
<u>Lab</u>

Multiple loop tuning: *Question 91*, **completed objectives due by the end of day 5, section 3**

<u>Exam</u>

Day 6 of section 3

Capstone Assessment (see question 92)

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

- Electricity Review: Design a simple circuit to achieve a stated objective
- Identify cause of poor loop performance from a trend graph
- Identify problem in control loop based on faceplate display and field data
- Calculate either the numerical derivative or the numerical integral from a graph
- Solve for a specified variable in an algebraic formula (may contain exponents or logarithms)
- Determine the possibility of suggested faults in a 4-20 mA loop circuit given measured values (voltage, current), a schematic diagram, and reported symptoms
- Motor/relay/3phase/PLC Review: Determine status of PLC output given input conditions and RLL program
- INST240 Review: Determine suitability of different level-measuring technologies for a given process fluid type
- INST263 Review: Determine the effect of a component fault or condition change in a selector or override control system

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Recommended daily schedule

<u>Day 1</u>

Theory session topic: Cascade control

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

Discuss the upcoming Capstone Assessment due by the end of the course (*Question 92*)

<u>Day 2</u>

Theory session topic: Feedforward control

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

<u>Day 3</u>

Theory session topic: Loop problem diagnosis and optimization

Questions 41 through 60; <u>answer questions 41-49</u> in preparation for discussion (remainder for practice)

<u>Day 4</u>

Theory session topic: Loop problem diagnosis and optimization (continued)

Questions 61 through 80; <u>answer questions 61-68</u> 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

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.

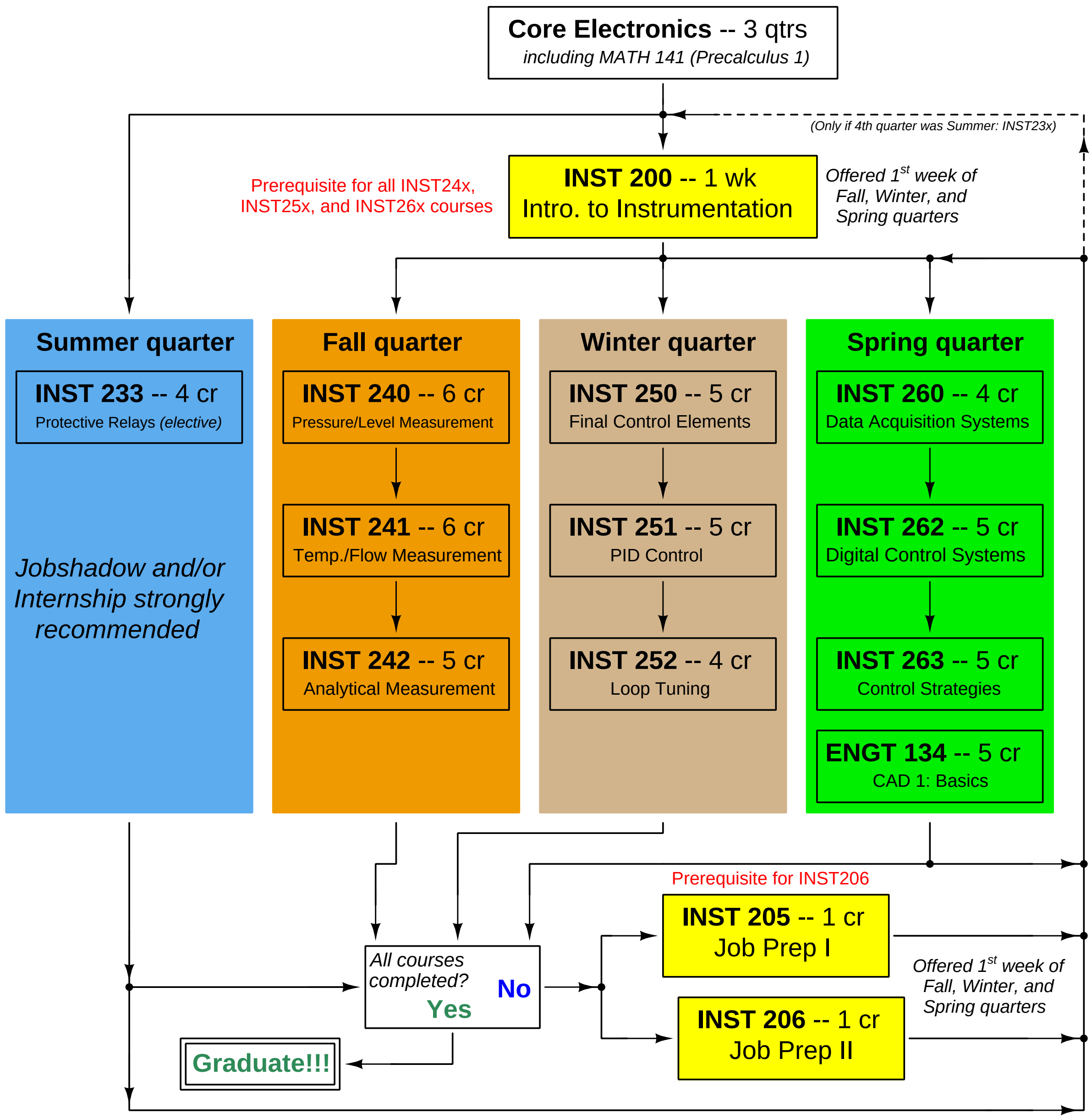
file `outcomes_program`

INST 252 Course Outcomes

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

- Tune multiple PID controllers for robust response to setpoint and process load changes. [Ref: Program Learning Outcome #6]
- Design and build a circuit to fulfill a function randomly selected by the instructor (voltage divider, passive filter, capacitive time-delay, or phase shift network) and demonstrate its proper operation using a signal generator and oscilloscope. [Ref: Program Learning Outcome #5]
- Diagnose a random fault placed in another team's PID control system by the instructor within a limited time using no test equipment except a multimeter, logically justifying your steps in the instructor's direct presence. [Ref: Program Learning Outcome #5]
- 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 PID tuning criteria (robust response to either setpoint or load changes) specified by the instructor. [Ref: Program Learning Outcomes #5 and #9]

file `outcomes_INST252`


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.

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.

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.

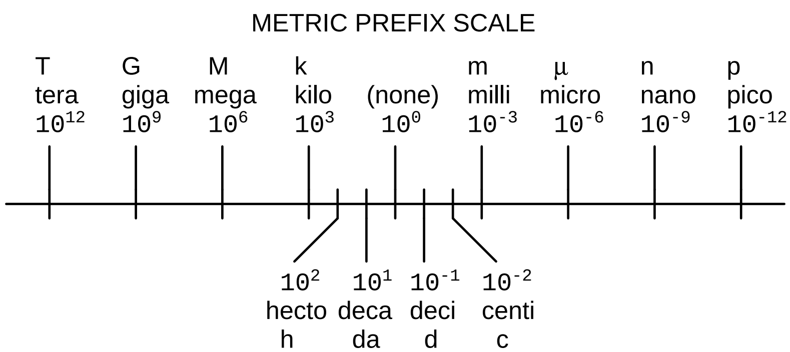
Labwork is perhaps the most difficult portion of the curriculum for a "distance" student to complete, since the equipment used in Instrumentation is typically too large and expensive to leave the school lab facility. "Distance" students must find a way to complete the required lab activities, either 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 (W/m^2·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·^{o}C = 1 BTU/lb·^{o}F = 4.1869 Joules/g·^{o}C

Specific heat of ice ≈ 0.5 calories/g·^{o}C

Specific heat of steam ≈ 0.48 calories/g·^{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)

file `conversion_constants`

How to get the most out of academic reading:

- Outline, don't highlight! Identify every major idea presented in the text, and express these ideas in your own words. A suggested ratio is one sentence of your own thoughts per paragraph of text read.
- Articulate your thoughts as you read (i.e. "have a conversation" with the author). This will develop *metacognition*: active supervision of your own thoughts. Note points of agreement, disagreement, confusion, epiphanies, and connections between different concepts or applications.
- Work through all mathematical exercises shown within the text, to ensure you understand all the steps.
- Imagine explaining concepts you've just learned to someone else. Teaching forces you to distill concepts to their essence, thereby clarifying those concepts, revealing assumptions, and exposing misconceptions. Your goal is to create the simplest explanation that is still technically accurate.
- Create your own questions based on what you read, as a teacher would to challenge students.

How to effectively problem-solve and troubleshoot:

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

How to manage your time:

- Avoid procrastination. Work now and play later, every single day.
- Consider the place you're in when deciding what to do. If there is project work to do and you have access to the lab, do that work and not something that could be done elsewhere (e.g. homework).
- Eliminate distractions. Kill your television and video games. Turn off your mobile phone, or just leave it at home. Study in places where you can concentrate, like the Library.
- Use your "in between" time productively. Don't leave campus for lunch. Arrive to school early. If you finish your assigned work early, begin working on the next assignment.

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

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.
- 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.
- 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

Read and outline the "Cascade Control" 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) Any points of confusion, and precisely why you found the text confusing.
(5) Questions of your own you would pose to another reader, to challenge their understanding.
(6) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.

file i04336

Question 2

Read and outline Loop Problem Signatures #17 ("Cascade 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) Any points of confusion, and precisely why you found the text confusing.
(5) Questions of your own you would pose to another reader, to challenge their understanding.
(6) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.

Be sure to answer the following questions:

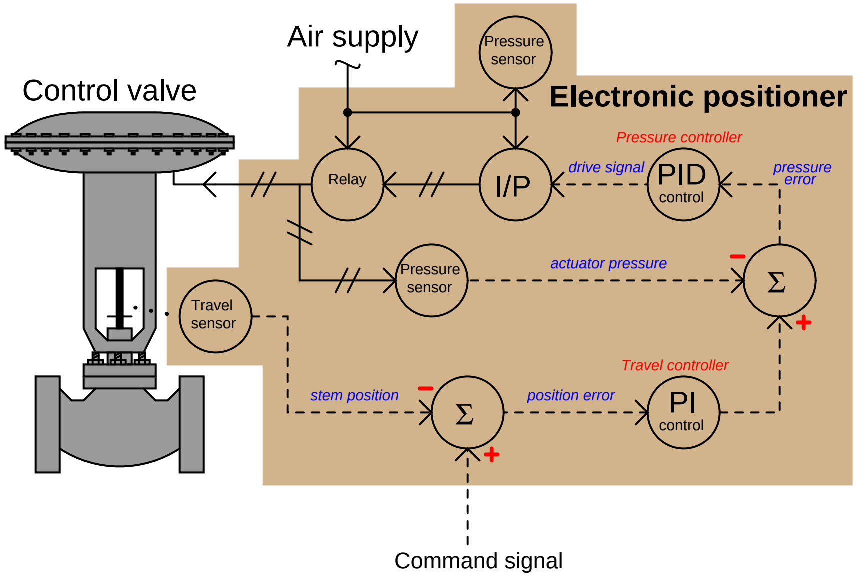
- This tutorial opens with an example of a temperature control loop that oscillated badly following setpoint changes. What was the cause of this problem, exactly?
- What general rule does Mr. Brown give for the tuning of integral action on a self-regulating process? How much integral action should one expect to use on any well-tuned self-regulating process?
- Explain how the inclusion of cascade control in the hypothetical heat exchanger system helps make an imperfect control valve more perfect.
- What type of process (in general) does Mr. Brown recommend using cascaded controllers on?
- Identify some of the common misconceptions of cascade control listed by Mr. Brown in his tutorial.

file i01670

Question 3

Explain how all valve positioners essentially act as *cascade* control systems in a loop, and why valve positioners generally improve control quality as a result.

Furthermore, examine this block diagram of an electronic ("smart") valve positioner and comment on its own internal "control strategy" for achieving optimum positioning:



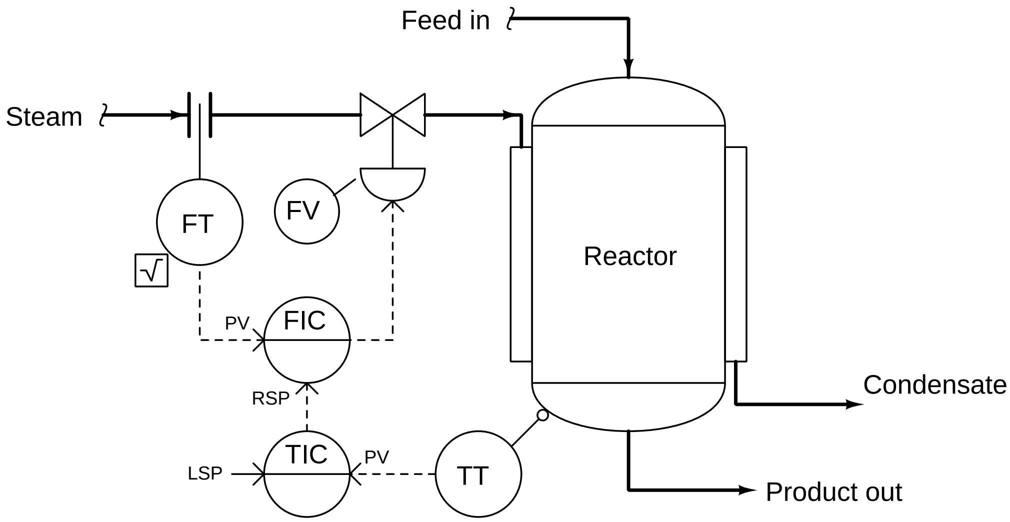
Suggestions for Socratic discussion

- Comment on the "+" and "−" symbols shown in this diagram. Based on these symbols, determine the control action (direct or reverse) for each of the controllers.
- Certainly, modern "smart" valve positioners promise superior control valve performance than mechanical valve positioners did. Can you think of any potential *disadvantages* of a smart valve positioner, especially after examining the block diagram in detail?
- For those who have studied control valve positioners, how exactly does a "smart" positioner sense the valve stem's position?
- For those who have studied control valve positioners, identify some of the special features offered by a "smart" positioner.
- Predict the effect(s) of the nozzle plugging inside the positioner's relay.
- Predict the effect(s) of the travel sensor failing with a 0% (fully-closed) signal.
- Predict the effect(s) of the pressure sensor failing with a 100% (full-pressure) signal.

file i01691

Question 4

Explain the operation of this *cascade* temperature control system:



Cascade control systems (also called *two-element* control systems) have two control "loops" functioning: a *master* and a *slave* (also known as *primary* and *secondary*, respectively). Identify the master (primary) and slave (secondary) loops in this temperature control system, and also determine which loop should be tuned *first* (and why!).

Also, identify the appropriate controller actions for each loop, assuming direct-acting transmitters and an air-to-open valve. Annotate this diagram with "+" and "−" symbols showing the influences PV and SP have on each controller, and explain how these symbols help your analysis of the controllers' actions.

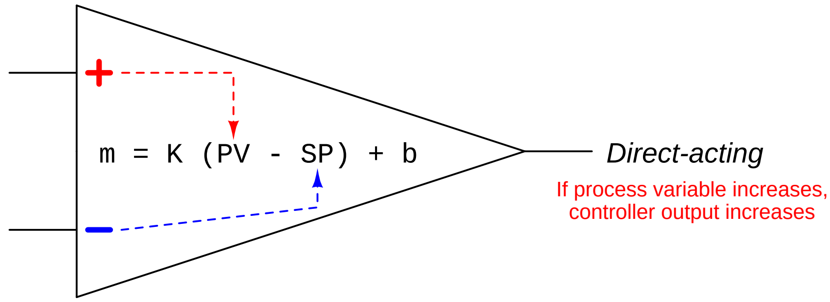
Suggestions for Socratic discussion

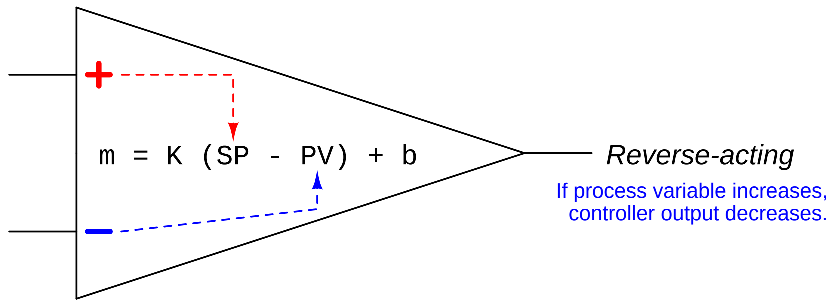
- A useful problem-solving strategy for determining necessary controller actions in a cascade control system is to replace the ISA-standard "bubble" symbols for controllers with triangular opamp symbols, complete with "+" and "−" symbols at the inputs. One input of each "opamp" controller will be the PV, while the other input of each "opamp" controller will be the SP. The inverting and noninverting inputs standard to all operational amplifiers helps remind you that the PV and SP inputs of a loop controller always have opposite effects on the output signal.
- When tuning each loop controller (TIC, FIC), what should be done with the *other* controller? Should the other controller be in automatic mode or manual mode, and why?
- Suppose the control valve were switched from air-to-open to air-to-close. Would *both* master and slave controller actions need to be reversed, or just one of the controllers? If just one, which one?
- Identify any load(s) on this process that are *not* being corrected or otherwise compensated for by cascade control.

file i01690

Question 5

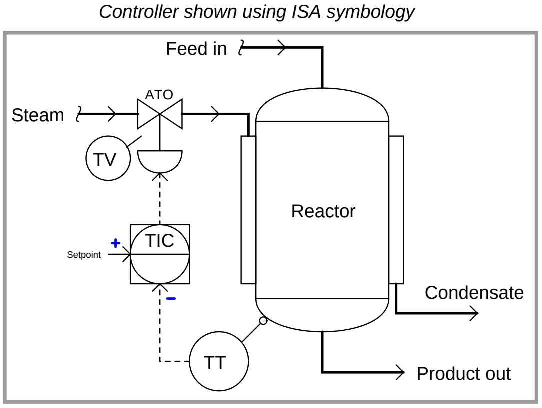
A helpful strategy for qualitatively analyzing control strategies is to mark the inputs of multi-input functions shown in those strategies with either "+" or "−" labels to denote direction of action. This is the same symbology used to mark the inputs of an operational amplifier, where "+" represents 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:



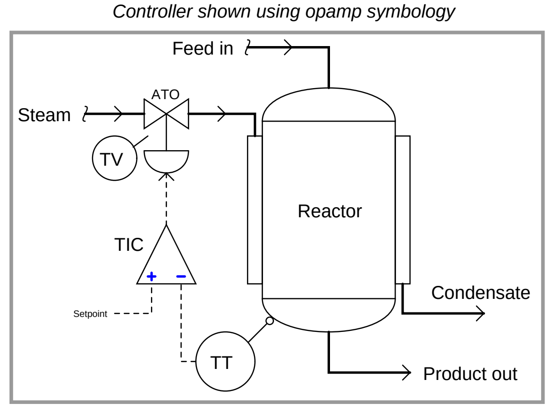


To illustrate this concept, examine these two diagrams of a single-loop control system. In the left-hand diagram, the controller is shown using standard ISA symbology. In the right-hand sketch, the controller is shown using opamp symbology instead. In both cases, the controller must be *reverse-acting* 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:

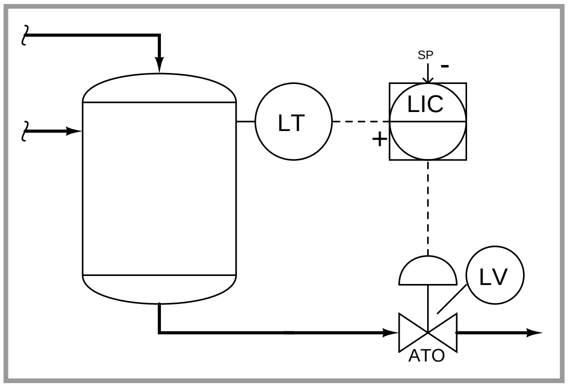
Controller shown using ISA symbology

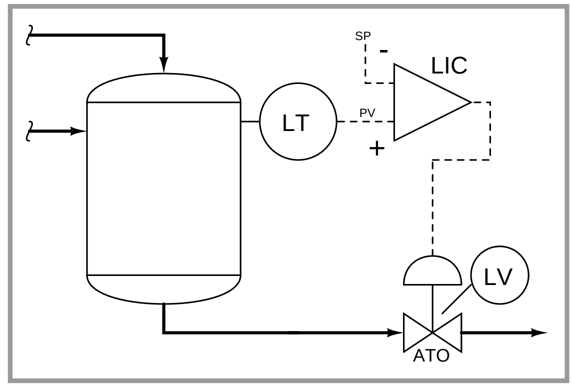


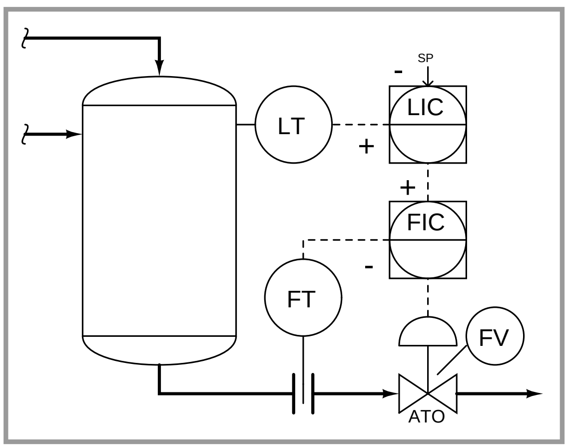
Controller shown using opamp symbology

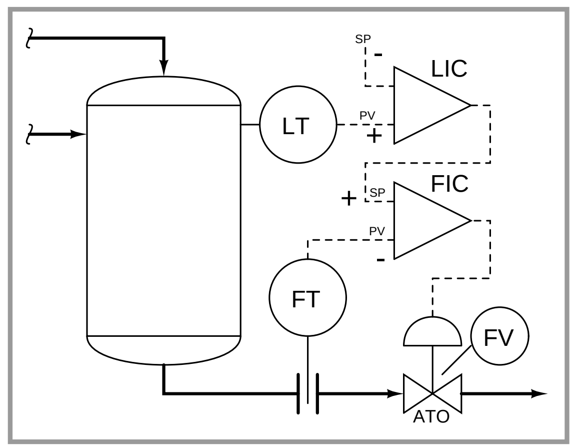


Sketch your own "+" and "−" labels at the input(s) of each controller in each of these control strategy diagrams, to denote the proper directions of action to make each system work properly. In order to help you do this, the right-hand version of each diagram uses opamp symbology for the controller rather 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:









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 6

Read and outline Case History #51 ("Faulty Positioner Causes Instability") 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) Any points of confusion, and precisely why you found the text confusing.
(5) Questions of your own you would pose to another reader, to challenge their understanding.
(6) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.

Be sure to answer the following questions:

- Describe the purpose of the control system being optimized by Mr. Brown and his class at this chemical plant.
- Which loop is the *master* and which is the *slave*?
- Which loop did they begin to optimize *first*, and why do you suppose they began with that one?
- Which test – closed-loop or open-loop – provided the most information on the source of the problem?
- The introduction to this Case History states, "Repeated attempts had been made by the plant over an extended period of time to tune the loop to stop the cycling." Explain why you think this was that case. How come Michael and his class could find and correct the problem when others at the chemical plant could not? Although the Case History does not tell us, what do you suppose the plant workers tried to do to tame this unruly loop before the optimization class was held?

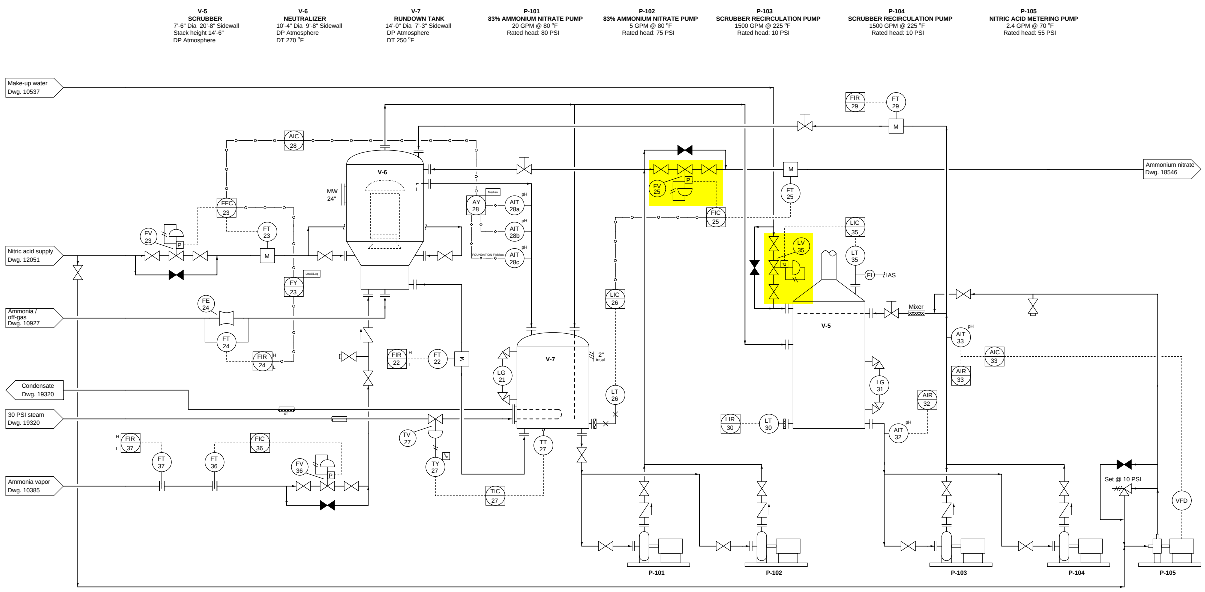
Suggestions for Socratic discussion

- Suppose during this loop-optimization exercise that no problems were found in any of the field instruments. Can you think of anything else that might cause the strange "overshoot" responses seen in the trend of Figure 3?
- Other than a valve problem, what else may we determine about the fuel pressure process from the tests shown in Figure 3?

file i01793

Question 7

The following ammonium nitrate production process was shut down for an extended period of time (typically, this kind of event is called an "outage" or a "turnaround") to perform maintenance on components that could not be worked on while the unit was running:



Unfortunately, the purchasing agent for the company mistakenly ordered the wrong type of valve trim on all the control valves being rebuilt. Instead of ordering equal-percentage trim for each of the valves as originally specified, the purchaser accidently ordered *linear* trim.

When the work was completed and the unit re-started, operations personnel began to notice the scrubber level control loop behaving poorly: the scrubber liquid level would not remain stable at setpoint the way it used to before the outage.

An instrument technician sent to diagnose this problem noticed that valve LV-35 was sporting a fresh coat of paint, suggesting it had been rebuilt during the outage, and following this clue the technician was able to discover the trim misconfiguration as being the cause of the instability.

After fixing this problem, the same technician decided to investigate other control valves in the unit that had been rebuilt. FV-25 was another one of the valves that had the wrong characterization of trim installed, and yet the rundown tank level control system was not misbehaving: LIC-26 was able to maintain liquid level at setpoint regardless of load changes or setpoint changes.

Explain why a change of valve trim characteristic caused problems for the scrubber's level control system, but not for the rundown tank's level control system.

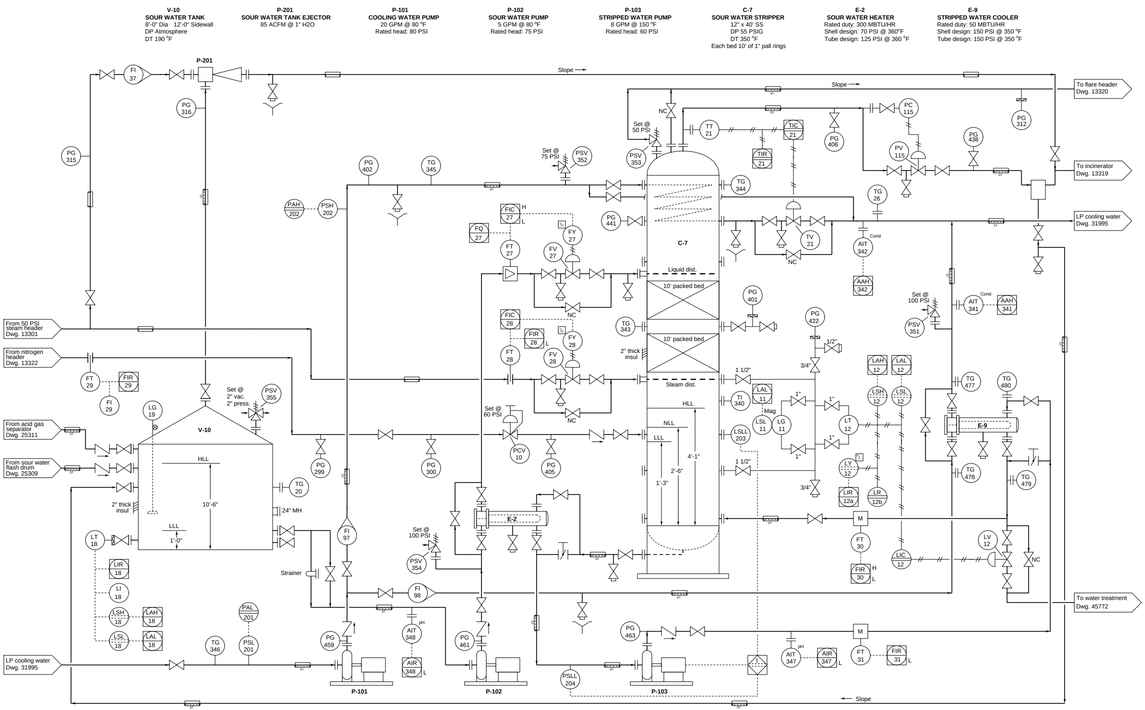
Suggestions for Socratic discussion

- Will an incorrect trim characterization in FV-25 have any deleterious effects at all?

file i01694

Question 8

The stripper overhead temperature control system (loop #21) works adequately, but not as good as it could. In its present form, the temperature tends to be affected by variations in cooling water supply pressure, because this affects the differential pressure drop across control valve TV-21, and thus the flow rate through the cooling pipes in the upper section of the sour water stripping vessel:



Modify this system for better control of stripper overhead temperature, using *cascade* control.

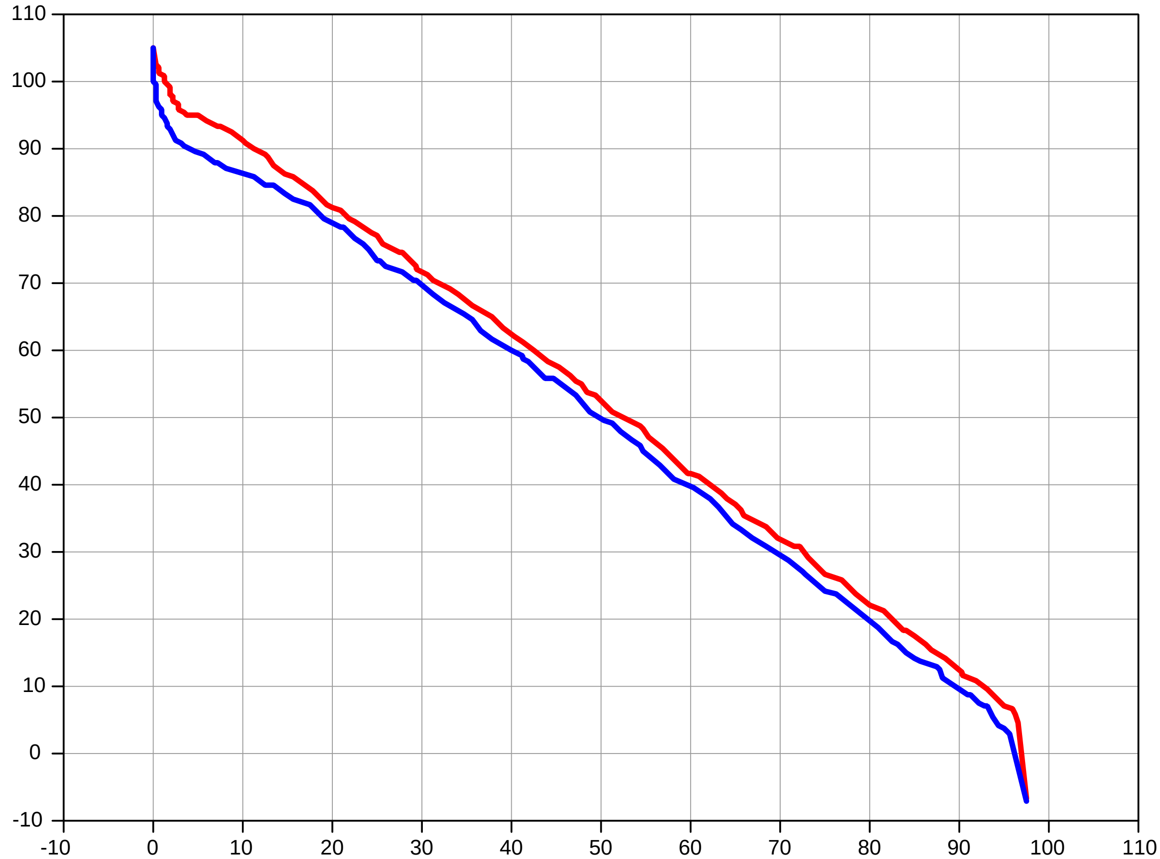
Suggestions for Socratic discussion

- Suppose you discovered that the stripper overhead temperature was also being affected by variations in the cooling water's *temperature* as well as by the cooling water's pressure. Can you think of any control strategy that might help overcome this load variation?

file i01696

Question 9

Examine this *valve signature* taken from a valve that clearly has problems, and answer the questions that follow:

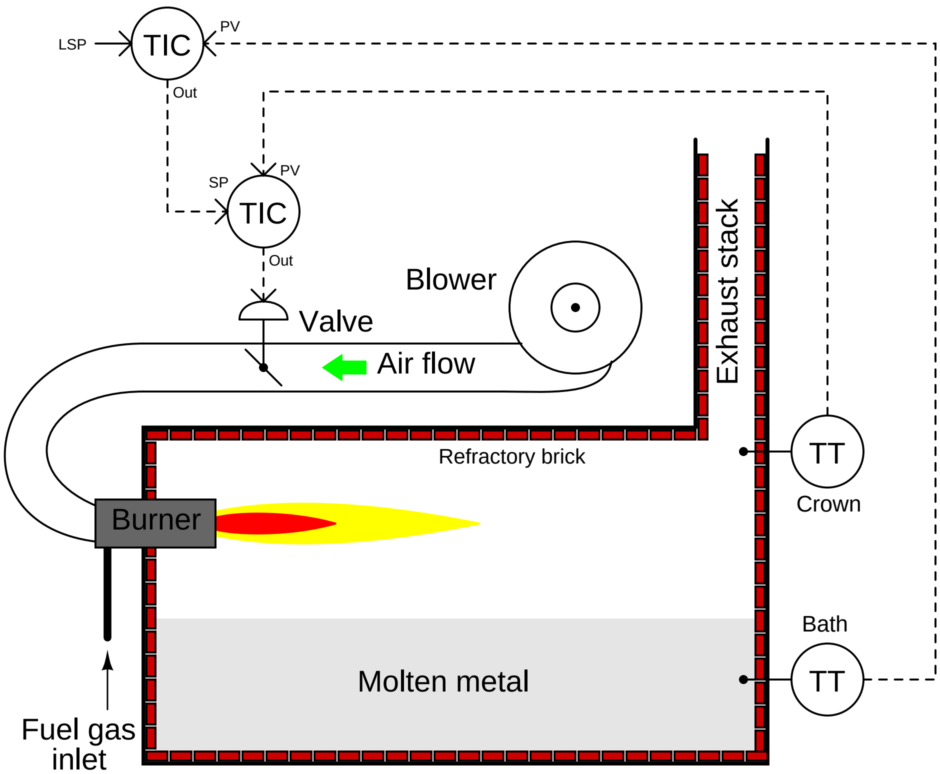


- Is this an air-to-open valve, or an air-to-close valve?
- Which axis of the graph (horizontal or vertical) represents (percent of) valve stem position?
- Which axis of the graph (horizontal or vertical) represents (percent of) actuator air pressure?
- What kind of problem does this valve have, and how might it be fixed?

file i00426

Question 10

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?

