Lab

Multi-input control strategy: *Question 91 and 92*, **completed objectives due by the end of day 5, section 2**

Exam

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

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

Recommended daily schedule

Day 1

Theory session topic: Supervisory and cascade control

Questions 1 through 20; <u>answer questions 1-7</u> in preparation for discussion (remainder for practice)

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

Day 2

Theory session topic: Ratio control

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

Day 3

Theory session topic: Feedforward control

Questions 41 through 60; <u>answer questions 41-47</u> in preparation for discussion (remainder for practice)

Day 4

Theory session topic: Feedforward with dynamic compensation

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

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

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

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

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

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

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

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

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

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

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

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

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

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

file `howto`

General Values, Expectations, and Standards

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

Learning is the purpose of any educational program, and a worthy priority in life. Every circumstance, every incident, every day here will be treated as a learning opportunity, every mistake as a "teachable moment". Every form of positive growth, not just academic ability, will be regarded as real learning.

Responsibility means *ensuring* the desired outcome, not just *trying* to achieve the outcome. To be a responsible person means you *own* the outcome of your decisions and actions.

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

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

Diligence in study means exercising self-discipline and persistence, realizing that hard work is a necessary condition for success. This means, among other things, investing the necessary time and effort in studying, reading instructions, paying attention to details, utilizing the skills and tools you already possess, and avoiding shortcuts. Diligence in work means the job is not done until it is done *correctly*: all objectives achieved, all problems solved, all documentation complete, and no errors remaining.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Academic Progress: your instructor will record your academic achievement, as well as comments on any negative behavior, and will share all these records with employers if you sign the FERPA release form. You may see these records at any time, and you should track your own academic progress using the grade spreadsheet template. Extra-credit projects will be tailored to your learning needs.

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

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

file expectations

Program Outcomes for Instrumentation and Control Technology (BTC)

| #1 | Communication |

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

| #2 | Time management |

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

| #3 | Safety |

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

| #4 | Analysis and Diagnosis |

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

| #5 | Design and Commissioning |

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

| #6 | System optimization |

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

| #7 | Calibration |

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

| #8 | Documentation |

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

| #9 | Independent learning |

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

| #10 | Job searching |

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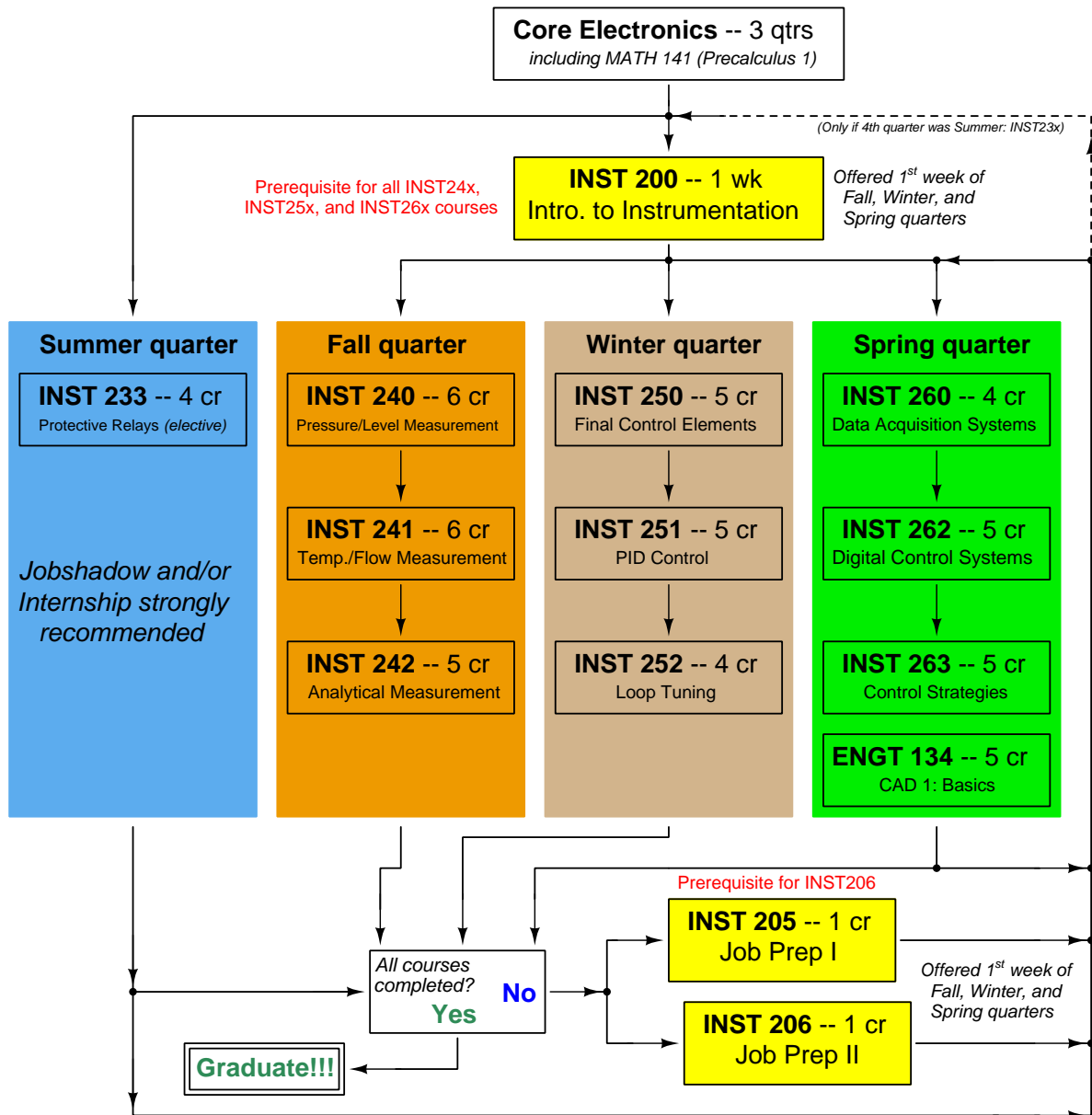
file outcomes_program

INST 263 Course Outcomes

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

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

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

- Predict the response of a cascade, ratio, or feedforward control system to a component fault or process condition change, given a pictorial and/or schematic illustration. [Ref: Program Learning Outcome #4]

- Calculate instrument input and output values given calibrated ranges. [Ref: Program Learning Outcome #7]

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

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

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

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

- Construct and commission a cascade-, ratio-, or feedforward-controlled process. [Ref: Program Learning Outcome #5]

- Augment an automatic control loop with safety shutdown logic. [Ref: Program Learning Outcome #5]

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

- Build a circuit using an electromechanical relay to energize an AC load, and measure current in this circuit, given a switch and relay both randomly selected by the instructor. [Ref: Program Learning Outcome #5]

- Design and build a circuit to fulfill a function randomly selected by the instructor (voltage divider, passive filter, capacitive time-delay, or phase shift network) and demonstrate its proper operation using a signal generator and oscilloscope. [Ref: Program Learning Outcome #5]

- Test the proper function of safety shutdown logic in a PID control system within a limited time, logically justifying your steps in the instructor's direct presence. [Ref: Program Learning Outcome #6]

- Construct a working control loop consisting of a pre-made process unit with transmitter and final control element, properly connected to a controller, within a limited time. Both the process and the controller are randomly selected by the instructor, with data acquisition of a variable specified by the instructor. [Ref: Program Learning Outcomes #5 and #9]

<u>file</u> `outcomes_INST263`

Sequence of second-year Instrumentation courses

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

(Only if 4th quarter was Summer: INST23x)

Prerequisite for all INST24x, INST25x, and INST26x courses

INST 200 -- 1 wk
Intro. to Instrumentation

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

Summer quarter	Fall quarter	Winter quarter	Spring quarter
INST 233 -- 4 cr Protective Relays *(elective)*	**INST 240** -- 6 cr Pressure/Level Measurement	**INST 250** -- 5 cr Final Control Elements	**INST 260** -- 4 cr Data Acquisition Systems
	INST 241 -- 6 cr Temp./Flow Measurement	**INST 251** -- 5 cr PID Control	**INST 262** -- 5 cr Digital Control Systems
Jobshadow and/or Internship strongly recommended	**INST 242** -- 5 cr Analytical Measurement	**INST 252** -- 4 cr Loop Tuning	**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

July → Aug.
Summer quarter
INST 233 -- 4 cr
Protective Relays (elective)

Jobshadow and/or Internship strongly recommended

Sept. → Dec.
Fall quarter
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

Jan. → Mar.
Winter quarter
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

April → June
Spring quarter
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

Sept. → Dec.
Fall quarter
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

Jan. → Mar.
Winter quarter
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

April → June
Spring quarter
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

July → Aug.
Summer quarter
INST 233 -- 4 cr
Protective Relays (elective)

Jobshadow and/or Internship strongly recommended

Graduation!

Beginning in Winter

Jan. → Mar.
Winter quarter
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

April → June
Spring quarter
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

July → Aug.
Summer quarter
INST 233 -- 4 cr
Protective Relays (elective)

Jobshadow and/or Internship strongly recommended

Sept. → Dec.
Fall quarter
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

April → June
Spring quarter
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

July → Aug.
Summer quarter
INST 233 -- 4 cr
Protective Relays (elective)

Jobshadow and/or Internship strongly recommended

Sept. → Dec.
Fall quarter
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

Jan. → Mar.
Winter quarter
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**
- $^{o}\text{F} = (^{o}\text{C})(9/5) + 32$
- $^{o}\text{C} = (^{o}\text{F} - 32)(5/9)$
- $^{o}\text{R} = ^{o}\text{F} + 459.67$
- $\text{K} = ^{o}\text{C} + 273.15$

Conversion equivalencies for distance

1 inch (in) = 2.540000 centimeter (cm)

1 foot (ft) = 12 inches (in)

1 yard (yd) = 3 feet (ft)

1 mile (mi) = 5280 feet (ft)

Conversion equivalencies for volume

1 gallon (gal) = 231.0 cubic inches (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 $= 32^oF = 0^oC$

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

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

Specific heat of water at $14^oC = 1.00002$ calories/g·$^oC = 1$ BTU/lb·$^oF = 4.1869$ Joules/g·^oC

Specific heat of ice ≈ 0.5 calories/g·^oC

Specific heat of steam ≈ 0.48 calories/g·^oC

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

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

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

Properties of Dry Air at sea level

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

Absolute viscosity of dry air at 20^oC and 760 torr $= 0.018$ centipoise (cp) $= 1.8 \times 10^{-5}$ 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

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

General follow-up challenges for assigned problems

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

file `license`

Question 1

Examine these two control "loops" (transmitter-controller-valve systems) for an industrial boiler, controlling both water level and steam pressure:
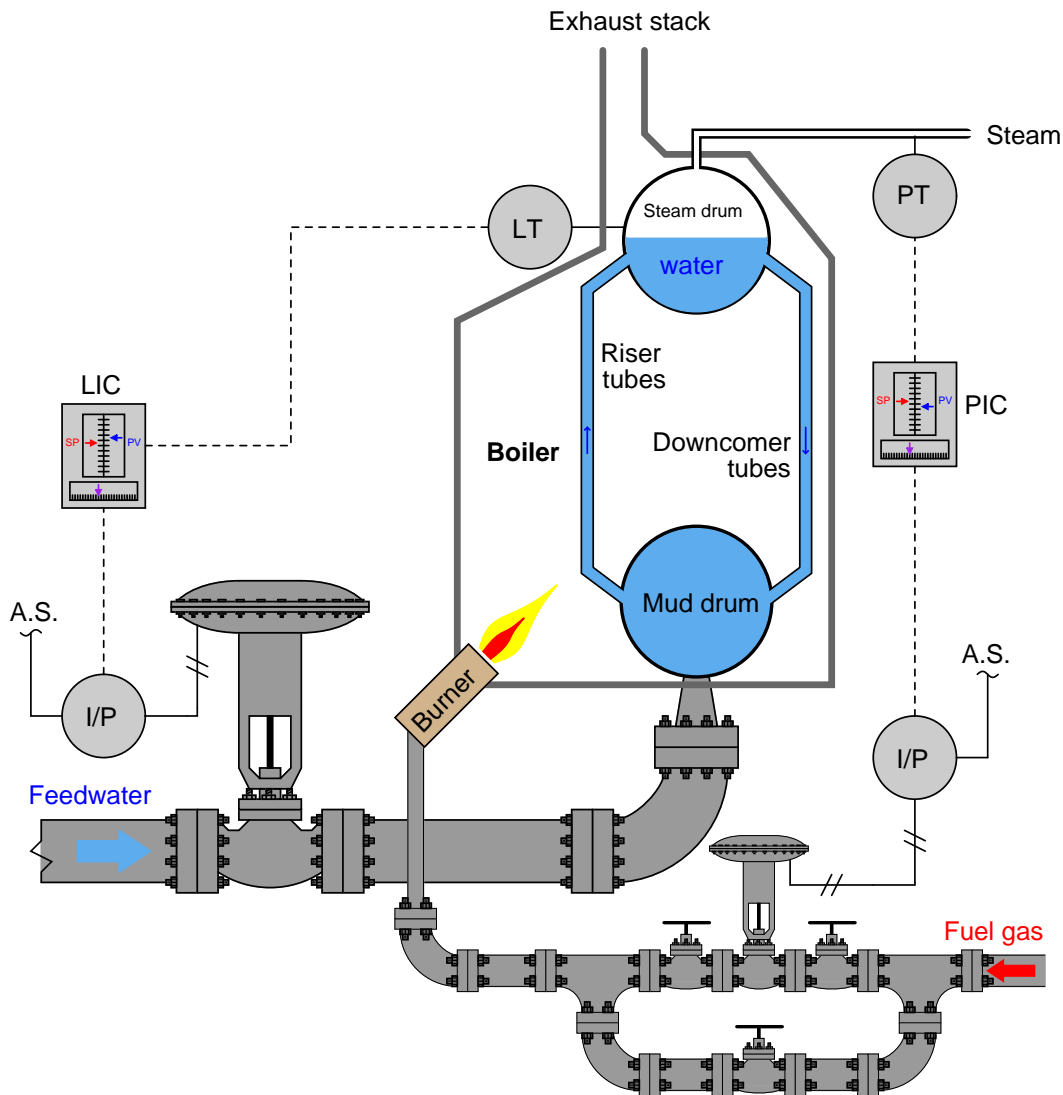
If the PIC setpoint is 225 PSI and the measured steam pressure begins to rise above that value, how should the PIC respond, and how will this response bring the steam pressure back down to setpoint?

Describe a situation where the *block* and *bypass* hand valves installed on the fuel gas line might ever be used, either by operations or by maintenance personnel.

If the I/P transducer on the level control loop suddenly fell out of calibration in such a way that it output a pneumatic signal that was too low, how would this affect the control of water level in the steam drum?

- Explain what would happen to this process if the air supply to the feedwater valve's I/P transducer failed.
- Explain what would happen to this process if the air supply to the fuel valve's I/P transducer failed.
- Explain how both control loops will respond to a sudden increase in steam demand.

file i01688

Question 2

Read and outline the "Supervisory Control" section of the "Basic Process Control Strategies" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

(1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A "Table of Contents" format works well for this.
(2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author's problem-solving strategies, etc.).
(3) General principles, especially physical laws, referenced in the text.
(4) 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 i04335

Question 3

Read and outline the "Cascade Control" section of the "Basic Process Control Strategies" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

(1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A "Table of Contents" format works well for this.
(2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author's problem-solving strategies, etc.).
(3) General principles, especially physical laws, referenced in the text.
(4) 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 i04336

Question 4

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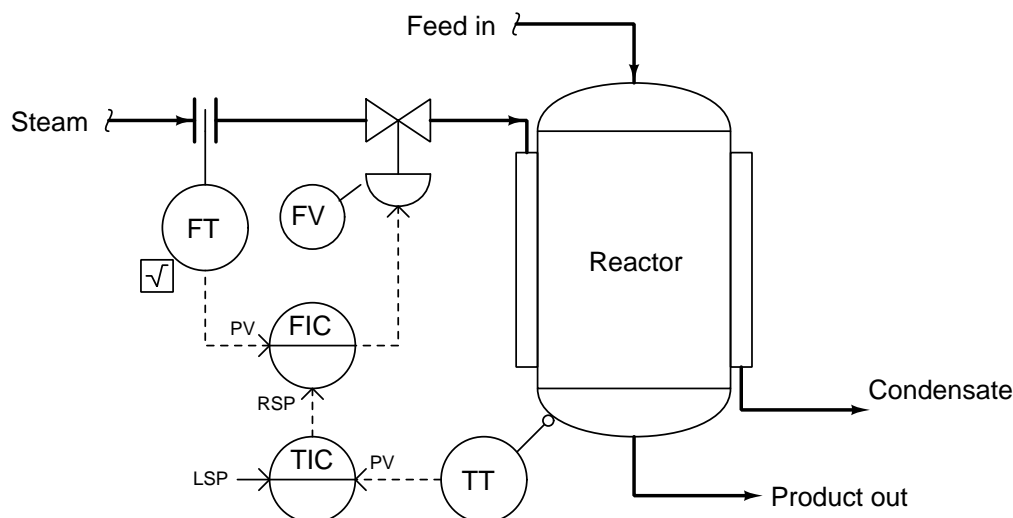
Cascade control systems (also called *two-element* control systems) have two control "loops" functioning: a *master* and a *slave* (also known as *primary* and *secondary*, respectively). Identify the master (primary) and slave (secondary) loops in this temperature control system, and also determine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

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

| Suggestions for Socratic discussion |

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

file i01690

Question 5

This water level control system (for a municipal water supply operation) is supposed to maintain constant water level in the filter and in the clearwell. Unfortunately, it has a problem. Operators call you urgently to determine why the clearwell is completely empty:
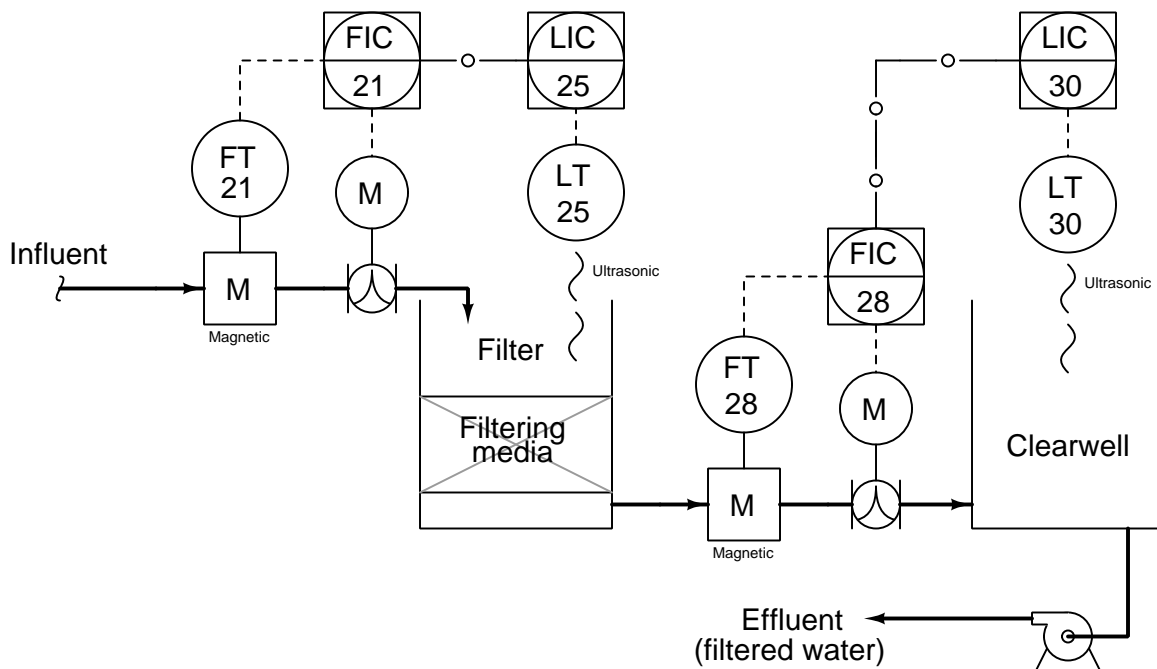
Your first step is to ask the operator if they have actually inspected the clearwell to verify that it is empty. They have, and it is. They also point to the display for level controller LIC-30 and show you that it reads 0% level.

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

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

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

Suggestions for Socratic discussion

- A useful problem-solving strategy for determining necessary controller actions in a cascade control system is to replace the ISA-standard "bubble" symbols for controllers with triangular opamp symbols,

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complete with "+" and "−" symbols at the inputs. One input of each "opamp" controller will be the PV, while the other input of each "opamp" controller will be the SP. The inverting and noninverting inputs standard to all operational amplifiers helps remind you that the PV and SP inputs of a loop controller always have opposite effects on the output signal.

- A valuable principle to apply in a diagnostic scenario such as this is *correspondence*: identifying which field variables correspond with their respective controller faceplate displays, and which do not. Apply this comparative test to the scenario described, and use it to explain why the technician's proposed test was probably not the best first step.

file i02326

Question 6

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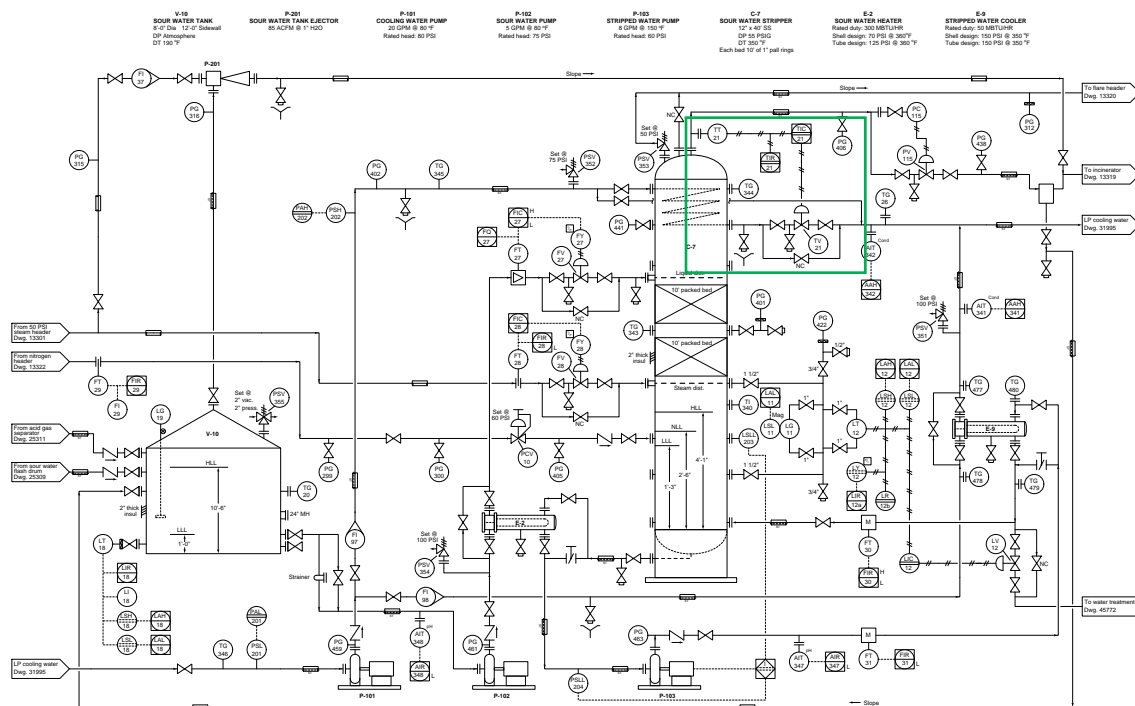
Modify this system for better control of stripper overhead temperature, using *cascade* control.

Suggestions for Socratic discussion

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

file i01696

Question 7

This water filter's discharge pressure is controlled by a PID controller, throttling the amount of water returned to the sump:
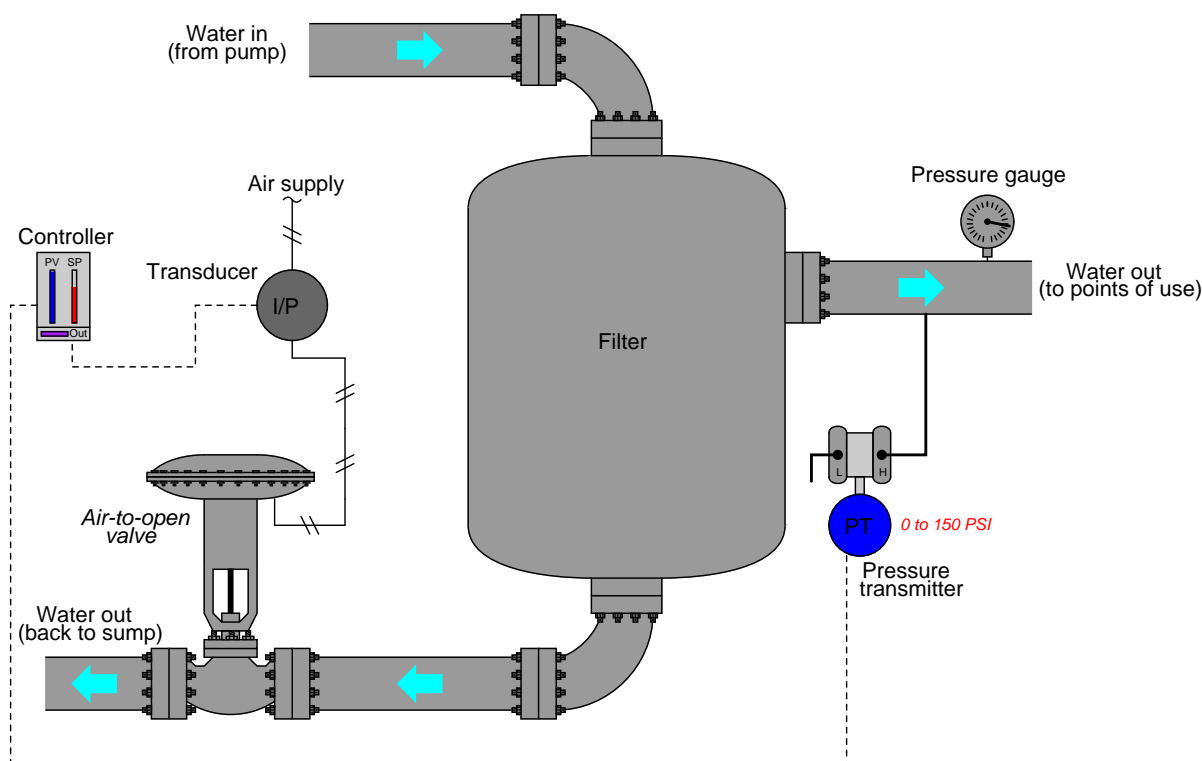
An operator tells you there is a problem with this system, though: the controller faceplate registers 146 PSI of water pressure, with a setpoint at 100 PSI. You happen to notice that the bargraph on the controller faceplate showing output is at 100%. Another operator in the field (near the exchanger) reports via radio that the control valve stem is at the "closed" position, and that the pressure gauge mounted on the filter's discharge line registers 143 PSI.

