Lab

Automatically-controlled process: *Questions 91 and 92*, **completed objectives due by the end of day 5, section 4**

Exam

Day 5 of next section – **Complete mastery of these objectives due by the next exam date**

Specific objectives for the "mastery" exam:
- Electricity Review: Calculate voltages, currents, and phase shifts in an AC reactive circuit
- Perform numerical differentiation on a simple mathematical function (graphed)
- Perform numerical integration on a simple mathematical function (graphed)
- Identify the graphed response of a controller as being either P, I, or D; direct or reverse
- 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: Calculate voltages and currents within balanced three-phase AC electrical circuits
- INST241 Review: Determine suitability of different flow-measuring technologies for a given process fluid type
- INST263 Review: Determine the effect of a component fault or condition change in a cascade-, ratio-, or feedforward-controlled process

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Recommended daily schedule

Day 1

Theory session topic: Proportional-only offset

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

Day 2

Theory session topic: Integral-only control

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

Day 3

Theory session topic: Proportional + integral control

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

Day 4

Theory session topic: Proportional + integral control (continued)

Questions 61 through 80; <u>answer questions 61-69</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. <u>Download</u> and <u>save</u> 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: <u>Mastery exams</u> 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. <u>Proportional exams</u> 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 <u>all</u> 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.

<u>file `howto`</u>

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 251 Course Outcomes

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

- Calculate voltages and currents in an ideal AC transformer circuit. [Ref: Program Learning Outcome #4]

- Calculate voltages, currents, and phase shifts in an AC reactive circuit. [Ref: Program Learning Outcome #4]

- Predict the response of an automatic control system to a component faults or process change, given pictorial and/or schematic illustrations. [Ref: Program Learning Outcome #4]

- Determine the effect of a component change on the gain of a pneumatic controller mechanism. [Ref: Program Learning Outcome #4]

- Compute the value of the numerical derivative at a single specified point on a graph. [Ref: Program Learning Outcome #4]

- Compute the value of the numerical integral over a specified interval on a graph. [Ref: Program Learning Outcome #4]

- Identify the response of a loop controller as being either P, I, or D based on a comparison of process variable, setpoint, and output trend graph recordings. [Ref: Program Learning Outcome #6]

- Solve for specified variables in algebraic formulae. [Ref: Program Learning Outcome #4]

- Determine the possibility of suggested faults in simple circuits given measured values (voltage, current), schematic diagrams, and reported symptoms. [Ref: Program Learning Outcome #4]

- Demonstrate proper use of safety equipment and application of safe procedures while using power tools, and working on live systems. [Ref: Program Learning Outcome #3]

- Communicate effectively with teammates to plan work, arrange for absences, and share responsibilities in completing all lab work. [Ref: Program Learning Outcomes #1 and #2]

- Construct and commission a hand control loop using a pneumatic controller and pair of split-ranged pneumatic control valves. [Ref: Program Learning Outcome #5]

- Connect a loop controller to the electronic transmitter and final control element of a pre-constructed process, then commission all components to form a working feedback control loop. [Ref: Program Learning Outcome #5]

- Generate accurate loop diagrams compliant with ISA standards documenting your team's control systems. [Ref: Program Learning Outcome #8]

- Adjust the PID settings of your team's control loop for stable operating behavior. [Ref: Program Learning Outcome #6]

- Wire and program a VFD (Variable Frequency motor Drive) for remote starting and stopping of an AC induction motor using pushbutton switches, measuring motor line current with a clamp-on ammeter. [Ref: Program Learning Outcome #5]

- Research equipment manuals to sketch a complete circuit connecting a loop controller to either a 4-20 mA transmitter or a 4-20 mA final control element, with all DC voltages and currents correctly

annotated, all electrical sources and loads properly identified, given components randomly selected by the instructor. [Ref: Program Learning Outcomes #5 and #9]

- Diagnose a random fault simulated by computer in a 4-20 transmitter circuit, logically justifying your steps before an instructor. [Ref: Program Learning Outcome #4]

file `outcomes_INST251`

Sequence of second-year Instrumentation courses

Core Electronics -- 3 qtrs
including MATH 141 (Precalculus 1)

(Only if 4th quarter was Summer: INST23x)

INST 200 -- 1 wk
Intro. to Instrumentation

Prerequisite for all INST24x, INST25x, and INST26x courses

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

All courses completed? **No** **Yes**

INST 205 -- 1 cr
Job Prep I

INST 206 -- 1 cr
Job Prep II

Offered 1st week of Fall, Winter, and Spring quarters

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:

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

Beginning in Summer

Summer quarter (July – Aug.)
- INST 233 -- 4 cr — Protective Relays (elective)
- Jobshadow and/or Internship strongly recommended

Fall quarter (Sept. – Dec.)
- INST 200 -- 1 wk — Intro. to Instrumentation
- INST 240 -- 6 cr — Pressure/Level Measurement
- INST 241 -- 6 cr — Temp./Flow Measurement
- INST 242 -- 5 cr — Analytical Measurement

Winter quarter (Jan. – Mar.)
- INST 205 -- 1 cr — Job Prep I
- INST 250 -- 5 cr — Final Control Elements
- INST 251 -- 5 cr — PID Control
- INST 252 -- 4 cr — Loop Tuning

Spring quarter (April – June)
- INST 206 -- 1 cr — Job Prep II
- 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

Graduation!

Beginning in Fall

Fall quarter (Sept. – Dec.)
- INST 200 -- 1 wk — Intro. to Instrumentation
- INST 240 -- 6 cr — Pressure/Level Measurement
- INST 241 -- 6 cr — Temp./Flow Measurement
- INST 242 -- 5 cr — Analytical Measurement

Winter quarter (Jan. – Mar.)
- INST 205 -- 1 cr — Job Prep I
- INST 250 -- 5 cr — Final Control Elements
- INST 251 -- 5 cr — PID Control
- INST 252 -- 4 cr — Loop Tuning

Spring quarter (April – June)
- INST 206 -- 1 cr — Job Prep II
- 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

Summer quarter (July – Aug.)
- INST 233 -- 4 cr — Protective Relays (elective)
- Jobshadow and/or Internship strongly recommended

Graduation!

Beginning in Winter

Winter quarter (Jan. – Mar.)
- INST 200 -- 1 wk — Intro. to Instrumentation
- INST 250 -- 5 cr — Final Control Elements
- INST 251 -- 5 cr — PID Control
- INST 252 -- 4 cr — Loop Tuning

Spring quarter (April – June)
- INST 205 -- 1 cr — Job Prep I
- 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

Summer quarter (July – Aug.)
- INST 233 -- 4 cr — Protective Relays (elective)
- Jobshadow and/or Internship strongly recommended

Fall quarter (Sept. – Dec.)
- INST 206 -- 1 cr — Job Prep II
- INST 240 -- 6 cr — Pressure/Level Measurement
- INST 241 -- 6 cr — Temp./Flow Measurement
- INST 242 -- 5 cr — Analytical Measurement

Graduation!

Beginning in Spring

Spring quarter (April – June)
- INST 200 -- 1 wk — Intro. to Instrumentation
- 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

Summer quarter (July – Aug.)
- INST 233 -- 4 cr — Protective Relays (elective)
- Jobshadow and/or Internship strongly recommended

Fall quarter (Sept. – Dec.)
- INST 205 -- 1 cr — Job Prep I
- INST 240 -- 6 cr — Pressure/Level Measurement
- INST 241 -- 6 cr — Temp./Flow Measurement
- INST 242 -- 5 cr — Analytical Measurement

Winter quarter (Jan. – Mar.)
- INST 206 -- 1 cr — Job Prep II
- INST 250 -- 5 cr — Final Control Elements
- INST 251 -- 5 cr — PID Control
- INST 252 -- 4 cr — Loop Tuning

Graduation!

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.

Methods of instruction (continued)

Lab sessions

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

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

Troubleshooting assessments must meet the following guidelines:

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

file `instructional`

Distance delivery methods

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

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

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

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

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

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

file distance

Metric prefixes and conversion constants

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

METRIC PREFIX SCALE

T	G	M	k		m	μ	n	p
tera	giga	mega	kilo	(none)	milli	micro	nano	pico
10^{12}	10^{9}	10^{6}	10^{3}	10^{0}	10^{-3}	10^{-6}	10^{-9}	10^{-12}

10^{2} 10^{1} 10^{-1} 10^{-2}
hecto   deca   deci   centi
h   da   d   c

- **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 $(c) = 2.9979 \times 10^8$ meters per second (m/s) = 186,281 miles per second (mi/s)

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

Electronic charge $(e) = 1.602 \times 10^{-19}$ Coulomb (C)

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

Stefan-Boltzmann constant $(\sigma) = 5.67 \times 10^{-8}$ 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°F = 0°C

Boiling point at sea level = 212°F = 100°C

Density of water at 4°C = 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°C = 1.00002 calories/g·^{o}C = 1 BTU/lb·^{o}F = 4.1869 Joules/g·^{o}C

Specific heat of ice $\approx$ 0.5 calories/g·^{o}C

Specific heat of steam $\approx$ 0.48 calories/g·^{o}C

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

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

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

Properties of Dry Air at sea level

Density of dry air at 20°C and 760 torr = 1.204 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°C and 760 torr = 0.018 centipoise (cp) = 1.8×10^{-5} Pascal-seconds (Pa·s)

file `conversion_constants`

How to get the most out of academic reading:
- 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: <u>reading</u> provides the learner with knowledge, <u>writing</u> focuses the learner's thoughts, and <u>critical dialogue</u> 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 <u>all</u> of the following after reading any instructional text:

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

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

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

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

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

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

General challenges following a tutorial reading assignment

- <u>Summarize</u> 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 <u>intelligent child</u>: as simple as you can without compromising too much accuracy.
- <u>Simplify</u> 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 <u>make the most sense</u> to you? What was it about the text's presentation that made it clear?
- Identify where it might be easy for someone to <u>misunderstand the text</u>, and explain why you think it could be confusing.
- Identify any <u>new concept(s)</u> presented in the text, and explain in your own words.
- Identify any <u>familiar concept(s)</u> such as physical laws or principles applied or referenced in the text.
- Devise a <u>proof of concept</u> experiment demonstrating an important principle, physical law, or technical innovation represented in the text.
- Devise an experiment to <u>disprove</u> a plausible misconception.
- Did the text reveal any <u>misconceptions</u> 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 <u>problem-solving strategies</u> applied in the text.
- <u>Devise a question</u> of your own to challenge a reader's comprehension of the text.

General follow-up challenges for assigned problems

- Identify where any <u>fundamental laws or principles</u> apply to the solution of this problem.
- Describe in detail your own <u>strategy</u> 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 <u>more than one way</u> to solve this problem? Which method seems best to you?
- <u>Show the work</u> you did in solving this problem, even if the solution is incomplete or incorrect.
- What would you say was the <u>most challenging part</u> of this problem, and why was it so?
- Was any important information <u>missing</u> from the problem which you had to research or recall?
- Was there any <u>extraneous</u> information presented within this problem? If so, what was it and why did it not matter?
- Examine <u>someone else's solution</u> to identify where they applied fundamental laws or principles.
- <u>Simplify</u> 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 <u>limiting case</u> (i.e. altering a variable to some extreme or ultimate value).
- For quantitative problems, identify the <u>real-world meaning</u> of all intermediate calculations: their units of measurement, where they fit into the scenario at hand.
- For quantitative problems, try approaching it <u>qualitatively</u> instead, thinking in terms of "increase" and "decrease" rather than definite values.
- For qualitative problems, try approaching it <u>quantitatively</u> instead, proposing simple numerical values for the variables.
- Were there any <u>assumptions</u> 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 <u>go astray</u> in attempting to solve this problem.
- <u>Formulate your own problem</u> based on what you learned solving this one.

file `license`

Question 1

Read and outline the "Proportional-Only Offset" section of the "Closed-Loop Control" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

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

file i04283

Question 2

"Wet" natural gas is mostly methane (CH_4) mixed with significant amounts of heavier hydrocarbon species such as ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and pentane (C_5H_{12}) which condense into liquid at lower temperatures than methane. A process for separating these heavier hydrocarbons from the chief component (methane) using compression and cooling is shown here:
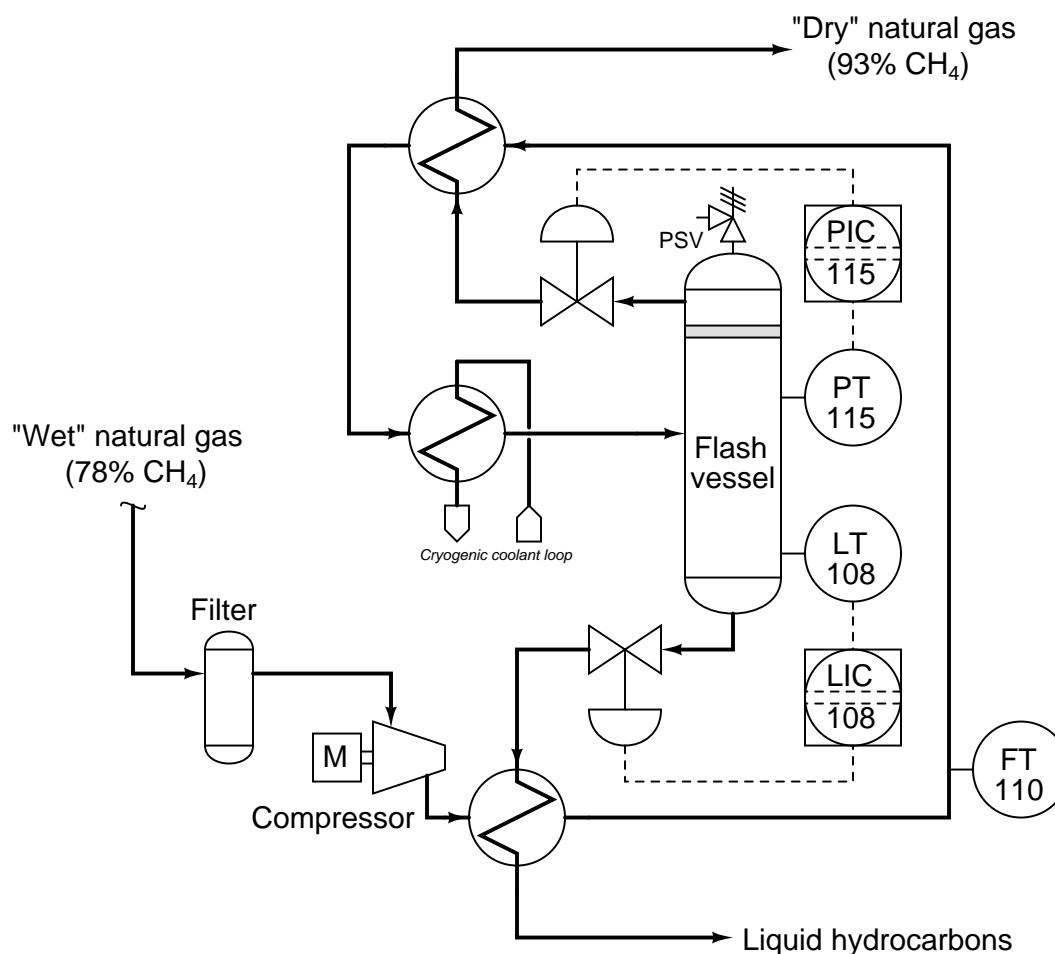
Chilled gases enter the flash vessel, where methane rises and escapes in gaseous form, while all the other (heavier) hydrocarbon molecules condense into liquid and exit out the bottom.

Suppose PIC-115 is a proportional-only controller, holding steadily and accurately to a setpoint value of 107 PSI with a valve position of 41%. How will this controller respond to a sudden change in natural gas composition that is much *drier* than usual, assuming the same total flowrate (as indicated by FT-110) as before? Be as specific as you can in your answer!

| Suggestions for Socratic discussion |

- Suppose level controller LIC-108 is also proportional-only just like pressure controller PIC-115. How will its process variable be affected by the same change in natural gas composition?
- Explain the purpose of the heat exchangers in this P&ID, especially the two exchanging heat between the incoming (compressed) gas and the products coming off the top and bottom of the flash vessel.

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- Identify and explain the purpose of the "PSV" valve in this diagram.
- Determine the proper directions of action for each controller in this system, assuming direct-acting transmitters and air-to-open valves.
- Suppose the operator of this process notices a consistent offset between PV and SP for controller PIC-115, with SP = 60% and PV = 65%. Describe steps the operator can take to eliminate this offset and get the PV equal to 60%.

file i01863

Question 3

An antimicrobial agent called *acrolein* used to protect diesel fuel from fungal growth may be manufactured by reacting propylene with steam and air in a reactor vessel:

Acrolein reactor detail

LP steam

FC-203
PV = 56%
SP = 55%
Out = 34%

Propylene

75 PSI

FC-188
PV = 1%
SP = 44%
Out = 100%

E-61

HP steam

30 PSI

62%   Blower

Air

Condensate
to boilerhouse

327 °F

TC-99
PV = 51%
SP = 50%
Out = 43%

Dowtherm

29 PSI   311 °F

R-23   Cooling water
from cooling tower

75 °F

203 °F

TC-101
PV = 48%
SP = 49%
Out = 36%

Dowtherm   E-77

177 °F

To cooling tower
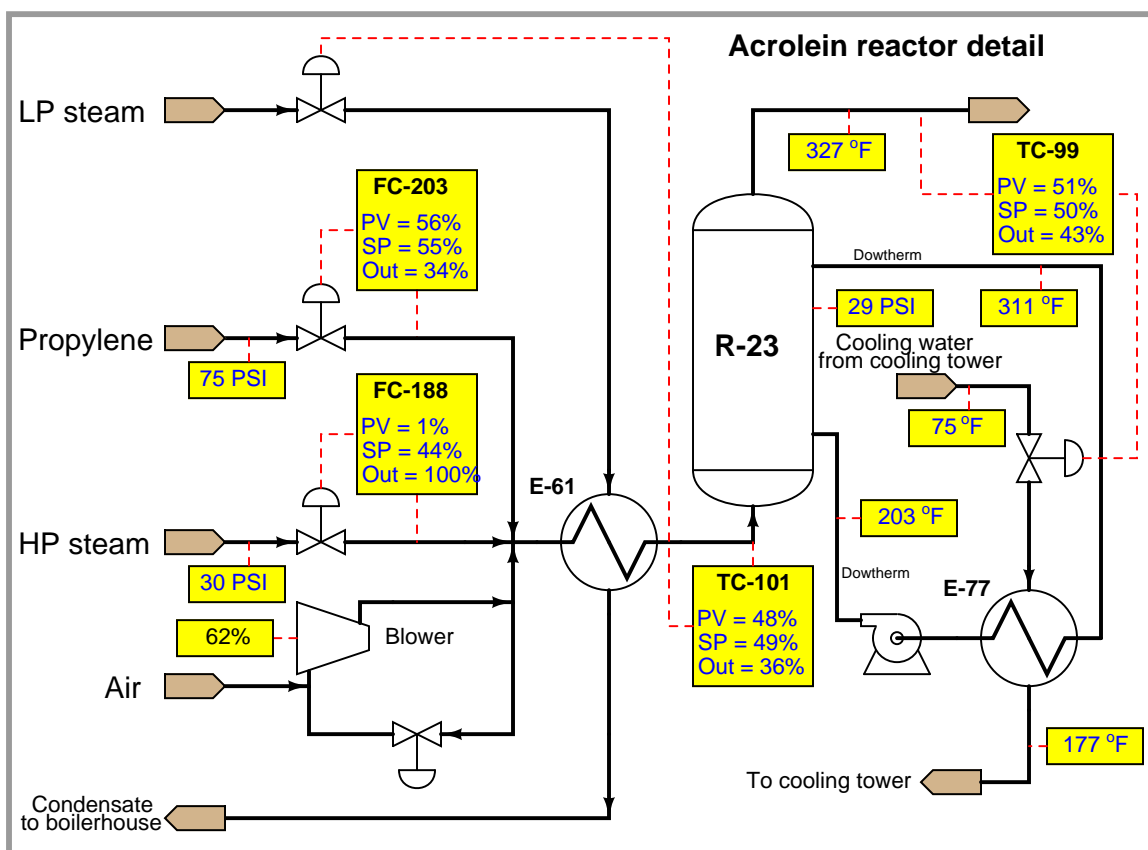
Suppose operators call you to troubleshoot a problem they are having with this process, and to help you start they show you this graphic display on one of their DCS workstations. Identify the problem in this process, suggest at least two possible causes for it, and identify the next diagnostic step you would take to confirm the cause(s).

| Suggestions for Socratic discussion |

- Identify a good troubleshooting strategy to apply to a control system graphic such as this, to quickly *identify which part of the system* is experiencing trouble.
- Determine the proper directions of action for each controller in this system, assuming direct-acting transmitters and air-to-open valves.

file i00735

Question 4

| Desktop Process exercise |

Set up one of the Desktop Process units (or PID simulation software running on a personal computer) to experiment with:
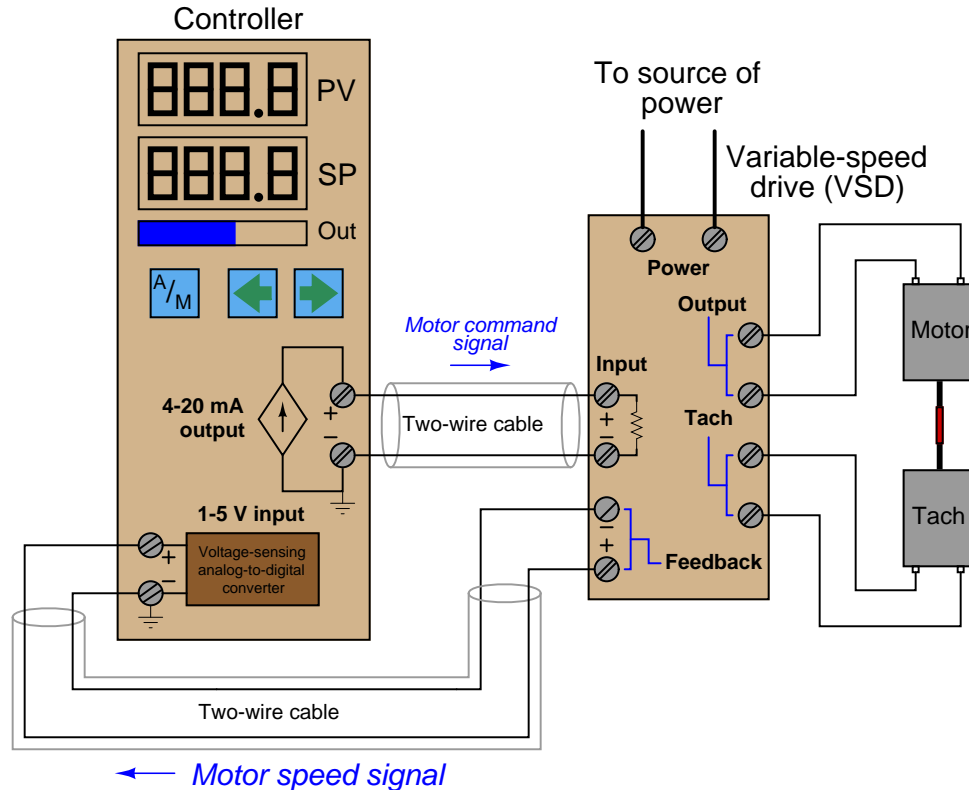
With the controller in manual mode, you should be able to drive the PV to different values, and see those speeds reflected as percentage values on the controller's process variable (PV) display.

Now, configure the controller as follows:

- Control action = *appropriate for the process being controlled*
- Gain = 1 (Proportional Band = 100%)
- Reset (Integral) = *minimum effect = 100+ minutes/repeat = 0 repeats/minute*
- Rate (Derivative) = *minimum effect = 0 minutes*

Adjust the controller's output in manual mode to achieve a PV of approximately 50%, then switch the controller to *automatic* mode and try changing the setpoint (SP) value to see if the motor speed tracks. Experiment with controlling the process in both automatic and manual modes, to better understand the purpose of each controller mode.

Once you have been able to achieve automatic control of the process, try re-configuring the controller for the *opposite* control action. How does this change affect the controller's operation in manual mode (if at all)? How does this change affect the controller's operation in automatic mode (if at all)? Explain why the controller behaves as it does with this new action.

file i04262

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Question 5

Configure the controller as follows (for "proportional-only" control). If you are using PID simulation software instead of a real physical process, select a process that is self-regulating with minimal noise or load changes:

- Control action = *appropriate for the process being controlled*
- Gain = 1 (Proportional Band = 100%)
- Reset (Integral) = *minimum effect = 100+ minutes/repeat = 0 repeats/minute*
- Rate (Derivative) = *minimum effect = 0 minutes*

Check to see that the controller is able to function in automatic mode (regulating the process variable as you adjust the setpoint value). Now, you are set to experiment with the effect of different "gain" values in the PID algorithm. You may access the "gain" parameter by entering the controller's *tuning* function.

Try setting the "gain" value to a number significantly less than 1, then changing the setpoint (SP) value several times to observe the system's response. If you have a data acquisition (DAQ) unit connected to measure controller PV and output signal values, note the relationship between the two graphs plotted on the computer display following each setpoint change.

Now try setting the "gain" value to a number significantly greater than 1, changing the setpoint value again and again to observe the system's response.

Answer the following questions:

- Which gain settings result in the swiftest PV response to SP changes?

- Which gain settings result in the most sluggish PV response to SP changes?

- Are there any gain setting values that result in *oscillation* of the PV?

- Do you notice any *proportional-only offset*?

- Determine the "optimal" gain setting for your process resulting in swift response and minimum offset without too much oscillation.

- Generalizing to all proportional controllers, explain the effect of decreasing the controller gain value further and further.
- Generalizing to all proportional controllers, explain the effect of increasing the controller gain value further and further.

file i04263

Question 6

Configure the controller as follows (for "proportional-only" control). If you are using PID simulation software instead of a real physical process, select a process that is self-regulating with minimal noise or load changes:

- Control action = *appropriate for the process being controlled*
- Gain = *set to whatever value yields optimal control*
- Reset (Integral) = *minimum effect = 100+ minutes/repeat = 0 repeats/minute*
- Rate (Derivative) = *minimum effect = 0 minutes*

After determining the "ideal" gain setting value for your process controller yielding the swiftest possible response to setpoint changes without oscillation, place the controller in manual mode and adjust the output until the process variable is approximately 50%. Now, place the controller back into automatic mode. Thanks to the "setpoint tracking" feature programmed into most digital electronic controllers, the SP should be precisely equal to the PV (i.e. no error).

Now, increase the setpoint by 10% and watch closely to observe the new value that the process variable settles at. Does this new PV value exactly match the new SP value? Try increasing the SP by 10% again and re-observe the PV's new value once it settles. Is the error greater or less than before?

Explain how *proportional-only offset* (otherwise known as "droop") accounts for the error you are seeing in this experiment.

Try demonstrating proportional-only offset by moving the SP to values less than original (below 50%). How does the amount of offset compare to the offset exhibited with higher SP values?

Suggestions for Socratic discussion

- Do your best to explain to your teammates *why* an offset develops between PV and SP in a proportional-only controller.
- Explain why proportional-only offset is a concern to us at all. Can you think of an application where such offset would be intolerable? Can you think of an application where it would not matter at all?

file i04285

Question 7

Configure the controller as follows (for "proportional-only" control). If you are using PID simulation software instead of a real physical process, select a process that is self-regulating with minimal noise or load changes:

- Control action = *appropriate for the process being controlled*
- Gain = *set to whatever value yields optimal control*
- Reset (Integral) = *minimum effect = 100+ minutes/repeat = 0 repeats/minute*
- Rate (Derivative) = *minimum effect = 0 minutes*

You will now purposely create a condition of proportional-only offset. I recommend switching the controller to manual mode, adjusting the output until a low value for process variable (PV) is reached, then switching back to automatic mode and adjusting the setpoint (SP) toward the top end of the scale. The PV should exhibit offset (inability to equal SP) due to proportional action.

Once the controller is exhibiting a significant amount of offset, practice using the controller's "manual" mode to eliminate the offset. For example, if the SP is 70% and the PV is 63% in automatic mode, switch to manual mode and manually adjust the output to get the PV equal to 70% (the desired value) then switch back to automatic mode.

After eliminating offset, move the SP to some new value to re-create an offset again and practice using manual mode to eliminate the offset once more.

Explain how the common feature of *setpoint tracking* programmed into the controller helps you in your task of manually eliminating offset.

Suggestions for Socratic discussion

- Explain how the feature of *output tracking* is also seen at work in your controller during this exercise.

  file i04286

Question 8

Configure the controller as follows (for "proportional-only" control). If you are using PID simulation software instead of a real physical process, select a process that is self-regulating with minimal noise or load changes:

- Control action = *appropriate for the process being controlled*
- Gain = *set to whatever value yields optimal control*
- Reset (Integral) = *minimum effect = 100+ minutes/repeat = 0 repeats/minute*
- Rate (Derivative) = *minimum effect = 0 minutes*

In this exercise, you will experiment with the effect of different controller gain (proportional band) settings on the amount of proportional-only offset developed.

First, place the controller in manual mode and check to see all the tuning parameters (gain, reset, and rate) have been set properly. While still in manual mode, adjust the output until the process variable is approximately 50%. Now, place the controller back into automatic mode. Thanks to the "setpoint tracking" feature programmed into most digital electronic controllers, the SP should be precisely equal to the PV (i.e. no error). Increase the setpoint by 10% and note how much proportional-only offset develops.

Switch to manual mode and decrease the controller's gain setting (increase the proportional band) by a factor of two, then adjust the output to once again stabilize the process variable at approximately 50%. Switch to automatic mode and increase the setpoint by 10%, watching closely to observe the new value that the process variable settles at. Note the amount of proportional-only offset exhibited by the controller.

Switch to manual mode and decrease the controller's gain setting (increase the proportional band) once again by a factor of two, then adjust the output to once again stabilize the process variable at approximately 50%. Switch to automatic mode and increase the setpoint by 10%, watching closely to observe the new value that the process variable settles at. Note the amount of proportional-only offset exhibited by the controller.

Do you see any relationship between the amount of gain programmed into the proportional-only controller versus the amount of proportional-only offset experienced?

Suggestions for Socratic discussion

- Explain how to convert between "gain" and "proportional band" values.

  file i04287

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Question 9

In their seminal 1942 paper *Optimum Settings for Automatic Controllers*, J.G. Ziegler and N.B. Nichols describe the compromise that must be struck when adjusting the gain ("sensitivity") of a controller having only proportional action:

"The rational adjustment of proportional-response sensitivity is then simply a matter of balancing the two evils of offset and amplitude ratio." (page 761)

Ziegler and Nichols used the phrase "amplitude ratio" to describe the severity of oscillations following a sudden change in setpoint or load. The "amplitude ratio" of an oscillation was a measure of each successive peak's height compared to the previous peak. A large amplitude ratio therefore referred to oscillations requiring many cycles to dampen, while a small amplitude ratio referred to oscillations dampening in very short order.

Describe this balancing act between the "two evils" of offset and oscillation while adjusting the gain setting on a process controller, making reference to your own experiences of adjusting gain settings on process controllers.

| Suggestions for Socratic discussion |

- Being that the solution to proportional-only offset is to use *integral* action in the loop controller in addition to proportional action, why do you suppose Ziegler and Nichols even bothered to suggest finding a compromise between low gain and high gain? Why not just suggest the use of integral action as a universal solution for the "two evils" of offset and amplitude ratio?

  file i04288

One of the simplest linear operational amplifier circuit is the *voltage follower*, so-called because the output voltage very closely "follows" the input voltage within the opamp's operating range:

Voltage follower circuit
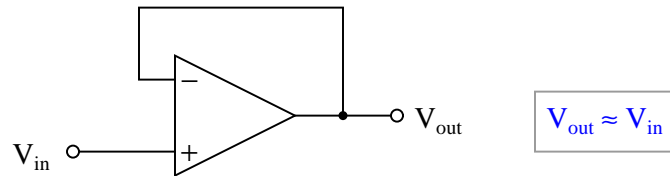
$$V_{out} \approx V_{in}$$

This approximation is so good that it is all but forgotten by most technicians, and most simply treat the circuit's behavior as $V_{out} = V_{in}$. In actuality, though, there will always be a slight difference between the input and output voltages. The difference is not difficult to calculate. Suppose we have a perfect operational amplifier (zero noise, no offset voltage, no input bias current) with an internal (differential) voltage gain of 50,000:
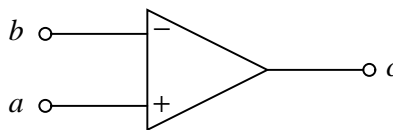
Labeling the input and output terminal voltages (with reference to ground, of course) as the variables a, b, and c, we have a transfer function for the opamp that looks like this:

$$c = 50,000(a - b)$$

If we connect the output of the opamp to its inverting input for negative feedback, we eliminate one of the variables from the equation because now the output terminal and the $(-)$ input terminal are electrically common:
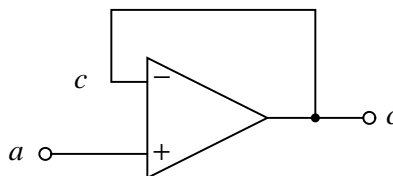
$$c = 50,000(a - c)$$

Solve for the output voltage of this voltage follower circuit (c) when the input voltage (a) is exactly 5 volts, and explain why the output and input voltages are not precisely equal. Then solve for the output voltage when the input voltage is exactly 5 volts and the opamp's gain is only 20,000 instead of 50,000.

Suggestions for Socratic discussion

- In general terms, would you say negative feedback *increases* or *decreases* the overall gain of an amplifier system?
- What do you suppose would happen if we configured the operational amplifier for *positive* feedback instead of negative feedback? How would it behave then?

file i01585

Shown here is a simple flow control system for distributing water from an irrigation reservoir to a crop field at a controlled flow rate. The flowmeter is ranged from 0 to 300 gallons per minute:
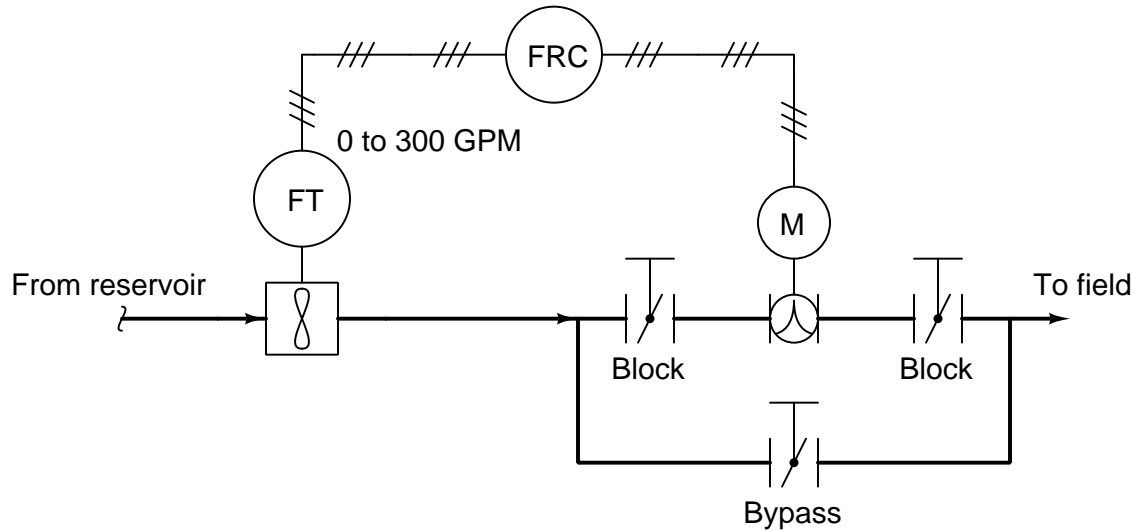
The flow-recording controller (FRC) is a proportional-only unit with the following algorithm:

$$m = K_p(\text{SP} - \text{PV}) + 50\%$$

Where,

m = Manipulated variable (output)

K_p = Controller gain

SP = Setpoint

PV = Process Variable (water flow)

One day the controller is found to be working perfectly: the setpoint is set to 180 GPM, and the process variable reads exactly the same: 180 GPM. The controller's output is seen to be 50% in this condition. Then, the operator adjusts the setpoint to a new flow rate: 250 GPM. As expected, the controller's output automatically increases and the valve opens up to allow more flow through the pipe. As the flow rate approaches the new setpoint of 250 GPM, the valve begins to close off. This makes the flow rate approach setpoint slower and slower, like a capacitor slowly charging to a new voltage value over time. However, the operator notices something unexpected: the flow rate never makes it all the way to the new setpoint value of 250 GPM. Instead, it stabilizes at about 239 GPM and does not increase beyond that.

Confused as to why the controller does not reach the new setpoint of 250 GPM like it did the old setpoint of 180 GPM, the operator calls an instrument technician to investigate. "What is wrong with this controller?" the operator asks the technician. "It stops increasing the flow rate shy of its new setpoint." After a moment of investigation, the technician notices that this is a proportional-only controller. Seeing this, the technician just smiles and proceeds to explain to the operator why the controller *never will* reach the new setpoint like it did at 180 GPM. For that matter, it cannot perfectly reach any setpoint less than 180 GPM either! If it perfectly attained setpoint at 180 GPM, then that is the *only* setpoint value it will.

