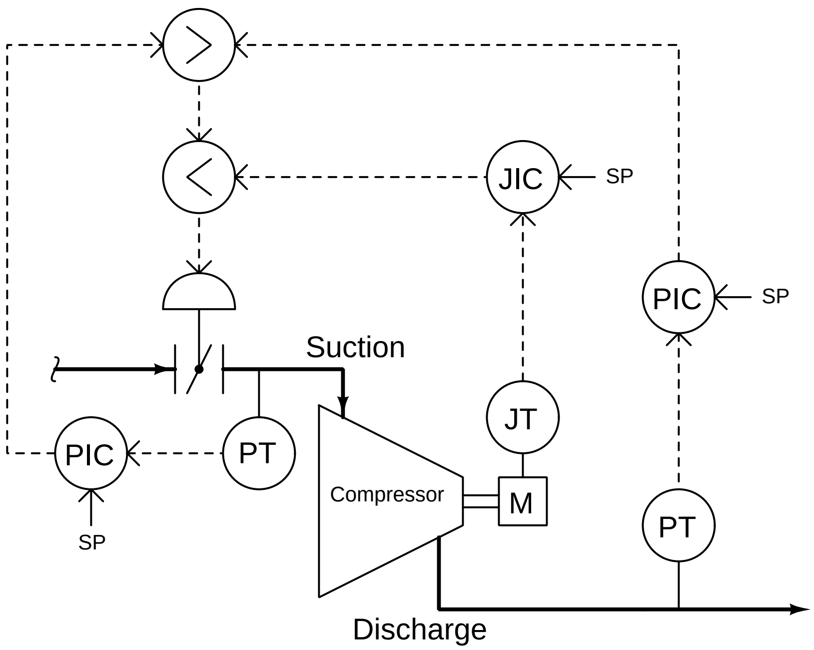


Note that the placement of each input signal is irrelevant to the selection of that signal. Only the signals' values matter!