Another instrument technician happens to be with you, and recommends you connect a multimeter to the transmitter's signal wiring to measure the 4-20 mA signal. 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.
- Determine the proper action for this loop controller (direct or reverse).
- For those who have studied PID tuning, qualitatively determine appropriate P, I, and D parameters for the loop controller based on how you would expect this process to respond.

file i00434

Question 8

This clearwell water level control system for a drinking water treatment facility maintains a constant level of water following filtration, for sourcing to customers:
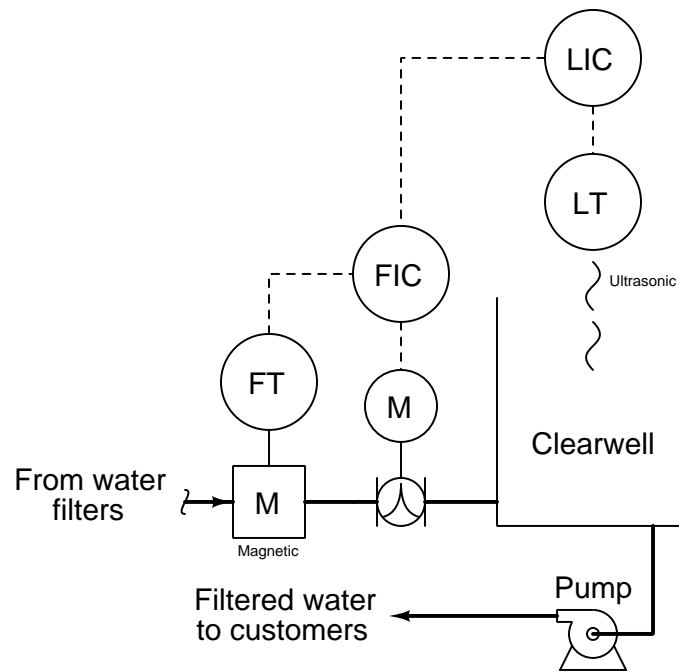

Determine what both controllers (LIC and FIC) will do over time if the flow transmitter fails in such a way that it registers zero flow regardless of the actual flow rate of water through it. Assume the level transmitter is direct-acting (i.e. greater signal with greater water level) and that the control valve is signal-to-open (fail closed).

file i04509

This clearwell water level control system for a drinking water treatment facility maintains a constant level of water following filtration, for sourcing to customers:
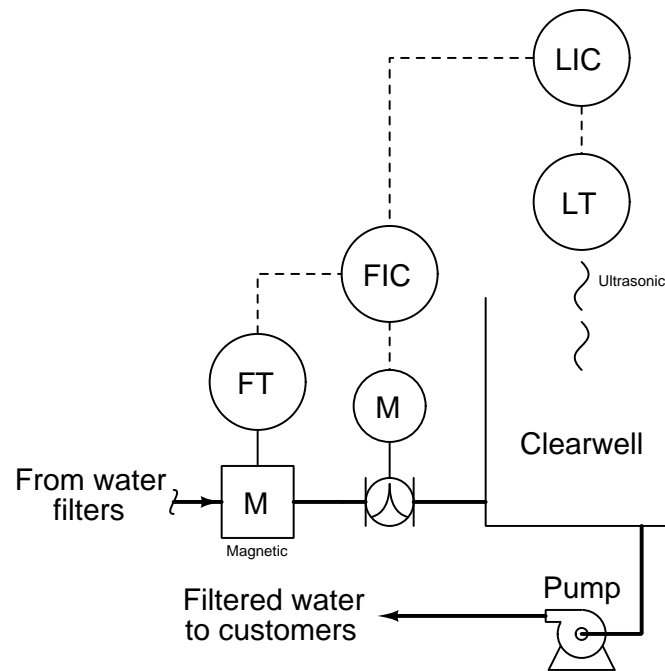
Determine what both controllers (LIC and FIC) will do over time if the control valve fails in such a way that it ignores the controller's output and opens wide. Assume both transmitters are direct-acting (i.e. greater signal with greater flow ; greater signal with greater water level) and that the control valve is signal-to-open (fail closed).

file i01998

Question 10

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

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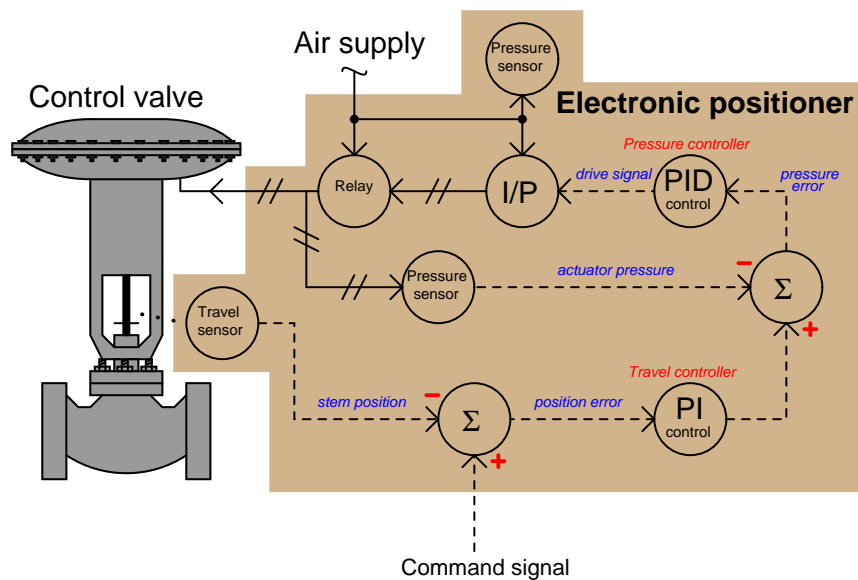
Suggestions for Socratic discussion

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

file i01691

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Question 11

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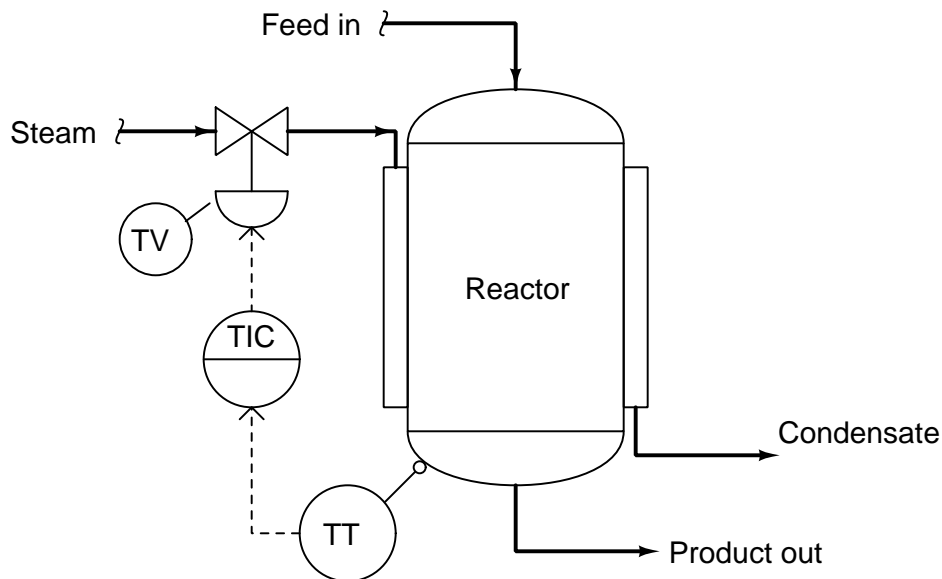
Ever since this process was placed into service, operators have complained about poor temperature control. Several technicians have tried to tune the PID controller, but no combination of tuning constants seems to solve the problem of random reactor temperature fluctuations. Then one day you notice that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

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

Suggestions for Socratic discussion

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

file i01689

An operator tells you the stack temperature of this incinerator is running high as indicated by TIC-37. The setpoint is set at 1400 degrees F, but the PV display shows a steady 1489 ^{o}F:

F-1
INCINERATOR
DP Atmosphere
DT 1650 ^{o}F
Res Time 1.5 sec minimum

(3) - 3" nozzles
90° apart at
elev. 50' 6"

67' above grade

Rain shield from 24' to 67'

NOTES:
1. Gas safety vent pipes to extend 10 feet above grade, situated at least 30 feet from any source of ignition.
2. Burner management system supplied by vendor, located in NEMA4X enclosure at base of incinerator tower. See drawing 17003 for wiring details.
3. Gas chromatograph supplied by vendor, located in analyzer shack at base of incinerator tower. See drawing 17059 for wiring and tubing details.

AE 35 / AT 35 / AAH 35
AE 34 / AT 34 / AIR 34/35

TIR 36 / TAL 36 / TAH 36
TT 36 / TE 36
TE 37 / TT 37 / TIC 37

34' 6" above grade

2" thick from grade to 24' 0"

F-1

24" MW

Waste stream #1 Dwg. 12022 / PG 41
Waste stream #2 Dwg. 12022 / PG 42
Waste stream #3 Dwg. 12022 / PG 43

6"x2"

SV 101 / PSH 107 / BAL 106 / BE 108 / BE 109 / PSH 110
Vent (Note 1)
SV 102 / SV 103

PG 104 / PSL 105
From natural gas header Dwg. 32915 / PCV 39 / PG 44
From fuel gas header Dwg. 32915 / PCV 40 / ZS 38 / FT 38

BMS (Note 2)

SV 111 / SV 112 / SV 113
Vent (Note 1)

SV 115 / FY 38b / FIC 38 / FV 38 FC
BMS (Note 2) / PSL 114

AT 33 (Note 3) / RS-485 Modbus
AY 33 Gateway / Ethernet
AIR 33a H2S / AIR 33b C2H2 / AIR 33c NH3 / AIR 33d HNO3 / AIR 33e CH4

FY 38c HART to analog / DIR 38
FIQ 38 / TIR 38
FY 38a

Fault	Possible	Impossible
TT-37 miscalibrated (reading too low)		
TT-37 miscalibrated (reading too high)		
TIC-37 in manual mode		
TIC-37 in auto mode		
FIC-38 in manual mode		
FIC-38 in auto mode		
FIC-38 in cascade mode		
FT-38 miscalibrated (reading too low)		

Identify the likelihood of each specified fault in this process. 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 process.

file i03529

Question 13
_____
Question 14
_____
Question 15
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Question 16
_____
Question 17
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Question 18
_____
Question 19
_____
Question 20
_____
Question 21

Read and outline the "Ratio Control" section of the "Basic Process Control Strategies" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

(1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A "Table of Contents" format works well for this.
(2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author's problem-solving strategies, etc.).
(3) General principles, especially physical laws, referenced in the text.
(4) 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 i04337

Question 22

Modern automobile engines use computer controls to adjust the *air/fuel ratio* for an optimum balance between economy, performance, and emissions. Explain how a typical spark-ignition engine accomplishes this ratio control. What constitutes the process variable (PV), setpoint, output, "wild" flow, and load(s) in such a control system?

Hint: for those who have never worked on a car engine before, the air flow to the engine is controlled by a butterfly valve mechanism directly actuated by the accelerator pedal, while fuel flow to the engine is controlled by precise timing spray valves called *injectors* (actuated by the electronic engine control computer).

Suggestions for Socratic discussion

- For those who have studied engines and/or chemistry, explain why fuel-ratio control is critical in spark-ignition engines.
- Carbureted engines used to be equipped with *choke* valves to richen the mixture going into the engine when it was first started, because the normal air/fuel ratio is simply too lean for a cold engine to run on. Explain why fuel-injected engines don't require choke valves.
- Engines with computer-controlled air:fuel mixture ratios typically employ an *oxygen sensor* in the exhaust pipe of the engine to monitor how much unreacted oxygen is left in the exhaust gas stream. Explain why this is done, and how that sensor's signal may be used to optimize the engine's air:fuel ratio.
- One of the more popular air flowmeters used in engine ratio control systems is the so-called *hot-wire anemometer* which places an electrically heated metal wire in the path of the incoming air and senses the temperature of that wire as it is cooled by the air flowing by. For those who have studied flowmeters, identify the general category of flowmeter that best applies to a hot-wire anemometer, and explain why this is a very good flowmeter choice for this particular application.

file i01736

Question 23

A byproduct of the *kraft process* used in the paper industry for turning wood chips into pulp is a liquid called *black liquor*. This liquid contains many volatile sulfur compounds such as hydrogen sulfide (H_2S) and mercaptans, both of which are strongly scented, and if released to the atmosphere will constitute a hazardous (or at least strongly objectionable) emission. Loss of volatile sulfur compounds also constitutes a loss of sulfur, which is a raw material in the kraft pulping process.

These sulfur compounds may be stabilized for less volatility and easier recovery by a process of oxidation: exposing the black liquor to pure oxygen gas. To minimize consumption of oxygen, the gas flow is metered proportionately to liquor flow:

Explain how this is an example of *ratio control*, and identify the following about the system:

- Which flow stream is the "wild" flow?
- Which flow stream is the "captive" flow?
- What is the purpose of the "hand controller" (HC)?
- What factor(s) dictate the setting of the hand controller's output?
- What safety hazards accompany the use of pure oxygen as a process stream?

Suggestions for Socratic discussion

- Identify some hazards associated with this process, given the types of substances going in and out of the reactor.
- For those who have studied flow measurement, explain the significance of the "square root" symbols attached to each flow transmitter.
- Explain what would happen in this process if the liquor flow transmitter failed with a low signal.
- Explain what would happen in this process if the liquor flow transmitter failed with a high signal.
- Explain what would happen in this process if the oxygen flow transmitter failed with a low signal.
- Explain what would happen in this process if the oxygen flow transmitter failed with a high signal.
- Explain what would happen in this process if the control valve failed fully shut.
- Explain what would happen in this process if the control valve failed wide-open.

file i01733

Question 24

A variety of chemicals are added to raw water when treating it for human consumption, and also when treating water for many industrial processes. In the *coagulation* stage, chemicals are added to cause suspended solids in the raw water to coalesce into larger particles called *floc*, which precipitate out of solution more readily. To maximize effectiveness and to reduce waste, these chemicals need to be added to the water in specific proportions:
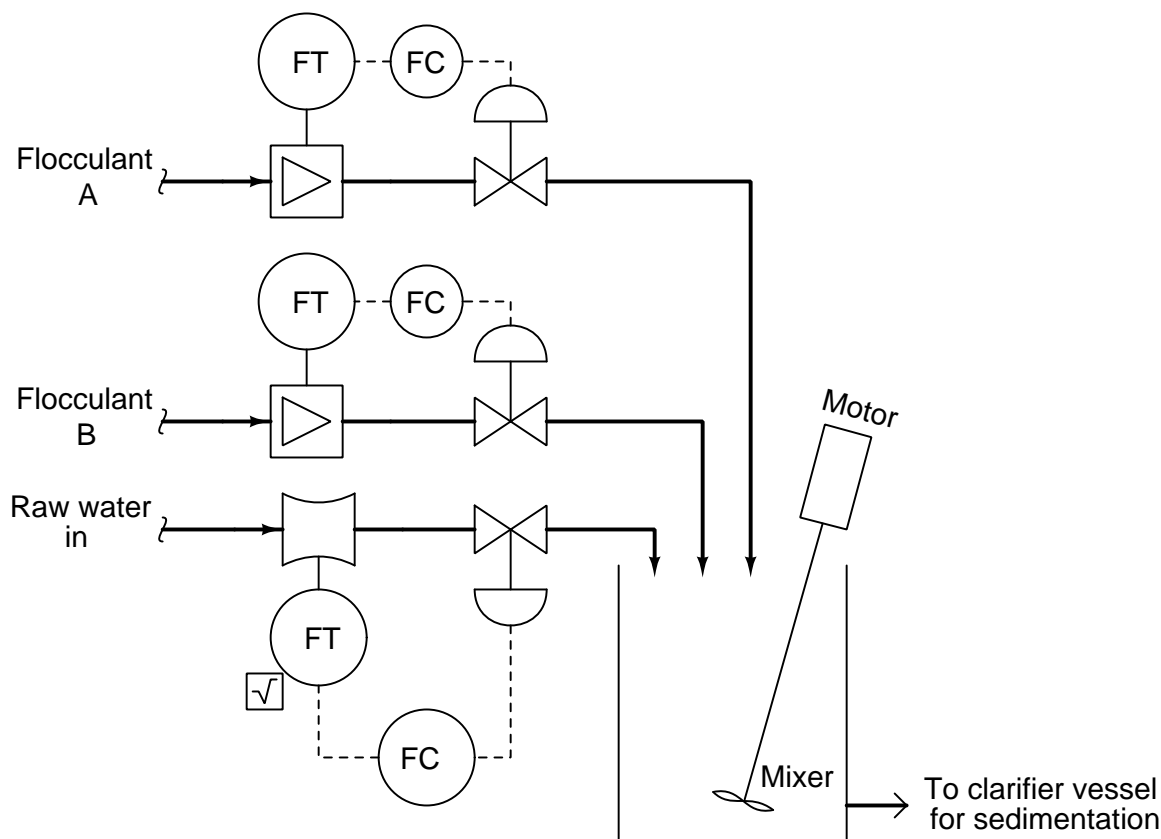
If the raw water inlet flow and composition never change, the flocculant flow control setpoints may be left unchanged as well. Once the correct proportions are set, the flocculant chemicals will continue to be added at just the right amounts.

But what if the raw water inlet flow *is* subject to change? It would be quite inconvenient for operators to re-adjust the flocculant control setpoints every time a water flow rate change took place. Can you think of a way to implement ratio control in this system to handle such changes automatically?

| Suggestions for Socratic discussion |

- For those who have studied flowmeter technology, identify the types of flowmeters shown in this diagram and explain how each of them works.
- After implementing your control strategy, analyze the effects of the raw water flow transmitter failing with a *low* signal.

file i01732

Weighfeeders are conveyor belts equipped with weight sensors (load cells) to measure the weight of material on a section of the belt, and variable-speed motor drives to adjust the rate at which the belts feed material into a process. When different solid materials are mixed together to make a blend, the weighfeeders must be connected together in a *ratio* configuration to maintain the desired proportion(s):
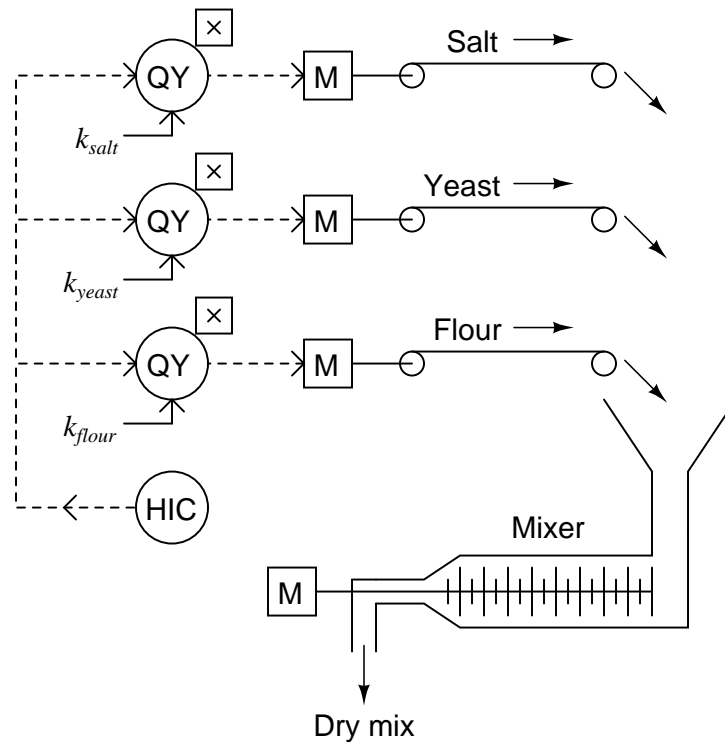
This particular system mixes salt, yeast, and flour together to make dry bread mix in a large factory. The "hand controller" is nothing more than an operator station where a person can set a voltage signal value, in this case to be sent to a series of multiplier relays (QY) to tell each variable-speed motor drive how fast to turn.

Like many variable-speed motor drives, these units accept a 0 to 10 volt DC speed signal as an alternative to the standard 4-20 mA DC signal used in loop-powered instrumentation. This makes the multiplier relays (QY) nothing more than potentiometers:
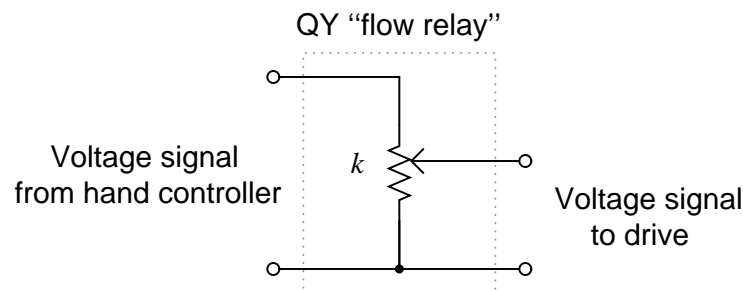
Given the following full-scale weighfeeder capacities (pounds per minute at full 10 volt speed signal), determine the actual ratios of salt to yeast to flour when the three potentiometers are set to the following values:

Weighfeeder capacities:

- Flour weighfeeder: 100 pounds per minute
- Yeast weighfeeder: 1.5 pounds per minute
- Salt weighfeeder: 0.5 pounds per minute

Potentiometer settings:

- $k_{flour} = 50\%$
- $k_{yeast} = 60\%$
- $k_{salt} = 45\%$

Also, determine the total mix flow rate in pounds per minute with a hand controller setting of 70%.
file i01734

Question 26

Reforming furnaces are special process furnaces used to generate pure hydrogen gas from a hydrocarbon feed gas, such as methane. The balanced chemical reaction for this process is as follows:

$$CH_4 + H_2O \rightarrow 3H_2 + CO$$
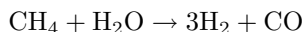
Methane gas (CH_4) added to steam (H_2O) at high temperatures forms hydrogen gas (H_2) and carbon monoxide gas (CO), the latter converted into CO_2 and more hydrogen gas in subsequent reactions. The chemical reaction is *endothermic*, meaning that it requires energy input rather than liberating energy (as what happens in an *exothermic* process such as combustion). Typically, the reaction takes place in the presence of a catalyst. A simplified control system for a reforming furnace is shown here:
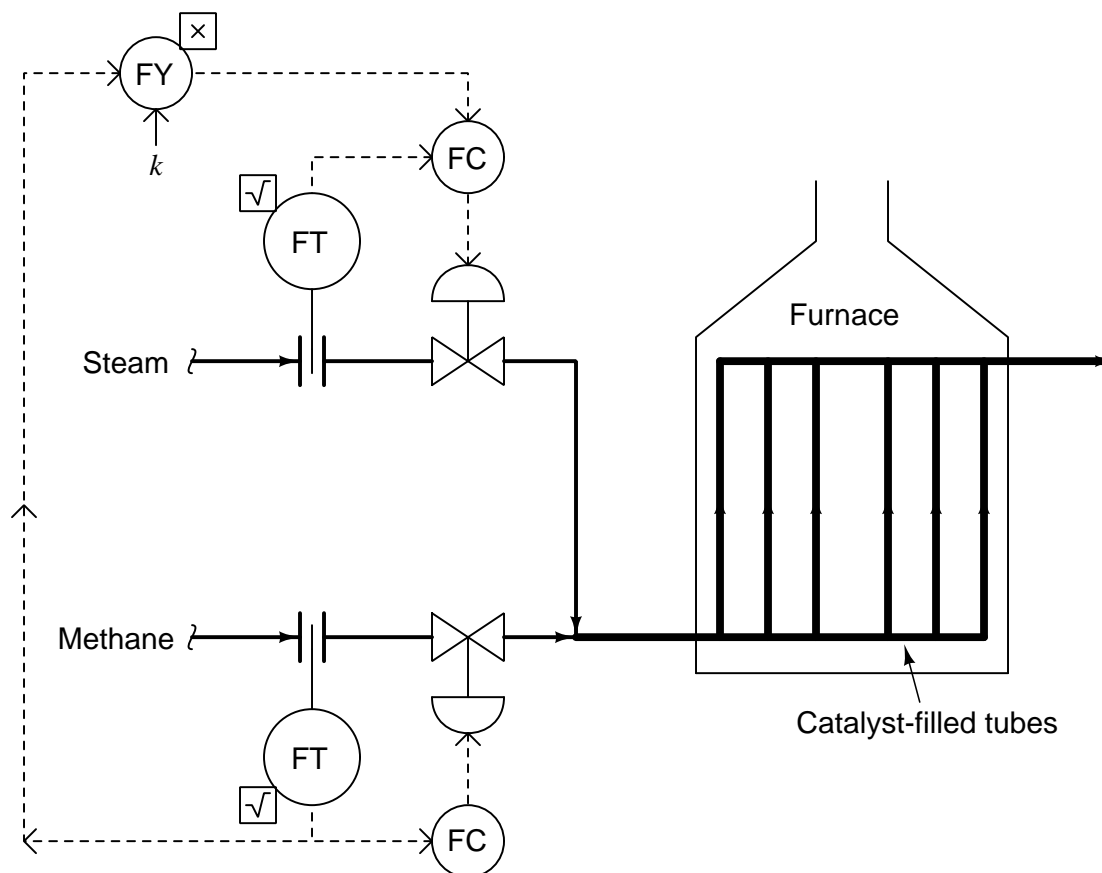
What factor or factors determine the setting of the multiplying constant k? Is this factor something that is liable to change much? Why or why not?

Suggestions for Socratic discussion

- For those who have studied chemistry, write a balanced chemical equation showing how methane and steam could combine to form hydrogen and carbon *dioxide* (CO_2) rather than carbon monoxide (CO).
- Explain what would happen in this process if the methane flow transmitter failed with a low signal.
- Explain what would happen in this process if the methane flow transmitter failed with a high signal.
- Explain what would happen in this process if the steam flow transmitter failed with a low signal.
- Explain what would happen in this process if the steam flow transmitter failed with a high signal.