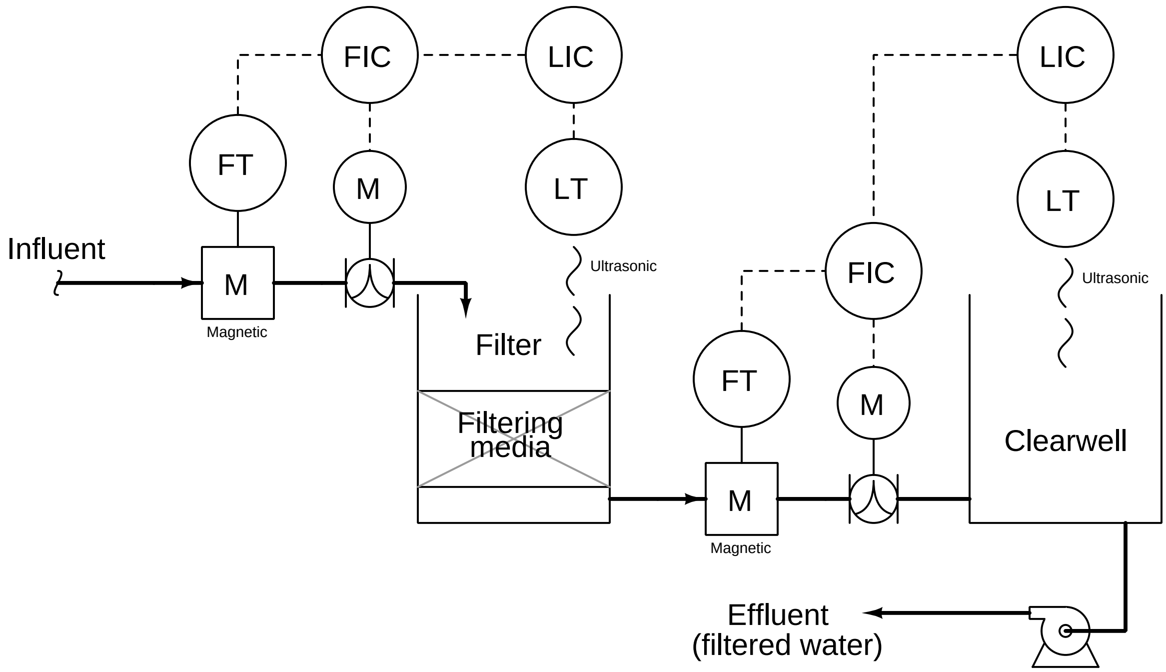
Suggestions for Socratic discussion

- 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 11

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?

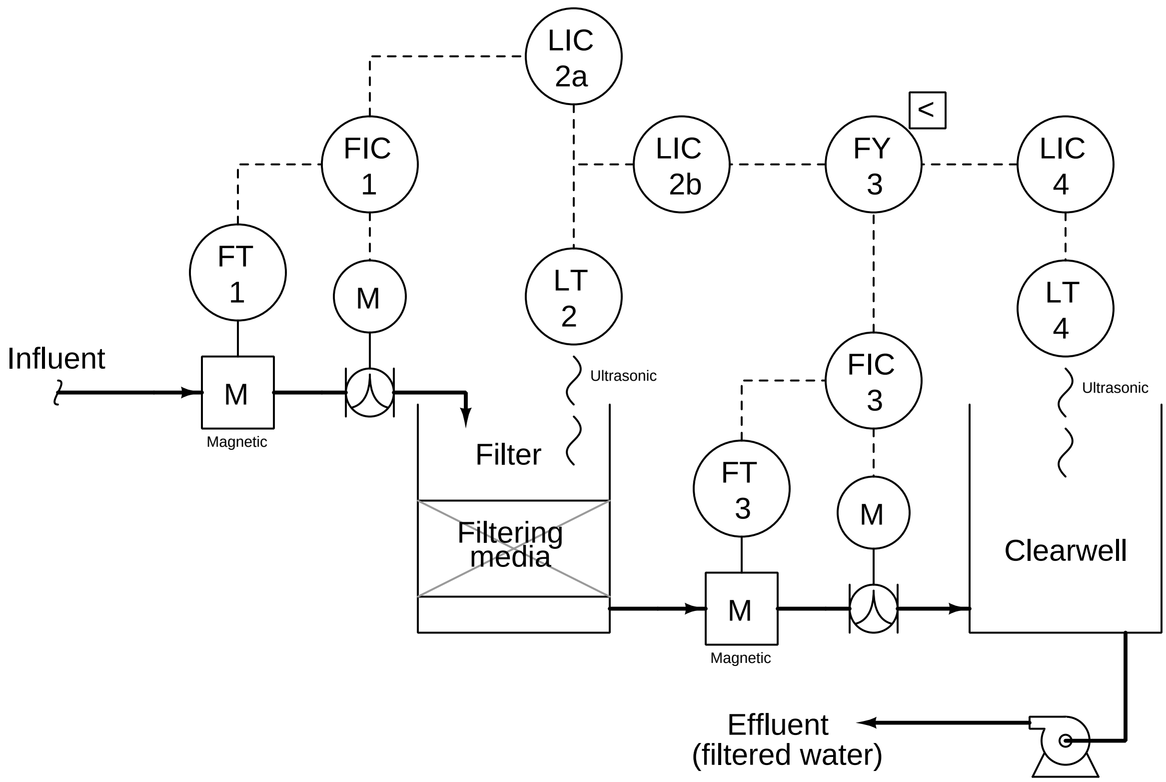
Suggestions for Socratic discussion

- 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 12

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?

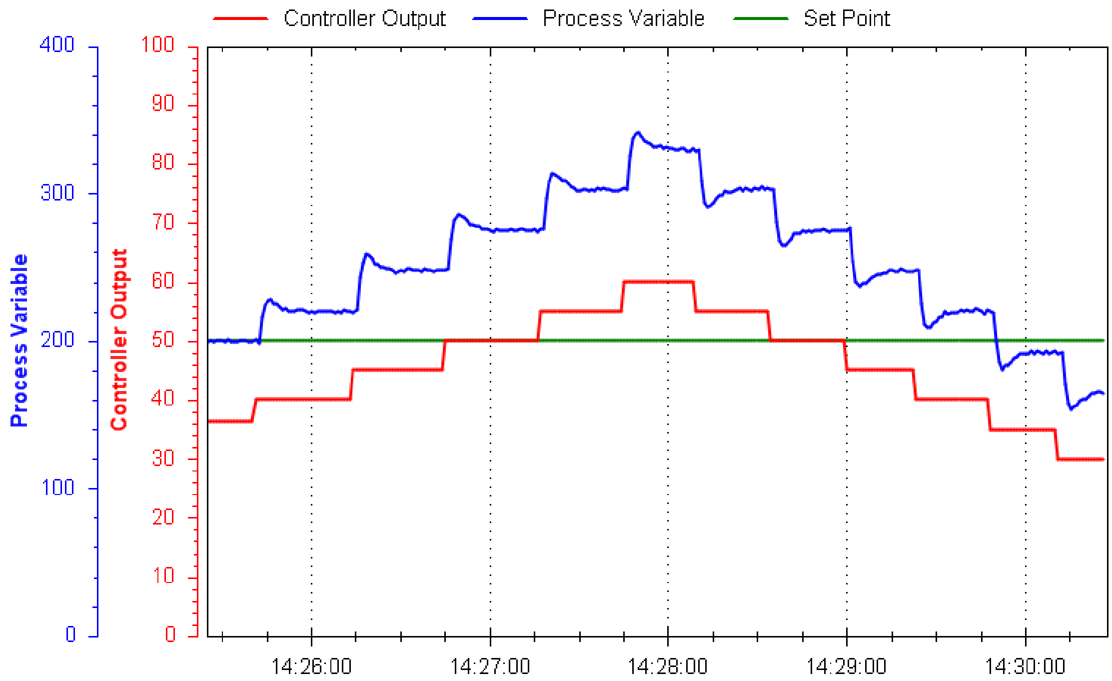
Suggestions for Socratic discussion

- 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 13

Examine this process trend showing the PV, SP, and Output of a loop controller:



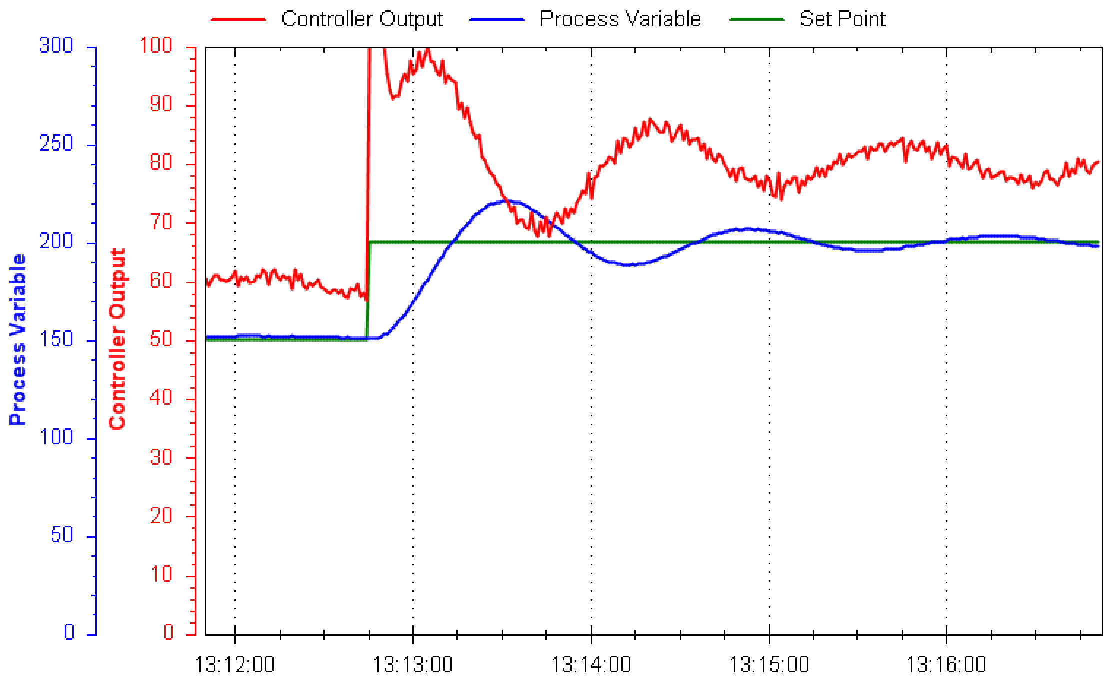
Based on what you see here, determine the following:

- Whether this is an open-loop or a closed-loop response
- Whether the controller is (or needs to be) *direct-acting* or *reverse-acting*
- If possible, identify any problems with the field instrumentation
- If possible, identify any problems with the controller PID tuning
- Qualitatively identify the kind of PID tuning we will need for robust control

file i01923

Question 14

Examine this process trend showing the PV, SP, and Output of a loop controller:



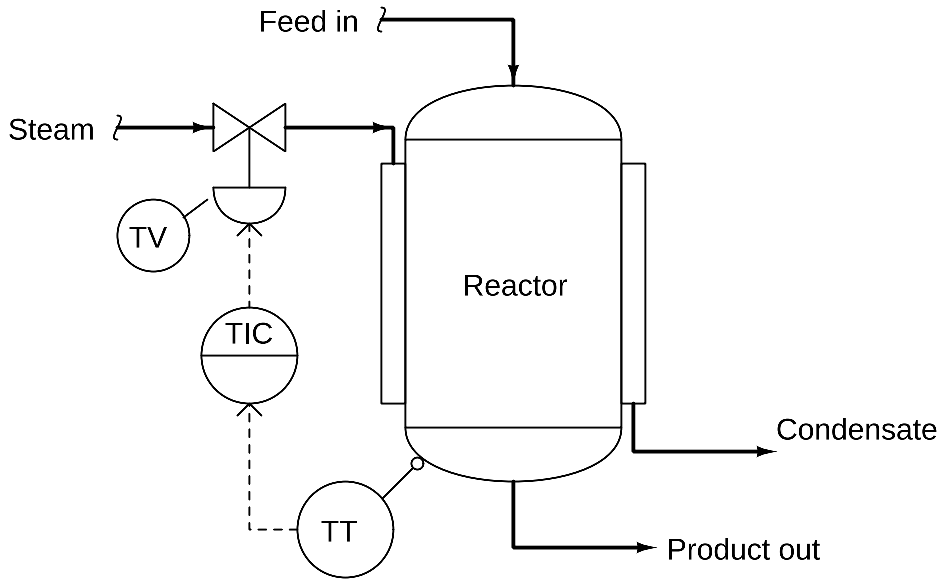
Based on what you see here, determine the following:

- Whether this is an open-loop or a closed-loop response
- Whether the controller is (or needs to be) *direct-acting* or *reverse-acting*
- If possible, identify any problems with the field instrumentation
- If possible, identify any problems with the controller PID tuning
- Qualitatively identify the kind of PID tuning we will need for robust control

file i01928

Question 15

Suppose a chemical reactor is heated by steam. A temperature controller varies the amount of steam admitted to a "jacket" surrounding the reactor:



Ever since this process was placed into service, operators have complained about poor temperature control. Several technicians have tried to tune the PID controller, but no combination of tuning constants seems to solve the problem of random reactor temperature fluctuations. Then one day you notice that the "random" fluctuations of temperature are not really random at all: they directly follow fluctuations in steam supply pressure over time.

Explain the nature of the control problem (why do variations in steam supply pressure affect the reactor temperature?), and propose a solution for it.

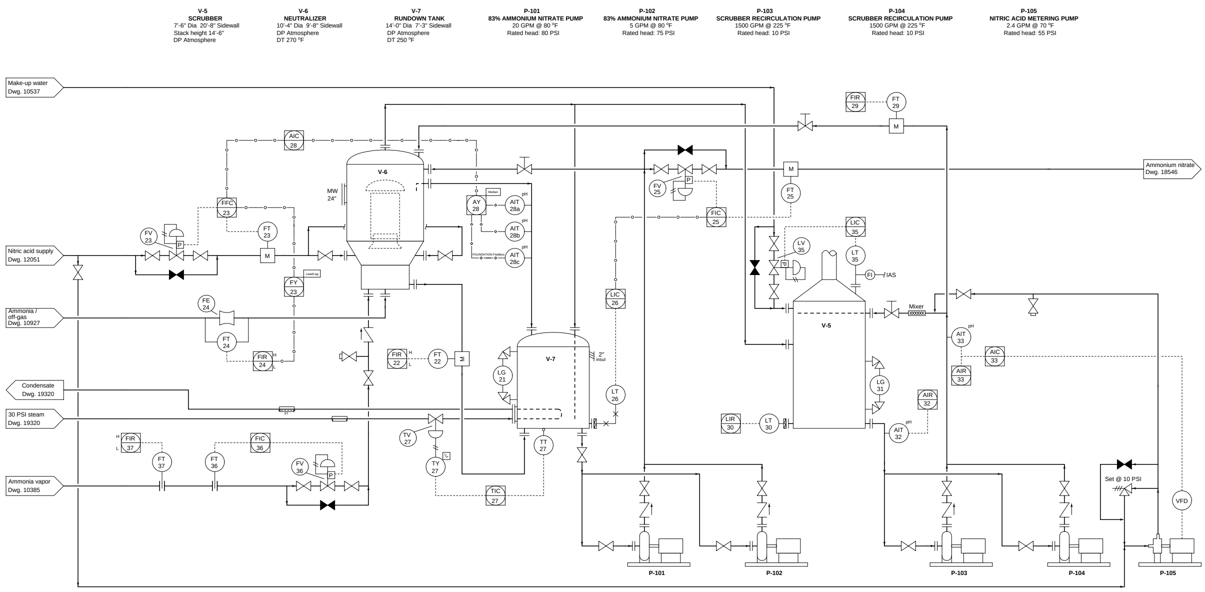
Suggestions for Socratic discussion

- Like so many real-life problems, there are usually multiple solutions. Try brainstorming more than one practical solution to this control problem!

file i01689

Question 16

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

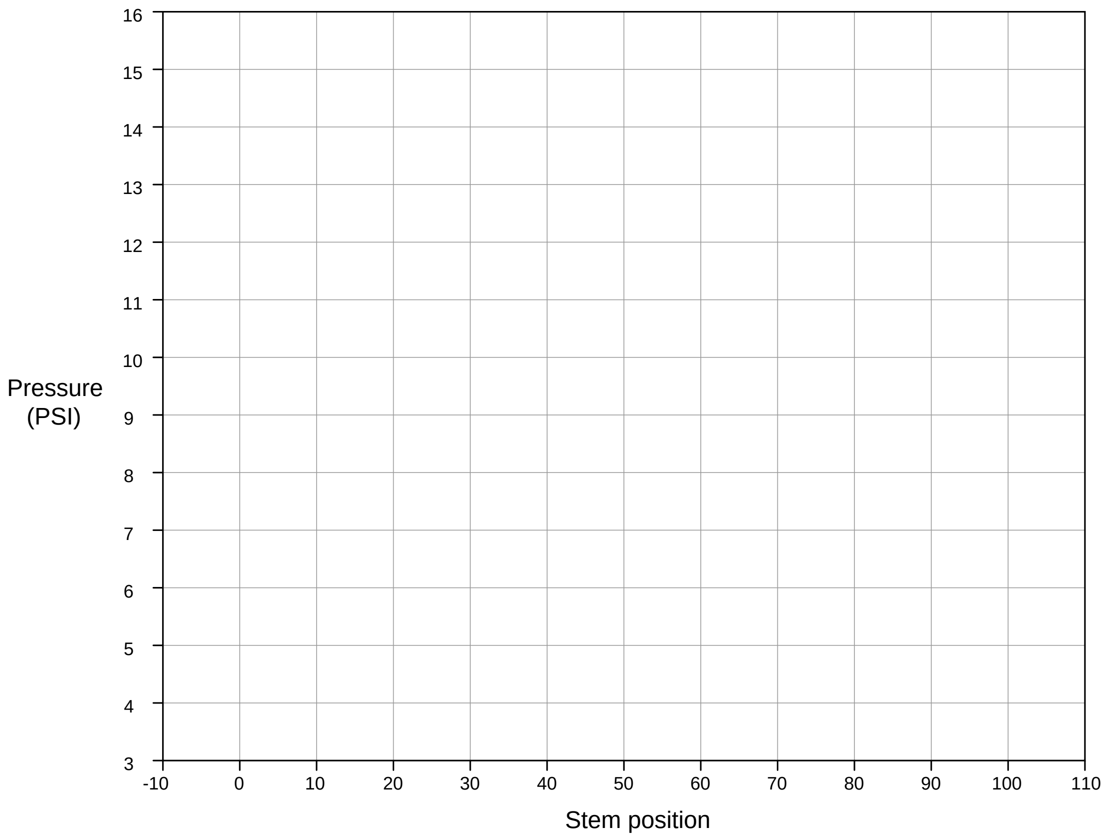


Examine the level control system for the scrubber vessel (V-5). Suppose you were informed that the make-up water header supply pressure tends to vary significantly, and that this was acting as a load in V-5's level control loop. Explain how you could add cascade control to that level control loop to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

file i01277

Question 17

One extremely useful capability of a "smart" valve positioner is the ability to measure and plot the relationship between valve stem position and actuator air pressure. Sketch what a "healthy" *valve signature* should look like, assuming a valve with the following properties:



- Stem-guided globe trim
- Reverse-acting pneumatic actuator
- Direct-acting valve body
- Equal-percentage trim characteristic
- 6 PSI lower bench-set pressure
- 15 PSI upper bench-set (end-of-stroke) pressure

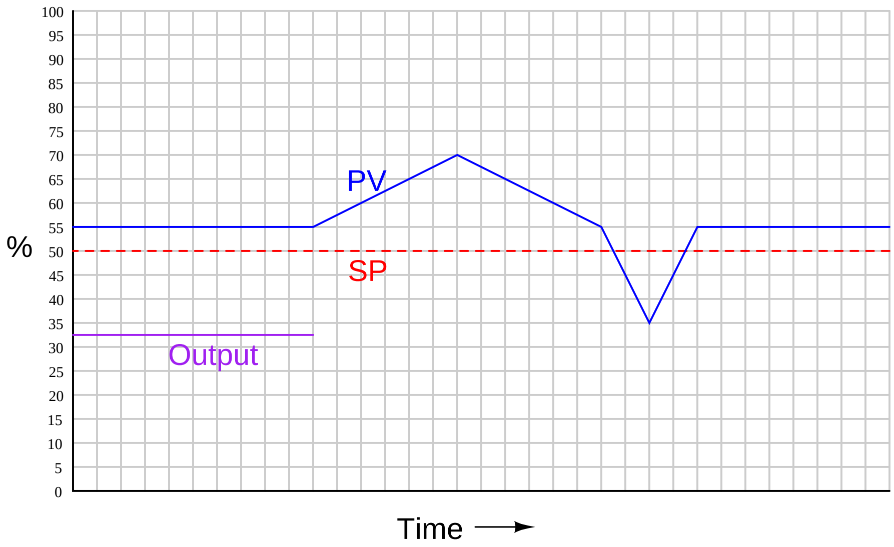
Suggestions for Socratic discussion

- Identify some of the control valve problems that may be diagnosed by skillful examination of a valve signature plot.

  file i01539

Question 18

Qualitatively graph the response of a proportional-plus-derivative controller over time to the following changes in process variable:



Assume *reverse* control action.

file i01540

Question 19

Question 20

Question 21

Read and outline the introduction and the "Load Compensation" subsection of the "Feedforward Control" 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) Any points of confusion, and precisely why you found the text confusing.
(5) Questions of your own you would pose to another reader, to challenge their understanding.
(6) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.

file i04338

Question 22

In the United States of America, where the Superbowl is a very popular sporting event to watch from home, water and wastewater treatment plant operators have learned to pay attention to the game in order to improve process control. They know that a significant percentage of the population in any metropolitan area will simultaneously use the bathroom during breaks in the game, particularly the half-time break. This places unusual demands on both the water supply and the wastewater handling systems at very specific times.

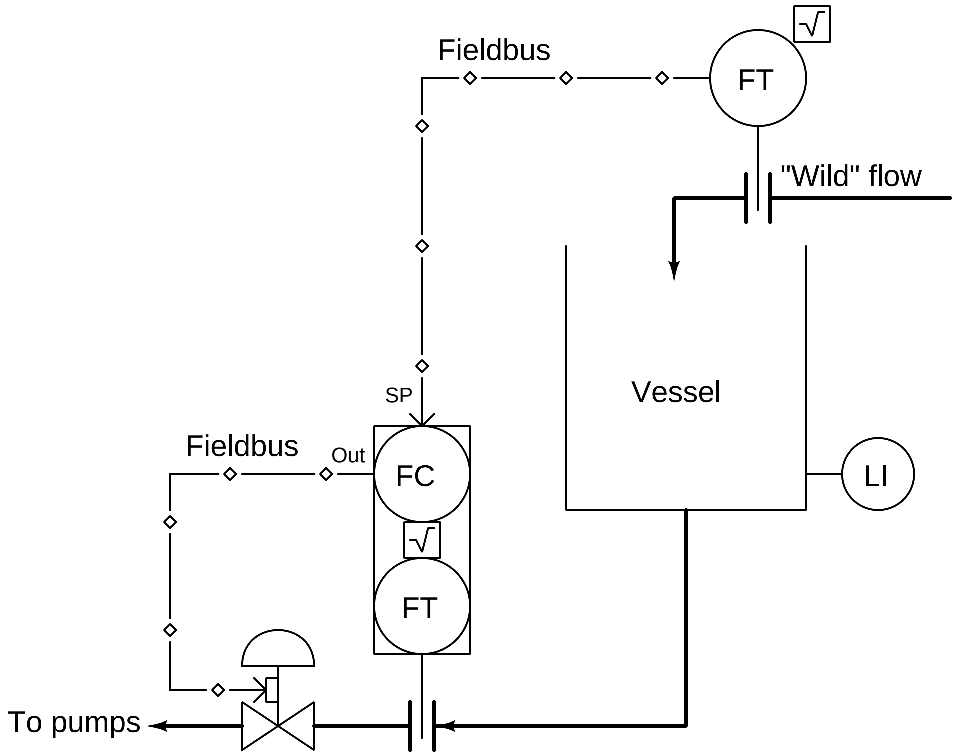
So, when a break begins, these operators at the water and wastewater treatment facilities preemptively turn on spare pumps to handle the impending flow rates, so that the systems do a better job maintaining setpoint. There is a technical term for this sort of control strategy: *feedforward*. Explain what "feedforward" control is, in your own words, and compare it against the more customary "feedback" control philosophy.

A practical example of feedforward control on a grand scale is the control of reservoir water level at hydroelectric dams. The dam must use or "spill" excess water when the reservoir is nearing full capacity, in order to avoid over-filling of the reservoir. A feedforward variable relevant to this control problem is ambient air temperature in the high mountain regions surrounding the reservoir. Explain how mountain temperature relates to reservoir level, and how such a feedforward control strategy might work in a hydroelectric dam.

file i01751

Question 23

Since liquid level can only change in a vessel if there is an imbalance of inlet and outlet flow rates, would this system be practical to achieve steady liquid level control? Explain why or why not.



Note: the philosophy behind this control system is a principle known as *mass balance*, and it is a very valid principle. Explain what the principle of "mass balance" is, and how it is implied in the design of this control system.

Also, mark the SP and PV inputs of the controller in this system with "+" and "−" symbols as appropriate to show the correct controller action.

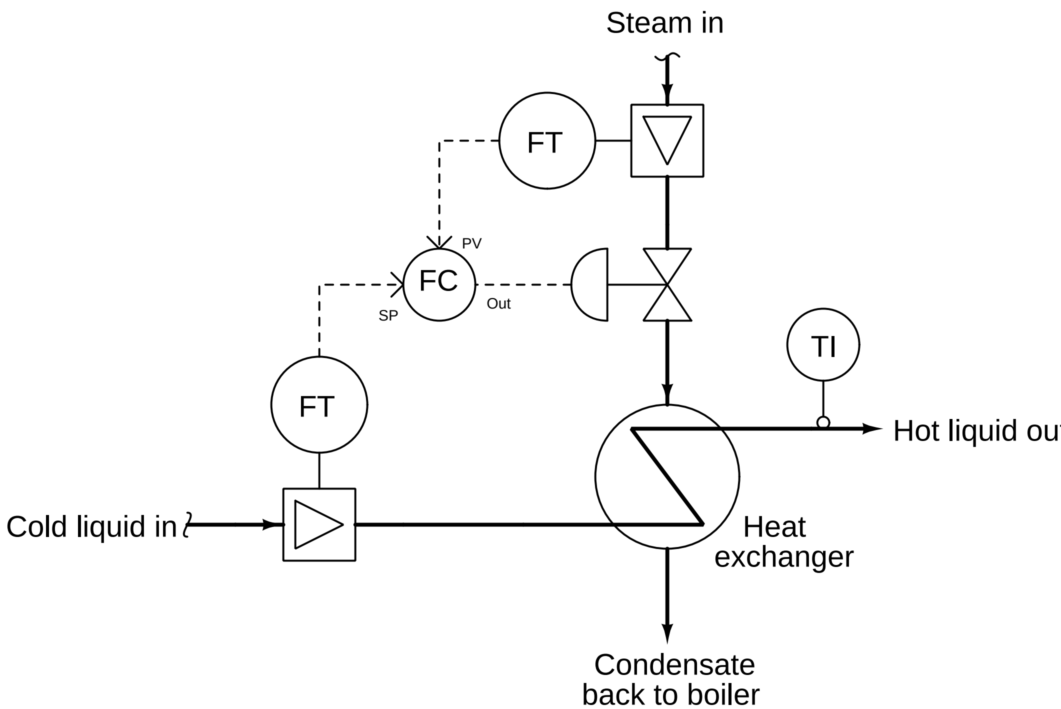
Suggestions for Socratic discussion

- Explain why the control system as shown is impractical for real-life use, despite the fact that it does represent a very effective and important control strategy frequently used in industry.
- Explain what "Fieldbus" instruments are, and how they differ from traditional instrumentation.
- How will this control system respond if the "wild" flow transmitter fails with a high signal?
- How will this control system respond if the "drain" flow transmitter fails with a high signal?
- How will this control system respond if the control valve's air supply fails?
- How will this control system respond if the "wild" flow line becomes partially plugged?
- How will this control system respond if the "drain" flow line becomes partially plugged?
- Are there any loads unaccounted for in this feedforward control strategy?

file i01749

Question 24

Since the outlet temperature of a heat exchanger can only change if there is an imbalance of inlet and outlet heat rates (assuming constant liquid inlet temperature and constant liquid composition), would this system be practical to achieve steady liquid outlet temperature control? Explain why or why not.



Note: the philosophy behind this control system is a principle known as *energy balance*, and it is a very valid principle. Explain what the principle of "energy balance" is, and how it is implied in the design of this control system.