Explain, in your own words, why this is true.

file i01584

Question 12

The following water heater process is automated with a pneumatic temperature transmitter, controller, and control valve:
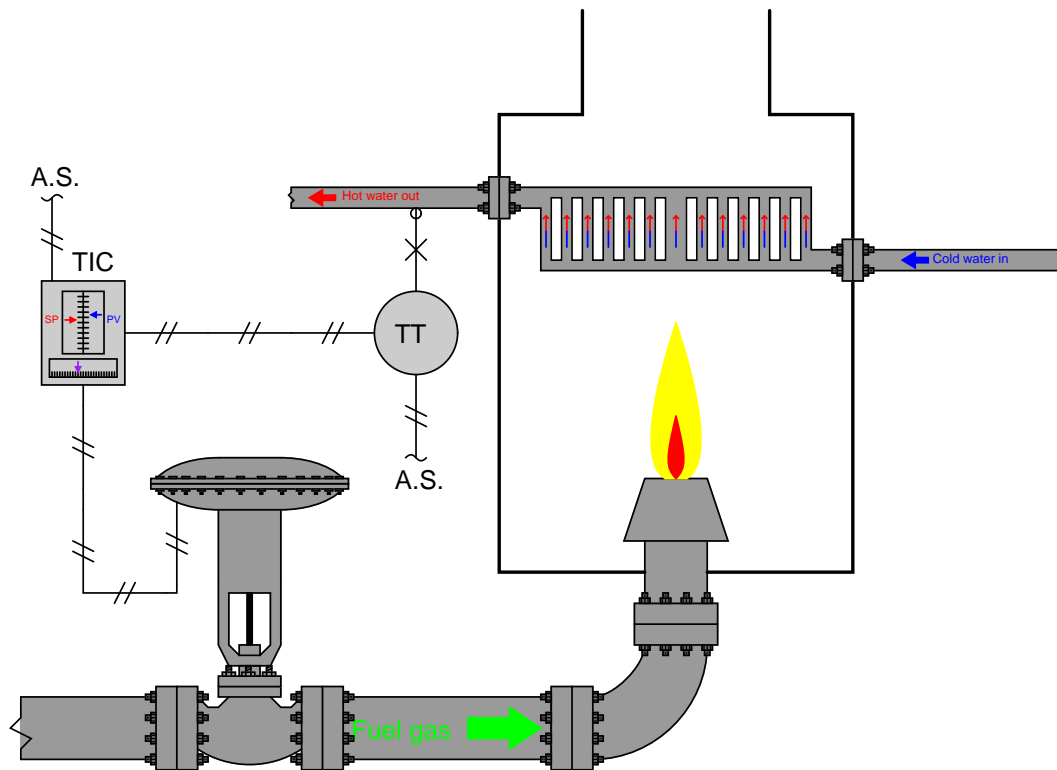
The process variable (PV), setpoint (SP), and output signals (manipulated variable, or MV) of the controller are recorded in a table at random time intervals:

PV (Process Variable)	SP (Setpoint)	MV (Output)
50%	50%	50%
45%	50%	55%
30%	50%	70%
25%	50%	75%
65%	50%	35%
72%	50%	28%
50%	40%	40%
50%	71%	71%
80%	65%	35%
37%	42%	55%
40%	30%	40%

Develop a mathematical expression describing the data you see here in the table. Hint: it may be easier if you begin with a *qualitative* assessment of the figures (i.e. *"when the PV exceeds the SP, the MV . . ."*).

file i01460

Question 13

Digital proportional controllers generate their output signal values using a microprocessor to repeatedly evaluate the proportional equation:

$$m = K_p e + b$$

What would happen if a *negative* value were entered for gain (K_p) into the digital controller's program?
file i01467

Question 14

Suppose that a reverse-acting, proportional-only controller has a gain (K_p) setting of 2 and a bias (b) setting of 40%. What will its output be for the following input conditions?

- PV = 37%; SP = 50%; Output = _____

- PV = 92%; SP = 80%; Output = _____

- PV = 81%; SP = 75%; Output = _____

- PV = 33%; SP = 42%; Output = _____

- PV = 79%; SP = 76%; Output = _____

- PV = 15%; SP = 20%; Output = _____

- PV = 38%; SP = 38%; Output = _____

- PV = 0%; SP = 0%; Output = _____

file i01489

Question 15

A useful operational amplifier circuit is the *voltage follower*, so-called because the output voltage very closely "follows" the input voltage within the opamp's operating range. This particular follower circuit includes a power transistor for additional current-sourcing capability to the load:

Voltage follower circuit
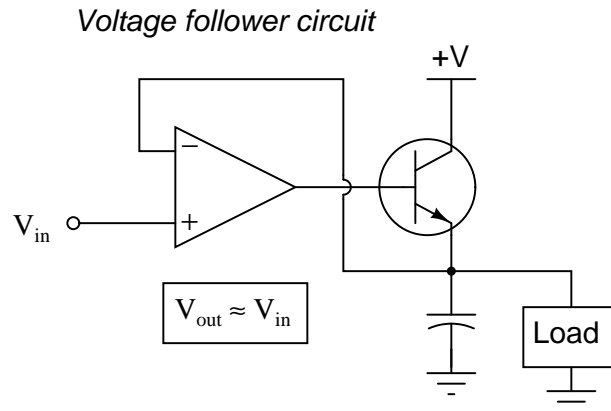
From an instrumentation point of view, the operational amplifier acts like a very high-gain proportional-only controller. Looking at this circuit, we see that the opamp's job is to drive the base of the power transistor sufficient to make the load voltage approximately equal to whatever signal voltage we apply at the noninverting (+) input. In other words, the opamp's output is the *output* of the controller (m), the inverting input is the *process variable* (PV, because it senses the voltage delivered to the load), and the noninverting input is the *setpoint* (SP, because it sets the target value for load voltage):
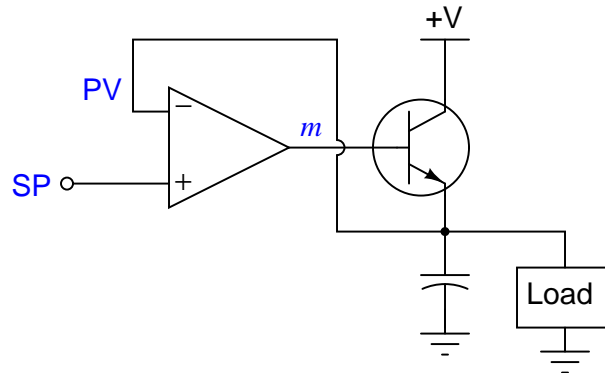
Like all proportional-only control systems, this voltage follower circuit exhibits something called *proportional-only offset*. This means that the process variable usually stabilizes at a value near the setpoint value, but it is almost never *exactly equal* to the setpoint value, no matter how much gain the controller has.

Explain why perfect control (PV = SP) is unattainable for proportional-only control systems, just as a perfect condition of $V_{out} = V_{in}$ is unattainable for this operational amplifier circuit.

file i01586

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Question 16

Some electronic controllers provide the option of a *time-proportioning* output instead of the customary *current-proportioning* output. With the time-proportioning output, the two output terminals of the controller connect (internally) to a relay contact or transistor, capable only of turning an electrical load fully on and fully off:
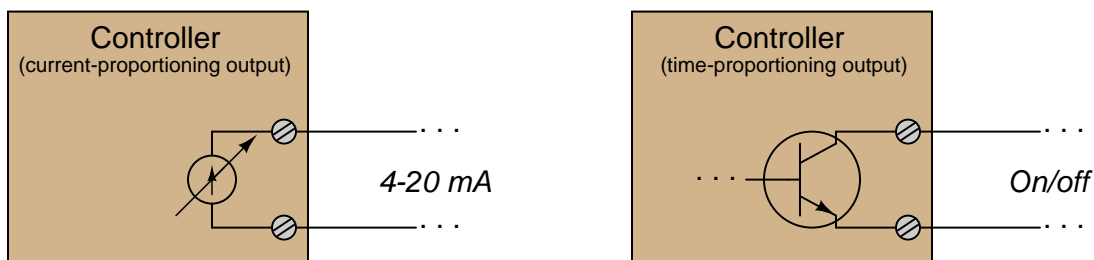
Time-proportional control is most often used when the final control element is an electric heater. Explain how time-proportional control works to maintain a process variable at setpoint while only being able to turn a heater on and off (and not in-between).

file i01487

Question 17

Imagine a scenario where we are measuring municipal water flow through a pipe, using a turbine meter:
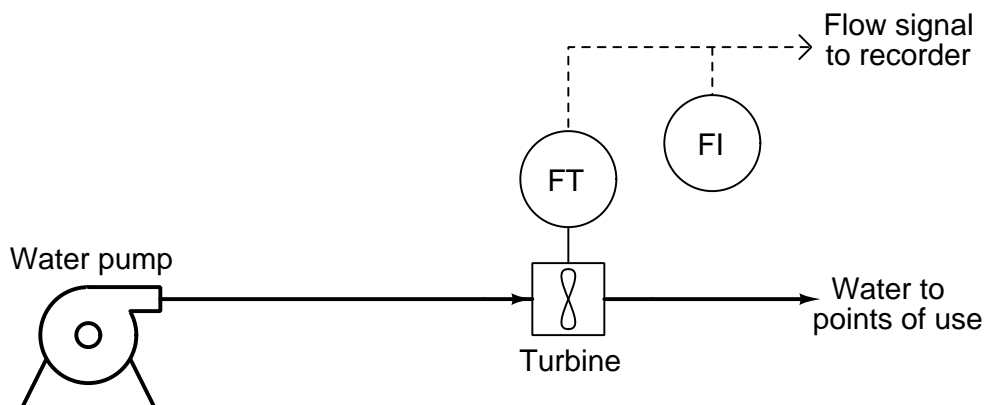
Suppose the municipality management decides they need a running total of water *volume* as well as water flow. In other words, they want a counter that tallies up the number of gallons passed through this flowmeter. An operator will record this total volume at the end of every day and then re-set the counter for the next day's tally.

Two instrument technicians have different ideas about how to do this. One technician says it would be easy to electronically *integrate* the 4-20 mA flow signal to obtain a volume signal, while the other technician advocates a scheme to directly intercept the turbine's "pick-up" unit signal rather than the 4-20 mA flow signal and send that pulse signal to a digital counter.

Elaborate on these two technicians' plans, and then cast your own vote either for one of these plans or for an entirely different idea.

file i00543

Question 18

Question 19

Question 20

Question 21

Read and outline the "Integral (Reset) Control" section of the "Closed-Loop Control" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

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

Further exploration . . . (optional)

The now-famous paper on PID controller tuning written by Ziegler and Nichols in 1942 contains many useful insights into behavior of the basic PID control algrithm. Here is one of them:

> In most controllers using automatic reset, some adjustment of the reset rate is provided, though continuous adjustment appears in only a few. In one, the reset rate is adjustable from zero to 20 per min. In order to determine reset rates on an instrument without a calibrated dial, it is only necessary to move the pen away from the set pointer far enough to cause a 1 psi output change and note the additional output-pressure change per minute. The same value can be put on the reset adjustment in controllers other than those of the air-operated type, by making a sustained pen change from the set point, noting the altered valve position which results from proportional response and the additional travel at the end of 1 min from automatic reset. The reset rate is the travel from reset divided by the travel from proportional.

Expressing the meaning of this passage in your own words. What are Ziegler and Nichols trying to say here? What does this suggest about the pneumatic PID controllers of their era? Do you suspect this same procedure might work on a modern electronic controller?

file i04284

Question 22

Calculate the output voltage rate-of-change (volts per second) of this controller circuit if the PV signal is 3.0 volts and the SP signal is 2.5 volts, assuming the potentiometer is set for maximum resistance. Also calculate the "time constant" value of τ for this circuit at this same potentiometer position:
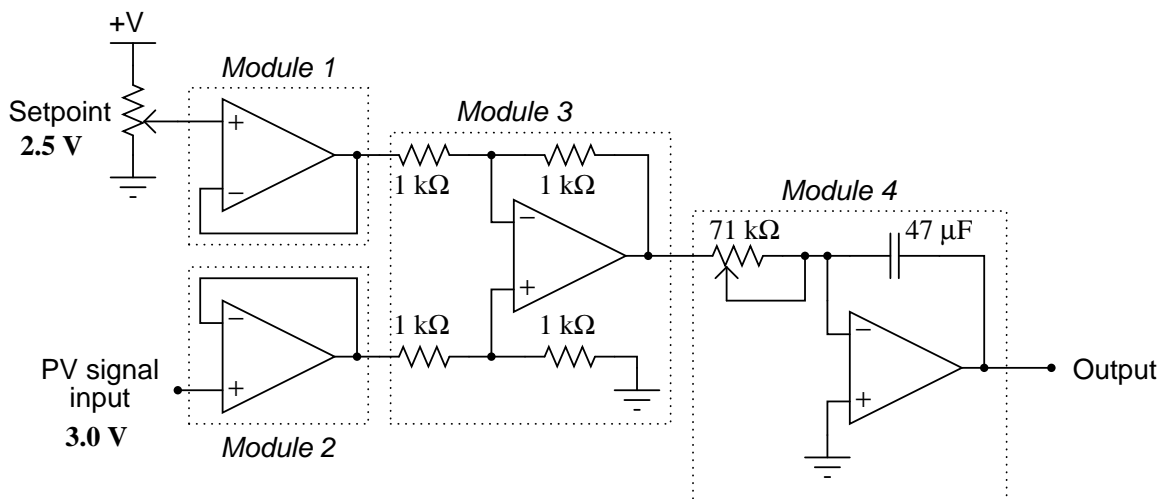
Next, calculate the amount of time it takes for the output to change by 0.5 volts (the same amount as the difference between PV and SP) when the potentiometer is exactly at the half-way position. How does this time figure compare with the new value for τ at this pot position?

Suggestions for Socratic discussion

- Identify a way to shorten the integration time constant of this controller without adjusting the 71 kΩ potentiometer located in module 4.
- Identify a way to shorten the integration time constant without changing anything at all in module 4.
- Identify the action (direct or reverse) of this controller, and then identify what you would have to alter in the circuit to reverse that action.

file i01589

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Question 23

Suppose an integral-only (I-only) loop controller receives a process variable signal of 44%, a setpoint value of 50%, and is configured for reverse action. Assuming an integral coefficient of 1.6 repeats per minute and a constant error (i.e. PV and SP both remain constant over time), calculate the amount of time required for the output of this controller to change by 10%. Also, calculate how long it will take for the output to change by the same amount as the error (PV − SP).

Suggestions for Socratic discussion

- A useful problem-solving technique for calculus-based problems is to sketch a graph of the variables being considered. The *derivative* of a function is the slope of the graph, while the *integral* of a function is the area bound by the graph. Apply this problem-solving technique to the problem at hand in this question.
- In a real process, will the error hold constant as we are assuming it does in this question? Why or why not?
- Express the integration rate of this controller in units of *minutes per repeat*.
- Express the integration rate of this controller in units of *seconds per repeat*.
- Express the integration rate of this controller in units of *repeats per second*.

file i01583

Question 24

This is a simple rate-of-change detector circuit, designed to produce an alarm if the input signal rate-of-change becomes excessive:
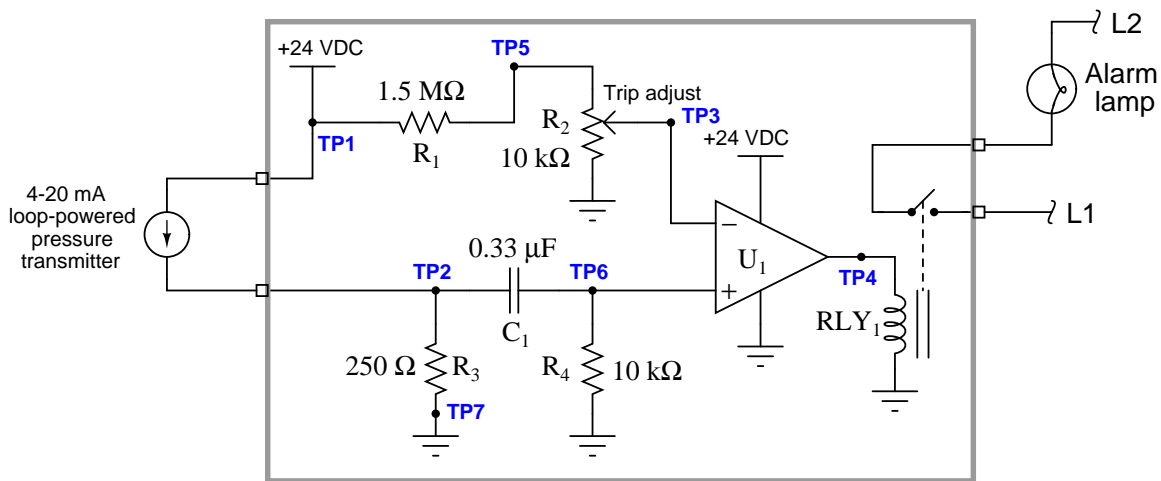
Unfortunately, though, this circuit has a problem. The alarm light always stays on, even when the pressure is known to be steady. Your first diagnostic measurement is DC voltage between TP2 and TP7: there you measure a steady value of 2.39 volts. Your next diagnostic measurement is between TP4 and TP7: there you measure 23.1 volts.

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
C_1 failed open		●
R_1 failed open	?	
R_3 failed open		●
R_4 failed open	●	
C_1 failed shorted	●	
R_1 failed shorted		●
R_3 failed shorted		●
R_4 failed shorted		●
RLY_1 coil failed open		●
U_1 output failed to low supply rail		●
U_1 output failed to high supply rail	●	

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 |

- Explain how this circuit is supposed to sense the *rate* at which the measured variable (pressure) changes, as opposed to simply sensing the magnitude of that variable at any given time.
- Identify the effects of resistor R_1 failing open.
- Identify the effects of resistor R_3 failing open.
- Identify the effects of resistor R_4 failing open.

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- Identify the effects of the relay coil failing open.
- Explain how electrical "noise" in the transmitter's signal could cause false alarms.

file i01868

Question 25

$\boxed{\text{Desktop Process exercise}}$

Configure the controller as follows:

- Control action = *appropriate for the process being controlled*
- Gain = 1 (100% proportional band)
- Reset (Integral) = *0.1 minutes/repeat = 10 repeats/minute*
- Rate (Derivative) = *minimum effect = 0 minutes*

In this exercise you will watch the action of integral in your controller as it attempts to eliminate a persistent error (difference between PV and SP). Follow these steps in order:

1. Place controller in manual mode, with the output at 0%

2. Disconnect electrical power from the motor so it cannot spin

3. Switch controller to automatic mode

4. Raise setpoint value to 10%

5. Observe what the controller's output value does in automatic mode

6. Lower setpoint value to 0%

7. Observe what the controller's output value does in automatic mode

Feel free to experiment with different errors (values other than 10%) and different repeat/minute values to see what effect these parameters have on the controller's integration.

$\boxed{\text{Suggestions for Socratic discussion}}$

- Identify which units your controller uses to express integral action: minutes per repeat, repeats per minutes, or something else?
- Identify and explain in your own words what factor(s) influence the speed at which the controller output integrates.

file i01810

Question 26

Configure the controller as follows (for "proportional-only" control). If you are using PID simulation software instead of a real physical process, select a process that is self-regulating with minimal noise or load changes:

- Control action = *appropriate for the process being controlled*
- Gain = *one-quarter the value yielding optimal control = four times the proportional band value yielding optimal control*
- Reset (Integral) = *minimum effect = 100+ minutes/repeat = 0 repeats/minute*
- Rate (Derivative) = *minimum effect = 0 minutes*

In this exercise you will purposely establish a large proportional-only offset, then introduce reset (integral) action to correct this offset. I recommend switching the controller to manual mode, adjusting the output until a low value for process variable (PV) is reached, then switching back to automatic mode and adjusting the setpoint (SP) toward the top end of the scale. The PV should exhibit offset (inability to equal SP) due to proportional action.

Once the controller is exhibiting a significant amount of offset, adjust the controller's reset (integral) setting to a value of 1 repeat per minute (equal to 1 minute per repeat). Observe the controller's output value carefully as integral action begins to compensate for the offset. Once the controller has finally eliminated offset between PV and SP, feel free to change the setpoint value to create another offset and then observe integral action at work once again.

Explain in your own words what the controller's integral action is doing to eliminate the "offset" that proportional action can never completely eliminate.

- If you desired a swifter integral response from the loop controller, what could you alter in this system to make the integral action respond more aggressively?

  file i04289

Question 27

Configure the controller as follows. If you are using PID simulation software instead of a real physical process, select a process that is self-regulating with minimal noise or load changes:

- Control action = *appropriate for the process being controlled*
- Gain = *one-tenth the value yielding optimal control = ten times the proportional band value yielding optimal control*
- Reset (Integral) = *1 minute/repeat = 1 repeat/minute*
- Rate (Derivative) = *minimum effect = 0 minutes*

Use the controller's manual mode to establish the process variable at approximately 50%, then switch to automatic mode. Make a sudden setpoint adjustment (at least 10%, in either direction) and observe the controller's *slow* integral-action response to this change.

Try increasing the "aggressiveness" of the integral action (i.e. more repeats per minute, or fewer minutes per repeat) until a more satisfactory control response is seen from the controller. Without adjusting the controller's gain (proportional action), experiment with different integral settings until good control response is seen with large setpoint changes. Your goal is to achieve a quality of control that eliminates offset quickly while minimizing "overshoot" and oscillation of the process variable.

Suggestions for Socratic discussion

- Explain in your own words why more "repeats per minute" yields a more aggressive integral response, and why more "minutes per repeat" yields a tamer integral response.

  file i04290

Question 28

Desktop Process exercise

Configure the controller as follows:

- Control action = *appropriate for the process being controlled*
- Gain = *very low = very large proportional band value*
- Reset (Integral) = *set to whatever value yields optimal control*
- Rate (Derivative) = *minimum effect = 0 minutes*

Get the process into a condition where the PV is holding at approximately 50% in automatic mode, then turn off the electric power to the final control element (e.g. the power to the motor drive). Observe the response of the controller's output to the sudden change in PV. Describe what you see here in terms of *integral windup*.

After the controller's output has "wound up" in response to the halted process, turn the power back on to the final control element and observe the control response. Does the PV immediately settle at its proper setpoint value? Is there "overshoot" or "undershoot" of the PV in relation to SP following the power-up? Determine whether or not changes in the reset (integral) setting will improve the quality of control following a power outage.

Suggestions for Socratic discussion

- Will the controller's integral action "wind up" while in manual mode? Explain why or why not.

  file i04291

Question 29

Tune the controller in your Desktop Process first using proportional action only (reset and rate settings at minimum effect), testing the control quality by observing the graph produced by the data acquisition software. Your goal is quick response to setpoint changes with minimal oscillation of the PV. If you are using PID simulation software instead of a real physical process, select a process that is self-regulating with minimal noise or load changes.

After determining a reasonable value for the controller's gain setting, incorporate some reset (integral) action in order to eliminate offset following a setpoint or load change. Once again, your goal is quick response with minimal oscillation and overshoot of the PV.

Record these gain and reset settings for future use.

file i04292

Question 30

A human operator is charged with controlling the temperature of water in a gas-fired water heater. The "setpoint" (SP) is an ideal water temperature value held in the operator's mind, and the "process variable" (PV) of course is whatever the temperature gauge indicates:
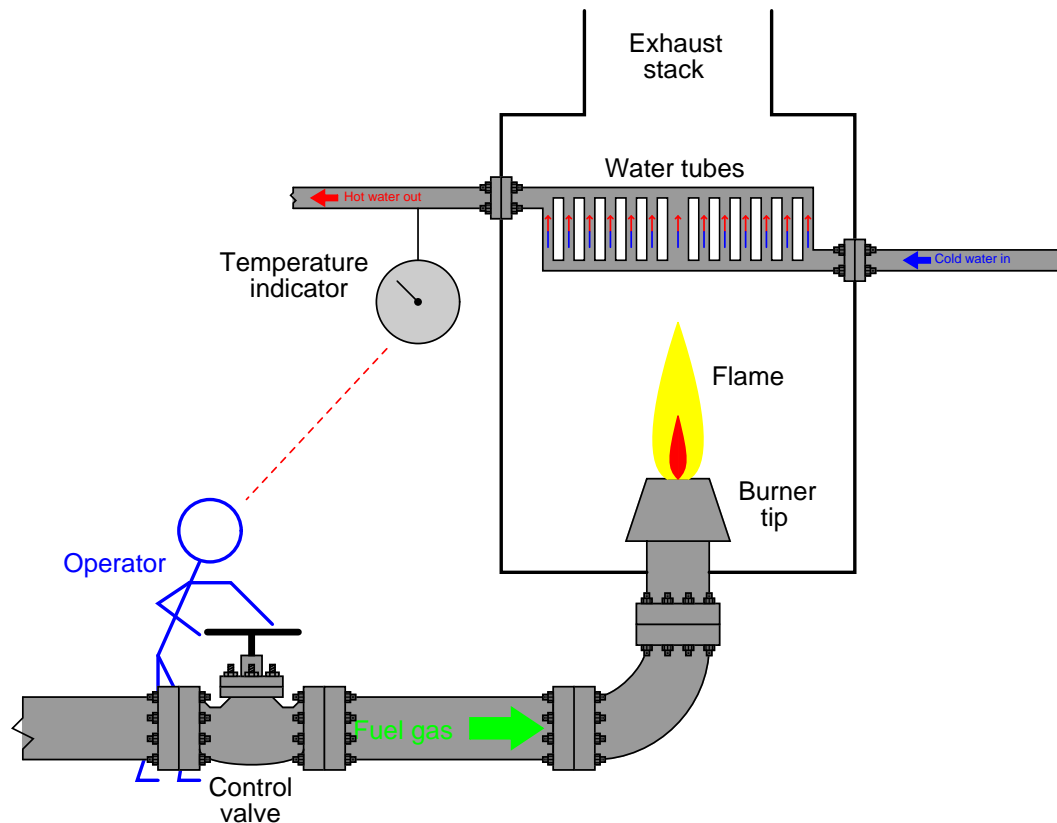
Imagine a situation where the water temperature is exactly at setpoint. The operator is standing next to the gas control valve, bored, because there is nothing to do. Then suddenly there is a demand for more hot water. As the water flow through the heater increases, the outlet temperature begins to fall. Noticing this decrease in PV, the operator opens the fuel valve by a proportional amount. This causes the temperature to slowly climb back up to setpoint. At some point in time, though, the water temperature settles at an equilibrium value that is less than setpoint. The operator recognizes this and begins to become impatient, opening the valve a little bit more with each minute of time that goes by. Eventually, after several additional "opening" motions of the valve, the water temperature rises to the setpoint value and stabilizes there. Happy with the new situation, the operator resumes his previous condition of boredom.

Now let us examine the operator's action in terms of how an automatic controller would handle the situation. The operator's initial response to open the valve proportional to the amount of temperature decrease can be easily accounted for by *proportional* control action – the name reveals it all. But the operator's actions after noticing the PV settling at a temperature less than setpoint – when he begins to feel impatient and opens the valve a little more each minute – is definitely not characteristic of proportional control. In fact, this action goes *against* what proportional control would do, by continuing to *increase* the valve's opening little by little even as temperature continues to *rise* to setpoint.

What the operator did was to examine how much error there was left between SP and PV, and also how long this condition of error persisted, and move the control valve accordingly. Explain how the operator's action in doing this could be described as *integration* in the calculus sense of the word.

Question 31

We know that the output rate-of-change of an integrator circuit is proportional to the input voltage:
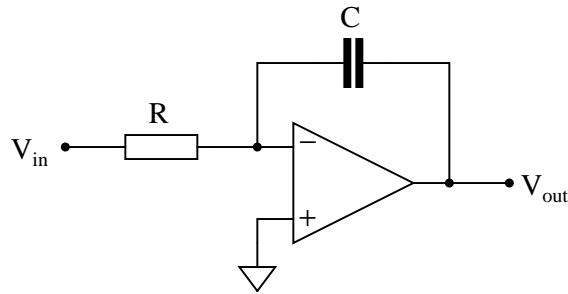
$$V_{in} \propto \frac{dV_{out}}{dt}$$

But how do we turn this proportionality into an exact equality, so that it accounts for the values of R and C? Although the answer to this question is easy enough to simply look up in an electronics reference book, it would be great to actually derive the exact equation from your knowledge of electronic component behaviors! Here are a couple of hints:

$$I = \frac{V}{R} \qquad i = C\frac{dv}{dt}$$

file i01567

Question 32

Some instrument technicians find it helpful to think of the integral tuning constant (τ_i) as the measure of *impatience* within a controller. What is meant by this analogy? On the same line of thought, is aggressive integral action more desirable for controlling inherently fast-responding processes, or inherently slow-responding processes?

file i01611

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Question 33

Describe what the output voltage of this operational amplifier circuit will do with a constant input voltage of +2 volts:
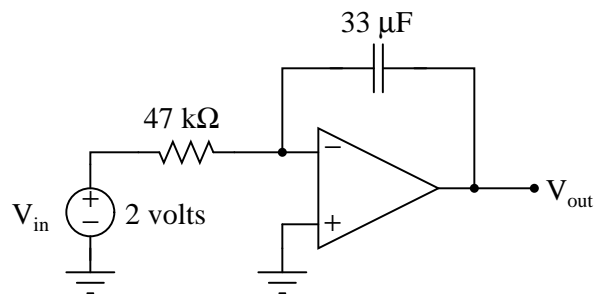
Be as specific as you can in your answer!

Suggestions for Socratic discussion

- A useful problem-solving technique for calculus-based problems is to sketch a graph of the variables being considered. The *derivative* of a function is the slope of the graph, while the *integral* of a function is the area bound by the graph. Apply this problem-solving technique to the problem at hand in this question.

file i01576

Question 34

The *integral* function appears in a variety of physical systems encountered in process measurement and control applications. One such application is liquid flow. Shown here is a liquid-holding vessel equipped with a vortex flow indicator for measuring incoming liquid flow and a level indicator for measuring liquid volume accumulating in the vessel:
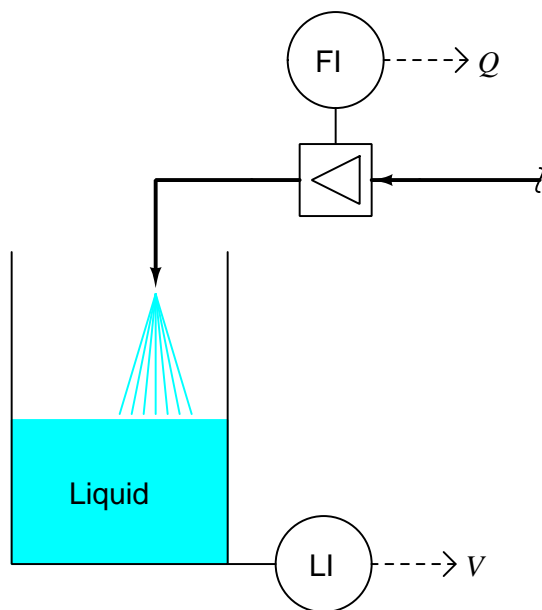
If you were to graph both the liquid flow rate (Q) and the liquid volume (V) accumulated in the vessel over time, which of these two variables would be the *integral* of the other with respect to time? How would you write this in mathematical form, as a calculus expression?

Suggestions for Socratic discussion

- A useful problem-solving technique for calculus-based problems is to sketch a graph of the variables being considered. The *derivative* of a function is the slope of the graph, while the *integral* of a function is the area bound by the graph. Apply this problem-solving technique to the problem at hand in this question.

file i01578

Question 35

Determine the value of the specified *integral* for this function:
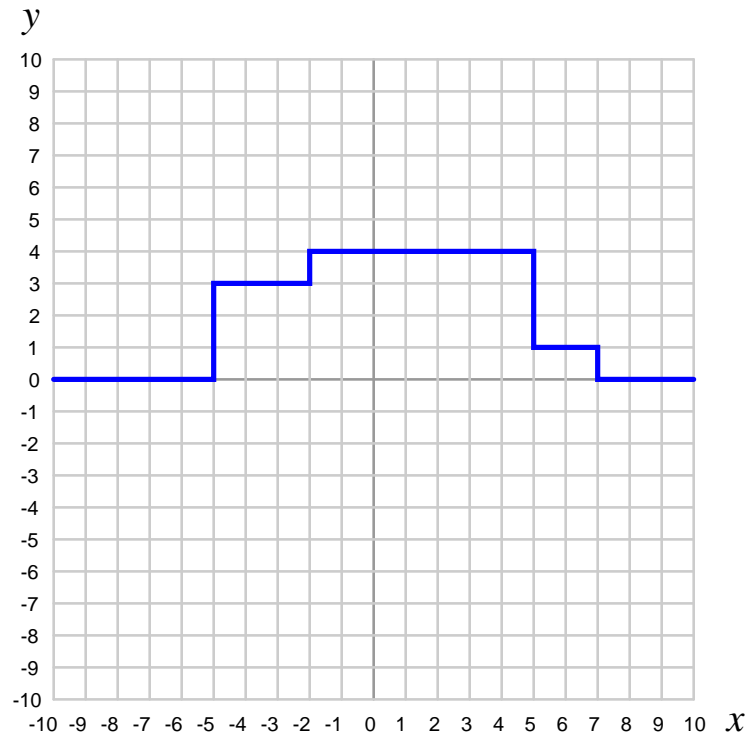
$$\int_0^{+4} f(x)\, dx$$

Determine the value of the specified *integral* for this function:
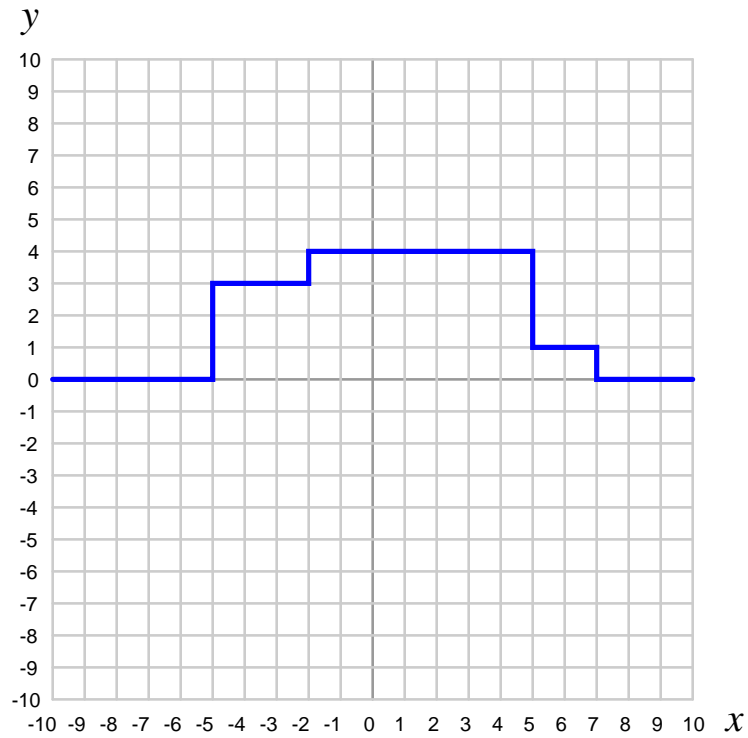
$$\int_{-5}^{-2} f(x)\, dx$$

file i03283

Determine the value of the specified *integral* for this function:
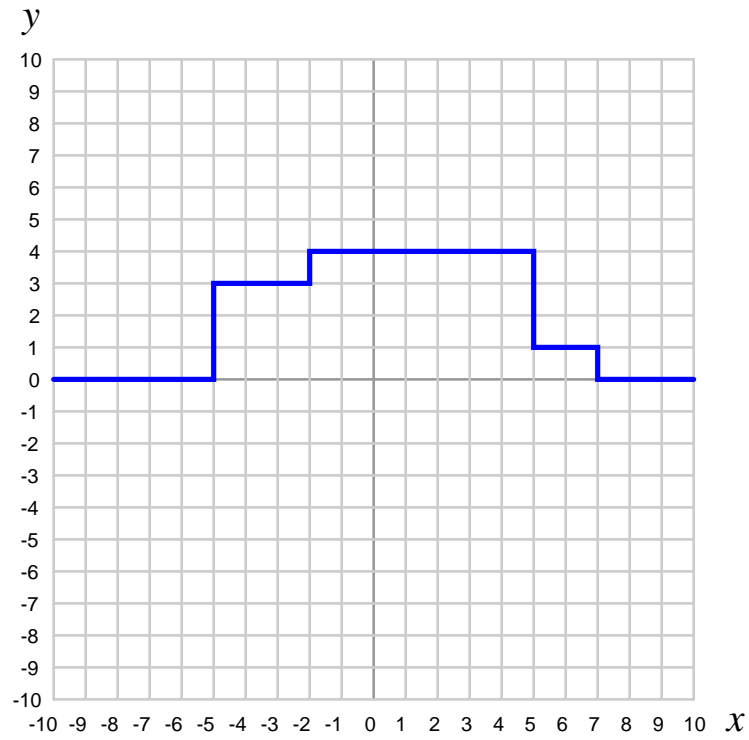
$$\int_5^4 f(x)\, dx$$

file i04425

Question 38

Some processes may be controlled by an automatic controller only having *integral* control action. Here is a schematic diagram of one such controller:
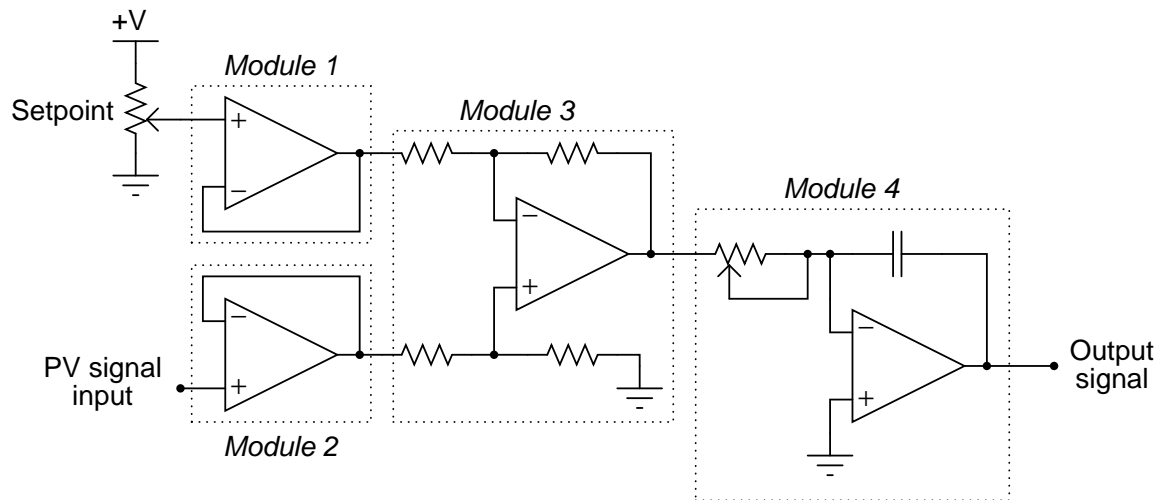
Examine this schematic diagram and then answer the following questions about it:

- Show where "error" is calculated in the circuit
- Determine whether this is a direct-acting controller or a reverse-acting controller
- Identify how to *decrease* the integration time constant (τ_i); i.e. how to *increase* the aggressiveness of integral action

Suggestions for Socratic discussion

- If used to control a real process, would this controller suffer from *offset* like a proportional-only controller would? Explain why or why not?
- Identify the effects of the feedback wire in module 2 failing open.
- Identify the effects of the lower-left resistor in module 3 failing open.
- Identify the effects of the upper-left resistor in module 3 failing open.
- Identify the effects of the lower-right resistor in module 3 failing open.
- Identify the effects of the upper-right resistor in module 3 failing open.
- Identify the effects of the capacitor in module 4 failing shorted.

file i01588

Question 39

Question 40

53

Question 41

Integral control action is usually combined with proportional control action in a process controller. Contrast these two modes of control in the simplest terms possible.