- Explain what would happen in this process if the methane control valve failed fully shut.
- Explain what would happen in this process if the methane control valve failed wide-open.
- Explain what would happen in this process if the steam control valve failed fully shut.
- Explain what would happen in this process if the steam control valve failed wide-open.
- Explain what would happen in this process if some of the catalyst-filled tubes were to become partially plugged with carbon (coke) deposits.

file i01738

Question 27

This paint mixing system mixes (clear) base and (colored) pigment to achieve a desired coloring, according to the ratio setpoint:
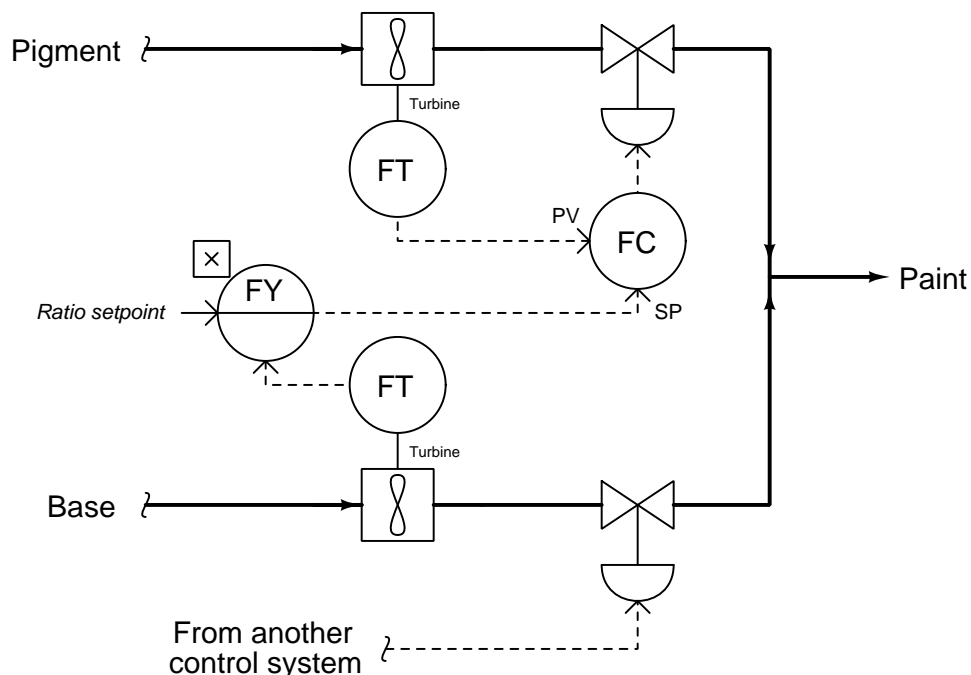

Determine what will happen to the paint's color over time if the base flowmeter turbine seizes so that it does not turn even when there is adequate flow through the pipe. Also, explain *why* the paint's color will be affected as you predict.
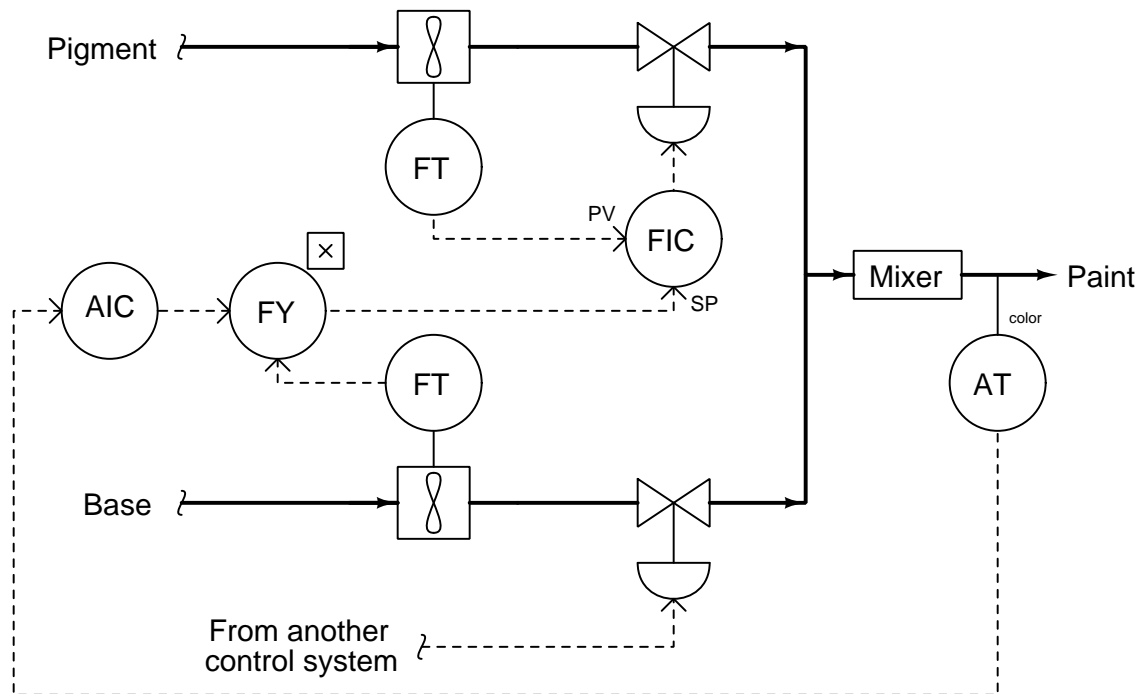
Suggestions for Socratic discussion

- For those who have studied flow measurement, explain how a turbine flowmeter functions.
- Explain what would happen in this process if the base control valve failed fully shut.
- Explain what would happen in this process if the base control valve failed wide-open.
- Explain what would happen in this process if the pigment control valve failed fully shut.
- Explain what would happen in this process if the pigment control valve failed wide-open.
- Explain what would happen in this process if the pigment flow controller (FC) were switched from remote setpoint to local setpoint.

file i01999

Question 28

This solar hot-air collector bank uses a variable-speed fan as the final control element, the temperature controller commanding the fan to blow air at different rates in order to maintain a relatively constant discharge temperature. The hot air is being used to dehydrate wheat grain prior to grinding it into wheat flour. Unfortunately, this system is not operating as it should – the grain is taking longer to dry out than it usually does, despite enjoying the same amount of sunlight (heat source) as it has in the past:
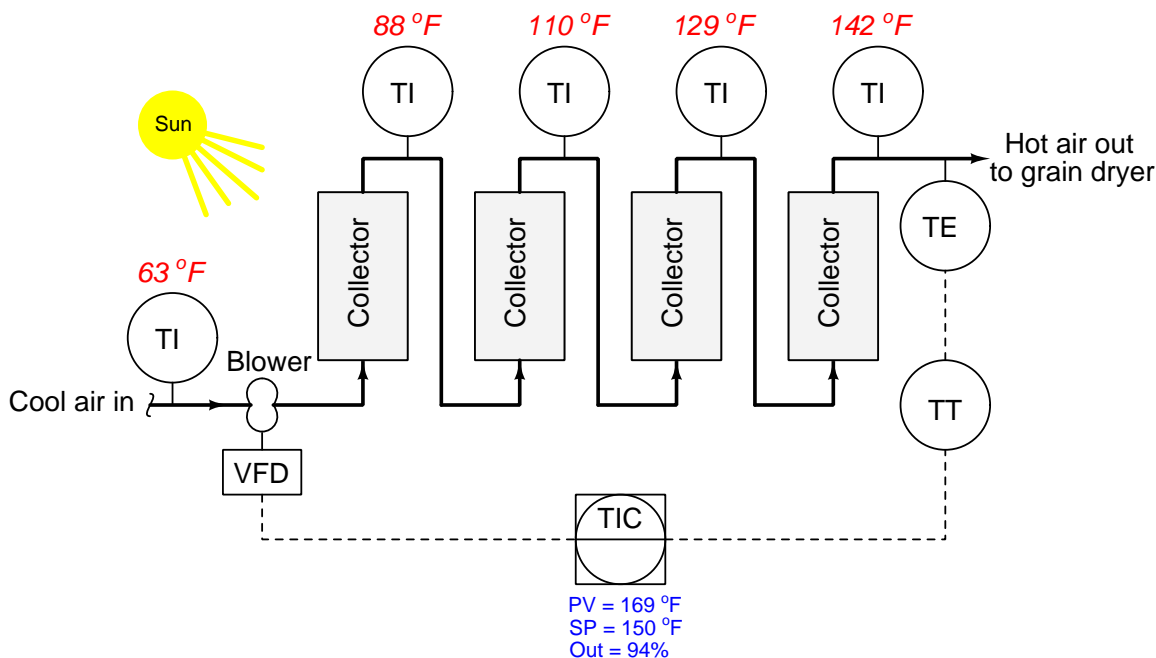
A fellow instrument technician proposes that the VFD is causing the blower motor to spin at the wrong speed, while an operator thinks the solar collectors' glass panes probably need to be cleaned of dust and dirt accumulation. Explain why both of these hypotheses are incorrect, and suggest at least two of your own hypotheses to account for the what we see happening in this system.

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.
- Determine the proper action for this loop controller (direct or reverse).
- Why is the temperature gain less for each successive panel? Is this a problem, or do you think this is how the system normally operates?

file i01699

This paint mixing system mixes (clear) base and (colored) pigment to achieve a desired coloring, according to the ratio setpoint:
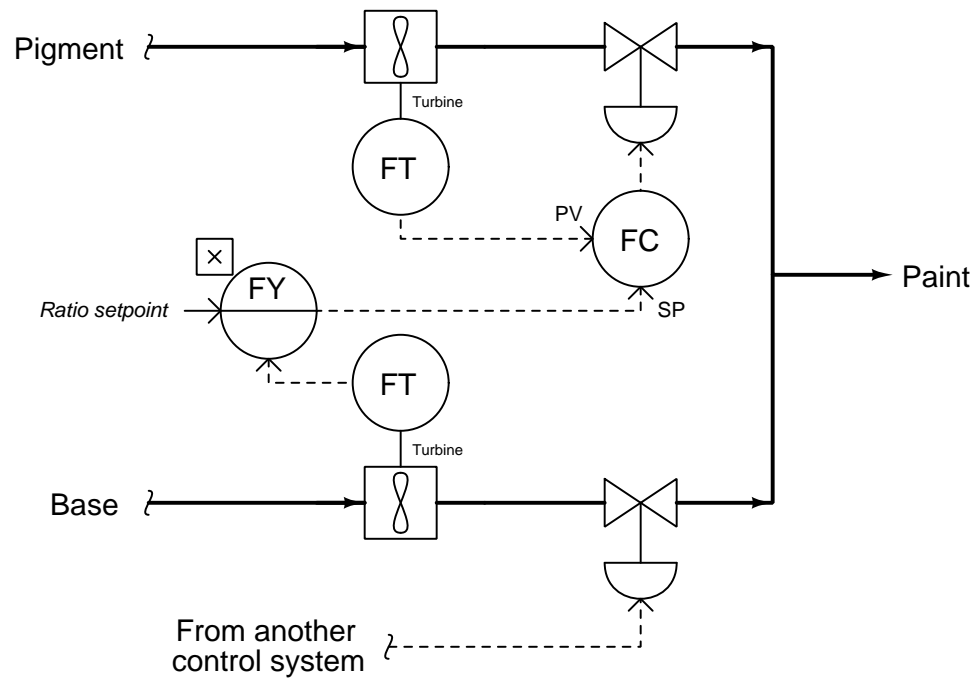
Determine what will happen to the paint's color over time if the pigment flowmeter turbine seizes so that it does not turn even when there is adequate flow through the pipe. Also, explain *why* the paint's color will be affected as you predict.

file i04510

Question 30

Identify the purpose of the flow ratio controller FFC-41 in this distillation process:
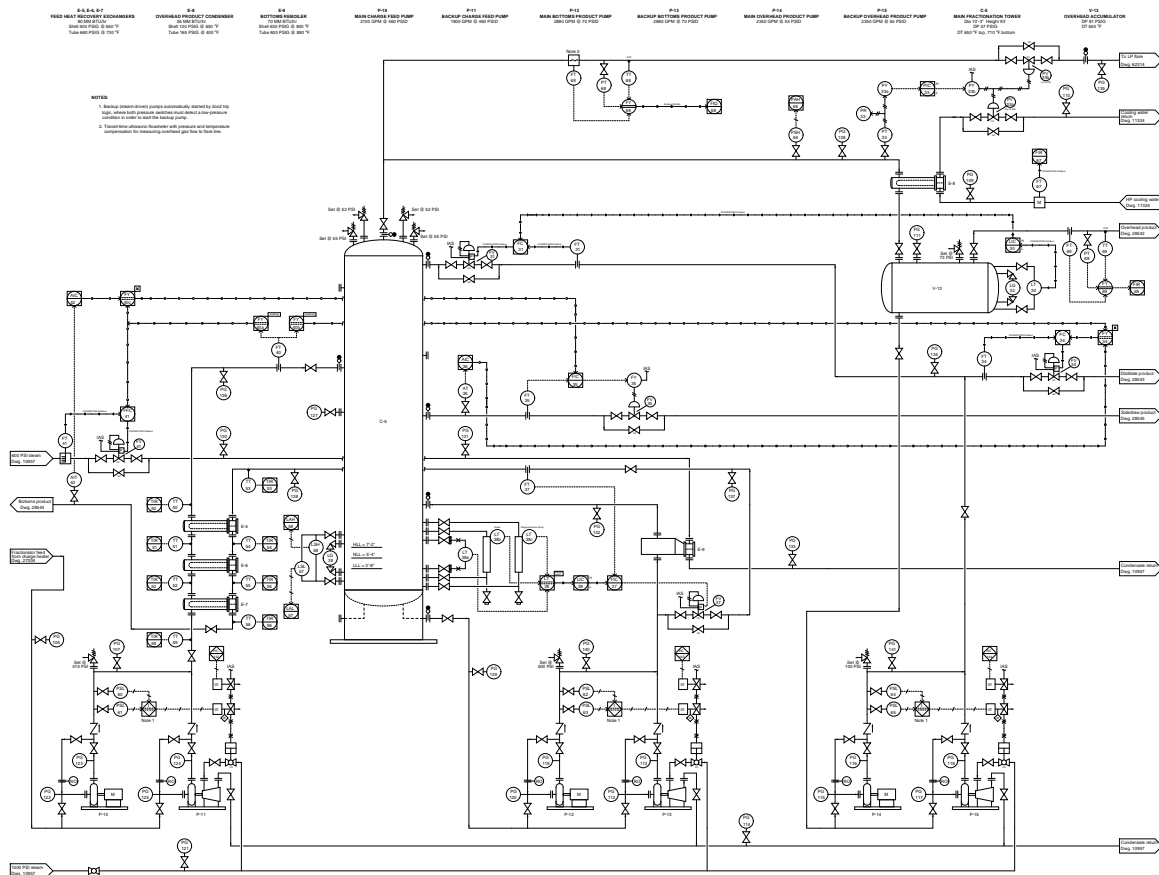
file i01262

Question 31

The ratio between base flow and pigment flow in this paint-mixing control system is not fixed. Rather, it comes from the output of an "analytical" controller:

Explain the rationale behind this ratio control system. Also, identify what the "other control system" might be that drives the base control valve.

- Identify sources of *dead time* in this process, and which control loop(s) will have to manage despite the presence of dead time.
- Analyze the effects of the base flowmeter turbine jamming, so that it does not spin even while liquid is still flowing.
- Analyze the effects of the pigment flowmeter turbine jamming, so that it does not spin even while liquid is still flowing.
- Assuming the AT outputs a greater signal as the paint becomes more pigmented, determine the correct action for the AIC controller.

file i01737

Question 32

A *current mirror* circuit may be thought of as a kind of control system. Identify the *process variable* (PV), the *setpoint* (SP), the *output*, and the *loads* as they apply to a current mirror circuit:
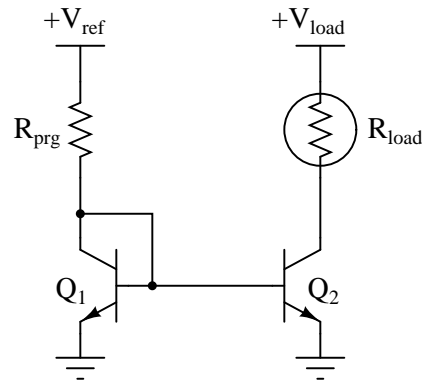
Now, consider this circuit modification, and how it may be thought of as a *ratio* control system. Identify what the "ratio" is, and what determines its value:
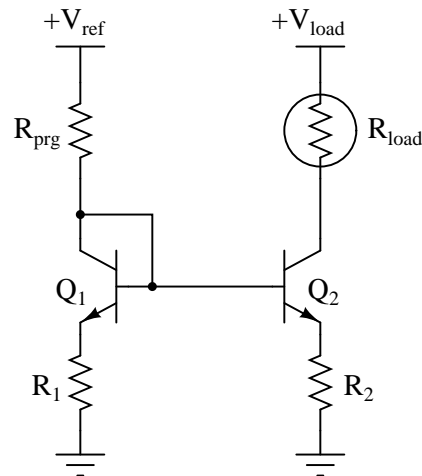
Suggestions for Socratic discussion

- A good problem-solving technique to apply here is assigning numerical values to the components (resistors). For example, you might imagine a case where $R_1 = R_2$, just to prove to yourself how the circuit works, then after that imagine a case where $R_1 \neq R_2$.
- Write an equation solving for the "process variable" current given R_1 and R_2 resistor values and the "setpoint" current.
- Explain what will happen in this circuit if R_{prg} fails open.
- Explain what will happen in this circuit if R_{prg} fails shorted.
- Explain what will happen in this circuit if R_{load} fails open.
- Explain what will happen in this circuit if R_{load} fails shorted.
- Explain what will happen in the lower circuit if R_1 fails open.
- Explain what will happen in the lower circuit if R_1 fails shorted.
- Explain what will happen in the lower circuit if R_2 fails open.
- Explain what will happen in the lower circuit if R_2 fails shorted.

Question 33

The purpose of this circuit is to maintain a constant current through the thermistor, so that V_{out} will be an accurate representation of the thermistor's resistance (and therefore its temperature):

+24 VDC

R₁ 2.2 kΩ   R₂ 2.2 kΩ

Rprg

Vout

Rthermistor = 200 Ω to 3.5 kΩ
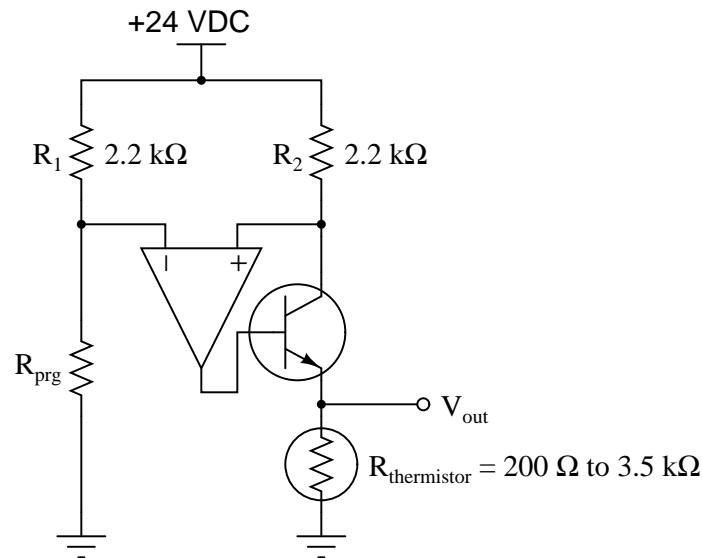
First, identify the necessary value for R_{prg} in order to establish the thermistor's current at 145 microamps.

Next, suppose we find one day that V_{out} is 0 volts, even though the power supply to this circuit has been verified to be 24 VDC just as it should. Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

Fault	Possible	Impossible
R_1 failed open		
R_2 failed open		
R_{prg} failed open		
Thermistor failed open		
Transistor failed open C-E		
R_1 failed shorted		
R_2 failed shorted		
R_{prg} failed shorted		
Thermistor failed shorted		

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 the opamp's connection to the two 2.2 kΩ resistors and to the NPN transistor forms a *negative feedback* system, although it appears to be positive feedback at first glance due to which side of the circuit the transistor is on.

file i01698

46

Question 34

Question 35

Question 36

Question 37

Question 38

Question 39

Question 40

Question 41

Read and outline the introduction and the "Load Compensation" subsection of the "Feedforward Control" section of the "Basic Process Control Strategies" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

(1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A "Table of Contents" format works well for this.
(2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author's problem-solving strategies, etc.).
(3) General principles, especially physical laws, referenced in the text.
(4) 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 i04338

Question 42

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

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

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

file i01751

Question 43

Since liquid level can only change in a vessel if there is an imbalance of inlet and outlet flow rates, would this system be practical to achieve steady liquid level control? Explain why or why not.
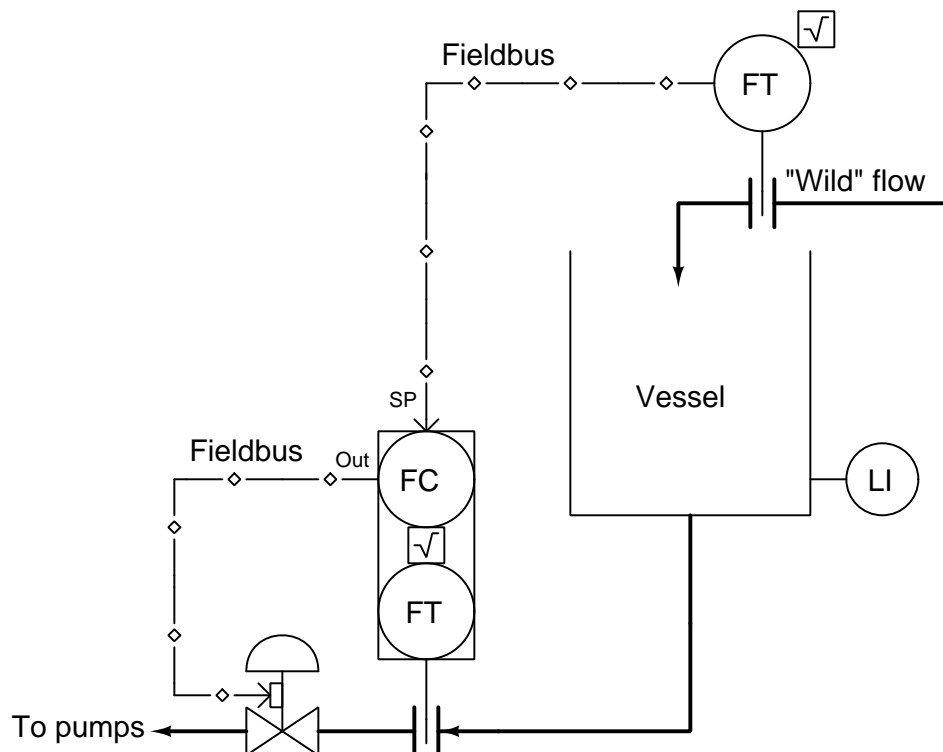
Note: the philosophy behind this control system is a principle known as *mass balance*, and it is a very valid principle. Explain what the principle of "mass balance" is, and how it is implied in the design of this control system.

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

Suggestions for Socratic discussion

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

file i01749

Question 44

Since the outlet temperature of a heat exchanger can only change if there is an imbalance of inlet and outlet heat rates (assuming constant liquid inlet temperature and constant liquid composition), would this system be practical to achieve steady liquid outlet temperature control? Explain why or why not.
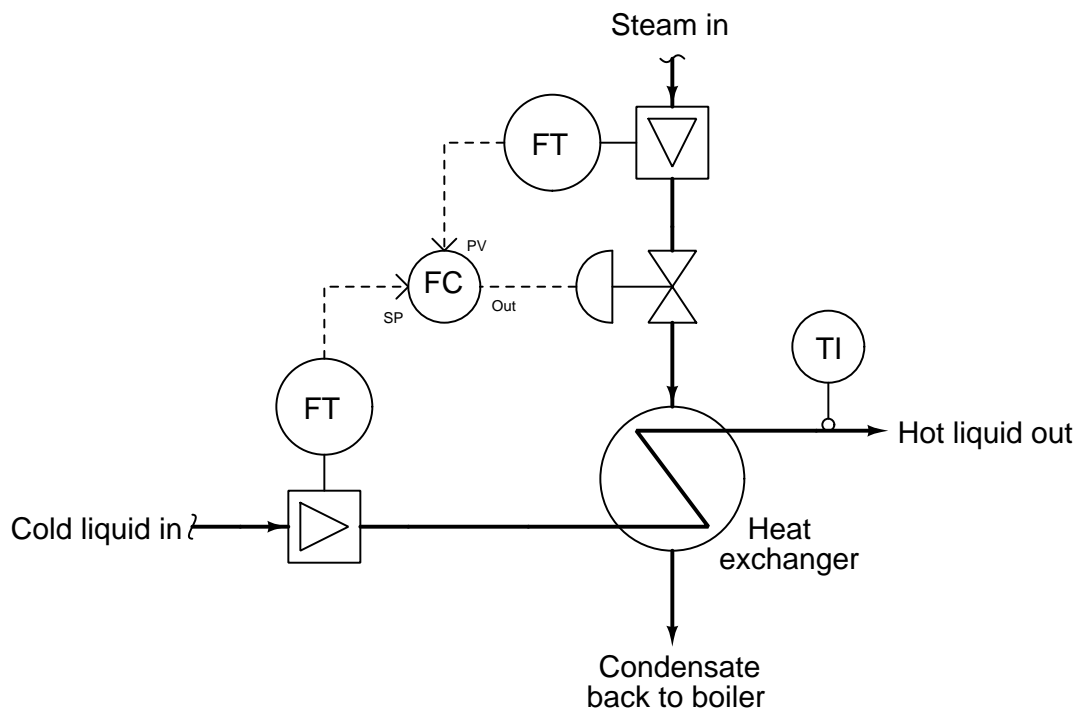
Note: the philosophy behind this control system is a principle known as *energy balance*, and it is a very valid principle. Explain what the principle of "energy balance" is, and how it is implied in the design of this control system.

Suggestions for Socratic discussion

- A powerful problem-solving technique is performing a *thought experiment* where you mentally simulate the response of a system to some imagined set of conditions. Describe a useful "thought experiment" for this system, and how the results of that thought experiment are helpful to answering the question.
- Explain why the control system as shown is impractical for real-life use, despite the fact that it does represent a very effective and important control strategy frequently used in industry.
- Determine whether the controller needs to be *direct* acting or *reverse* acting.
- A problem-solving technique useful for analyzing control systems is to mark the PV and SP inputs of all controllers with "+" and "−" symbols, rather than merely label each controller as "direct" or "reverse" action. Apply this technique to the control strategy shown here, identifying which controller input(s) should be labeled "+" and which controller input(s) should be labeled "−".
- Modify this control strategy to incorporate "feedback trim" in addition to the feedforward action it currently possesses.
- Are there any loads unaccounted for in this feedforward control strategy? If so, see if you can modify this control strategy to account for them as well.

file i01770

50

Question 45

In this process, raw maple syrup is heated by steam to evaporate water and make it more concentrated. An analytical sugar-concentration analyzer at the end monitors the concentration of the finished syrup:
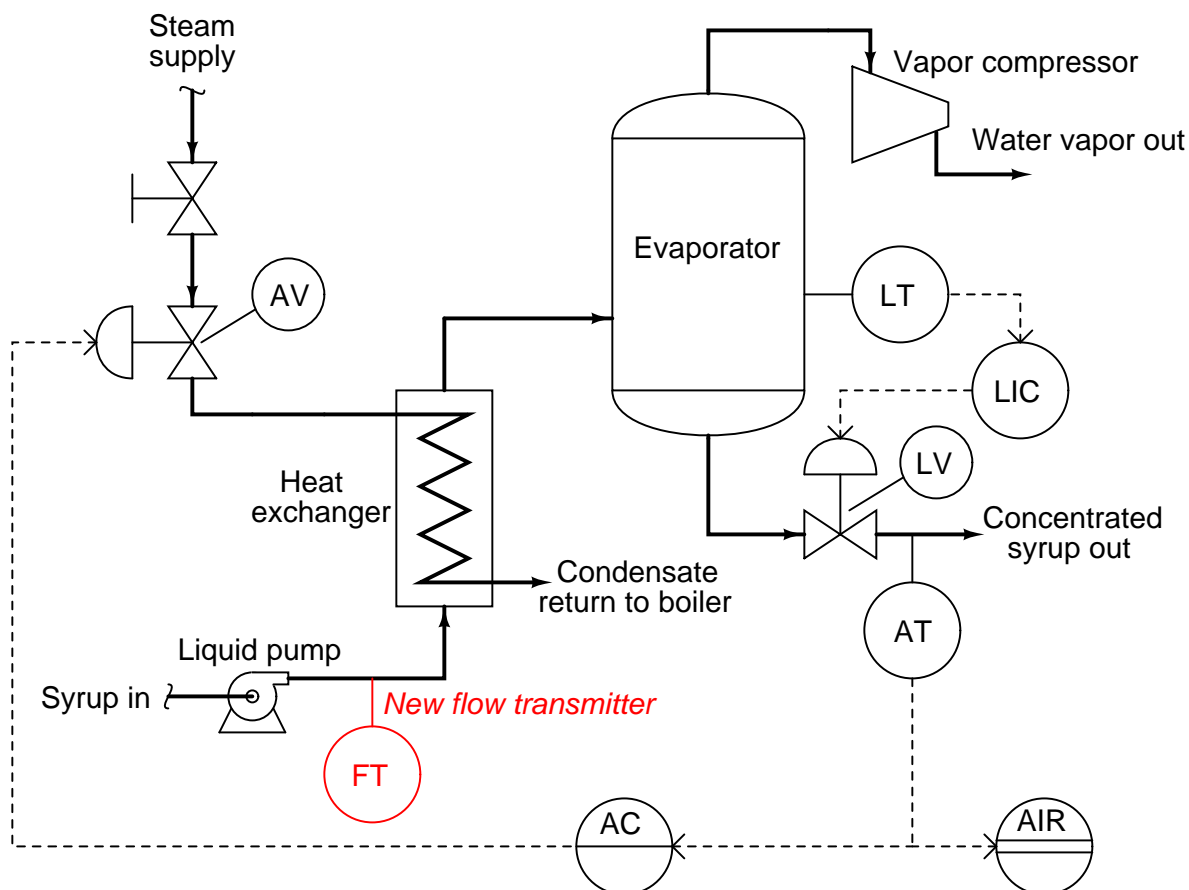
A flowmeter has been installed on the raw syrup line to monitor changes in feed flow rate. Operations personnel have determined that variations in feed flow rate are adversely affecting product quality, and have asked you to implement a solution to stabilize product quality (syrup concentration) despite changes in flow rate.

Modify the control strategy shown in the diagram to achieve better sugar-concentration control despite significant changes in raw syrup feed flow.