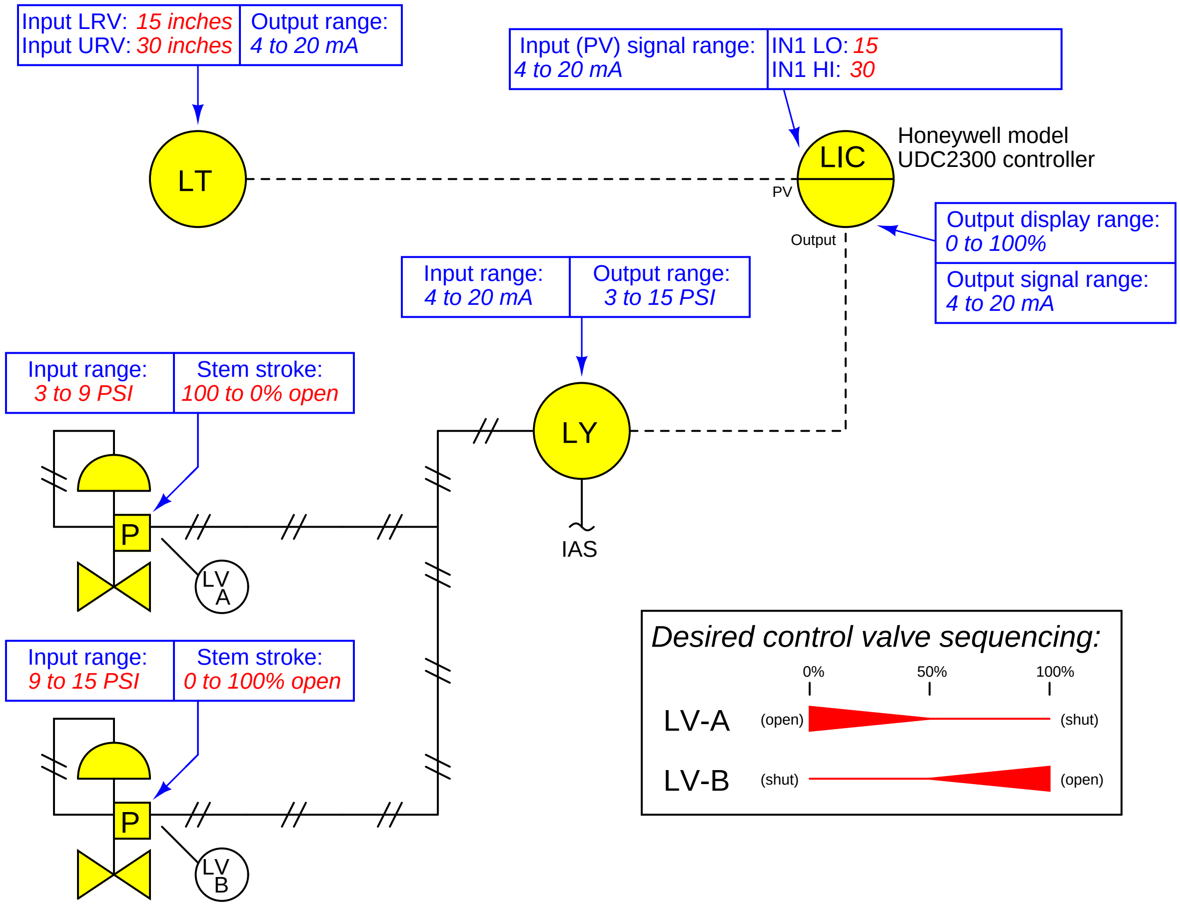
Answer 51

Diagnostic test	**Yes**	**No**
Measure AC line voltage		$\surd$
Measure DC power supply output voltage	$\surd$	
Inspect PID tuning parameters in controller	$\surd$	
Check pressure transmitter calibration	$\surd$	
Measure transmitter current signal	$\surd$	
Put controller into manual mode and move valve	$\surd$	
Measure DC voltage between TB1-3 and TB1-4	$\surd$	
Measure DC voltage between TB1-7 and TB1-8	$\surd$	