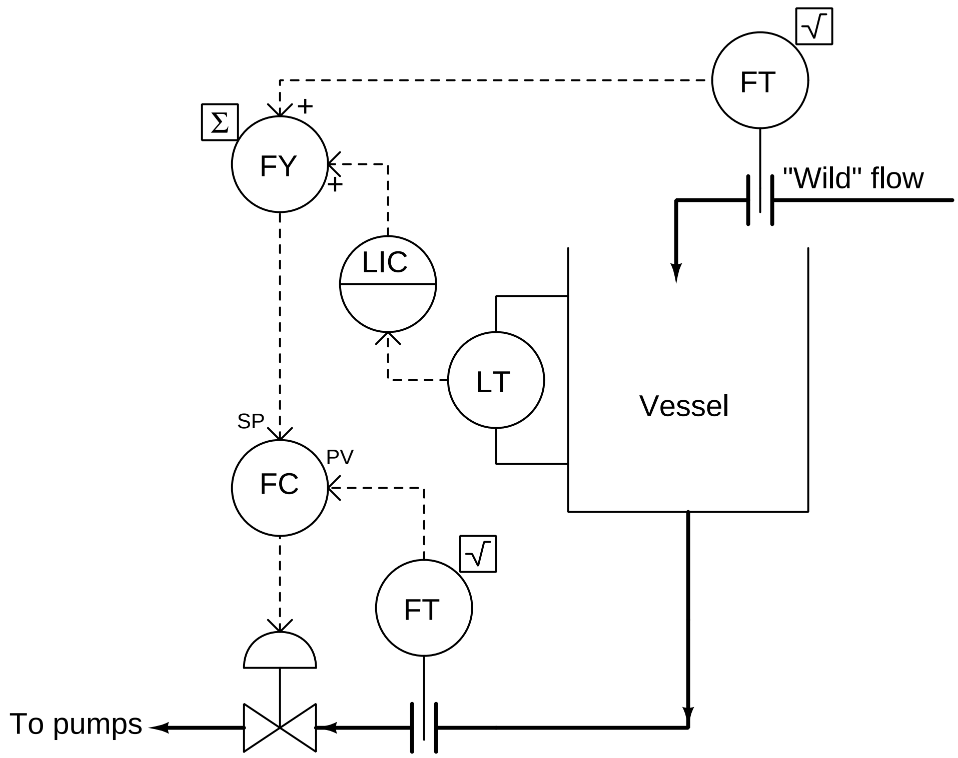
Suggestions for Socratic discussion

- A powerful problem-solving technique is performing a *thought experiment* where you mentally simulate the response of a system to some imagined set of conditions. Describe a useful "thought experiment" for this system, and how the results of that thought experiment are helpful to answering the question.
- Explain why the control system as shown is impractical for real-life use, despite the fact that it does represent a very effective and important control strategy frequently used in industry.
- Determine whether the controller needs to be *direct* acting or *reverse* acting.
- 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 "−".
- Modify this control strategy to incorporate "feedback trim" in addition to the feedforward action it currently possesses.
- Are there any loads unaccounted for in this feedforward control strategy? If so, see if you can modify this control strategy to account for them as well.

file i01770

Question 25

This control strategy for liquid level control is called *feedforward with trim*, *feedforward-feedback* control, or *three-element* control:



What will this system do to maintain a constant level in the vessel if the "wild" flow input to the vessel suddenly increases?

Also, what will this system do to maintain a constant liquid level if a leak suddenly develops in the vessel?

Suggestions for Socratic discussion

- Explain why pure feedforward control is almost never used in industry. Instead, we almost always see feedforward used as part of a larger feedback control strategy.
- 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 "−".
- Explain what will happen if the level transmitter fails with a low signal.
- Explain what will happen if the level transmitter fails with a high signal.
- Explain what will happen if the summing relay fails with a low signal.
- Explain what will happen if the summing relay fails with a high signal.
- Explain what will happen if the flow controller is left in manual mode.
- Explain what will happen if the level controller is left in manual mode.
- Explain what will happen if the wild flow transmitter fails with a low signal.
- Explain what will happen if the wild flow transmitter fails with a high signal.
- Explain what will happen if the captive flow transmitter fails with a low signal.
- Explain what will happen if the captive flow transmitter fails with a high signal.

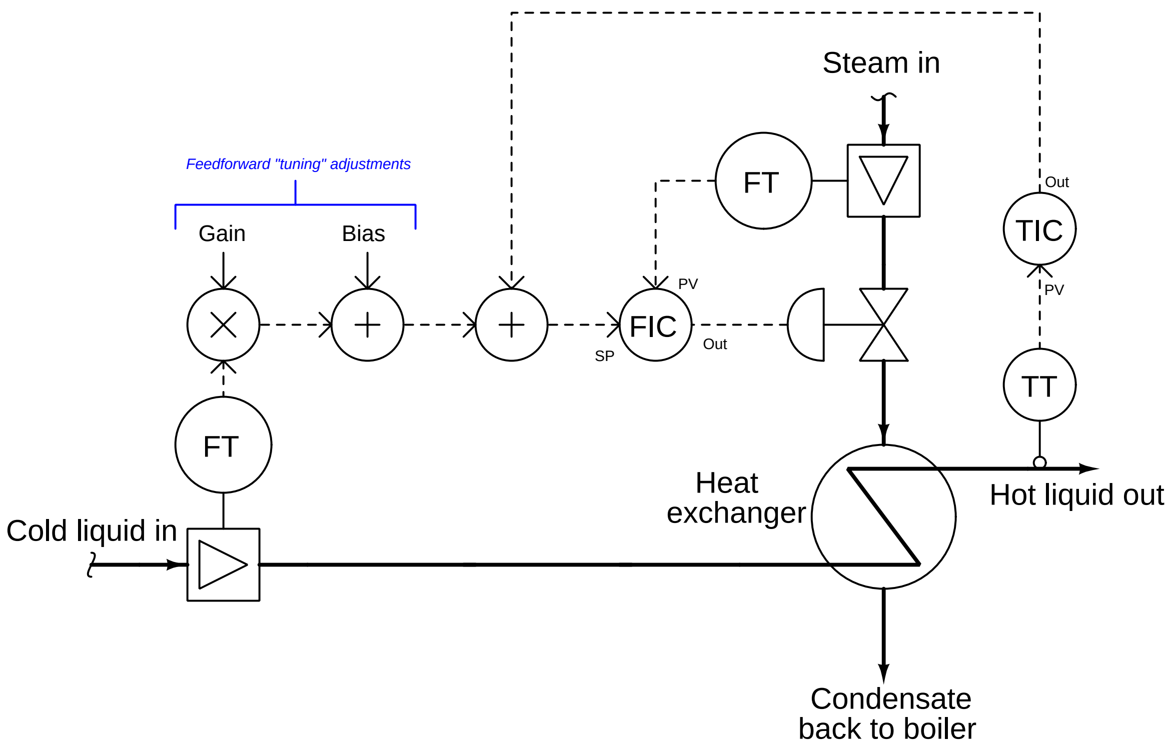
file i01750

Question 26

When the loop controller in a *feedback* control system is tuned too aggressively, it will result in process oscillations. This is a well-known fact of loop tuning, and indeed is regarded as a reliable indication of overly-aggressive controller action.

Feedforward control loops, by contrast, cannot create oscillations. However, it is still possible to have "too much" feedforward action in a loop, so that process control quality suffers.

Examine the following P&ID of a practical feedforward control system on a heat exchanger, complete with "gain" and "bias" functions to allow the feedforward action to be adjusted:



How would this feedforward control system respond to load changes if it were "over-tuned" so that it took *too much* corrective action? What could you do to this system to test the feedforward control response, in order to tell whether or not the magnitude of its corrective action was appropriate? Identify the specific adjustments that you would make to this feedforward system so that its action was more appropriate, if it were discovered that the feedforward action was too aggressive.

Suggestions for Socratic discussion

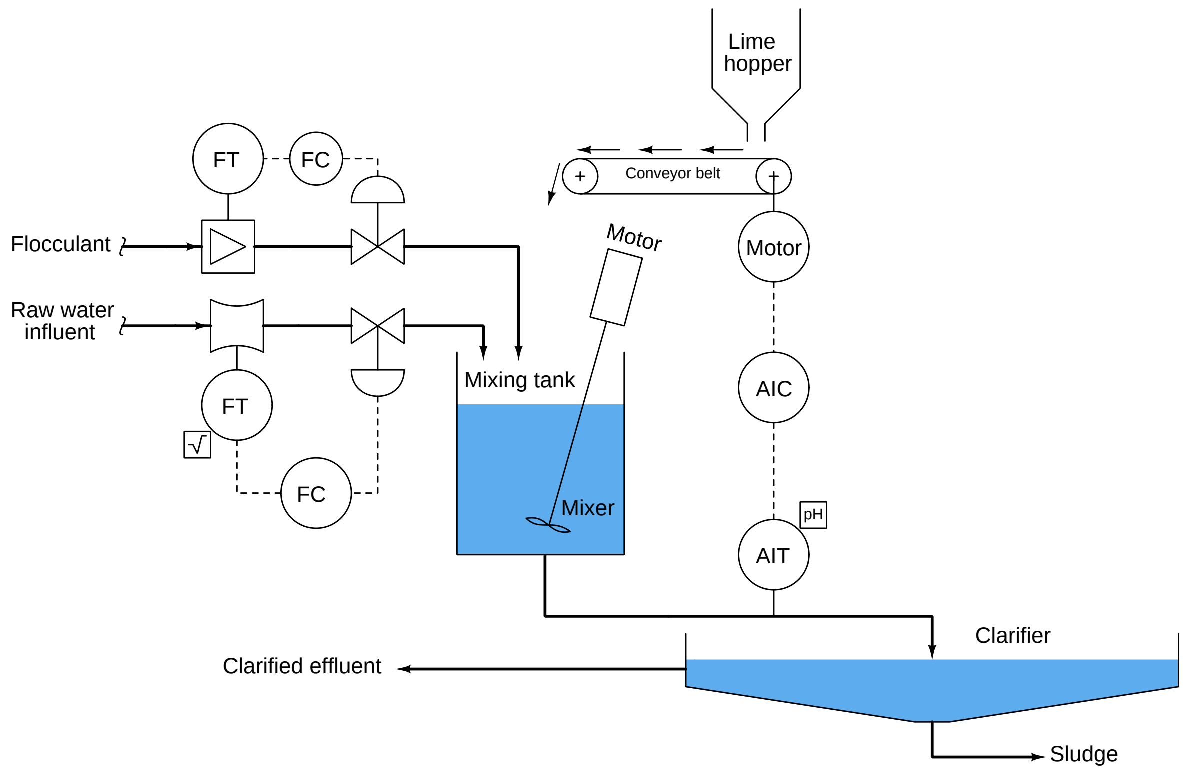
- Determine the appropriate actions (*direct* acting or *reverse* acting) for each controller shown in this system, labeling all inputs with either "+" or "−" symbols as appropriate to show the correct action for each controller.
- What types of flowmeters are shown in this P&ID, and how do they work?
- Identify the individual effects of improper *gain* adjustment, versus improper *bias* adjustment in the feedforward loop. Are the effects the same for both? Why or why not?
- Explain what would happen in this process if the liquid flow transmitter failed with a low signal.
- Explain what would happen in this process if the liquid flow transmitter failed with a high signal.
- Explain what would happen in this process if the steam flow transmitter failed with a low signal.

- Explain what would happen in this process if the steam flow transmitter failed with a high signal.
- Explain what would happen in this process if the temperature transmitter failed with a low signal.
- Explain what would happen in this process if the temperature transmitter failed with a high signal.
- Explain what would happen in this process if the flow controller were switched from "Cascade" mode to "Automatic" mode.
- Explain what would happen in this process if the flow controller were switched from "Cascade" mode to "Manual" mode.
- Explain what would happen in this process if the temperature controller were switched from "Automatic" mode to "Manual" mode.

file i04339

Question 27

Water treatment processes use chemicals called *flocculants* to force suspended solids to clump together and readily fall out of suspension. Some flocculants such as polymers have the undesirable effect of lowering the water's pH value, which not only poses problems for further use of the water but also (ironically) minimizes flocculation efficiency. In order to counter-act this decrease in pH, powdered lime may be added to the water in addition to flocculant to raise the pH level back to a more neutral value:



A pH transmitter measures the pH level of the water exiting the mixing tank, on its way to the clarifier where the floc will settle to the bottom over time and cleaner water is collected at the outer rim.

If someone happens to change the setpoint on the flocculant flow controller, the flow of powdered lime into the mixing tank will not change until the pH controller (AIC) sees a change in pH, which by then may be too late to make a swift correction. The result will be a "bump" in pH over time that may take a while to correct.

Modify this control system to include feedforward, so that any change in flocculant flow rate will *immediately* alter the flow rate of lime, in order to help stabilize pH and thereby improve water treatment quality.

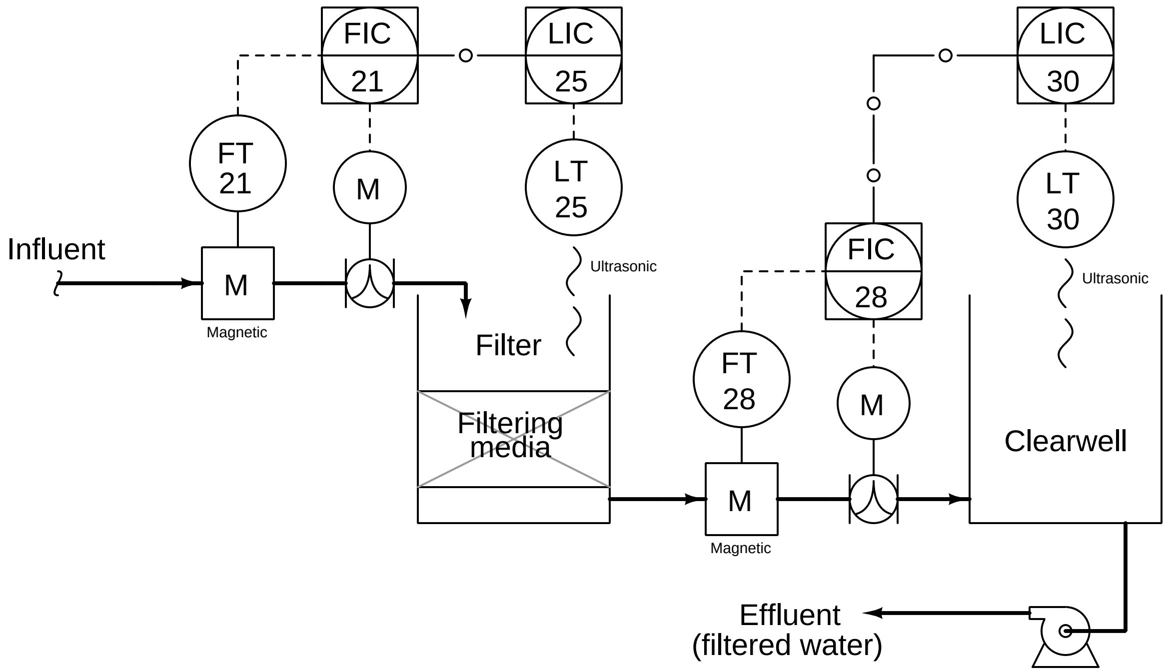
Suggestions for Socratic discussion

- Perhaps the most common mistake made in this problem is to place the feedforward summing function block at the PV input to a controller, when it should actually be located at the output of a controller instead. Explain how we may determine the correct location for the summing block in the control scheme of this process, and/or explain why the other location is wrong.
- For those who have previously studied chemistry, explain what *pH* is and why it is important.
- Why is a *mixing tank* important to have in a system like this where pH is being continuously controlled?

file i03445

Question 28

This water level control system (for a municipal water supply operation) is supposed to maintain constant water level in the filter and in the clearwell. Unfortunately, it has a problem. Operators call you urgently to determine why the clearwell is completely empty:



Your first step is to ask the operator if they have actually inspected the clearwell to verify that it is empty. They have, and it is. They also point to the display for level controller LIC-30 and show you that it reads 0% level.

Identify the likelihood of each specified fault for this water filtration 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
Transmitter FT-21 failed with low output		
Transmitter FT-21 failed with high output		
Transmitter LT-25 failed with low output		
Transmitter LT-25 failed with high output		
Transmitter FT-28 failed with low output		
Transmitter FT-28 failed with high output		
Transmitter LT-30 failed with low output		
Transmitter LT-30 failed with high output		
Effluent pump turned off		

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

Suggestions for Socratic discussion

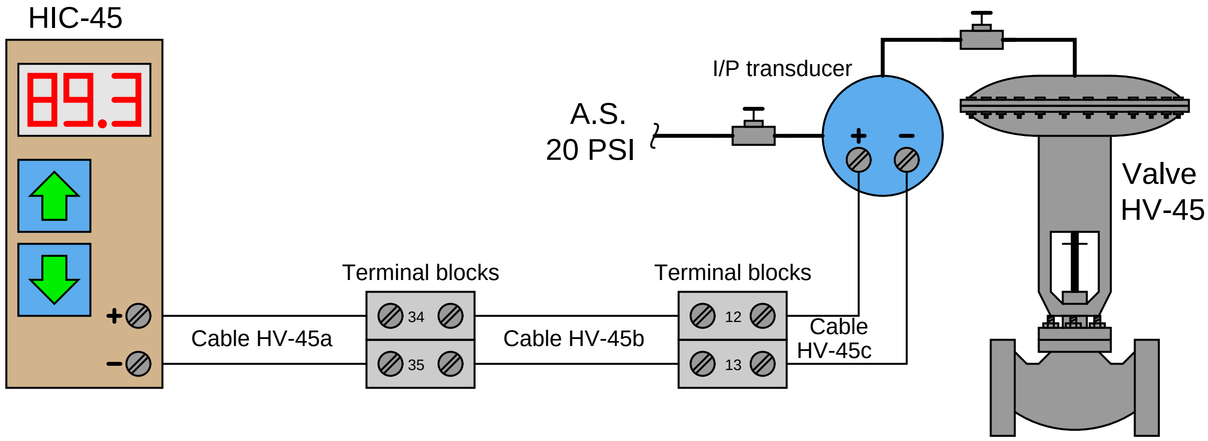
- A useful problem-solving strategy for determining necessary controller actions in a cascade control system is to replace the ISA-standard "bubble" symbols for controllers with triangular opamp symbols, complete with "+" and "−" symbols at the inputs. One input of each "opamp" controller will be the PV, while the other input of each "opamp" controller will be the SP. The inverting and noninverting inputs standard to all operational amplifiers helps remind you that the PV and SP inputs of a loop controller always have opposite effects on the output signal.

- 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.

file i02326

Question 29

This valve control circuit has a problem. No matter what the setting on the hand indicating controller (HIC), the valve remains fully open all the time:



The technician before you used a clamp-on (Hall effect) milliammeter to check loop current at terminal 34 (cable HV-45a conductor), measuring 5.71 mA. The same clamp-on meter used at the (+) terminal of the I/P converter showed 0 mA.

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 discernable from the measurements and symptoms given so far), mark "no."

Diagnostic test	Yes	No
Measure DC voltage between terminals 34 and 35		
Measure DC voltage between terminals 12 and 13		
Measure DC voltage between both terminals labeled 12 (same block)		
Measure DC voltage between I/P terminals		
Measure DC current at terminal 35 (cable HV-45a conductor)		
Measure DC current at terminal 12 (cable HV-45b conductor)		
Measure DC current at terminal 12 (cable HV-45c conductor)		
Check air supply to see that it is at least 20 PSI		
Remove tube from valve diaphragm to check for air pressure there		

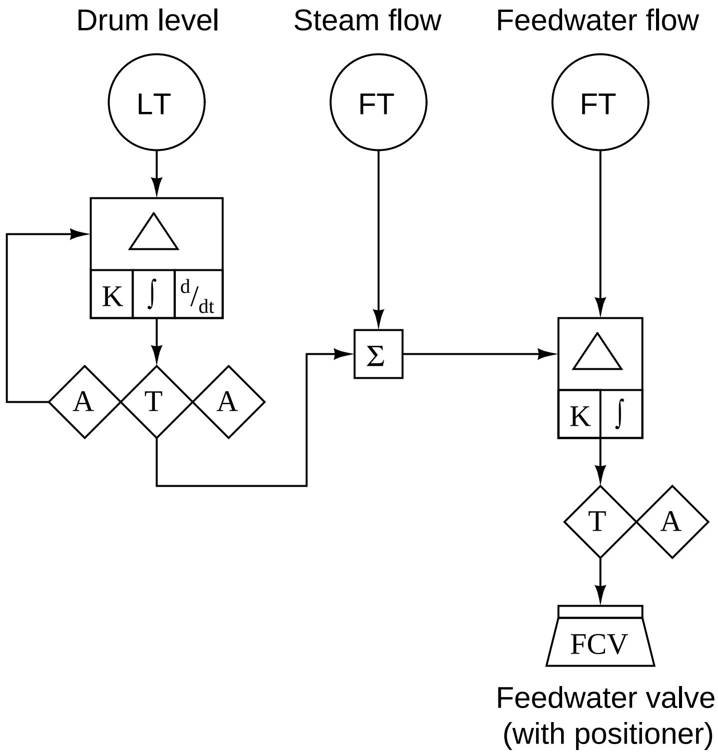
Suggestions for Socratic discussion

- The different current measurements at the two locations is a clear indication of what *type* of problem this is. Identify the problem type, and explain how we know this to be so.
- Given that this valve is air-to-close, and the hand controller is configured to read in percent open, does the indication of 89.3% match the measured current of 5.71 mA? Why or why not?

file i00258

Question 30

Working on a boiler commissioning project, you are tasked with tuning the feedwater controls, documented in this functional diagram:



In what order would you calibrate and/or tune the following components of this control system, and why?

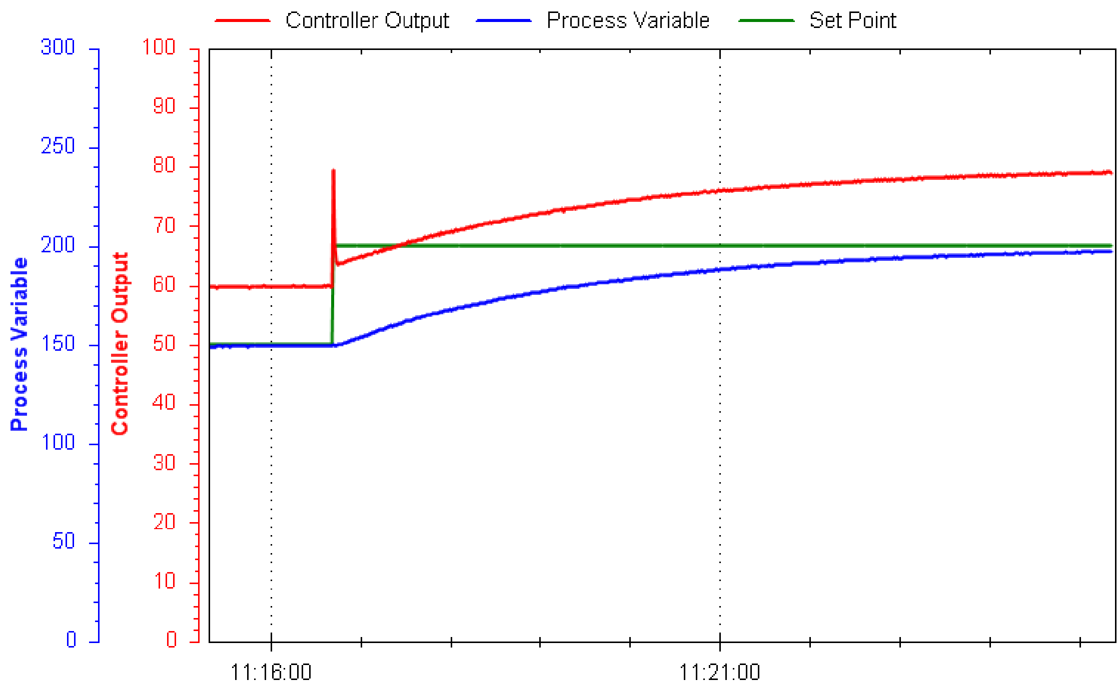
- Steam flow transmitter
- Feedwater flow transmitter
- Level transmitter
- Level controller
- Feedforward summer (bias and gains)
- Flow controller

Describe how you would safely tune the two controllers with the boiler operating. In other words, how would you recommend everything be set up so as to tune one controller at a time with a minimum of upset to the boiler? Also, qualitatively propose the PID constant values needed by each controller (e.g. "aggressive integral action," etc.).

file i01800

Question 31

Examine this process trend showing the PV, SP, and Output of a loop controller:



Based on what you see here, determine the following:

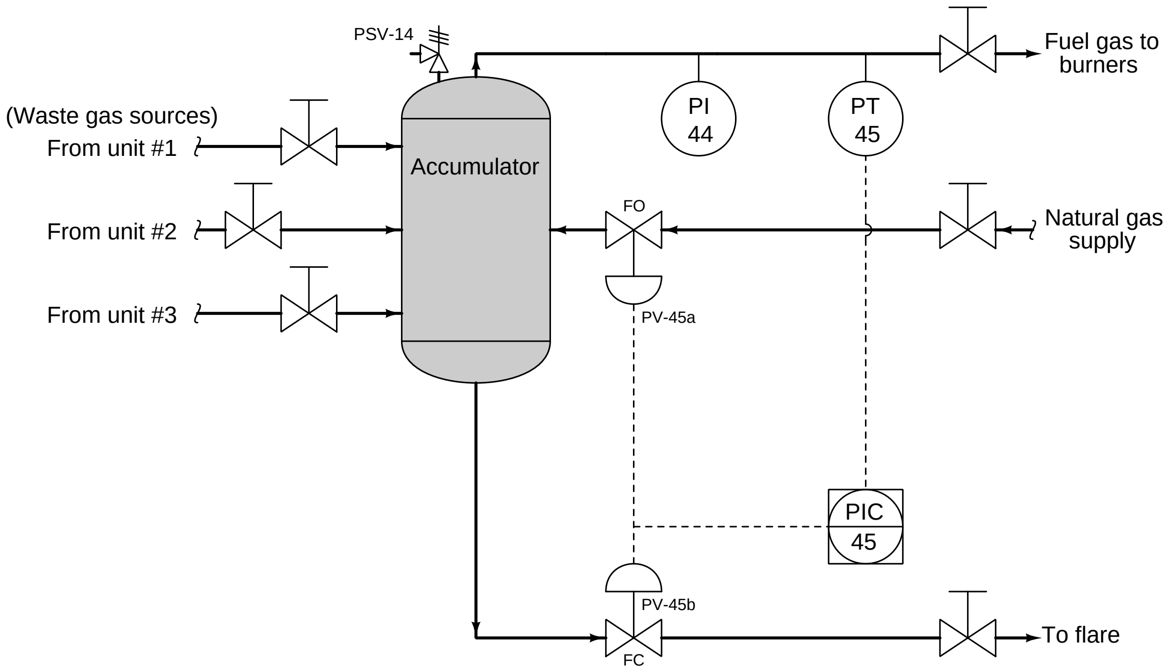
- Whether this is an open-loop or a closed-loop response
- Whether the controller is (or needs to be) *direct-acting* or *reverse-acting*
- If possible, identify any problems with the field instrumentation
- If possible, identify any problems with the controller PID tuning
- Qualitatively identify the kind of PID tuning we will need for robust control

file i01927

Question 32

Many flammable gases are produced in chemical processing and oil refineries as "waste" products. These "waste" gases may be used as fuel for steam boilers and combustion heaters in other parts of the refinery. The problem is, "waste" fuel gas production is often unsteady, and the demand for fuel gas in boilers and heaters is unsteady as well. There are times when there will be a surplus of waste gas (more than can be used), and times when there will not be enough.

The following pressure control system works to maintain constant fuel gas pressure in the accumulator vessel despite changes in waste gas flows and fuel gas demands:

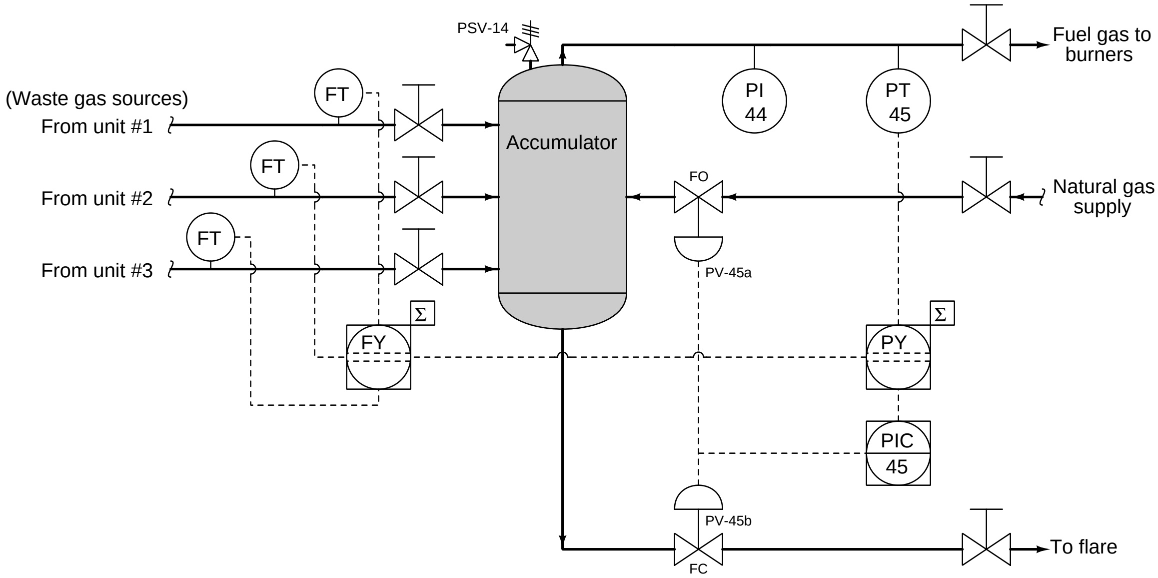


A pair of split-ranged control valves (PV-45a and PV-45b) work together to either admit natural gas into the accumulator (when the gas pressure is too low) or release excess gas to the flare (when pressure is too high).

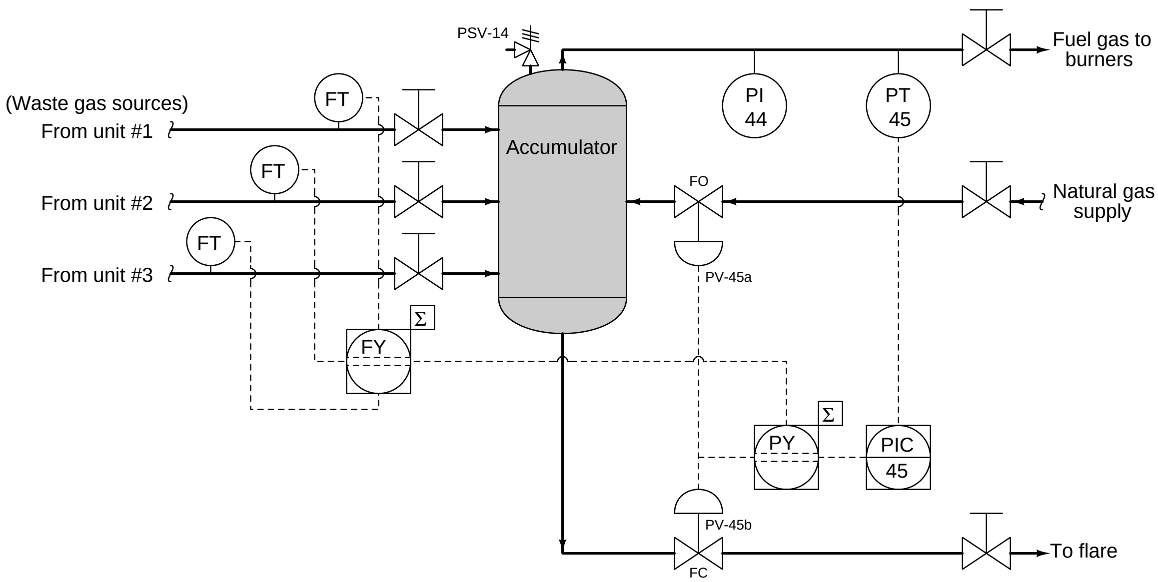
Operations personnel have determined that the pressure inside this accumulator is not steady enough for their operational needs. They have also determined that fast-changing waste gas flows are the source of the instability, and so they ask instrumentation personnel to implement a solution. The instrumentation personnel, in turn, decide to implement a *feedforward* control strategy to meet this need.

The first step, of course, is to install flowmeters on each of the waste gas lines entering the accumulator, the signals of which will be used in the feedforward strategy to pro-actively compensate for changes in waste gas flows. A controversy erupts between instrumentation personnel, however, regarding how to implement the feedforward strategy.