- A good practice when learning new concepts is to imagine yourself having to explain those concepts to an intelligent child, forcing yourself to express the new ideas in the simplest and clearest terms possible. Explain why this is a good practice to cultivate, especially after you are out of school and in the workplace!

file i01591

Question 42

Qualitatively graph the response of a proportional-only controller over time to the following changes in process variable:
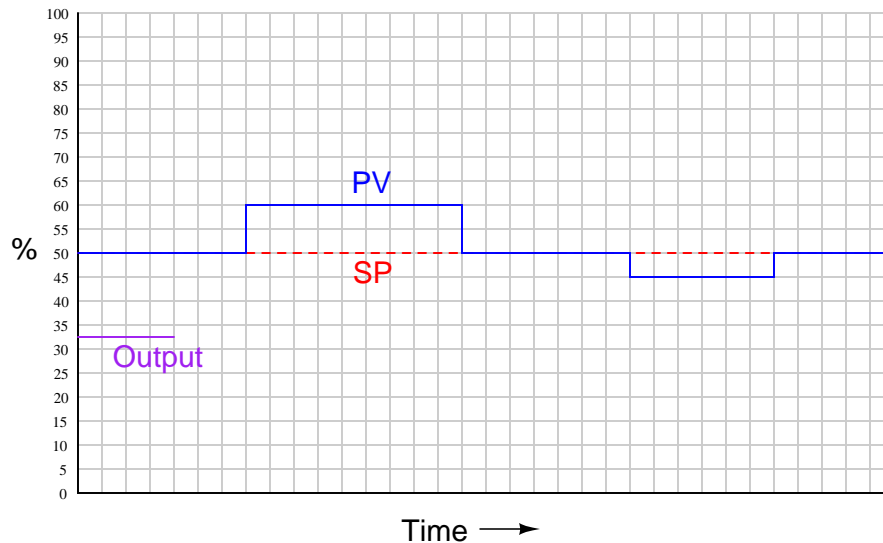
Assume *reverse* control action.

- What defines a "reverse" acting controller, in contrast to a "direct" acting controller?
- Explain why it would be highly unusual to see a trend like this in a real, working process loop. Why is this trend unrealistic, assuming a working process where all components are functioning properly?
- Given that this trend is unrealistic, why is it something we're studying? In other words, what value does a "toy" trend like this have for us?

file i01593

Question 43

Qualitatively graph the response of an integral-only controller over time to the following changes in process variable:
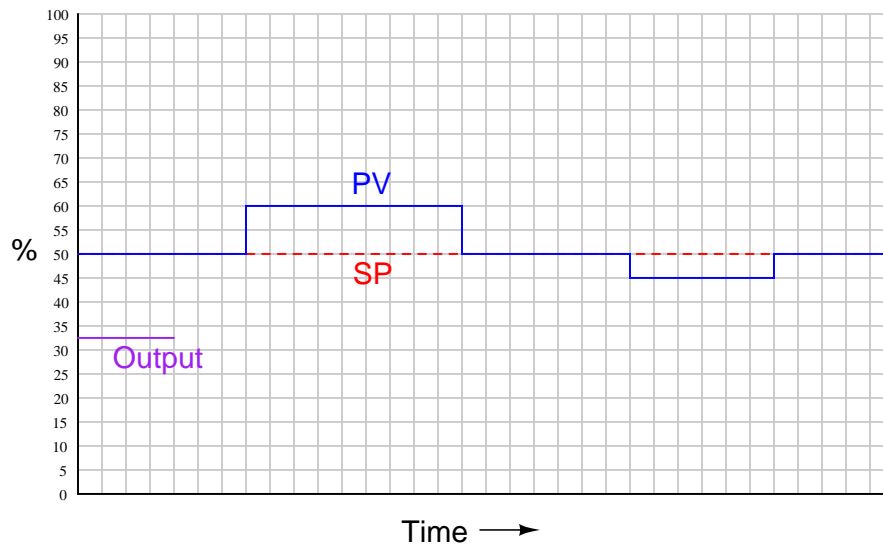
Assume *reverse* control action.

Suggestions for Socratic discussion

- How would the controller's response differ if it were configured for *direct* action instead?
- What factor(s) dictate the use of direct versus reverse controller action?
- Explain why it would be highly unusual to see a trend like this in a real, working process loop. Why is this trend unrealistic, assuming a working process where all components are functioning properly?
- Given that this trend is unrealistic, why is it something we're studying? In other words, what value does a "toy" trend like this have for us?

file i01594

Question 44

Qualitatively graph the response of a controller having *both proportional and integral* modes over time to the following changes in process variable, marking the features of the output plot corresponding to proportional action (P) and to integral action (I).
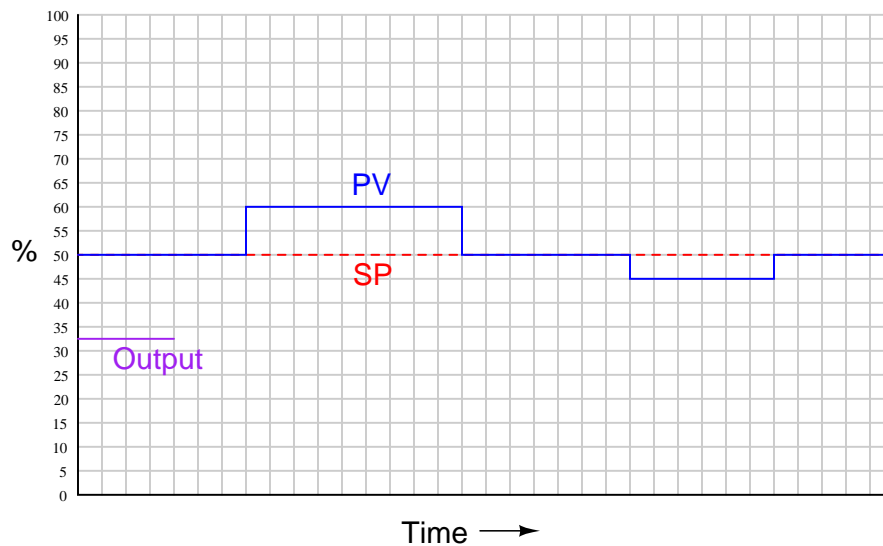
Assume *reverse* control action.

Suggestions for Socratic discussion

- A useful problem-solving strategy is to sketch the P and I actions separately (with their own trends) before combining them to make one final output trend. A subsection in the *Lessons In Industrial Instrumentation* textbook entitled "Note to Students Regarding Quantitative Graphing" illustrates this problem-solving technique.
- Why should any controller combine proportional and integral actions? What is wrong with just using one or the other action alone?

file i01595

Question 45

Shown here is the mechanism for a simplified (no amplifying relay, no bias spring) proportional-only pneumatic controller:
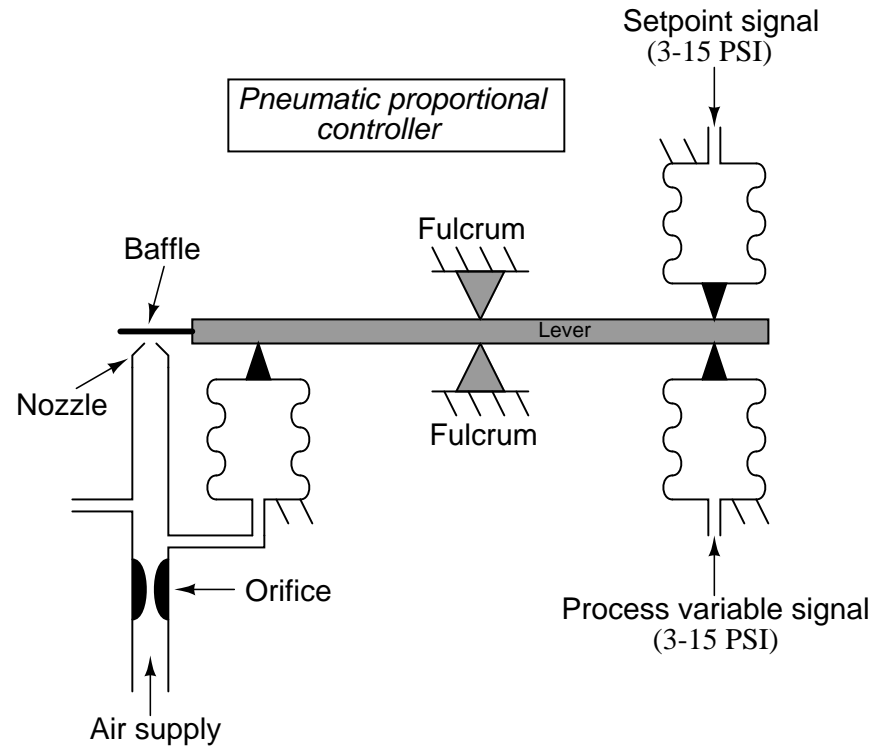
What needs to be changed or adjusted in this mechanism to *decrease* the controller's proportional band? Also, determine whether this controller is *direct-acting* or *reverse-acting*.

| **Suggestions for Socratic discussion** |

- Is this a *force-balance* mechanism or a *motion-balance* mechanism? How can you tell for certain?
- Could the mechanism be modified to convert it into the other type of balance? If so, how?
- Once you have determined a way to decrease the controller's proportional band, devise at least two *other* ways to do the same.

file i01596

57

Question 46

Read and outline the "Integral Control Action" subsection of the "Pneumatic PID Controllers" section of the "Closed-Loop Control" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

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

file i04298

Question 47

Identify how to increase the integration time (the number of minutes per repeat) of this pneumatic controller:
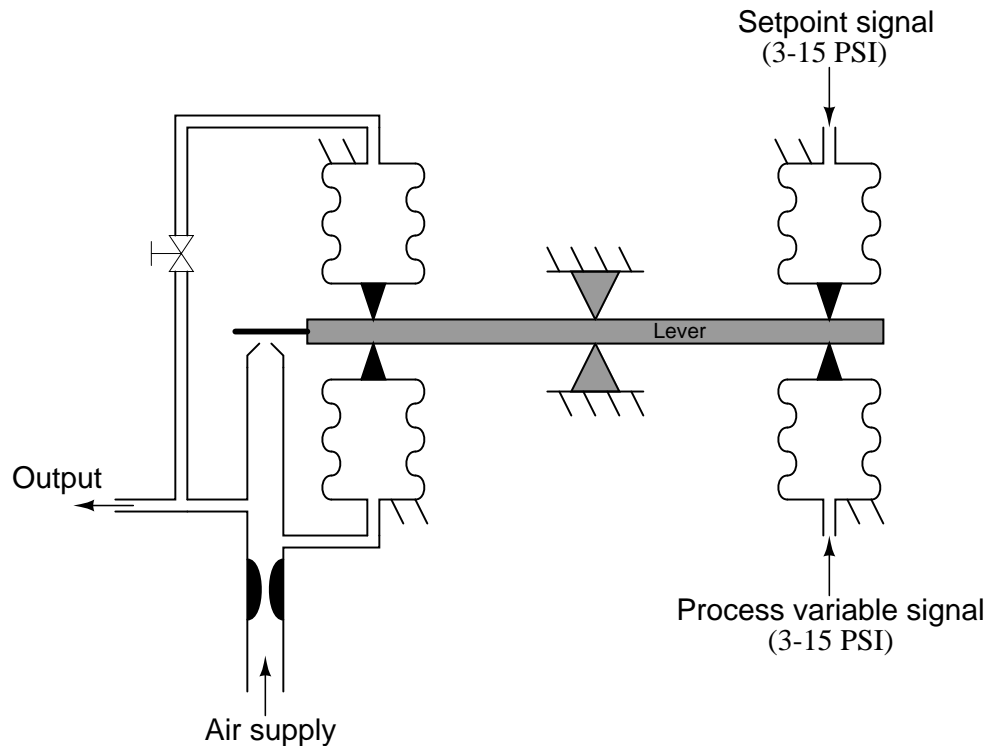
Also, determine whether this is a *proportional + integral* (PI) controller, or an *integral-only* (I) controller, and explain your reasoning.

- How would you modify this mechanism for the opposite direction of action (e.g. direct versus reverse)?
- Explain how this mechanism would respond to an error (PV − SP) if the restrictor valve were placed in-line with the lower-left bellows rather than the upper-left bellows as shown.
- Suppose both the output and reset bellows were replaced with bellows having the same surface area but more volume (i.e. *longer* bellows). What effect(s) would this alteration have on the *gain* of the controller, and also the *integral time constant* of the controller?
- Suppose both the output and reset bellows were replaced with wider bellows having larger surface area as well as more volume. What effect(s) would this alteration have on the *gain* of the controller, and also the *integral time constant* of the controller?
- Is it possible to adjust the gain of this controller without affecting its integral time constant, by only changing one aspect of it (e.g. moving a bellows, moving the fulcrum, etc.)? Explain why or why not.
- Note that this pneumatic controller lacks the *bias spring* seen on P-only pneumatic controllers. Explain why this is.
- Suppose some water vapor in the compressed air supply condensed into liquid water, settling at the bottom of the reset bellows. What effect(s) might this have on the performance of the controller, if any?
- Suppose someone replaced the reset bellows with a wider unit having more surface area (and more volume) than the output bellows. This modification would result in the controller being rendered useless. Explain why!

Question 48

Imagine a situation where the PV signal pressure is 8 PSI and the SP signal pressure is 10 PSI:
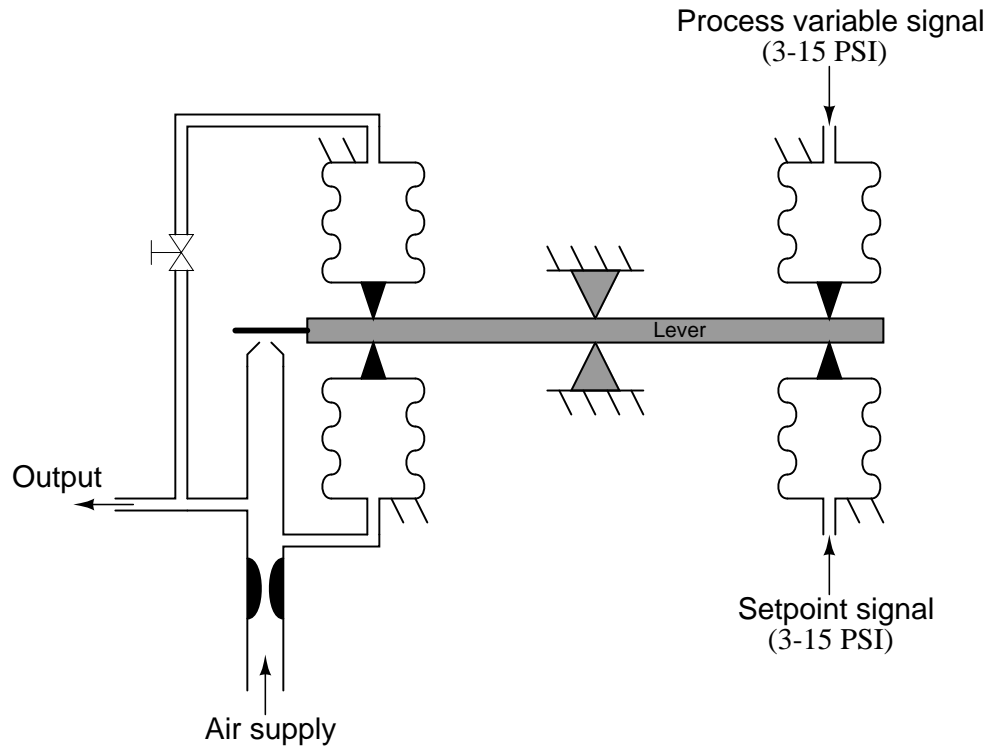
Explain what the output pressure in this pneumatic controller will do over time so long as this imbalance between PV and SP persists. Assume all bellows are equal in size (effective area), and that the fulcrum is precisely centered in the middle of the beam.

Now imagine a situation where the output pressure of this mechanism reaches 11 PSI, and at that exact moment the setpoint pressure is suddenly reduced from 10 PSI to 8 PSI, so that now PV = SP. Explain what effect this will have on the output pressure, both immediately and over time.

| Suggestions for Socratic discussion |

- A general problem-solving principle to apply to a problem such as this is a *force diagram*. This means representing each and every active force in a mechanical system using arrows, showing both magnitude and direction.
- How will the situation differ if the reset valve is opened just a bit more?
- Why is there no bias spring in this mechanism? Is this merely a simplification, or is there a deeper meaning to the spring's omission?

file i01761

Question 49

An operator summons you to investigate a strange control problem she's been having on a liquid flow control loop. This trend shows the behavior of the control loop following a major change in setpoint:
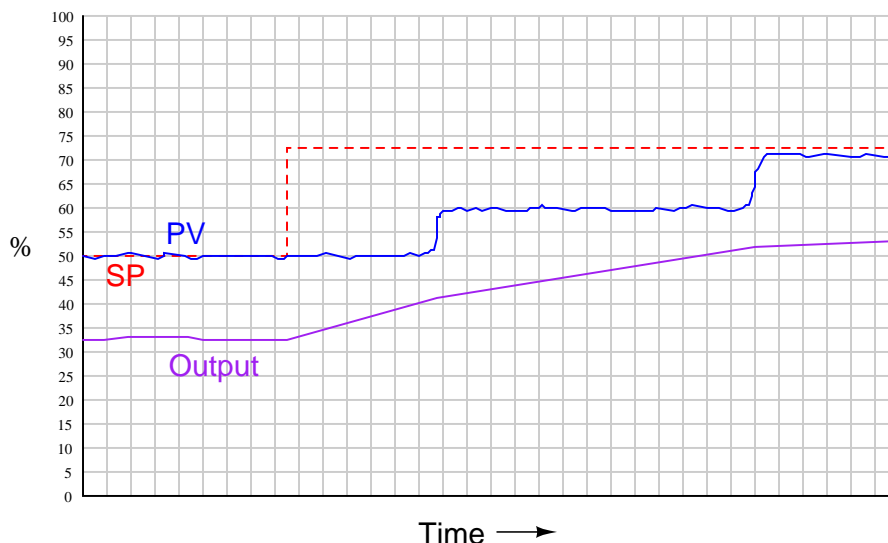
Instead of quickly rising to meet the new (higher) setpoint, the PV remains unchanged until it suddenly steps up (twice!) toward the new setpoint. The controller output, meanwhile, continues to drive upward.

Given what you see here, identify one or more likely causes of this strange behavior. What other diagnostic tests might you do next, and where would you concentrate your search for problems in the system?

Suggestions for Socratic discussion

- Follow along the trend from left to right (progressing forward in time), narrating what the trend says about the process variable, the setpoint, and the controller output over time. It is a good problem-solving technique to do this *first* before arriving at any conclusions as to what is wrong with the loop.
- Do you think this controller is *proportional-only*, *integral-only*, or *P+I*? How can you tell?
- What would the trend look like if this controller implemented some *other* kind of action?
- An immediate response of some technicians is to begin changing the controller's tuning constants (gain, reset period, etc.) when they see poor control response on a trend. Do you think this would be a wise decision in this particular case? Why or why not?

file i01869

Question 50

Qualitatively graph the response of an *integral-only* controller over time to the changes in process variable shown here:
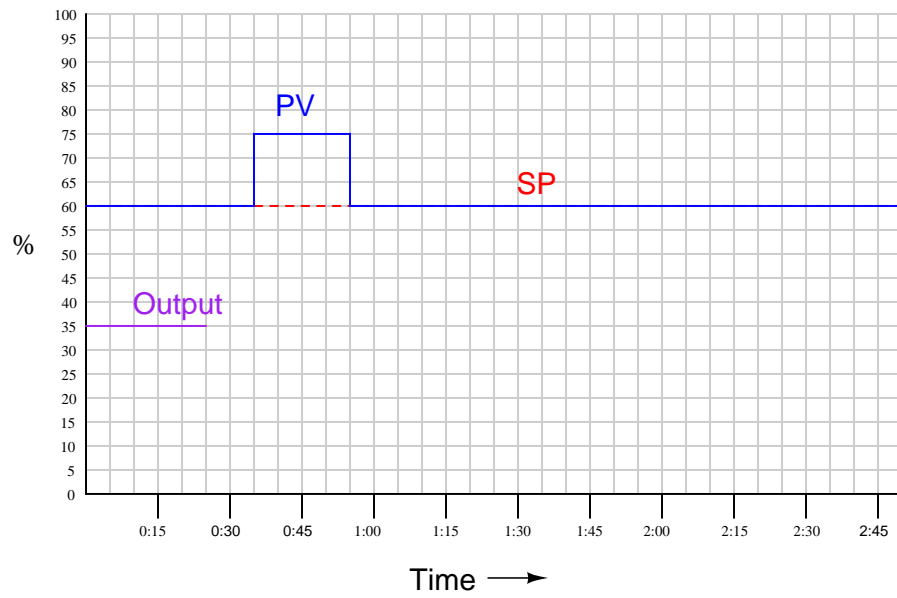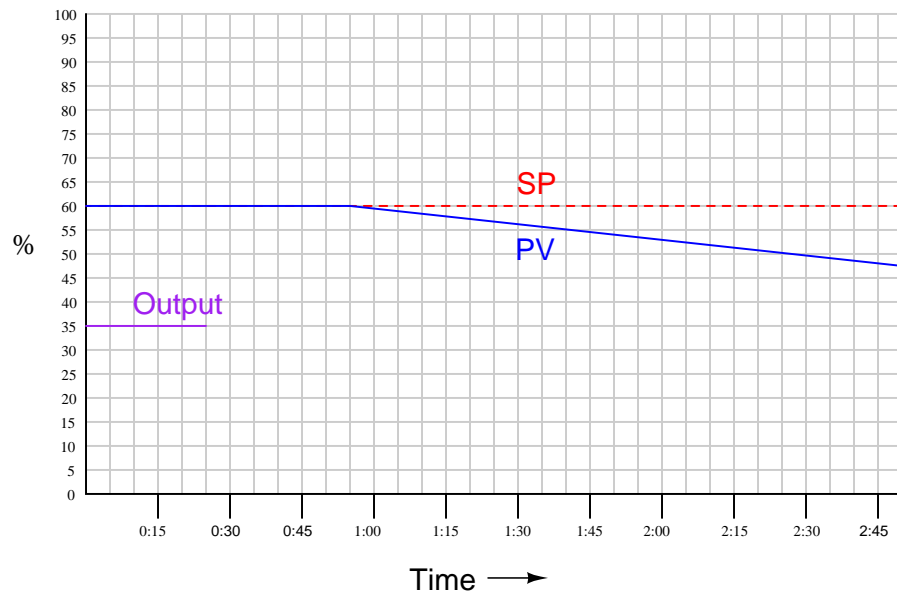

Assume *direct* control action.

file i03761

Question 51

Qualitatively graph the response of an *integral-only* controller over time to the changes in process variable shown here:
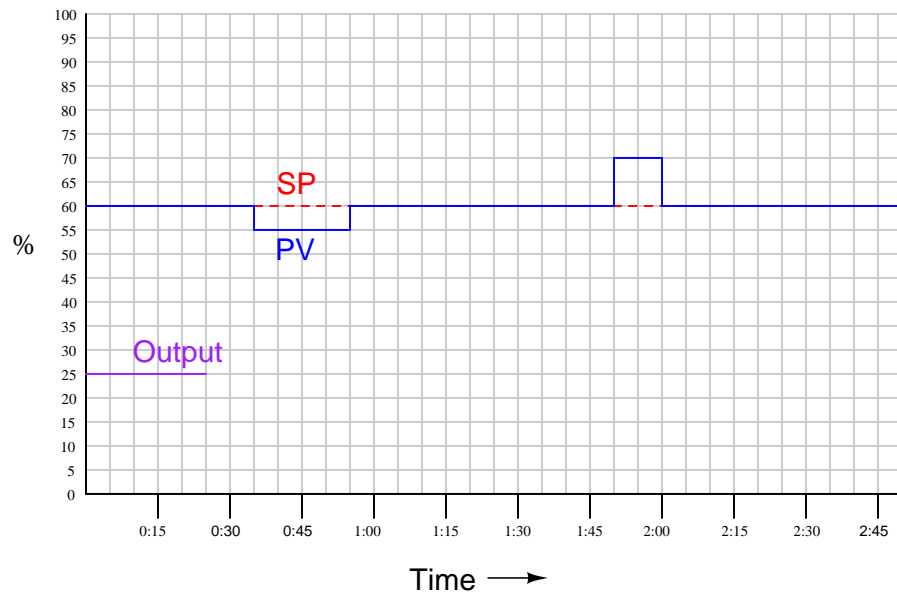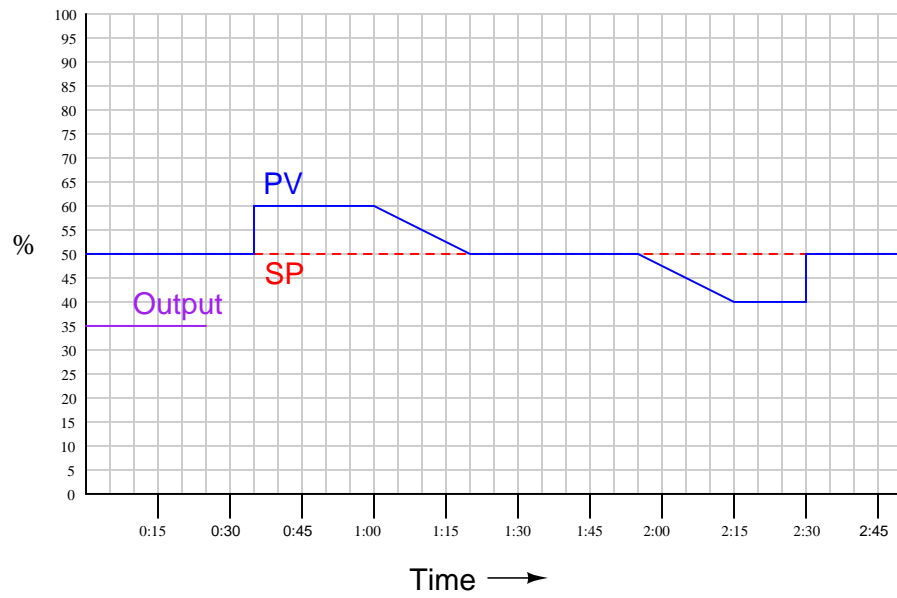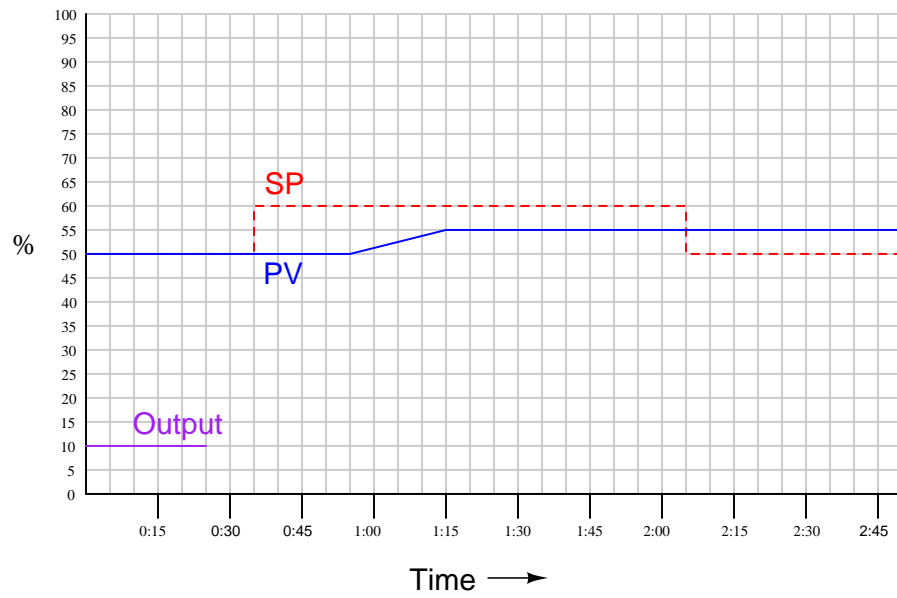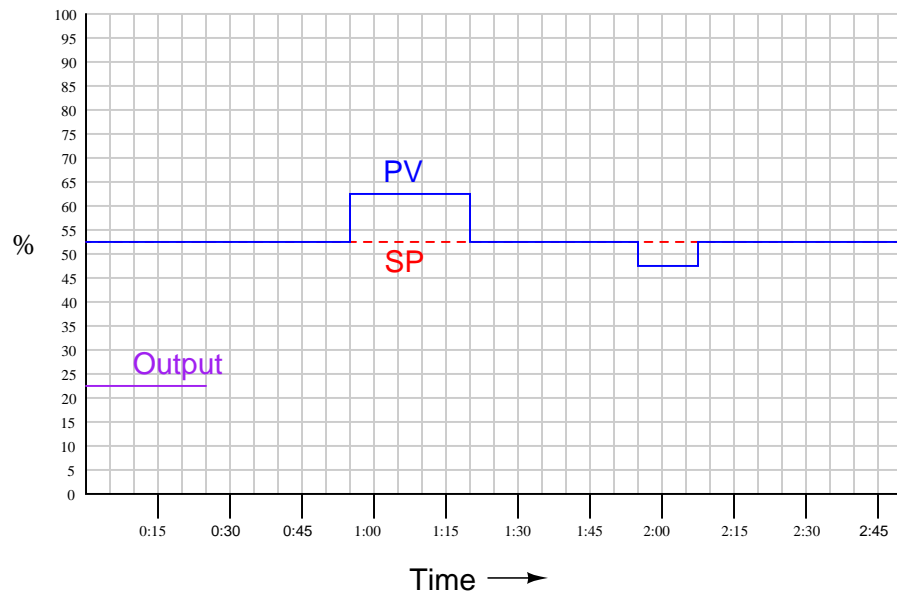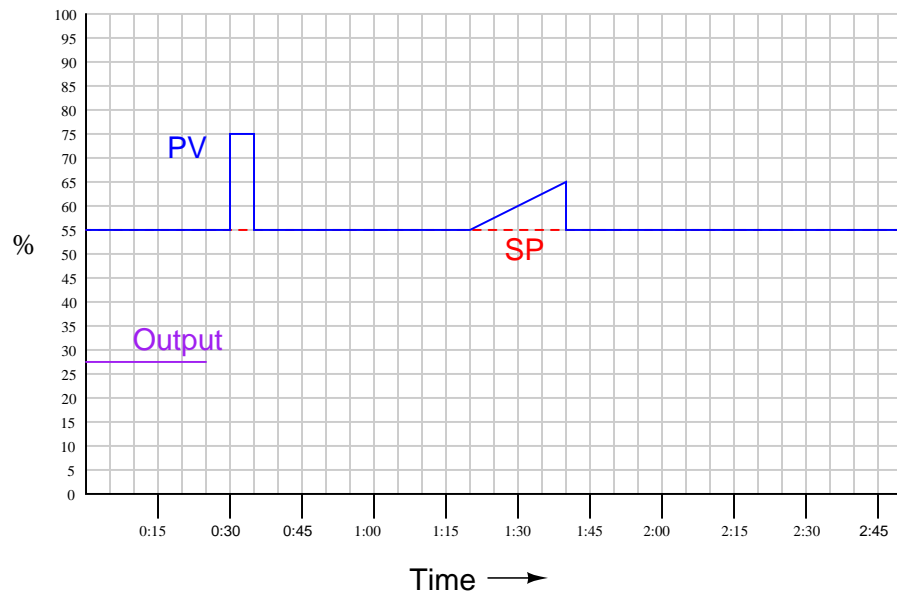

Assume *direct* control action.

file i03762

Question 52

Qualitatively graph the response of an *integral-only* controller over time to the changes in process variable shown here:
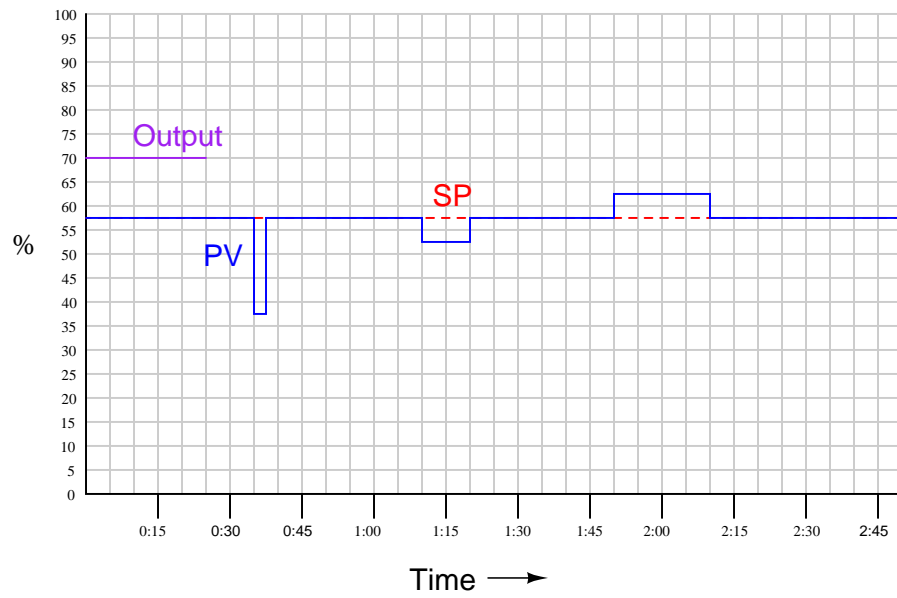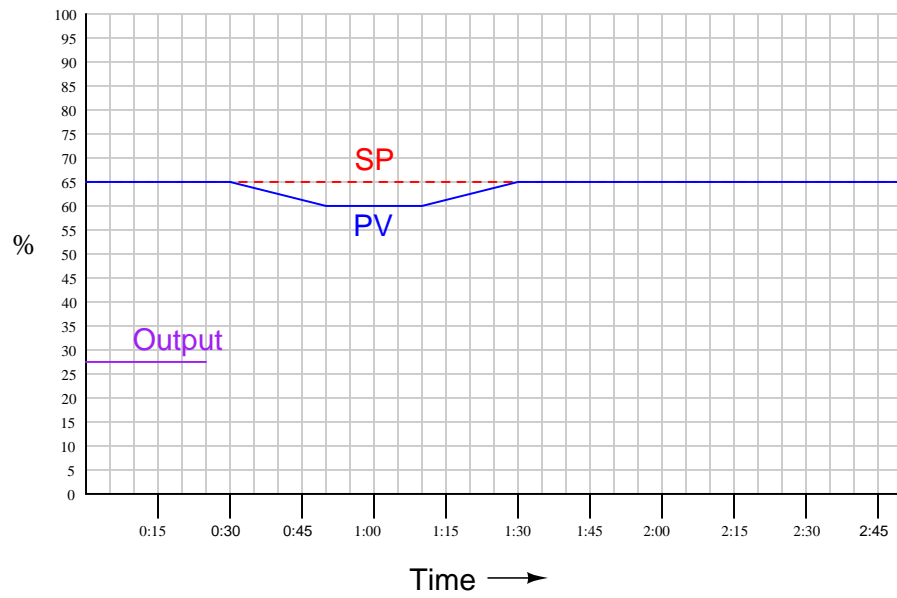

Assume *reverse* control action.

file i03764

Question 53

Integral control action is where the output signal of a controller changes at a rate directly proportional to the magnitude of *error* (the difference between process variable and setpoint).

Given this definition, identify how a integral-acting controller would respond to the following process variable (PV) and setpoint (SP) values over time:
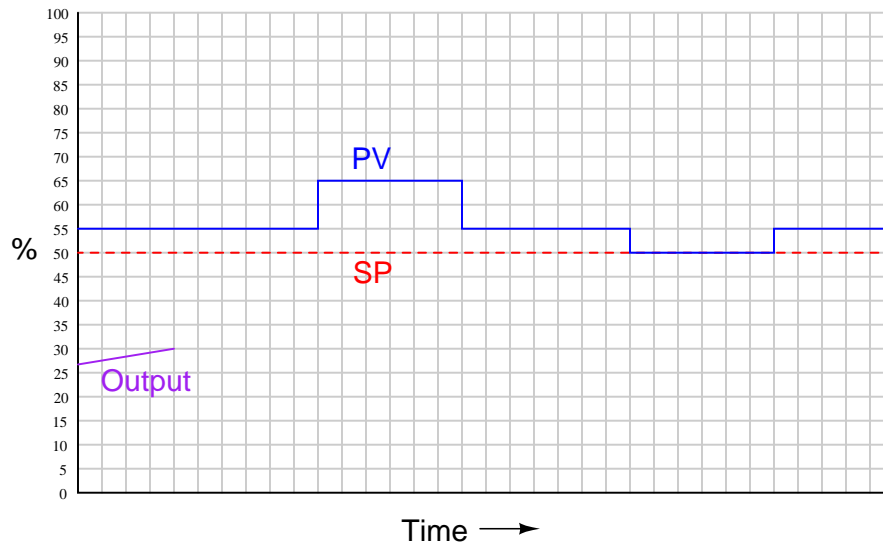
Assume *direct* control action.

file i02418

Question 54

Qualitatively graph the response of an *integral-only* controller over time to the changes in process variable shown here:
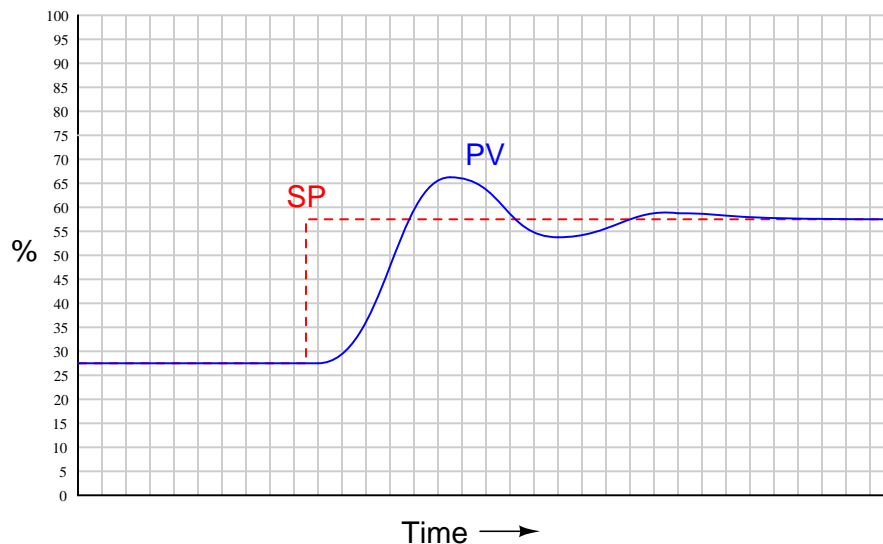

Assume *reverse* control action.