Suggestions for Socratic discussion

- A vitally important step to formulating a solution is to completely understand the problem. Perform some "thought experiments" to specifically determine what the adverse effects of feed flow changes are on the outgoing maple syrup quality.
- Perhaps the single most common mistake students make when planning a feedforward system is misplacing the location of the *summing* function block, where the load signal adds to the feedback control signal. Explain why the load signal should always be added to the feedback controller *output* signal, and never to the feedback controller *PV* signal.

file i00424

Question 46

A gas-fired heater is used to increase the temperature of a liquid feed, working to hold that temperature constant at the value specified by a local setpoint (LSP):
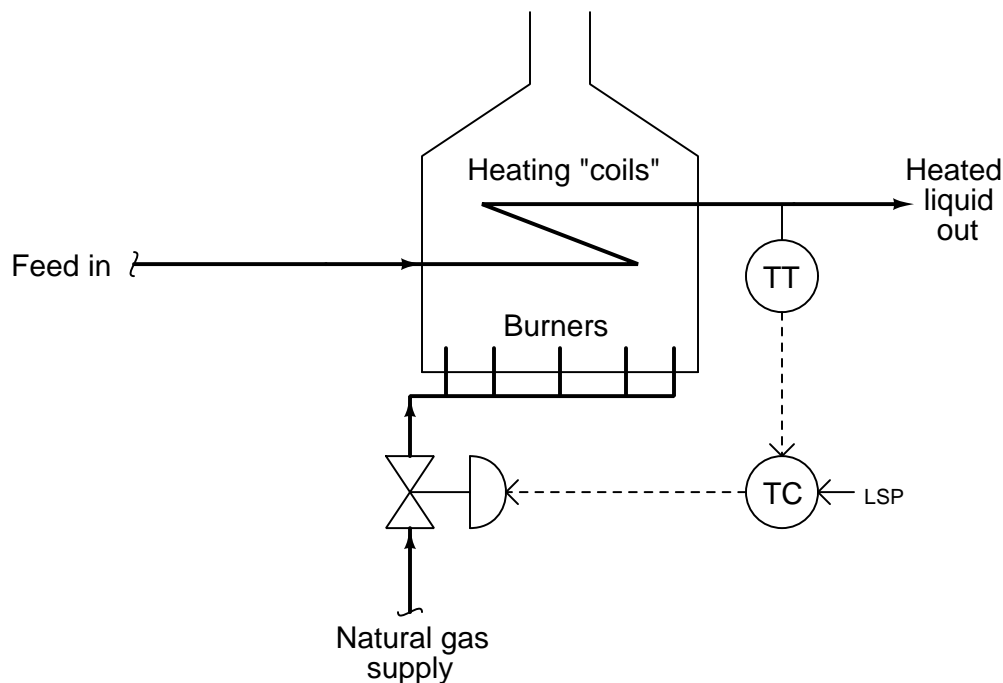
This simple control strategy may be adequate for most purposes, but there is room for improvement. Consider, for instance, how the system will react if the temperature of the cold feed entering the heater suddenly increases. Certainly, the temperature controller (TC) will take corrective action, but only after a rise in outlet temperature is sensed by the transmitter (TT).

One way to improve the system's response to changes is to add *feedforward* control. Modify the control scheme to include a feedforward signal from a feed temperature transmitter, and explain how the modified system will be better than the system in place now.

Suggestions for Socratic discussion

- Perhaps the single most common mistake students make when planning a feedforward system is misplacing the location of the *summing* function block, where the load signal adds to the feedback control signal. Explain why the load signal should always be added to the feedback controller *output* signal, and never to the feedback controller *PV* signal.
- Survey the incorrect solutions presented in the Answer section to this question, and perform a "thought experiment" on each to demonstrate how each strategy fails to achieve the desired end.
- What do you suppose the heating "coils" look like in real life?
- For those who have already studied temperature measurement, what kind(s) of temperature-sensing elements do you think could be used in this application?
- Are there any loads unaccounted for in the requested feedforward control strategy? If so, see if you can modify this control strategy to account for them as well.

file i01776

Question 47

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

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

Examine the following P&ID of a practical feedforward control system on a heat exchanger, complete with "gain" and "bias" functions to allow the feedforward action to be adjusted:
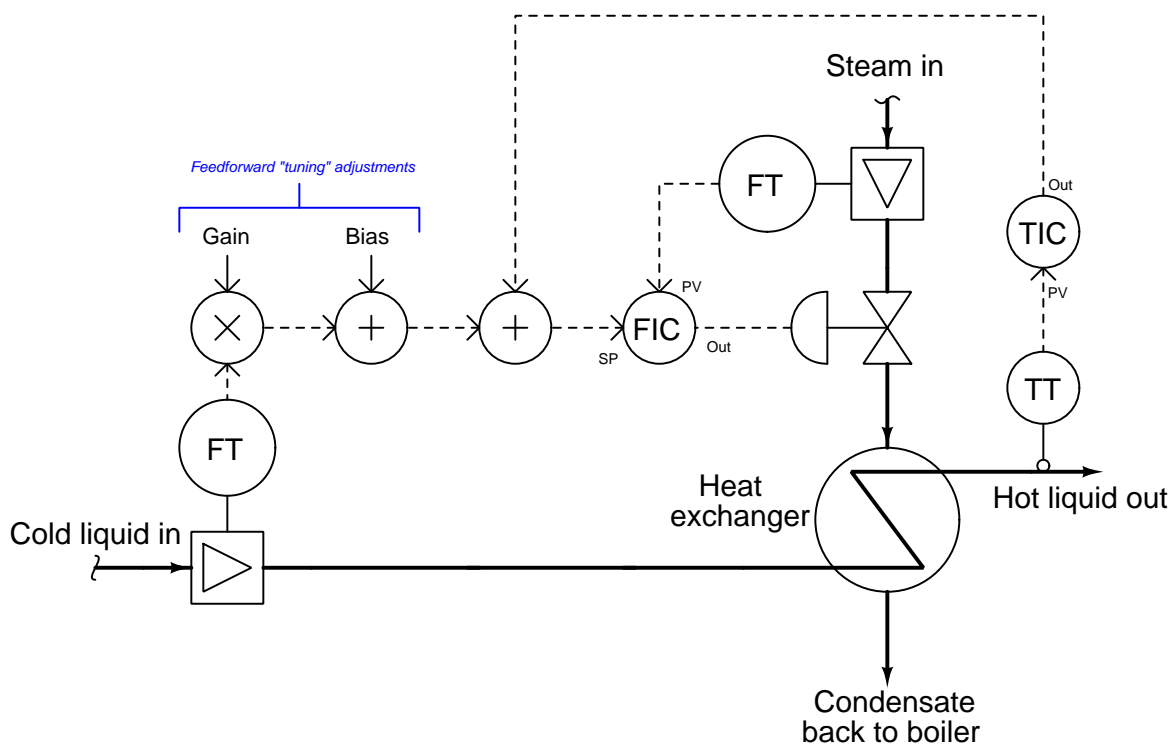
How would this feedforward control system respond to load changes if it were "over-tuned" so that it took *too much* corrective action? What could you do to this system to test the feedforward control response, in order to tell whether or not the magnitude of its corrective action was appropriate? Identify the specific adjustments that you would make to this feedforward system so that its action was more appropriate, if it were discovered that the feedforward action was too aggressive.

Suggestions for Socratic discussion

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

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

file i04339

Question 48

Steam boilers are common in many process industries, and offer many challenges for process control. Let's begin with a simple, "single element" steam drum level control system:
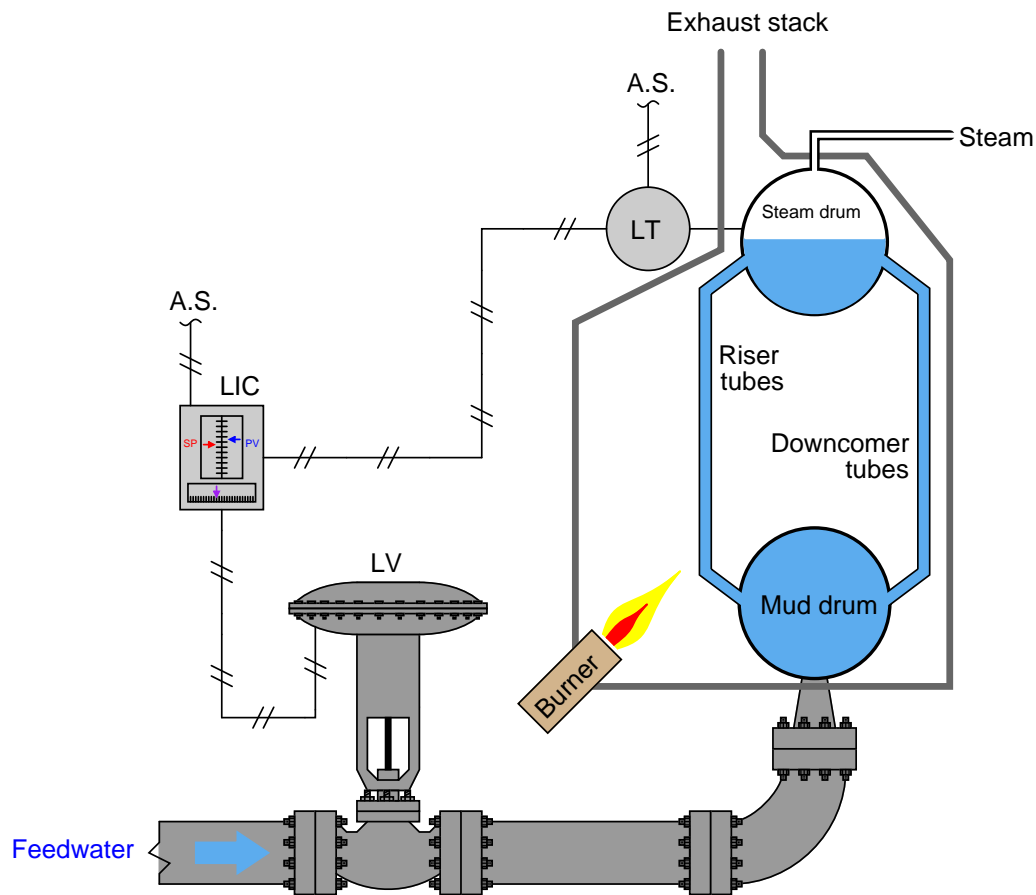
This simplest type of drum level control is suitable only for boilers with very constant "loading" (steam demand). If the boiler is subjected to large fluctuations in steam demand, the drum level will be erratic, possibly leading to boiler tube damage.

As you have seen though, *feedforward* control benefits processes with varying loads. Since steam demand is a type of load in a boiler system, determine how feedforward control could be added to this system to minimize the effects of changing demand (load) on drum level. Hint: this alteration to the control scheme will turn it from a "single-element" to a "two-element" level control system.

file i01788

Question 49

Most large power boilers use a *three-element* control strategy to control the level of water in the steam drum. Explain what "three-element" means, and illustrate the control strategy in the form of a P&ID:
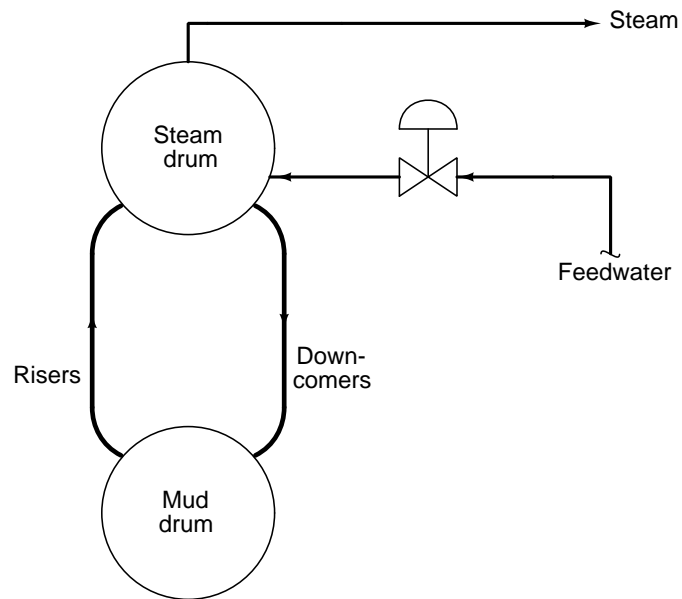
file i01789

The following functional diagram documents a three-element boiler feedwater control system:
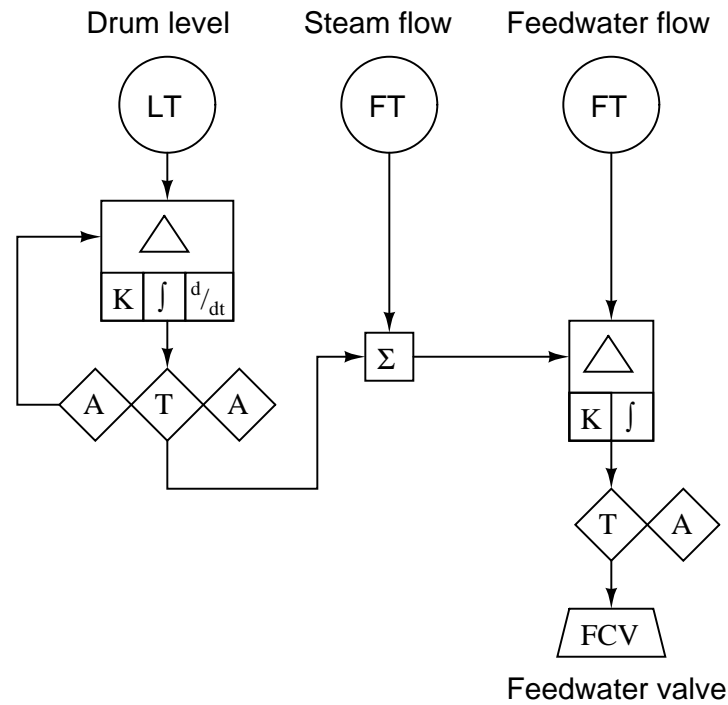
Identify all symbols in this diagram, explaining how they illustrate the control strategy of a three-element system.

file i01791

Question 51

This control strategy for liquid level control is called *feedforward with trim*, *feedforward-feedback* control, or *three-element* control:
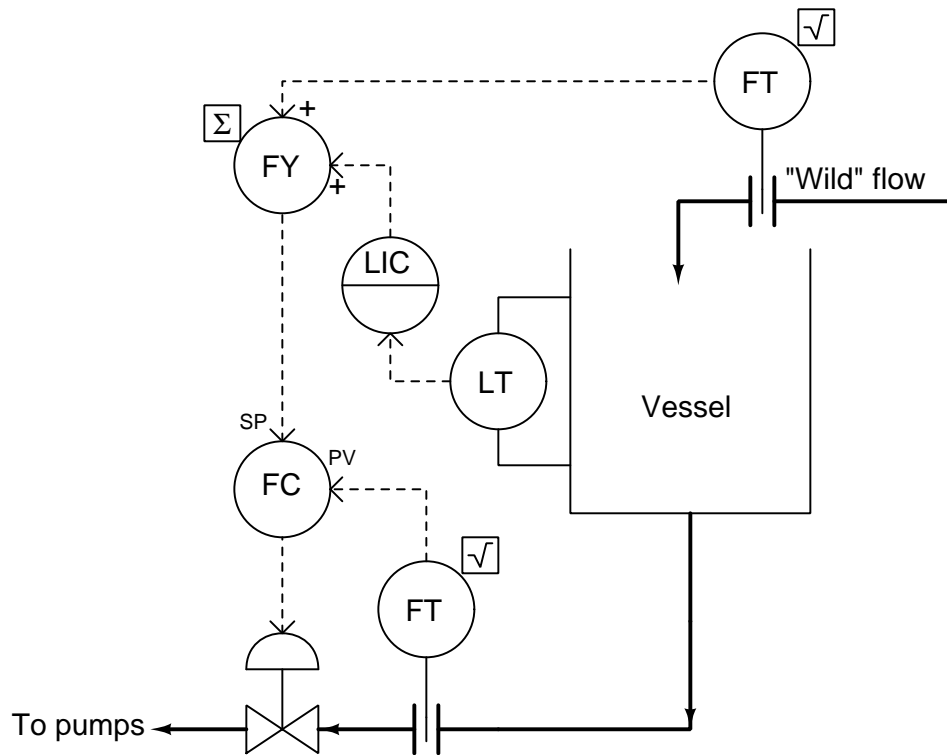
What will this system do to maintain a constant level in the vessel if the "wild" flow input to the vessel suddenly increases?

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

Suggestions for Socratic discussion

- Explain why pure feedforward control is almost never used in industry. Instead, we almost always see feedforward used as part of a larger feedback control strategy.
- A problem-solving technique useful for analyzing control systems is to mark the PV and SP inputs of all controllers with "+" and "−" symbols, rather than merely label each controller as "direct" or "reverse" action. Apply this technique to the control strategy shown here, identifying which controller input(s) should be labeled "+" and which controller input(s) should be labeled "−".
- Explain what will happen if the level transmitter fails with a low signal.
- Explain what will happen if the level transmitter fails with a high signal.
- Explain what will happen if the summing relay fails with a low signal.
- Explain what will happen if the summing relay fails with a high signal.
- Explain what will happen if the flow controller is left in manual mode.
- Explain what will happen if the level controller is left in manual mode.
- Explain what will happen if the wild flow transmitter fails with a low signal.
- Explain what will happen if the wild flow transmitter fails with a high signal.
- Explain what will happen if the captive flow transmitter fails with a low signal.
- Explain what will happen if the captive flow transmitter fails with a high signal.
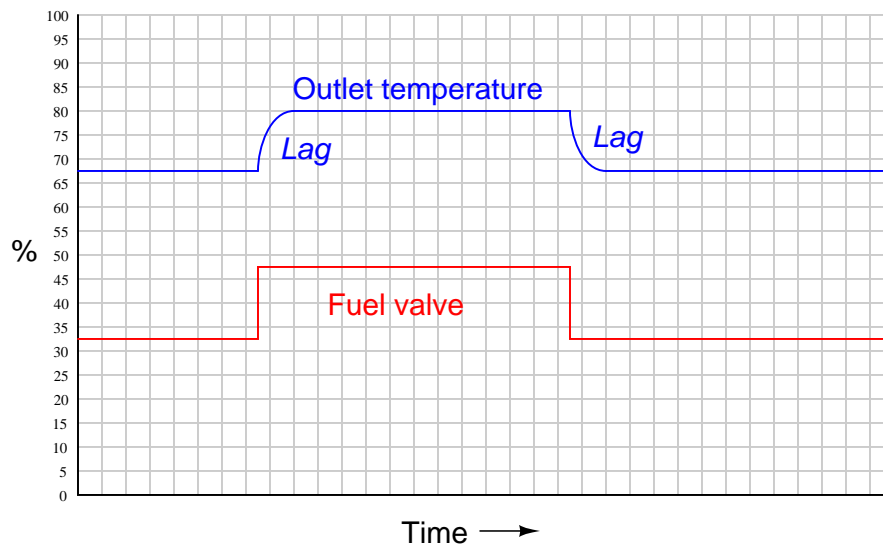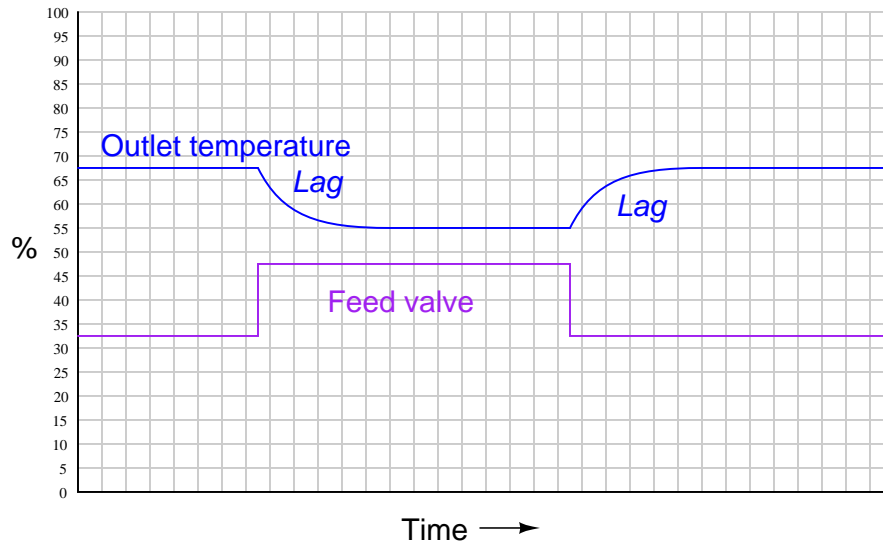
Question 52

Shown here is a simple feedforward control system (with trim), which attempts to compensate for changes in cold feed flow by immediately adjusting fuel flow to the burners proportionately (*before* the outlet temperature has time to change):
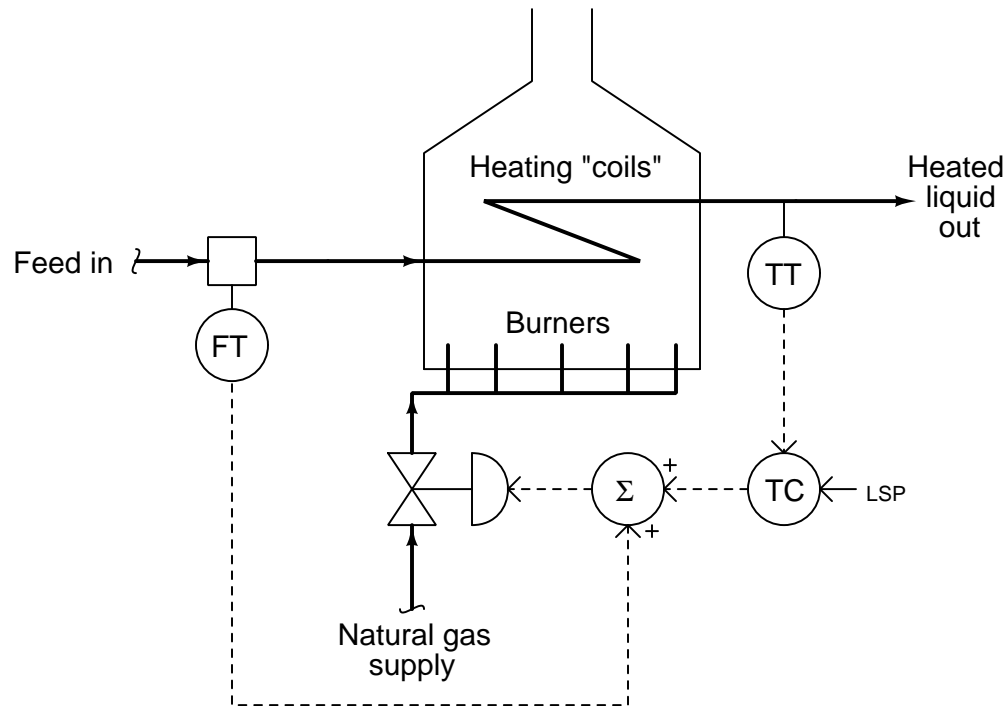
A problem lurks within this process, however, which is not very obvious. The problem is *lag time*. Imagine removing all automatic controls from the process, and replacing them with hand valves so we could have manual control over feed flow and fuel flow while we graphed outlet temperature on a trend recorder:
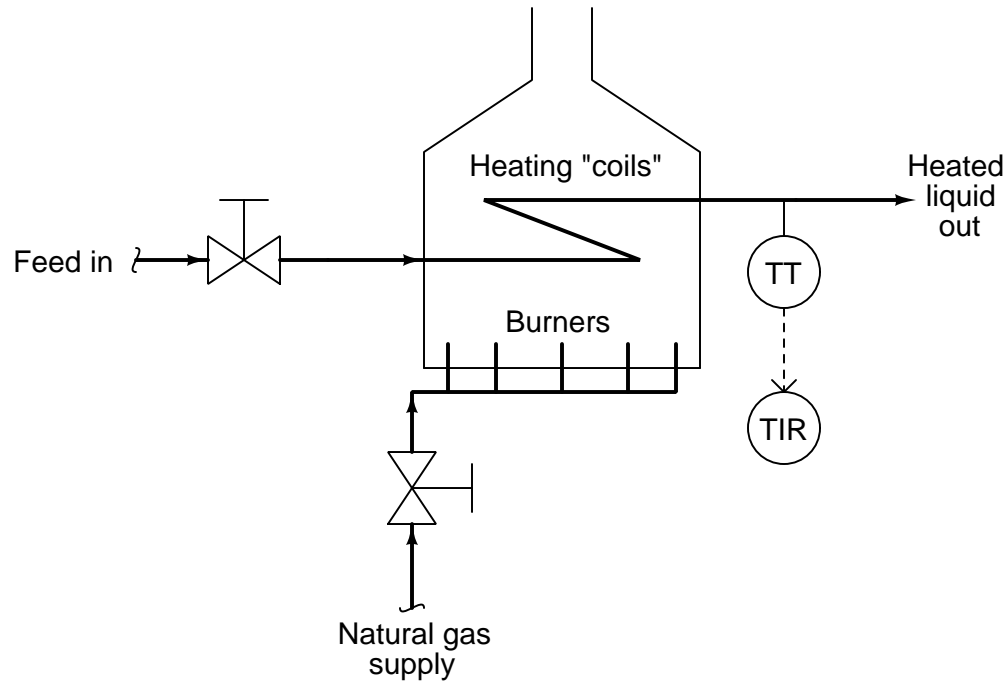
Now, imagine introducing a step change in feed flow, and a step change in fuel gas flow, in two separate tests:


If these two lag times (one for feed flow and one for fuel flow) are exactly the same, then a simple feedforward compensation system such as that shown at the beginning of the question will work just fine. However, if these lag times are *not* equal, as shown in above trends, a simple feedforward system will not perfectly compensate for changes in feed flow. Explain why.

file i01779

Question 53

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

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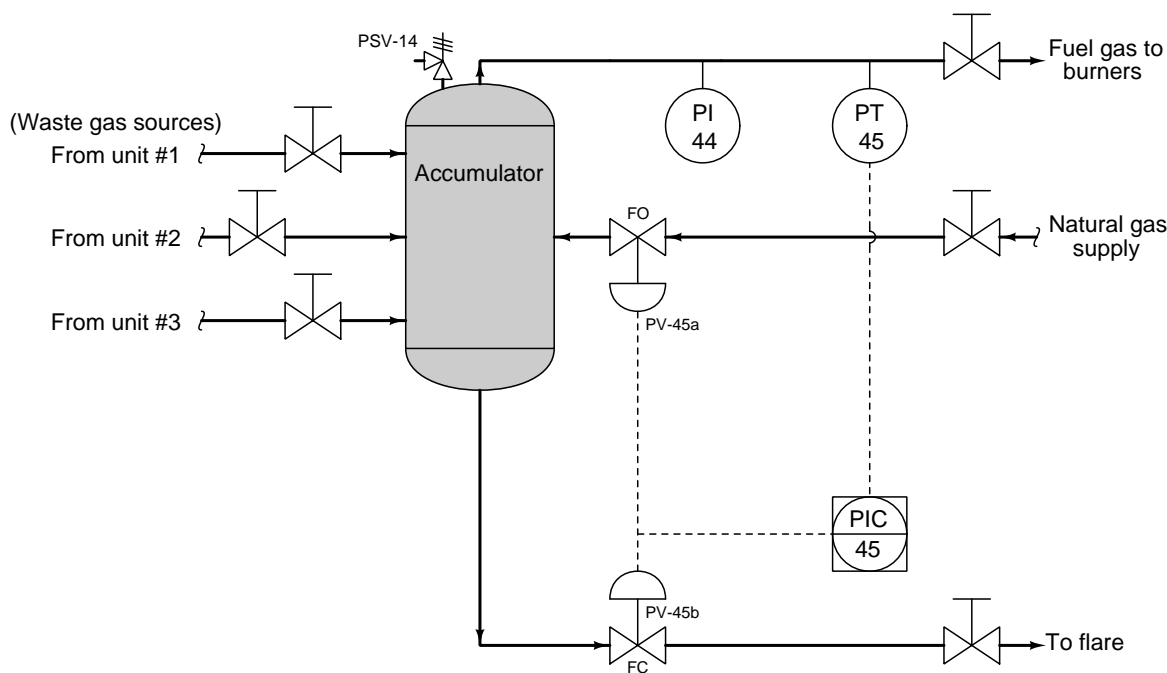

A pair of split-ranged control valves (PV-45a and PV-45b) work together to either admit natural gas into the accumulator (when the gas pressure is too low) or release excess gas to the flare (when pressure is too high).