One team says the strategy should look like this:



Another team says the strategy should look like this:

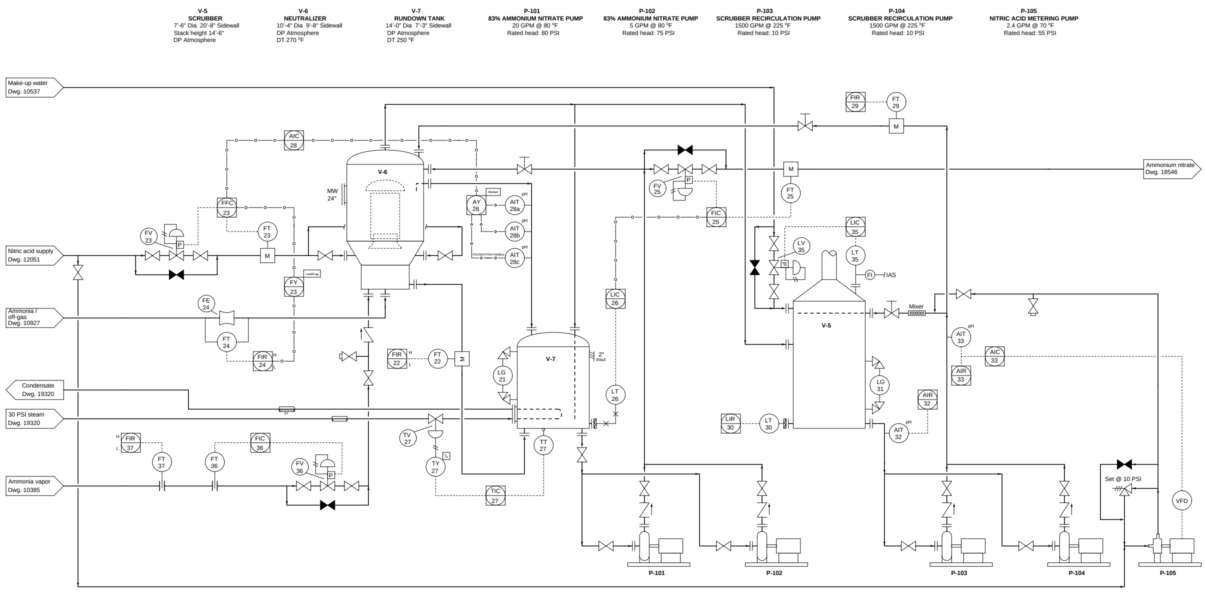


Which team do you agree with, and why? Note: *this is a very important concept to grasp in feedforward control strategies, and in fact is one of the most commonly mis-understood concepts associated with feedforward!*

file i01263

Question 33

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

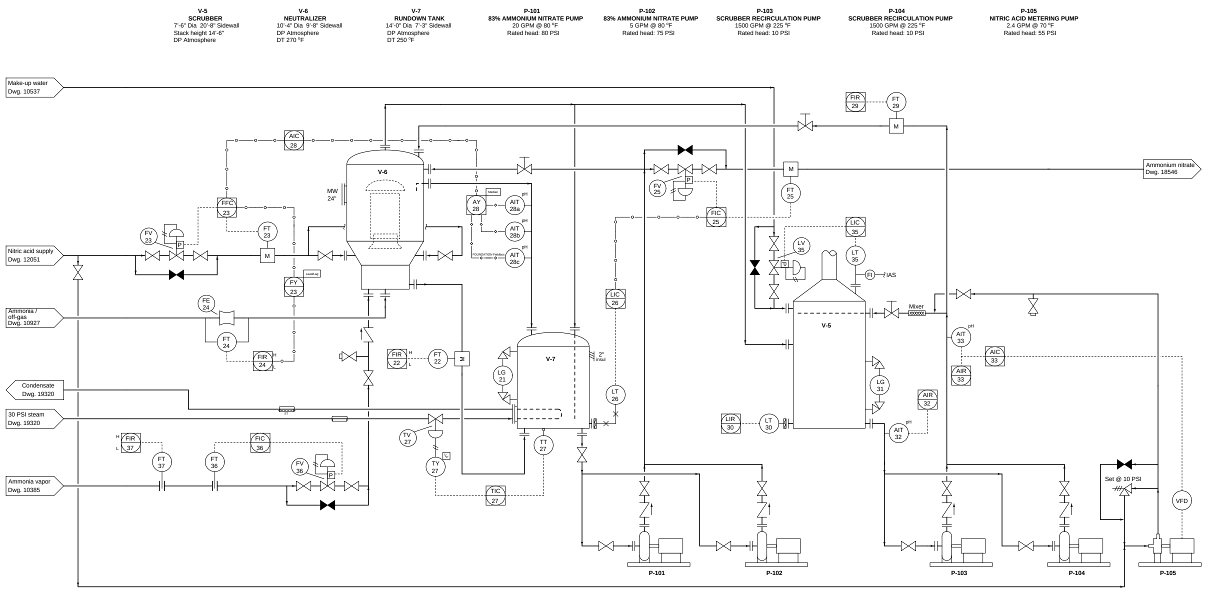


Examine the level control system for the rundown tank (V-7), and identify one of the loads in that control loop. After identifying the load, add a transmitter to sense that load variable, and add necessary control functions to implement a *feedforward* control strategy to the rundown tank's level control.

file i01276

Question 34

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.

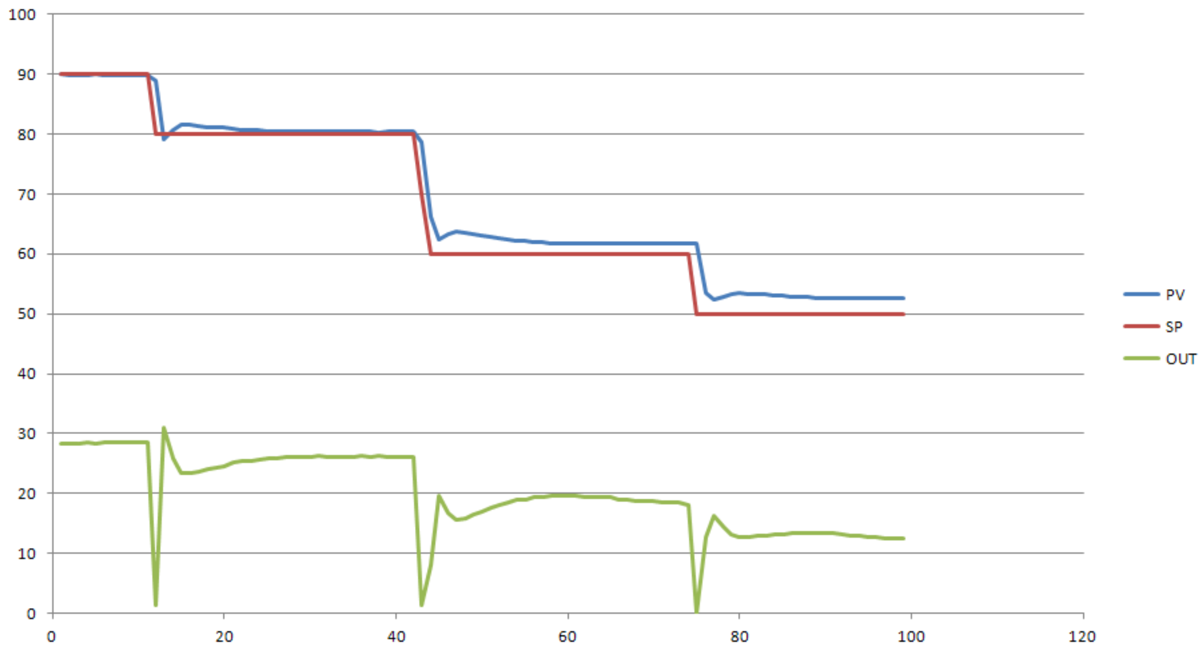
Examine the pH control system for that scrubber vessel and identify one of the loads in that control loop. After identifying the load, add a transmitter to sense that load variable, and add necessary control functions to implement a *feedforward* control strategy to the scrubber's pH control system.

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 35

Examine this process trend showing the PV, SP, and Output of a loop controller:



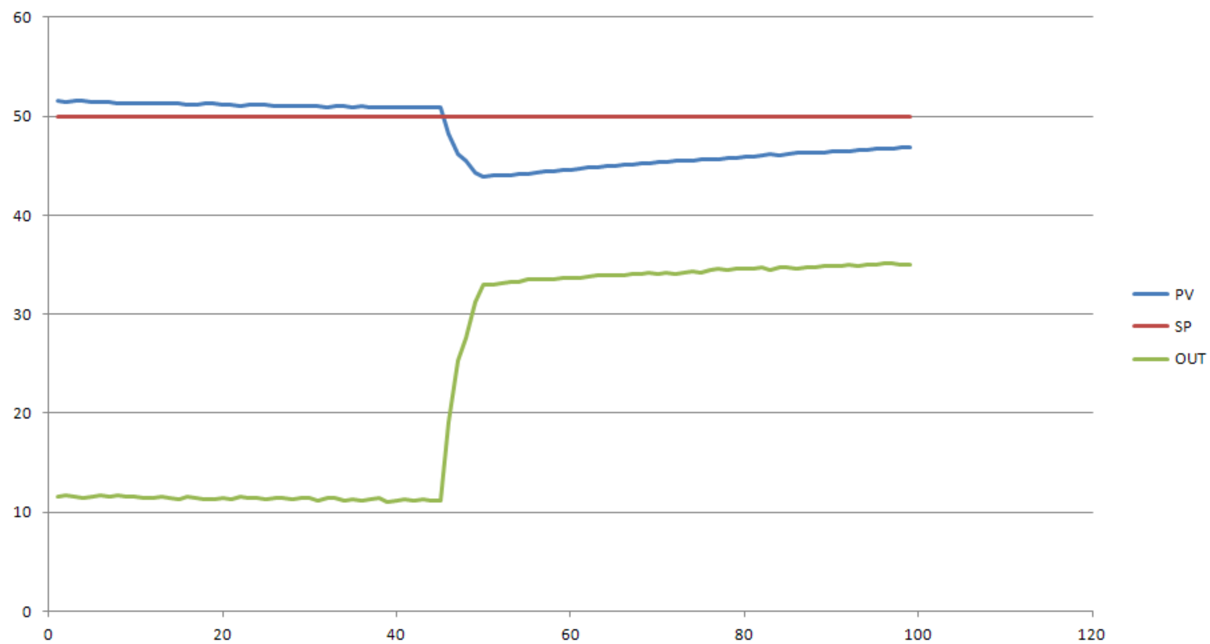
Based on what you see here, determine the following:

- Whether this is an open-loop or a closed-loop response
- Whether the controller is (or needs to be) *direct-acting* or *reverse-acting*
- If possible, identify any problems with the field instrumentation
- If possible, identify any problems with the controller PID tuning
- Qualitatively identify the kind of PID tuning we will need for robust control

file i02567

Question 36

Examine this process trend showing the PV, SP, and Output of a loop controller:



Based on what you see here, determine the following:

- Whether this is an open-loop or a closed-loop response
- Whether the controller is (or needs to be) *direct-acting* or *reverse-acting*
- If possible, identify any problems with the field instrumentation
- If possible, identify any problems with the controller PID tuning
- Qualitatively identify the kind of PID tuning we will need for robust control

file i02568

Question 37

Question 38

Question 39

Question 40

Question 41

Read and outline Case History #66 ("A Depressing Day In The Plant With No Miracles") 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) Any points of confusion, and precisely why you found the text confusing.
(5) Questions of your own you would pose to another reader, to challenge their understanding.
(6) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.

Be sure to answer the following questions:

- Examine Figure 1, showing a closed-loop test of the process. Identify the features of the controller output trend where *integral action* is clearly evident, and also features of the same trend where *proportional action* is clearly evident.

- Examining Figure 1 again, explain why the upward ramp of the controller output in the middle of the display is steeper than the downward ramp toward the end (right-hand side) of the display. Based on what you know of PID controller behavior, what explains the differences in ramp steepness, as well as their different directions (ramping up versus ramping down)? Note that Figure 4 shows the same phenomenon!

- Explain what we may determine about the control valve from the open-loop test results shown in Figure 2. In particular, what is this phenomenon referred to by Mr. Brown as "negative hysteresis?"

- One of the problems this control valve has is that it is over-sized. Explain how we may determine this from an examination of *either* the open-loop test or the closed-loop tests (Figures 1 through 3).

- At the end of this Case History, Mr. Brown poses an interesting question: "How does one differentiate between cycles caused by unstable tuning, and those caused by valve problems as illustrated in this article?" Explain in your own words how you may make this determination by examining a closed-loop trend of the process. *Note: this is a simple yet extremely valuable tip to remember, as it will make your loop problem troubleshooting go a lot quicker!*

Suggestions for Socratic discussion

- Identify where "porpoising" behavior appears in the trend of Figure 1, and identify the controller action (P, I, or D) responsible for it. For more information on "porpoising," refer to the "Recognizing a 'Porpoising' Controller" subsection of the "Heuristic PID Tuning Procedures" section of the "Process Dynamics and PID Controller Tuning" chapter in your *Lessons In Industrial Instrumentation* textbook.
- Examine the trend of Figure 3 and identify the controller's dominant action (either P, I, or D), based on the information contained in the "Recognizing an Over-Tuned Controller by phase shift" subsection of the "Heuristic PID Tuning Procedures" section of the "Process Dynamics and PID Controller Tuning" chapter in your *Lessons In Industrial Instrumentation* textbook.

- Mr. Brown claims that open-loop step-changes "shock" the control valve and are therefore not good for revealing sticking and slipping behavior. Does this mean it's impossible to test for valve stiction using open-loop output steps? Explain why or why not.

file i01659

Question 42

Read and outline Case History #63 ("Problems On A Plant With No Positioners On Valves") 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) Any points of confusion, and precisely why you found the text confusing.
(5) Questions of your own you would pose to another reader, to challenge their understanding.
(6) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.

Be sure to answer the following questions:

- According to Mr. Brown, what is the purpose for installing a positioner on a control valve?

- Examine the closed-loop test shown in Figure 1. What can you determine about the condition of the loop from this test?

- Mr. Brown claims you can tell the integral action of the controller is too slow based on the closed-loop test results shown in Figure 1. Explain how his conclusion is justified by the data.

- Figure 2 shows the response of the system during an open-loop test. What can you determine about the condition of the valve from this test?

- In this Case History, Mr. Brown expresses his low opinion of "quarter-amplitude damping" as a standard for good control behavior. Explain his objection to quarter-wave damping, in your own words.

- Compare the "As-Found" controller tuning with the "As-left" tuning, and identify how the tuning parameters were changed for better performance. How do you suppose the tuning could be "tightened" even further had the valve been repaired or at least equipped with a positioner?

file i01697

Question 43

Read and outline Case History #59 ("The Regulatory Controls In Most Plants Do Not Work Properly") 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) Any points of confusion, and precisely why you found the text confusing.
(5) Questions of your own you would pose to another reader, to challenge their understanding.
(6) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.

Be sure to answer the following questions:

- The title of this Case History gives a sweeping indictment of process control quality in industry. According to Mr. Brown, what percentage of loops does he typically find in poor condition? Identify the specific industries mentioned in this short collection of (four) case histories.

- How is it possible for industrial plant operators to manage decent production when the underlying control loops tend to behave so poorly? What, specifically, do some operators do to manage poor loops?

- Describe the problem in Case #2, and how it was determined from an open-loop test.

- Explain what is so bizarre about the results of the open-loop test in Case #3, and why there was no possible way to overcome this problem through PID tuning (adjusting the P, I, and D parameters).

- In Case #4, one of the problems mentioned is the presence of too much "damping" in the flowmeter. Damping often goes by the synonym "filtering," and it can cause a lot of problems in a control loop. Why was this particular flowmeter configured to have so much damping in it?

Suggestions for Socratic discussion

- For those of you who have studied flowmeter technologies, briefly review the operating principle of a *magnetic* flowmeter. Mr. Brown states the flow range accuracy of a magnetic flowmeter being about 10:1. How does this amount of turndown compare with other flowmeter types such as orifice plates and Coriolis flowmeters?
- For those of you who have studied flowmeter technologies, explain why a DC-excited magnetic flowmeter might be susceptible to noise caused by solid particles moving through the liquid flowstream.
- For those of you who have studied transmitters in detail, briefly review the concept of *filtering* and identify what useful purpose(s) it may serve in a measurement system.

file i01674

Question 44

Read and outline Case History #79 ("Are Smart Positioners The Answer To All Valve Problems?") 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) Any points of confusion, and precisely why you found the text confusing.
(5) Questions of your own you would pose to another reader, to challenge their understanding.
(6) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.

Be sure to answer the following questions:

- Explain how even a smart positioner can exhibit poor behavior if the valve actuator is under-sized.

- Examine Figure 1 showing an open-loop test of a control valve equipped with a smart positioner. What *should* the trend look like if the positioner were properly doing its job?

- Describe some of the awful valve behavior evident in the trend of Figure 3, another open-loop test of a control valve equipped with a smart positioner.

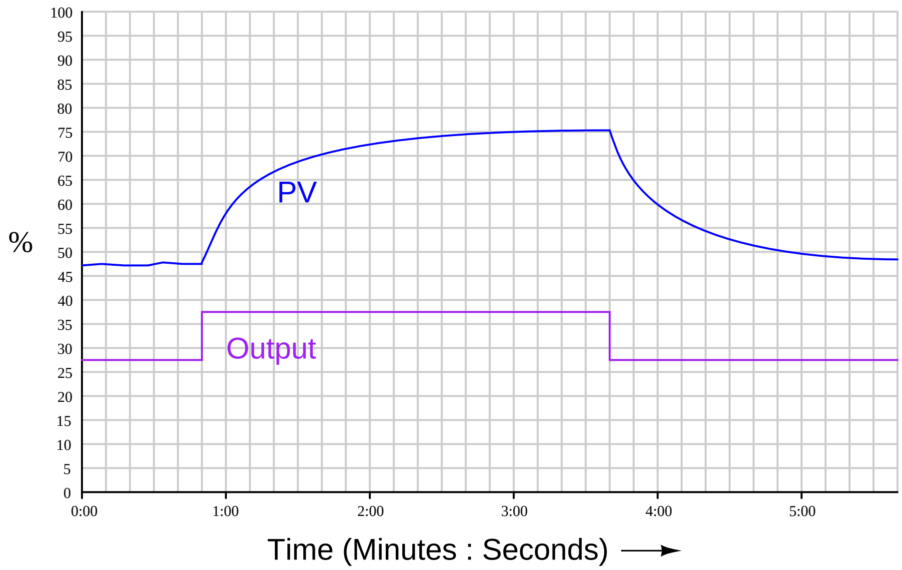
Suggestions for Socratic discussion

- Should the pitiful performance of these control valves be taken as an indictment of smart valve positioners? Why or why not?
- Suppose you were the instrument technician tasked with *repairing* one of the bad control valves identified by a loop optimization team. What kind of diagnostic test would you consider running, using the smart positioner's diagnostic capabilities?
- How do you suppose the Fisher DVC6000 series of control valve positioners perform in light of Michael Brown's concerns?

file i03260

Question 45

Examine this process trend, showing the response of the process variable to a 10% up-and-down step change in the controller output (placed in manual mode):



What characteristics of the process (and its related instrumentation) can you discern from this trend? Based on this information, hypothesize how you think the controller should be tuned to respond. In other words, how aggressive should the controller's P, I, and D terms be relative to each other?

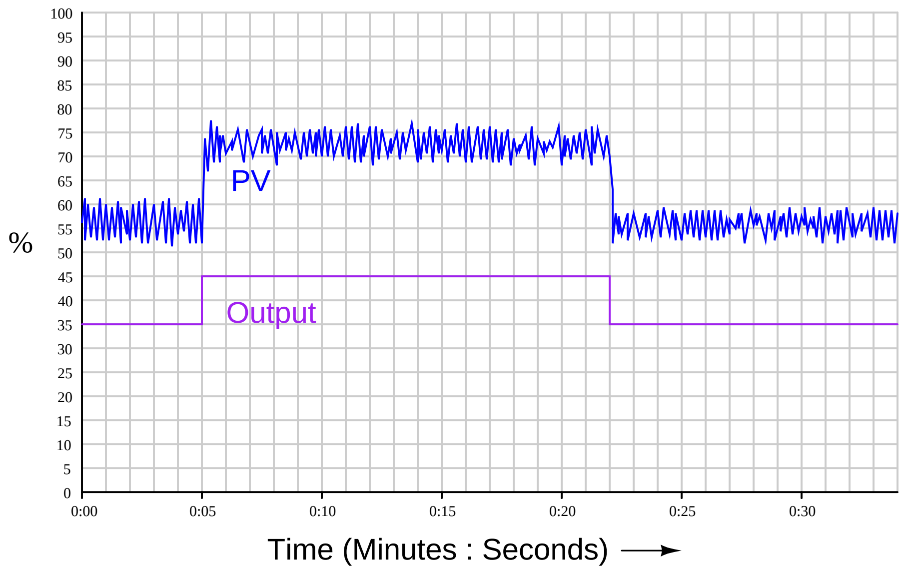
Suggestions for Socratic discussion

- The possibility exists that this process is not really dominated by first-order lag at all, but rather the transmitter is heavily damped by an aggressive filtering constant. How would the process be affected by the recommended controller tuning if in fact the first-order lag characteristic were entirely due to transmitter filtering and not the process?
- The possibility exists that this process is not really dominated by first-order lag at all, but rather the control valve is slow to respond to sudden changes in controller output. How would the process be affected by the recommended controller tuning if in fact the first-order lag characteristic were entirely due to valve lag and not the process?
- Describe a diagnostic test by which you could determine whether this first-order lag is really part of the process, or is due to transmitter damping, or is due to control valve slowness.

file i01729

Question 46

Suppose you are asked to tune the controller of a liquid flow process. After obtaining permission from the operator, you analyze the response of the process variable (liquid level) to a 10% up-and-down step change in the controller output (placed in manual mode):



The first thing you notice is that the PV trend is extremely noisy. Investigating a little further, you find that the flow transmitter is a differential pressure sensor connected across an orifice plate, and that the transmitter is mounted on a pipe that vibrates a lot.

How does the presence of this noise affect your decisions on how to tune it? Would you tune this liquid flow controller the same as you would any other liquid flow controller, or would you tune it differently? Explain your reasoning.

Suggestions for Socratic discussion

- Identify at least one way this noise could be mitigated, so it no longer posed a challenge to controller tuning.
- Would you recommend re-locating the DP transmitter to a location with less vibration? Why or why not?

file i01728

Question 47

When tuning a PID controller by "trial-and-error" in automatic mode, it is advisable to "bump" the setpoint either up or down to test the response of the new P, I, and D settings. Why is periodic "bumping" of the setpoint necessary when tuning a controller? What does it tell us about the tuning? More importantly, what does it *not* tell us about the tuning?

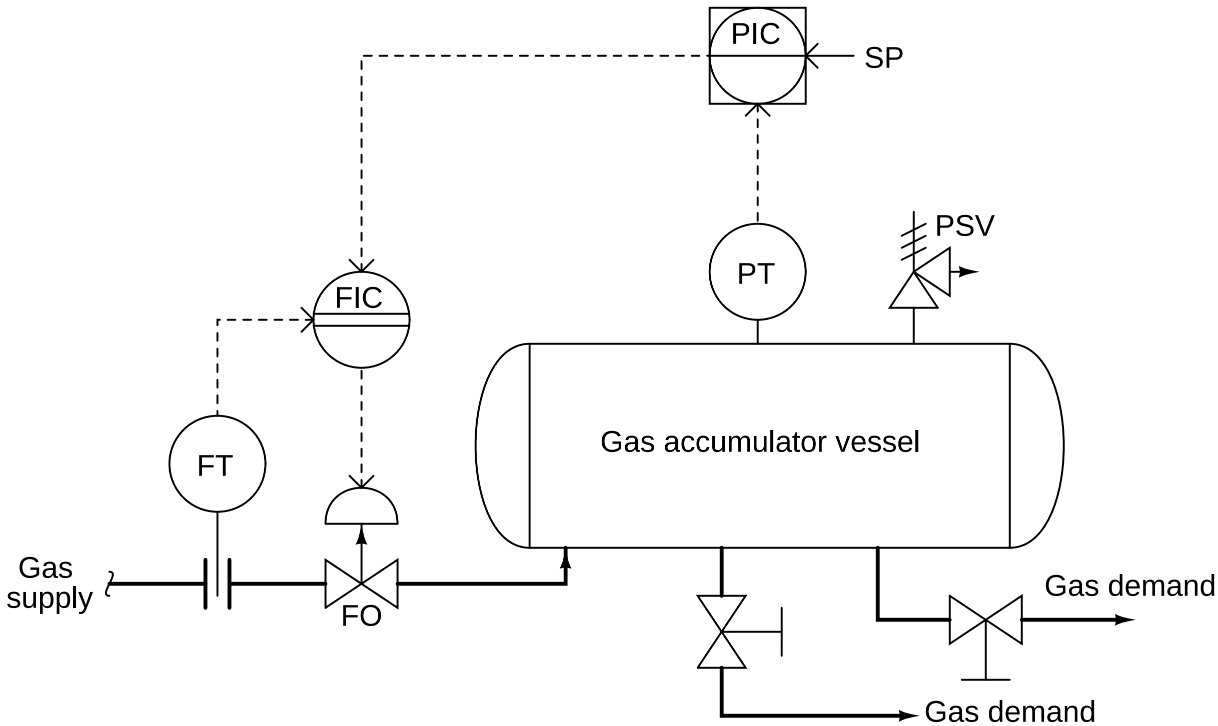
Suggestions for Socratic discussion

- A point of confusion for many students learning PID control is the practical difference between performing an open-loop "bump" test (step-changing the controller's output) versus a closed-loop "bump" test (step-changing the controller's setpoint). Explain the difference between these two tests, and why it is necessary to do *both* when optimizing a control loop.

  file i01672

Question 48

Examine this P&ID for a cascaded gas-pressure control system:



Assuming both transmitters are direct-indicating (i.e. greater pressure/flow results in greater signal to the respective controllers), determine the necessary control actions (direct or reverse) for each controller. In addition to determining "direct" or "reverse" action for each controller, label each controller's inputs with "+" and "−" symbols showing the direction of action for PV and for SP individually.

- Pressure Indicating Controller (PIC): *direct* or *reverse* action?

- Flow Indicating Controller (FIC): *direct* or *reverse* action?

Suggestions for Socratic discussion

- What must be configured in the FIC to allow the operator to see 0-100% (registered on the controller faceplate) as true valve position (i.e. 0% on faceplate = shut valve and 100% on faceplate = open valve)?
- Would your answer(s) be different if the control valve throttled gas *leaving* the vessel rather than gas *entering* the vessel? This, of course, would mean that at least one of the (currently) out-going pipes would have to supply gas to the vessel instead.
- Would your answer(s) be different if the control valve were fail-closed (FC) instead of fail-open (FO)?
- Would your answer(s) be different if the flow transmitter were located downstream of the control valve instead of upstream?
- Describe the purpose of the device labeled "PSV" in this diagram.

file i00079

Question 49

Desktop Process exercise

Configure your Desktop Process for full proportional-plus-integral-plus-derivative (PID) control. Experiment with different "gain," "reset," and "rate" tuning parameter values until reasonably good control is obtained from the process (i.e. fast response to setpoint changes with minimal "overshoot," good recovery from load changes). Record these "optimum" P, I, and D settings you find for your process, for future reference.

Next, purposely add excessive filtering ("damping") to the process variable (PV) input of the controller. If the controller is programmed using function blocks, the filtering parameter will most likely be found in the *Analog Input* function block. The purpose of this exercise is to see how excessive filtering compromises what would otherwise be good control, so be sure to enter a value that is truly too slow for your process. For motor speed control, a filtering time of 5 seconds should be adequate (equivalent to a filter breakpoint frequency of 0.2 Hz, if your controller accepts frequency rather than time for the filtering parameter).

After entering this filter value into the controller, place it in automatic mode and observe how well (or poorly) it controls the process now. Pay close attention to the actual process variable value as compared to the process variable display on the controller faceplate. Does the faceplate PV display overshoot setpoint? Does the real process variable (as directly observed by you) overshoot as well? Do they overshoot the same amount? Do they overshoot at the same time?

Try re-tuning the controller's PID function to achieve better control (i.e. less overshoot) than you have now. Are you able to achieve better control than the previous (optimum) PID tuning values? If so, how? If you succeed in getting the controller's PV display to "control" well with different tuning values, does the real process variable (as directly observed by you) control as well as the displayed PV, or worse?

Feel free to set the filtering parameter to different values and re-tuning the controller again to achieve the best control possible.

Discuss with your teammates how you see PV filtering affecting process stability. This exercise should clearly demonstrate how excessive filtering compromises control quality, but do you think there are beneficial applications for PV filtering in a controller?

file i01787

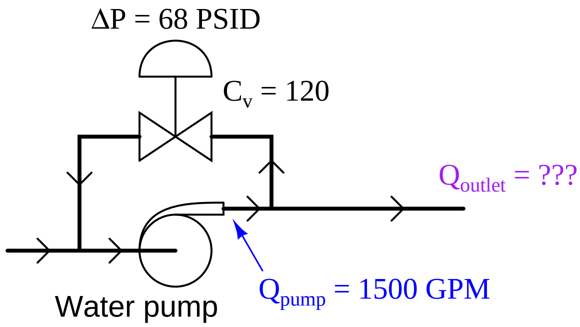
Question 50

Determine a suitable control valve C_v to handle a maximum water flow rate of 750 gallons per minute with an upstream pressure of 125 PSI and a downstream pressure of 110 PSI. Also, calculate the approximate pipe size (in inches) if the control valve type is a 90^o butterfly valve with an offset seat.

file i01816

Question 51

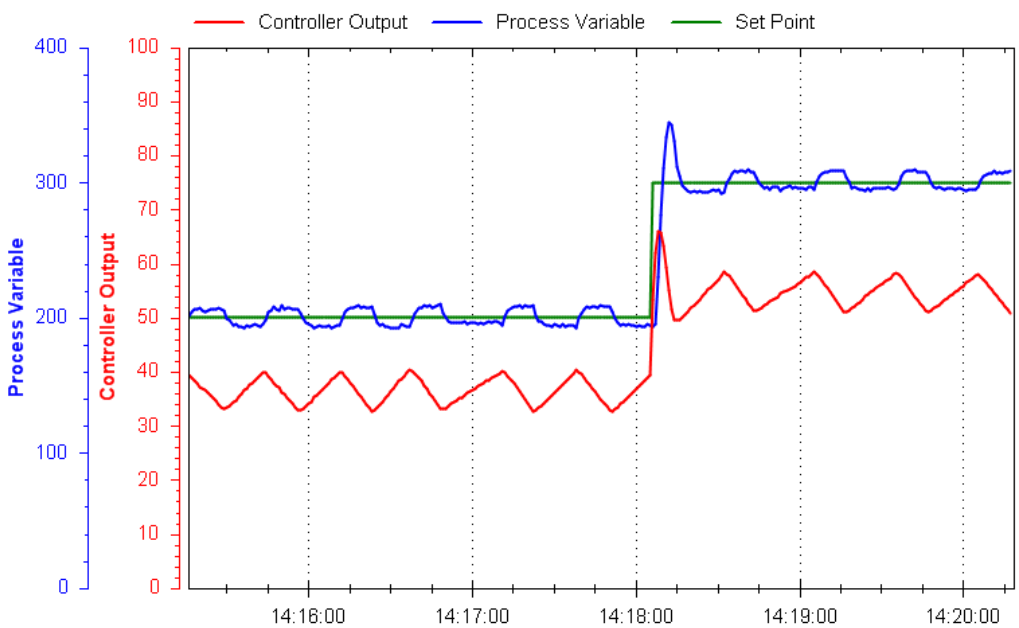
A water pump bypass valve has a full-open C_v rating of 120. If the pump outputs a flow of 1500 GPM of water at a differential pressure (outlet pressure - inlet pressure) of 68 PSID, what will be the total water flow output by the system when the bypass valve is 100% open?



file i01817

Question 52

Examine this process trend showing the PV, SP, and Output of a loop controller:



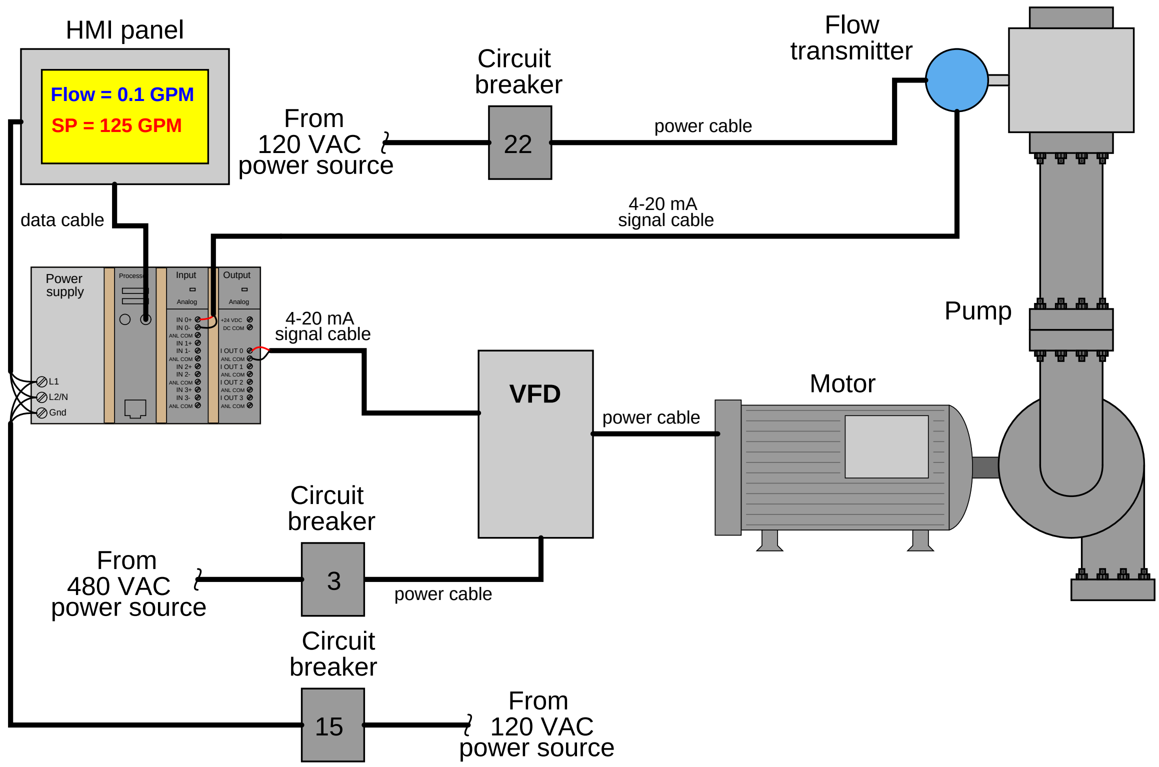
Based on what you see here, determine the following:

- Whether this is an open-loop or a closed-loop response
- Whether the controller is (or needs to be) *direct-acting* or *reverse-acting*
- If possible, identify any problems with the field instrumentation
- If possible, identify any problems with the controller PID tuning
- Qualitatively identify the kind of PID tuning we will need for robust control

file i02640

Question 53

This flow control loop used to function just fine, but now it has a problem. No matter what the setpoint value is set for on the HMI panel (touch-screen), no actual liquid flow ever goes through the pipe:



Identify the likelihood of each specified fault for this flow loop. 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.