Answer 52



Answer 53



Answer 54

Answer 55

Answer 56

Answer 57

Answer 58

Answer 59

Answer 60

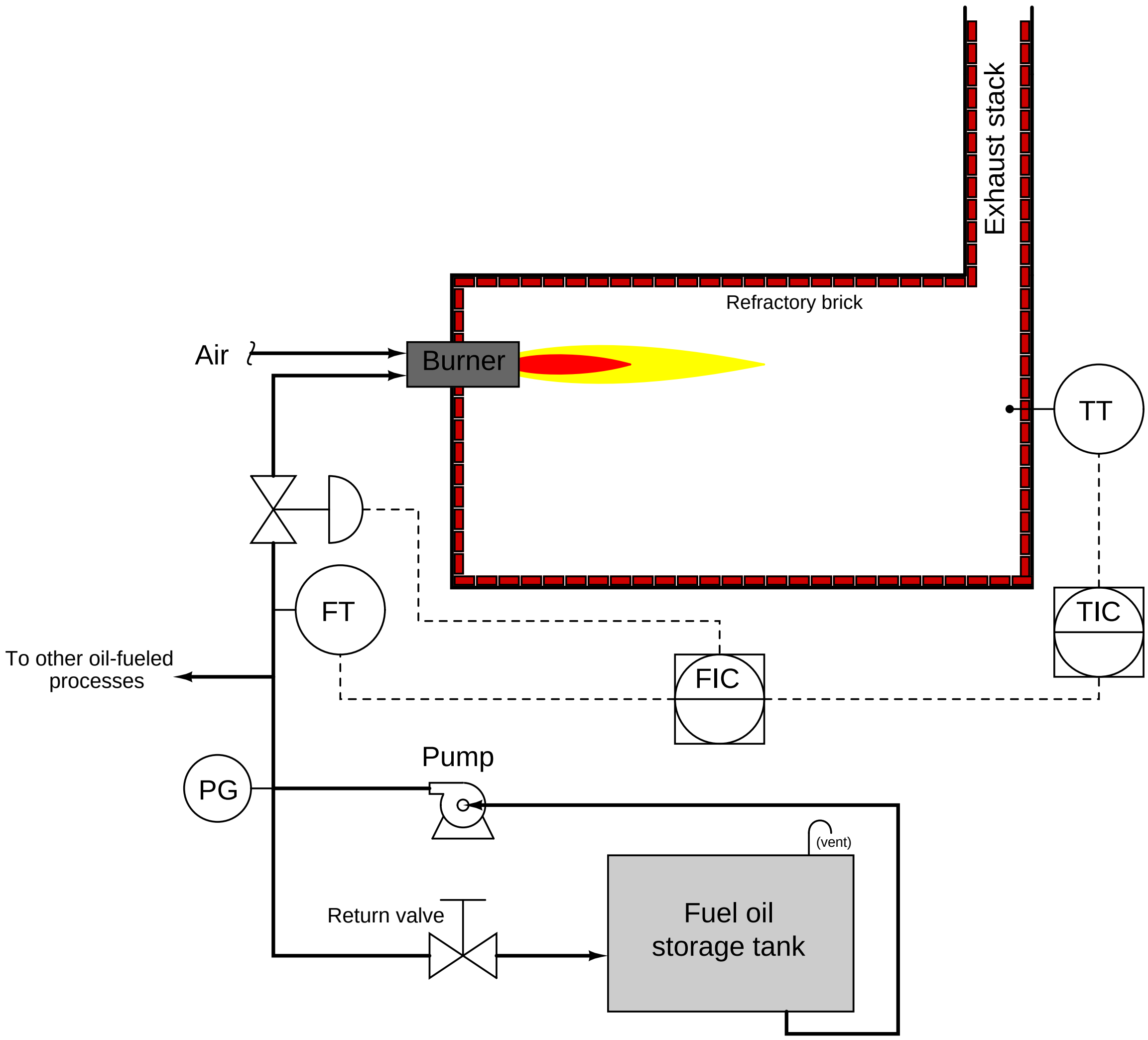
Answer 61

Answer 62

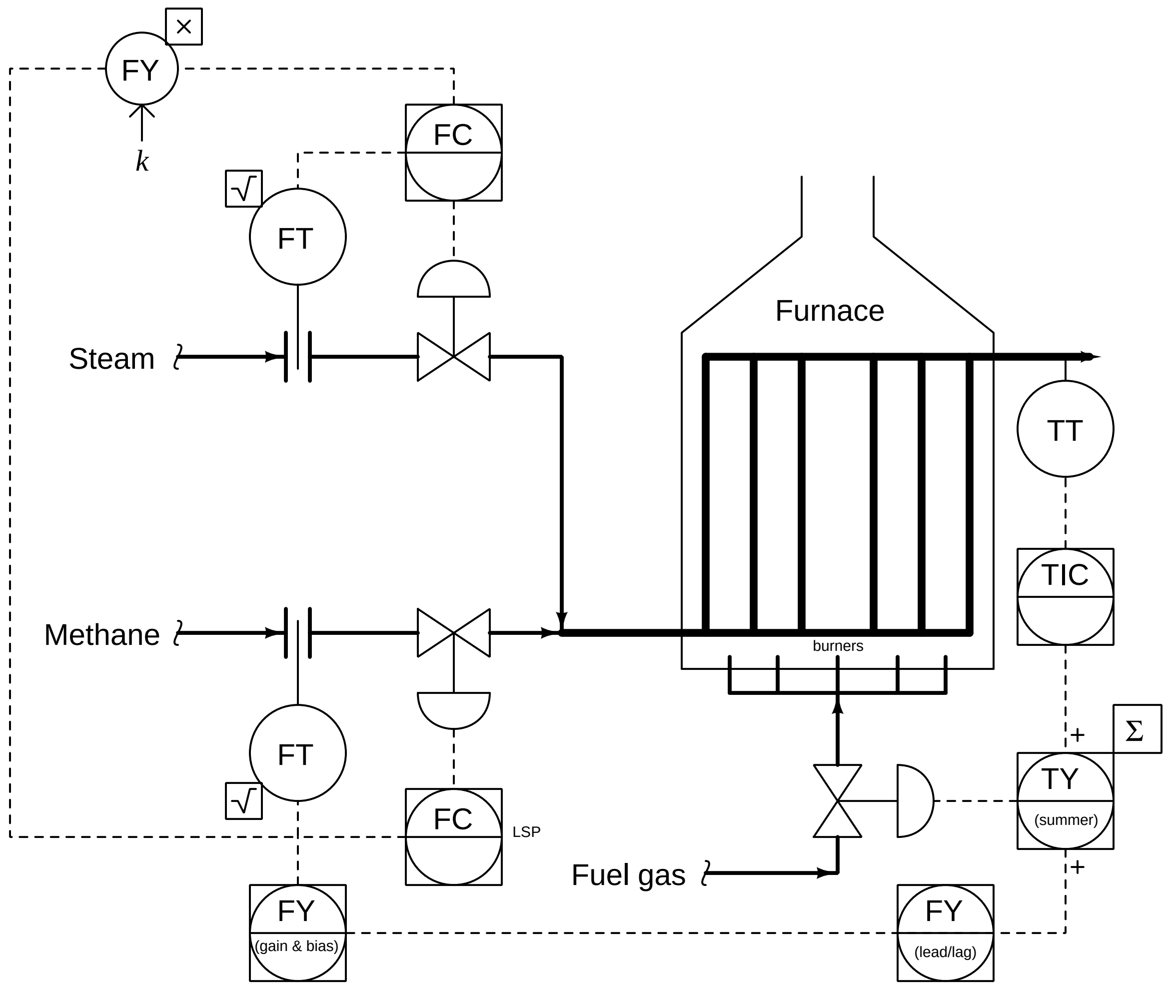
Here is one possibility: *the steam valve is jammed open and cannot shut far enough.*

Answer 63

There are multiple solutions one could implement to fix this problem. Here is one:



Answer 64



Answer 65

Right now there is too much *gain* in the feedforward signal path, which means the feedforward control is *overcompensating* for changes in feed flow.

Answer 66

Answer 67

Answer 68

Fault	Possible	Impossible
No AC power to VFD	√	
Controller has dead 4-20 mA output	√	
Level transmitter out of calibration		√
Level switch contacts failed shorted		√
Level switch contacts failed open		√
250 ohm resistor failed open		√
Cable between TB12 and TB13 failed open	√	
Cable between TB13 and LSL failed open		√

Answer 69

If the screw on JB1-4 were to come loose, it would interrupt the current to the I/P transducer, thus making its pneumatic output fail low. We know this because the upward-pointing arrow next to FY-42b denotes it as direct-acting (more mA = more air pressure out). With low air pressure to the bypass valve, the valve will fail open (as indicated by the arrow on the valve stem symbol). This will bypass flow from output to input on the compressor, reducing the amount of gas flow to the process.

For your information, compressor surge is a fluid dynamic phenomenon whereby the blades in a non-positive-displacement compressor (e.g. axial or centrifugal vane) "stall" just like the wings of an airplane flying too slowly and/or at too great an angle of attack. When the blades of a compressor stall, they lose "traction" on the compressed gas, unloading the mechanical driver (engine, motor, or turbine) and allowing the compressor to gain speed, then the blades will "un-stall" and re-load the driver, continuing the cycle.