66

Question 55

Qualitatively graph the response of an *integral-only* controller over time to the changes in process variable shown here:

Assume *direct* control action.

67

Question 56

Qualitatively graph the response of an *integral-only* controller over time to the changes in process variable shown here:

Assume *reverse* control action.

file i03301

Question 57

Qualitatively graph the response of a *proportional + integral* controller over time to the changes in process variable shown here:

Assume *direct* control action.

file i03765

Question 58

Qualitatively graph the response of a *proportional + integral* controller over time to the changes in process variable shown here:

Assume *reverse* control action.

file i03766

70

Question 59

Qualitatively graph the response of a *proportional + integral* controller over time to the changes in process variable shown here:

Assume *reverse* control action.

file i03767

Question 60

Numerical integration is not only useful for controllers ("reset" control action), but it may also serve as a means of gauging how well a controller holds the process variable (PV) equal to setpoint (SP). Explain how the following integral measures the "tightness" of control between two points in time (t_1 and t_2):

$$\int_{t_1}^{t_2} |PV - SP| \, dt$$

Explain why we need to integrate the *absolute value* of the error rather than the error itself.

Use shading to show the error integrated by this control-quality measurement integral in the following example:

Suggestions for Socratic discussion

- What would happen if an integral-mode loop controller calculated its integral in this manner, using the *absolute value* of the error, rather than using the error including its sign?
- Which condition will be deemed "tighter" control: a large amount of error for a short time, or a small amount of error (half as much) for a long time (twice as long)? Or, will these two conditions be assessed as equivalent by the integral algorithm shown?

file i04293

72

Question 61

Qualitatively graph the response of an *integral-only* controller over time to the changes in process variable and setpoint shown here:
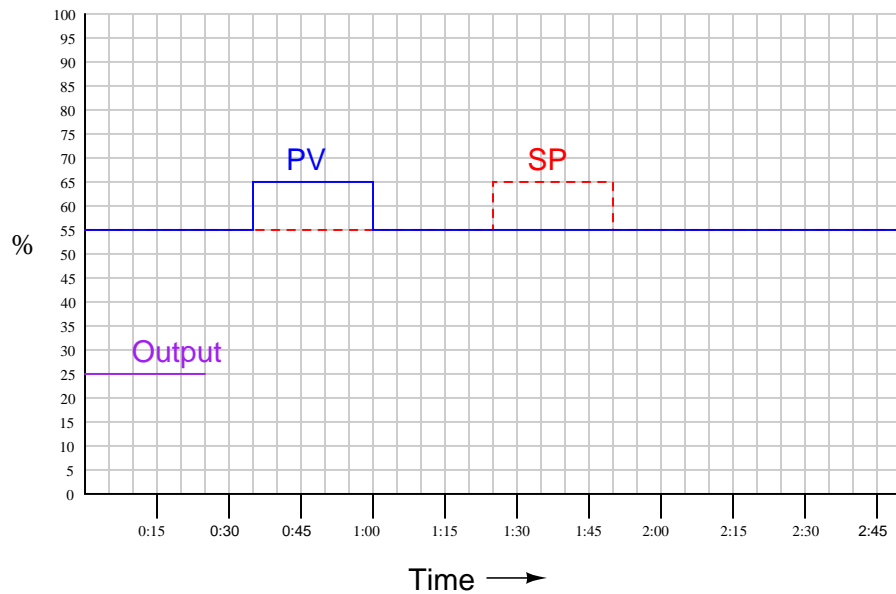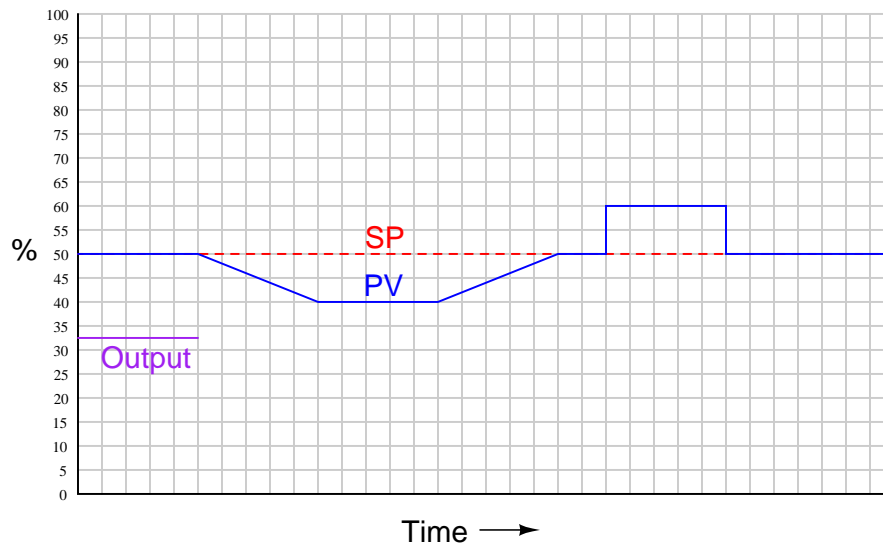

Assume *direct* control action.

Suggestions for Socratic discussion

- A handy rule for plotting the output of a proportional-only controller is that the output will always return to the bias value when PV=SP. Is this rule true for integral controllers as well? Why or why not?
- Explain how the output trend would look different if the time period of the second error (where SP steps away from PV) were longer in duration.
- Explain how the output trend would look different if the magnitude of each error (where SP steps away from PV) were larger (higher).
- Explain how the output trend would look different if the controller's integration rate (i.e. the number of repeats per minute) were decreased from what it is now.

file i03763

73

Question 62

Qualitatively graph the response of an *integral-only* controller over time to the changes in process variable shown here:
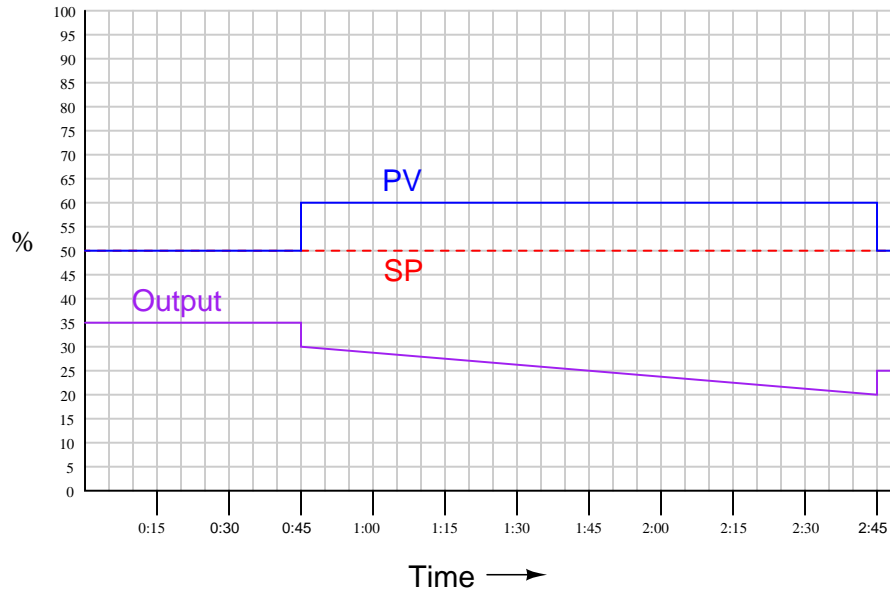

Assume *direct* control action.

74

Question 63

Shown here is the response of a proportional+integral controller to a step-change in process variable (with a constant setpoint). Calculate the controller's proportional and integral constant settings, based on what you see in the graph. Also, determine whether this controller is direct or reverse acting, and mark the features of the output plot corresponding to proportional action and to integral action.

The time scale on the chart is minutes:seconds, and the PI algorithm is as follows:

$$m = K_p \left(e + \frac{1}{\tau_i} \int e \, dt \right) + b$$

Where,

m = Controller output (manipulated variable)
K_p = Gain
e = Error signal (SP−PV or PV−SP)
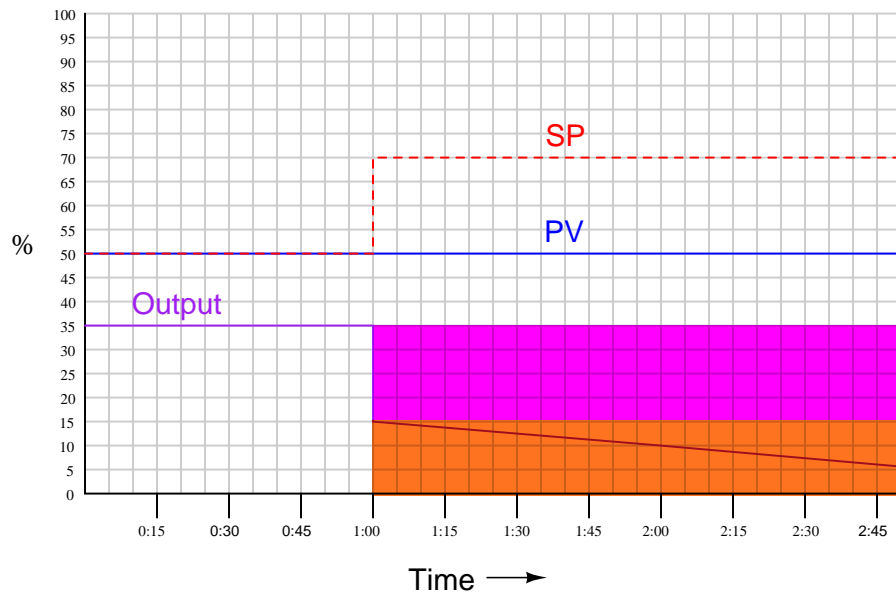τ_i = Integral time constant
b = Bias

Suggestions for Socratic discussion

- When analyzing the output trend of a PI controller, the definition of the reset time constant as being "the number of minutes required to per repeat proportional action" is most useful. Identify the magnitude of proportional action in response to the PV step-change, and then explain how this value is helpful in identifying τ_i.
- Re-sketch what the output trend would look like if this controller's gain value (K_p) were doubled.
- Re-sketch what the output trend would look like if this controller's integral time constant (τ_i) were doubled.
- Re-sketch what the output trend would look like if this controller's bias value (b) were increased.

file i01601

75

Question 64

Shown here is the response of a proportional+integral controller to a step-change in setpoint (with a constant process variable). Calculate the controller's proportional and integral constant settings, based on what you see in the graph. Express your answer for the integral constant both in units of "repeats per minute" and "minutes per repeat." Also, determine whether this controller is direct or reverse acting, and mark the features of the output plot corresponding to proportional action and to integral action.

The time scale on the chart is minutes:seconds, and the PI algorithm is as follows:

$$m = K_p \left(e + \frac{1}{\tau_i} \int e \, dt \right) + b$$

Where,

m = Controller output (manipulated variable)
K_p = Gain
e = Error signal (SP−PV or PV−SP)
τ_i = Integral time constant
b = Bias

| **Suggestions for Socratic discussion** |

- When analyzing the output trend of a PI controller, the definition of the reset time constant as being "the number of minutes required to per repeat proportional action" is most useful. Identify the magnitude of proportional action in response to the PV step-change, and then explain how this value is helpful in identifying τ_i.
- If you really saw this type of response on a process controller trend (chart recorder), what might you suspect about the system? Hint: this type of trend is definitely *not* normal for a properly functioning control system!

file i01602

Question 65

Examine this process, where the temperature of water sitting at the bottom of a "water seal drum" vessel is regulated by passing hot steam through a heating tube immersed in the water:
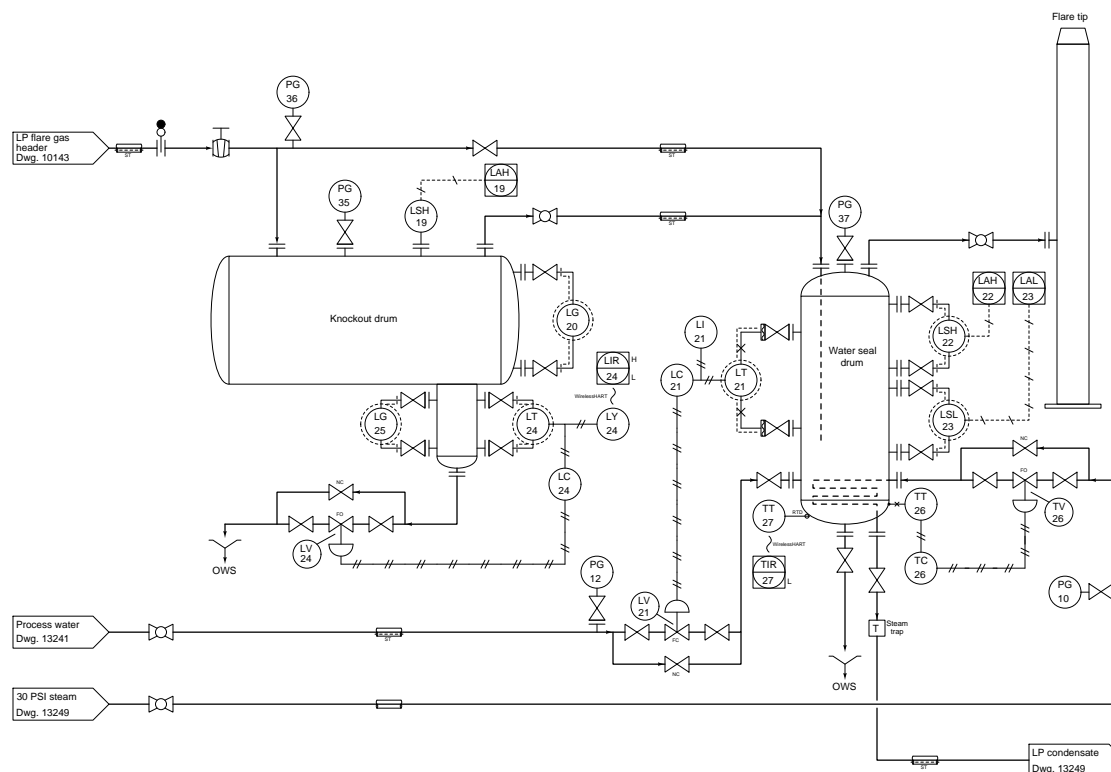
Suppose that one day the 30 PSI steam supply boiler shuts down, ceasing the flow of steam to the TV-26. With no supply of steam to heat the seal drum, the water begins to cool down. What will controller TC-26 do in response to this event, assuming it is a proportional+integral (P+I) controller?

Now suppose that the steam "outage" lasts for a very long time. How will the controller's proportional and integral modes respond if left in the automatic mode the entire time? Is there a way to avoid this problem?


Suggestions for Socratic discussion

- Examining the diagram, what do you suppose the function of the water seal drum is, in the larger context of the flare process?
- Which is the worst-case scenario: the water in the seal drum becoming too cold or becoming too hot? How can we tell based on details found in this diagram?
- Suppose operations personnel approached you to install instrumentation to measure the total quantity of substance released to the flare each month, for emissions monitoring purposes. For those who have studied flowmeters, identify at least one practical solution to this problem, including the specific types of technologies used to sense the vapors going to the flare.

file i01608

Question 66

This amount of vacuum (negative pressure) in this knock-out drum is controlled by varying the compressor's bypass valve:
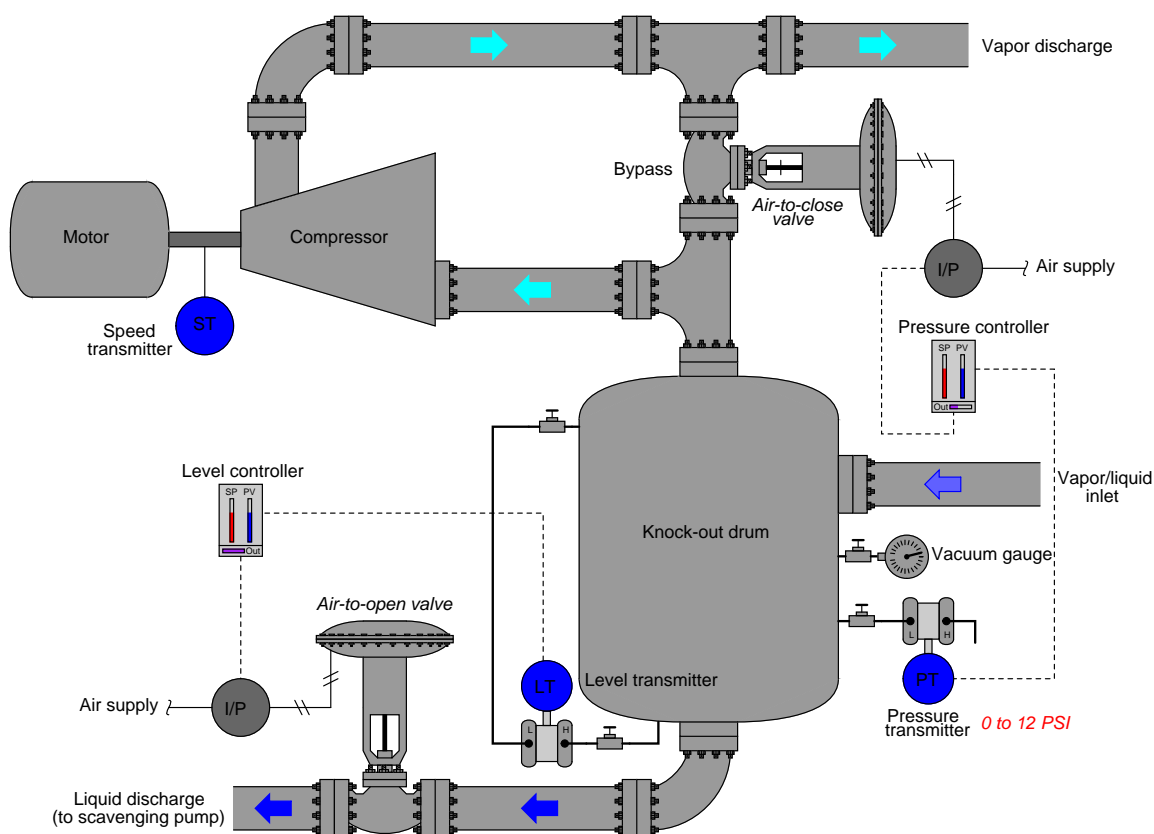
An operator tells you there is a problem with this system, though: the vacuum gauge near the pressure transmitter registers −6.9 PSI, even though the controller faceplate registers −8.0 PSI which is the same as the setpoint. The same operator notes that the control valve position is approximately 30% open, with the controller's output bargraph registering 31.4% open.

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

Suggestions for Socratic discussion

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

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

    file i02489

Question 67

Suppose an aging controller needs to be replaced, and its tuning constants are documented as such:

- Proportional band = 130%

- Reset = 2.7 minutes per repeat

The new controller destined to replace this old unit is also a proportional+integral controller, but its tuning constant units are different. Instead of "proportional band," the K_p constant is labeled as "gain." Instead of "minutes per repeat," the new controller bears the unit of "repeats per second" for its integral constant.

Convert the old tuning constants into the new units, so that when the new controller is installed, it does the same exact job as the old controller. Note: assume the use of the same algorithm type (P+I equation) in both controllers.

Suggestions for Socratic discussion

- Explain what would happen if the new controller were installed and programmed (by someone who didn't know better) with a gain of 1.30 for proportional action and 2.7 repeats per second for integral action.

    file i01612

Question 68

Suppose an operator wishes to have a computer display the total amount of water consumed by a process for each week of continuous operation. A flowmeter presently exists on the water pipe measuring the flow rate of water into the process. Identify whether the computer will need to *differentiate* or *integrate* the flowmeter signal to calculate a total water quantity for the operator. Provide example units of measurement for the flowmeter and for the total water quantity.

Suppose an operator wishes to have a computer signal an alarm if a chemical reactor heats or cools too quickly. A thermocouple presently exists on the reactor vessel to measure process temperature. Identify whether the computer will need to *differentiate* or *integrate* the thermocouple signal in order to activate the alarm. Provide example units of measurement for the thermocouple and for the temperature alarm setpoint.

Suggestions for Socratic discussion

- A useful problem-solving technique for calculus-based problems is to sketch a graph of the variables being considered. The *derivative* of a function is the slope of the graph, while the *integral* of a function is the area bound by the graph. Apply this problem-solving technique to the problem at hand in this question.
- Mathematically express each of these computations, using proper calculus notation.
- Explain how *units of measurement* are especially in determining when to apply differentiation, versus when to apply integration.
- If you chose British units of measurement for your answer, identify some suitable metric units of measurement instead.
- If you chose metric units of measurement for your answer, identify some suitable British units of measurement instead.

    file i04294

When sulfur-containing fuels are burned, one of the reaction products is sulfur dioxide (SO_2), which is an atmospheric pollutant. Fortunately, SO_2 is relatively easy to "scrub" out of hot flue gases by spraying a liquid solution down on the rising gases and then chemically treating (regenerating) that scrubbing solution:
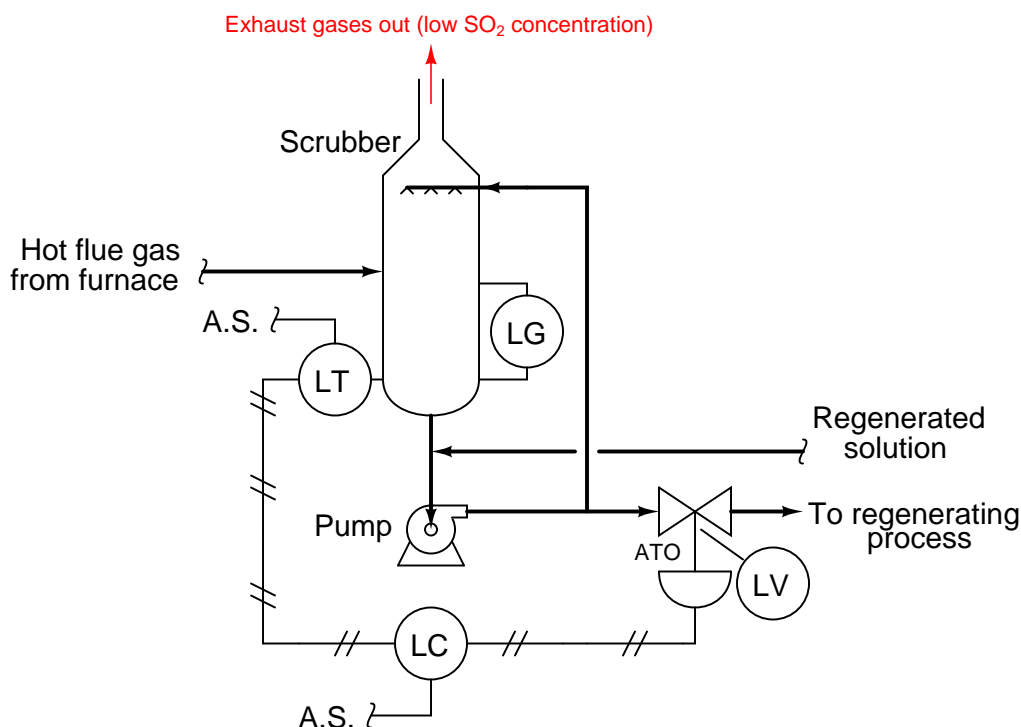
After years of successful operation, the level control loop begins to exhibit problems. The liquid level inside the scrubbing tower mysteriously drops far below setpoint, as indicated by the level gauge (LG) on the side of the scrubber. The operators have tried to rectify this problem by increasing the setpoint adjustment on the level controller (LC), to no avail.

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

Fault	Possible	Impossible
Air supply to LT shut off		
Air supply to LC shut off		
Pump shut off		
Broken air line between LT and LC		
Broken air line between LC and LV		
Plugged nozzle inside LC		
Plugged orifice inside LC		
Leak in bottom of scrubber		

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 i01867

Question 70

Examine this liquid flow controlling system, using two flow switches and a motor-actuated control valve. Then, answer the questions that follow:


P&ID

Flow control ladder logic
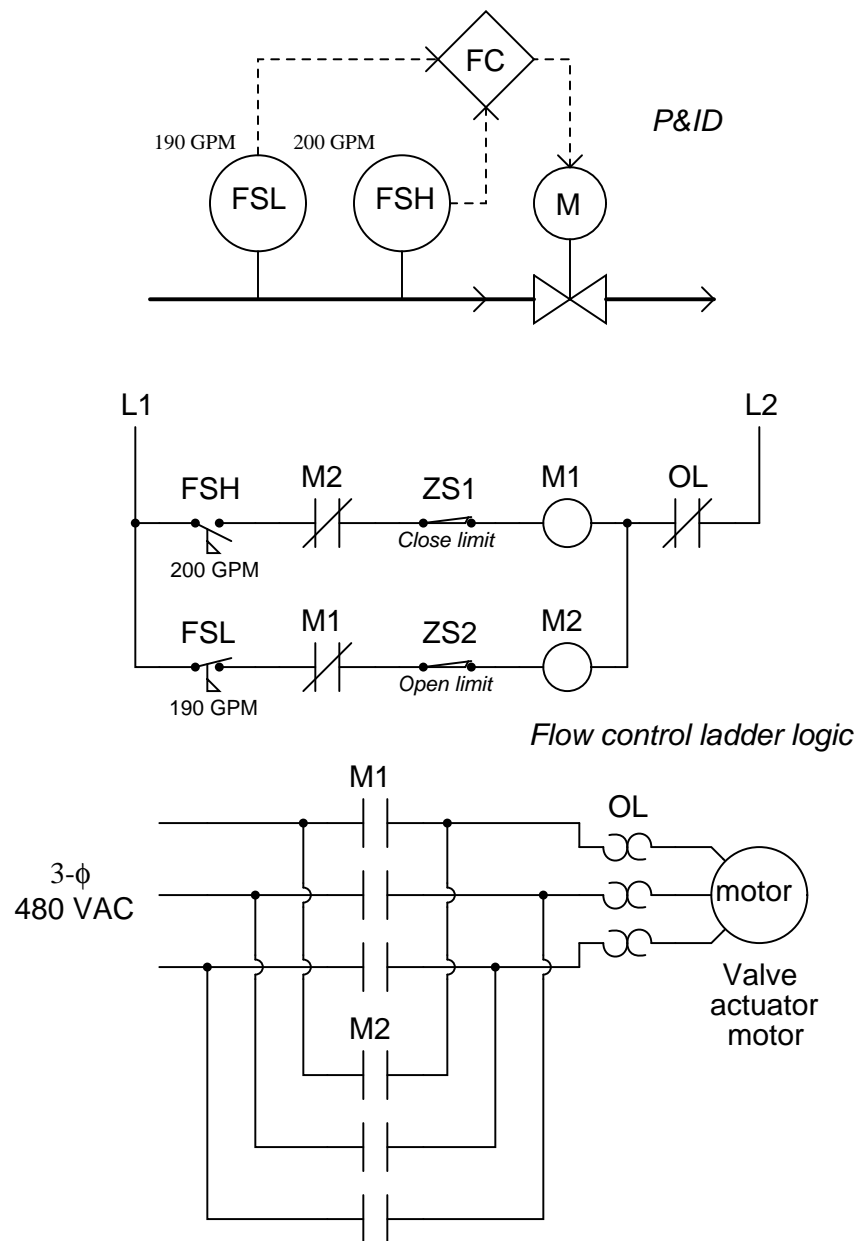
- Which motor contactor (M1 or M2) opens the valve? Which one closes the valve?
- How will the control valve respond if the flow is continually below 190 GPM?
- What purpose does each normally-closed "M" contact serve?
- Would you say this control circuit performs a *proportional* action or an *integrating* action? Why??

file i01814

81

Question 71

Graph the response of a proportional+integral controller to the following input conditions, assuming a proportional band of 100% and an integral constant of 8 minutes per repeat. The controller's action is *direct*, and the algorithm it follows is shown below the graph:
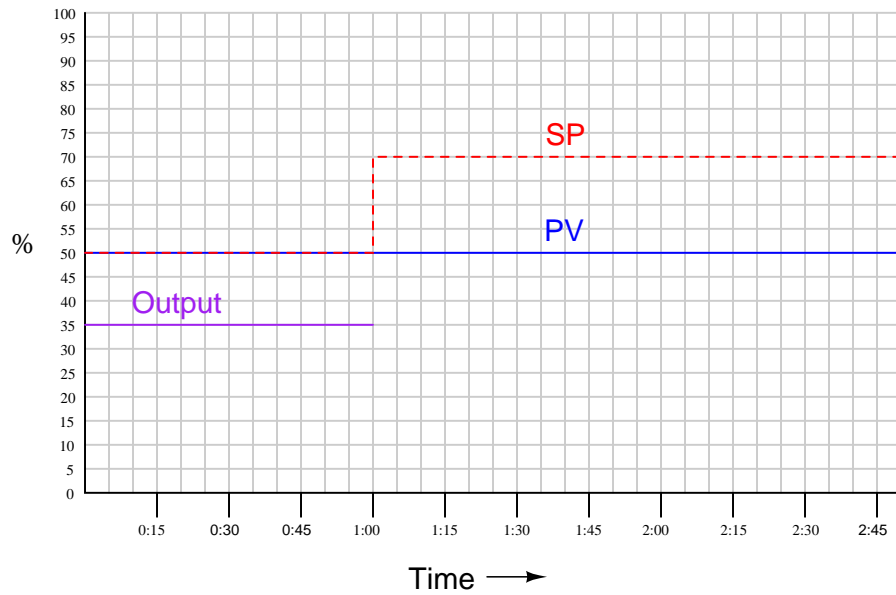
The time scale on the chart is minutes:seconds, and the PI algorithm is as follows:

$$m = K_p \left(e + \frac{1}{\tau_i} \int e \, dt \right) + b$$

Where,

m = Controller output (manipulated variable)
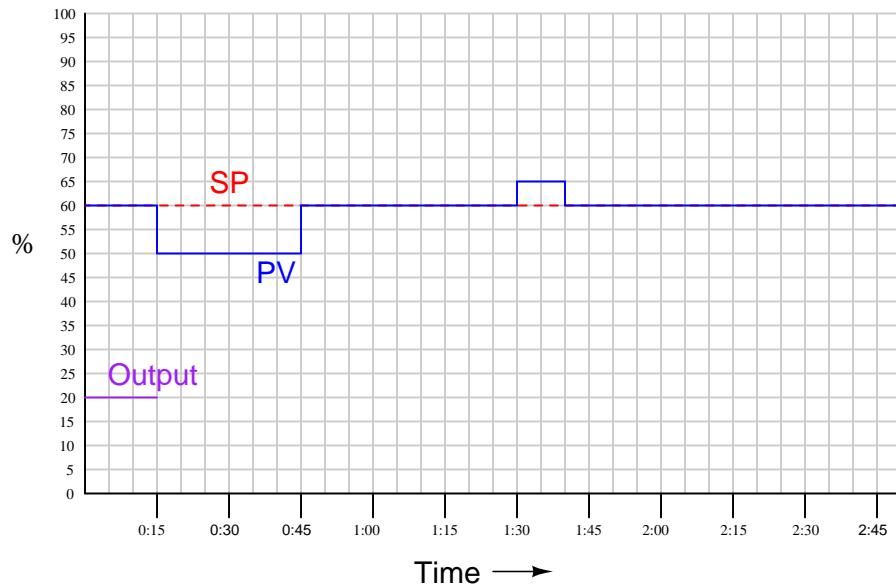K_p = Gain
e = Error signal (PV−SP)
τ_i = Integral time constant
b = Bias

file i01603

82

Question 72

Graph the response of a proportional+integral controller with a proportional band of 50% and an integral constant of 1.25 minutes per repeat to the following input conditions. Assume a control action that is *reverse-acting*:

The time scale on the chart is minutes:seconds, and the PI algorithm is as follows:

$$m = K_p \left(e + \frac{1}{\tau_i} \int e \, dt \right) + b$$

Where,

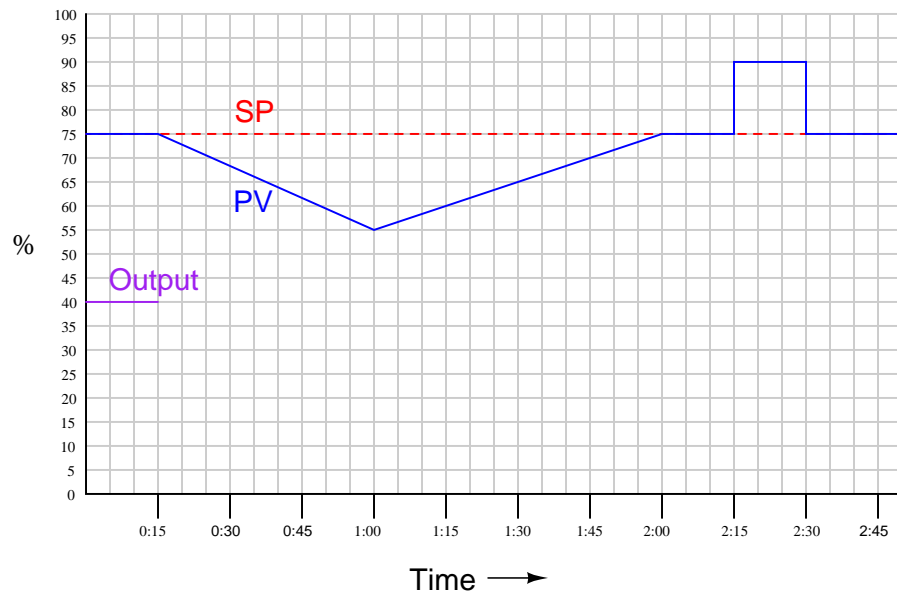m = Controller output (manipulated variable)
K_p = Gain
e = Error signal (SP−PV)
τ_i = Integral time constant
b = Bias

file i01604

83

Question 73

Graph the response of an *integral-only* controller with an integral constant of 1 minute per repeat to the following input conditions. Assume a control action that is *direct-acting*:

The time scale on the chart is minutes:seconds, and the I-only algorithm is as follows:

$$m = \frac{1}{\tau_i} \int e \, dt$$

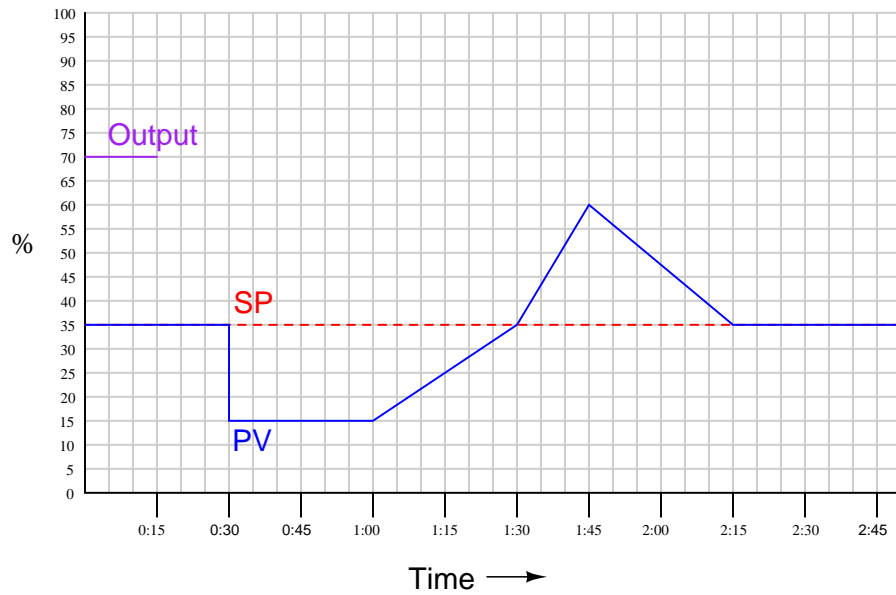Where,

m = Controller output (manipulated variable)

e = Error signal (PV−SP)

τ_i = Integral time constant

file i01605

Question 74

Graph just the integral response of a *proportional+integral* controller with a proportional band of 75% and an integral constant of 2 minutes per repeat to the following input conditions. Assume a control action that is *direct-acting*:

The time scale on the chart is minutes:seconds, and the PI algorithm is as follows:

$$m = K_p \left(e + \frac{1}{\tau_i} \int e \, dt \right) + b$$

Where,

m = Controller output (manipulated variable)
K_p = Gain
e = Error signal (PV−SP)
τ_i = Integral time constant
b = Bias

file i01606

85

Question 75

Graph just the integral response of a *proportional+integral* controller with a proportional band of 50% and an integral constant of 4 minutes per repeat to the following input conditions. Assume a control action that is *reverse-acting*:

The time scale on the chart is minutes:seconds, and the PI algorithm is as follows:

$$m = K_p \left(e + \frac{1}{\tau_i} \int e \, dt \right) + b$$

Where,

m = Controller output (manipulated variable)
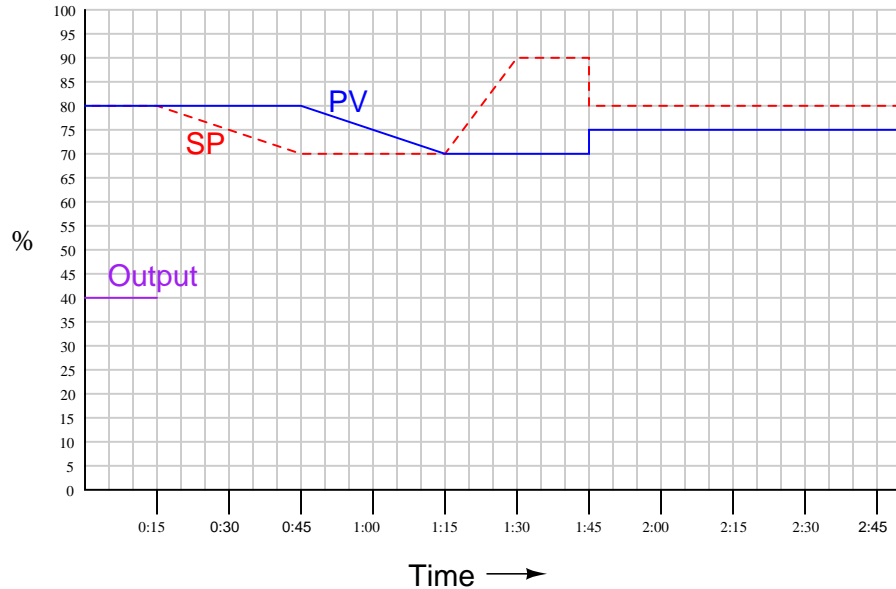K_p = Gain
e = Error signal (SP−PV)
τ_i = Integral time constant
b = Bias

file i01607

Question 76

Read the sections of the Fisher "2506 Series Receiver-Controller" product bulletin (document 34.3:2506) pertaining to the model 2506 Multi-Trol (ignore portions discussing the model 2516), and answer the following questions:

Identify the adjustable range of gain for this controller, expressed as a gain ratio (not as a proportional band value).