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

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

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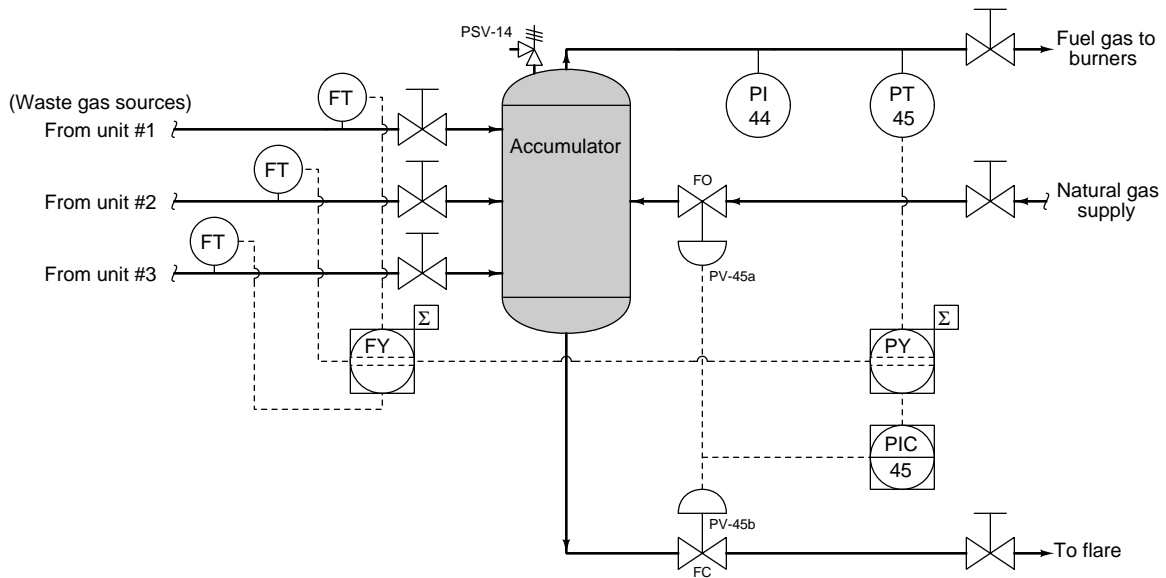
Another team says the strategy should look like this:
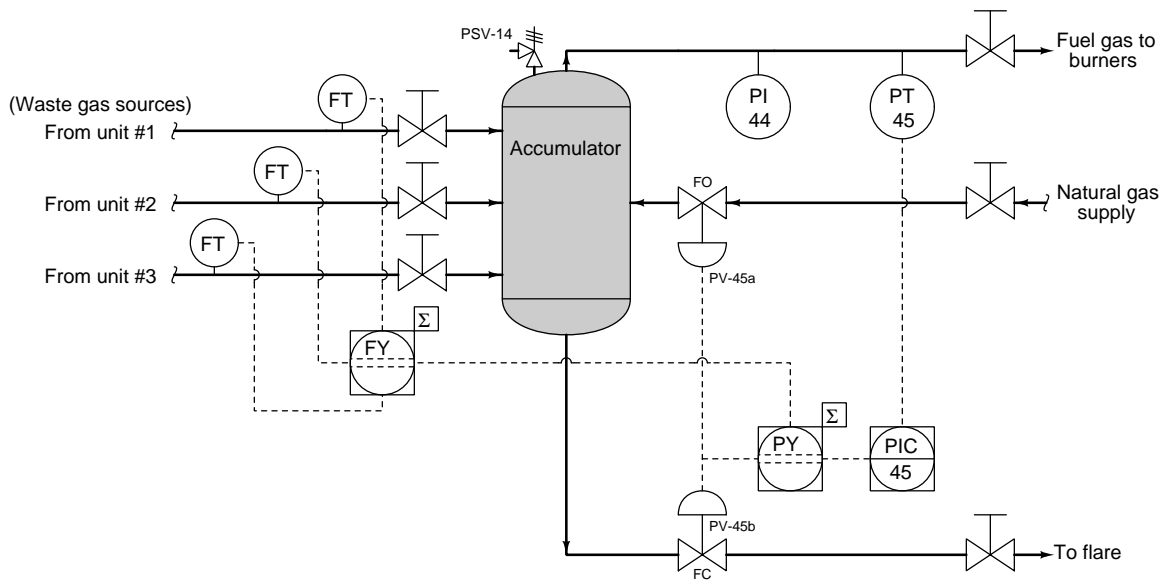
Which team do you agree with, and why? Note: *this is a very important concept to grasp in feedforward control strategies, and in fact is one of the most commonly mis-understood concepts associated with feedforward!*

file i01263

63

Question 54

Water treatment processes use chemicals called *flocculants* to force suspended solids to clump together and readily fall out of suspension. Some flocculants such as polymers have the undesirable effect of lowering the water's pH value, which not only poses problems for further use of the water but also (ironically) minimizes flocculation efficiency. In order to counter-act this decrease in pH, powdered lime may be added to the water in addition to flocculant to raise the pH level back to a more neutral value:
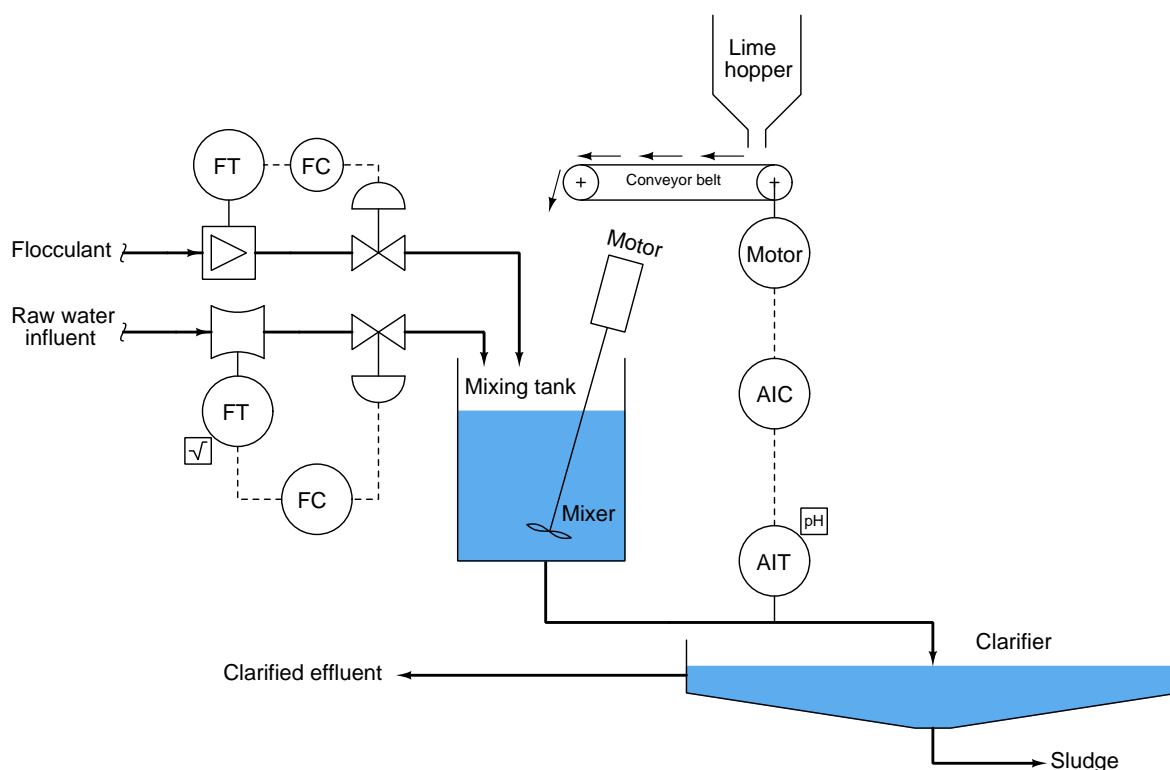
A pH transmitter measures the pH level of the water exiting the mixing tank, on its way to the clarifier where the floc will settle to the bottom over time and cleaner water is collected at the outer rim.

If someone happens to change the setpoint on the flocculant flow controller, the flow of powdered lime into the mixing tank will not change until the pH controller (AIC) sees a change in pH, which by then may be too late to make a swift correction. The result will be a "bump" in pH over time that may take a while to correct.
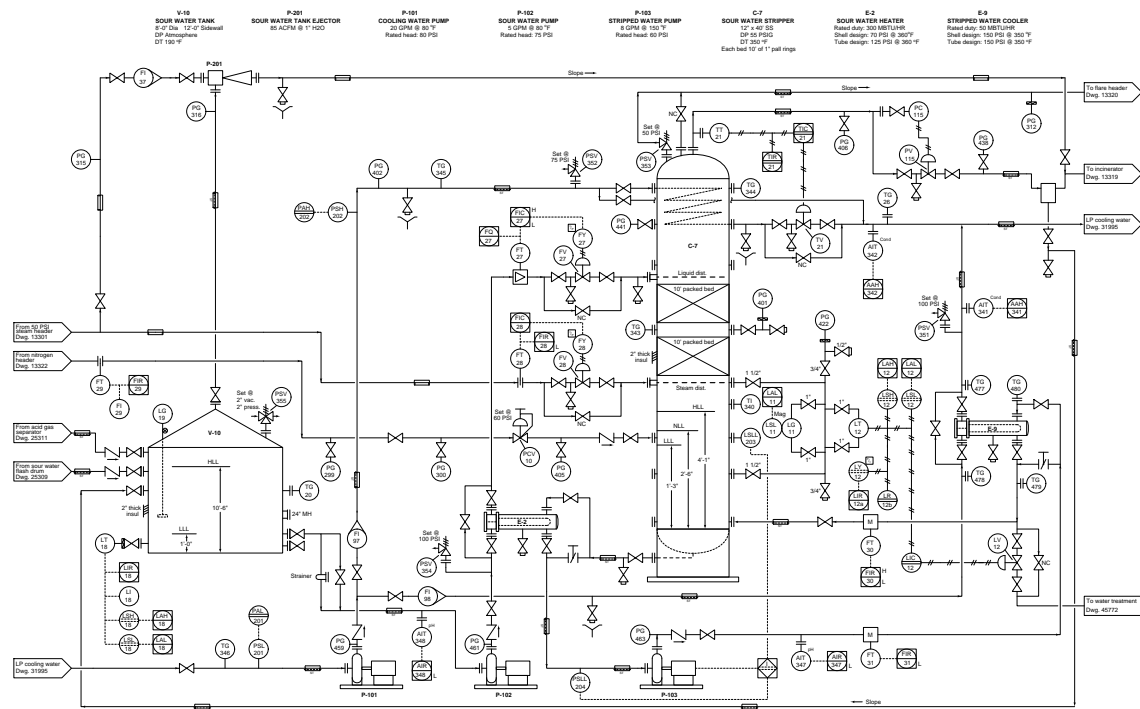
Modify this control system to include feedforward, so that any change in flocculant flow rate will *immediately* alter the flow rate of lime, in order to help stabilize pH and thereby improve water treatment quality.

| Suggestions for Socratic discussion |

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

Question 55

In this process, sulfur-laden water is "stripped" of sulfur compounds by the addition of hot steam:

Operators note that changes made to the setpoint value of FIC-27 have the undesired effects of pushing the process variables of TIC-21 and LIC-12 off of their respective setpoints. Modify the control strategy(ies) shown here to include *feedforward* as a solution to these observed load changes.

file i02884

Question 56

Question 57

Question 58

Question 59

Question 60

Question 61

Read and outline the "Dead Time Compensation" subsection of the "Feedforward with Dynamic Compensation" section of the "Basic Process Control Strategies" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

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

file i04341

Question 62

Read and outline the "Lag Time Compensation" subsection of the "Feedforward with Dynamic Compensation" section of the "Basic Process Control Strategies" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

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

file i04342

Question 63

Read and outline the "Lead/Lag and Dead Time Function Blocks" subsection of the "Feedforward with Dynamic Compensation" section of the "Basic Process Control Strategies" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

(1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A "Table of Contents" format works well for this.

(2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author's problem-solving strategies, etc.).

(3) General principles, especially physical laws, referenced in the text.

(4) Questions of your own you would pose to another reader, to challenge their understanding.

(5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.

(6) Any points of confusion, and precisely why you found the text confusing.

file i04343

Question 64

Explain the purpose of the *lead/lag* unit installed in this feedforward system:
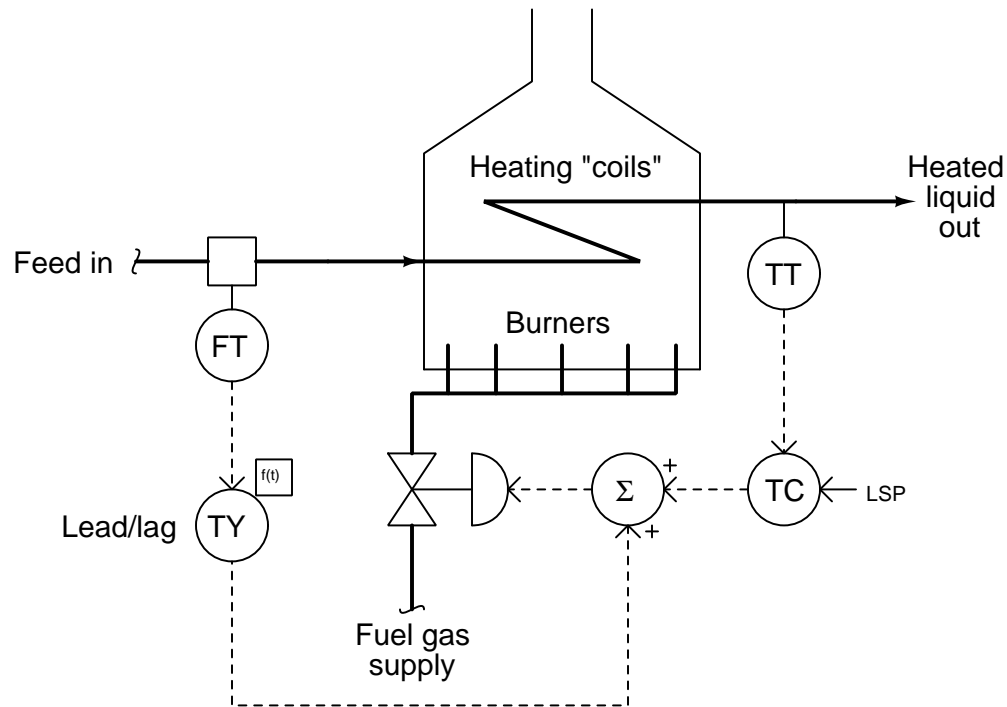
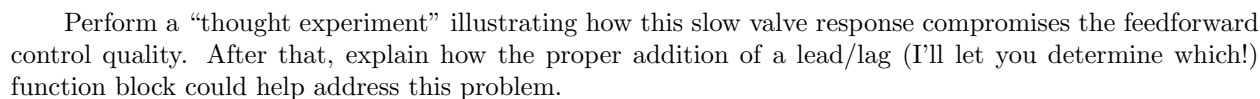Hint: this control strategy is usually called *dynamic compensation*.

Determine whether the lead/lag unit should be set for *lead* or for *lag* if we happen to know that the process temperature naturally responds to load changes faster than to fuel gas valve changes (i.e. a sudden decrease in feed flow causes a quicker rise in outlet temperature than a sudden increase in fuel gas flow to the burner assembly).

Suggestions for Socratic discussion

- Explain the significance of the "+" symbols next to the summer input lines. How well would the system work if one or more of these inputs were inverting ("−") rather than non-inverting?
- Explain the consequence(s) of not having any dynamic compensation at all in this feedforward system.
- Describe the test you would perform to determine whether or not this feedforward system required *lead* compensation or *lag* compensation, prior to introducing the lead/lag function block to the control strategy.
- Explain why you suppose the load (feed flow) has a faster effect on temperature than the compensation (fuel gas flow), based on the physics of heat transfer in this process.
- Explain what would happen in this process if the flow transmitter failed with a low signal.
- Explain what would happen in this process if the flow transmitter failed with a high signal.
- Identify what process characteristic(s) would dictate the lead/lag time ratio in the function block.
- Identify what process characteristic(s) would dictate the lag time value in the function block.

file i01780

68

Question 65

Suppose the flow control valve in this two-element control system is slow to respond because it does not have a volume booster to help actuate it quickly:


Perform a "thought experiment" illustrating how this slow valve response compromises the feedforward control quality. After that, explain how the proper addition of a lead/lag (I'll let you determine which!) function block could help address this problem.

Next, explain how the judicious use of *cascade* control would be a better solution to the problem.

Suggestions for Socratic discussion

- Identify at least one *mechanical* solution to this problem.
- Explain the significance of the "+" symbols next to the summer input lines. How well would the system work if one or more of these inputs were inverting ("−") rather than non-inverting?
- Suppose the suction produced at the discharge line by the pumps proved to be a significant load in the system (i.e. starting or stopping pumps caused excursions in the vessel's level). Explain how you might incorporate feedforward control to stabilize liquid level against that load.
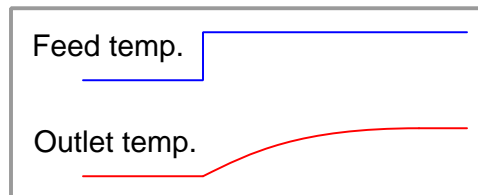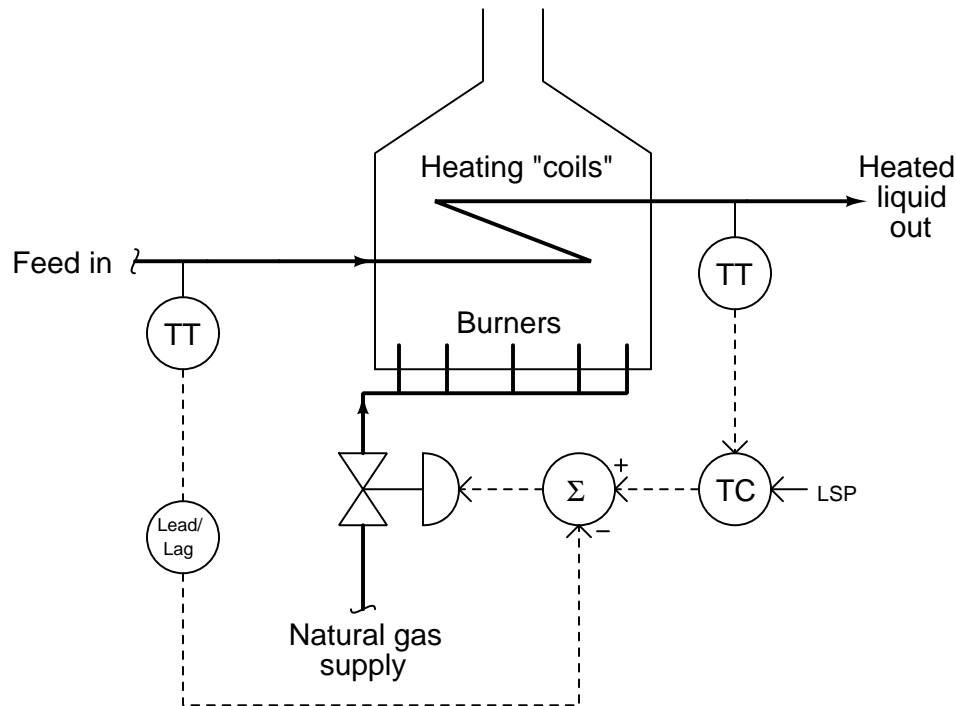
file i04344

Question 66

Identify whether the lead/lag function block needs to be configured for *lead* behavior or for *lag* behavior, based on the open-loop (i.e. control valve fixed at one position) step-change responses shown below, and also explain your answer in detail:
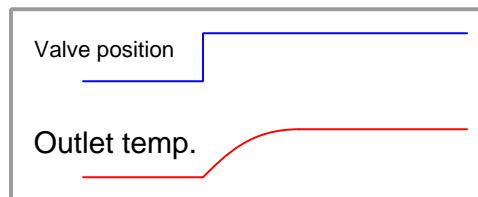
- An effective strategy for solving a complex problem is to *simplify the problem* and solve that simplified problem, then add complexity back into the problem layer by layer (solving each of those problems) until you arrive at the given problem (and its solution). Apply that to this case: find ways to simplify the control system so that you can analyze how it reacts to changes in feed.
- An effective strategy for simplifying a problem where you must compare two slightly different quantities (such as the two time lags here) is to make those two quantities *extremely* different until their relative

effects become obvious to see.

- Explain why it is critically important that the natural gas control valve *not move* during these tests.
- Explain the significance of the "+" and "−" symbols next to the summer input lines. How well would the system work if both of these inputs were non-inverting ("+")?
- How would this control system function if the summer function were moved to a location between the TT and TC?
- How would this control system function if the lead/lag function were moved to a location between the TT and TC?
- How would this control system function if the lead/lag function were moved to a location between the summer and the control valve?

file i04511

Question 67

This production process manufactures *ammonium nitrate*, a principal ingredient of synthetic fertilizer, from the chemical combination of nitric acid and ammonia. The balance of nitric acid to ammonia is critical to controlling the pH of the ammonium nitrate solution exiting the neutralizer. A combination cascade/feedforward control system exerts control over the nitric acid valve FV-23 while sensing ammonia flow (FT-24) and neutralizer effluent pH (AIT-28a, -28b, and -28c):
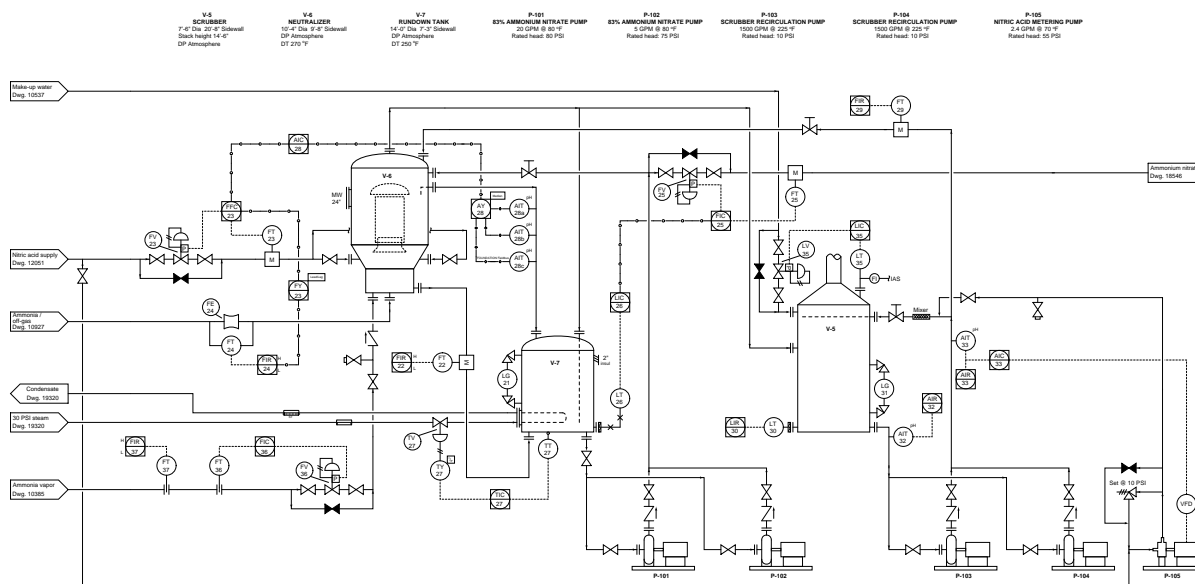
The chemistry of the process is as such: the addition of more nitric acid will drive pH down to lower values. If ammonia off-gas flow happens to rise, nitric acid flow will also have to rise in order to balance the chemical reactions taking place inside the neutralizer.

Knowing this, explain how this control system works to maintain a stable effluent pH from the neutralizer vessel. Specifically, identify the primary and secondary cascaded loops, the wild variable and captive variables, and the feedforward dynamic compensation.

| Suggestions for Socratic discussion |
| --- |

- Explain how we could empirically test this system to determine whether the dynamic compensation needs to be *lead* or *lag*.
- Why are *three* different pH transmitters being used to monitor the neutralizer effluent pH?

file i03394

72

Question 68

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

One way to make this counter-acting lime addition more responsive to changes in flocculant flow is to use a *feedforward* control strategy to pre-emptively alter lime feed rate before the change in flocculant rate has an opportunity to affect the water's pH value. Unfortunately, someone implemented the feedforward incorrectly, as shown in this P&ID:
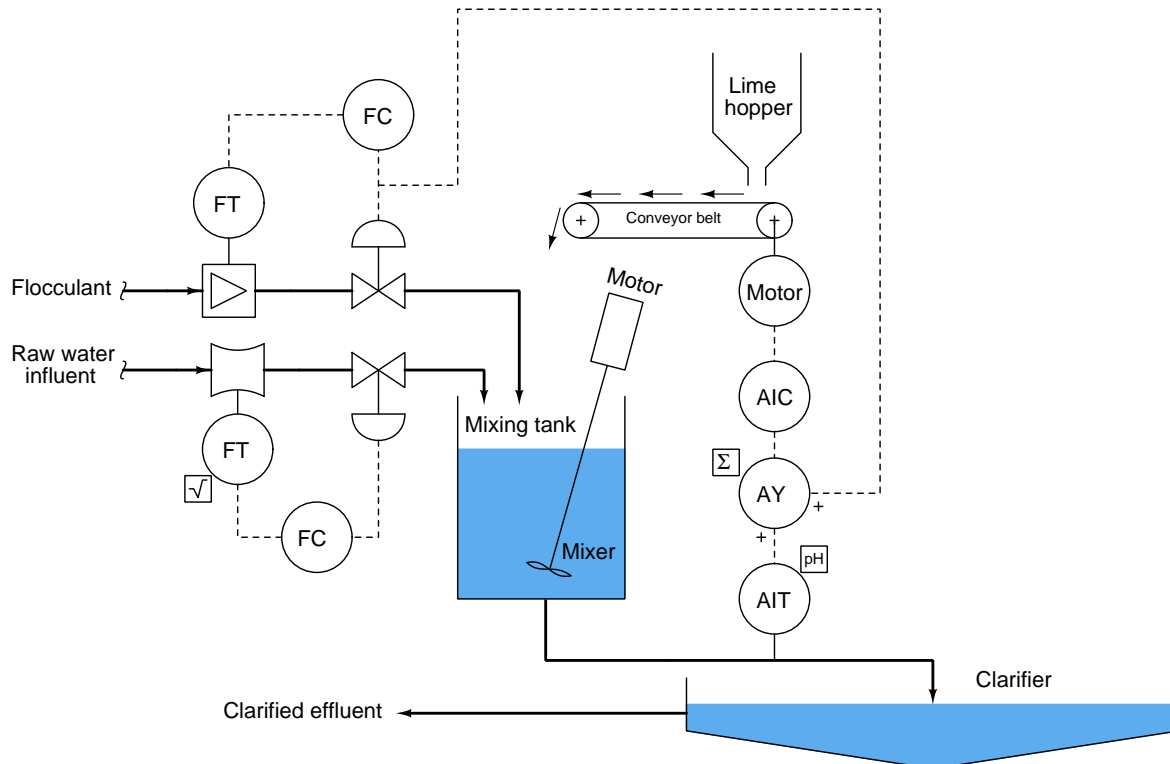
First, identify the mistakes you see in this P&ID, explaining how the system *would* behave if it were actually built and operated like this. Then, correct all the mistakes you see in this control strategy so that the feedforward strategy will work as it should.

Suggestions for Socratic discussion

- Explain why someone might be inclined to sketch the control strategy in this (incorrect) manner. The mistakes shown here are quite common, and so there is likely a logical explanation for why they are so often made!
- Identify where you think *dynamic compensation* might best be applied in this system, after correcting the errors in this proposed feedforward control strategy.

file i00436

Question 69

An energy-efficiency engineer decides to install an advanced temperature control system in a large building, which receives input from a weather prediction service to offset the effects of ambient temperature changes on the building's interior temperature:
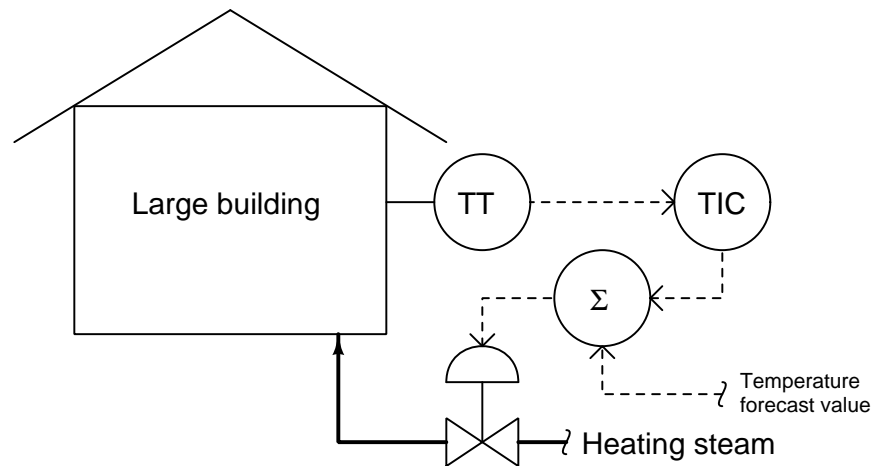
Add polarity symbols (+, −) to the summing function to show how the forecast temperature should be combined with the controller output to effectively implement feedforward control to this system. Hint: you may find a "thought experiment" to be a helpful problem-solving technique here!