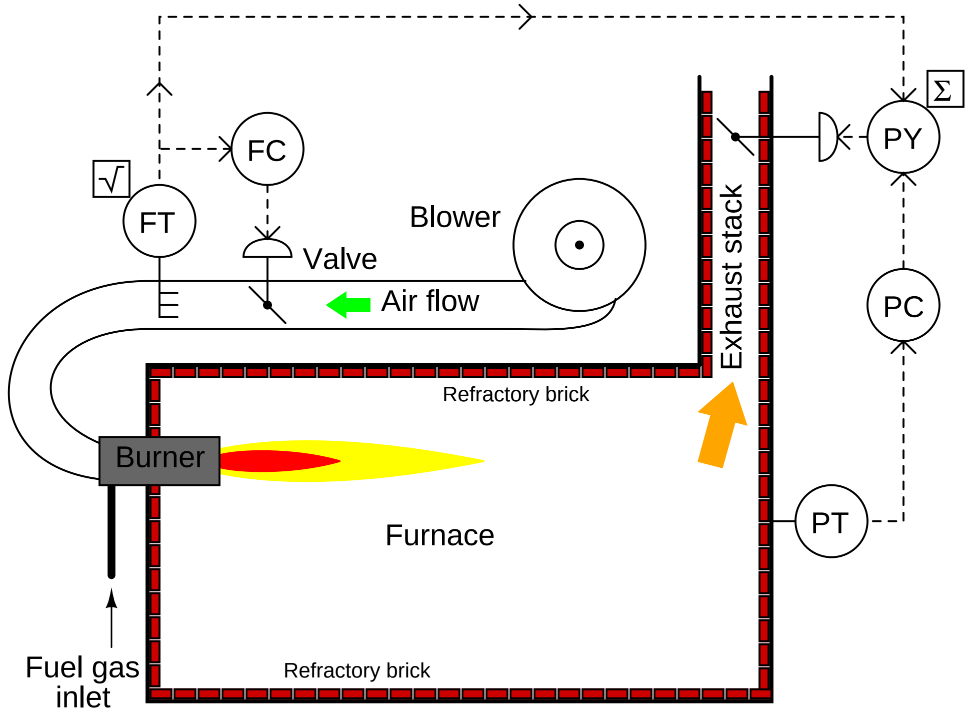
The following passage is taken from Francis Shinskey's excellent book *Energy Conservation and Control*, published by Academic Press in 1978, describing compressor surge:

> "The most demanding aspect of controlling compressors is surge protection. The problem lies in being unable to determine with absolute certainty the degree of approach to surge. Once a compressor begins to surge, it will continue until corrective action is applied, so automatic protection is mandatory. A small centrifugal compressor may surge several times without damage, but a 100,000-hp axial could require reblading after a single incident."
>
> "When a compressor begins to surge, the suction flow falls to zero within a few milliseconds, reverses momentarily, and begins to recover in less than a half second. If the situation is not corrected, the cycle repeats immediately, resulting in a series of thunderclaps less than a second apart. The sudden fall in suction flow can be detected and used to open a recirculating valve, but not before at least one surge cycle is sustained. To prevent surge from developing at all requires a control system which skirts the unstable area altogether."

Answer 70

Since the stack damper is actuated by the flow controller's output in addition to the pressure controller's output, it will move in tandem with the inlet air damper to minimize the effect on furnace pressure. The pressure controller then merely serves a "trim" function.

Challenge question: true feedforward control would look something like this, but it would *not* fix the coupling problem. Explain why:



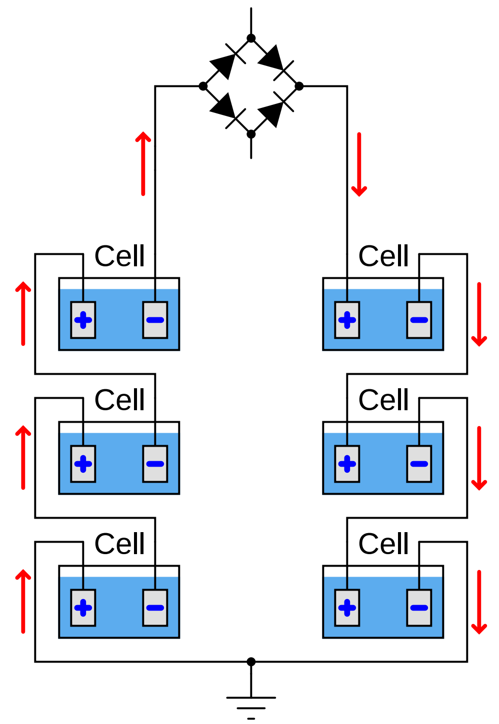
Answer 71

This system varies steam header pressure to keep the furthest-open temperature control valve at 90% opening. The ZIC should be tuned for slow integral action (little or no proportional action, no derivative action): slower than the PIC, which of course must be slower than the boiler's natural response. In tuning these controllers, the PIC should be tuned first, then the ZIC.

It is irrelevant how or when the TIC's are tuned from the perspective of the header pressure control system, as they are not part of the pressure control system, but merely loads.

Answer 72

Electrical current direction (conventional flow notation) and voltage polarities:



Fault	Possible	Impossible
Poor controller tuning	√	
Rectifying diode failed open		√
Rectifying diode failed shorted		√
SCR drive output unstable	√	
Chemical problems in one or more cells	√	
High-resistance earth ground connection		√
IT-1 faulty	√	
IT-2 faulty		√

In this particular scenario, controller tuning would have to be "poor" in such a way that it takes insufficient action to regulate normal variations in cell current. In other words, an *under-tuned* controller is possible because it would behave much the same as a controller placed in manual mode, given the assumption that cell current typically varies in the system.

Variations in cell current may be caused by gas bubbles accumulating and then dissipating at the cell electrodes, effectively varying each cell's resistance randomly over time.

Answer 73

The reason that the technician's proposed test would have been a waste of time is because the issue at hand is a significant disagreement between the vacuum gauge and the controller display. No valve problem or controller output problem could cause this to happen.

A far better test would be to place the pressure controller in manual mode, then vent the pressure transmitter to check that the controller reads 0 PSI. If there is a transmitter calibration problem, it will likely appear as a zero error (not reading 0 PSI at 0 PSI).

Alternatively, one could also perform the same test on the vacuum gauge to see if it is in error.

The level controller needs to be direct-acting. The pressure controller needs to be reverse-acting.

Although there is a discrepancy between the controller's output (displayed) and the actual valve position, an error of (approximately) 1.4% is nothing to worry about. In fact, so long as the valve is somewhere within its throttling range, the controller should be able to hold the PV equal to SP.

Answer 74

The feedforward gain value is correctly set in this system, as evidenced by the temperature's return to its prior value after deviating for a short period of time. The deviation in temperature is *upward*, which is the natural direction of change we would expect for this load (decreasing feed flow rate, resulting in fluid spending more time inside the exchanger absorbing heat). This tells us that the feedforward action is of the correct magnitude, but is arriving too *late* to immediately compensate for the load.

What this feedforward system needs for better performance is *dynamic compensation*. Specifically, it needs a *lead* function somewhere in the feedforward signal path to accelerate the control valve's response and compensate more quickly for the load change.

Answer 75

Answer 76

Answer 77

Answer 78

Answer 79

Answer 80

Answer 81

This is a graded question – no answers or hints given!

Answer 82

This is a graded question – no answers or hints given!

Answer 83

This is a graded question – no answers or hints given!

Answer 84

This is a graded question – no answers or hints given!

Answer 85

This is a graded question – no answers or hints given!

Answer 86

This is a graded question – no answers or hints given!

Answer 87

This is a graded question – no answers or hints given!

Answer 88

This is a graded question – no answers or hints given!

Answer 89

This is a graded question – no answers or hints given!

Answer 90

This is a graded question – no answers or hints given!

Answer 91

Answer 92

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

Answer 93

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