Explain how the "reversing switch" is used to switch the controller action between *direct* and *reverse*. Identify whether the controller shown in figure 4 is configured for direct or reverse action.

Identify how this pneumatic controller mechanism would respond to a slight leak in the "proportional" bellows, explaining your reasoning.

file i04282

Question 77

Question 78

Question 79

Question 80

Question 81

Suppose you needed to control the temperature of an "incubation" vessel at a biopharmaceutical manufacturing facility, to ensure the bacteria were held at the correct temperature for optimum growth. The vessel is heated by an electric heater, and the only controller you have available is one with a time-proportioning output (transistor).

Unfortunately, the controller's transistor is not able to directly handle the 240 volt AC power required by the heater, partly because of the voltage and current limitations of the transistor, and partly because an NPN transistor can only switch DC, not AC.
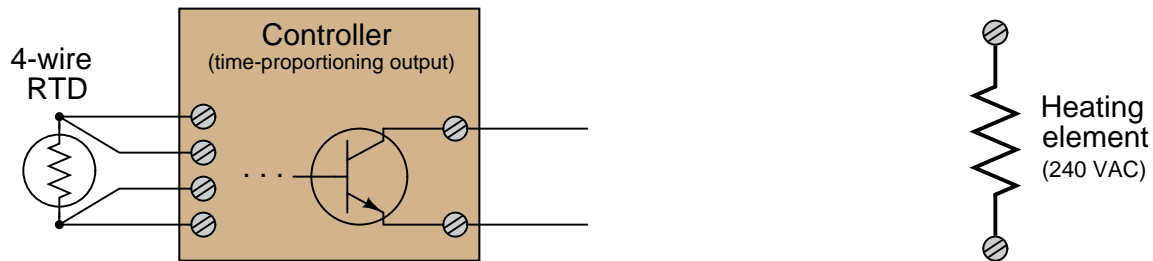
Sketch an "interposing" circuit between the controller and heating element that allows the controller to do its task.

<u>file i01488</u>

Question 82

Numerically integrate the following function of x for two different intervals:

$$\int_4^{11} f(x)\, dx =$$

$$\int_{18}^{12} f(x)\, dx =$$

file i04296
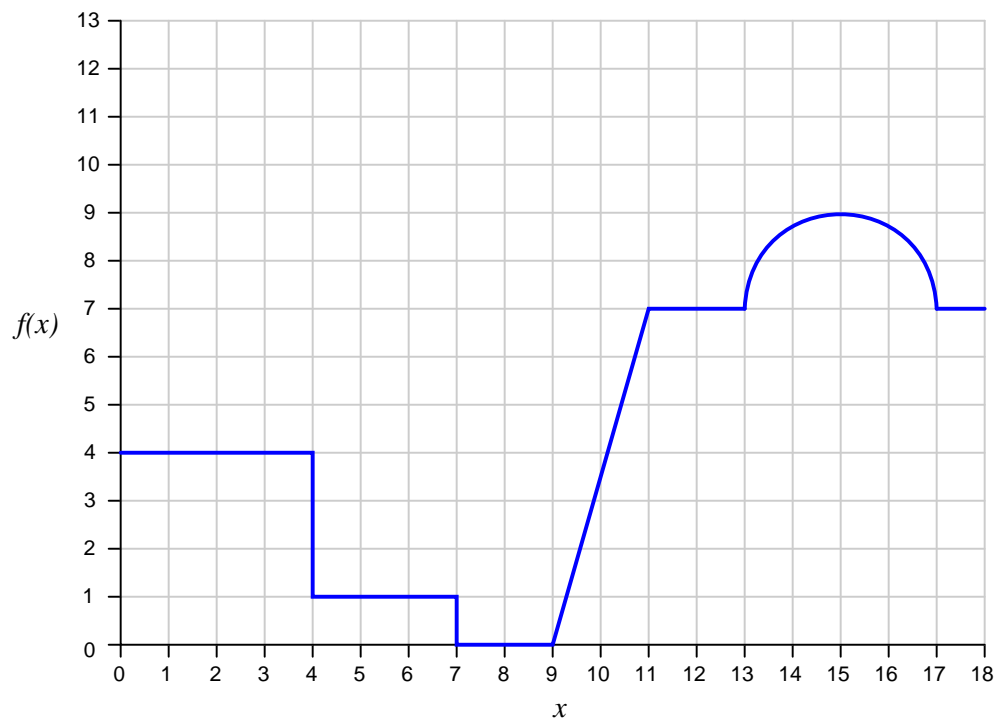
Question 83
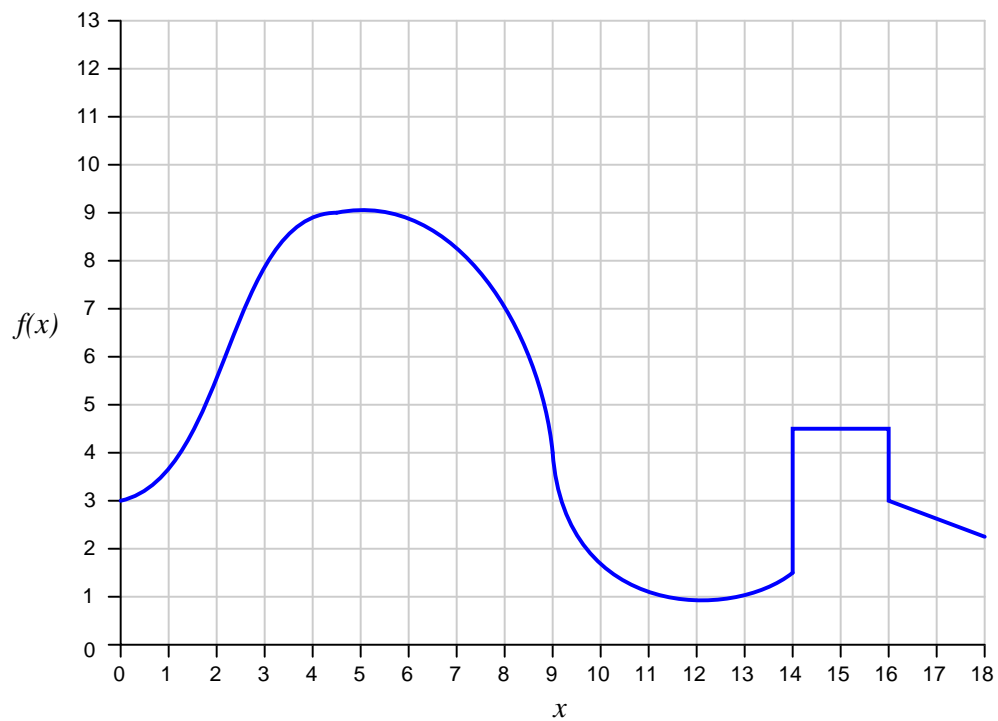
Identify all values of x where the derivative of the function has a value of -1:

Question 84

Suppose we have a condition where the PV signal is 5.8 PSI and the SP signal is 7.2 PSI. Determine the pressure inside the reset bellows at the moment when the output signal is 11.3 PSI, and determine whether the output pressure will be *rising* or *falling*:

Setpoint signal
(3-15 PSI)

Reset
adjust

Lever

Output

Air supply

Process variable signal
(3-15 PSI)
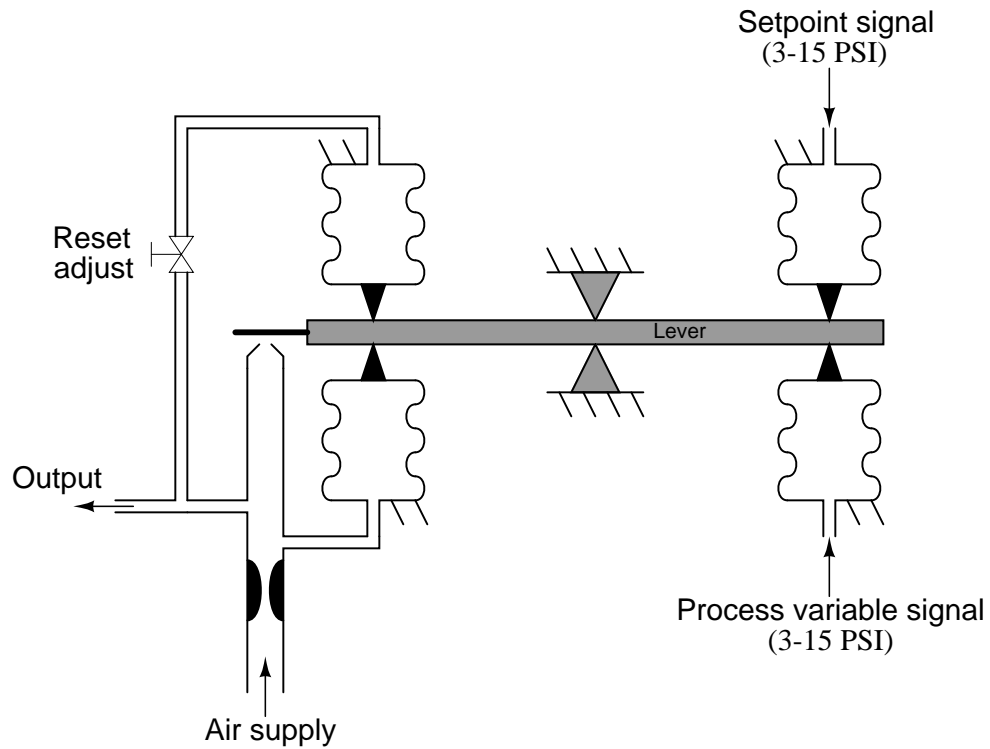
Assume all four bellows are identical in dimensions and construction, and that the fulcrum is placed exactly mid-way between the two sets of bellows.

Question 85

The process trend shown below reveals a controller's response to the process variable signal and the setpoint. Based on what you see in this trend, determine whether the controller is direct or reverse acting, and also whether it implements a P-only, I-only, or P+I control algorithm.
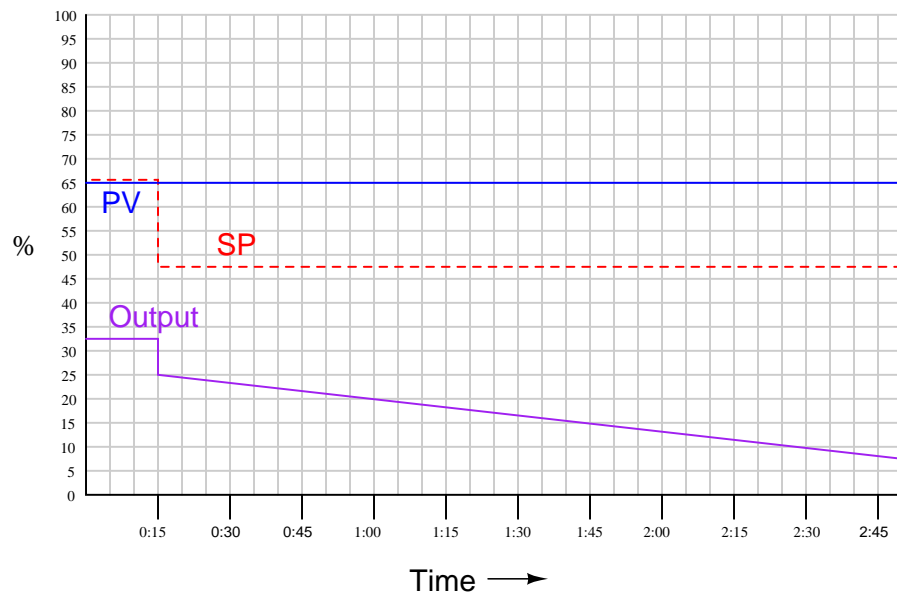
Question 86

Observing this process trend, we see the PV, SP, and Output variables represented:

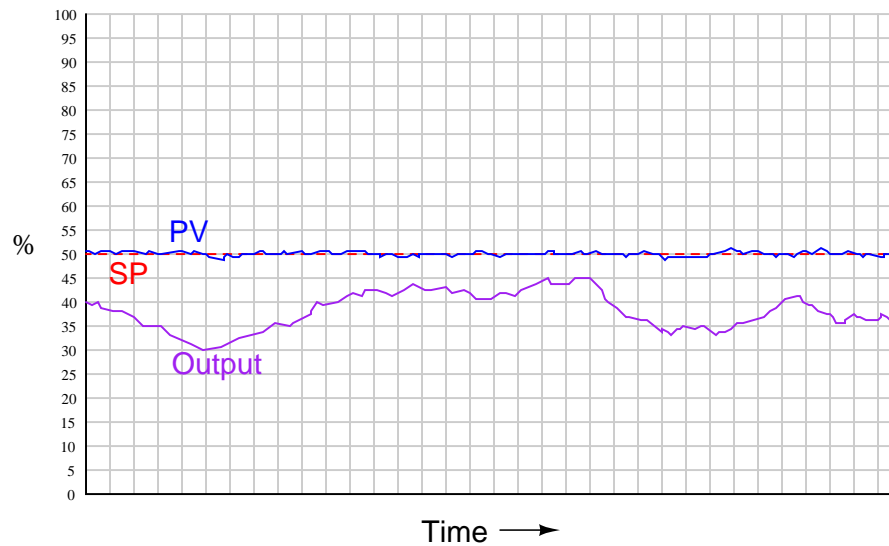The setpoint (SP) is the flat line at 50%. The process variable (PV) is the slightly bumpy plot wavering just above and below the flat setpoint line. The output is the very erratic plot below both PV and SP plots.

The operator of this process calls you, the technician, to complain about the quality of control in this process. He claims the controller needs to be tuned in order to stabilize the Output plot so that it is not so erratic. Based on your observations of this trend, what do you think is happening with this process? Is the controller in need of tuning?

What do you think might happen if we placed this controller in "manual" mode? How would that change the appearance of the process trend?

file i01647

Question 87

Determine the phase angle (θ) of the current in this circuit, with respect to the supply voltage:
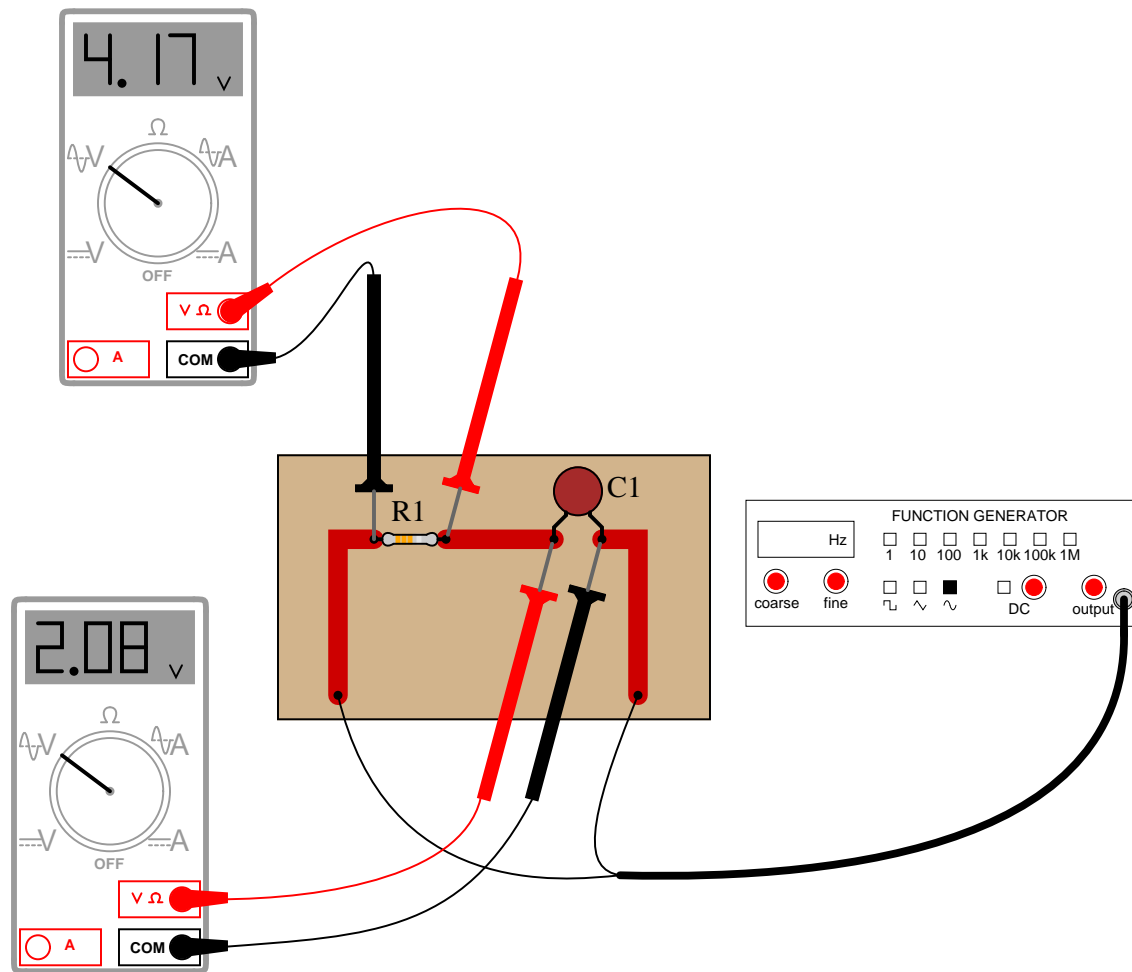
Question 88

Suppose a pair of split-ranged control valves are used to cool hot product liquid through a heat exchanger. Cooling water flows from a utility water header (constant pressure of 80 PSI) through the tube side of a shell-and-tube heat exchanger, while product flow may be throttled through the shell side:

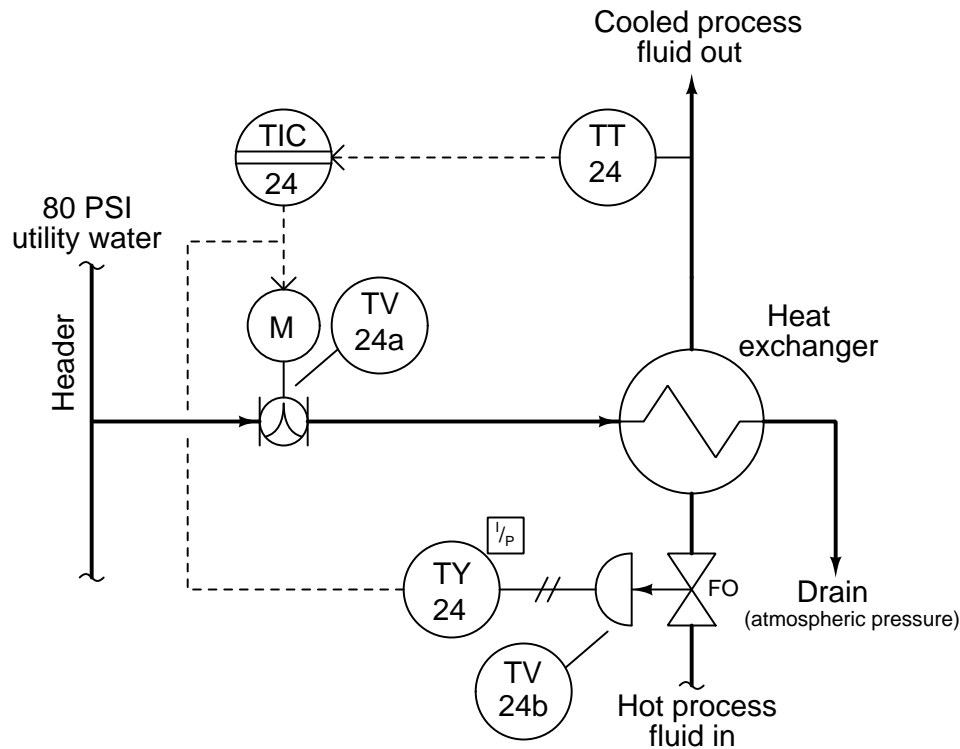The sequenced valve control strategy needs to work like this: first, the product valve (TV-24b) needs to remain wide-open if possible to allow maximum production flow rate, temperature control being done by modulating the flow of cooling water to the heat exchanger. However, if even a wide-open cooling water valve (TV-24a) is not enough to maintain the product temperature at setpoint, the product valve must begin to pinch off the flow to maintain temperature at setpoint.

The only thing you are told about these two valves is that the process valve (TV-24b) is fail-open.

Determine the proper split-range sequencing for these two valves, assuming they both operate on the same 4-20 mA analog signal from the temperature controller's output. Assuming a standard direct-acting calibration (4-20 mA = 3-15 PSI) for the I/P transducer.

Also, determine the necessary action for the controller, assuming a direct-acting response from the temperature transmitter.

file i03409

94

Question 89

The Rockwell/Allen-Bradley MicroLogix 1000 programmable logic controller (PLC) can handle up to four analog input signals: two with a 0-10 V maximum range and two with a 0-20 mA maximum signal range. This PLC's analog input terminal block looks like this (the internal resistors are shown inside the PLC box):
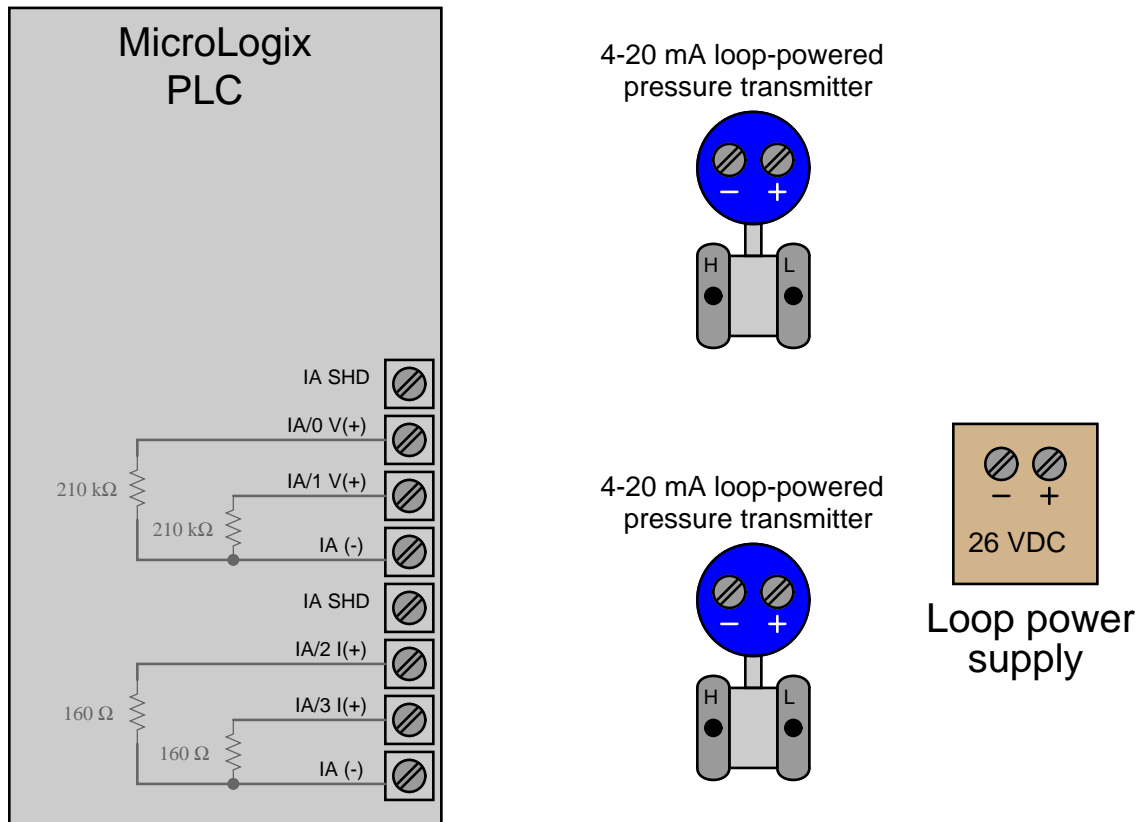
Sketch the appropriate wiring to connect a pair of 4-20 mA loop-powered transmitters to the two voltage inputs (IA/0 and IA/1) on the PLC. Sketch precision resistors in the appropriate locations to convert the 4-20 mA current signals into 1-5 V voltage signals appropriate for those input channels.

Note: the two "IA SHD" terminals are provided for cable shield conductor attachment. You may ignore cable shield wires and these terminals for simplicity's sake.

file i03253

Suppose a voltmeter registers 0 volts between test points **A** and **D**, and also 0 volts between test points **A** and **G**:
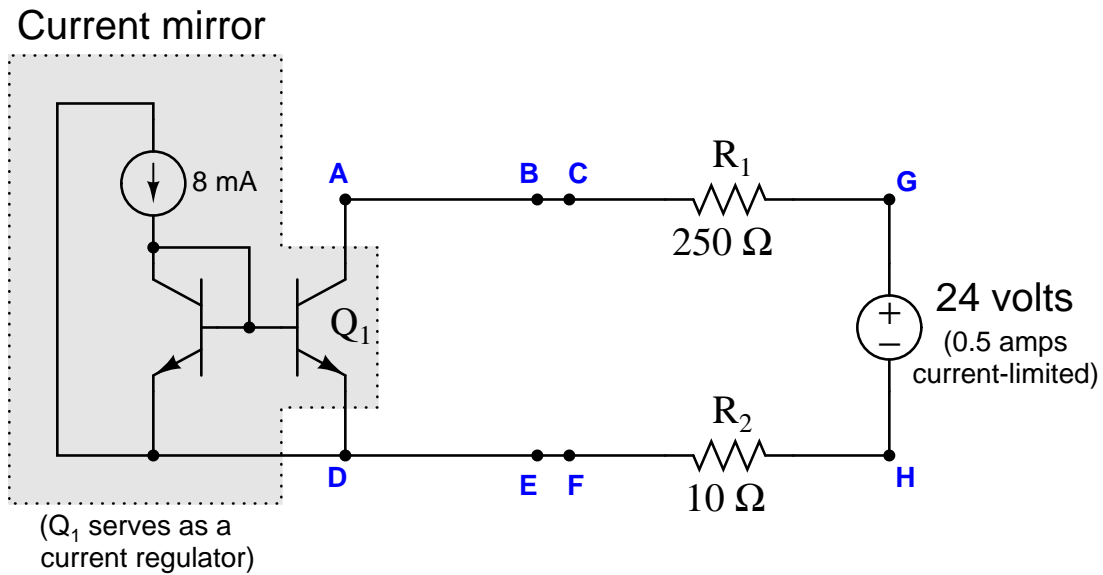
Current mirror

8 mA

R_1
250 Ω

24 volts
(0.5 amps current-limited)

R_2
10 Ω

Q_1

(Q$_1$ serves as a current regulator)

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		
Q_1 failed open		
R_1 failed shorted		
R_2 failed shorted		
Q_1 failed shorted		
Voltage source dead		
Current 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 i00439

Lab Exercise

Your task is to commission, document, and successfully operate a process controlled by a recording PID controller. Several alternative process types exist and are documented in subsequent pages. The working process you commission will be used in future lab exercises this quarter to meet other learning objectives, which means you will *not* disassemble this project at the completion of these lab objectives as you normally would.

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

Objective completion table:

Performance objective	Grading	1	2	3	4	Team
Team meeting and prototype sketch	mastery	–	–	–	–	
Circuit design challenge	mastery					– – – –
Final loop diagram and system inspection	mastery	0				– – – –
Simulated troubleshooting of 4-20 mA circuit	mastery	0				– – – –
Trend graph displays PV and Output	mastery	–	–	–	–	
PV alarms defined and enabled	mastery	–	–	–	–	
Process exhibits good control behavior	mastery	–	–	–	–	
Safety and professionalism	deduction					
Lab percentage score	proportional					– – – –

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

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

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

Lab Exercise – objectives and expectations

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

Team meeting and prototype sketch

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

Circuit design challenge

Sketch a correct circuit for a 4-20 mA instrument "loop" based on random instrument selections by the instructor and reference manuals for each instrument.

Final loop diagram and system inspection

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

Troubleshooting simulation

Logically diagnose the nature and location of a fault simulated by computer in a 4-20 mA transmitter circuit (either loop-powered or externally-powered), using the TROUBLESHOOT simulation program. Successful completion of this objective consists of identifying the simulated fault at or below "par" in all measures and logically defending each and every step taken.

Trend graph displays PV and Output

Use the trend graph provided by your controller to show both the process variable and output signals graphed in real time. If your controller does not provide this function, you must connect a data acquisition unit (DAQ) or a digital oscilloscope to the proper circuit points to graph representative voltage signals.

PV alarms defined and enabled

Activate and set process variable high and low values to serve as warnings for anyone operating the control system, alerting them when the PV has drifted too high or too low.

Process exhibits good control behavior

Adjust the P, I, and/or D parameters in your loop's controller to achieve stable automatic-mode control for both varying setpoint values and varying process loads.

Lab Exercise – objectives and expectations (continued)

Lab percentage score

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

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

Safety and professionalism (deduction)

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

General format and philosophy

This lab exercise is *project-based:* the instructor serves as the project engineer, while each student's role is to implement the standards set for the project while budgeting time and resources to complete it by the deadline date. Students perform real work as part of the lab exercise, managing their work day and functioning much the same as they will on the job. The tools and equipment and materials used are all industry-standard, and the problems encountered are realistic. This instructional design is intentional, as it is proven effective in teaching project management skills and independent working habits.
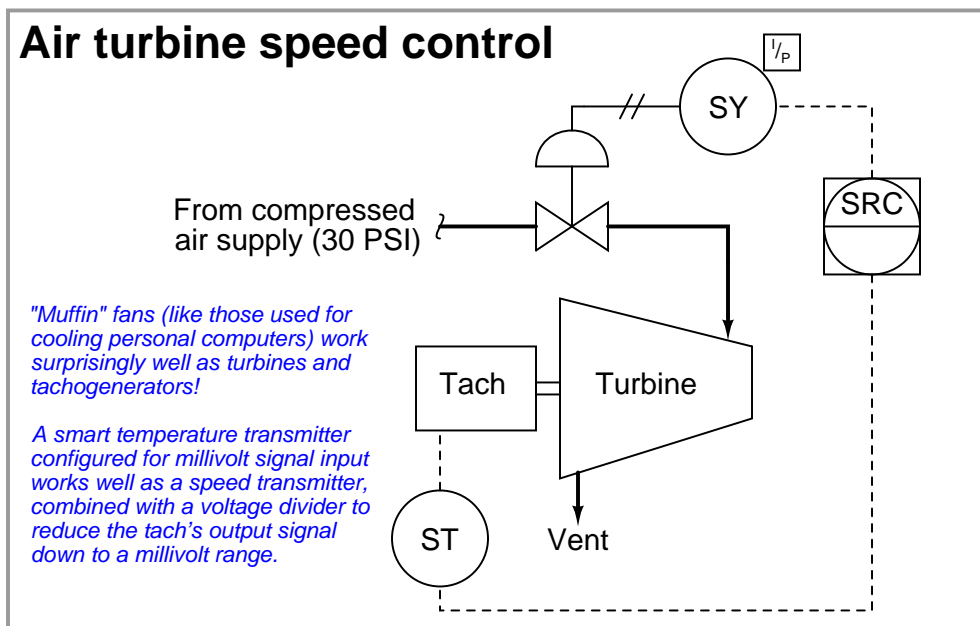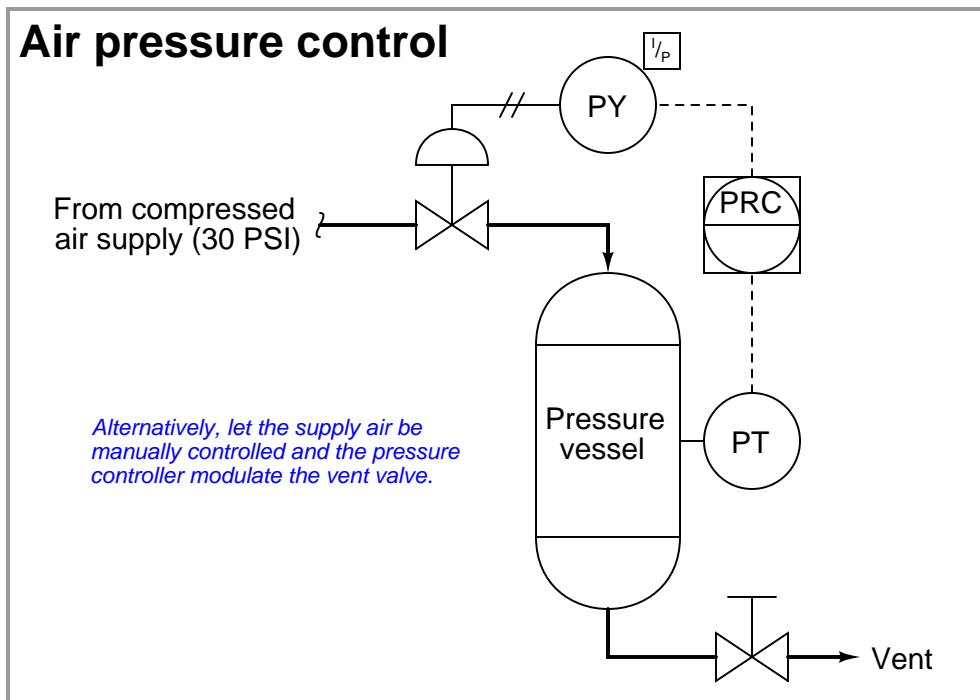
When you require the instructor's assistance to answer a question or to check off an objective, write your name (or your team's name) on the lab room whiteboard. Questions take priority over checkoffs, so please distinguish questions from other requests (e.g. writing a question-mark symbol "?" after your name makes this clear). **There will be times when you must wait for extended periods** while the instructor is busy elsewhere – instant service is an impossibility. Adequate time *does* exist to complete the lab exercise if you follow all instructions, communicate well, and work productively. Use all "down time" wisely: filling it with tasks not requiring the instructor's assistance such as other lab objectives, homework, feedback questions, and job searches.

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

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

**Lab Exercise – choosing a process to commission**

There are a number of process types to choose from when selecting the one you will commission with your team. The only non-negotiable limitations is that the process must be safe, legal, and possible to complete in the time allotted for this lab. A number of process units have already been constructed on 2' × 2' plywood boards, but you are welcome to construct your own. Your instructor may assign new process units to be constructed or modified, time permitting. What follows are some examples of physical processes (documented in P&ID form) that work well for the purpose of exploring closed-loop control in the lab:

Air pressure control

From compressed air supply (30 PSI)

Alternatively, let the supply air be manually controlled and the pressure controller modulate the vent valve.

Pressure vessel

PY   PRC   PT

Vent

Air turbine speed control

From compressed air supply (30 PSI)

"Muffin" fans (like those used for cooling personal computers) work surprisingly well as turbines and tachogenerators!

A smart temperature transmitter configured for millivolt signal input works well as a speed transmitter, combined with a voltage divider to reduce the tach's output signal down to a millivolt range.

SY   SRC

Tach   Turbine

ST   Vent

Water level control

Fountain-style water pumps work well for this purpose, so long as the total pumping height (head) is not too great.

Alternatively, let the in-flow be manually controlled and the level controller modulate the drain valve.

LY

I/P

LRC

LT

Bypass
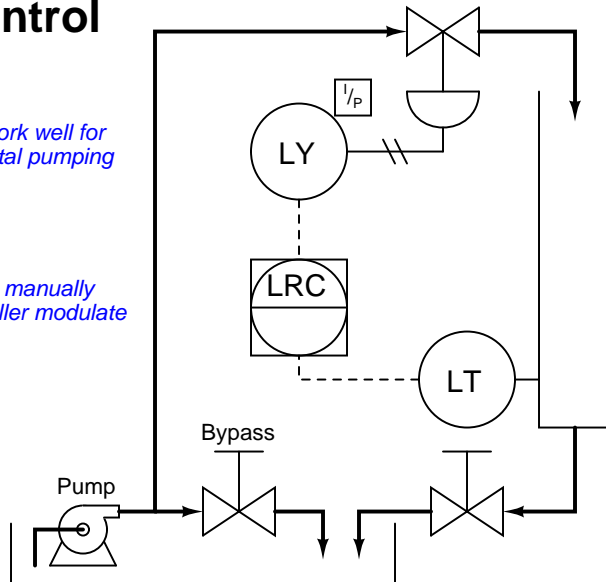
Pump

# Water flow control

Fountain-style water pumps work well for this purpose, so long as the total pumping height (head) is not too great.

Simple venturi tubes may be fabricated using bell reducers and straight pipe sections, in either plastic or metal.

Alternatively, let the venturi flow be manually controlled and the flow controller modulate the bypass valve.

√

FT

I/P

FY

FRC

Bypass

Pump
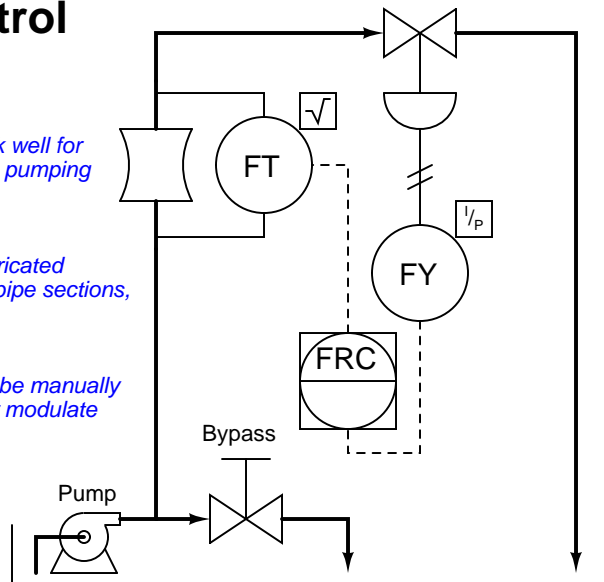
Oven temperature control

A cheap electric toaster oven or convection oven works well for this purpose. The only "hard-to-find" part is the power controller (JC) which modulates AC power to the heating element in accordance with the temperature controller's 4-20 mA output signal.