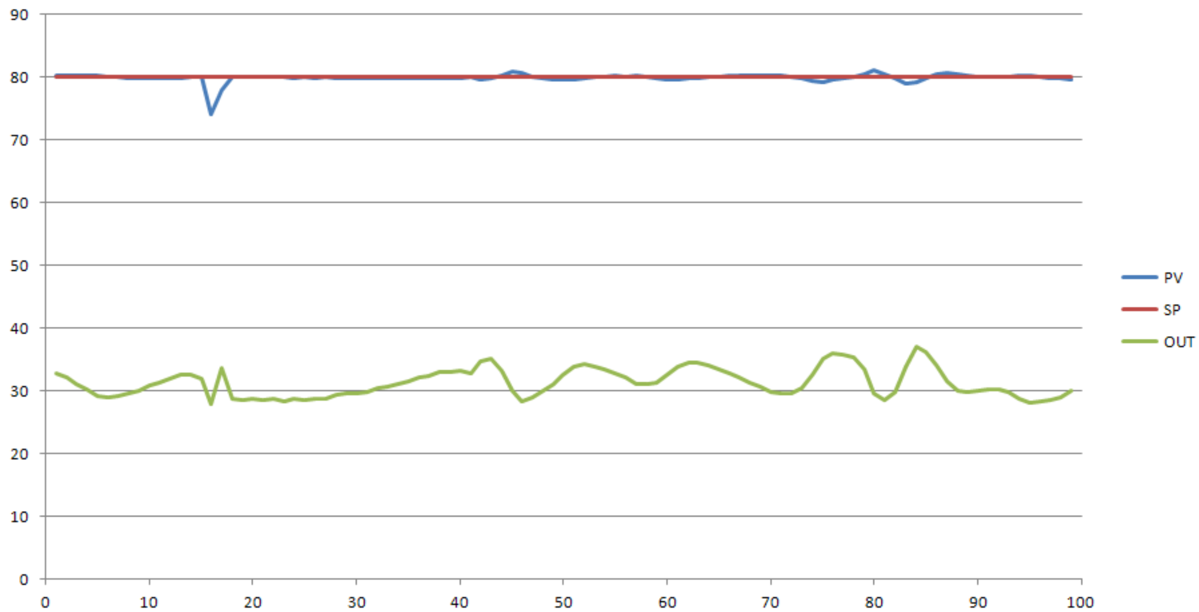
Fault	Possible	Impossible
FT signal cable failed open		
FT signal cable failed shorted		
VFD signal cable failed open		
VFD signal cable failed shorted		
HMI data cable failed open		
PID control block in manual mode		
Insufficient integral control action		
Circuit breaker 3 tripped		
Circuit breaker 15 tripped		
Circuit breaker 22 tripped		

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

file i02989

Question 54

Examine this process trend showing the PV, SP, and Output of a loop controller:



Based on what you see here, determine the following:

- Whether this is an open-loop or a closed-loop response
- Whether the controller is (or needs to be) *direct-acting* or *reverse-acting*
- If possible, identify any problems with the field instrumentation
- If possible, identify any problems with the controller PID tuning
- Qualitatively identify the kind of PID tuning we will need for robust control

file i02569

Question 55

Question 56

Question 57

Question 58

Question 59

Question 60

Question 61

Read and outline Case History #50 ("Sometimes You Have To Use A Filter") 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) Any points of confusion, and precisely why you found the text confusing.
(5) Questions of your own you would pose to another reader, to challenge their understanding.
(6) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.

Be sure to answer the following questions:

- Process variable filtering is also known by another term: *damping*. Most transmitters have a programmable damping feature in them, as well as most controller PV inputs, which may be set to provide a wide range of signal filtering. Explain what this "filtering" does to the process variable signal.

- Figure 1 of this report shows the closed-loop trend for a liquid level control system, slowly settling down to setpoint with much oscillation. It is a fair assessment that the main problem in this loop is a controller that is tuned too aggressively, as opposed to an instrument problem such as friction in the valve. Explain how we can tell this from the shapes of the PV and Output waves.

- Figure 1 of this report shows the closed-loop trend of PV and Output for a level control system. Given that the controller is reverse-acting, determine which is the dominant control action (P, I, or D) in this over-tuned controller by examining the *phase shift* between PV and Output.

- As far as industrial processes are concerned, the amount of noise present on this PV signal is not extreme. However, it was a bit too much for the PID tuning recommended by the Protuner software. Identify how we typically tune (integrating) level control processes, and why this particular tuning does not agree well with a noisy PV signal.

- Explain how Mr. Brown was able to overcome the noise problem in this process, to use the PID tuning parameters suited for this (integrating) process type.

Suggestions for Socratic discussion

- Discuss in general how we may use PV/Output phase shift to identify a controller's dominant action, based on the information contained in the "Recognizing an Over-Tuned Controller by phase shift" subsection of the "Heuristic PID Tuning Procedures" section of the "Process Dynamics and PID Controller Tuning" chapter in your *Lessons In Industrial Instrumentation* textbook and discuss this with your classmates.
- Identify the controller's mode (i.e. auto or manual) in each of the trend graphs shown in this article.
- Mr. Brown mentions something at the beginning of this article about an *anti-aliasing filter*. Explain what "aliasing" is, and why a low-pass filter helps to guard against it. Note that your *Lessons In Industrial Instrumentation* textbook discusses this concept.

file i01790

Question 62

Read and outline Case History #27 ("Interesting Problems In A Cascade Level Loop") 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) Any points of confusion, and precisely why you found the text confusing.
(5) Questions of your own you would pose to another reader, to challenge their understanding.
(6) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.

Be sure to answer the following questions:

- Mr. Brown claims that cascade loops have the advantage of "making the valve intelligent." Explain what this means in detail.

- Which loop in a cascaded control system should be optimized *first* if your goal is to optimize the entire system? Why should you choose that particular loop as the first one to tune?

- Figure 2 in this report shows a very interesting comparison: the PV as recorded by the Protuner analyzer (connected directly to the DCS input terminals) shows a different trend than the PV graphed by the DCS itself! How is such a thing possible?

- Figure 3 shows an open-loop test of this same flow controller, with the flow signal "spiking" at each leading edge. Mr. Brown attributes this to a problem with the valve's positioner. Based on what you know about valve positioners (especially *digital* "smart" positioners), how would you suggest fixing this positioner problem?

Suggestions for Socratic discussion

- Based on the open-loop test results shown in Figure 3, does the control valve appear to exhibit significant hysteresis? Why or why not?
- In the end, do you think it was beneficial to have cascade control on this process, as opposed to direct (single-controller) PID control on the level?
- Had the filtering been located in the transmitter rather than in the DCS, would the Protuner software have recorded a different PV trend than the DCS? Why or why not?
- Explain how we may properly determine that the cycling seen in Figure 4 is indeed due to control valve stiction.
- For those who have studied flow measurement technologies, explain the principle behind not trusting an orifice-based flowmeter below 25% (or even 33%) of its full-scale range.
- Explain how excessive filtering in a control loop not only makes the trend graph appear "smoother" than the actual process variable is, but in fact leads to the real PV being much less stable than it would be without any filtering applied.
- For those who have studied flow measurement technologies, explain what the British standard means by saying orifice-based flow measurements should be maintained at least 33% of full scale.

file i01665

Question 63

Read and outline Case History #60 ("Do Mines Have Particularly Bad Control Problems?") 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) Any points of confusion, and precisely why you found the text confusing.
(5) Questions of your own you would pose to another reader, to challenge their understanding.
(6) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.

Be sure to answer the following questions:

- Mr. Brown has some unkind words to say about PLCs used as loop controllers, especially when compared to DCSs. What, specifically, is his criticism, and do you think this is valid given your exposure to PID control algorithms in PLC systems you've seen (e.g. Allen-Bradley Logix5000)?

- One of the anecdotes related in this Case History was a PLC used as a loop controller for a furnace pressure control system, where the programmer decided to make the control valve shut every time the controller was switched from manual mode to automatic mode. What happened as a result of this?

- Figure 1 shows the closed-loop response of a system where the integral action was far too slow. Explain how we may make this determination on our own just from examining the trend of SP and PV, even without a trend of the controller Output to compare.

- Figure 2 shows a loop in "continuous cycle" (oscillation). Examine the *phase shift* between the PV and Output and use this information to determine whether the controller's action is dominated by P, I, or D. Hint: this is a *direct-acting* controller.

- Figure 4 shows a textbook example of a "stick-slip" cycle. Explain what causes this, and why this problem cannot be eliminated simply by adjusting the tuning parameters on the controller.

- Explain how we are able to tell the valve has stiction problems by examining the trend graph shown in Figure 5.

Suggestions for Socratic discussion

- In this article the author refers to a cyanide concentration analyzer with a scan rate of once per 17 minutes. Explain why this scan rate may be problematic if this type of analyzer happens to be the transmitter in a feedback control loop.
- Describe what a "safety bursting plate" is, and what other term(s) this kind of a device may be known by?
- The controller seen cycling in Figure 2 is direct-acting, yet Mr. Brown does not specify this fact anywhere in the text. How is it possible for us to know this? Hint: examine Figure 3, which is an *open-loop* test of that same process. Figure 2 (closed-loop) also contains enough information for us to tell this is a direct-acting controller.

- If you experience difficulty answering the question on PV/Output phase shift as a way of identifying dominant control action, read the "Recognizing an Over-Tuned Controller by phase shift" subsection of the "Heuristic PID Tuning Procedures" section of the "Process Dynamics and PID Controller Tuning" chapter in your *Lessons In Industrial Instrumentation* textbook and discuss this with your classmates.
- One way that a "stick-slip" cycle may be ceased is to eliminate integral action from the controller (i.e. set τ_i to a very large number). Explain why this will stop the cycling, but unfortunately introduce another control problem in its place.
- Identify where "porpoising" behavior is revealed in one of this article's trend graphs. Explain why porpoising is always a bad thing for a control loop, and what causes it to happen.

file i01426

Question 64

Read and outline Case History #90 ("Tuning Is Also Important") 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) Any points of confusion, and precisely why you found the text confusing.
(5) Questions of your own you would pose to another reader, to challenge their understanding.
(6) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.

Be sure to answer the following questions:

- Figure 1 shows the response of a gas flow control loop (supplying gas to a chemical reactor). Based on your observation of this trend, is the controller in automatic or manual mode? In other words, is this a *closed-loop* test or an *open-loop* test, and how can you tell for certain?

- After properly tuning this gas flow loop, how much quicker did it respond to setpoint changes than it did before with the old PID tuning? Calculate a ratio, if possible, from the data shown in the trends (Figures 1 versus 2).

- The day after Mr. Brown optimized this reactor flow loop, another section of this South African chemical plant issued a complaint. Describe what their complaint was, and why it was caused by the work done on this flow control loop. Also describe the "compromise" solution implemented after this complaint.

- Explain why Mr. Brown began optimizing the flow controller before optimizing the temperature controller on this distillation tower reflux control system.

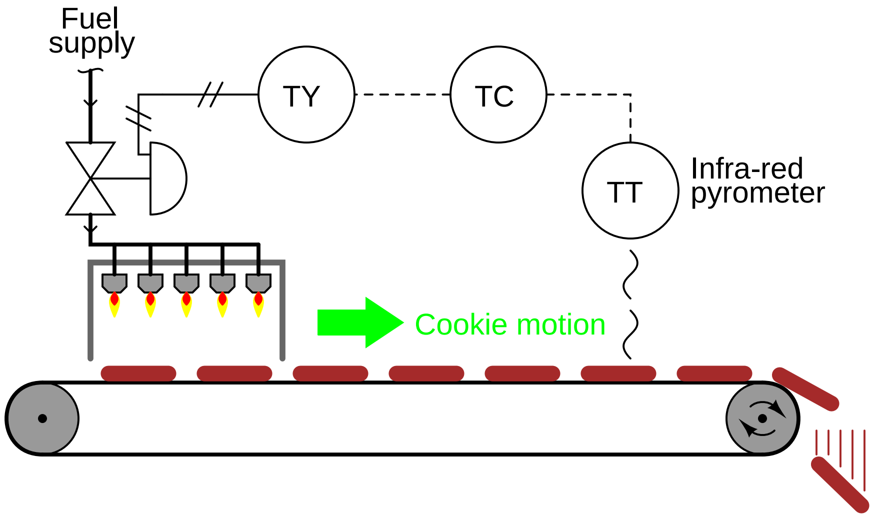
Suggestions for Socratic discussion

- Although Mr. Brown does not provide the "before" or "after" P-I-D tuning parameter values for the gas pressure control system shown in figures 1 and 2, try to discern what sort of tuning was there before (e.g. "predominantly proportional; predominantly integral; how much gain?"), and what sort of tuning was used to make it respond so much faster.
- Mr. Brown states that "quarter-wave damping" is often taught as the optimum response for a well-tuned PID control loop. Where do you think this popular standard for control quality came from?

file i03080

Question 65

In this continuous cookie-baking process, cookies are transported through an oven on a conveyor, the temperature of the cookies being measured "downstream" of the oven. A non-contact temperature transmitter is used in this process for sanitary reasons, so that the instrument never physically contacts the food:



Suppose that the transport time of the cookies from the oven to the point where the infra-red pyrometer senses their temperature is 15 seconds. In process control terms, what is this delay called, and what effect will it have on the stability of control in this system?

Suggestions for Socratic discussion

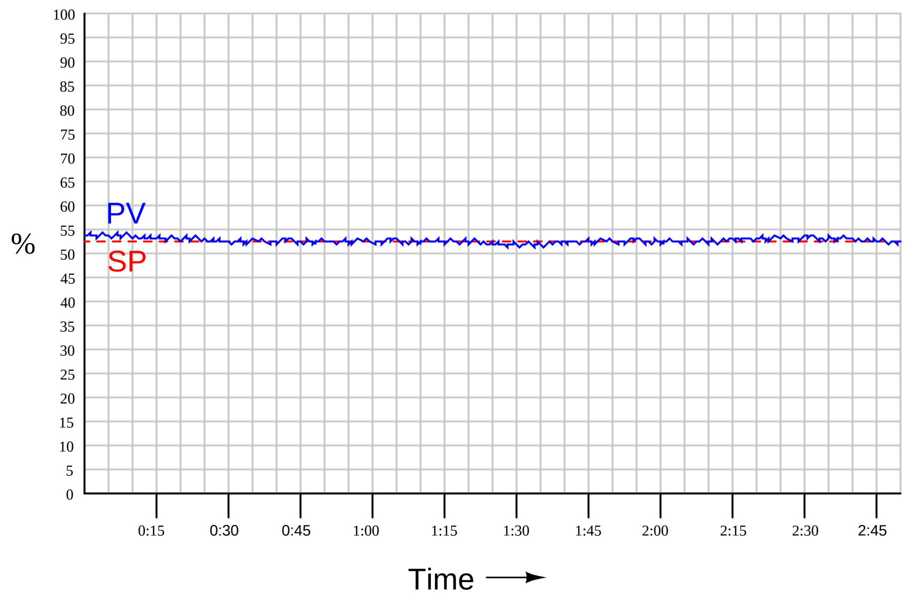
- Explain how you might improve the performance of this control system.
- Explain how the temperature transmitter (TT) senses cookie temperature. Specifically, what physical principle(s) does this transmitter use to perform its measurement?

file i00110

Question 66

Derivative control action is especially useful in processes characterized by slow lag times, especially when the process has a natural tendency to "overshoot" the setpoint due to multiple lags. The purpose of derivative mode control is to make decisions based on how *quickly* the process variable changes over time, taking action in the present to avoid setpoint overshoot in the future.

However, derivative mode control cannot be used in processes where the PV signal is tainted with *noise*, as is the case in this trend:



It does not matter how well-suited the process may be for derivative control in any other regard, so long as the noise is there. Noise and derivative control are simply incompatible – explain why.

Also, identify whether or not *integral* mode control is affected by noise in the PV signal, and explain your answer.

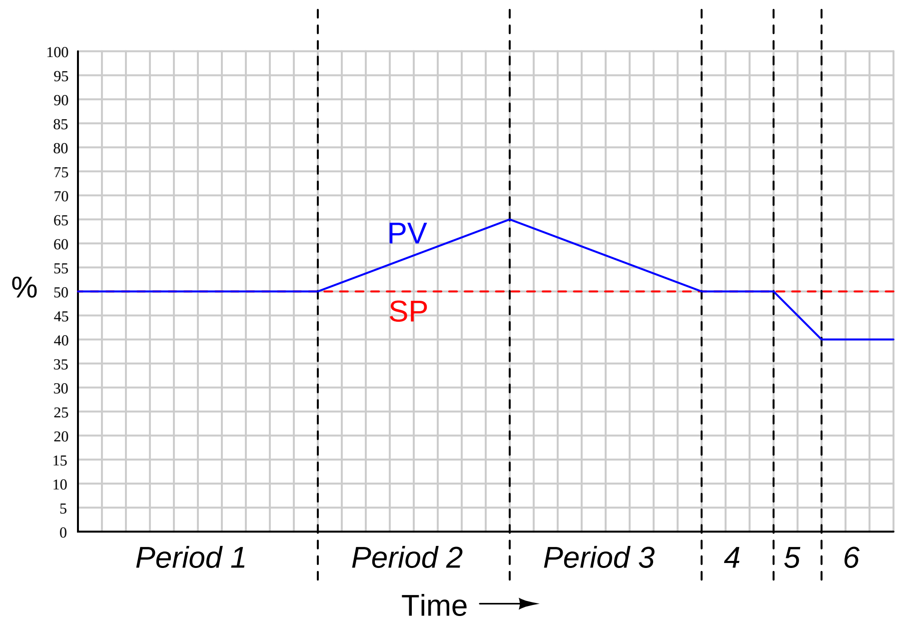
Suggestions for Socratic discussion

- Observing the trend graph shown here, can we tell whether this controller is in manual mode or automatic mode? If so, identify its operating mode.
- Observing the trend graph shown here, can we tell whether this controller is direct-acting or reverse-acting? If so, identify its direction of action.
- Observing the trend graph shown here, can we tell anything about the P, I, and/or D settings of this controller? If so, identify what its dominant control action is (P, I, or D).

file i01671

Question 67

Determine how each control action (P, I, and D) would react during the periods marked on this process trend by using the symbols ↑ (driving up), ↓ (driving down), + (steady positive), − (steady negative) or 0 (zero), compared to the actions of each at the beginning of the trend. Do this for P, as well as for I and D. Assume *direct action* for the controller.



Suggestions for Socratic discussion

- Identify any good problem-solving strategies you might apply to this problem.
- Sketch a qualitative graph showing the output of a full PID controller given these PV and SP graphs.

file i01640

Question 68

Suppose you are tuning a temperature controller for a heat-treating furnace, the purpose of which is to measure and control the temperature of metal castings, raising their temperature to just under the melting point and then holding it there for a specified "soak" time.

Do you recommend that the controller be configured for proportional-only control, proportional + integral (P+I) control, or full PID? Why? What would be considered the "optimum" process variable response for this controller, once tuned? Is "quarter-amplitude damping" an acceptable response, or not? Why?

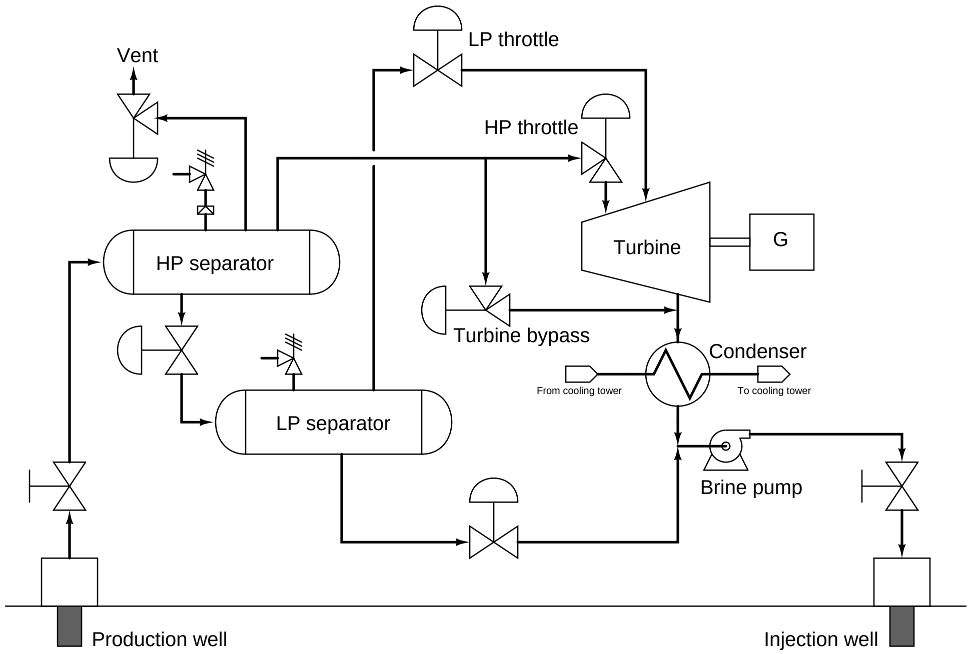
Suggestions for Socratic discussion

- Explain how you might configure this control system to be "fool-proof" so that no one could accidently cause the furnace temperature to rise too high and melt the metal castings.
- Suppose an instrument technician configured the temperature controller to have a high limit on the PV input, so that the controller could not register any temperature above the melting point of this metal. Would this prevent the furnace from overheating? Explain why or why not.

file i01669

Question 69

This is a PFD for a simple geothermal power plant, drawing a mixture of superheated steam and entrained minerals from a "production well" drilled deep into the earth, and injecting the condensed water and minerals into a second "injection well" to be re-heated by geothermal heat:



The HP throttle and turbine bypass control valves are split-ranged, to allow the turbine's power output to be adjusted according to how much electricity we wish to generate and not how much geothermal steam is available. In essence, they act like the variable-pitch blades on wind turbines: when wind is low, they adjust for maximum power generation; when wind is high, they "spill" the excess wind to limit power generation at the generator's maximum limit. Both valves are controlled by a single power controller monitoring power output of the generator.

Determine a proper split-range for these two control valves, assuming we wish the HP throttle valve to be fail-closed and the bypass valve to be fail-open, and that the actuator operating range for each valve is 3-15 PSI:

Valve	**Fully shut at** (PSI)	**Fully open at** (PSI)
HP throttle		
Turbine bypass		

Now suppose a maintenance mechanic accidently leaves a block valve shut in line with the turbine bypass valve. Explain what effects this change will have on the entire power plant system (power output, level controls, pressures).

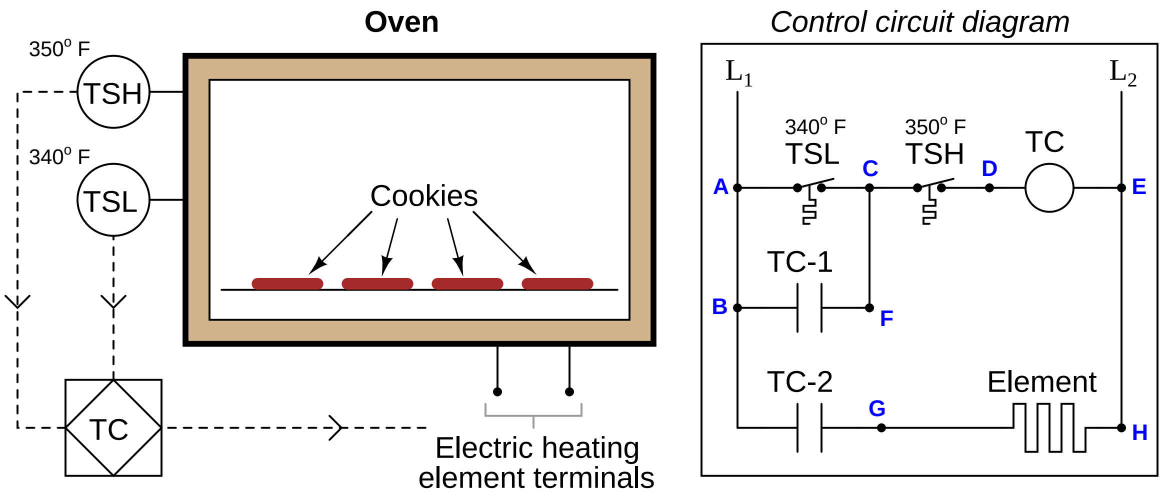
Suggestions for Socratic discussion

- If the block valve left shut by the mechanic is still *locked* and *tagged*, what do you think would be the proper procedure for un-locking and un-tagging the valve so that it may be opened? Can anyone do this? Why or why not?

file i00736

Question 70

This electrically-heated oven has a problem: instead of cycling between 340 ^{o}F and 350 ^{o}F as it is designed to, the temperature cycles between 349 ^{o}F and 351 ^{o}F:



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

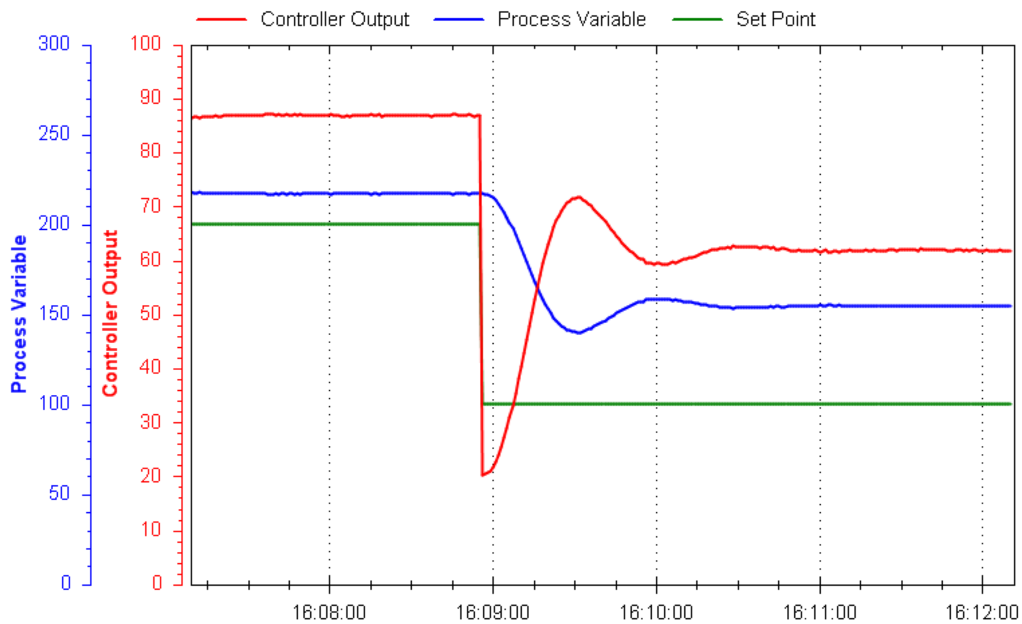
Fault	**Possible**	**Impossible**
TSL contact failed open		
TSL contact failed shorted		
TSH contact failed open		
TSH contact failed shorted		
TC-1 contact failed open		
TC-1 contact failed shorted		
TC-2 contact failed open		
TC-2 contact failed shorted		
TC relay coil failed open		
TC relay coil failed shorted		
Broken wire between points C and F		
Broken wire between points A and B		

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

file i00296

Question 71

Examine this process trend showing the PV, SP, and Output of a loop controller:



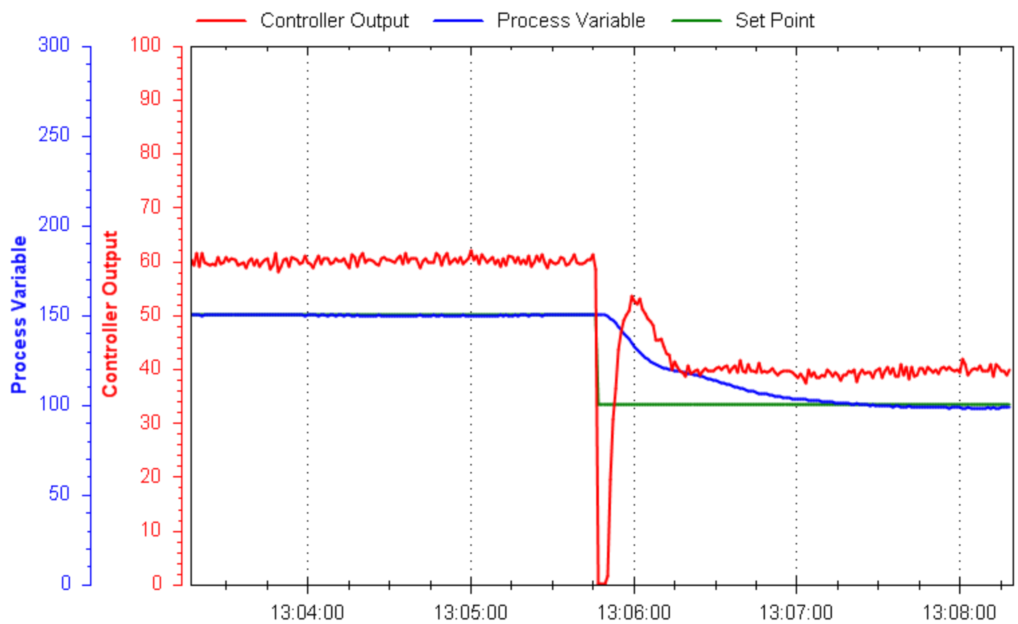
Based on what you see here, determine the following:

- Whether this is an open-loop or a closed-loop response
- Whether the controller is (or needs to be) *direct-acting* or *reverse-acting*
- If possible, identify any problems with the field instrumentation
- If possible, identify any problems with the controller PID tuning
- Qualitatively identify the kind of PID tuning we will need for robust control

file i02641

Question 72

Examine this process trend showing the PV, SP, and Output of a loop controller:



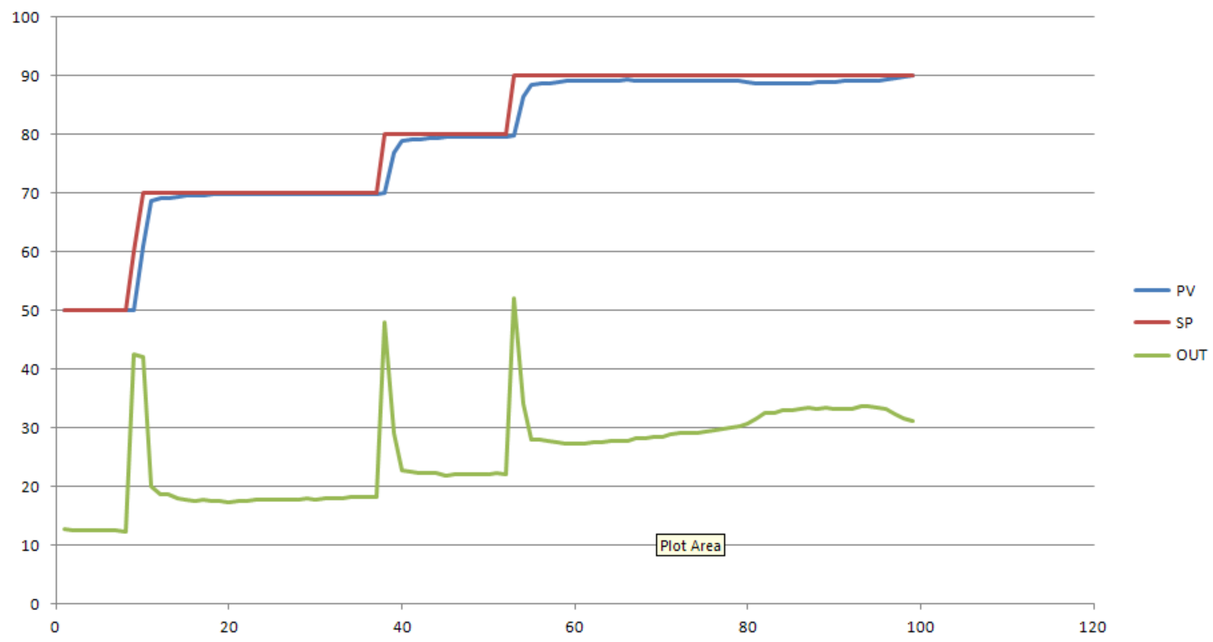
Based on what you see here, determine the following:

- Whether this is an open-loop or a closed-loop response
- Whether the controller is (or needs to be) *direct-acting* or *reverse-acting*
- If possible, identify any problems with the field instrumentation
- If possible, identify any problems with the controller PID tuning
- Qualitatively identify the kind of PID tuning we will need for robust control

file i02642

Question 73

Examine this process trend showing the PV, SP, and Output of a loop controller:



Based on what you see here, determine the following:

- Whether this is an open-loop or a closed-loop response
- Whether the controller is (or needs to be) *direct-acting* or *reverse-acting*
- If possible, identify any problems with the field instrumentation
- If possible, identify any problems with the controller PID tuning
- Qualitatively identify the kind of PID tuning we will need for robust control

file i02570

Question 74

Question 75

Question 76

Question 77

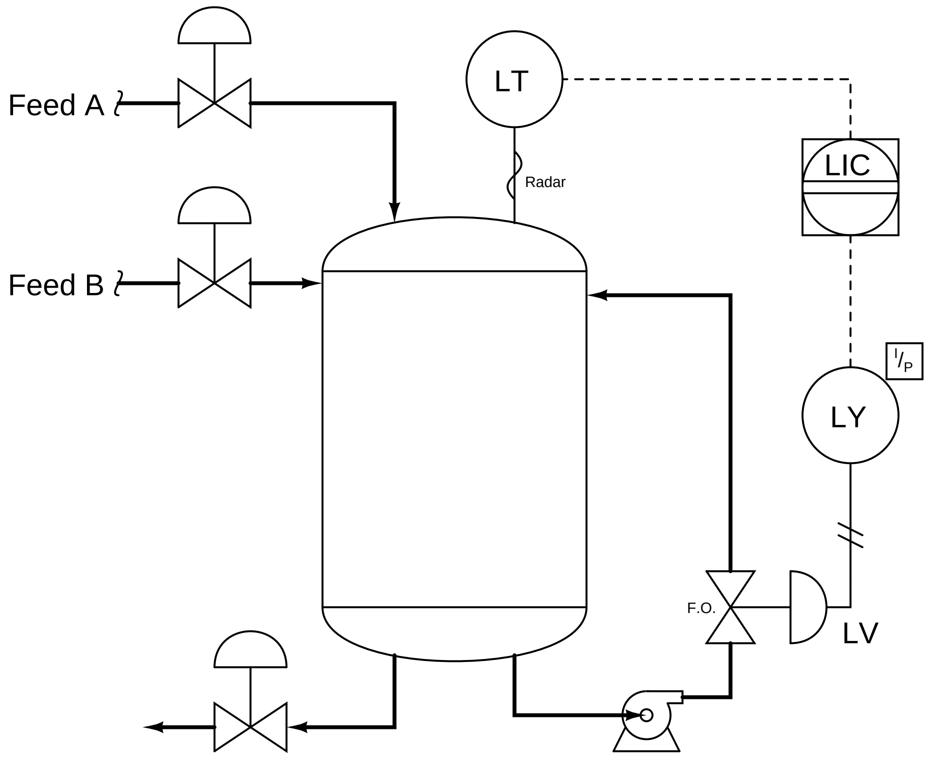
Question 78

Question 79

Question 80

Question 81

A design team recommends the following control strategy for regulating liquid level in this process vessel:



Explain why this control strategy *cannot* work, and re-design it so that it can.

file i01821

Question 82

The following table shows flow coefficients for three differently-characterized control valves as they are all stroked from 0% (fully shut) to 100% (fully open):

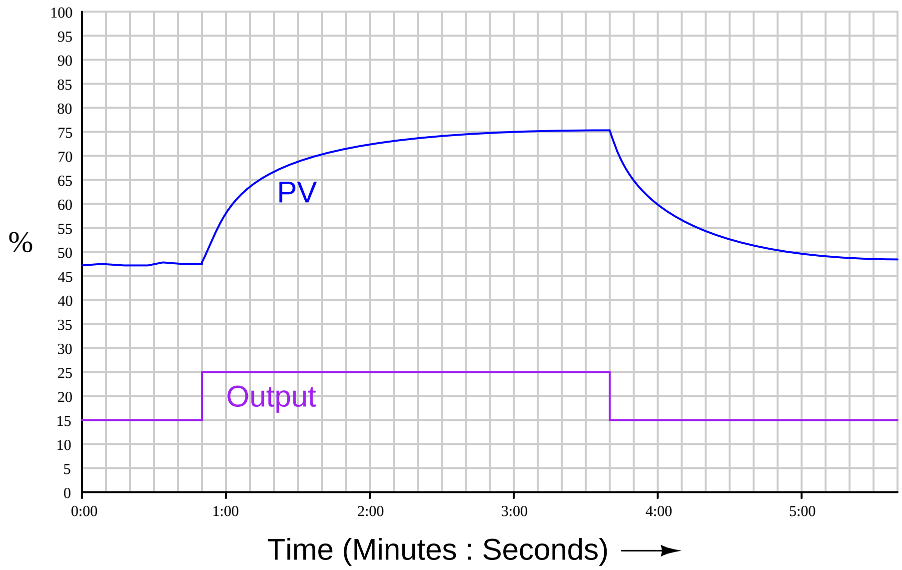
Stem position	C_v (Valve #1)	C_v (Valve #2)	C_v (Valve #3)
0 %	0.00	0.00	0.00
10 %	1.50	6.60	2.90
20 %	2.47	11.4	5.55
30 %	3.68	16.9	9.11
40 %	5.30	22.9	13.1
50 %	7.90	29.7	17.0
60 %	12.1	37.0	21.7
70 %	18.8	42.4	27.7
80 %	28.0	45.7	34.5
90 %	39.3	48.5	41.7
100 %	50.0	50.0	50.0

Plot all three valve characteristics on a graph and then identify which valve is quick-opening, which valve is linear, and which valve is equal-percentage.

file i03214

Question 83

Examine this process trend, showing the response of a flow transmitter to a 10% up-and-down step change in the controller output (placed in manual mode) signal to the flow control valve:



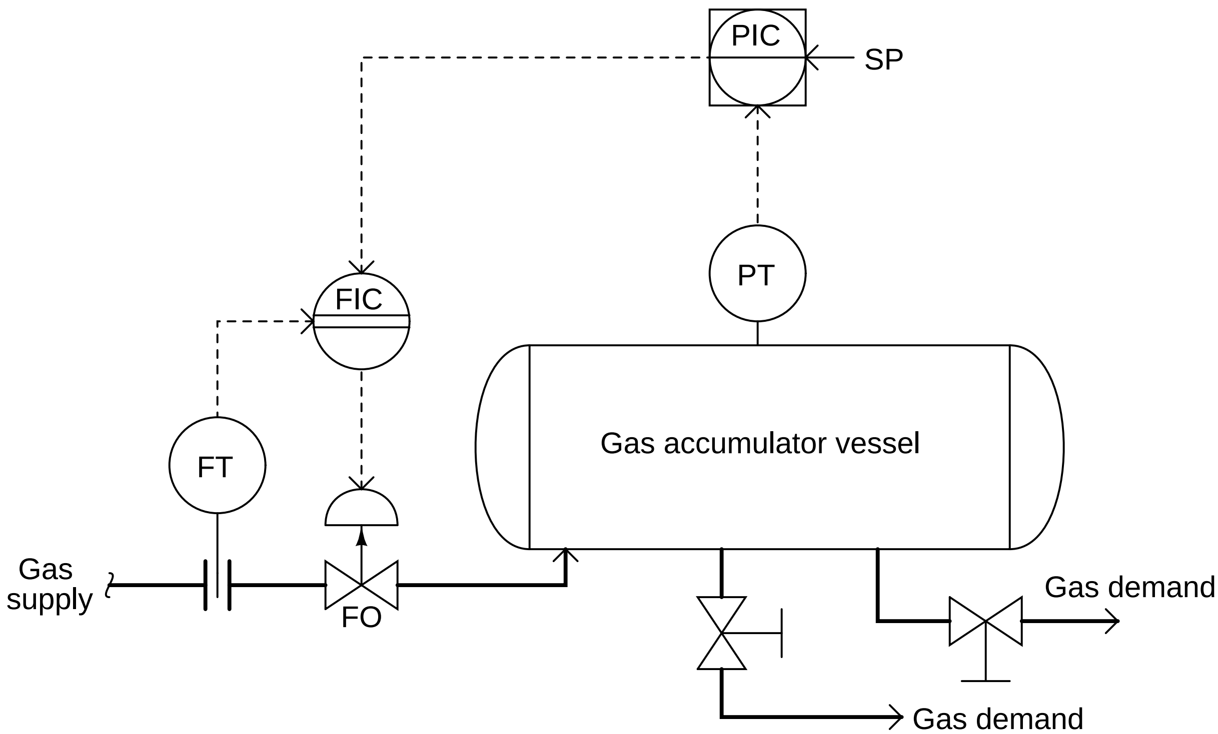
Two technicians have examined this trend and are debating over the cause of this sluggish response. One says it is probably due to a transmitter with too much filtering (damping) programmed in. The other says it's a sluggish control valve. Both explanations are plausible.

Devise a conclusive test by which we may prove or disprove these hypotheses.

file i01654

Question 84

This gas pressure control system has a problem. The operator tells you that the pressure in the accumulator vessel pressure registers below setpoint on the pressure controller's display, and refuses to come up to setpoint. He calls you to diagnose the problem in this system:



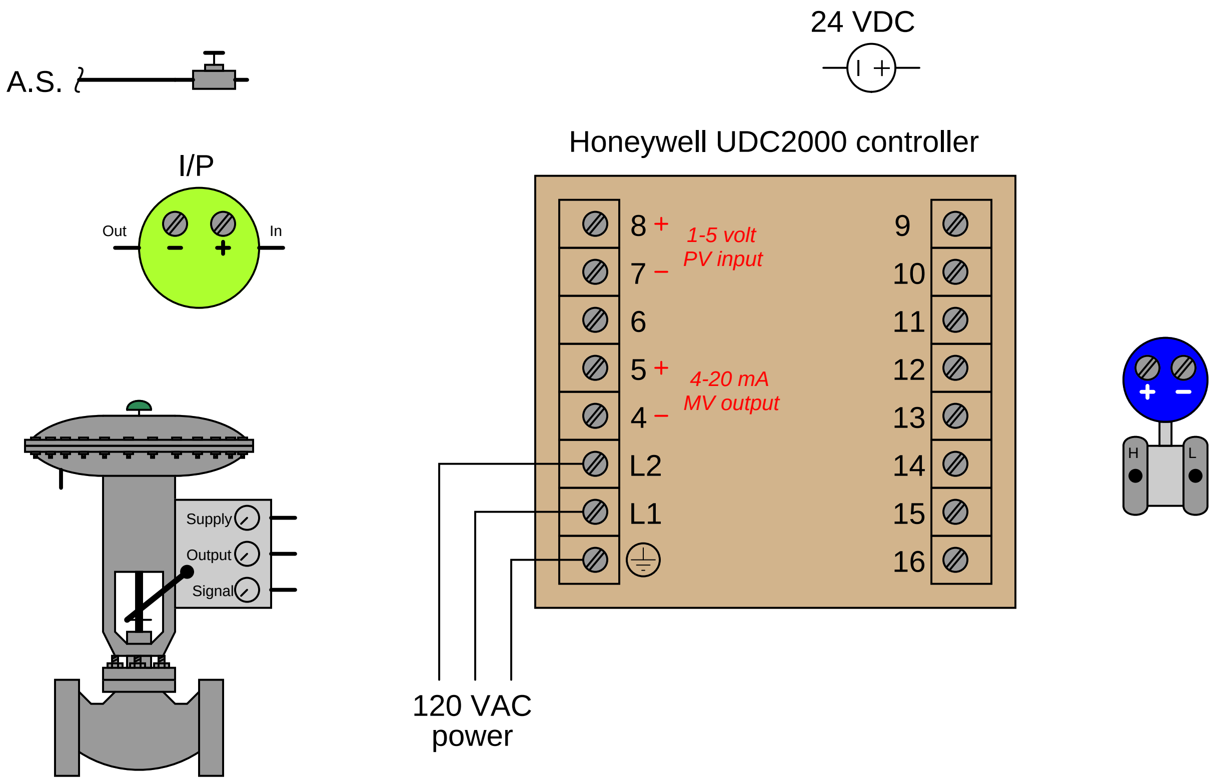
Your first diagnostic check is to note the percentage output signal on the pressure controller (PIC): the controller's display shows an output of 68%. Identify the likelihood of each possible cause in this list by checking boxes in the table – whether the cause is "probable" (worth considering as a cause of this system's trouble) or is "unlikely" (either completely ruled out as a cause, or just not worth considering at this point in the diagnosis):

Fault	**Probable**	**Unlikely**
Control valve leaking (non-tight shutoff)		
PT miscalibrated (reads too low)		
PT miscalibrated (reads too high)		
FT miscalibrated (reads too low)		
FT miscalibrated (reads too high)		
4-20 mA wiring to valve failed open		
4-20 mA wiring to valve failed shorted		
Excessive gas supply pressure		
No integral action in pressure controller		

file i01820

Question 85

Suppose you are asked to build a complete control system using a DP transmitter, Honeywell UDC2000 PID controller, an air-to-open control valve (with positioner), and an I/P transducer:



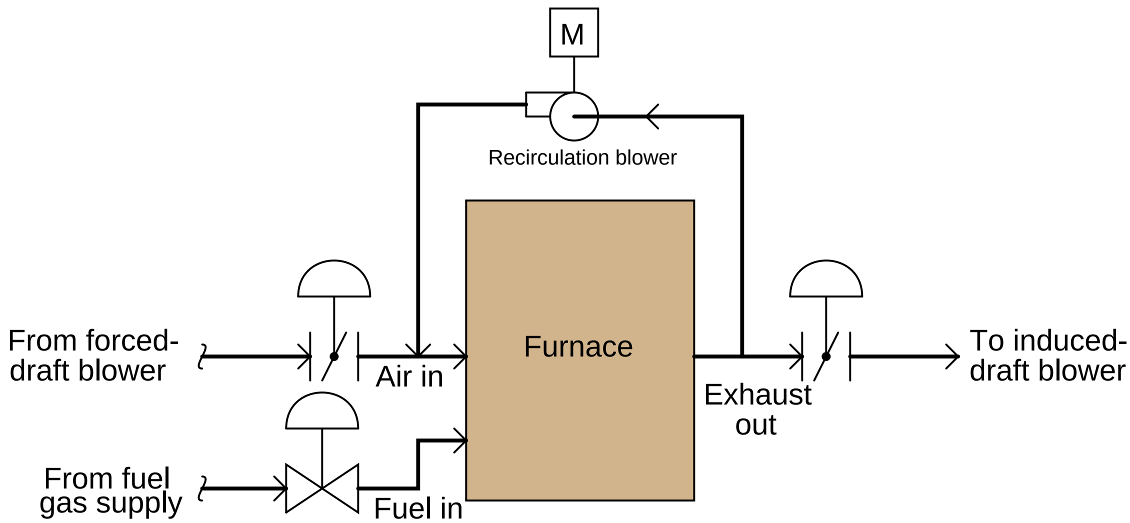
Sketch the necessary tube and wire connections to make this a working system. Feel free to add any other components as needed.

file i00432

Question 86

One of the pollutants generated by high-temperature combustion processes is NO_x: oxides of nitrogen. NO_x forms at high temperatures when nitrogen and oxygen gases in the combustion air combine to form nitrogen-oxygen molecules. These molecules are considered a pollutant because they form nitric acid upon emission to the atmosphere, and they also contribute to the formation of smog.

A common method of mitigating NO_x emissions is to recirculate exhaust gas into the intake of the combustion system. Doing so reduces combustion temperature: a critical variable in the production of NO_x:



The reduction in combustion temperature approximately relates to exhaust gas recirculation by the following formula:

$$X = \frac{T_M - T}{T - T_W}$$

Where,

X = Recirculation fraction (between 0 and 1, unitless)
T_M = Maximum (theoretical) flame temperature
T = Actual flame temperature
T_W = Exhaust gas temperature

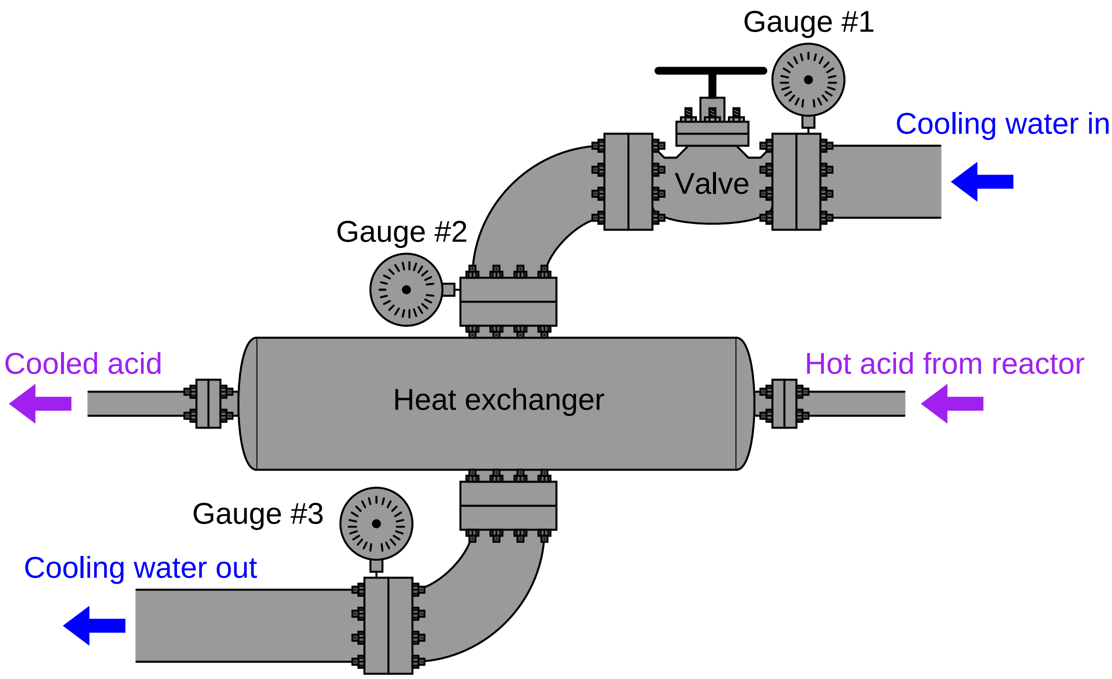
Algebraically manipulate this equation to solve for T, then calculate the actual flame temperature given a maximum theoretical temperature of 3100^o F, an exhaust gas temperature of 480^o F, and a recirculation factor of 22%.

Also, explain why we must have a recirculation *blower* installed at the location shown in the diagram, rather than a simple recirculation *valve*.

file i01830

Question 87

A heat exchanger is used to lower the temperature of sulfuric acid (H_2SO_4) exiting an exothermic reactor in an acid manufacturing process, using water as the coolant. An automatic control valve will eventually be installed in the water line, but for now a hand (manual) valve performs the role of coolant throttling over a range of 0 to 25 GPM (gallons per minute):



An experienced instrument technician is summoned to test this heat exchanger system and determine what kind of valve characterization (quick-opening, linear, equal-percent) is best for throttling the water flow. The technician proceeds to set the manual valve to different positions while recording the three pressure gauge readings and the flow rate (measured by a flowmeter not shown in this illustration). The results are shown in this table:

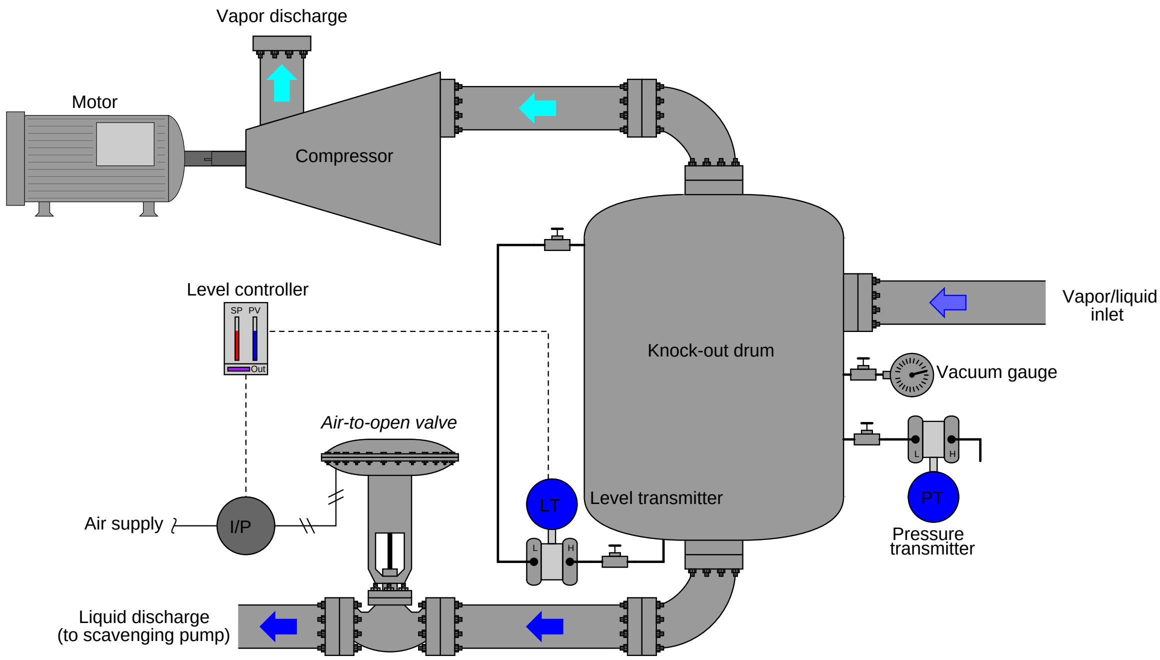
Water flow	Gauge #1	Gauge #2	Gauge #3
0 GPM	83 PSI	0 PSI	0 PSI
15 GPM	83 PSI	1.1 PSI	0.4 PSI
25 GPM	82 PSI	2.0 PSI	0.6 PSI

Interpret these pressure measurements to select the best control valve characterization for the task (*linear*, *equal percentage*, or *quick-opening*), explaining your rationale.

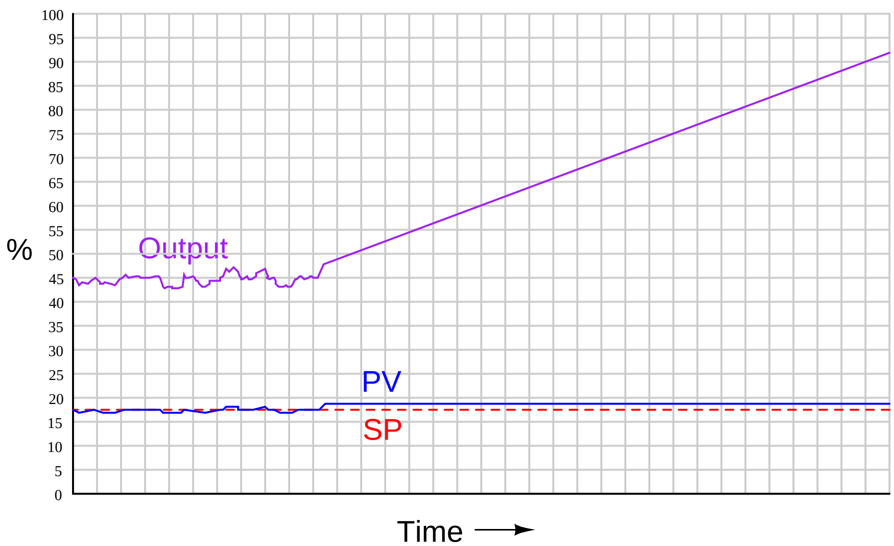
file i03410

Question 88

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 gas did manage to enter the scavenging pump, causing a major fire in that area leading to a complete shut-down of the unit:



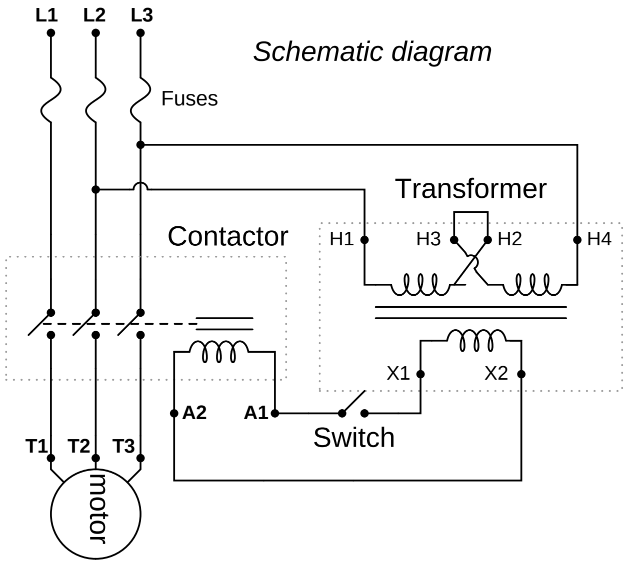
A trend recording of liquid level and control valve position captured before the explosion holds the only clue as to why this happened. Examine it to see if you can determine the source of the trouble:



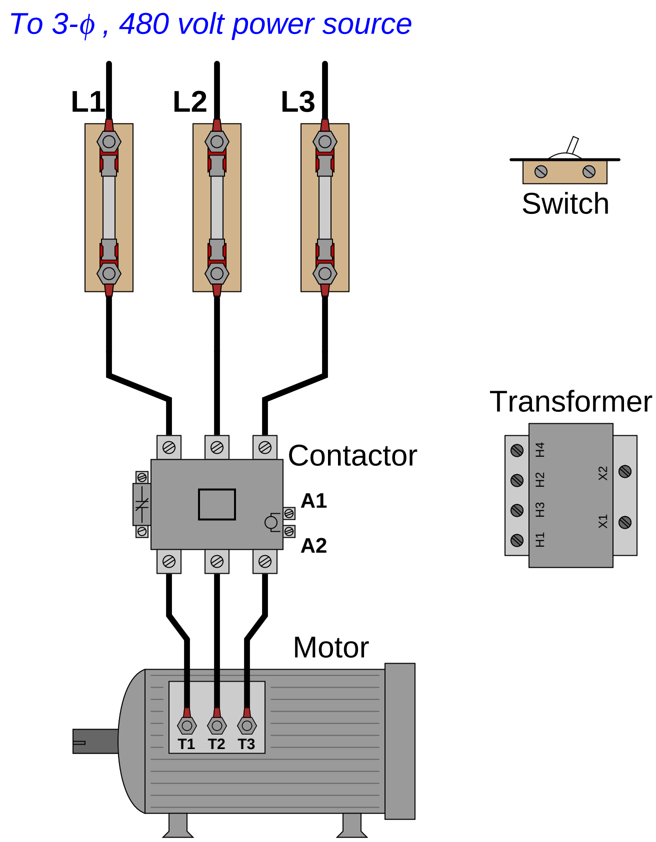
file i03411

Question 89

Shown here is a simple schematic diagram for a motor control circuit, using a contactor ("starter") to switch 3-phase AC power on and off to the motor:



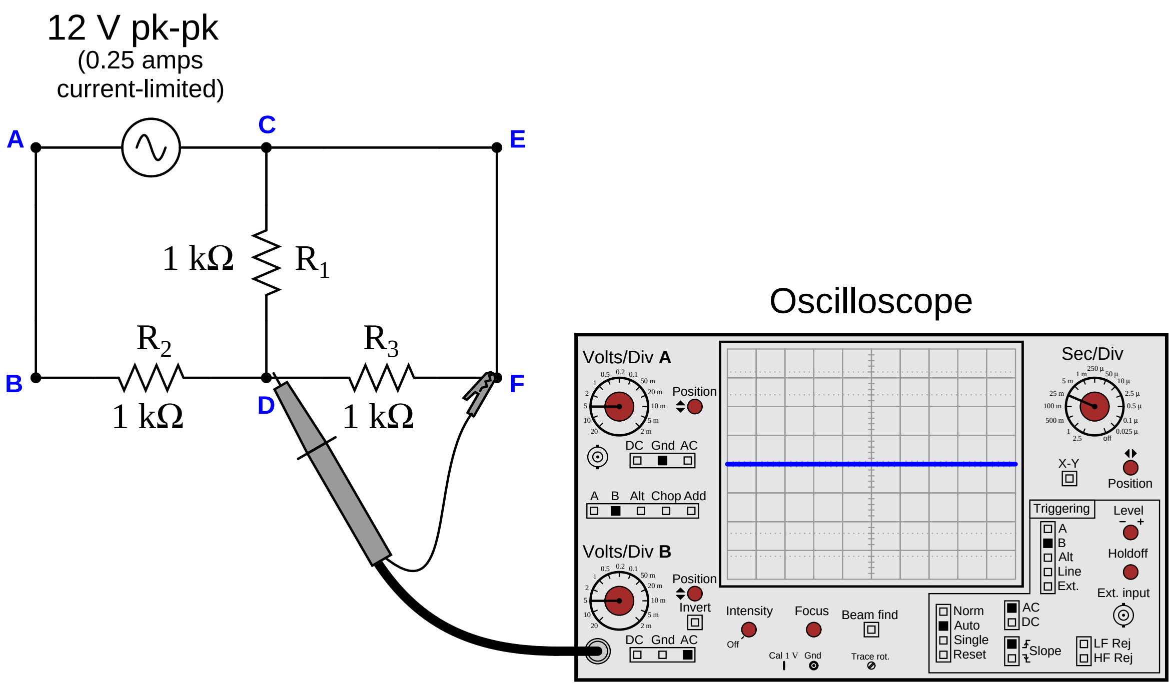
Draw the necessary connecting wires between components to build this circuit:



file i03623

Question 90

Note the oscilloscope measurement of AC voltage between test points **D** and **F** in this series-parallel circuit:



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

Fault	Possible	Impossible
R_1 failed open		
R_2 failed open		
R_3 failed open		
R_1 failed shorted		
R_2 failed shorted		
R_3 failed shorted		
Voltage source dead		

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

file i01655

Question 91

Lab Exercise

Your primary task is to independently (i.e. no assistance from team members or other classmates) tune multiple control loops, documenting the process open-loop response as well as the process closed-loop responses to both setpoint and load changes. This documentation must be in the form of computer screen captures, showing the graphic trends of the process as it responds to open-loop and closed-loop tests. You must do your own loop testing and tuning, the consequence of plagiarism being a failing grade for the course.

Two of the processes you will tune must be *real*, working processes of differing type (e.g. pressure versus temperature). The last process may be simulated, or it may be another real process with different characteristics than the first two. All tuning objectives are "mastery" – they must be demonstrated to instructor satisfaction for completion, with no penalty for multiple attempts.

Performance objective	**Real #1**	**Real #2**	**Real #3 or Simulated**
Description of process			
PV alarm points (*set by instructor*)			
Self-reg. *vs.* Integ. *vs.* Runaway?			
Measurement of dead time (sec)			
Measurement of time constant (sec)			
Measurement of valve stiction (%)			
P value after tuning (K_p)			
I value after tuning (K_i or τ_i)			
D value after tuning (K_d or τ_d)			
Robust response to SP change?			
Robust response to load change?			
Instructor initials			

In addition to process tuning, you must also complete a circuit design challenge and troubleshoot a control system the same as in regular team-based lab exercises. A crucial different is that none of the objectives in this entire lab exercise are team-based; rather, all are individual.

Performance objective	**Grading**	**Individual**
Circuit design challenge	mastery	
Troubleshooting	mastery	
Safety and professionalism	deduction	
Lab percentage score	proportional	
Decommission and lab clean-up	(ungraded)	

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

When all students are finished with their circuit design challenges, as well as tuning and troubleshooting their control loops, the last step is to decommission all the working systems as per usual procedure. On the last day of the quarter (dedicated to lab clean-up) each team will show their team tool locker for inspection.

Note: this lab worksheet is your only record of the instructor's validation (signed initials). Do not lose it, and do not lose your screen-captures of the process responses either!

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.

Loop tuning

Gather data and tune three different processes (one of which may be a computer simulation of a process). Capture screenshots of trend graphs as evidence of your work, both for characterizing the process (e.g. measuring dead time) and for demonstrating robust control response. The instructor will assign high and low process alarm values prior to your working on that system, and all trend graphs must show the PV between these prescribed limits in order to receive credit.

Circuit design challenge

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

Troubleshooting

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

Lab percentage score

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

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

Safety and professionalism (deduction)

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

General format and philosophy

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

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

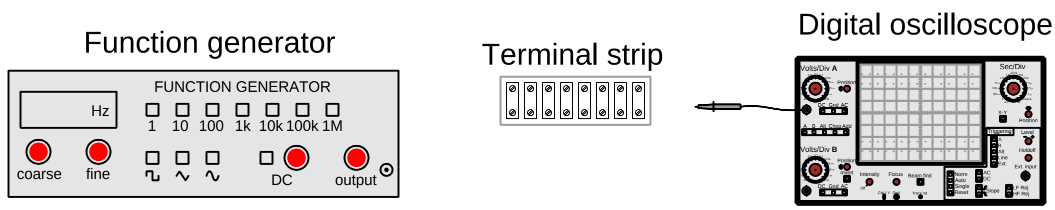
Remember that the lab facility is available to you at all hours of the school day. Students may perform non-hazardous work (e.g. circuit work at less than 30 volts, documentation, low air pressures, general construction not requiring power tools) at *any time during the school day* without the instructor's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

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

Lab Exercise – circuit design challenge

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

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



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

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

Circuit function (randomly selected by the instructor):

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

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

Lab Exercise – PV alarm points

Most loop controllers have built-in *alarm* capability to signal whenever the process variable (PV) goes outside of prescribed bounds. In this lab exercise you will configure your controller's "high" and "low" PV alarm points according to values set by the instructor. The purpose in doing this is to set limits beyond which you should never take the process variable for two different reasons: (1) to mimic real-life constraints whereby process quality may be affected if the PV wanders too far away from normal values, and (2) to force you to tune the controller differently to match the process characteristics in a different range.

This second reason for PV alarm limits bears further explanation. It is quite common for processes to exhibit different operating characteristics at different PV ranges. Parameters such as dead time, lag time, and/or self-regulation may vary depending on the exact value of the process variable. This is why PID controller tuning parameters which may work very well to control a process within a certain PV range fail to achieve the same level of robust control within a different PV range. When the instructor sets PV alarm points at different values for each student, the process essentially poses a new tuning challenge for each student so that the PID tuning work of another student cannot simply be copied.