Suggestions for Socratic discussion

- Would this strategy be most useful on a *small* building or on a *large* building? Explain your answer.

  file i04345

Question 70

An energy-efficiency engineer decides to install an advanced temperature control system in a large building, which receives input from a weather prediction service to offset the effects of ambient temperature changes on the building's interior temperature:
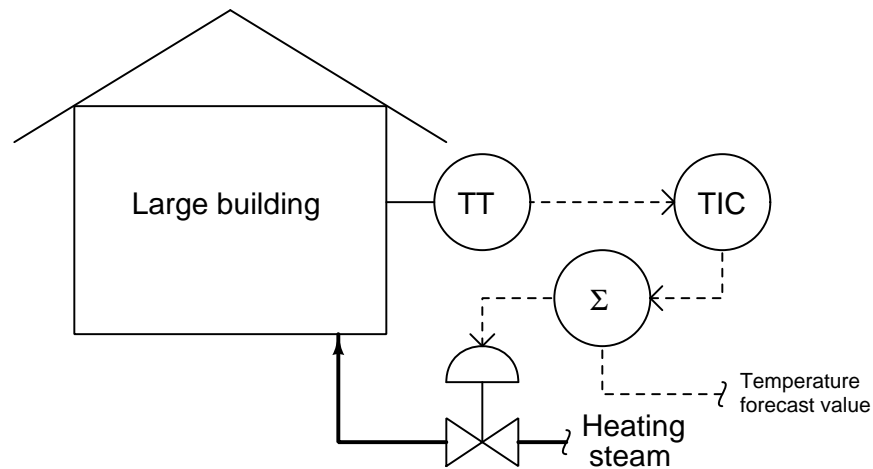

The only problem with this system as it stands is that the forecast temperature causes the building's temperature to rise and fall prematurely, since the forecast is predicted much longer in advance than the building takes to heat up or cool down.

Identify what type of dynamic compensation function you would install in this control system to correct this problem, and where exactly in the strategy (function block diagram) you would choose to install it.

Suggestions for Socratic discussion

- Would the amount of dynamic compensation needed in this system vary with the range of the forecast, the size of the building, or both?

file i04346

Question 71

This P&ID shows the control system for a *fractionator* (otherwise known as a *distillation column* whereby a multi-component liquid is separated into its constituent components by boiling and condensing. The incoming "feed" is pre-heated by a gas-fired "charge heater" unit (not shown in this diagram), then heated more by passing through a bank of heat exchangers (E-5 through E-7) cooling off distilled product while heating incoming feed, and then introduced into the middle of the fractionator vessel (C-5) where the lighter fractions rise up and the heavier fractions fall down to be collected at different heights along the vessel. "Bottoms" liquid at the bottom of the fractionator is re-boiled by a steam-heated exchanger (E-9) while "Overhead" vapors are condensed by a water-cooled exchanger (E-8) and collected in an accumulator vessel (V-13), some of which is re-introduced into the fractionator as "reflux" flow:
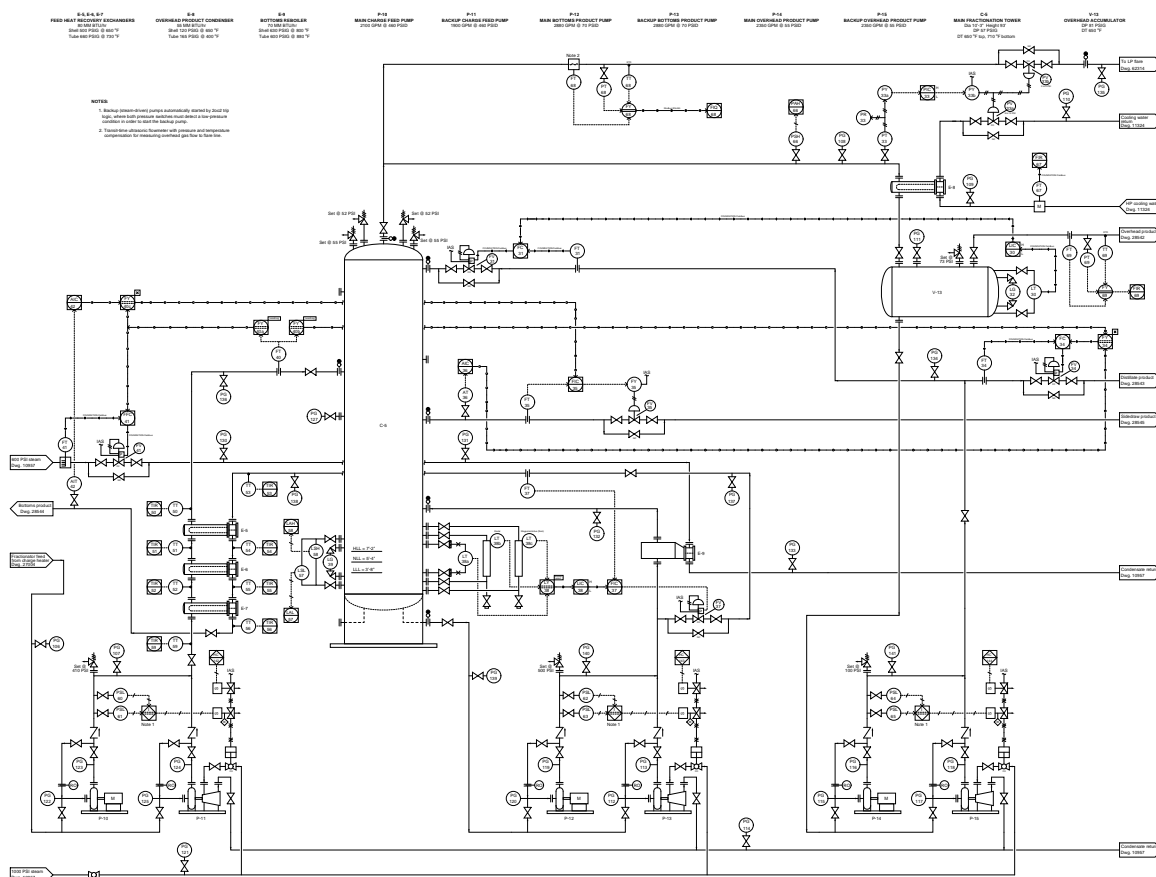
Feed flow transmitter FT-40 plays an important role in this control system, monitoring the rate at which fresh feed enters the fractionator tower. This flow signal is used in multiple feedforward control schemes in this system. Identify those feedforward systems and explain what they do.

Also identify where *dynamic compensation* is employed in this system, and explain the purpose for doing so.

Finally, explain how you would "tune" the feedforward systems for the correct amount of action, and also "tune" the dynamic compensation for the correct amount of time.

file i02885

Question 72

Combustion heaters fired with a solid fuel such as coal often use *pulverizing mills* (sometimes called *ball mills*) to crush the coal into a powder for more efficient combustion. The following is a P&ID showing a fuel "flow" control system for such a solid fuel:
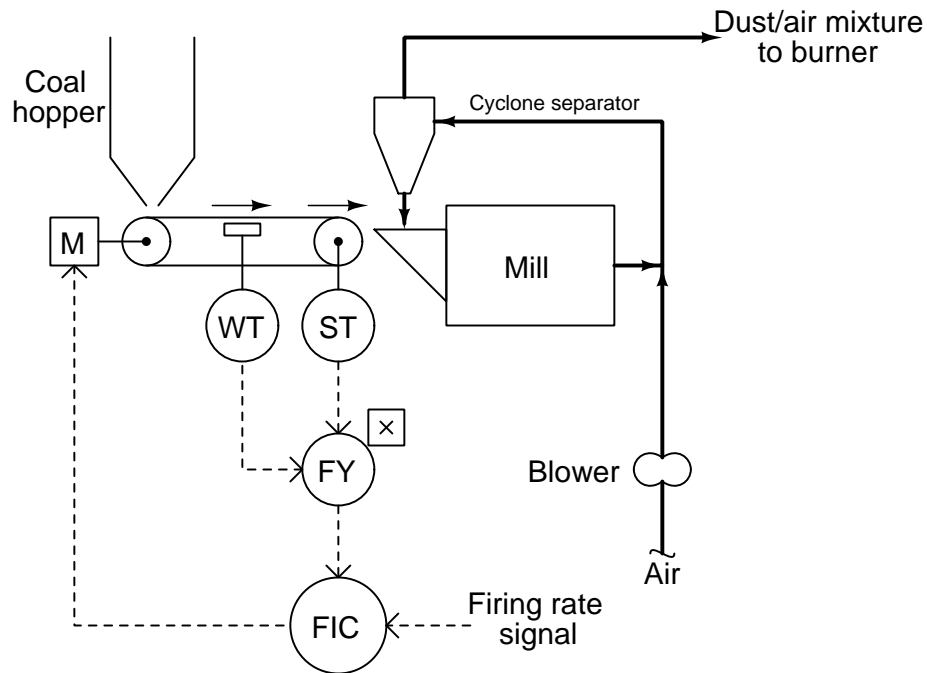
Solid coal from the hopper is weighed and fed by a variable-speed conveyor belt, then dumped into the ball mill where many steel balls tumbling in the cylindrical barrel of the mill grind the coal into smaller pieces, then carried into a "cyclone" separator where only the fine dust continues to the burner. Coarser pieces falling out of the separator go back into the ball mill for additional pulverizing.

Determine the purpose of the multiplying relay (FY) in this control system. Hint: since the weight scale only measures the weight of a section of loaded conveyor belt, its output is expressed in units of pounds per foot (of belt). The speed transmitter, of course, outputs a speed signal with units such as feet per minute (of belt).

One problem with this control system is that the ball mill and cyclone separator introduce lag and dead time into the process. That is, a sudden change in flow rate as detected by the weighfeeder conveyor equates to a delayed change in dust/air flow to the burner due to the time it takes for this additional fuel to make its way through the mill and separator. A modification made to the control system helps avoid potential fuel flow control problems:
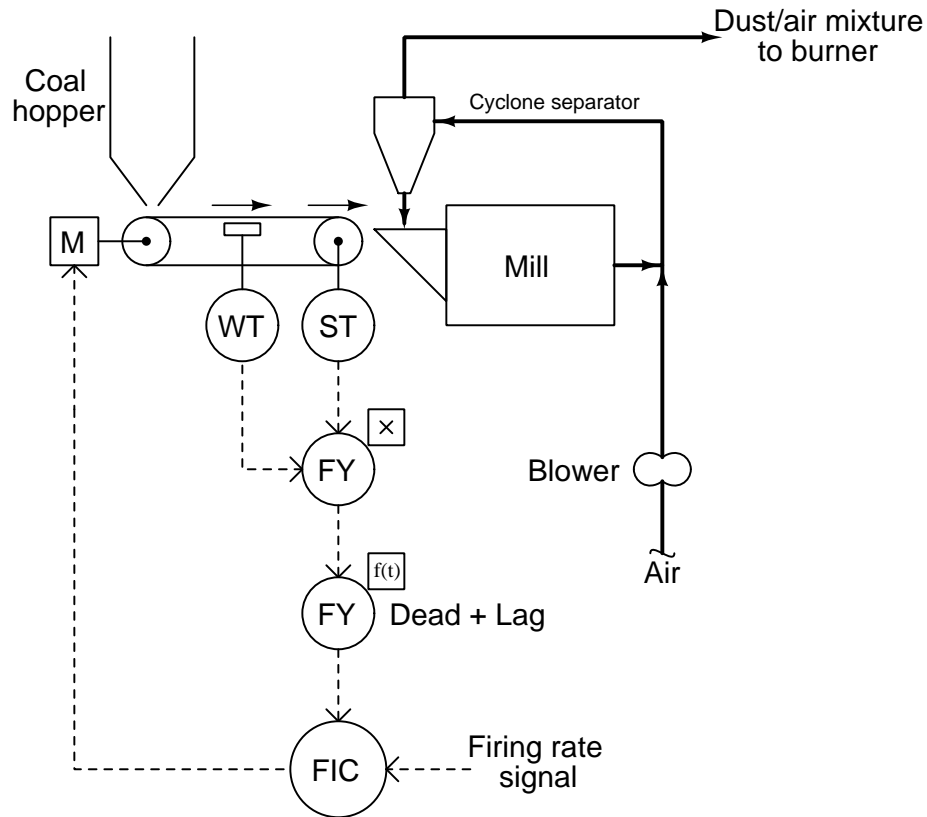
Explain how the addition of this lag function helps the flow controller (FC) do a better job of controlling fuel flow to the burner.

- Explain exactly how a "cyclone" separator does its job.

  file i01818

Question 73

A byproduct of the *kraft process* used in the paper industry for turning wood chips into pulp is a liquid called *black liquor*. This liquid contains many volatile sulfur compounds such as hydrogen sulfide (H_2S) and mercaptans, both of which are strongly scented, and if released to the atmosphere will constitute a hazardous (or at least strongly objectionable) emission. Loss of volatile sulfur compounds also constitutes a loss of sulfur, which is a raw material in the kraft pulping process.

These sulfur compounds may be stabilized for less volatility and easier recovery by a process of oxidation: exposing the black liquor to pure oxygen gas. To minimize consumption of oxygen, the gas flow is metered proportionately to liquor flow in a ratio control system:
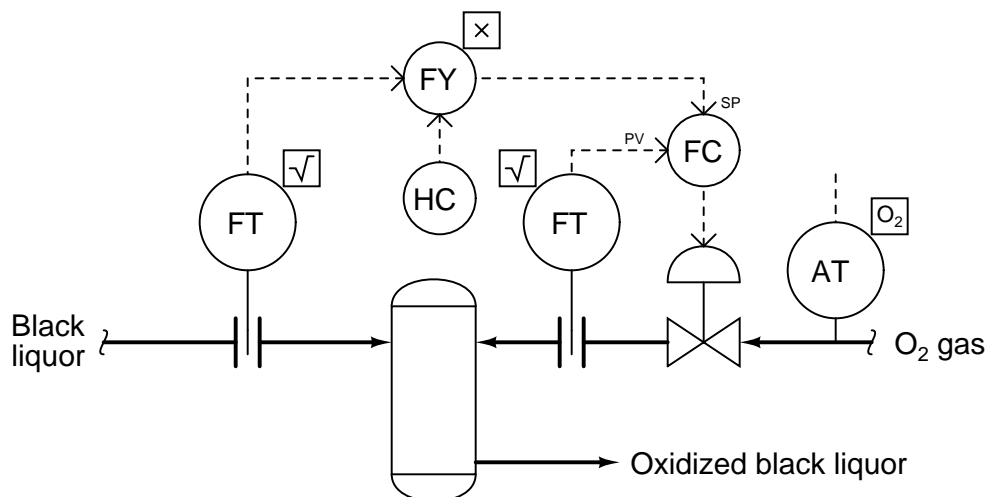
One problem with this system, though, is that the purity of the oxygen gas varies over time. Some days it is near 95% pure, while other days it may sink down to 80% purity. The balance is made up of nitrogen gas, which does nothing to oxidize the liquor. Operations personnel discovered this problem when they had an oxygen analyzer installed on the O_2 line coming in to the oxidation reactor. Now they want a control system that takes this on-line measurement and automatically compensates the gas flow in to properly oxidize the liquor no matter what the oxygen concentration happens to be.

A useful problem-solving technique to apply here is a "thought experiment" where you imagine the oxygen purity changing between two easy-to-calculate values: suppose the purity begins at 100%, then suddenly changes to 50%. How should an automatic compensating system respond to the O_2 purity *being cut exactly in half*, in order to maintain proper oxidation of the liquor? Then, take that conclusion and implement it using one or more additional function blocks.

Suggestions for Socratic discussion

- Explain how the suggested thought experiment makes this a relatively easy problem to solve.
- For those who have studied flow measurement, explain why each flow transmitter has *square root* characterization.

file i00435

Question 74

Question 75

Question 81

Geothermal power plants rely on multiple "production wells" drilled deep into the earth to extract hot fluids which are then used to drive steam turbines. The following control system cascades the pressure controller's output to three flow control loops in order to "balance" the production rates of three different wells rather than over-use or under-use any one of them:
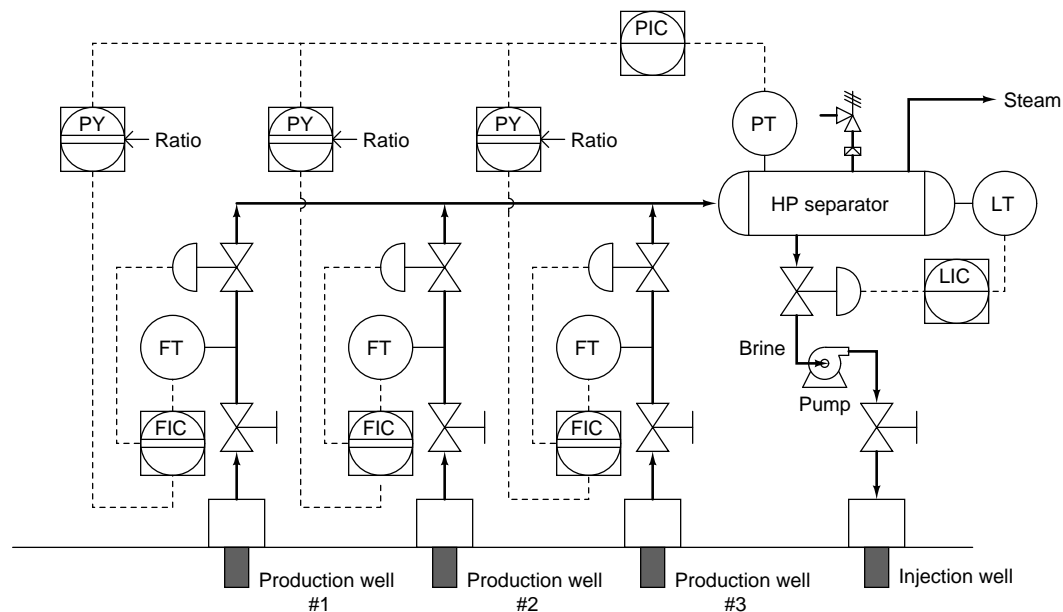
The ratio value for each production well is determined by operations engineers, their sum totaling to 100%.

Suppose an engineer makes a mistake one day, setting the ratio for well #1 at 25%, the ratio for well #2 at 41%, and the ratio for well #3 at 43%. Obviously, these three ratio values do *not* add up to 100%. Calculate the actual flow ratios of wells #1, #2, and #3 as percentages of the total (true) flow entering the HP separator vessel.

file i03495

Question 82

One of the major processes used to treat municipal wastewater is *aeration*, where the dissolved oxygen concentration of the wastewater is enhanced by bubbling air through the water in an *aeration basin*. A dissolved oxygen ("DO") analyzer measures the oxygen concentration in the wastewater, and a controller varies the speeds of blowers pumping air into the basins using AC motors powered through variable-frequency drives (VFDs):
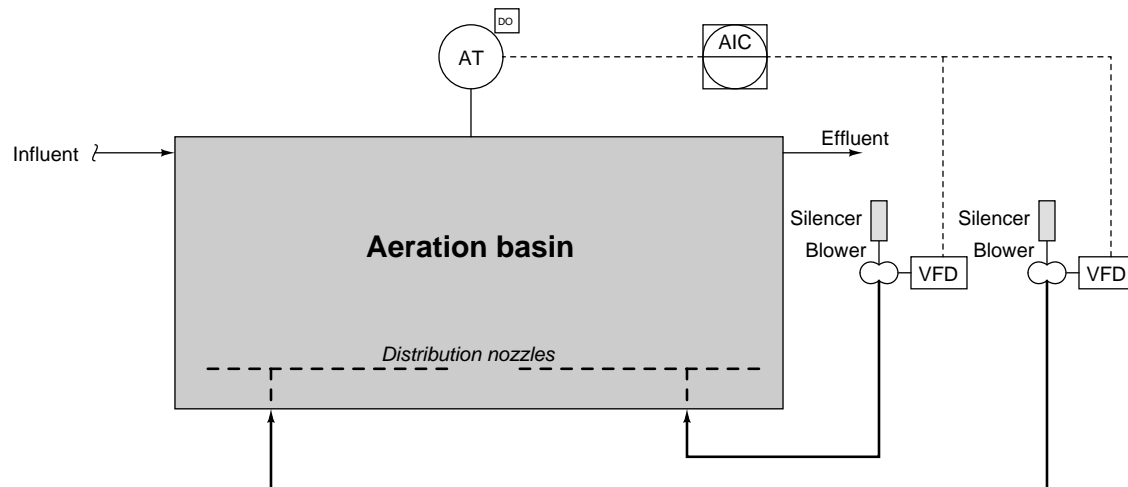
A problem with this particular system is that the nozzles at the bottom of the aeration chamber have a tendency to plug up, thus impeding air flow into the chamber. The controller (AIC) will compensate for this over time by commanding the blowers to spin faster, but the correction is not immediate which results in temporary deviations from setpoint.

Modify this control strategy so that any plugging of the nozzles will be immediately sensed and compensated for, avoiding the temporary deviations from setpoint. Feel free to add any needed field instruments to make this happen.

file i03292

81

Question 83

One of the major processes used to treat municipal wastewater is *aeration*, where the dissolved oxygen concentration of the wastewater is enhanced by bubbling air through the water in an *aeration basin*. A dissolved oxygen ("DO") analyzer measures the oxygen concentration in the wastewater, and a controller varies the speeds of blowers pumping air into the basins using AC motors powered through variable-frequency drives (VFDs):
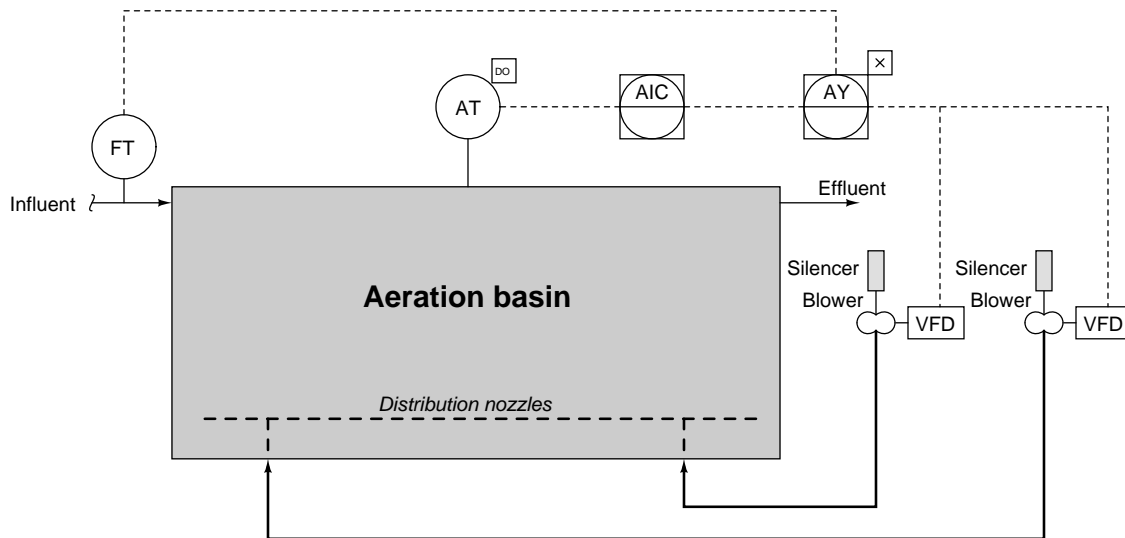
The control strategy used here is called *adaptive gain*. While similar in configuration to feedforward – where a load variable (in this case, influent flow rate) is used to alter the MV signal going to the final control element(s) of a feedback control loop – the relay used in this case is a *multiplier* rather than the more customary *summer* seen in conventional feedforward strategies.

Explain why adaptive gain is an appropriate control strategy for this kind of application, "demonstrating" your explanation by posing a thought experiment of your own design.

file i03291

Question 84

This solar hot-air collector bank uses a variable-speed fan as the final control element, the temperature controller commanding the fan to blow air at different rates in order to maintain a relatively constant discharge temperature. The hot air is being used to dehydrate food, and so precise temperature control is important:
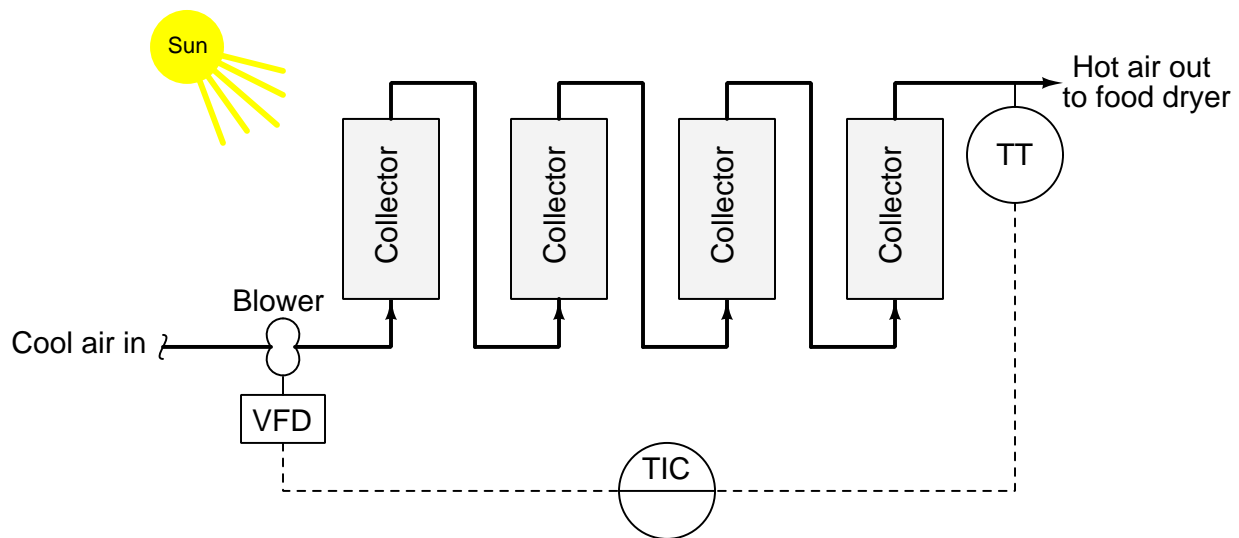
The single most significant load in this process is sunlight intensity. As the sun becomes covered by clouds, the heat output of the collector bank rapidly drops. This, of course, affects the temperature of the air going to the food dryer. Even though the feedback controller will eventually get the temperature back to setpoint, there are moments of deviation (error).

Suppose a sunlight radiation transmitter (RT) were installed to detect incident sunlight intensity. Sketch how this RT could be connected to the rest of the control system components to form a *feedforward* loop.