TT   TRC

TZ (PWM)

Convection oven
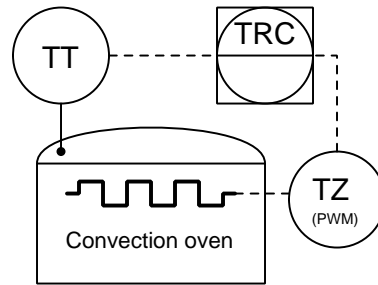
Solar air heater control

For the purposes of this lab exercise, the solar collector may be made out of cardboard with clear plastic food wrap as the cover material.

Paint the inside of the collector flat black for maximum heat absorption capability.

Use a variable-frequency motor drive (VFD) if the fan is turned by an AC motor. If using a DC fan (e.g. computer cooling fan), you may use a simpler PWM power controller.

TT   TRC

TZ (VFD or PWM)

Collector

Air fan
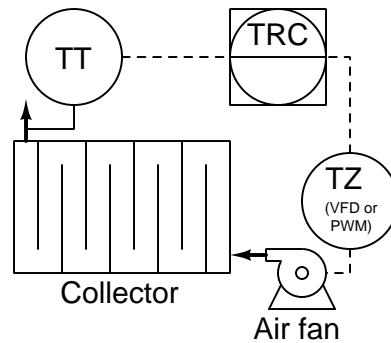
Other process ideas include:

- Soldering iron temperature control (blowing air over tip with variable-speed fan).

- Draft pressure control (controlling very low air pressure inside of a box).

- Pneumatic piston height control (using lengths of PVC pipe to build a simple piston/cylinder which may be used to lift small weights using modest air pressures). A good way to control air pressure to the piston is to route the I/P transducer's output to a *volume booster* relay and let the relay's output directly drive the piston. Piston height may be sensed using a flexible water tube attached to the piston rod, running to a stationary pressure transmitter.

- Sterno-fired air heat exchanger.

- Miniature steam boiler. *Note: this is an advanced project!*

- Air/Fuel ratio burner control. *Note: this is an advanced project!*

- Servomechanism position control. *Note: this is an advanced project!*

- Inverted pendulum balance. *Note: this is a <u>very</u> advanced project!*

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

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

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

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

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

When selecting field instruments for this lab exercise, choose a *transmitter* suitable for measuring your process variable, and likely an *I/P converter* used to convert the controller's 4-20 mA output signal into an air pressure that a control valve may operate on. Electronic process controllers are in several locations throughout the lab, ready to be used for controlling processes. Your instructor will help you select appropriate instruments for the process you have chosen.

You may also need a *data acquisition unit* (*DAQ*) or a digital oscilloscope set to a very slow timebase value to function as a trend recorder. When used with a personal computer and connected properly to the loop circuit, either device will provide graphical displays of loop variables over time. Students usually find the connection of a DAQ unit or oscilloscope to their loop controller to be the trickiest part of their loop wiring. You will need to consult the manufacturer documentation on the DAQ/scope as well as the field instruments and controller in order to figure out how to wire them together. Even if your process controller already provides trending capability, you may find connection of a DAQ or oscilloscope to your loop circuits a useful exercise because the ability to quickly connect and use these tools to monitor electrical parameters in a system is a valuable diagnostic skill in this career.

You will find your teammates who have already taken the Measurement course series (INST24X) will be very helpful in showing you how to check, configure, calibrate, and install the measuring instrument(s) you will need for your process!

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

Lab Exercise – circuit design challenge

Your instructor will choose one 4-20 mA field instrument and one control system from the lists shown below, for which you must sketch and annotate an accurate circuit diagram showing how the two instruments would connect to each other. If this interconnection between controller and field instrument requires additional electrical components to function (e.g. DC or AC power source, precision 250 Ω resistor, diode, relay, etc.), those must be incorporated into your diagram as well. The required annotation will consist of denoting all expected directions of current (marked by arrows pointing in the direction of conventional flow) and all expected voltage polarities (marked by + and − symbols), as well as identifying all electrical sources and loads as such. Instruction manuals for all instrument listed are available on the electronic Instrumentation Reference for your convenience. When your sketch is complete, you must show the relevant manual pages to your instructor for verification of correct connections.

This exercise tests your ability to locate appropriate information in technical manuals, to sketch a correct 4-20 mA loop circuit for a given pair of instruments, and to correctly annotate all voltages and currents. The electronic Instrumentation Reference will be available to you in order to answer this question.

Since all 4-20 mA "loops" are basically series DC circuits, it is highly recommended that you approach their design the same as for any other DC circuit: carefully identify all *sources* and *loads* in the circuit, trace directions of all currents, and mark the polarities of all voltages. Most of the mistakes made in this type of circuit design challenge may be remedied by careful consideration of these specific circuit-analysis details.

4-20 mA transmitter options

- Pressure
  - → Rosemount 1151 Alphaline (analog), 1151 HART, or 3051 HART
  - → Yokogawa DPharp EJX110A or EJX910
  - → Honeywell ST3000
- Level
  - → Rosemount APEX non-contact radar, 3300 GWR, or 5300 GWR
- Temperature
  - → Rosemount 444, 644, 3044, or 3144
  - → Foxboro RTT15 or RTT30
  - → Moore Industries SPT with sourcing (4-wire) 4-20 mA output
  - → Moore Industries SPT with sinking (2-wire) 4-20 mA output
  - → Moore Industries TRX or TDY
- Flow
  - → Foxboro CFT50 coriolis
- Analytical
  - → Rosemount 5081-P (pH)
  - → Daniel 700 gas chromatograph (4 analog output channels)
  - → Foxboro 876PH (pH/ORP/ISE)

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Controller options

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- Monolithic
    - → Siemens 352P
    - → Siemens 353
    - → Foxboro 716C
    - → Foxboro 718TC
    - → Foxboro 762CNA
    - → Moore Industries 535
    - → Honeywell UDC2300
    - → Honeywell UDC3500
- Modular – *you choose the appropriate I/O module*
    - → Siemens 353R
    - → Emerson ROC800 SCADA/RTU
- Distributed Control System (DCS) – *you choose the appropriate I/O module*
    - → Emerson DeltaV with M-series I/O
    - → Emerson DeltaV with S-series I/O
    - → Honeywell Experion with 2MLF series I/O
- Programmable Logic Controller (PLC) – *you choose the appropriate I/O module*
    - → Automation Direct "CLICK"
    - → Siemens S7-300
    - → Rockwell ControlLogix (catalog number 1756)
    - → Rockwell CompactLogix (catalog number 1769)

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4-20 mA Final Control Element options

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- Pneumatic control valve positioners
    - → Fisher 3582i positioner
    - → Fisher DVC6000 positioner
- Electrically actuated valves (MOV)
    - → Limitorque actuator with Modutronic-20 II controller
    - → Rotork AQ with Folomatic controller
- AC motor drives (VFD)
    - → Rockwell PowerFlex 4
    - → Automation Direct GS1

Correct circuit sketch (instructor verifies): ____

Correct voltage annotations (instructor verifies): ____ (+ and − symbols)

Correct current annotations (instructor verifies): ____ (arrows showing conventional flow)

Correct source/load identifications (instructor verifies): ____

Study reference: the "Analog Electronic Instrumentation" chapter of *Lessons In Industrial Instrumentation*, particularly the section on HART.

Lab Exercise – building the system

The Instrumentation lab is set up to facilitate the construction of working instrument "loops," with over a dozen junction boxes, pre-pulled signal cables, and "racks" set up with 2-inch vertical pipes for mounting instruments. These racks also provide structure for building physical processes, with more than enough weight-bearing capacity to hold any process vessels and equipment. The only wires you should need to install to build a working system are those connecting the field instrument to the nearest junction box, and then small "jumper" cables connecting different pre-installed cables together within intermediate junction boxes.

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

Select a specific loop controller for your system. Your instructor may choose the controller for your team, to ensure you learn more than one type of controller during the course of a quarter.

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

Common mistakes:

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

Building a functioning process complete with instrumentation for control typically takes one or two sessions (3 hours each) if all components are readily available and the team is working efficiently!

Notes on instrument ranging

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

The reason this is an issue at all is because loop controllers operating on 4-20 mA analog signals don't "know" what those signals are supposed to represent unless someone configures the controller with the proper range reflecting real-world conditions. For example, if a student is assigned a temperature transmitter with a range of 300 to 800 degrees Fahrenheit, not only does the transmitter have to output 4 mA when sensing 300 ^{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:
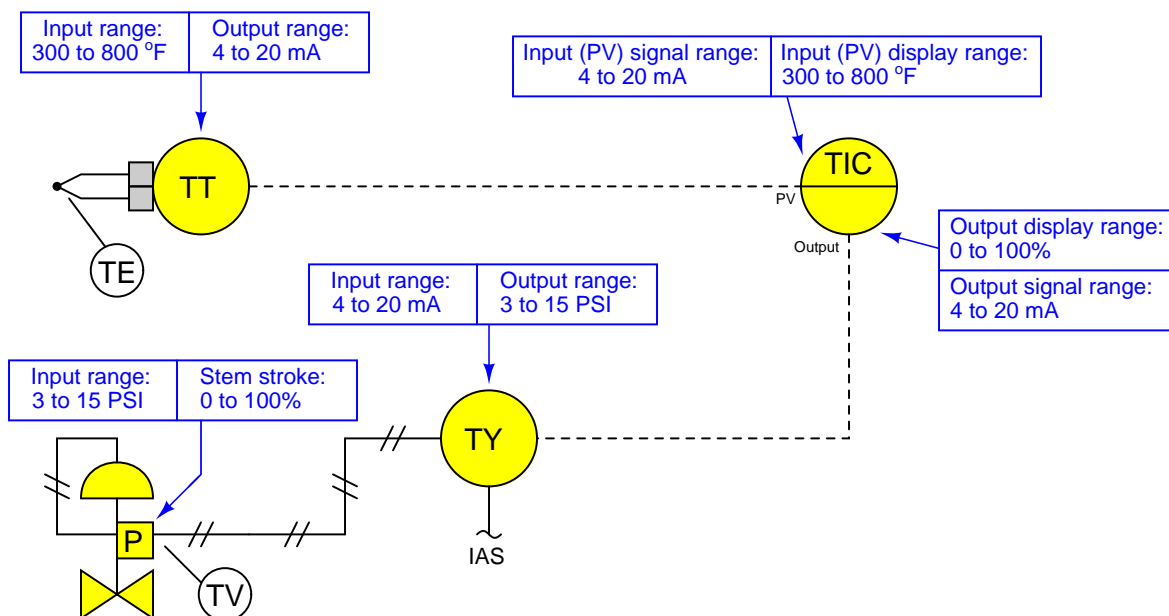
Analog (non-"smart") transmitters, I/P transducers, and valve positioners are ranged using "zero" and "span" adjustments, typically screws or nuts. The ranging of analog instruments is discussed in the "Instrument Calibration" chapter of the *Lessons In Industrial Instrumentation* textbook.

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 <u>not</u> 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 = $pid[0].URV$

<u>file</u> `ranging`

Notes on controller action

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

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

- Siemens/Moore 352 controller: control action parameters are located in the "PID" function block (FB13). Note that the P, I, and D tuning parameters may be quickly accessed by pressing the "Tune" button rather than by entering the PID function block edit menu:
  - → Direction (Direct/Reverse)= *SA1*
  - → Proportional (P) = *SPG1* as a unitless gain value
  - → Integral (I) = *STI1* in units of minutes per repeat
  - → Derivative (D) = *STD1* in units of minutes

- Siemens/Moore 352P and 353 controller: control action parameters are located in the "PID" function block (PID). Note that the P, I, and D tuning parameters may be quickly accessed by pressing the "Tune" button rather than by entering the PID function block edit menu:
  - → Direction (Direct/Reverse)= *DIR ACT*
  - → Proportional (P) = *PG* as a unitless gain value
  - → Integral (I) = *TI* in units of minutes per repeat
  - → Derivative (D) = *TD* in units of minutes

- Emerson DeltaV DCS: control action parameters are located in the "PID" function block (PID) conforming to the FOUNDATION Fieldbus standard:
  - → Direction (Direct/Reverse)= Found in the *CONTROL_OPTS* set of parameters as a "check-box" where a checked box sets direct action and an unchecked box sets reverse action.
  - → Proportional (P) = *GAIN* as a unitless gain value
  - → Integral (I) = *RESET* in units of seconds per repeat
  - → Derivative (D) = *RATE* in units of seconds

- Honeywell UDC 2500 controller: control direction is located in the "CONTRL" set-up group of parameters, while the PID tuning coefficients are located in the "TUNING" set-up group of parameters:
  - → Direction (Direct/Reverse)= *Action*
  - → Proportional (P) = *PB* or *Gain* as a proportional band percentage or as a unitless gain value, respectively
  - → Integral (I) = *I Min* or *I RPM* in units of minutes or repeats per minute, respectively
  - → Derivative (D) = *Rate T* in units of minutes

- Automation Direct "SOLO" controller: process variable range parameters are located in the following registers:
  - → Direction (Direct/Reverse)= *P3-7 Heating/Cooling*
  - → Proportional (P) = *P1-4 Proportional band* as a proportional band percentage
  - → Integral (I) = *P1-5 Integral time* in units of seconds
  - → Derivative (D) = *P1-6 Derivative time* in units of seconds

- Allen-Bradley PLC5, SLC500, and MicroLogix controllers: control action parameters are located in the "PID" instruction. A YouTube video on our BTCInstrumentation channel shows how to do this for the networked MicroLogix PLCs in the lab (reading the PV on the first analog input and sending the output to the first analog output of the I/O card):
  - → Direction (Direct/Reverse)= Found in the *Control Mode* field where E=PV−SP represents direct action and E=SP−PV represents reverse action.
  - → Proportional (P) = *Controller Gain K_c* as a unitless gain value
  - → Integral (I) = *Reset T_i* in units of minutes per repeat
  - → Derivative (D) = *Rate T_d* in units of minutes

- Allen-Bradley Logix5000 controller: control action parameters are located in the "PID" instruction (PID):
  - → Direction (Direct/Reverse)= *E* where PV−SP represents direct action and SP−PV represents reverse action.
  - → Proportional (P) = K_p or K_c as a unitless gain value
  - → Integral (I) = K_i in units of seconds per repeat
  - → Derivative (D) = K_d in units of minutes

- caSCADA "`pid`" control program: control action parameters are located on the operator interface screen, above the trend graph. This control program may be initiated from the Linux command line by typing `./pid` and pressing the Enter key. Once the `pid` control program is running (reading the PV on analog input AIN0 and sending the output to analog output DAC0 of the LabJack DAQ), each parameter may be selected by pressing the `S` key as often as needed, and the parameter values changed by pressing the arrow and page up/down keys. Note that the control direction may only be switched while the controller is in manual mode. Tuning parameters may be altered in either manual or automatic modes.
  - → Direction (Direct/Reverse)= will either show "`Direct-acting`" or "`Reverse-acting`"
  - → Proportional (P) = `K_P` as a unitless gain value
  - → Integral (I) = `K_I` in units of repeats per minute
  - → Derivative (D) = `K_D` in units of seconds

Notes on controller tuning

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

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

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

file `control`

Lab Exercise – loop diagram and system inspection

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

Construction Standards

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

Documentation Standards

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

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

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

Common mistakes:

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

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

Lab Exercise – troubleshooting

An important aspect of this lab exercise is *troubleshooting*, where you demonstrate your ability to logically isolate a fault in a simulated circuit. You will use the open-source software called TROUBLESHOOT for this objective, which natively runs on the Linux operating system and is already installed on the caSCADA nodes in the main lab room (under the /tshoot directory). You may also compile and run this free software natively on an Apple personal computer, or if running Windows you may install the free Cygwin emulator complete with development tools and use that to compile and run TROUBLESHOOT.

The TROUBLESHOOT software offers multiple simulated circuits to select, *the particular circuit for this lab exercise being specified earlier in this outline.* The software tracks every step you take, and the amount of time taken for each step. Scores are given at the end for such metrics as number of steps taken, total "cost" incurred (with different cost values associated with different actions), and total time taken. The software also provides reasonable "par" scores for each of the randomly-selected faults.

Included with every installation of TROUBLESHOOT is a set of PDF files, each one depicting the schematic diagram for a simulated circuit. It is advisable for you to print a paper copy of this schematic so that you can easily annotate measurements you take during the simulation.

In order to successfully pass this objective, you must start up the simulation in the instructor's presence, document the randomly-selected circuit values on paper (in order to later verify it is the exact same simulation scenario), complete the simulation on your own, and then logically defend each of your steps (recounted by the software after your declaration of the fault). You must meet or improve upon *all* of the "par" values given by the software. Like all mastery objectives, multiple re-tries will be permitted. You are also welcome to practice using this software on your own before committing to a graded demonstration.

Failure to achieve all par scores, or failure to apply logical reasoning to the defense of every step take, or simple failure to identify the random fault will disqualify the effort, in which case you must re-try with a different (random) fault.

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:

- Not practicing the use of the TROUBLESHOOT software.
- Relying on voltage measurement across a suspected open wire to confirm that it has failed open. This test only works if there are no other opens (e.g. "off" switch, blown fuse, etc.) in that circuit!

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!

Lab Exercise – PV alarms

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 to serve as warnings to the operator. A good general recommendation is to set the PV high alarm to 90% and the PV low alarm to 10%, unless specified otherwise by the project engineer (i.e. your instructor). While "tuning" your process for optimal performance, you may determine it to be most stable within a certain range of PV values, in which case you are free to set the high and low alarm limits to the boundary values for that stable range.

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.

Alarm settings are especially important when *tuning* a controller, to delineate how far the PV is allowed to stray without adversely affecting the process. This will become an important performance criteria in the *next* lab exercise when students individually tune PID controllers for different processes.

Lab Exercise – operating the system

All networked loop controllers in the lab (DCS, DDC, PLC, single-loop networked) provide graphing functionality so that you may plot your process variable (PV) and output values over time. This graphical data is essential for tuning PID-controlled loops. If you happen to be using a controller that does not provide graphing capability, your team must attach a trend recorder and/or a data acquisition unit (plus a personal computer) to the necessary signal cables so that these values are recorded over time.

PID tuning is a subject worthy of its own course, and so you will not be expected to achieve perfect control on your process. You will find, however, that one of the best ways to learn PID tuning is by "playing" with your process as it responds to different tuning parameters entered into the loop controller. The expectation for "good control behavior" in the context of this lab exercise is for the loop to exhibit response that is no less stable following large setpoint changes than the classic "quarter-wave damping" described by Ziegler and Nichols in their 1942 paper.

Most student-built processes are quite safe to operate. However, if your process harbors any unique hazards (e.g. overflowing water may present a slip hazard, overheated oven may cause materials to smoke or burn), you must be aware of these hazards and limit everyones' exposure to them. All team members for each process must be familiar with the inherent hazards of their process and how to mitigate them. One operational step to help avoid problems is to configure the controller for *setpoint limits* preventing the setpoint value from being placed at "dangerous" values in automatic mode. Just what these setpoint limit values should be set to varies with the process and the team's experience operating it.

As your time with the process builds, you will no doubt arrive at ideas for improving it. Feel free to work with your team to optimize the process in any way you see fit. The goal is to have your process as robust and "problem-free" as possible for other teams to use it in later coursework!

A tendency of students when they first learn to tune PID control loops is to proceed carelessly because they know the "toy" processes they are learning to tune aren't going to harm anything if their PVs go out of bounds. While this assumption might be true for your team's process, it is not good to form or reinforce bad habits. Thus, the inclusion of alarm point(s) on your process PV – especially if connected to some form of signaling device that is annoying and/or embarrassing to trip such as a loud buzzer – makes for a better teaching tool for others learning PID tuning!

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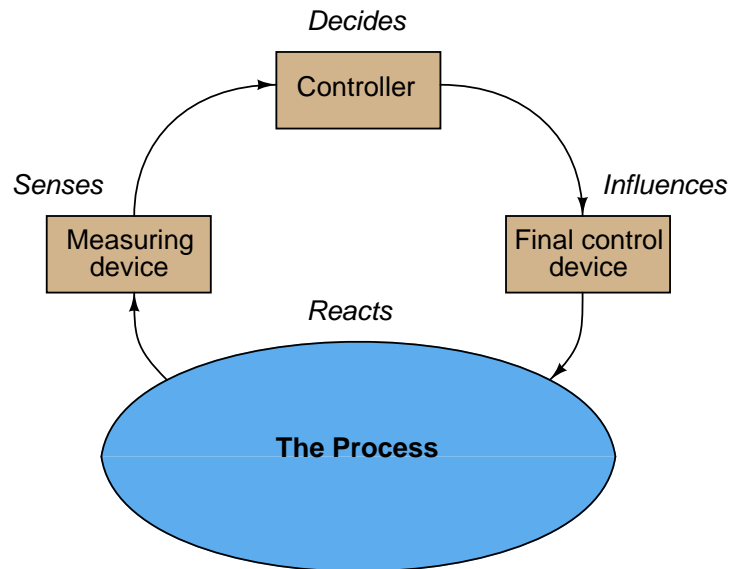
You can check each element of your feedback control loop by comparing its input with its output to see if each element is doing what it should:

(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.

A crude closed-loop PID tuning procedure

Tuning a PID controller is something of an art, and can be quite daunting to the novice. What follows is a primitive (oversimplified for some situations!) procedure you can apply to many processes.

Step 1

Understand the process you are trying to control. If you do not have a fundamental grasp on the nature of the process you're controlling, it is pointless – even dangerous – to change controller settings. Here is a simple checklist to cover before touching the controller:

- What is the process variable and how is it measured?
- What is the final control element, and how does it exert control over the process variable?
- What safety hazards exist in this process related to control (e.g. danger of explosion, solidification, production of dangerous byproducts, etc.)?
- How far am I allowed to "bump" the process while I tune the controller and monitor the response?
- How is the controller mode switched to "manual," just in case I need to take over control?
- In the event of a dangerous condition caused by the controller, how do you shut the process down?

Step 2

Understand what the settings on the controller do. Is your controller configured for gain or proportional band? Minutes per repeat or repeats per minute? Does it use reset windup limits? Does rate respond to error or PV alone? You had better understand what the PID values do to the controller's action if you are going to decide which way (and how much) to adjust them! Back in the days of analog electronic and pneumatic controllers, I would recommend to technicians that they draw little arrow symbols next to each adjustment knob showing which way to turn for more aggressive action – this way they wouldn't get mixed up figuring out gain vs PB, rep/min vs min/rep, etc.: all they had to think of is "more" or "less" of each action.

Step 3

Manually "bump" the manipulated variable (final control element) to learn how the process responds. In manual mode, *you* are the controller! What you need to do is adjust the process to learn how it responds: is it an integrating process, a self-regulating process, or a runaway process? Is there significant dead time or hysteresis? Is the response linear and consistent? Many process control problems are caused by factors other than the controller, and this "manual test" step is a key diagnostic technique for assessing these other factors.

Step 4

Set the PID constants to "minimal" settings and switch to automatic mode. This means gain less than 1, no integral action (0 rep/min or maximum min/rep), no derivative action, and no filtering (i.e. damping).

Step 5

"Bump" the setpoint and watch the controller's response. This tests the controller's ability to manage the process on its own. What you want is a response that is reasonably fast without overshooting or undershooting too much, and without undue cycling. The nature of the process and the constraints of quality standards will dictate what is "too much" response time, over/undershoot, and cycling.

Step 6

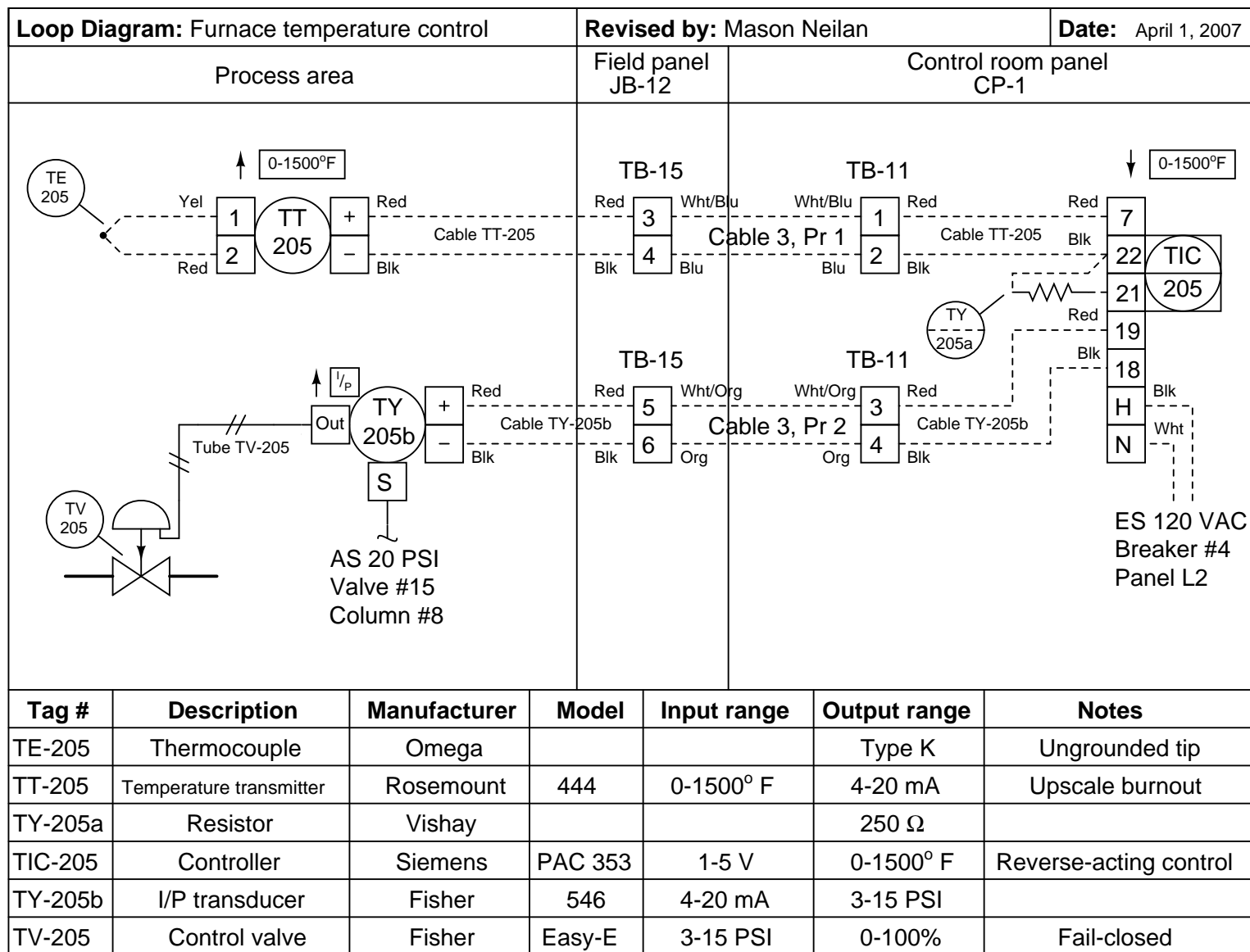Increase or decrease the control action aggressiveness according to the results of Step 5.
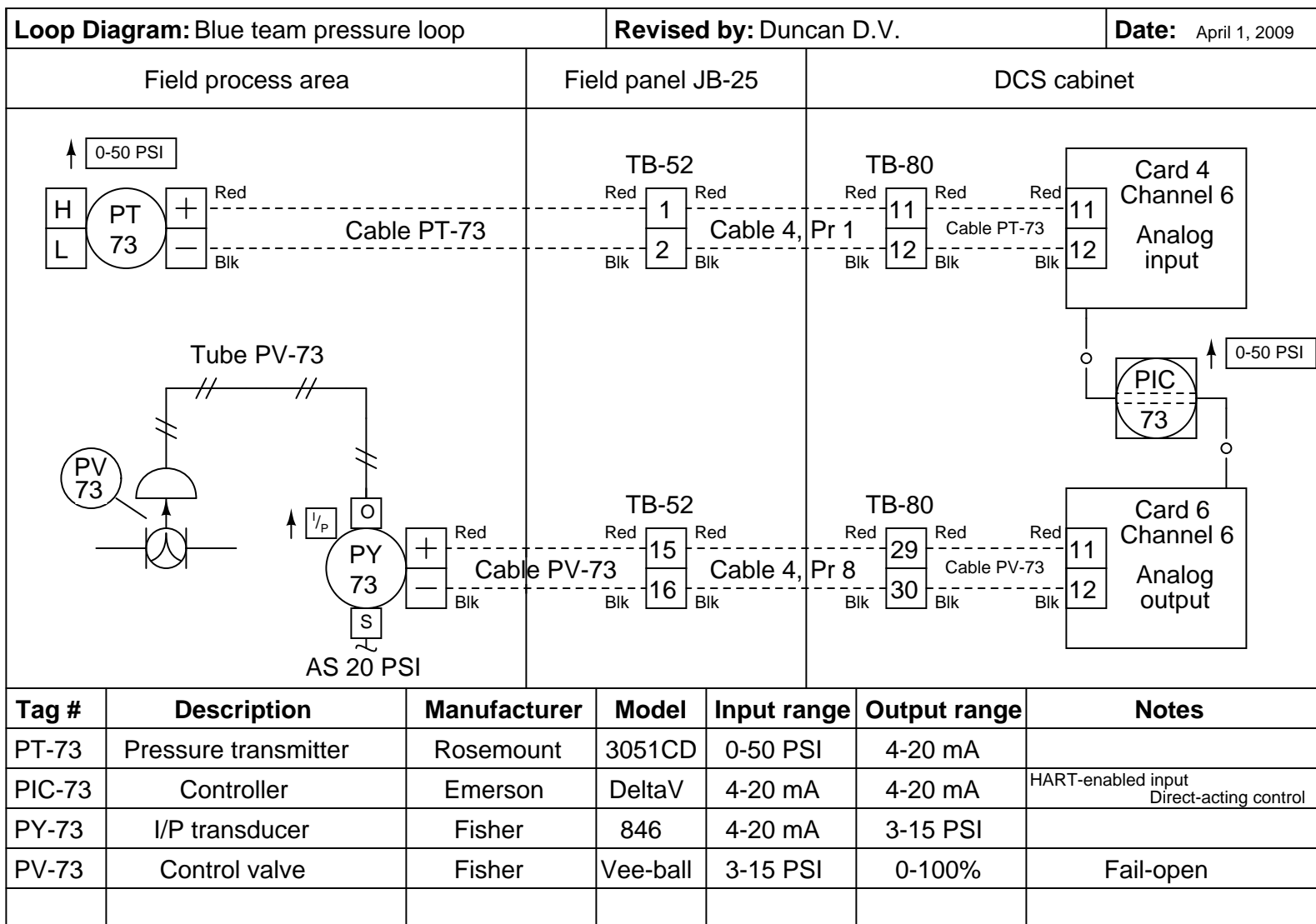
Step 7

Repeat steps 5 and 6 for P, I, and D, one at a time, in that order. In other words, tune the controller first to act as a P-only controller, then add integral (PI control), then derivative (PID), each as needed.
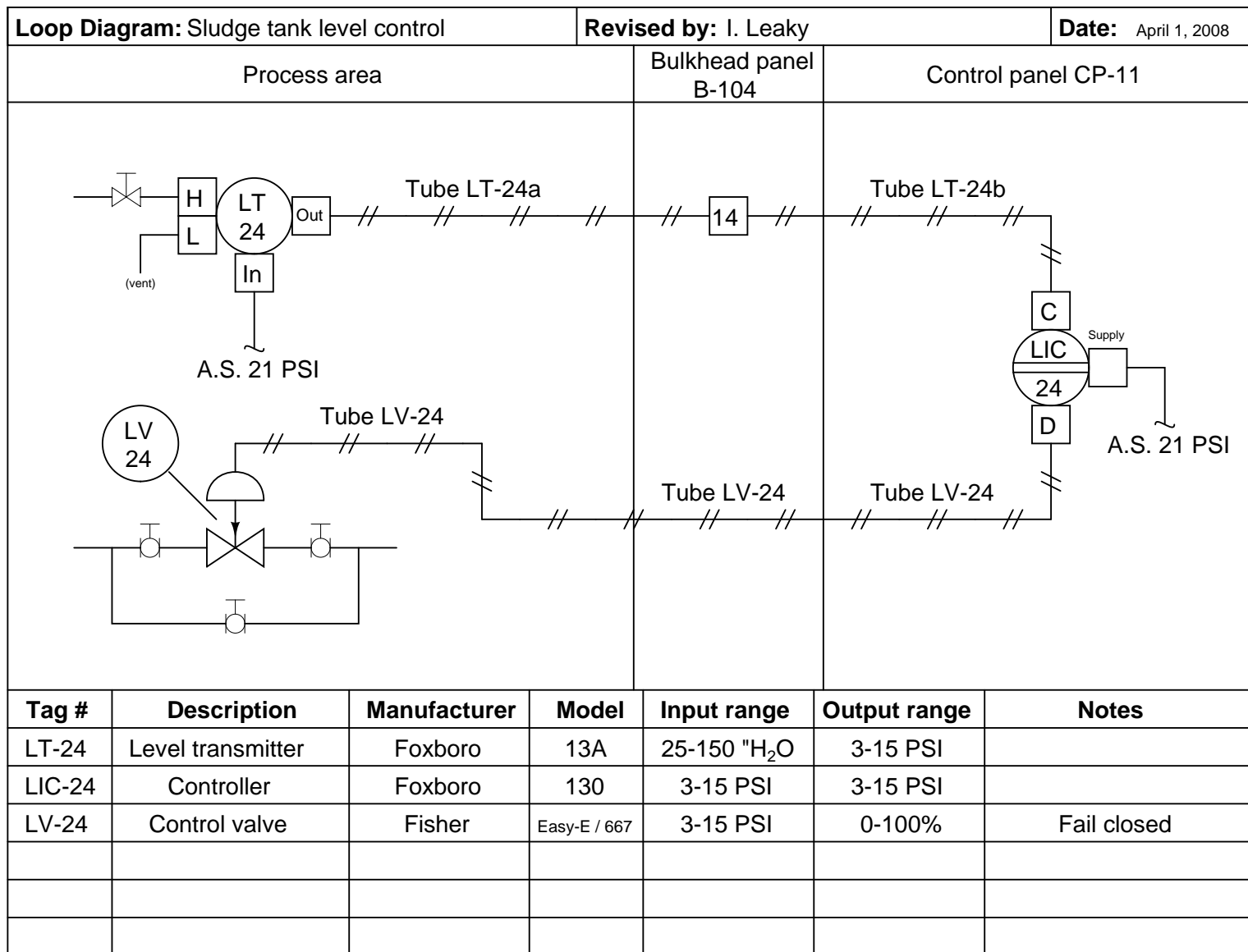
Step 8

"Bump" a load in the process and watch the controller's response. This tests the controller's ability to manage variations in process load over time. A controller's response to load changes will often differ from its response to setpoint changes. You still want controller response that is reasonably fast without overshooting or undershooting too much, and without undue cycling. However, you may have to find some compromise in tuning between good setpoint response and good load response. How you decide that compromise depends on whether the controller really needs to respond mostly to setpoint changes (e.g. the slave controller of a cascade loop) or to load changes.

Step 9

Increase or decrease the control action aggressiveness according to the results of Step 8.