The procedure for setting alarm point values is documented in the manufacturer's manual for the control system, and is typically a setting available to operations personnel (i.e. not requiring engineering-level privileges on the control system to change). You will need to research how to do this.

When showing your screen-shots of open-loop testing and closed-loop PID response to the instructor, these high and low PV limits should be denoted on the trend graph for easy reference, as proof that the system's PV never strayed beyond these prescribed limits.

Note that if you are using the `looptune` application on a caSCADA system to simulate a process, all PV alarm values (low-low, low, high, and high-high) are randomly assigned by the computer upon invocation. Your documented work needs to show the PV remaining between the low and high alarm limits at all times, but know that the simulation will automatically abort if the process variable goes beyond either the low-low or high-high limits, resulting in a complete loss of data (your PID tuning parameter values, the simulation process parameters, etc.)!

Lab Exercise – how to capture "screen-shots" on a PC

An essential part of this lab exercise is capturing graphical trend data from the screen of a personal computer, either running control software (e.g. Emerson DeltaV Operate) or data acquisition software used to monitor process data (e.g. WinDAQ, LabVIEW). Fortunately, this is really easy to do on any personal computer.

When you have the screen of the computer displaying what you wish to capture, simply press the "Print Screen" key on your keyboard. This key is usually located to the right of the "Function" key row at the top (on a standard desktop keyboard layout – laptop keyboards are famous for locating seldom-used keys like this in random places). Pressing the "Print Screen" key tells the computer's operating system to copy the entire screen image into a buffer for pasting into any graphics-manipulation or word-processing program you desire.

A utility standard on every Windows operating system is *Paint*: a bitmap image creation and manipulation program. Paint is simple to the point of being crude, but it works just fine for this purpose. After starting Paint, simply "Paste" the captured screen-shot image and save it under any filename you wish. I strongly recommend using a filename that is unique to you (e.g. `John_Doe_process1_trend2.bmp`). Remember that you will be capturing multiple screen-shots in this lab exercise, and will need to save every one for presentation to the instructor.

You may also use Paint (or even a more sophisticated image-manipulation program such as *Photoshop* or *Gimp*) to add text annotations to your screen-shot images. For example, some students like to add arrows and lines showing where they measured process gain, or arrows pointing to problems in the trend such as where the control valve sticks.

Common mistakes:

- Forgetting to move screenshot files to personal drive, leaving them on the hard drive of the school computer where they may be deleted by other students
- Not collecting enough screenshots to adequately document work done on the process
- Failing to label and organize the screenshot files so as to be able to remember what exactly was being done in each one of the trends

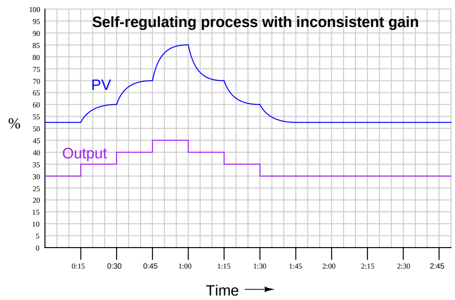
Lab Exercise – open-loop testing

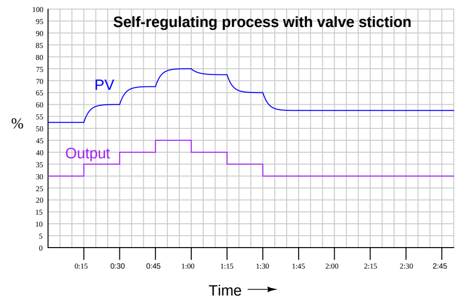
Before you can begin to successfully tune a PID-controlled process, you must first understand the characteristics of that process. A very good way to do this is by performing an *open-loop* test: placing the PID controller in manual mode and changing the output value (5% or so is usually a good amount for the first test) to see what effect this has on the process variable over time. The PV's response to this "step-change" in output can not only reveal the basic characteristics of the process (i.e. self-regulating, integrating, runaway, lag time magnitude, lag order(s), dead time magnitude) but also certain instrument problems (valve stiction, transmitter filtering, etc.).

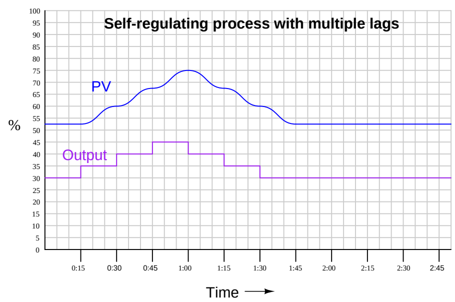
During all your testing, be sure to maintain the process variable within the alarm limits prescribed by the instructor! All of your documentation for the process characteristics (and the final tuning results) must show the PV remaining within these limits.

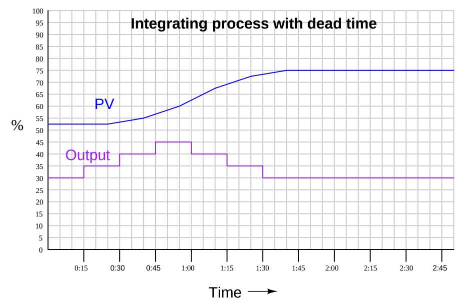
You should perform several open-loop step-changes to probe the process characteristics: a few in the same direction, then the rest in the other direction. An analysis of the PV responses following multiple output step-changes will reveal two important characteristics of the process:

- How consistent the process gain is
- Whether the valve has significant hysteresis or stiction (compare opening versus closing)



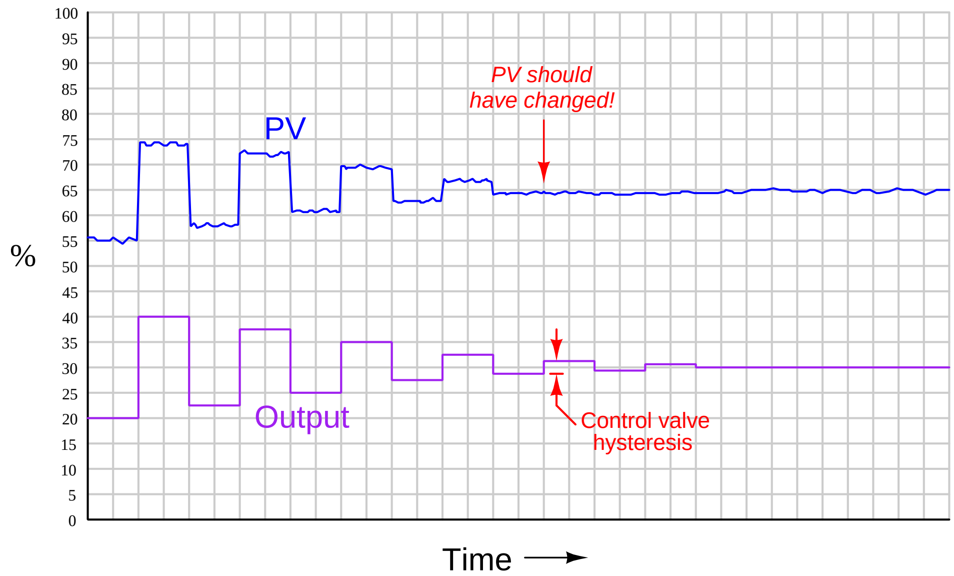






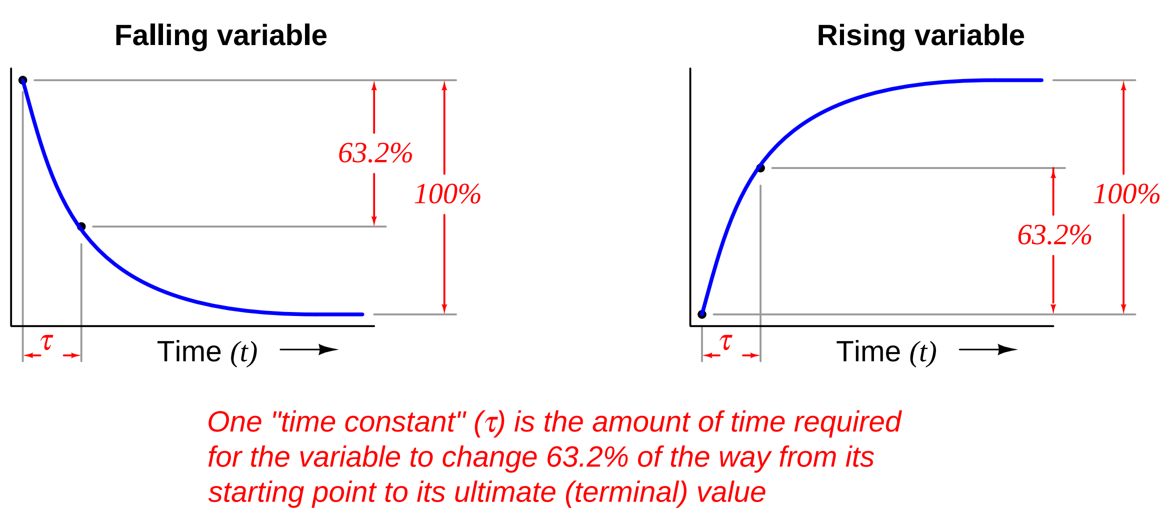
A common mistake among students is to try to determine process characteristics with the controller in *automatic* mode (i.e. closed-loop testing). This generally gives poor results because the process response seen on the trend graph while in automatic mode is not just the natural response of the process, but also the automatic (regulating) response of the controller. A controller that isn't tuned aggressively enough, for example, may make a fast process appear to have long lag times. By placing the controller in manual mode and performing open-loop tests, you get to see the natural response of the process itself without any controller interference.

Valve stiction is best determined by making alternating (up and down) step-changes in manual mode in progressively smaller intervals, noting the largest of those step-changes resulting in no measurable PV change. This is a superior test to multiple step-changes in the same direction because step-changes in the same direction tend to be additive while reversing steps are not. The following illustration shows this test applied to a fast, self-regulating process:



Another important test of process characteristics is the process *lag time*, also known as the process *time constant* symbolized by the Greek letter τ. This is precisely the same concept you have explored in previous courses with charging and discharging circuits (i.e. resistor-capacitor and inductor-capacitor circuits), and is empirically measured in precisely the same way.

With the controller in manual mode, you are to introduce a step-change in the output signal and then record the process variable's response. For self-regulating processes, the process variable will initially begin to ramp at a high rate of change, and then level off until it settles at its new self-regulated value. The amount of time it takes for the process variable to go 63.2% of the way from its initial to final values is the lag time (τ).



One of the common misconceptions regarding time constant is that you can first measure the amount of time it takes for the variable in question to reach its final value, and then divide that time by 5, because it is commonly taught that it takes 5 time constants' worth of time (5τ) for the changing variable to settle to its final value. *The truth is that five is the closest whole-number multiple of τ that gets you within just 1 percent of the variable's final (settled) value.* One percent is an entirely arbitrary figure, and so "five time constants' worth of time" is a poor standard to use in this manner.

Instead, what you must do to measure the lag time of a process is to follow the model presented to you in the previous graphs, where you base the time strictly by the horizontal distance on the trend that it takes for the process variable to traverse a 63.2% vertical interval. If the trend graph of your loop's controller does not provide fine-line divisions to help mark the variable's value (vertical) as well as the time (horizontal), you may have to resort to printing the trend on paper and sketching your own division lines to mark where these important points are.

One final note on the subject of lag time is that integrating processes do not strictly possess a lag time. Since in an integrating process the process variable never "levels out" on its own, there is no basis upon which to determine when it has traversed 63.2% of the way to its final value (because it *has no* final value).

Common mistakes:

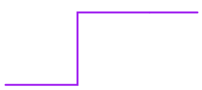
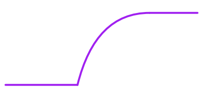
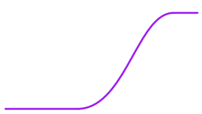
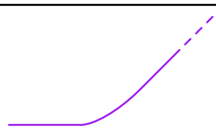
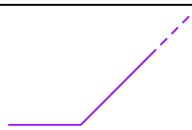
- Trying to probe the process characteristics with the controller in *automatic* mode rather than *manual* mode
- Making output step-changes that are too large (resulting in PV excursions beyond the alarm limit values)
- Not making enough step-changes to fully test process gain consistency or valve stiction
- Incorrectly measuring process lag time (time constant τ)

Notes on process characteristics and PID tuning strategies

After you have determined the characteristics of the process and corrected any instrument problems such as transmitter filtering or valve stiction, your next step is to determine how you will tune the PID controller. Several algorithmic procedures exist, including two methods proposed by Ziegler and Nichols in their 1942 paper, and several more modern methods. You are free to use whatever tuning method you would like to try, so long as you document the data supporting your tuning decisions (i.e. process characteristics) and also document the trend data showing improvement in process stability as you use your understanding of PID control to fine-tune each process.

Truth be told, many working professionals use algorithmic methods such as Ziegler-Nichols because they really don't understand how PID works, or is supposed to be applied to a real process. The goal of this lab exercise is to give you plenty of opportunity to try your hand at PID tuning, and to improve upon simple step-by-step methods such as Ziegler-Nichols. With practice, you will find it possible to make dramatic improvements over "canned" PID tuning methods simply by understanding the characteristics of the process and choosing control actions appropriate for those characteristics.

The following table shows several PV responses following a single controller output step-change in manual mode, with suggesting heuristic tuning strategies for each:

	Pure self-regulating	*May be controlled with aggressive integral action, and perhaps with a bit of proportional action. Use absolutely no derivative action!*
	Self-reg w/ pure 1^{st} order lag	*Responds well to aggressive proportional action, with integral action needed only for recovery from load changes.*
	Self-reg w/ multiple lags	*Proportional action needed for quick response to setpoint changes, integral action needed for recovery from load changes, and derivative needed to prevent overshoot. Proportional and integral actions are limited by tendency to oscillate.*
	Integrating w/ lag(s)	*Proportional action should be aggressive as possible without generating oscillations. Integral action needed only for recovery from load changes.*
	Pure integrating	*Responds well to aggressive proportional action, with integral action needed only for recovery from load changes.*

Remember that the presence of certain other characteristics in significant amounts (e.g. PV noise, dead time, etc.) also impacts how one should tune a controller.

Common mistakes:

- Making tuning parameter changes that are too large without considering the ill effects those changes might have (e.g. increasing gain by a factor of 10)
- Attempting to "de-tune" process or instrument problems that should be repaired (transmitter filtering, valve stiction, etc.)

Lab Exercise – robust PID response

In this exercise you will be asked to demonstrate "robust" loop response to both setpoint changes and load changes, which naturally demands a definition for "robust" response. In this context, robust PID response meets all of the following criteria:

- The process variable is brought to setpoint as fast as possible following both setpoint changes and load changes
- The process variable exhibits as little over/undershoot as possible following both setpoint changes and load changes
- The process variable *never* strays outside of the prescribed alarm limits
- The process variable *never* porpoises (i.e. oscillates prior to reaching setpoint)

A controller that is tuned too "fast" will take little time reaching setpoint, but it will do so at the expense of overshooting or undershooting the setpoint value before settling in to the setpoint value. A controller that is tuned too "slow" will not over- or under-shoot setpoint, but will exhibit extended periods of time where the PV is approaching setpoint yet the output value is nowhere near saturation (i.e. the controller is not "trying" as hard as it can).

When testing for robust response to load changes, you should introduce load changes in a manner similar to how you introduce setpoint changes: change the load *and leave the load in that new state long enough to watch the controller compensate for it.* A very common error students make when introducing load changes is to do so very briefly, so briefly in fact that the controller never gets a chance to correct for the new load condition. What you see in such a case is the PV changing due to the load change, and then returning back to setpoint *only because the load returned to its previous value, not because the controller actually did anything to make PV return to setpoint!* So remember, when you introduce load changes, do so the same way you introduce setpoint changes: change the load condition and leave it in that new state, then watch the controller's response to see how quickly the PV returns to the setpoint value, whether there is under- or over-shooting of the setpoint, and/or whether any porpoising occurs.

You will notice that ideal tuning for response to setpoint changes is often different from ideal tuning for response to load changes. One reason for this is that setpoint changes typically occur more suddenly than load changes. Another reason is that load changes tend to alter the processes' equilibrium point (i.e. the FCE value necessary to maintain the setpoint) more than setpoint changes. If you notice a great different between these two responses, you may wish to set the PID algorithm to one where more of the PID equation responds only to changes in PV and not to changes in *error*. If you cannot achieve robust control for both setpoint *and* load changes, you may consult your instructor as you would operations personnel on the job to see which of these two scenarios is more realistic to the process, and then optimize your controller's response accordingly.

If your controller "porpoises" at all, it is detrimental to process control. "Porpoising" occurs when either the controller's proportional action or derivative action is too aggressive, causing the controller to over-correct during the PV's approach to setpoint. Integral is incapable of causing porpoising, because integral action cannot reverse direction unless and until the error changes sign (i.e. until PV crosses setpoint), and porpoising is defined as oscillations occurring *prior* to setpoint. Perhaps the best tool for determining whether excessive gain or excessive derivative action is causing porpoising is to examine the *phase shift* between PV and Output during the porpoising period: little or no phase shift reveals excessive P action, while nearly 90^o phase shift reveals excessive D action.

Common mistakes:

- Not properly diagnosing field instrument problems (e.g. sticky valves, over-damped transmitters) prior to tuning. *Pay close attention to your open-loop tests prior to any PID tuning parameter adjustments!!!*
- Relying too much on proportional action (gain) to control fast-acting, self-regulating processes.
- Introducing transient load changes that don't persist long enough to test the controller's ability to correct (i.e. to bring the PV back to SP with different load conditions).

Lab Exercise – troubleshooting

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

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

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

Failure to correctly identify both the general location and nature of the fault within the allotted time, and/or failing to demonstrate rational diagnostic procedure to the supervising instructor will disqualify the effort, in which case the student must re-try with a different fault.

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

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

Common mistakes:

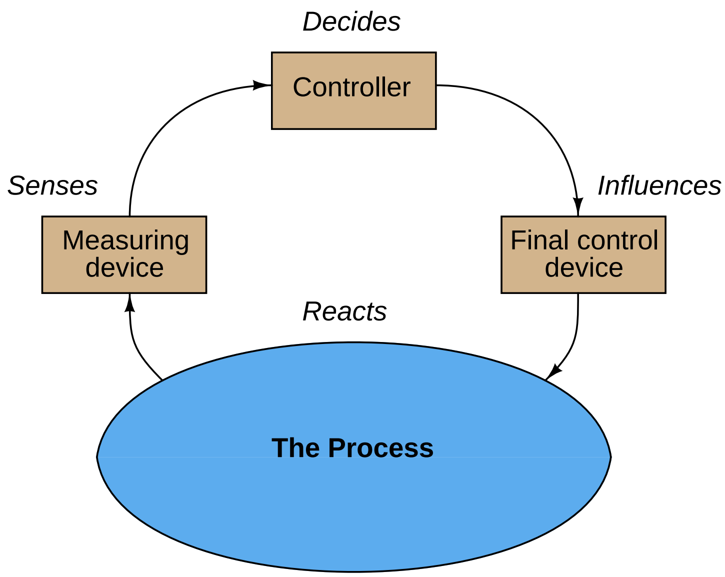
- Attempting to *visually* locate the fault.
- Neglecting to take measurements with your multimeter.
- Neglecting to check other measurements in the system (e.g. pressure gauge readings).
- Incorrectly interpreting the loop diagram (e.g. thinking you're at the wrong place in the system when taking measurements).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

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

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

Notes on troubleshooting feedback control loops

Recall that every feedback control loop consists of four basic elements: an element that *senses* the process variable (e.g. primary sensing element, transmitter), an element that *decides* what how to regulate this process variable (e.g. a PID controller), an element that *influences* the process variable (e.g. a control valve, motor drive, or some other final control device), and finally the process itself which *reacts* to the final control device's actions:



You can check each element of your feedback control loop by comparing its input with its output to see if each element is doing what it should:

(1) **Decision-making:** Carefully examine the controller faceplate, looking at the values of PV, SP, and Output. Is the controller taking appropriate action to force PV equal to SP? In other words, is the Output signal at a value you would expect if the controller were functioning properly to regulate the process variable at setpoint? If so, then the controller's action and tuning are most likely not at fault. If not, then the problem definitely lies with the controller.

(2) **Sensing:** Compare the controller's displayed value for PV with the actual process variable value as indicated by local gauges, by feel, or by any other means of detection. If there is good correspondence between the controller's PV display and the real process variable, then there probably isn't anything wrong with the measurement portion of the control loop (e.g. transmitter, impulse lines, PV signal wiring, analog input of controller, etc.). If the displayed PV disagrees with the actual process variable value, then something is definitely wrong here.

(3) **Influencing:** Compare the controller's displayed value for Output with the actual status of the final control element. If there is good correspondence between the controller's Output display and the FCE's status, then there probably isn't anything wrong with the output portion of the control loop (e.g. FCE, output signal wiring, analog output of controller, etc.). If the controller Output value differs from the FCE's state, then something is definitely wrong here.

(3) **Reacting:** Compare the process variable value with the final control element's state. Is the process doing what you would expect it to? If so, the problem is most likely not within the process (e.g. manual valves, relief valves, pumps, compressors, motors, and other process equipment). If, however, the process is not reacting the way you would expect it to given the final control element's state, then something is definitely awry with the process itself.

Lab Exercise – decommissioning and clean-up

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

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

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

Return the following components to their proper storage locations:

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

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

Lab Exercise – team tool locker inspection

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

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

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

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Question 92

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:** _______________

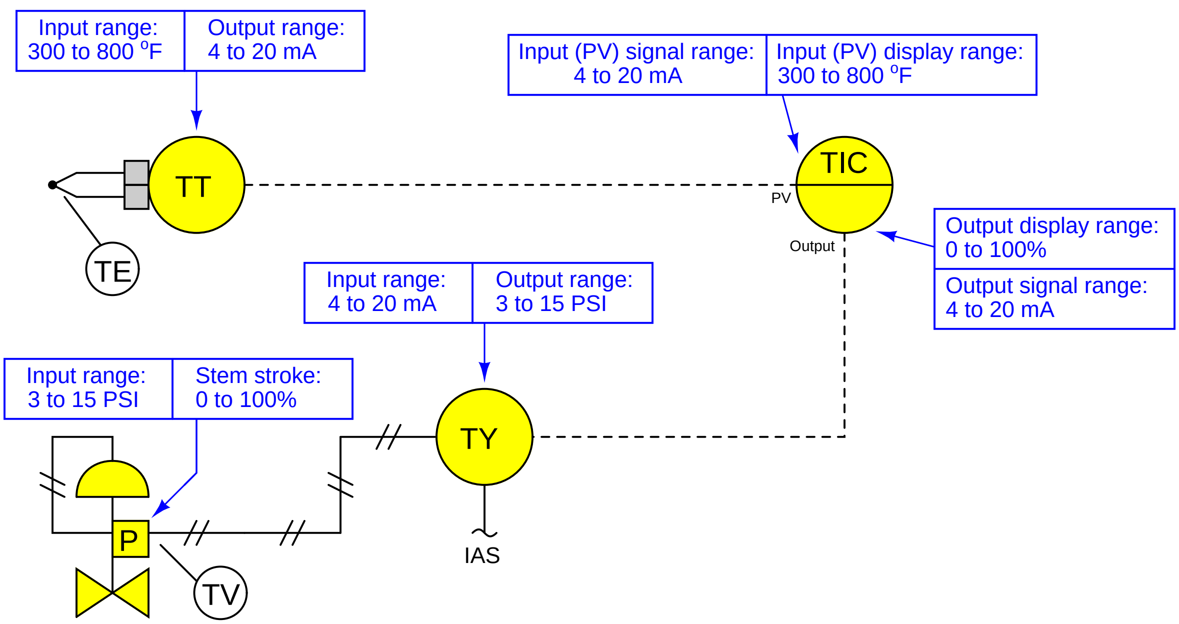
Criterion	**(Instructor verifies)**
Instructor verifies all signal wires/tubes disconnected	
Instructor verifies controller reset to original configuration	
Instructor verifies DAQ is returned to team tool locker	
Instructor collects your diagrams	

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*

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

Answer 2

Answer 3

Electronic valve positioners act as controllers of a sort by sensing stem position (PV), comparing that PV against the command value coming from the loop controller (the positioner's SP), and finally generating its own pneumatic output signal to drive the actuator and move the valve to where it should be.

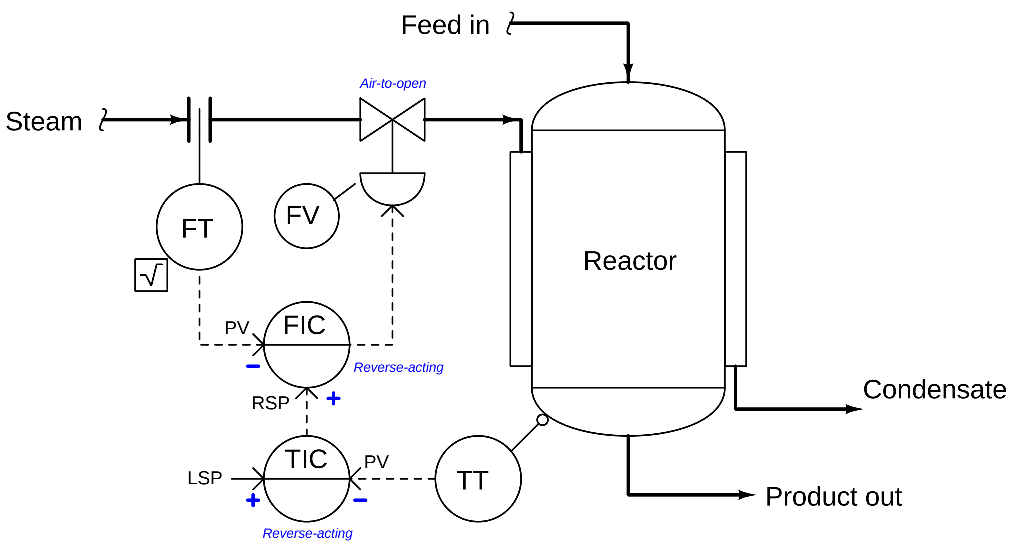
A potential problem with electronic positioners is the potential to mis-tune its internal control(lers), resulting in oscillations if the internal control is too aggressive and sluggishness if the internal control is not aggressive enough.

Answer 4

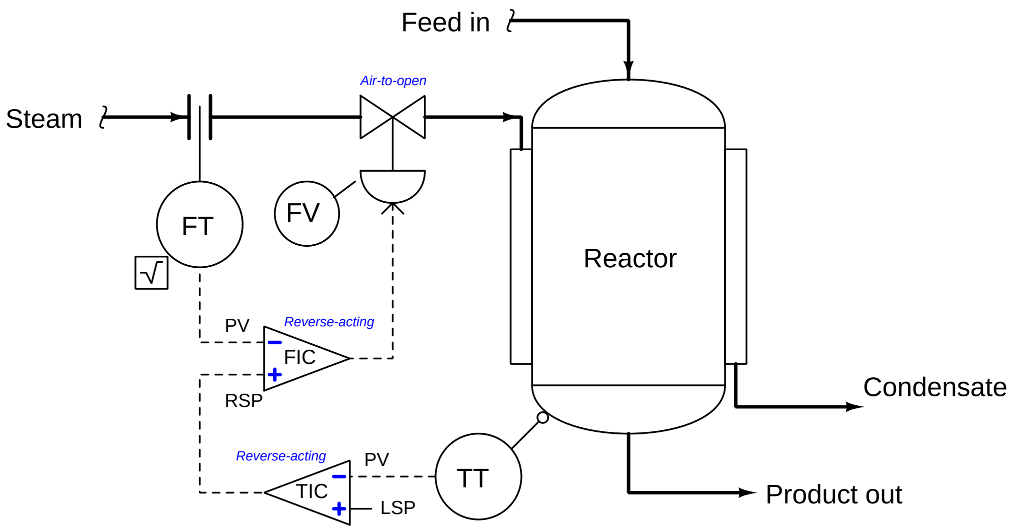
The temperature controller (TC) provides a "remote" setpoint to the flow controller (FC), which throttles the flow control valve (FV) to achieve the desired rate of steam flow.

- Master (primary) = Reactor temperature
- Slave (secondary) = Steam flow

When tuning cascaded loops, you should *always* ensure the slave loop is well-tuned before attempting to tune the master loop. I'll let you figure out why this is important!

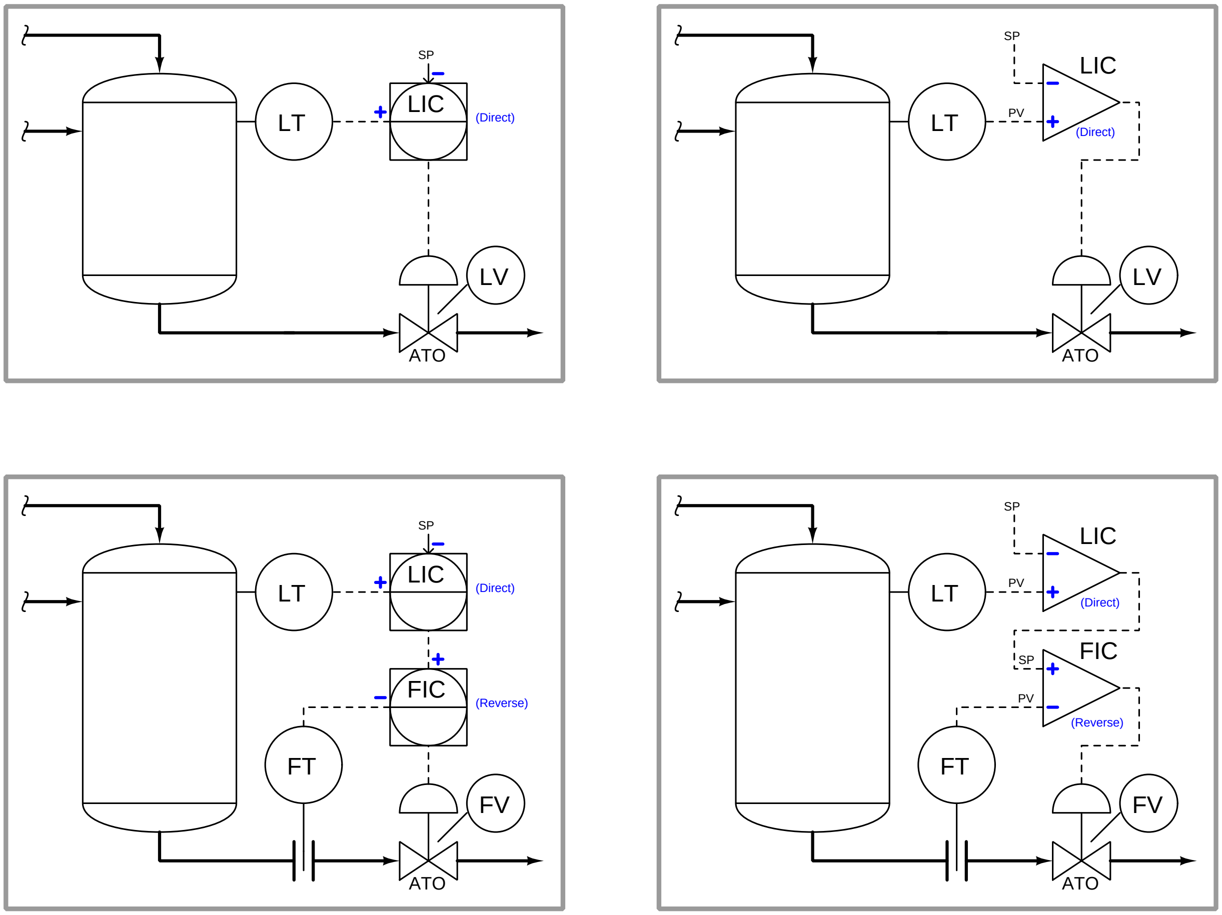


A helpful strategy for identifying necessary master and slave controller actions in a cascade control system is to re-draw the controller "bubbles" as opamp symbols instead, complete with "+" and "−" labels for noninverting and inverting inputs, respectively. Since all PID controllers have PV and SP inputs, and these inputs always have opposite effects on the output signal, the opamp conventions of "+" and "−" work very well to describe the action of any PID controller. If the PV input on the opamp controller must be noninverting ("+") in order to achieve loop stability, then that controller must be direct-acting. If the PV input on the opamp controller must be inverting ("−") in order to achieve loop stability, then that controller must be reverse-acting. The following diagram shows how to use opamp symbols to represent controller actions in the same cascaded flow/temperature control system:



Note that it is always the *inputs* of a controller we label with "+" or "−" symbols, never the *output* of a controller.

Answer 5



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 6

Answer 7

Answer 8

Answer 9

Answer 10

Answer 11

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 12

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 13

This is an *open-loop test*, based on the fact the output signal is square-wave stepping as it would when a human operator enters new values in manual mode.

Since this is a manual-mode test, we know we are looking at the response of the *process*, not the *PID controller*. Based on this test, we see the process has a direct response, which means the controller must be *reverse-acting* in order to have the negative feedback we need for stable control.

The control valve seems to be overshooting its intended stem position with each step-change in command signal. This could indicate a positioner problem on the valve.