Also, describe a real experiment you could do with this process to determine whether or not *dynamic compensation* (i.e. lead/lag) is necessary in the feedforward signal path for optimal control.

file i02474

Question 85

This turbine speed-control system does not appear to be regulating turbine speed properly. The PV as shown on the controller is substantially below SP, and has been for quite a while. You happen to notice that the controller output reads 100% on the faceplate:
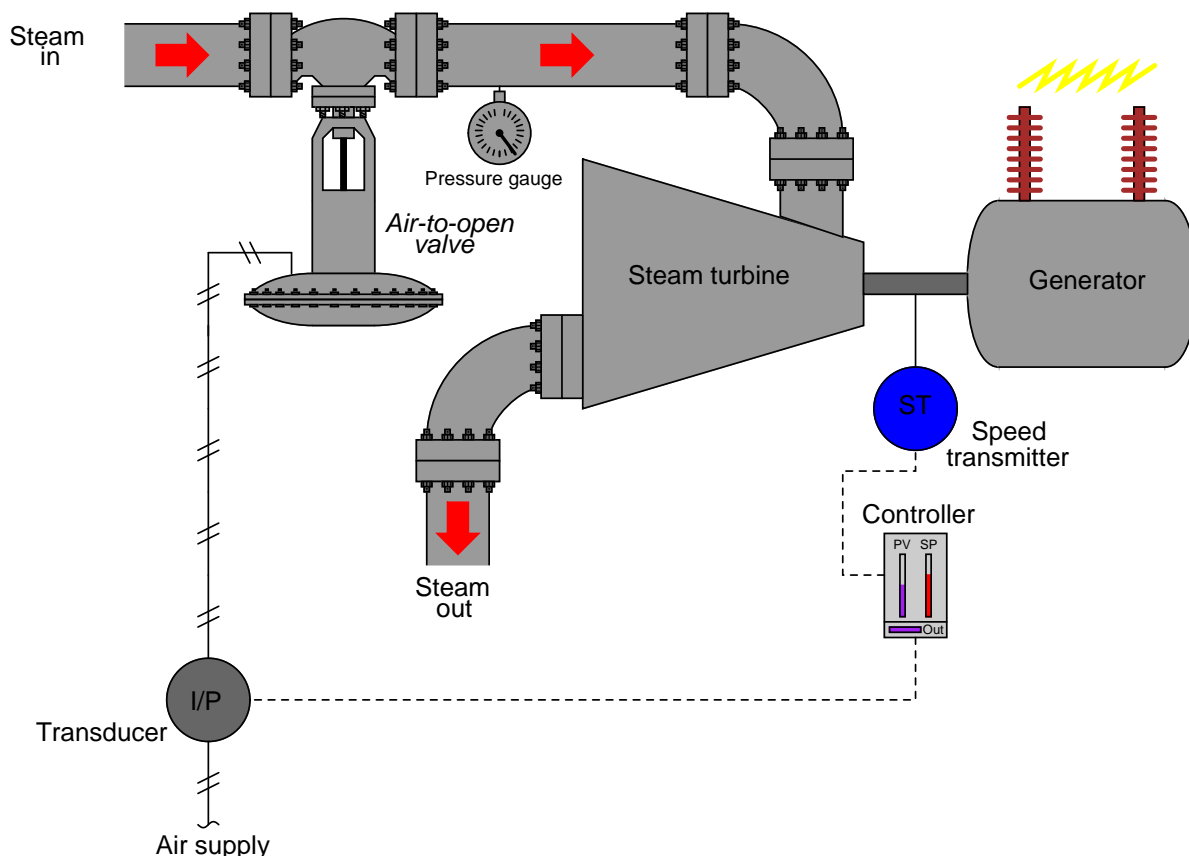
Your first test is to measure loop current in the control valve (I/P) circuit. There, your multimeter registers 20.03 milliamps.

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

Fault	Possible	Impossible
ST out of calibration (outputting wrong current)		
SIC input out of calibration (not interpreting signal properly)		
SIC output out of calibration (not sending correct mA signal to I/P)		
Pressure gauge out of calibration (not displaying pressure properly)		
I/P out of calibration (not outputting correct pressure)		
Control valve is oversized		
Control valve is undersized		
SIC is poorly tuned (not making good control "decisions")		
Instrument air supply not at full pressure		

file i00441

84

Question 86

In machining production technology, the time required to "broach" a hole in a plate may be estimated by the following equation:

$$T = \frac{L}{C} + \frac{L}{R_c}$$

Where,

T = Time to broach hole (minutes)
L = Length of stroke (feet)
C = Cutting speed (feet per minute)
R_c = Return speed (feet per minute)

Manipulate this equation as many times as necessary to express it in terms of all its variables.

file i01320

An Allen-Bradley SLC500 PLC is used as the controller for an oven. The process variable input from the temperature transmitter comes into channel 0 of a four-channel analog input card. The transmitter is ranged 100 to 600 degrees Celsius, and we need to scale this measurement so that it appears as a fixed-point number value inside the PLC ranging 1000 to 6000 (i.e. 100.0 to 600.0 with an implied decimal point).
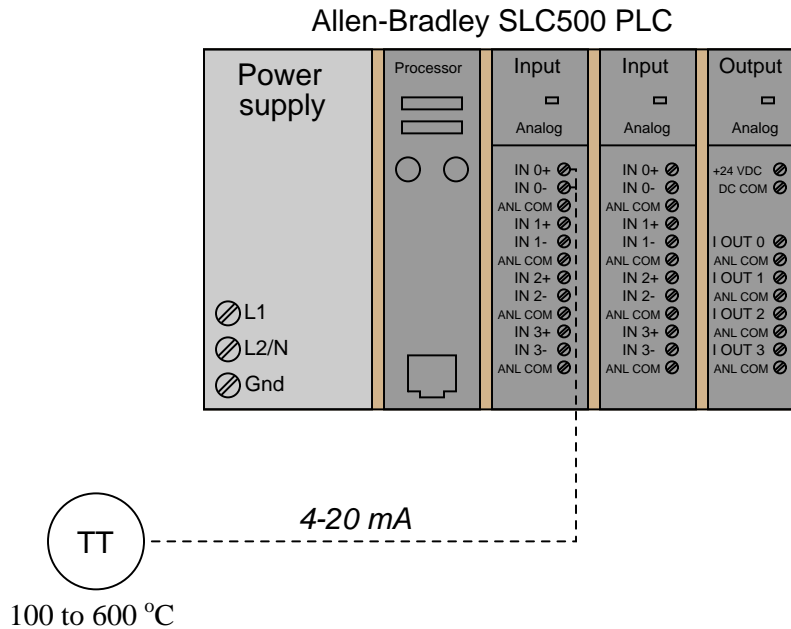
The analog input card is configured to convert a 4 milliamp signal into an integer value of 4000, and a 20 milliamp signal into an integer value of 20000.

First, develop a mathematical formula to take this 4000-20000 "count" range and translate it into the 1000-6000 range desired for our fixed-point representation of furnace temperature.

Second, translate this formula into the "Rate" and "Offset" parameters needed by the Allen-Bradley PLC's SCL instruction to perform this ranging:

file i03648
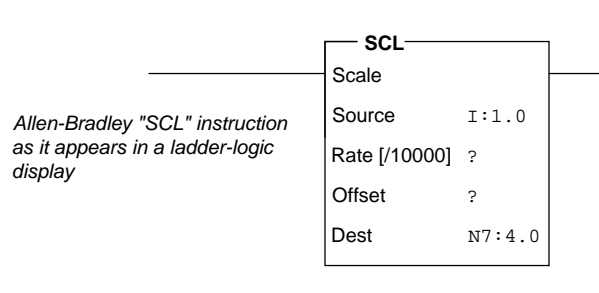
Question 88

Solve for all voltages and currents in this series LR circuit:

175 mH

15 V RMS
1 kHz

710 Ω
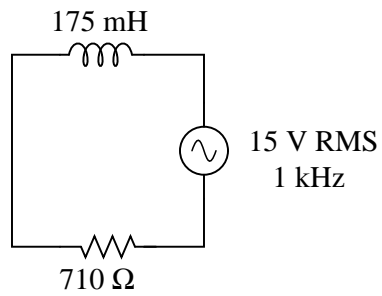
Also, calculate the phase shift between V_R and V_{supply}, as well as the phase shift between V_L and V_{supply}.

Question 89

Suppose you are asked to build a complete control system using a DP transmitter, Honeywell UDC2000 PID controller, an air-to-open control valve (with positioner), and an I/P transducer:
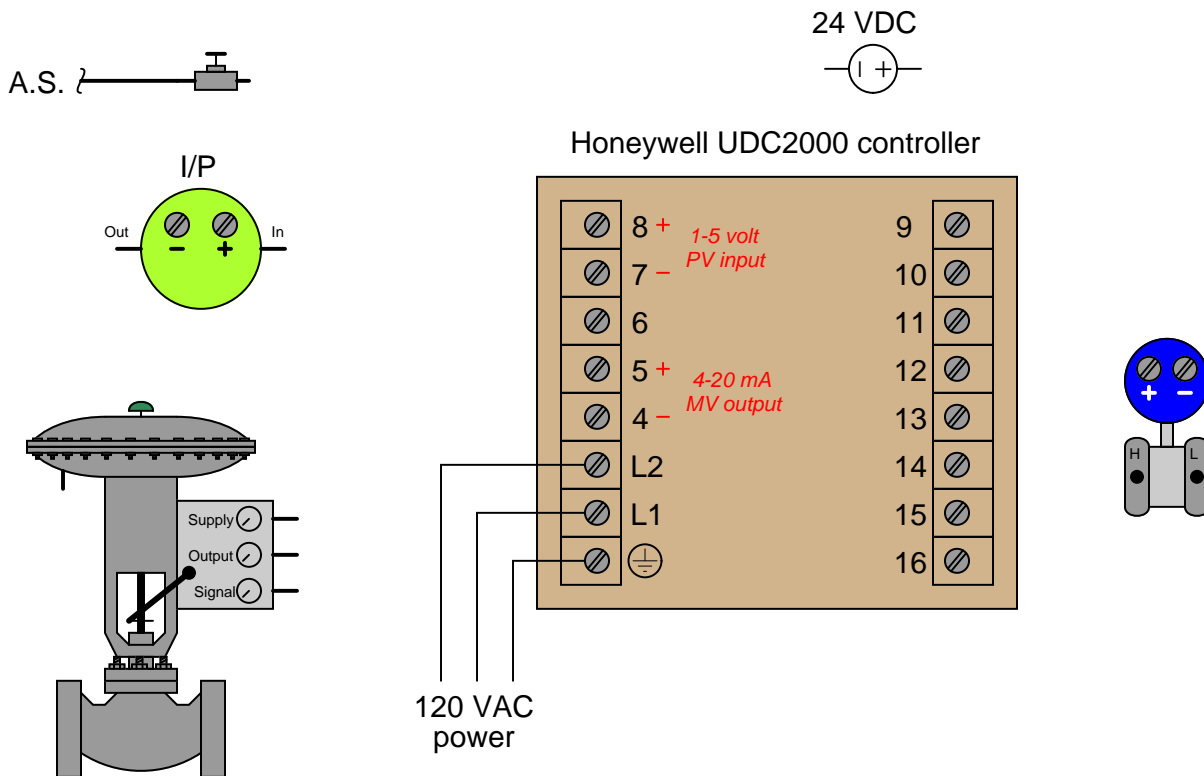
Sketch the necessary tube and wire connections to make this a working system. Feel free to add any other components as needed.

file i00432

Question 90

In this automotive fuel level sensing circuit, a current mirror is supposed to maintain a constant current (about 25 to 26 mA) through the fuel level sensor, which is nothing more than a variable resistance (rheostat) that changes with fuel level. The voltage dropped across this sensor resistance is then sent to a fuel gauge: a voltmeter with the scale calibrated in gallons of fuel level:
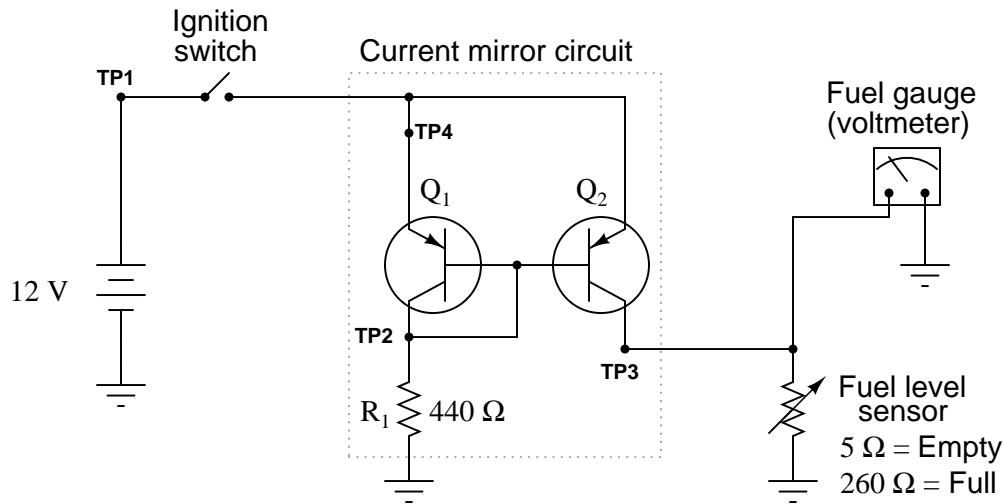
There is a problem in this circuit, though. The fuel gauge reads full even when you know the fuel tank is completely empty. You take two DC voltage measurements to begin your troubleshooting: +11.5 volts between TP2 and ground, and 11.7 volts between TP3 and ground.

From this information, identify two possible faults (either one of which could account for the problem and all measured values in this circuit), and also identify two circuit elements that could not possibly be to blame (i.e. two things that you know *must* be functioning properly, no matter what else may be faulted). The circuit elements you identify as either possibly faulted or properly functioning can be wires, traces, and connections as well as components. Be as specific as you can in your answers, identifying both the circuit element and the type of fault.

- Circuit elements that are possibly faulted
1.
2.

- Circuit elements that must be functioning properly
1.
2.

file i03286

89

Question 91

Lab Exercise – introduction

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

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

Objective completion table:

Performance objective	Grading	1	2	3	4	Team
Team meeting and prototype sketch	mastery	–	–	–	–	
Circuit design challenge	mastery					– – – –
Final loop diagram and system inspection	mastery					– – – –
P&ID showing control strategy	mastery					– – – –
Demonstration of working system	mastery	–	–	–	–	
Safety and professionalism	deduction					
Lab percentage score	proportional					– – – –

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

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

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

Lab Exercise – objectives and expectations

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

| Team meeting and prototype sketch |

Read the lab exercise documentation and discuss with your teammates the objectives to be achieved and the time allotted to do so. Formulate a plan to achieve these objectives and draft a prototype design for the system you intend to build. Then, meet with your instructor to present your team's action plan and prototype design. *This prototype sketch should be annotated with all expected physical parameters (e.g. voltage polarities, current directions, fluid pressures, etc.).* Be prepared to answer all manner of questions about your team's goals, planned schedule of work, available resources, and prototype design, including analysis of the design for specific faults and condition changes. 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 |

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

| Final loop diagram and system inspection |

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

| P&ID showing control strategy |

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

| Demonstration of working system |

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

Lab 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!

Notes on process control strategies

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

For example, here is a simple air pressure control system using a loop controller:
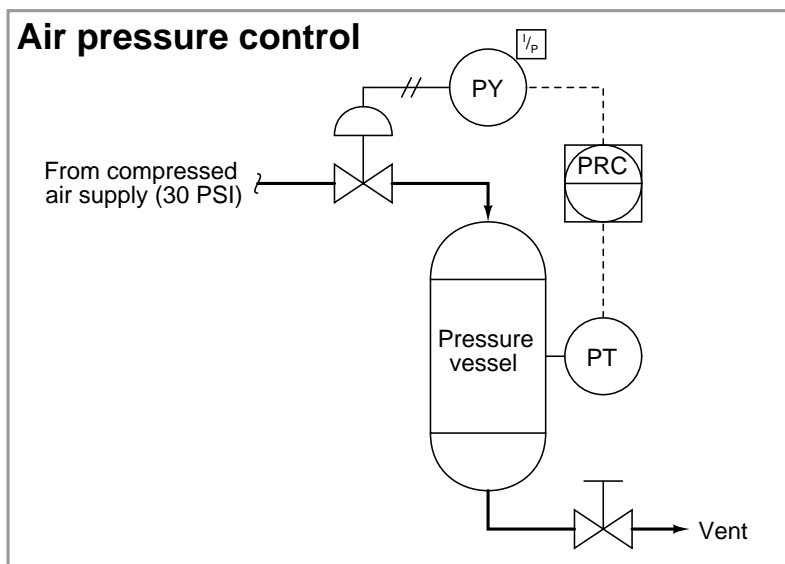
Next, we see this system modified for cascade control (additional control elements shown in red):
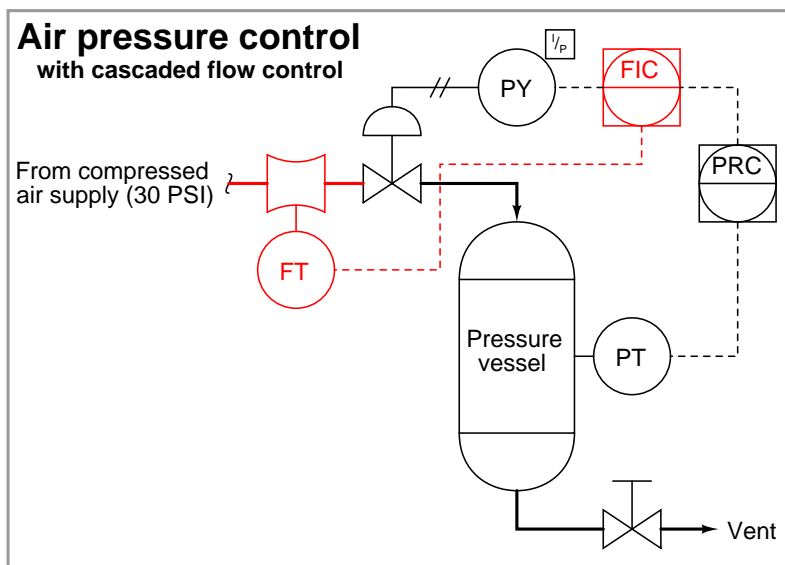
In the following example we see the same basic air pressure control system modified for feedforward control (additional control elements shown in red):
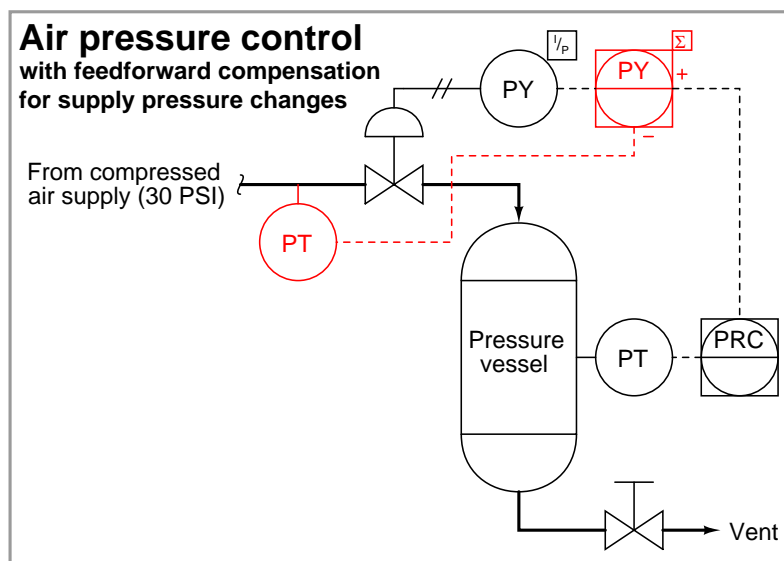
Other options include:

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

After deciding on a control strategy, your next step should be selecting the appropriate sensing instrument to measure the additional variable, drafting a prototype diagram to show how the instrument will be included in your existing system, and then installing this new instrument in the process. As usual, your team's prototype sketch is so important that the instructor will demand you provide this plan before any construction on your team's working system begins. *Any team found modifying their system's control strategy without a verified plan will be ordered to cease construction and not resume until a prototype plan has been drafted and approved!* Each member on the team should have ready access to this plan (ideally possessing their own copy of the plan) throughout the construction process. Prototype design sketching is a skill and a habit you should cultivate in school and take with you in your new career.

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

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

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

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

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

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

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

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

Common mistakes:

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

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

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

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

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

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

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

Lab Exercise – circuit design challenge

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

This exercise tests your ability to properly interpret the "pinout" of an electromechanical relay, properly wire a switch to control a relay's coil, properly wire a load to the contacts of a relay, properly select NO/NC contacts on both the switch and the relay, properly use a multimeter to measure current, and use a terminal strip to organize all electrical connections.
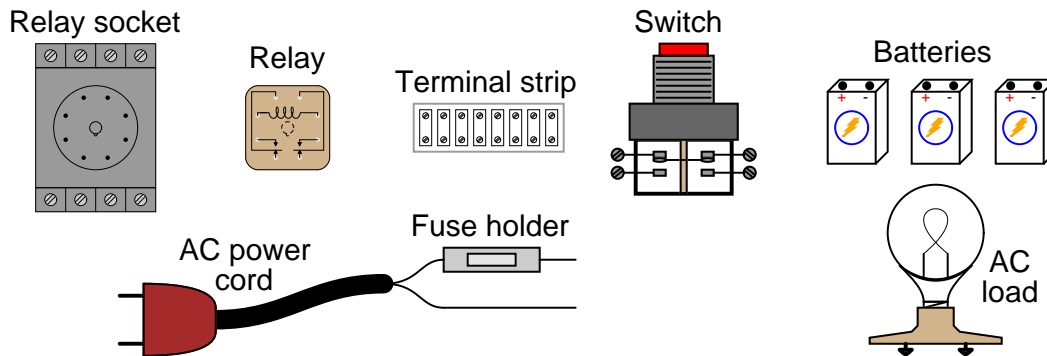
The following components and materials will be available to you: assorted "ice cube" **relays** with DC-rated coils and matching **sockets** ; assorted pushbutton **switches** ; **terminal strips** ; lengths of **hook-up wire** ; **batteries** ; 120 VAC **power cord** with **fuse assembly** ; 120 VAC **lamp or other suitable load**. You must provide your own tools and digital multimeter (DMM) as well as a copy of this page for your instructor to mark objectives.

SEQUENCE: (1) Instructor chooses criteria; (2) You build and test circuit without any power sources at all; (3) Instructor provides batteries and observes you energizing the circuit for the very first time; (4) You demonstrate to the instructor that the circuit fulfills its intended function. (5) You connect your DMM into the circuit and demonstrate the correct current being measured.

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

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

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

Lab Exercise – loop diagram and system inspection

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

Construction Standards

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

Documentation Standards

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

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

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

Common mistakes:

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

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

Notes on control strategy tuning

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

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

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

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

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

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

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

file i00921

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
Blk — Blk
2

Cable 4, Pr 1

TB-80
Red — Red
11
Blk — Blk
12

Cable PT-73
Red
11
Blk
12

Card 4
Channel 6

Analog
input

Tube PV-73

PV
73

I/P

PY
73
O
+
−
S
Red
Blk

AS 20 PSI

Cable PV-73

TB-52
Red — Red
15
Blk — Blk
16

Cable 4, Pr 8

TB-80
Red — Red
29
Blk — Blk
30

Cable PV-73
Red
11
Blk
12

Card 6
Channel 6

Analog
output

PIC
73

0-50 PSI

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

14

H
L
LT 24
Out
In

(vent)

A.S. 21 PSI

LV 24

Tube LV-24

Tube LV-24

Tube LV-24

C
LIC 24
D

Supply

A.S. 21 PSI

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

Sample Loop Diagram (using pneumatic controller)

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

Process area — Field panel FP-25

Process area:
- H / L — FT 18 — + Red / − Blk — Cable FT-18
- 0-75 GPM
- P — A / Loop + Red / Loop − Blk — Cable FV-18 — Supply — IAS 20 PSI
- FV 18

Field panel FP-25:
- Red — 21 Blu — 10 [800 mA] Blu — Blu — PS-1
- Blk — 22 Blu
- Blu — IN0+, IN0−, IN1+, IN1−, IN2+, IN2−, IN3+, IN3− — 1762-IF4 analog input card expansion slot 1
- 24 VDC 1 amp
- L1 | N | (ground) — 120 VAC — Blk / Wht / Grn
- Red — 11 Blu / Blk — 12 Blu — Cable FV-18
- Blu — I out 0, V out 0; I out 1, V out 1; I out 2, V out 2; I out 3, V out 3 — 1762-OF4 analog output card expansion slot 2
- Blu — Com / Com
- FC 18 — L2/N — L1
- FIR 18 (Located in main control room) — Ethernet
- ES 120 VAC From field panel disconnect — 1A | 1A — 1 | 2 | 3 | 4 — Blk / Wht / Grn

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

104

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.*

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- 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.

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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!

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Question 93

Capstone Assessment (end of quarter)

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

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

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

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

- If you have passed or are currently taking the *INST241* course, your transmitter and controller must be properly configured to register the process variable (in engineering units, not percent) over a range specified by the instructor. Note: if the transmitter is analog rather than "smart," the instructor will have you determine its "As-Found" range and direct you to range the loop controller to match the transmitter rather than calibrate the analog transmitter to a specified range.

- If you have passed or are currently taking the *INST252* course, the controller must be tuned for robust response to perturbations (changes) in either setpoint or load as selected by the instructor at or near a setpoint value also specified by the instructor. "Robust" control is defined here as the controller compensating for perturbations as quickly as possible without creating any process variable oscillations (i.e. a *critically damped* response). It will be your decision to use P, I, D, or any combination thereof in the controller's tuning.

- If you have passed or are currently taking the *INST260* course, you must connect a data acquisition unit (DAQ) to record a variable in the process selected by the instructor and display a trend graph and/or a scaled representation of the measured variable on a personal computer networked to the DAQ. For example, if you are instructed to display the controller's output value using the DAQ, the display should register on a scale of 0% to 100% just like the controller's output is ranged from 0% to 100%. If the DAQ needs to show the process variable, it must register that variable in the same range as the transmitter. If your DAQ provides a trend graph, the vertical scale markings of that trend graph must be similarly ranged.

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

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

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

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

No teamwork is allowed while wearing the vest!

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

The time clock starts now!   **Start time:** _____

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

Now you may begin wiring and configuring the components

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

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

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

Your mastery score will not be recorded until <u>all</u> steps are complete!

Notes on instrument ranging

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

The reason this is an issue at all is because loop controllers operating on 4-20 mA analog signals don't "know" what those signals are supposed to represent unless someone configures the controller with the proper range reflecting real-world conditions. For example, if a student is assigned a temperature transmitter with a range of 300 to 800 degrees Fahrenheit, not only does the transmitter have to output 4 mA when sensing 300 ^{o}F and output 20 mA when sensing 800 ^{o}F, but the controller must display an indication of 300 ^{o}F when it receives a 4 mA signal from the transmitter, and display an indication of 800 ^{o}F when it receives a 20 mA signal from the transmitter. None of this happens on its own – the student must range the transmitter for 300-800 ^{o}F input (and 4-20 mA output) as well as range the controller to display 300-800 ^{o}F over its 4-20 mA input scale. A typical loop is shown here with all instrument ranges displayed:
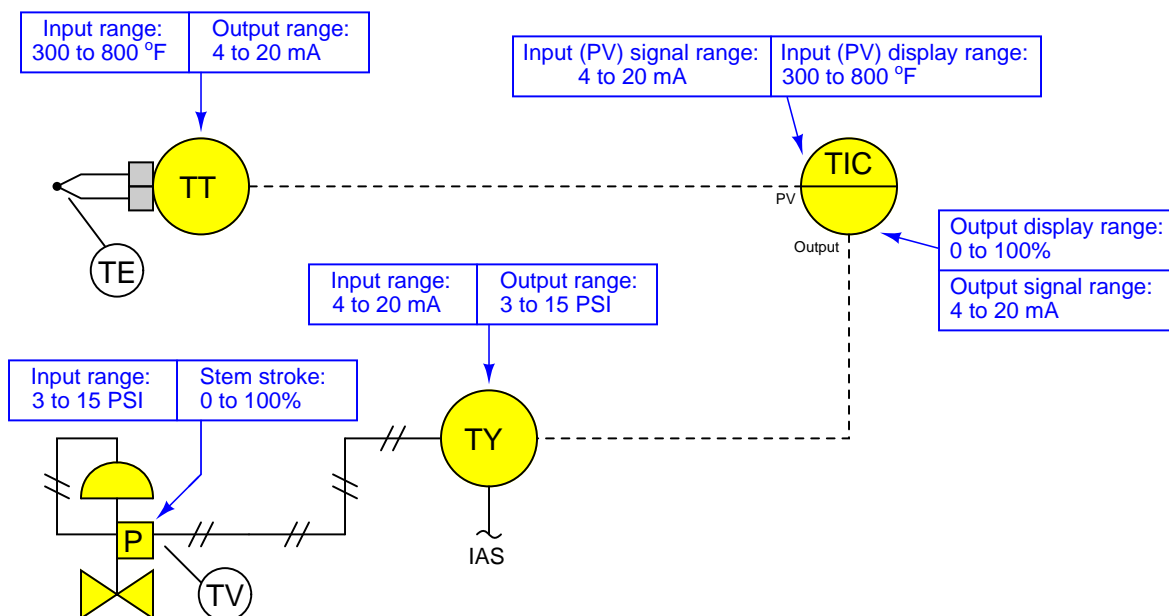
Analog (non-"smart") transmitters, I/P transducers, and valve positioners are ranged using "zero" and "span" adjustments, typically screws or nuts. The ranging of analog instruments is discussed in the "Instrument Calibration" chapter of the *Lessons In Industrial Instrumentation* textbook.