Step 10

Repeat steps 8 and 9 for P, I, and D, one at a time, in that order. In other words, tune the controller first to act as a P-only controller, then add integral (PI control), then derivative (PID), each as needed.
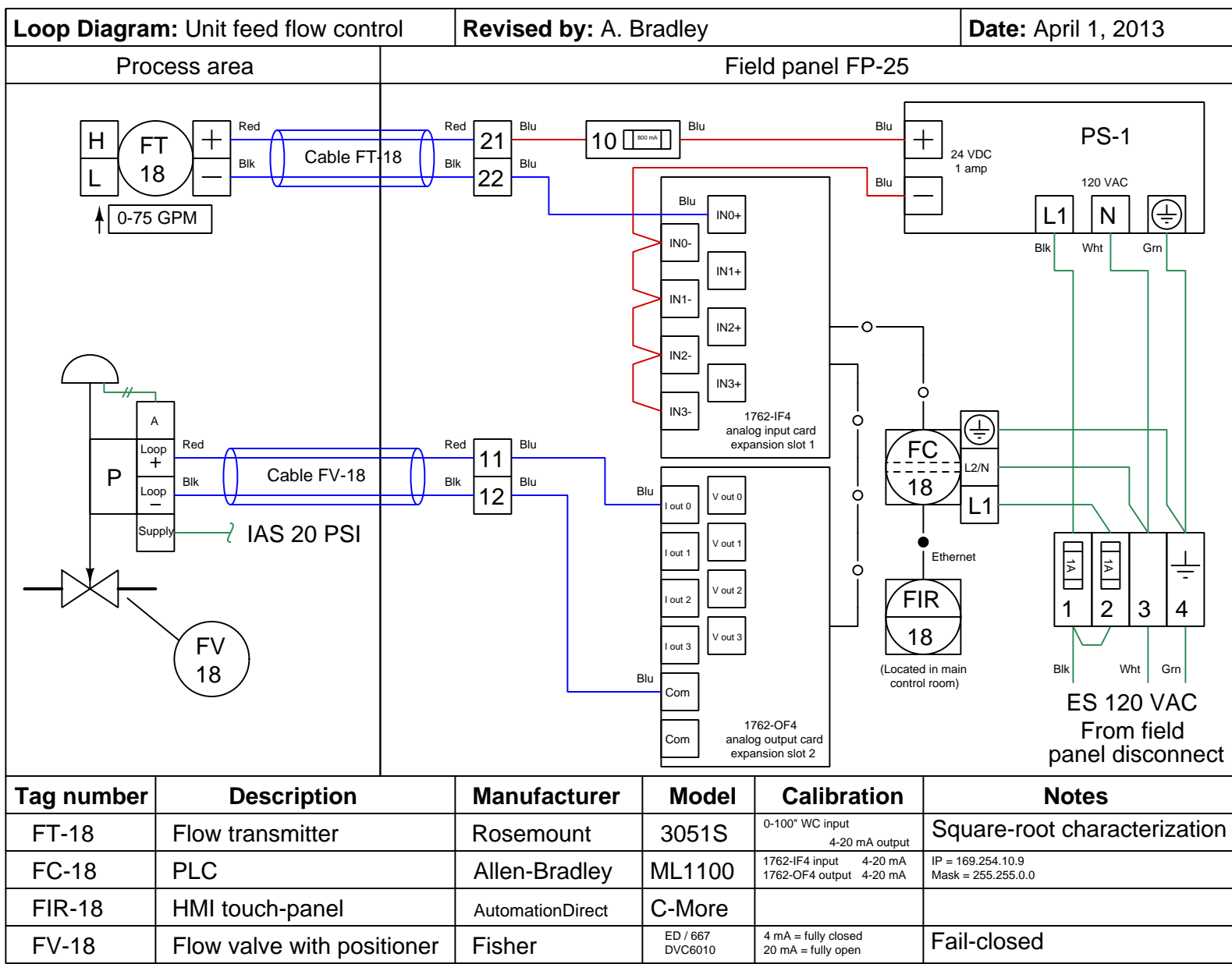
<div align="center">**Caveats**</div>

The procedure described here is *very* crude, and should only be applied as a student's first foray into PID tuning, on a safe "demonstration" process. It assumes that the process responds predominantly to proportional (P-only) action, which may not be true for some processes. It also gives no specific advice for tuning based on the results of step 3, which is the mark of an experienced PID tuner. With study, practice, and time, you will learn what types of processes respond best to P, I, and D actions, and then you will be able to intelligently choose what parameters to adjust, and what closed-loop behaviors to look for.

file i01558

Loop Diagram: Furnace temperature control | **Revised by:** Mason Neilan | **Date:** April 1, 2007

Process area | Field panel JB-12 | Control room panel CP-1

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

Loop Diagram: Blue team pressure loop	**Revised by:** Duncan D.V.	**Date:** April 1, 2009
Field process area	Field panel JB-25	DCS cabinet

0-50 PSI

H / L   PT 73   + / −   Red / Blk

Cable PT-73

TB-52
Red / Red
1
2
Blk / Blk

Cable 4, Pr 1

TB-80
Red / Red   Red
11
12
Blk / Blk   Blk

Cable PT-73

11
12

Card 4 Channel 6 Analog input

Tube PV-73

PIC 73   0-50 PSI

PV 73

I/P

PY 73   + / −   O / S   Red / Blk

Cable PV-73

AS 20 PSI

TB-52
Red / Red
15
16
Blk / Blk

Cable 4, Pr 8

TB-80
Red / Red   Red
29
30
Blk / Blk   Blk

Cable PV-73

11
12

Card 6 Channel 6 Analog output

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

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

Tube LT-24a

Tube LT-24b

H
L
LT 24
Out

(vent)

In

A.S. 21 PSI

14

C
LIC
24
D

Supply

A.S. 21 PSI

LV 24

Tube LV-24

Tube LV-24

Tube LV-24

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

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

Process area	Field panel FP-25

H
L
FT
18
+
−
0-75 GPM
Red
Blk
Cable FT-18
Red
Blk
21
22
Blu
Blu
10
800 mA
Blu
Blu
Blu
+
−
24 VDC
1 amp
PS-1
120 VAC
L1 N
Blk Wht Grn

Blu
IN0+
IN0-
IN1+
IN1-
IN2+
IN2-
IN3+
IN3-
1762-IF4
analog input card
expansion slot 1

A
Loop +
Loop −
Supply
P
Red
Blk
Cable FV-18
Red
Blk
11
12
Blu
Blu
Blu
IAS 20 PSI

FV
18

I out 0
I out 1
I out 2
I out 3
V out 0
V out 1
V out 2
V out 3
Com
Com
Blu
Blu
1762-OF4
analog output card
expansion slot 2

FC
18
L2/N
L1
Ethernet

FIR
18
(Located in main
control room)

1A 1A
1 2 3 4
Blk Wht Grn
ES 120 VAC
From field
panel disconnect

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

Lab Exercise – loop diagram and system inspection

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

Construction Standards

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

Documentation Standards

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

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

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

Common mistakes:

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

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

file i00654

Answers

Answer 1

Answer 2

Proportional-only offset will cause this controller's process variable to settle at some value slightly *greater* than setpoint.

Answer 3

The problem here is that steam flow controller FC-188 is having trouble maintaining setpoint. I'll let you figure out possible causes for this problem.

Answer 4

Answer 5

Proportional-only offset is the phenomenon that occurs with a controller lacking any integral ("reset") action, whereby the process variable cannot perfectly achieve most setpoint values, but rather will settle at some stable value that is offset from setpoint. The degree of offset between PV and SP is a function of the controller's bias value and process load(s).

Answer 6

Answer 7

Answer 8

Answer 9

Answer 10

$$c = A_V(a - c)$$

$$c = A_V a - A_V c$$

$$c + A_V c = A_V a$$

$$c(1 + A_V) = A_V a$$

$$c = \frac{A_V a}{1 + A_V}$$

$c = 4.999750012$ volts when $a = 5.0000$ volts (exactly) and $A_V = 20{,}000$.

Increasing the intrinsic differential gain of the opamp will decrease the "error" between output and input.

Answer 11

I will answer this question with another question: imagine if the controller actually *did* attain the new setpoint value of 250 GPM. If it did, what would the valve position be in this condition of equilibrium where both SP and PV are equal to 250 GPM? Now, compare this with the valve position when both SP and PV were equal to 180 GPM. Do you see now why PV = SP = 250 GPM is impossible?

Challenge question: what effect does gain (K_p) have on the controller's inability to attain setpoint values other than 180 GPM?

Answer 12

$$MV = SP - PV + 50\%$$

Answer 13

The effect of a negative K_p value in a digital controller's algorithm would be to reverse the control action (from reverse-acting to direct-acting, or from direct-acting to reverse-acting), because a positive error would *decrease* the output, and vice-versa. This is assuming, of course, that the controller is programmed to accept such values. A wise programmer might make it impossible to enter negative tuning constant values, to avoid confusion from someone accidently entering one and unintentionally reversing the control action.

Answer 14

- PV = 37%; SP = 50%; Output = **66%**
- PV = 92%; SP = 80%; Output = **16%**
- PV = 81%; SP = 75%; Output = **28%**
- PV = 33%; SP = 42%; Output = **58%**
- PV = 79%; SP = 76%; Output = **34%**
- PV = 15%; SP = 20%; Output = **50%**
- PV = 38%; SP = 38%; Output = **40%**
- PV = 0%; SP = 0%; Output = **40%**

Answer 15

In order for a proportional-only controller to adapt to changing process conditions and changing setpoints, its output must change as well. However, the only way a proportional-only controller's output can change is if an error (SP − PV, or PV − SP) develops. This means there must be times when the PV is not always equal to the SP!

Answer 16

The controller outputs a *Pulse-Width Modulated* signal, the duty cycle of the on/off cycling modulating energy input to the process through the heating element.

Answer 17

The calculus operation of *time-integration* mathematically "un-does" differentiation. If we know that flow is nothing more than rate of change of volume with respect to time, an "integrator" circuit should be able to un-do the flow signal to arrive at a volume signal:

$$Q = \frac{dV}{dt} \qquad \text{Flow is the time-derivative of Volume}$$

$$V = \int_0^T Q \, dt \qquad \text{Volume is the time-integral of Flow}$$

A simple analog circuit to perform the time-integral function is shown here:
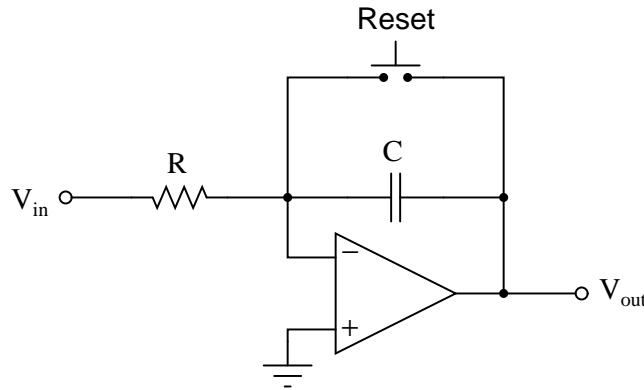
$$V_{out} = -\frac{1}{RC} \int_0^T V_{in} \, dt$$

Of course, we would have to add a lot of extra parts to this circuit to get it ready to receive a 4-20 mA signal in! It should be noted that integration over long time periods is almost always done digitally, due to the problems of drift associated with analog circuitry.

The second technician's idea – to clock a digital counter circuit off the turbine meter's pulse output – would be easier (a simpler circuit) and more practical (less to calibrate).

Answer 18

Answer 19

Answer 20

Answer 21

Answer 22

$\frac{d(\text{Output})}{dt} = -149.8$ mV/s with 0.5 volt error and maximum resistance.

$\tau_i = 3.337$ seconds per repeat (3.337 seconds to "repeat" the 0.5 volt error signal) when the pot is set for maximum resistance.

$\tau_i = 1.669$ seconds per repeat (1.669 seconds to "repeat" the 0.5 volt error signal) when the pot is set for 35.5 kΩ.

Answer 23

Given an error of 6%, and an integral coefficient of 1.6 repeats per minute, the controller output value will ramp at a rate of *9.6% per minute*. Use this ramping rate-of-change as the basis for all your calculations.

Answer 24

Partial answer:

Fault	Possible	Impossible
C_1 failed open		
R_1 failed open		
R_3 failed open		$\checkmark$
R_4 failed open		
C_1 failed shorted	$\checkmark$	
R_1 failed shorted		
R_3 failed shorted		
R_4 failed shorted		$\checkmark$
RLY_1 coil failed open		
U_1 output failed to low supply rail		
U_1 output failed to high supply rail		

Answer 25

Answer 26

Answer 27

Answer 28

Answer 29

Answer 30

I will let you discuss this with your classmates to arrive at an explanation!

Answer 31

$$\frac{dV_{out}}{dt} = -\frac{V_{in}}{RC}$$

. . . or . . .

$$V_{out} = -\frac{1}{RC} \int V_{in} \, dt$$

Follow-up question: why is there a negative sign in the equation?

Answer 32

Impatience is an apt analogy for integral action, because it relates the controller's output to the amount of *time* an error is present between PV and SP. Correspondingly, aggressive integral action may be appropriate for controlling *fast-responding* processes, but not for controlling slow-responding processes.

Answer 33

The output voltage will become increasingly negative at a rate of -1.289 volts per second.

Hint: remember the "Ohm's Law" formula for a capacitor, relating current to the rate-of-change of voltage over time,

$$i = C\frac{dv}{dt}$$

Answer 34

Volume is the time-integral of flow rate, in this system:

$$V = \int Q\, dt$$

Answer 35

+16

Answer 36

+9

Answer 37

-4

Answer 38

- Show where "error" is calculated in the circuit: **At the output of the differential amplifier circuit (module 3)**
- Determine whether this is a direct-acting controller or a reverse-acting controller: **Reverse-acting**
- Identify how to *decrease* the integration time constant (τ_i); i.e. how to *increase* the aggressiveness of integral action: **Smaller capacitor in module 4, lesser potentiometer setting in module 4, increased differential voltage gain in module 3**

Answer 39

Answer 40

Answer 41

It would be a shame for me to provide a ready-made answer for you! Do your best to cast these control modes into your own words, and you will understand them deeper than before.

Answer 42

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:
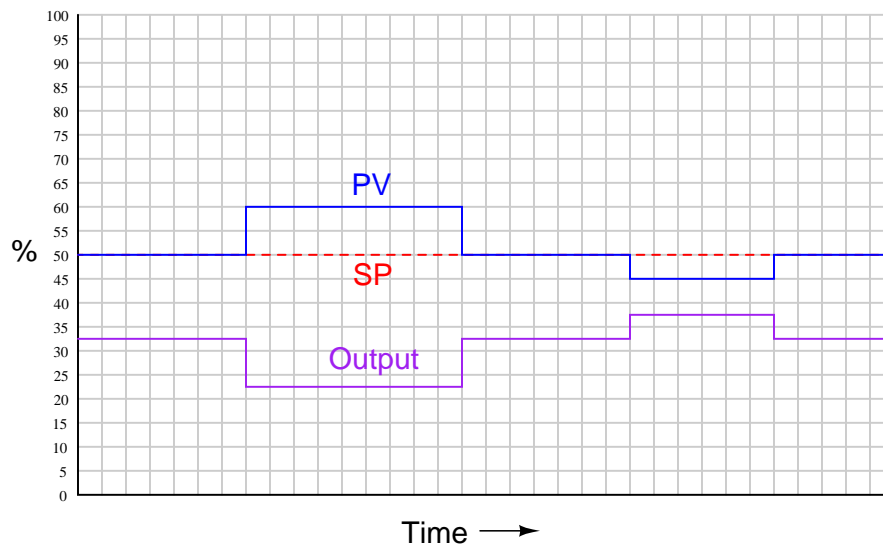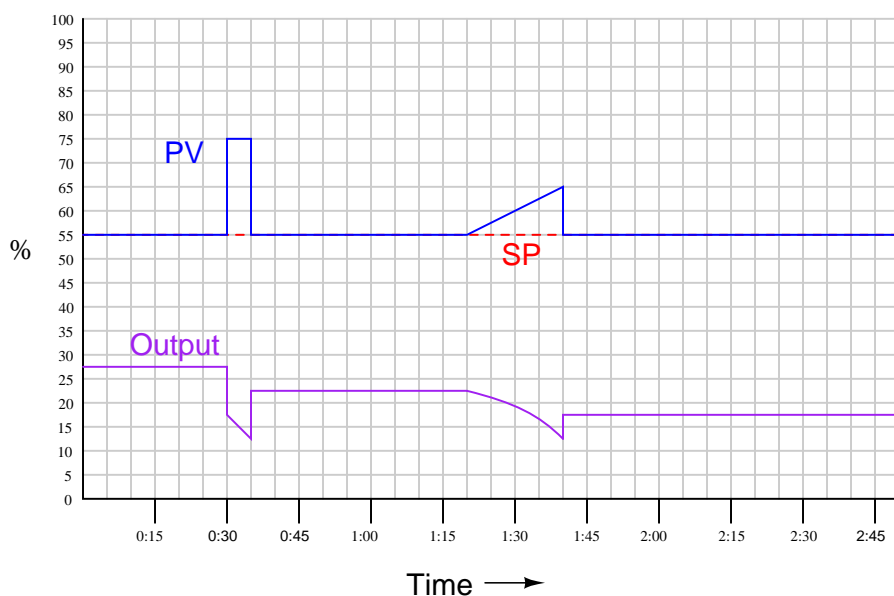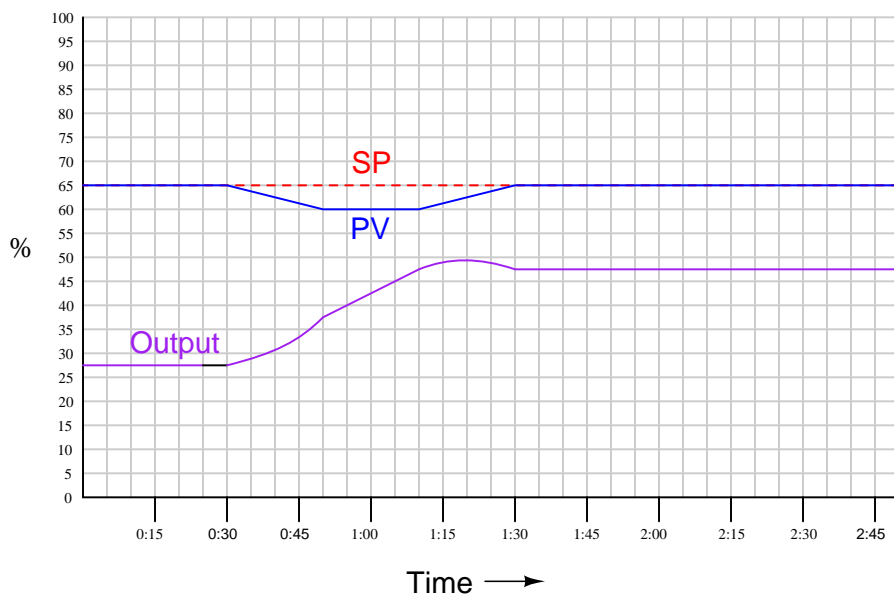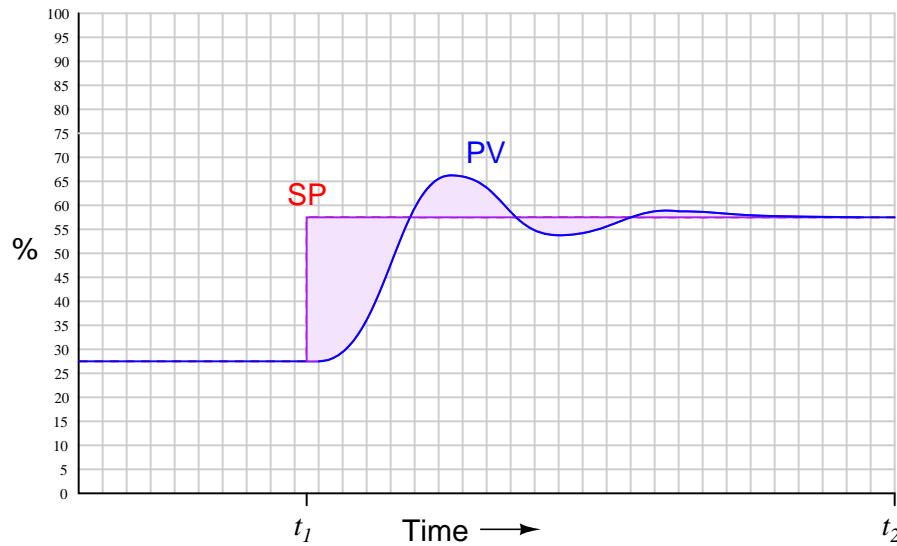

Answer 43

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 44
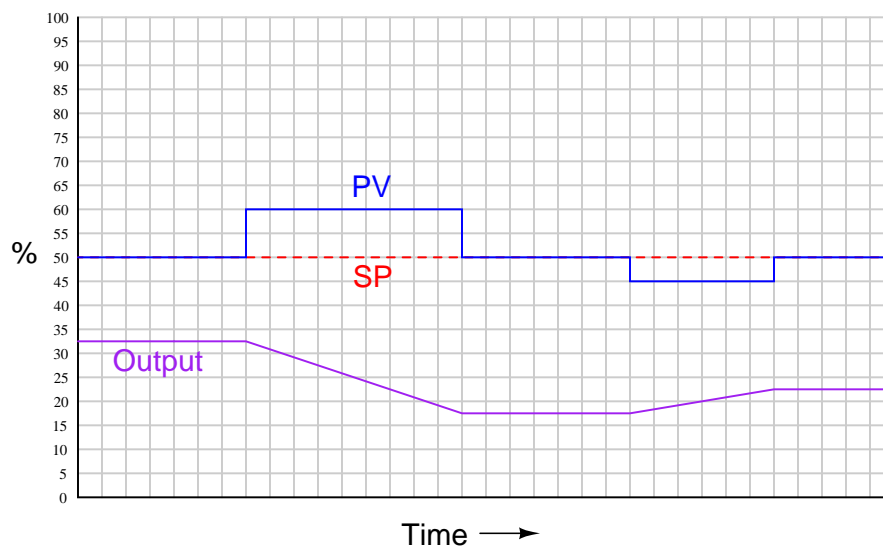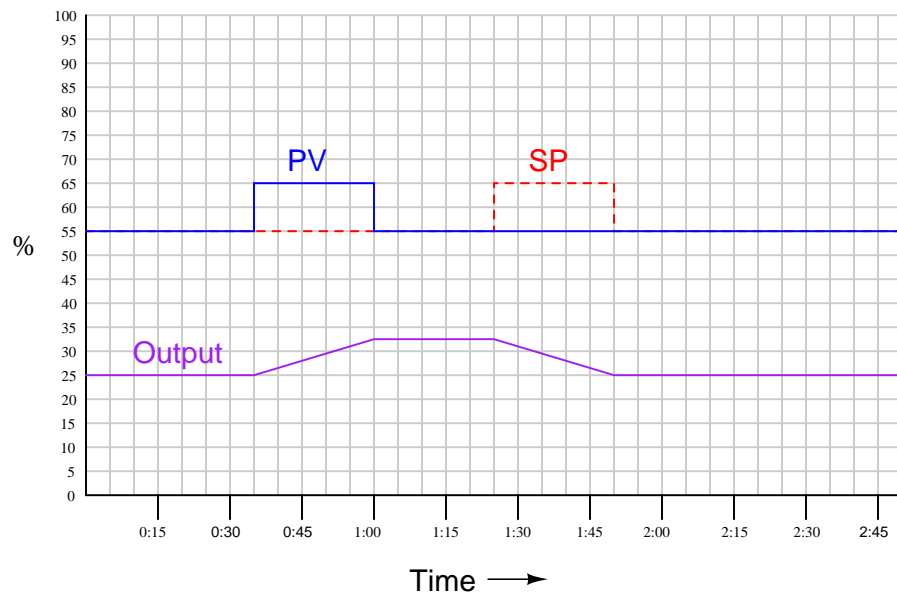
The controller output graph shown here is *qualitative* only. Although drawn to scale (i.e. all changes in the output are properly scaled relative to each other), the scale itself is arbitrary and therefore may not match the scale of your sketch:
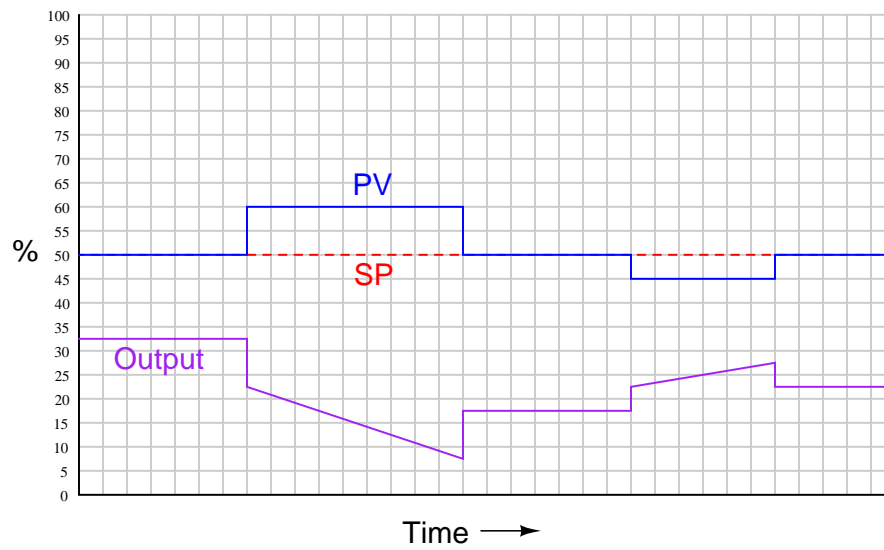
Answer 45

To decrease the controller's proportional band (increase its gain), move the fulcrum further to the left:
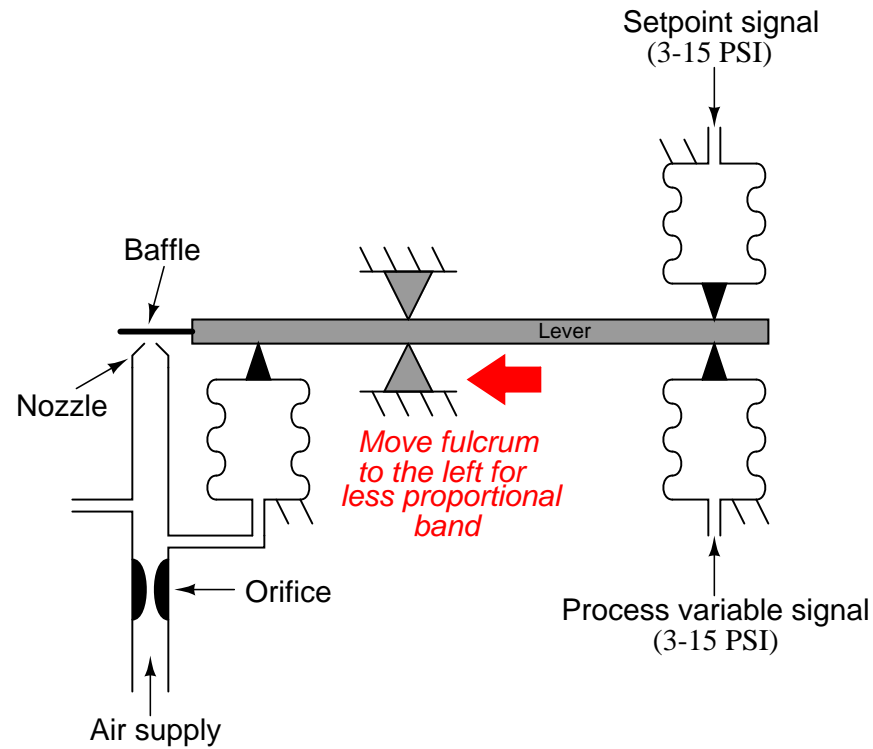
This controller mechanism is direct-acting.

Answer 46

Answer 47

Close off the valve to increase τ_i in this PI controller.

Answer 48

Partial answer:

When SP > PV, the output pressure will steadily rise.

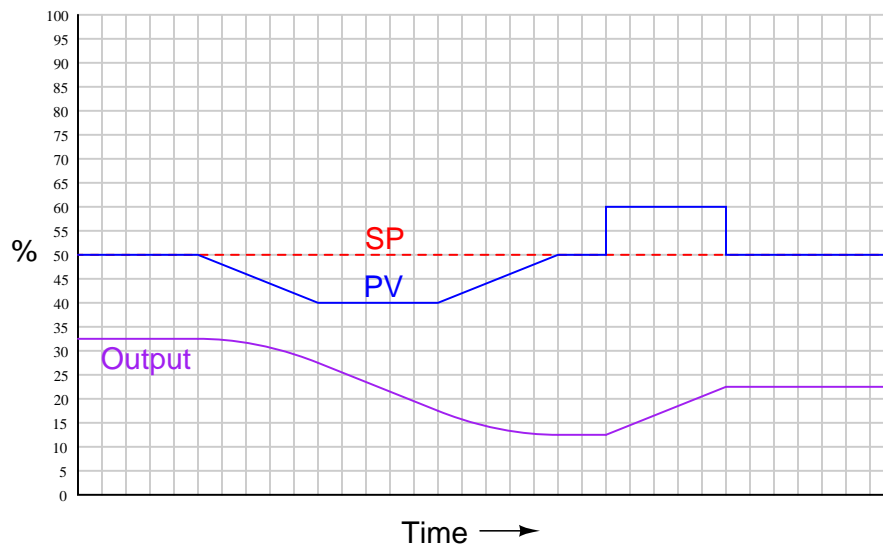## Answer 49

The control valve is most likely sticky.

Answer 50

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:
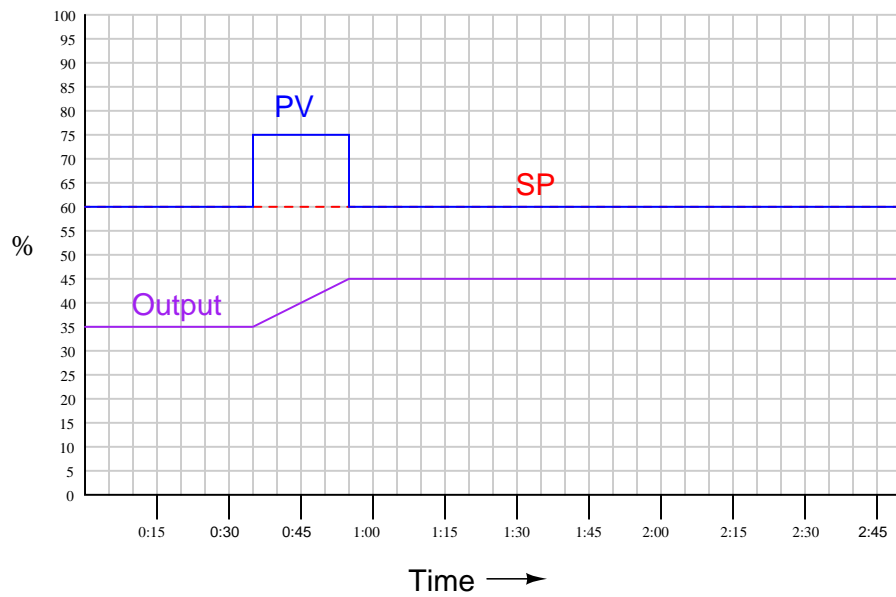
Answer 51

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:
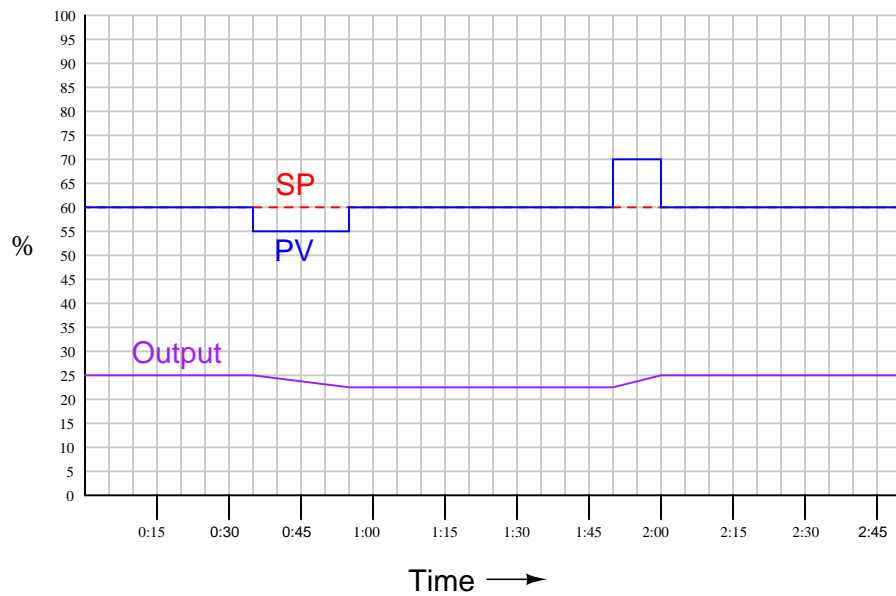
Answer 52

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:
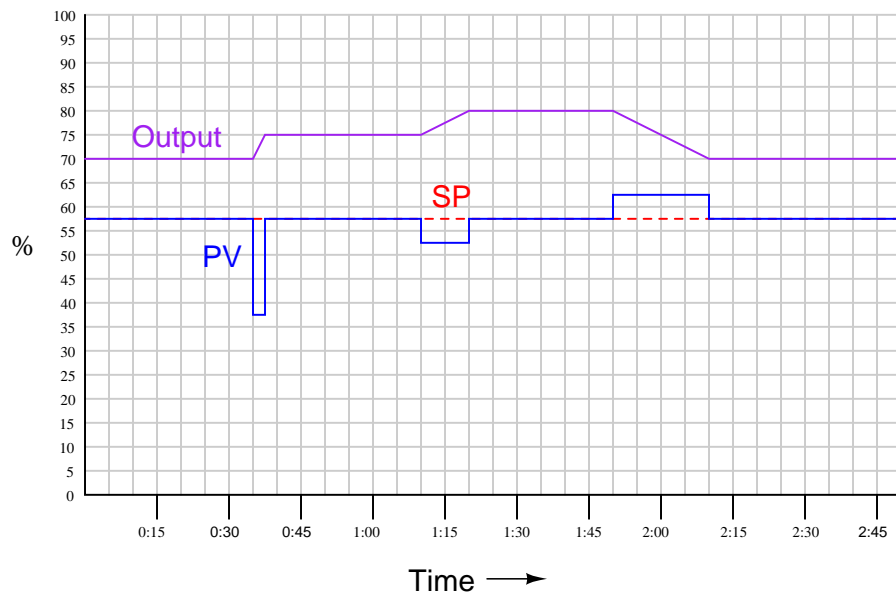
Answer 53

With integral action, the amount of error tells the output how **fast** to go:
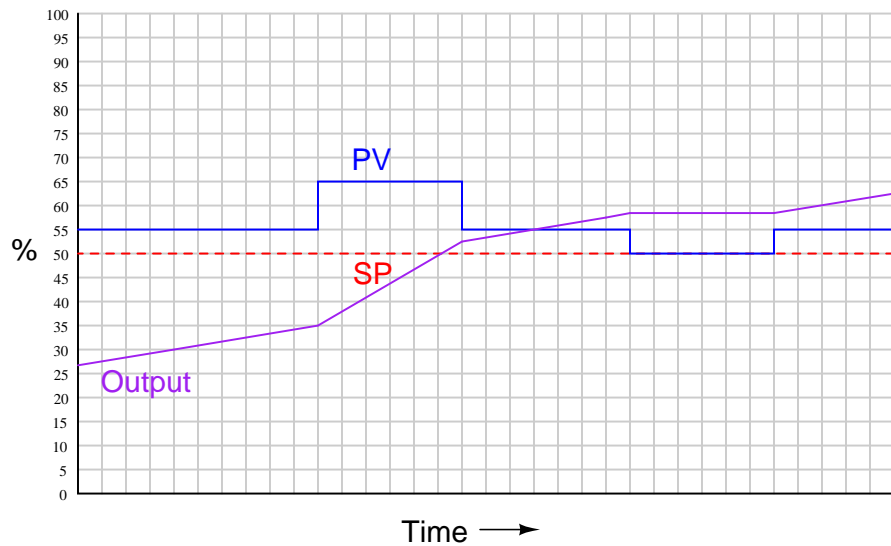
Answer 54

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:
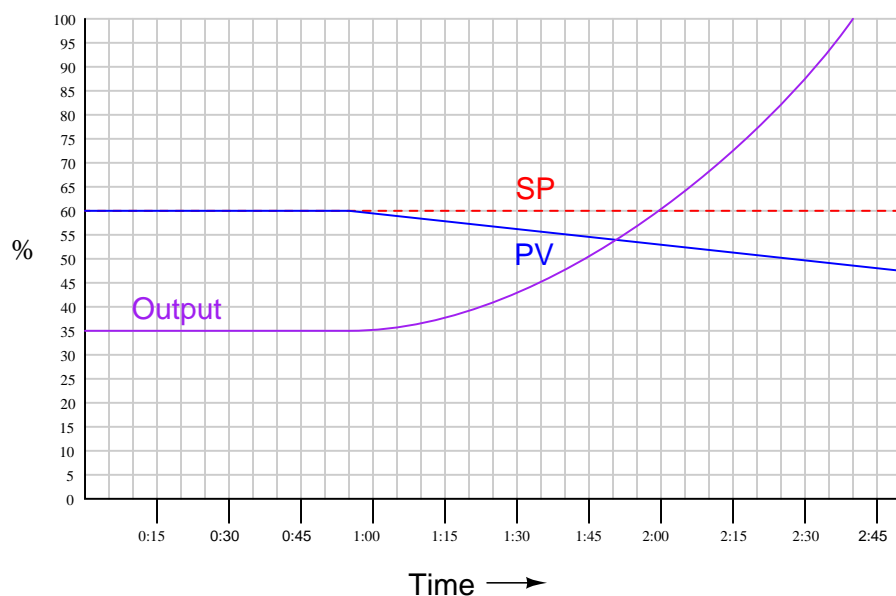
Answer 55

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:
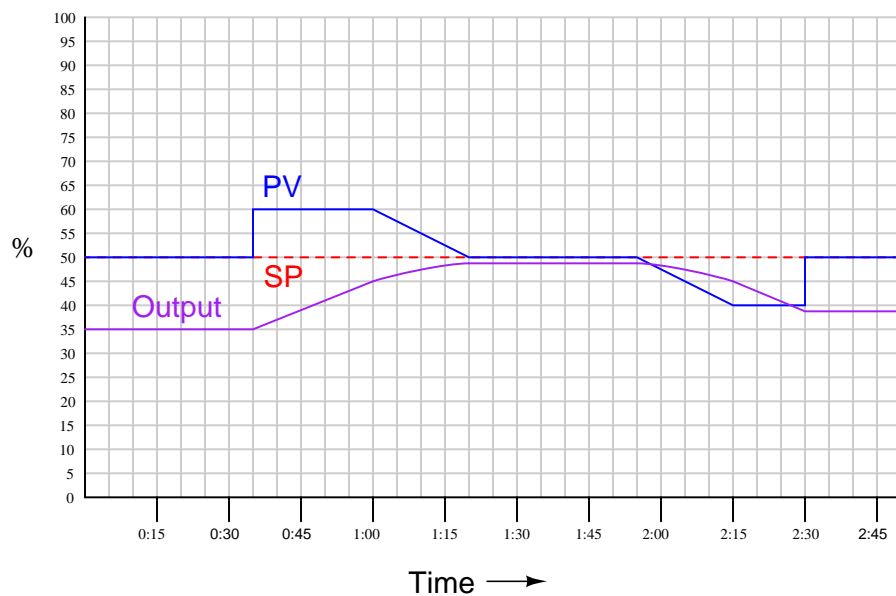
Answer 56

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:
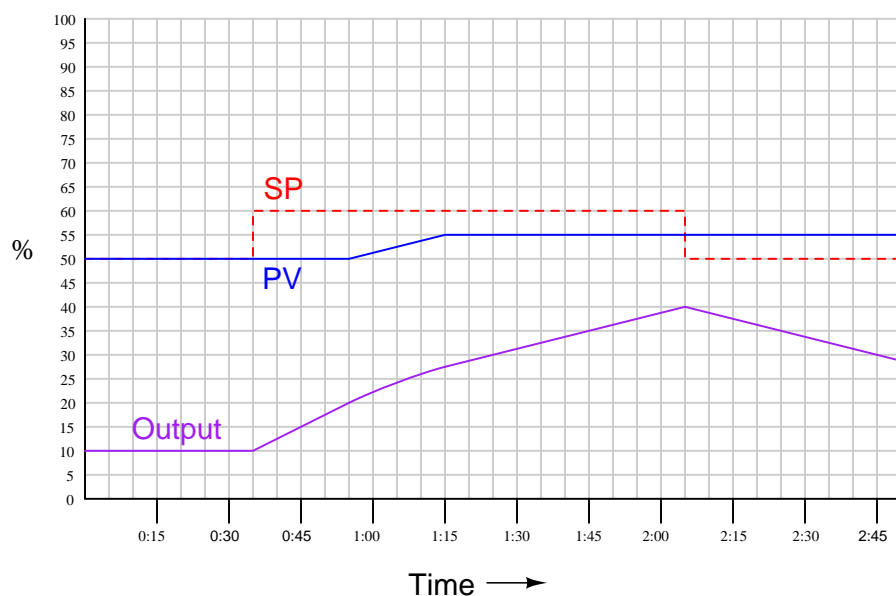
Answer 57

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:
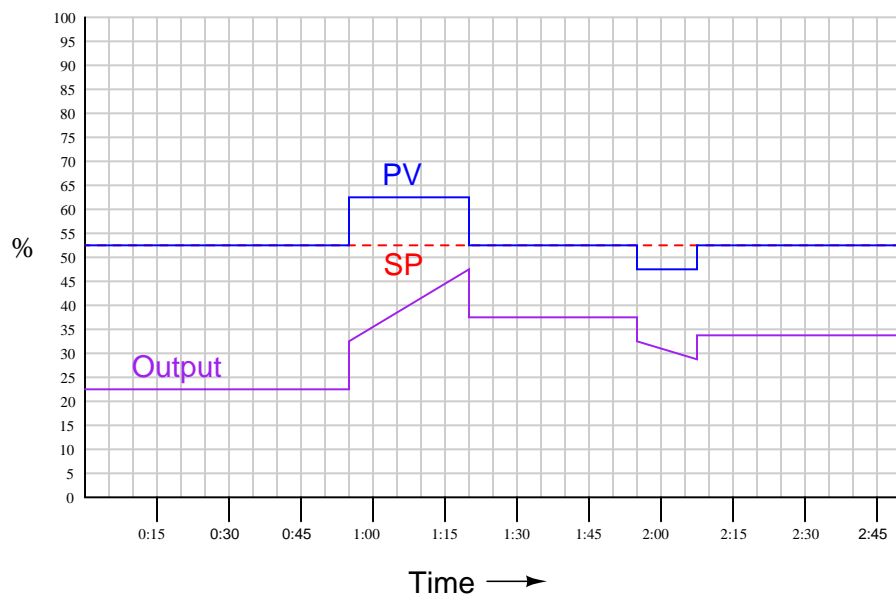
Answer 58

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 59

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 60

Error integrated to measure control quality:

We must integrate the absolute value of the error because otherwise over-shoots and under-shoots would cancel! What we want is a sum-total of all deviations from setpoint, not a canceling average of the highs and lows.