We cannot tell if there are any tuning problems with the controller, because this trend does not show us the results in automatic mode (closed-loop).

We can tell from the process response that this is a self-regulating process with very short lag/dead times and some noise. Most likely, we are dealing with liquid flow control. Consequently, we would expect to see excellent results with aggressive integral action, perhaps some proportional action, and no derivative action.

Answer 14

This is a *closed-loop test*, based on the fact the output signal responds dynamically to the changing process variable, as well as to the step-change in setpoint.

This is a *reverse-acting* controller: the output steps up when the setpoint steps up (implying the output would step down if the process variable stepped up).

We really cannot discern any problems with field instrumentation from this trend. A manual-mode (open-loop) test would be more informative in that regard.

The oscillation around setpoint shows that something is tuned too aggressively for the process. Based on the lagging phase shift of the output waveform, it looks as though integral action is the one that's too aggressive. It also appears we may have too much derivative action, based on the amount of noise present on the output signal versus the relatively "quiet" process variable signal. It would take a huge amount of gain to make proportional action amplify noise to this extent, and we can see by comparing the output oscillations versus the process variable oscillations that our gain cannot be much greater than 2.

Less derivative action (to tone down the noise amplification on the output), for sure! Less integral action to avoid the oscillation around setpoint.

Answer 15

As the steam supply pressure rises and falls, a greater or lesser steam flow will result through the temperature valve (TV) for any given stem position.

The simplest and most direct solution to this problem is to stabilize the steam supply pressure: determine what is causing the pressure to fluctuate, and fix it!

Answer 16

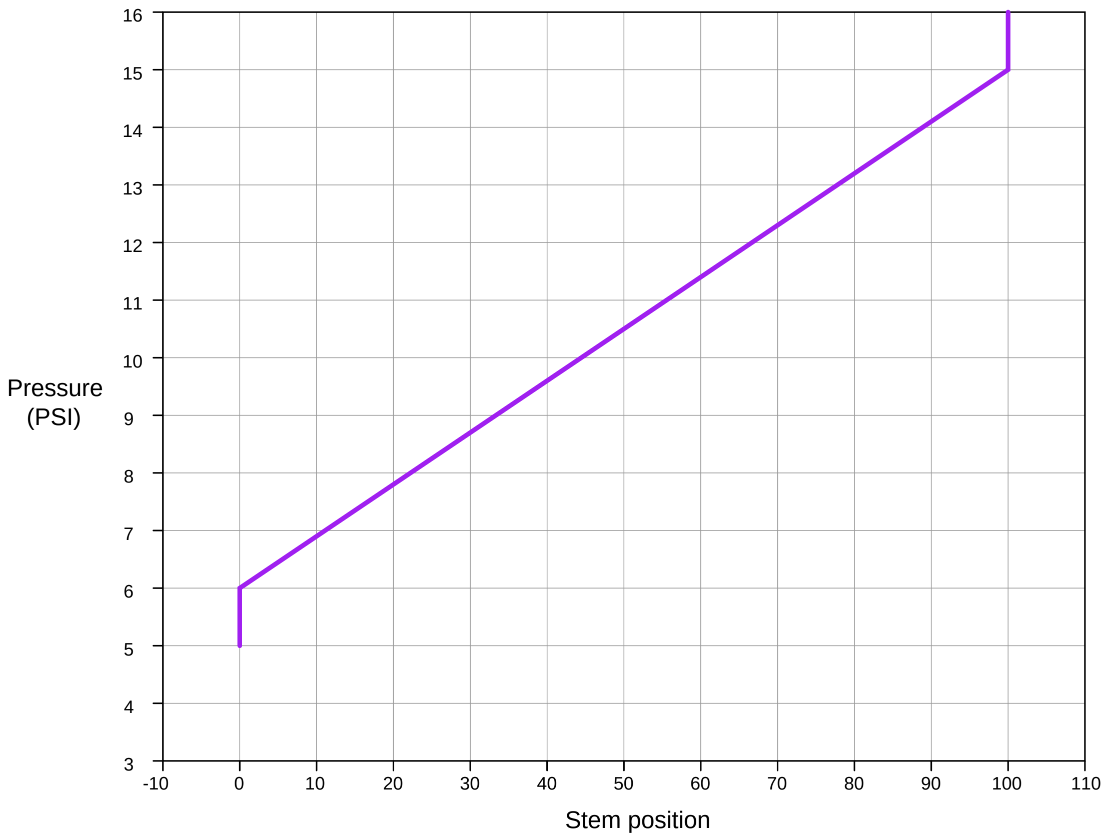
Cascade control works by adding another controller before the final control element, taking setpoint orders from the original loop controller to ensure the manipulated variable holds to that value. In this application level controller LIC-35 directly controls valve LV-35 to admit make-up water to the 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 17

This valve signature is *ideal*, showing no friction at all:

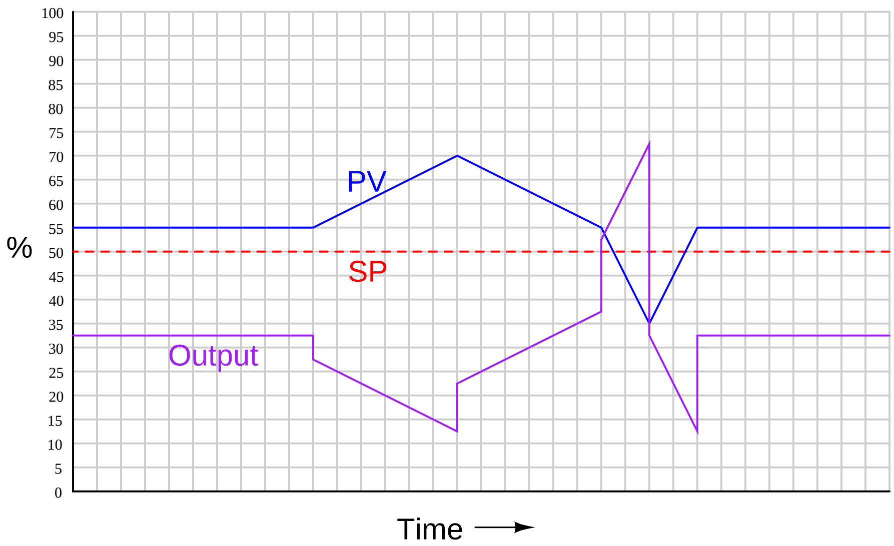


The fact that the trim is equal-percentage is irrelevant information, but it might cause some students to try and sketch the valve signature as a *curve*. The fact that this valve is stem-guided does not affect the signature either.

Technically, the fact that the valve body is direct-acting is relevant because it tells where the *seating profile* will be found on this valve. However, the crude valve signature I show doesn't give that level of detail and so we can say the valve body's action is irrelevant for the scope of this question.

Answer 18

The controller output graph shown here is *qualitative* only. Although drawn to scale (i.e. all changes in the output are properly scaled relative to each other), the scale itself is arbitrary and therefore may not match the scale of your sketch:



Answer 19

Answer 20

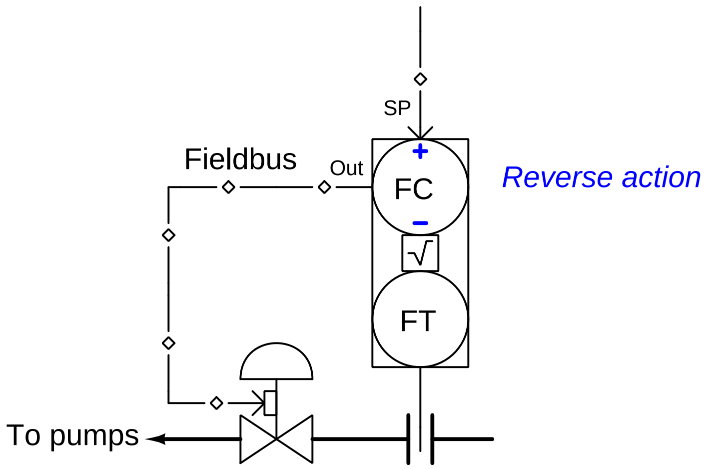
Answer 21

Answer 22

Answer 23

In theory, this *feedforward* system would work to hold the liquid level absolutely constant, because it will try to maintain flow out equal to flow in (mass out *balances* mass in). However, there are some practical reasons why it would not work.

The controller needs to be *reverse action*, assuming a signal-to-open control valve:



The "+" symbol at the SP input of the controller tells us there is a non-inverting relationship between the SP input and the controller output. The "−" symbol at the PV input of the controller tells us there is an inverting relationship between the PV input and the controller output. Both of these characteristics are consistent with what we call "reverse" action in a loop controller.

Answer 24

In theory, this *feedforward* system would work to hold the liquid outlet temperature absolutely constant, because it will try to maintain heat flow out equal to heat flow in (energy out *balances* energy in). However, there are some practical reasons why it would not work (even if the liquid inlet temperature and composition were held constant).

Answer 25

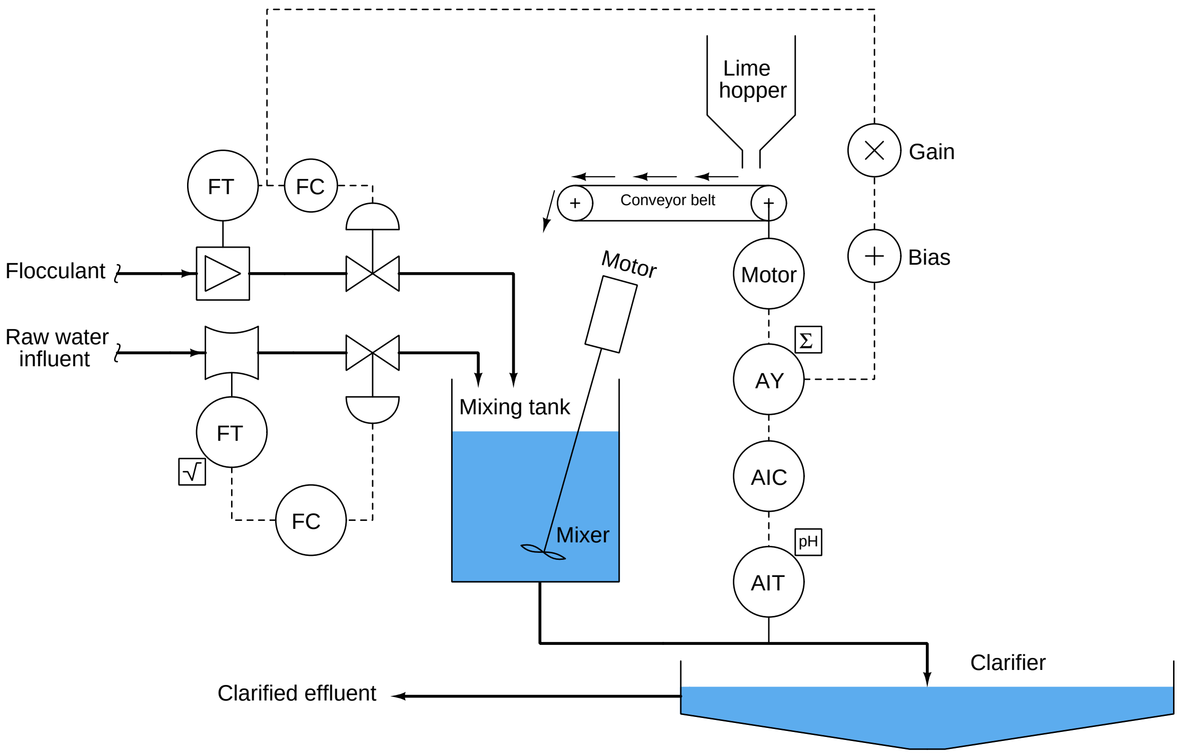
If the wild flow increases, the flow transmitter on that line will send an increased signal to the summer (FY), which will increase the setpoint to the outlet flow controller (FC), which will open the flow valve appropriately to handle the extra incoming flow, with no "bump" to the liquid level.

If the vessel springs a leak, the level transmitter will register a decrease in liquid level, the level indicating controller (LIC) will output a lesser signal to the summer (FY), decreasing the setpoint sent to the flow controller (FC) and compensating for the extra load on the process.

Answer 26

In order to test the effectiveness of feedforward control, we need to perturb the wild variable (in this case, feed flow rate) and watch the PV's response over time on a trend graph, *all with the feedback controller in manual mode so that we are only looking at the effects of feedforward.* If the feedforward action is "tuned" properly, there will be little or no effect on the process (controlled) variable.

Answer 27



Answer 28

Partial answer:

Fault	Possible	Impossible
Transmitter FT-21 failed with low output		
Transmitter FT-21 failed with high output		
Transmitter LT-25 failed with low output		$\surd$
Transmitter LT-25 failed with high output		
Transmitter FT-28 failed with low output		
Transmitter FT-28 failed with high output	$\surd$	
Transmitter LT-30 failed with low output		
Transmitter LT-30 failed with high output		
Effluent pump turned off		

Answer 29

Diagnostic test	Yes	No
Measure DC voltage between terminals 34 and 35		$\surd$
Measure DC voltage between terminals 12 and 13		$\surd$
Measure DC voltage between both terminals labeled 12 (same block)		$\surd$
Measure DC voltage between I/P terminals		$\surd$
Measure DC current at terminal 35 (cable HV-45a conductor)		$\surd$
Measure DC current at terminal 12 (cable HV-45b conductor)	$\surd$	
Measure DC current at terminal 12 (cable HV-45c conductor)	$\surd$	
Check air supply to see that it is at least 20 PSI		$\surd$
Remove tube from valve diaphragm to check for air pressure there		$\surd$

Answer 30

First, the transmitters may be calibrated at any time, even if the boiler is not ready to run, since all that is required is a bench calibration with instrument air.

For tuning purposes, the boiler should be started in manual mode and given a constant load (venting steam). The first controller to tune should be the flow controller. The next should be the level controller. Finally, the summer gains and biases should be adjusted. I'll let you describe how and why for each controller, and also estimate the PID values!

Answer 31

This is a *closed-loop test*, based on the fact the output signal responds dynamically to the changing process variable, as well as to the step-change in setpoint.

This is a *reverse-acting* controller: the output steps up when the setpoint steps up (implying the output would step down if the process variable stepped up).

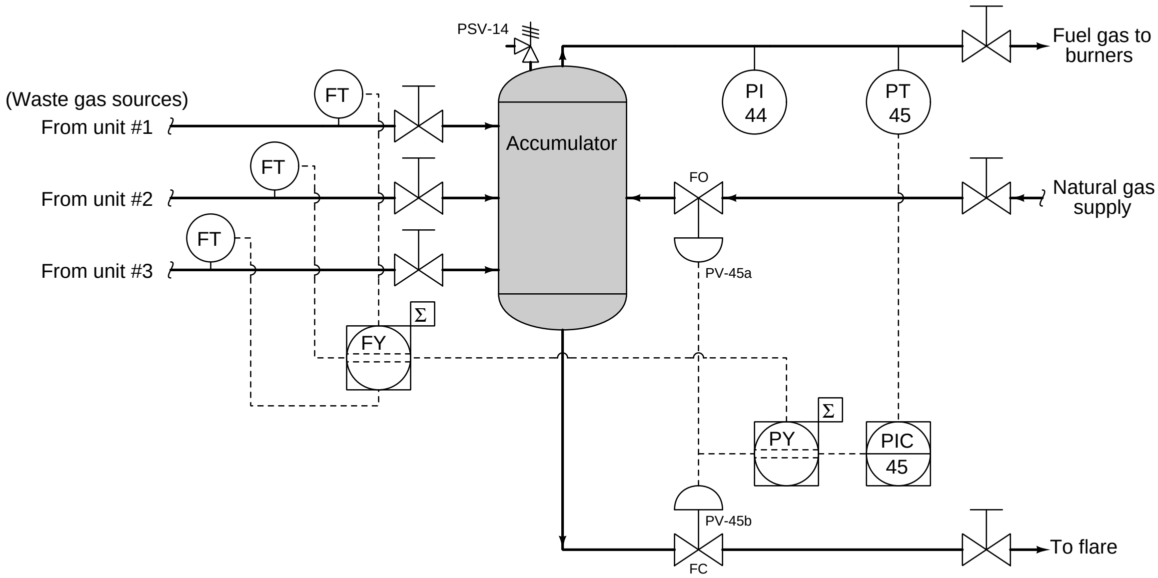
We really cannot discern any problems with field instrumentation from this trend. A manual-mode (open-loop) test would be more informative in that regard.

The response to the setpoint change shows some derivative action (as seen from the "spike"), a small amount of proportional action (as seen from the "step" of about 4% following the derivative spike), and a slow integral time. Integral action is the most challenging to see in this trend, as it looks almost like a proportional response: the long, inverse-exponential curve of the output that has the same shape and magnitude as the process variable's inverse-exponential curve toward setpoint. We can tell for sure that this is integral action rather than proportional action from the direction of its action: the output is driving up as the process variable continues to be below setpoint (this is reverse action, integral).

More gain (more aggressive proportional action) would probably help, and we could do with faster integral action as well. Less derivative action might even be helpful here, as its present level could be acting to slow down the response of the controller.

Answer 32

This is the correct solution, where the total load flow signal gets added to the *output* of the pressure controller, not to its *PV input*:



The reason for this is quite straightforward: we want the feedforward signal to directly contribute to the positions of the control valves, so that any change in waste gas flow immediately biases the control valves in order to pro-actively compensate. If the feedforward signal were to be added to the pressure controller's PV signal, it would cause the pressure controller to incorrectly see changes in pressure that were really changes in waste gas flow. Not only would this not achieve the desired effect, but it would also "lie" to the pressure controller, the result of which being it could never properly hold to setpoint!

Answer 33

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 34

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 35

This is a *closed-loop test*, based on the fact the output signal responds dynamically to the changing process variable, as well as to the step-change in setpoint.

This is a *reverse-acting* controller: the output steps down when the setpoint steps down (implying the output would step down if the process variable stepped up).

We really cannot discern any problems with field instrumentation from this trend. A manual-mode (open-loop) test would be more informative in that regard.

The response to the setpoint changes shows that most (if not all) of the control action is *proportional*. Note in particular the persistent offset between PV and SP, growing worse with each new SP change, while the output basically holds level during that time period and doesn't act to correct the offset.

Also note the evidence of some "porpoising" (oscillations prior to PV crossing SP) that indicates either too much proportional or too much derivative action, since integral action will never cause an oscillation (reversal of direction) prior to PV crossing SP. Based on a comparison of phase shift between the PV and SP wave peaks (in-sync with each other), it would appear the culprit is excessive proportional action.

This process appears to be a fast, self-regulating type. Therefore, we would expect it to control well with aggressive integral action, and not need much proportional or derivative action at all.

Answer 36

This is a *closed-loop test*, based on the fact the output signal responds dynamically to the changing process variable, as well as to the step-change in setpoint.

This is a *reverse-acting* controller: the output steps up when the process variable steps down.

We really cannot discern any problems with field instrumentation from this trend. A manual-mode (open-loop) test would be more informative in that regard.

The response to the setpoint changes shows that most (if not all) of the control action is *proportional*. Note how the shape of the output trend is nearly the same as the PV trend (inverted and enlargened). Note also how there is persistent offset between PV and SP prior to the sudden change in PV, while the output isn't changing very much to correct this error.

The fact that the output slopes upward while PV slopes upward during the last half of the trend shows us that there is some integral action at work here, just not enough to bring the PV quickly to SP.

We definitely need more integral action to move the PV faster to SP.

Answer 37

Answer 38

Answer 39

Answer 40

Answer 41

Answer 42

Answer 43

Answer 44

Answer 45

This is a self-regulating process dominated by first-order lag and no discernible dead time. As such, it should be easy to control, tolerating aggressive proportional and derivative action, but requiring little integral action due to the aggressive proportional action.

Answer 46

This is definitely a self-regulating process, with negligible dead time. The fact that it is self-regulating suggests it may be primarily controlled by integral action, and may not need much "help" from proportional action at all. This is good, because proportional action would try to duplicate the PV's noise on the output, to the detriment of the control valve.

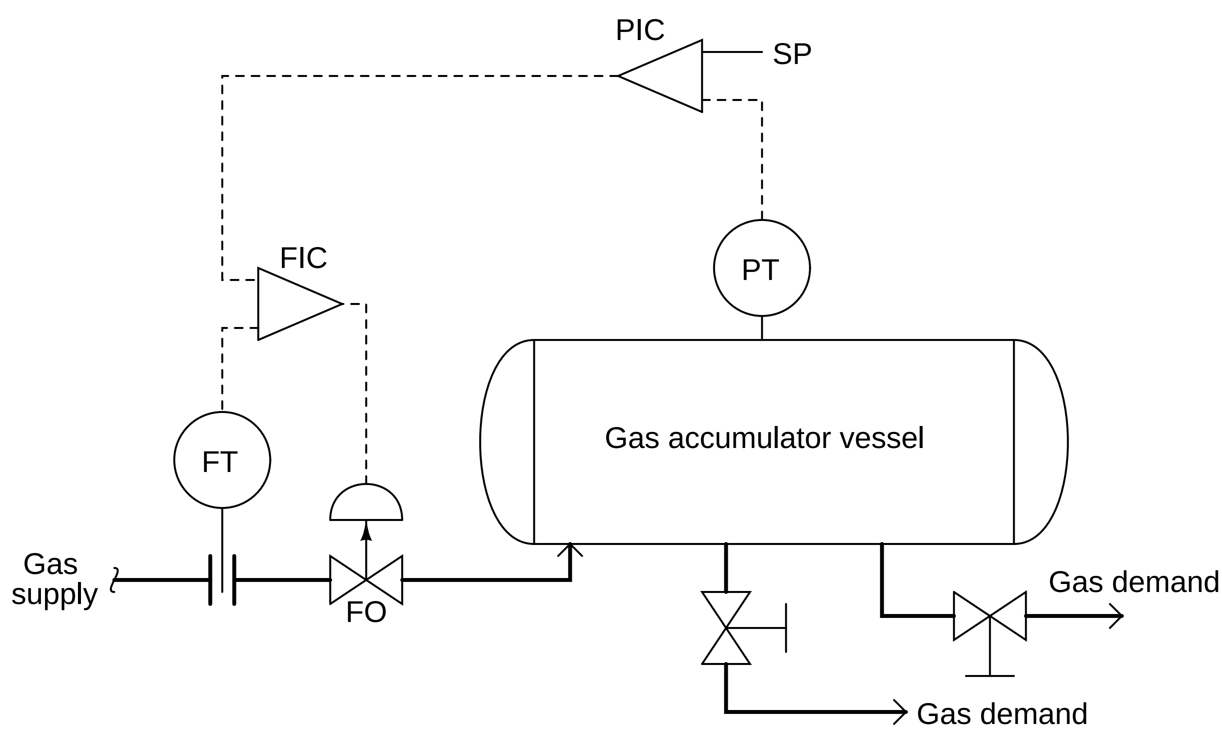
Whatever, do *not* use any derivative (rate) action on this process!

Follow-up question: does the fact that noise in this process does not influence our tuning decisions much mean that it is okay for this noise to be present? Why or why not?

Answer 47

Answer 48

To aid your analysis of the system (especially in labeling each controller's inputs with "+" and "−" symbols), feel free to annotate the controller actions in this modified version of the P&ID, where each controller is drawn as an operational amplifier:



Answer 49

Answer 50

$C_v = 193.6$

A 2.5 inch valve would almost be large enough. One size larger (perhaps 3 inches) should be adequate.

Answer 51

$Q_{outlet} = 510.5$ GPM

Answer 52

This is a *closed-loop test*, based on the fact the output signal responds dynamically to the changing process variable, as well as to the step-change in setpoint.

This is a *reverse-acting* controller: the output ramps up whenever the PV is below SP, and the output ramps down whenever the PV is above SP.

This loop definitely has hysteresis in the final control element (e.g. sticky valve), because this trend is a classic *slip-stick cycle* in a self-regulating process: the PV exhibits a square-wave shape while the output ramps up and down like a sawtooth wave.

There probably isn't anything wrong with the controller's tuning, and no tuning adjustments will fundamentally address the problem of valve stiction.

The process appears to be self-regulating with a fast response time (note how quickly the PV settles at a new value following each "slip" of the control valve), which means it should control very well with aggressive integral action. However, final control element hysteresis is the bane of integral action, as it causes repeated reset windup as we see here.

Answer 53

Fault	**Possible**	**Impossible**
FT signal cable failed open		$\surd$
FT signal cable failed shorted		$\surd$
VFD signal cable failed open	$\surd$	
VFD signal cable failed shorted	$\surd$	
HMI data cable failed open	$\surd$	
PID control block in manual mode	$\surd$	
Insufficient integral control action		$\surd$
Circuit breaker 3 tripped	$\surd$	
Circuit breaker 15 tripped		$\surd$
Circuit breaker 22 tripped		$\surd$

A good "next test" would be to measure the 4-20 mA analog signal coming out the of PLC, to see if the PLC is even trying to command the VFD to run the motor.

Answer 54

This is a *closed-loop test*, based on the fact the output signal responds dynamically to the changing process variable, as well as to the step-change in setpoint.

It's really challenging to discern the direction of action for this controller, because there aren't any obvious features in the trend to focus on, for example a step-change. Since the wave peaks seem to be nearly 180^o out of phase, *reverse* action seems the most likely.

We really cannot discern any problems with field instrumentation from this trend. A manual-mode (open-loop) test would be more informative in that regard.

It is worthy to note how far the output is having to wander in order to stabilize PV at or near SP. This may be due to load changes in the process (which of course do not appear directly in the trend), or it may be due to an unresponsive control valve (e.g. stiction). Again, placing the controller in manual mode would be an informative test: if the PV begins to wander around while in manual mode, you know there are significant load changes at work in the process. If the PV fails to respond to small step-changes in the output (in manual mode), then you know the FCE isn't responding properly and needs to be serviced.

The controller's tuning seems to be quite robust, as the output is continually "working" to hold the PV close to SP.

No recommendations for tuning can be given, since the controller appears to be doing a good job.

Answer 55

Answer 56

Answer 57

Answer 58

Answer 59

Answer 60

Answer 61

"Filtering" or "damping" is a low-pass frequency function that is placed either physically or digitally on the process variable signal, in order to screen out high-frequency noise on the PV signal.

Answer 62

Answer 63

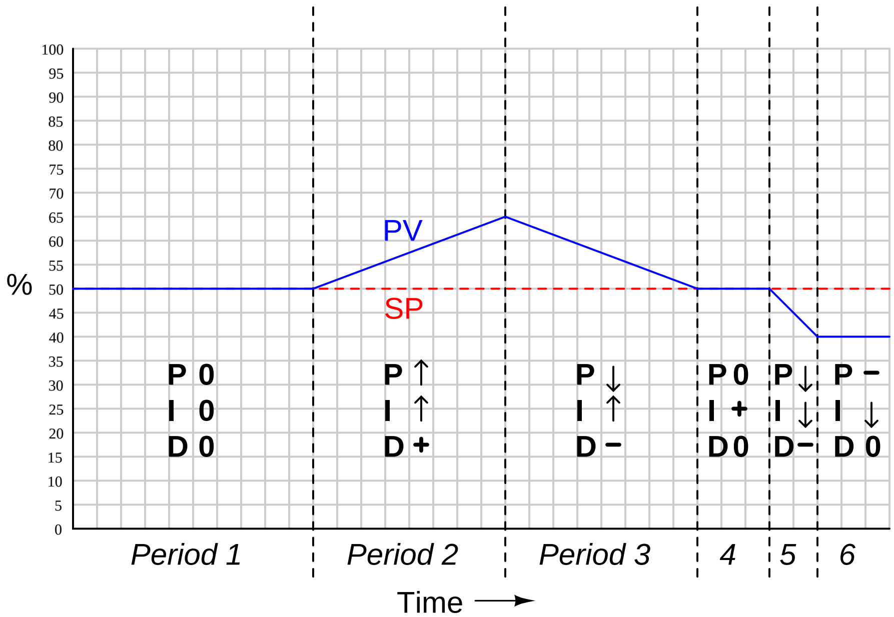
Answer 64

Answer 65

This delay is commonly referred to as *dead time* (or *transport delay*), and it wreaks havoc with feedback control systems because the controller only sees the delayed results of its control action. This is analogous to driving an automobile by looking *backward* out the rear window, controlling the steering wheel in response to the road you've already driven over!

Answer 66

Answer 67



Answer 68

Partial answer:

A full PID controller would be best, because a "P-only" controller will inevitably have offset, which may cause the process variable to settle at a point above setpoint, high enough above to melt the parts. A P+I controller will eliminate the offset, but a positive offset (PV too high) can only be corrected by integral action if the PV is allowed to accumulate positive error (i.e. PV remains mildly excessive for a period of time). In order to avoid overshoot in a P+I controller, which would melt the parts, it must be tuned for *very slow* response. Faster response may be obtained through the addition of derivative action, in a full PID controller.

Answer 69

Valve	**Fully shut at** (PSI)	**Fully open at** (PSI)
HP throttle	3 PSI	15 PSI
Turbine bypass	15 PSI	3 PSI

If the bypass line is blocked by a shut hand valve, the turbine power control system will still do its job to regulate output power, but other variables in the plant will certainly be affected!

Answer 70

Fault	Possible	Impossible
TSL contact failed open		$\surd$
TSL contact failed shorted	$\surd$	
TSH contact failed open		$\surd$
TSH contact failed shorted		$\surd$
TC-1 contact failed open		$\surd$
TC-1 contact failed shorted	$\surd$	
TC-2 contact failed open		$\surd$
TC-2 contact failed shorted		$\surd$
TC relay coil failed open		$\surd$
TC relay coil failed shorted		$\surd$
Broken wire between points C and F		$\surd$
Broken wire between points A and B		$\surd$

A good test would be to disconnect the wire between points **C** and **F** to see if the cycling changes at all.

Answer 71

This is a *closed-loop test*, based on the fact the output signal responds dynamically to the changing process variable, as well as to the step-change in setpoint.

This is a *reverse-acting* controller: the output steps up when the setpoint steps up (implying the output would step down if the process variable stepped up).

There do not appear to be any field instrumentation problems revealed in this trend. A manual-mode (open-loop) test would be more informative in that regard, but it appears as though the process is very quick to respond with no discernable dead time or other lags.

The controller tuning is clearly lacking integral action. Note the large offset between PV and SP (i.e. how the process variable never settles at the setpoint value). This tells us the controller is configured only for proportional action, and this process needs integral! We can also tell this from the 180^o phase shift between PV and output during the oscillations: this is the classic response of a reverse-acting proportional-only controller. The actual amount of gain appears to be appropriate for the loop, since the oscillations are not excessive (less than 1/4 wave damping). However, some processes are especially sensitive to overshoot, and if this is such a process we will need to use less proportional action (after fixing the integral problem) to avoid any overshoot of setpoint.

We desperately need to apply some integral action to this loop, because self-regulating loops absolutely need integral action to handle load changes and achieve new setpoint values.

Answer 72

This is a *closed-loop test*, based on the fact the output signal responds dynamically to the changing process variable, as well as to the step-change in setpoint.

This is a *reverse-acting* controller: the output steps up when the setpoint steps up (implying the output would step down if the process variable stepped up).

There do not appear to be any field instrumentation problems revealed in this trend. A manual-mode (open-loop) test would be more informative in that regard, but it appears as though the process is fairly quick to respond with little dead time or other lags.

The controller tuning is clearly too aggressive for this process. Note the "porpoising" action of the PV as it approaches SP following the SP step-change. Only two types of controller action can cause this to occur: *proportional*, or *derivative*. Porpoising is when an oscillation occurs in the PV prior to it crossing setpoint, which explains why integral action cannot ever be to blame for porpoising: the only way a loop oscillation can occur is when the final control element oscillates as well (i.e. changes direction), and since integral action will never change direction until PV crosses SP, oscillations that occur on one side of SP cannot be caused by integral action. Looking at the phase shift between PV and output during the oscillations, it appears the output peaks may slightly lead the PV peaks, but only slightly. This suggests that proportional is the action that is too aggressive (if it were derivative, there would be more of a leading phase shift).

This is definitely a self-regulating process, as revealed by the fact a new output value is required to achieve a new setpoint value. This means integral control action will definitely be necessary. Good control will require less gain (to eliminate the porpoising). Integral action looks like it could stand to be a bit more aggressive than it is right now. There is some overshoot of setpoint at the end of this trend, but not much at all.

Answer 73

This is a *closed-loop test*, based on the fact the output signal responds dynamically to the changing process variable, as well as to the step-change in setpoint.

This is a *reverse-acting* controller: the output steps up when the setpoint steps up (implying the output would step up if the process variable stepped down).

We really cannot discern any problems with field instrumentation from this trend. A manual-mode (open-loop) test would be more informative in that regard. Following the last SP step-change, we see a period of time where the error between PV and SP is nearly constant and the output is steadily driving upward. This may suggest a "sticky" control valve. However, a more definitive test would be to place the controller in manual mode and perform small step-changes in the output to see how responsive the PV is.

This controller's tuning is actually not bad at all, but there still is room for improvement. Toward the end of the trend we see a persistent error between PV and SP that may be correctable with more aggressive integral action. However, if an open-loop test (see previous comment) reveals a sticky control valve, then the best solution would be to repair the control valve rather than trying to re-tune the controller.

This process appears to be a fast, self-regulating type. Therefore, we would expect it to control well with aggressive integral action, and not need much proportional or derivative action at all.

Answer 74

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

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