Answer 61

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:

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Answer 62

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 63

Controller action = *reverse*

Gain constant = 0.5

τ_i = 1 minute per repeat (K_i = 1 repeat per minute)

Answer 64

Controller action = *direct*

Gain constant = 1, or 100% proportional band

Integral constant = 0.25 repeats per minute (τ_i), or 4 minutes per repeat (K_i)

Answer 65

The controller will decrease its output signal as it tries to open the air-to-close valve. Both the proportional and integral terms of the controller will work to open the steam valve as the reactor temperature decreases. If there is no steam supply for an extended period of time, the controller's integral action will *wind* to a condition of saturation (3 PSI or less output signal pressure).

Answer 66

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

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

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

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

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

Answer 67

- Gain = 0.769

- Reset = 0.00617 repeats per second

Answer 68

Partial answer:

Totalizing water flow = *integration*. Water flow rate in *gallons per minute*; water quantity in *gallons*.

Answer 69

Partial answer:

Fault	Possible	Impossible
Air supply to LT shut off		
Air supply to LC shut off		√
Pump shut off		√
Broken air line between LT and LC		
Broken air line between LC and LV		
Plugged nozzle inside LC		
Plugged orifice inside LC		√
Leak in bottom of scrubber		

Answer 70

If the flow rate is continually below 190 GPM, the valve will continue to open wider and wider, until (eventually) the "Open limit" switch actuates and stops the motor.

Answer 72
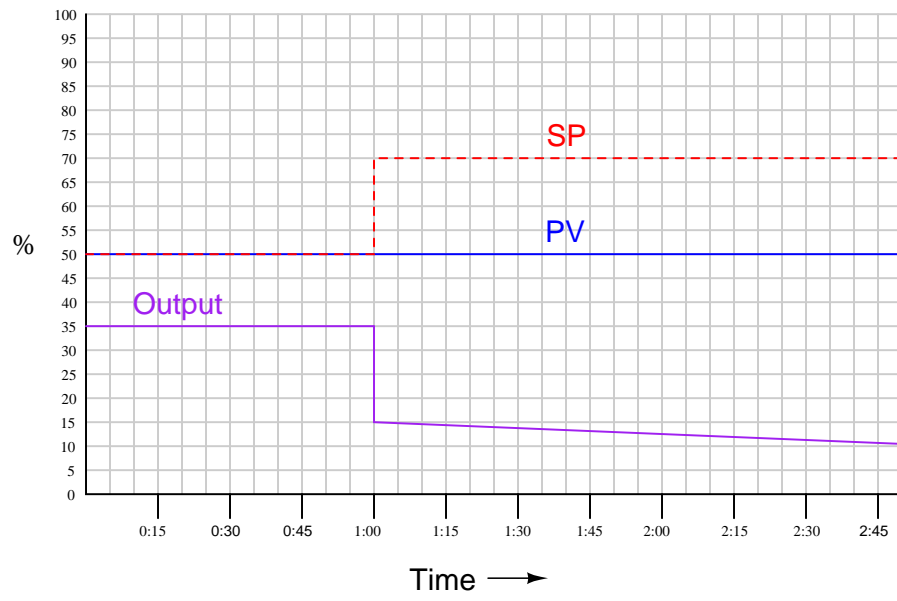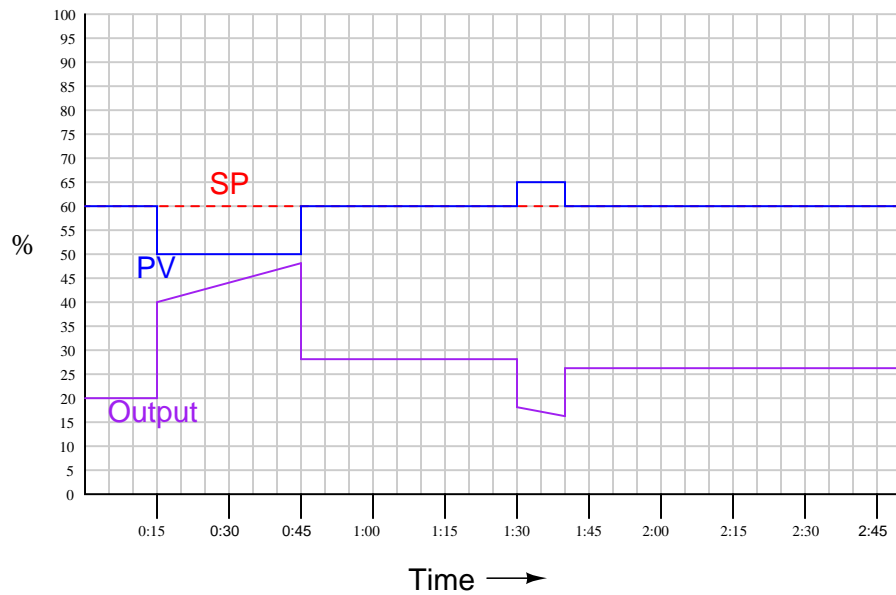
To the PV step-change of -10%, the controller immediately responds with an output step-change of 20% (the proportional band value of 50% is the same as a gain of 2), bringing the output from its original value of 20% to 40%. Then, the continuing error of -10% causes the integral action to ramp the output signal at a rate of 16% per minute (20% proportional response multiplied by 0.8 repeats per minute). Since the -10% deviation between PV and SP only lasts 30 seconds (between 0:15 and 0:45), the output signal only gets the chance to ramp up 8%, bringing the output to a value of 48% at the end of the first deviation period.

Then, when the PV returns to SP (a +10% step-change), the output jumps downward by 20%, leaving the output 8% higher than where it began (28%, from the original value of 20%).

When the next PV step-change arrives at 1:30, the +5% step upwards causes an immediate -10% step in output due to proportional action, bringing the output value to 18%. Integral action, working at a rate of 0.8 repeats per minute, takes the proportional response of -10% and produces an output slope of -8% per minute. Since this step-change period lasts only 10 seconds (1:30 to 1:40), the accumulated output change due to integral is -1.333%, bringing the output down to a final low value of 16.67%. When the PV returns back to SP (jumping down 5%), the output jumps up by 10%, leaving the final output value at 26.67% until the end of the graph.
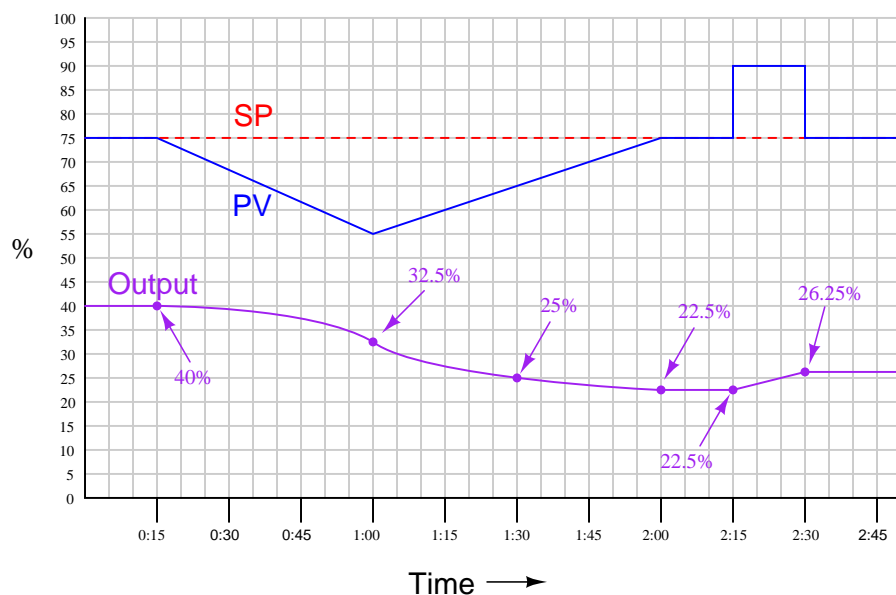
Calculating the integral action during the first phase of the PV's deviation from SP: the area accumulated under the curve between times 0:15 and 1:00 is 7.5 %-min (7.5 "percent-minutes," being the product of percentage deviation times time in minutes). Since the controller has an imaginary gain of 1 and an integral constant of 1 minute per repeat (or 1 repeat per minute), 100% of this accumulation will be contributed to the output, driving it down from 40% to 32.5%. The output signal moves down with the negative error (PV − SP), because this is a direct-acting controller:
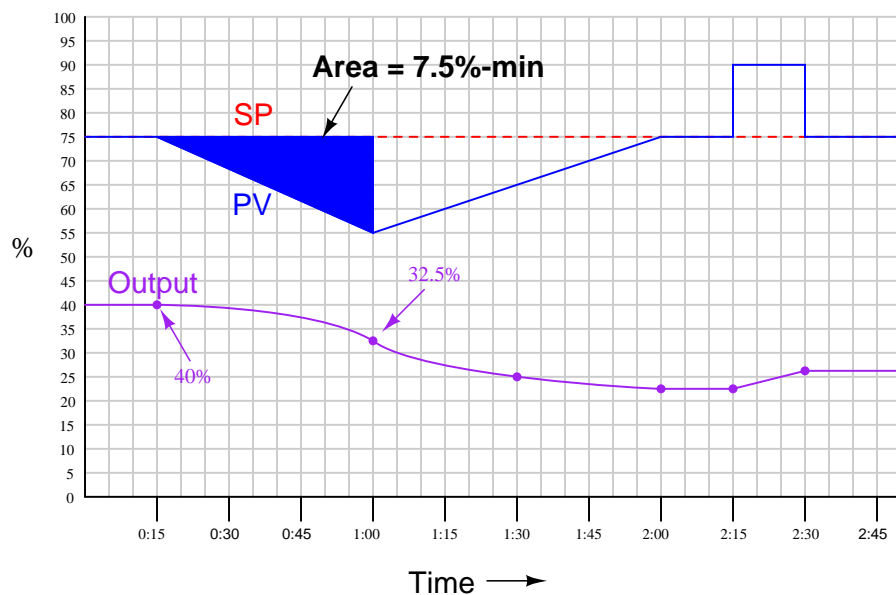
During the next phase of the PV's deviation, the triangular area accumulated is 10%-min (a triangle 20% high on one side, with a length of 1 minute). This drives the controller's output down another 10% at time = 2:00, from 32.5% to 22.5%.

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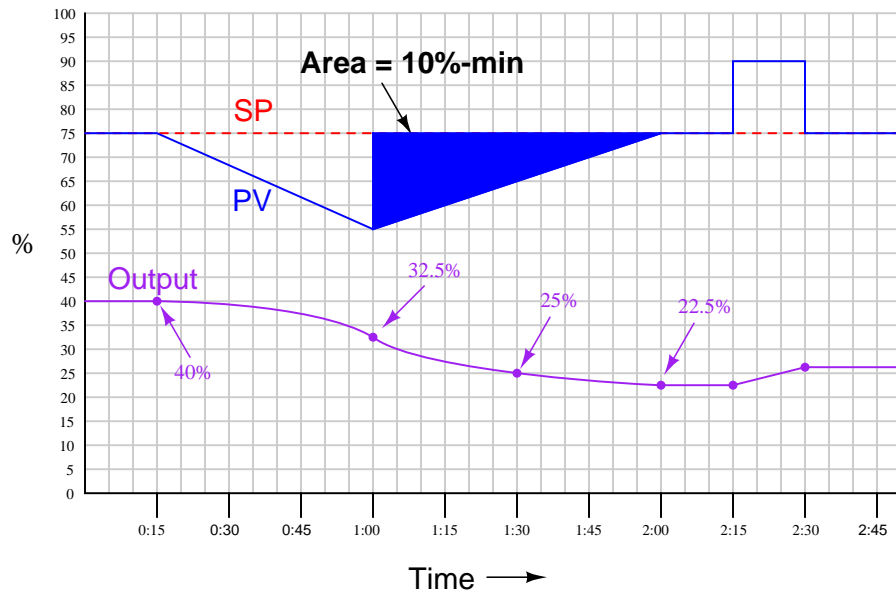
After the PV has returned to SP, the integral action creates no change in output. Then, between times 2:15 and 2:30, the deviation of 15% for 15 seconds (0.25 minutes) creates an error-time accumulation of 3.75 %-min, the total of that adding to the output signal to leave us with 26.25% output when the PV returns to SP:
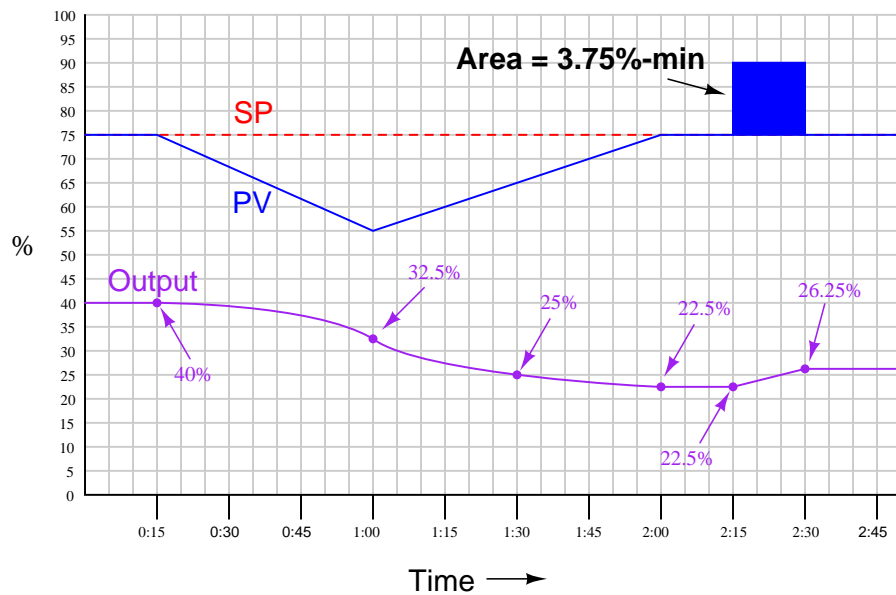
Note how the integral action causes the output to ramp at variable rates between 0:15 and 1:00, and again between 1:00 and 2:00. However, integral action produces a linear slope between 2:15 and 2:30 due to the rectangular deviation between those times.
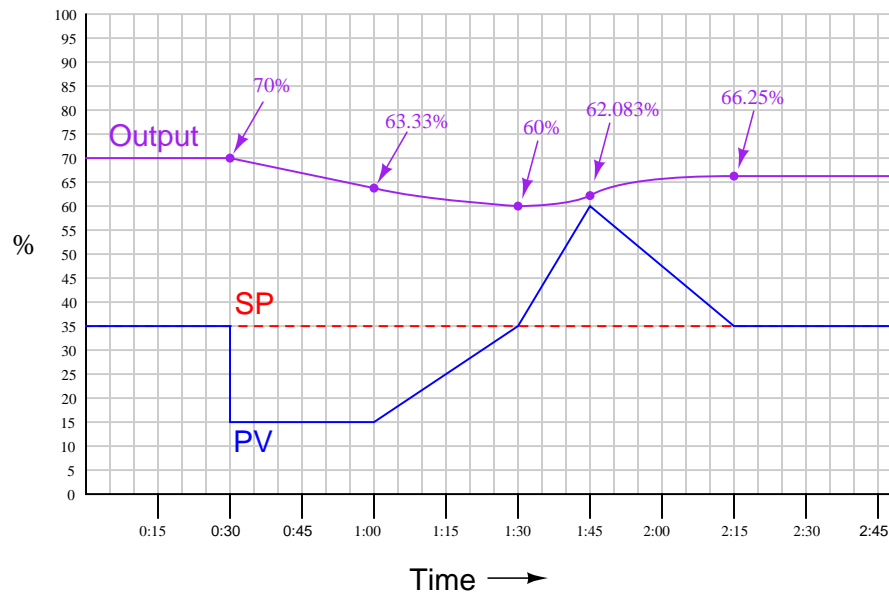
First, let's convert the given tuning constants into direct-indicating units (gain instead of P.B., and rep/min instead of min/rep):

Proportional band = 75% ; Gain = 1.333

2 minutes per repeat = 0.5 repeats per minute

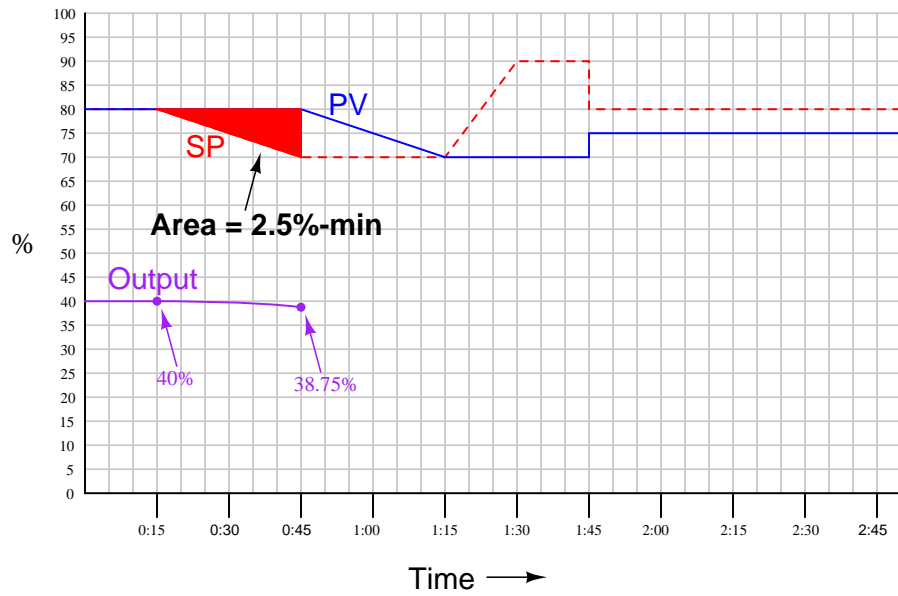Now, calculating the accumulated area under each deviation period:

Integral action = $K_p \frac{1}{\tau_i} \int e \, dt$

Integral action = (gain)(repeats/min)(error-time product)

Integral action = (1.333)(0.5/min)(10%-min)

Integral action = 6.667%

Output goes from 70% to 63.33%
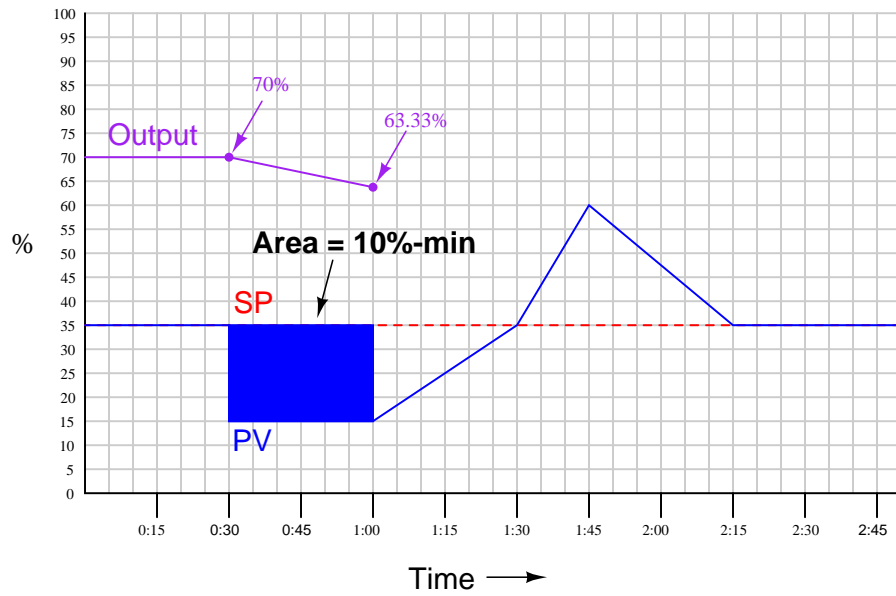
Integral action $= K_p \frac{1}{\tau_i} \int e \, dt$

Integral action $=$ (gain)(repeats/min)(error-time product)

Integral action $=$ (1.333)(0.5/min)(5%-min)

Integral action $= 3.333\%$

Output goes from 63.33% to 60%
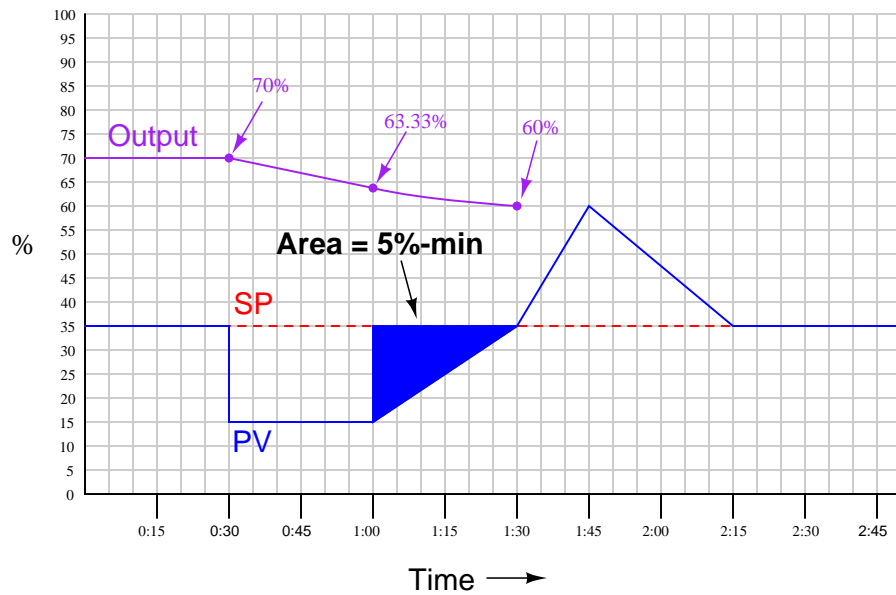
Integral action $= K_p \frac{1}{\tau_i} \int e \, dt$

Integral action $=$ (gain)(repeats/min)(error-time product)

Integral action $=$ (1.333)(0.5/min)(3.125%-min)

Integral action $= 2.083\%$

Output goes from 60% to 62.083%
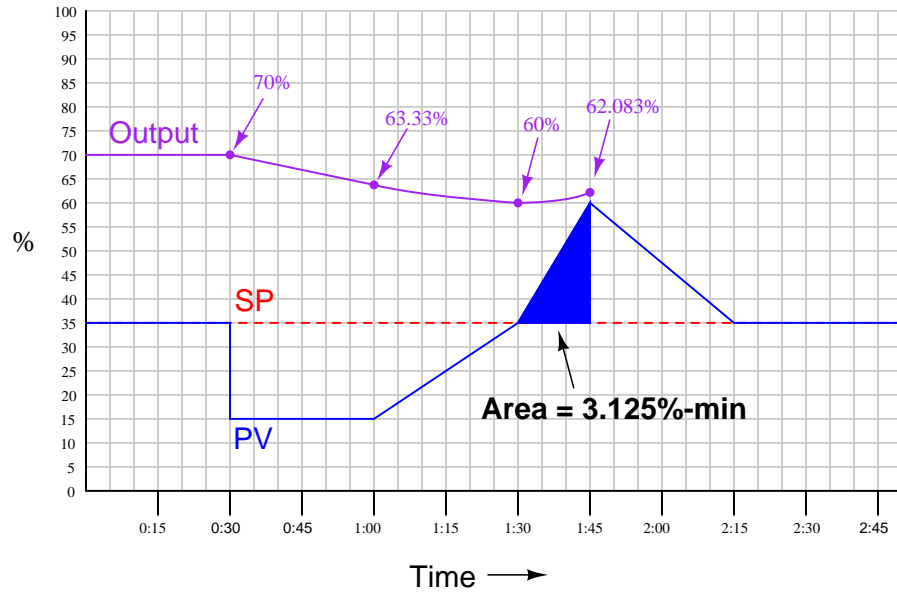
Integral action $= K_p \frac{1}{\tau_i} \int e\, dt$

Integral action $=$ (gain)(repeats/min)(error-time product)

Integral action $=$ (1.333)(0.5/min)(6.25%-min)

Integral action $= 4.167\%$

Output goes from 62.083% to 66.25%
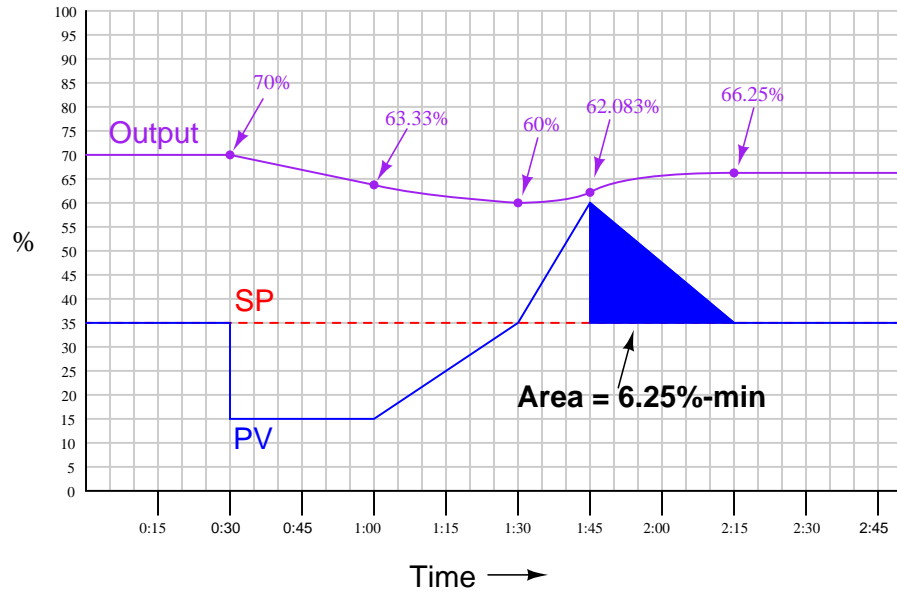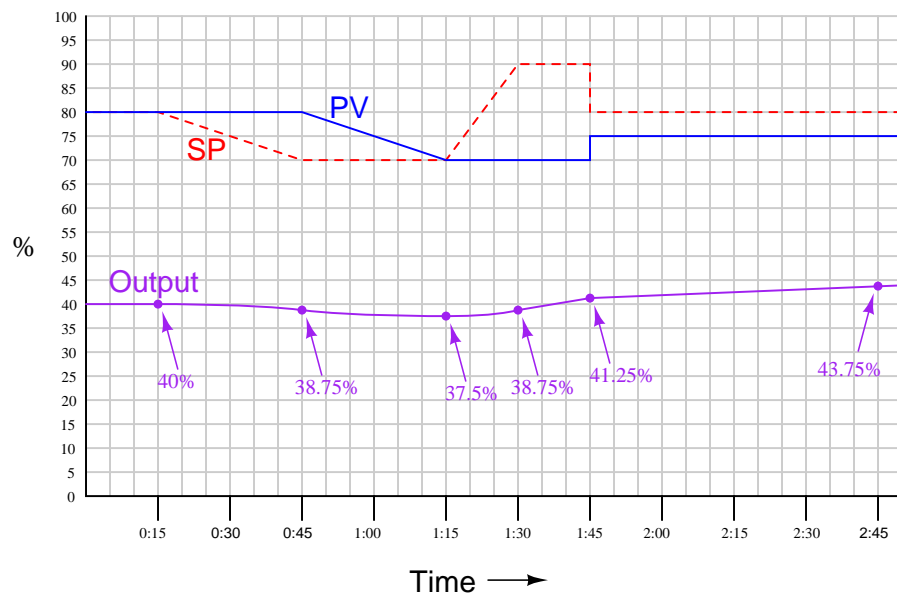
First, let's convert the given tuning constants into direct-indicating units (gain instead of P.B., and rep/min instead of min/rep):

Proportional band = 50% ; Gain = 2

4 minutes per repeat = 0.25 repeats per minute

Now, calculating the accumulated area under each deviation period:

Integral action = $K_p \frac{1}{\tau_i} \int e\, dt$

Integral action = (gain)(repeats/min)(error-time product)

Integral action = (2)(0.25/min)(2.5%-min)

Integral action = 1.25%

Output goes from 40% to 38.75%

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Integral action $= K_p \frac{1}{\tau_i} \int e\, dt$

Integral action $=$ (gain)(repeats/min)(error-time product)

Integral action $=$ (2)(0.25/min)(2.5%-min)

Integral action $= 1.25\%$

Output goes from 38.75% to 37.5%
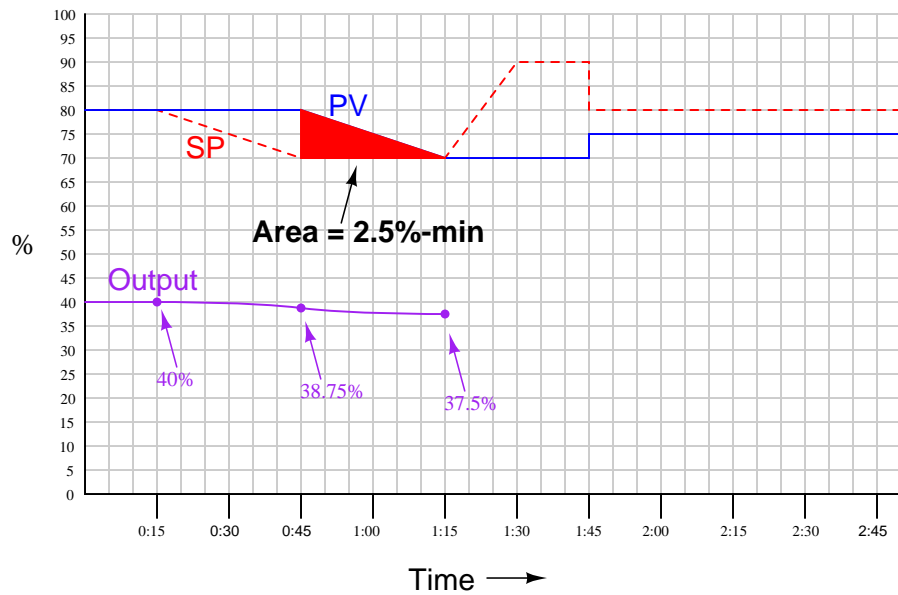
Integral action $= K_p \frac{1}{\tau_i} \int e \, dt$

Integral action $=$ (gain)(repeats/min)(error-time product)

Integral action $=$ (2)(0.25/min)(2.5%-min)

Integral action $= 1.25\%$

Output goes from 37.5% to 38.75%
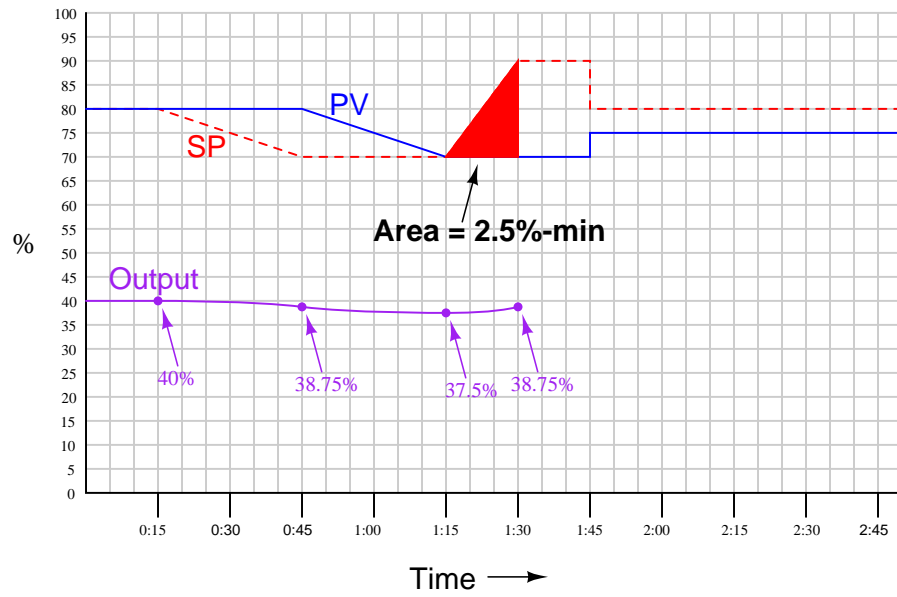
Integral action $= K_p \frac{1}{\tau_i} \int e \, dt$

Integral action $=$ (gain)(repeats/min)(error-time product)

Integral action $=$ (2)(0.25/min)(5%-min)

Integral action $= 2.5\%$

Output goes from 38.75% to 41.25%
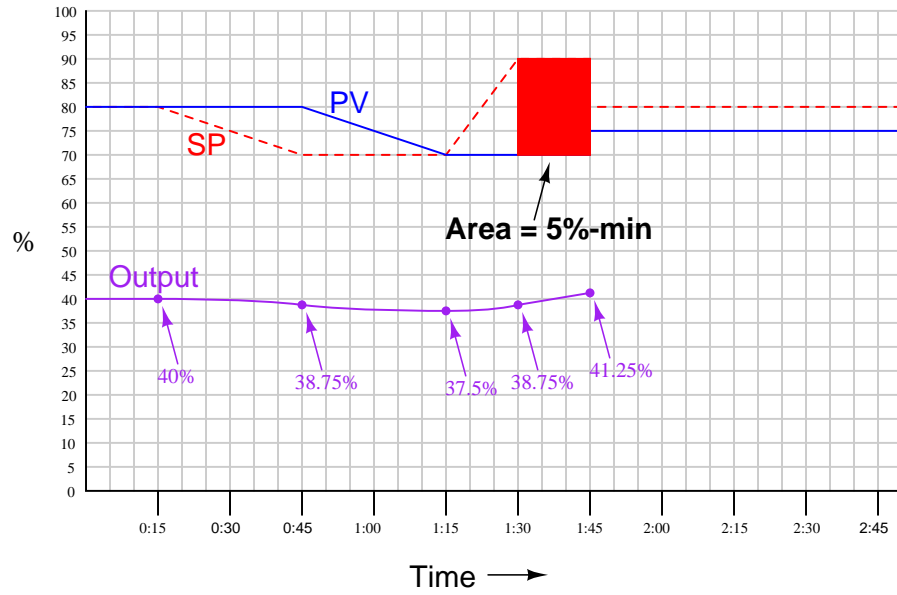
Integral action $= K_p \frac{1}{\tau_i} \int e\, dt$

Integral action $=$ (gain)(repeats/min)(error-time product)

Integral action $= (2)(0.25/\text{min})(5\%\text{-min})$

Integral action $= 2.5\%$

Output goes from 41.25% to 43.75%
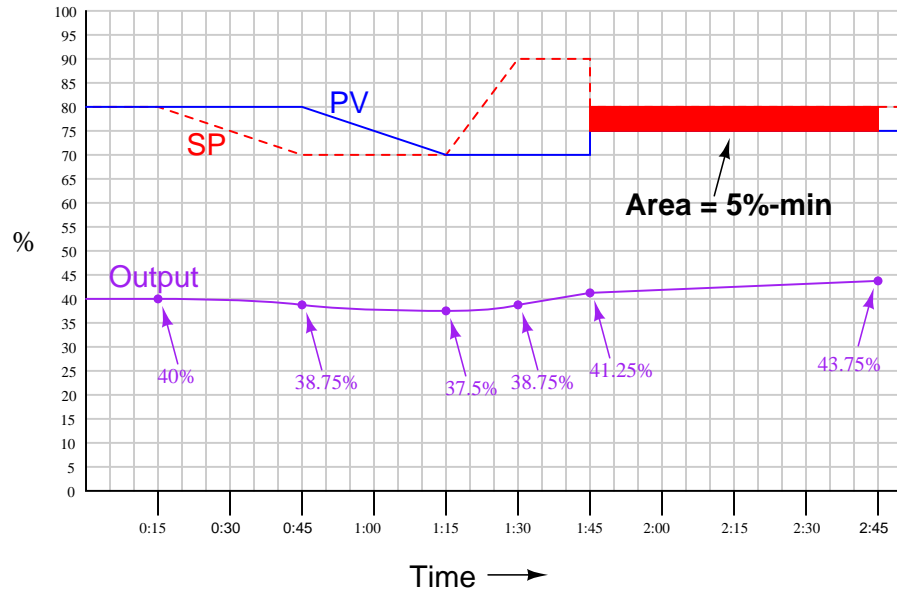
Answer 76

Answer 77

Answer 78

Answer 79

Answer 80

Answer 81

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

Answer 82

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

Answer 83

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

Answer 84

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

Answer 85

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

Answer 86

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

Answer 87

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

Answer 88

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

Answer 89

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

Answer 90

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

Answer 91

Answer 92

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