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

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

- Siemens/Moore 352 controller: process variable range parameters are located in the "Operator's Display" function block (FB15):
  - → LRV = *Process Lo*
  - → URV = *Process Hi*

- Siemens/Moore 352P and 353 controller: process variable range parameters are located in the "Analog Input" function block (AIN):
  - → LRV = *Minscale*
  - → URV = *Maxscale*

- Emerson DeltaV DCS: process variable range parameters are located in the "Analog Input" function block (AI) and "PID" function block (PID):
  - → (AI block) = the *OUT_SCALE* parameter contains both high and low range limits, engineering units (e.g. deg F), and decimal point position. The *L_Type* parameter needs to be set to "indirect" to allow scaling to occur ("direct" mode prohibits scaling), and the *XD_Scale* parameter needs to be ranged 0 to 100%. Note that the "direct" and "indirect" options for *L_Type* have absolutely nothing to do with "direct" and "reverse" PID controller action, which is configured elsewhere.
  - → (PID block) = the *PV_SCALE* parameter contains both high and low range limits, engineering units (e.g. deg F), and decimal point position. Note: the PID block's *PV_SCALE* range must exactly match the *OUT_SCALE* range of the AI block!

- Honeywell UDC 2500 controller: process variable input #1 range parameters are located in the "Input 1" set-up group of parameters:
  - → LRV = *IN1 LO*
  - → URV = *IN1 HI*

- Automation Direct "SOLO" controller: process variable range parameters are located in the following registers:
  - → LRV = *P3-4 Input Range Low*
  - → URV = *P3-3 Input Range High*

- Allen-Bradley PLC5, SLC500, and MicroLogix controllers: process variable scaling parameters are typically located either in a "Scale" instruction (SCL) or a "Scale with Parameters" instruction (SCP). In either case, the instruction takes the raw count value from the input channel's analog-to-digital converter and scales it into the desired process variable display range. A YouTube video on our BTCInstrumentation channel shows how to do this for the networked MicroLogix PLCs in the lab using the SCP instruction. *Note: SCP instruction parameters may be edited online. For this reason, downloading edits is not necessary for the MicroLogix PLCs in our lab. In fact, it is very important that you <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*

file `ranging`

Notes on controller action

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

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

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

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

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

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

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

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

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

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

Notes on controller tuning

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

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

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

file `control`

Answer 1

If steam pressure begins to fall below setpoint, the PIC should send a decreasing signal to the fuel gas valve, causing the burner to output less heat and thereby lowering the steam pressure to setpoint again. If well-tuned, a loop controller will drive its output signal to *whatever value is necessary* to achieve PV = SP.

The manual block and bypass valves are useful for taking the fuel control valve out of service while the boiler is still running. This allows technicians to stroke-test and even replace the control valve without shutting down the boiler. I will let you describe and explain the sequence of valve motions necessary to take a working control valve out of service.

A falsely-low pressure signal coming from the I/P might cause the actual water level to *drop* if the change was sudden, but the LIC will eventually compensate for this change by adjusting its output signal value until the control valve is at the correct position again.

Answer 2

Answer 3

Answer 4

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

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

When tuning cascaded loops, you should *always* ensure the slave loop is well-tuned before attempting to tune the master loop. I'll let you figure out why this is important!
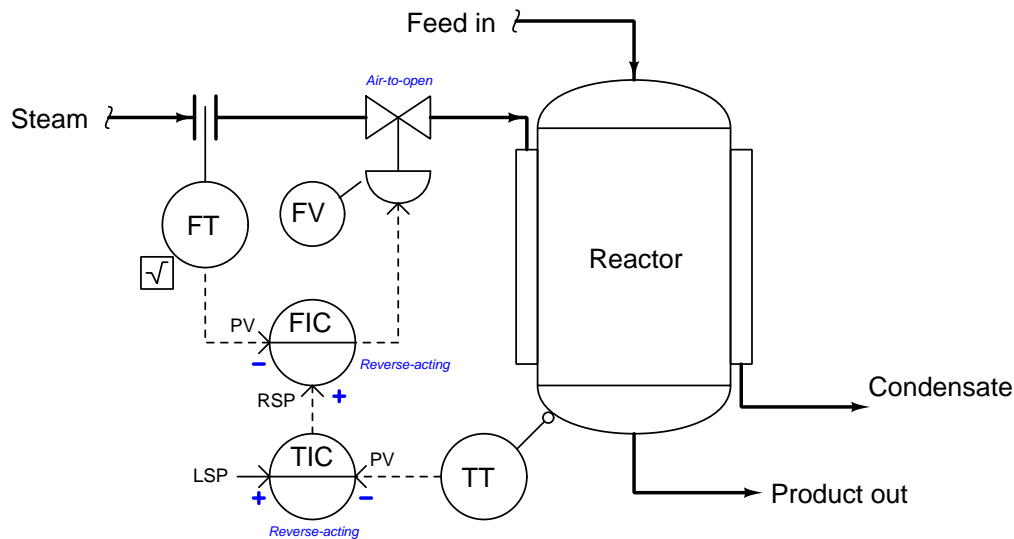
A helpful strategy for identifying necessary master and slave controller actions in a cascade control system is to re-draw the controller "bubbles" as opamp symbols instead, complete with "+" and "−" labels for noninverting and inverting inputs, respectively. Since all PID controllers have PV and SP inputs, and these inputs always have opposite effects on the output signal, the opamp conventions of "+" and "−" work very well to describe the action of any PID controller. If the PV input on the opamp controller must be noninverting ("+") in order to achieve loop stability, then that controller must be direct-acting. If the PV input on the opamp controller must be inverting ("−") in order to achieve loop stability, then that controller must be reverse-acting. The following diagram shows how to use opamp symbols to represent controller actions in the same cascaded flow/temperature control system:
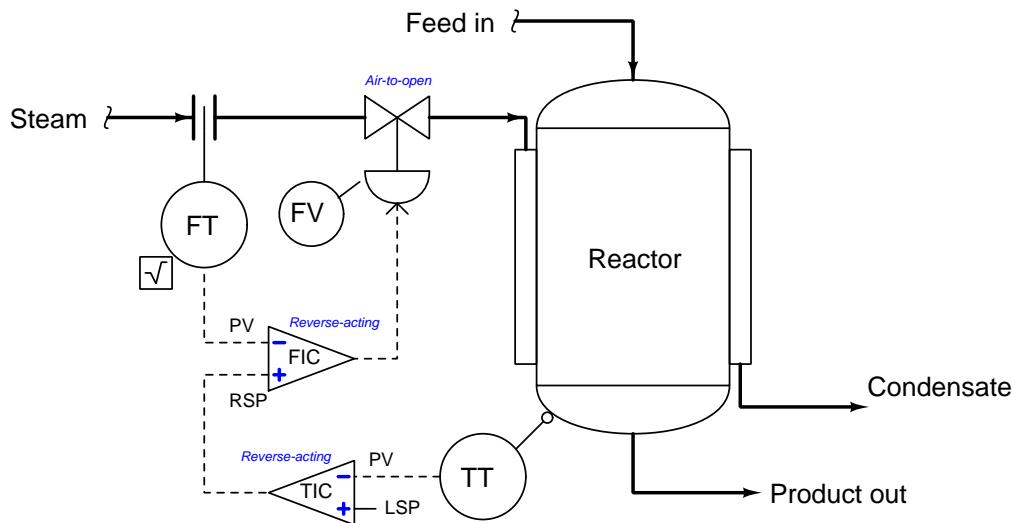
Note that it is always the *inputs* of a controller we label with "+" or "−" symbols, never the *output* of a controller.

Answer 5

Partial answer:

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

Answer 6

Answer 7

The reason that the technician's proposed test would have been a waste of time is because the controller is already registering a reasonable pressure (approximately the same as the field-mounted gauge). In other words, the controller PV indication corresponds with the gauge, suggesting there is no problem in that (input) portion of the control system.

Answer 8

The flow controller (FIC) will send a "full-open" signal to the valve, because its transmitter indicates the flow rate is less than it should be.

The level controller's output will saturate low, telling the flow controller to stop the flow as the clearwell level rises well above setpoint due to the uncontrolled flow coming in.

Answer 9

The flow controller (FIC) will send a "close" signal to the valve, because its transmitter indicates the flow rate is excessive.

The level controller's output will saturate low, telling the flow controller to stop the flow as the clearwell level rises well above setpoint due to the uncontrolled flow coming in.

Answer 10

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

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

Answer 11

As the steam supply pressure rises and falls, a greater or lesser steam flow will result through the temperature valve (TV) for any given stem position.
The simplest and most direct solution to this problem is to stabilize the steam supply pressure: determine what is causing the pressure to fluctuate, and fix it!

Answer 12

Fault	Possible	Impossible
TT-37 miscalibrated (reading too low)		√
TT-37 miscalibrated (reading too high)		√
TIC-37 in manual mode	√	
TIC-37 in auto mode		√
FIC-38 in manual mode	√	
FIC-38 in auto mode	√	
FIC-38 in cascade mode		√
FT-38 miscalibrated (reading too low)		√

Answer 13

Answer 14

Answer 15

Answer 16

Answer 17

118

Answer 18

Answer 19

Answer 20

Answer 21

Answer 22

- PV = fuel flow through injectors
- "Wild" flow = air flow into engine
- SP = multiplied air flow signal
- Output = timing pulses (PWM) to injectors
- Loads = Fuel pump pressure, air density

Answer 23

Partial answer:

- Which flow stream is considered the "wild" flow? *The black liquor flow.*
- What safety hazards accompany the use of pure oxygen as a process stream? *Any and all flammable materials must be kept out of the oxygen piping and valving!*

Answer 24

I'll let you sketch a possible solution to this problem!

Answer 25

Flour flow ratio = 97.8% of total flow
Yeast flow ratio = 1.76% of total flow
Salt flow ratio = 0.44% of total flow

Total mix flow rate at HC setting of 70% = 35.7875 pounds per minute

Answer 26

Stoichiometry is the primary determining factor for the value of k: setting the methane and steam mass flow rates such that the proper numbers of molecules of each enter the reaction furnace to produce hydrogen and carbon monoxide gas.

Answer 27

Answer 28

Answer 29

The paint will become more and more colored over time, as the control system turns up the flow of pigment. This will happen because the ratio control system sees no pigment flow anymore, and thus turns the pigment flow on fully to try to reach setpoint.

Answer 30

The purpose of FFC-41 is to control the flow of 600 PSI steam to the bottoms reboiler (heat exchanger E-9) in accordance with the feed flow rate in. The feed flow is therefore the "wild" flow and the steam flow is the "captive" flow. The ratio of steam flow to feed flow is automatically adjusted by AIT-42 sensing something about the composition of the bottoms product (perhaps density, or boiling point, or some other property related to the distillation of products within the tower).

Answer 31

The purpose of this control system is to control the coloring of the paint by analyzing its color using a special instrument, which feeds its color signal to a color controller (AIC), which then automatically adjusts the ratio between base and pigment to achieve the desired output color.

As for the "other control system," it would most likely be a flow (production) controller.

Answer 32

- PV = load current
- SP = "program" current (through R_{prg})
- Output = current to base of Q_2
- Loads = $+V_{load}$, R_{load}

If V_{BE} for both transistors will be approximately the same (≈ 0.7 V), the base terminals of both are common, and both resistors R_1 and R_2 are common at ground, then $V_{R1} \approx V_{R2}$. This means $I_{prg}R_1 \approx I_{load}R_2$, therefore $\frac{I_{load}}{I_{prg}} \approx \frac{R_1}{R_2}$.

Answer 33

A current of 145 microamps through the thermistor will be 145 microamps through R_2 (assuming the opamp inputs draw negligible current). Therefore, we need a voltage of 0.319 volts across R_2 (and by extension, across R_1 as well).

In order to get the same current through R_1, we need R_{prg} to be large enough that the whole supply voltage of 24 VDC is just enough to get 145 microamps through the series combination of R_1 and R_{prg}. Thus, $R_1 + R_{prg} = 24$ V / 145 μA = 165.52 kΩ. Subtracting R_2's value of 2.2 kilo-ohms yields this result for the programming resistor:

$$R_{prg} = 163.32 \text{ k}\Omega$$

Partial answer:

Fault	Possible	Impossible
R_1 failed open		$\checkmark$
R_2 failed open		
R_{prg} failed open		
Thermistor failed open		
Transistor failed open C-E	$\checkmark$	
R_1 failed shorted		
R_2 failed shorted		
R_{prg} failed shorted		
Thermistor failed shorted	$\checkmark$	

Answer 34

Answer 35

Answer 36

Answer 37
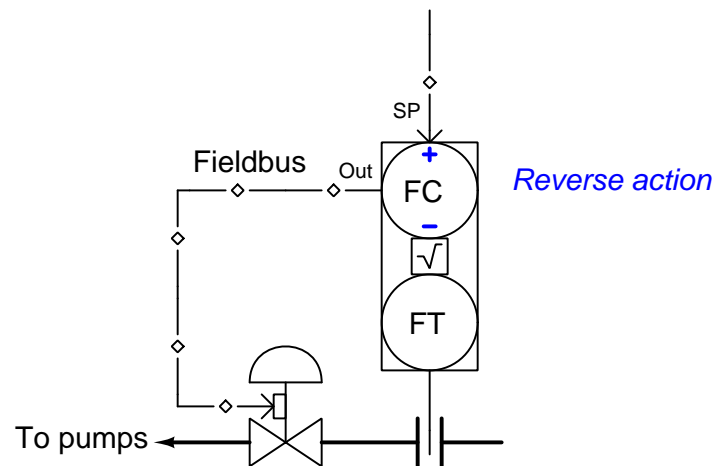
Answer 38

Answer 39

Answer 40

Answer 41

Answer 42

Answer 43

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

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

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

Answer 44

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

Feedforward action from the feed flow transmitter to the steam valve is one solution to this problem:

Answer 46
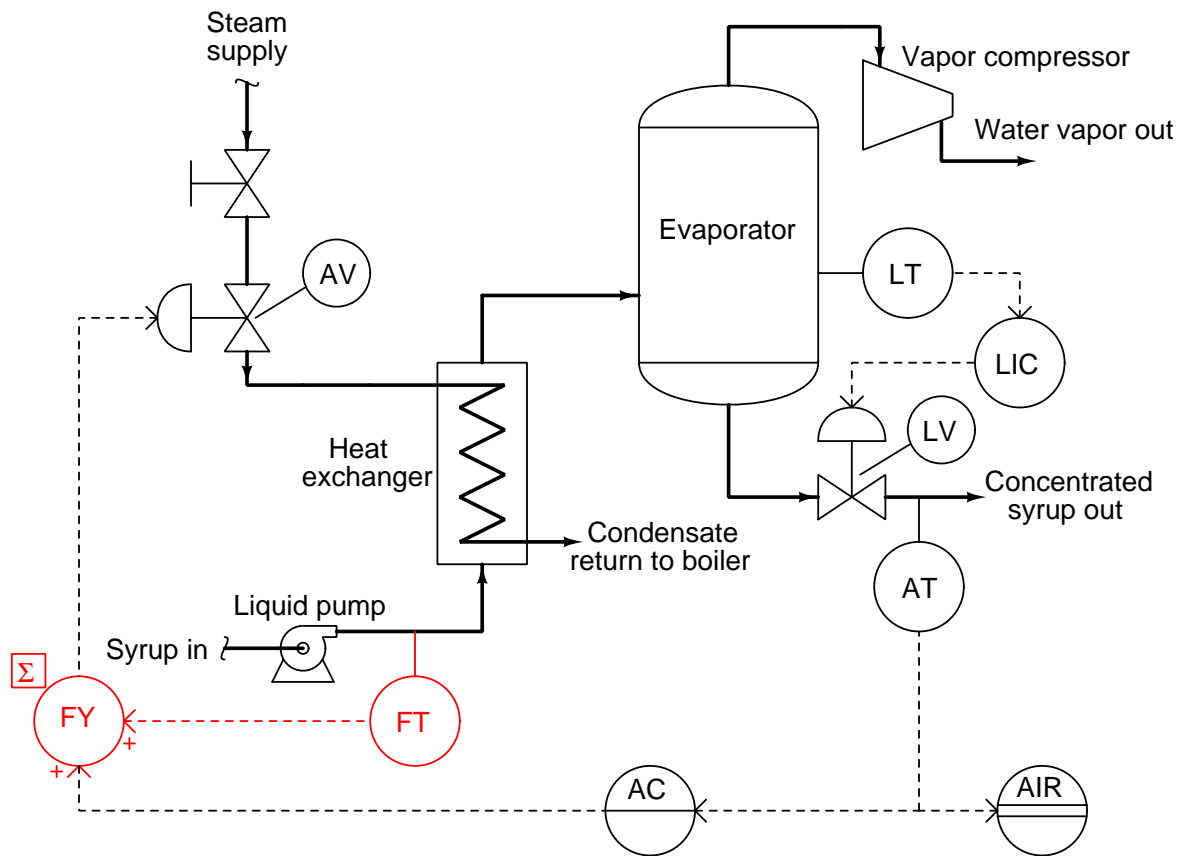
The following P&IDs show *incorrect* implementations of feedforward to this process. All of these incorrect solutions are commonly seen among students first learning about feedforward control.

Incorrect solution #1: A mysterious third input on the temperature controller (TC) is being used here. Although some loop controllers do provide an input for a feedforward transmitter's signal, to sketch this as a solution does not demonstrate understanding of the feedforward strategy. What needs to be shown is a more explicit function-block strategy whereby it is clear to see what the feedforward signal actually does to achieve its ends.
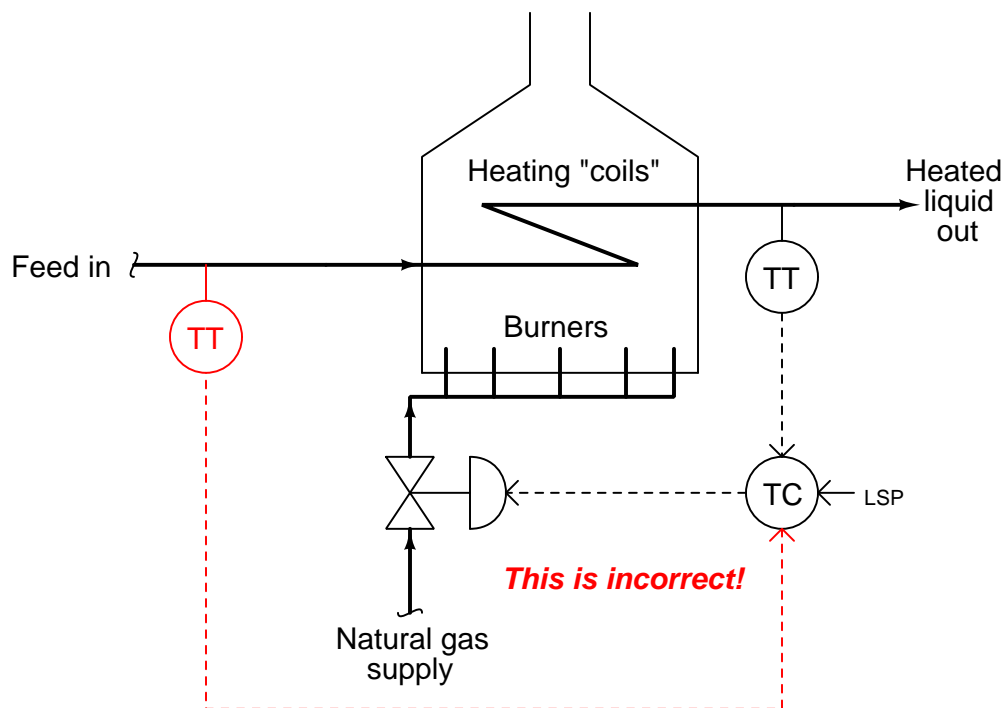
Incorrect solution #2: Here we see the feedforward signal being summed with the process variable signal before it enters the controller. The reason this won't work has to do with the purpose of the temperature controller (TC) – to maintain the outgoing product temperature at some operator-determined setpoint (local setpoint, or LSP). If that controller isn't able to directly and accurately sense the product temperature (because that temperature signal is being added to a different temperature signal) then there is no way the controller will ever be able to hold the product temperature to setpoint. In other words, summing the two temperature signals together effectively "lies" to the controller such that it never sees the real process variable, and therefore can never hold the real process variable stable at setpoint because it's operating on false information.
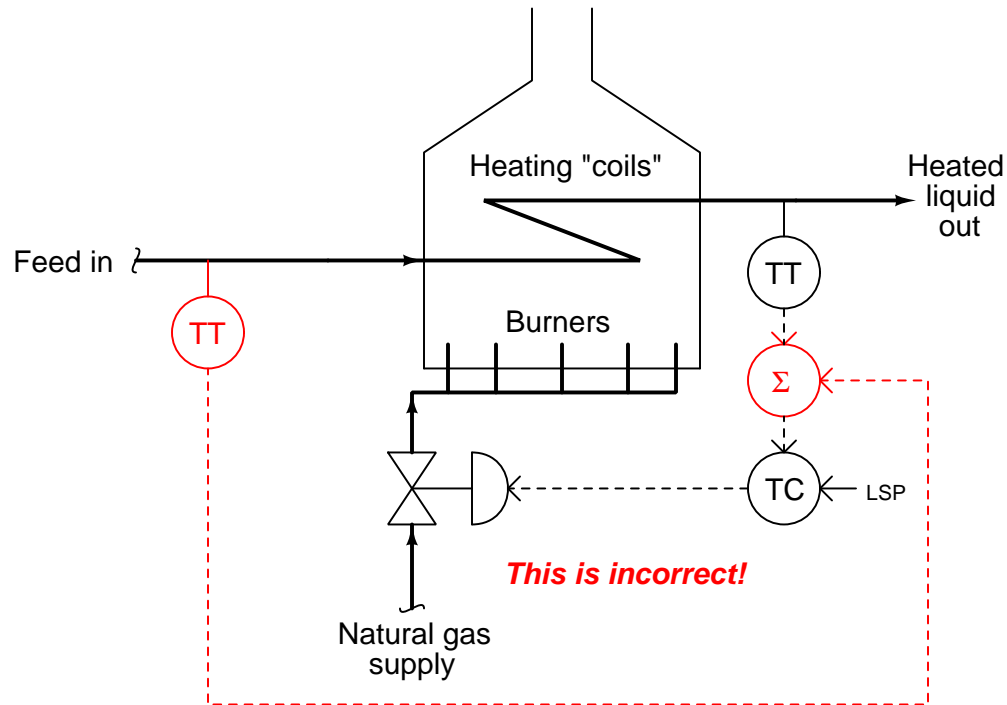
Incorrect solution #3: In this solution the feedforward signal is being used as a remote setpoint (RSP) to the temperature controller (TC), much like you would expect to see in a *ratio* control system. The trouble with this solution is again related to the purpose of the temperature controller – to maintain the outgoing product temperature at some operator-determined setpoint. Here there is no operator-determined setpoint at all, but rather a setpoint determined solely by the incoming feed temperature.
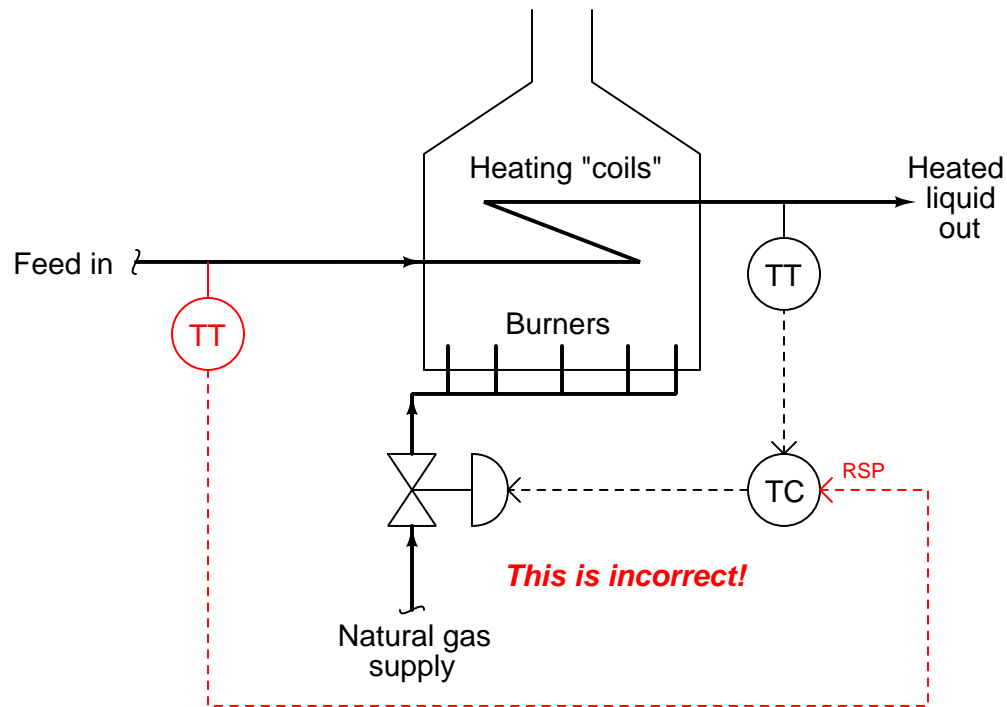
Furthermore, it makes absolutely no sense at all to have the controller's setpoint made equal to the incoming feed temperature. If we tried this strategy, the controller would maintain a closed-valve condition at all times, because the surest way to maintain the outgoing product temperature at a setpoint value equal to the incoming feed temperature is to not heat it up at all!

Incorrect solution #4: Similar to the last incorrect solution (#3), this one attempts to use the feedforward signal as *part* of a remote setpoint value (RSP) to the temperature controller (TC), while still maintaining an operator-determined local setpoint (LSP). Here we still have the same fundamental problem as before – so long as the feedforward signal modifies either the controller's view of the process variable (the outgoing product temperature) or its setpoint, the controller will be unable to perform its most basic function, to maintain the outgoing product temperature at some operator-determined setpoint.
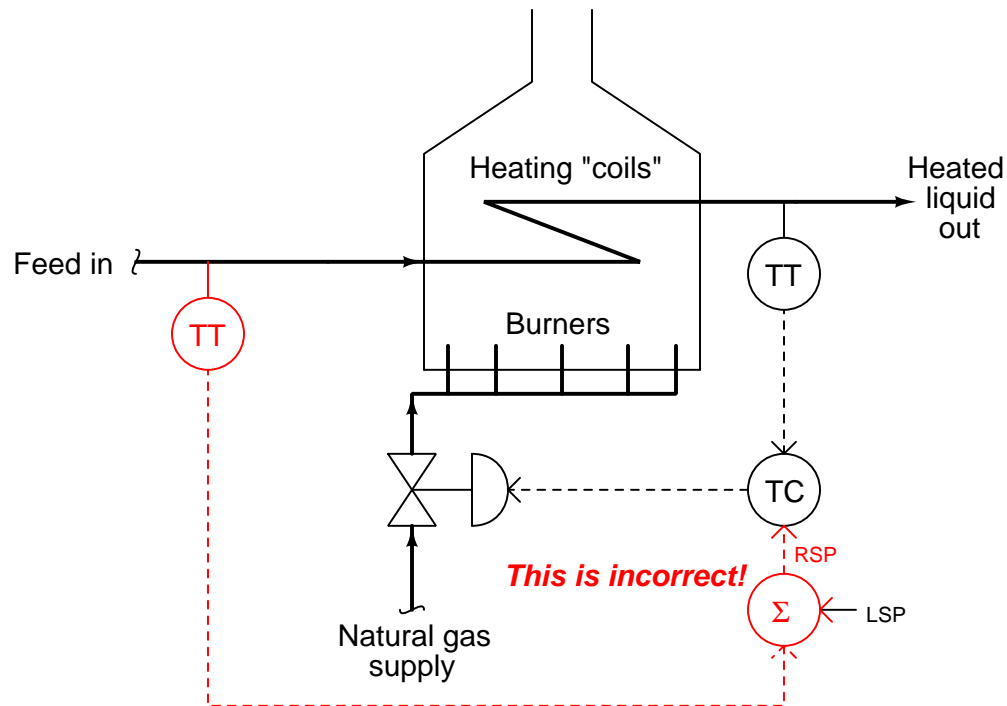
Incorrect solution #5: This solution comes closer than all the others with regard to conceptual correctness, but there is no way for it to be practically implemented. One cannot simple merge two different control signals together (i.e. the temperature controller's output signal somehow joining together with the feedforward signal). Whether these signals are physical (e.g. two 4-20 mA DC currents or two digital fieldbus messages), or virtual (e.g. binary values inside of a control system such as a DCS), we need some sort of algorithm to combine them together. The two signals will simply not merge together in any sensible way on their own.
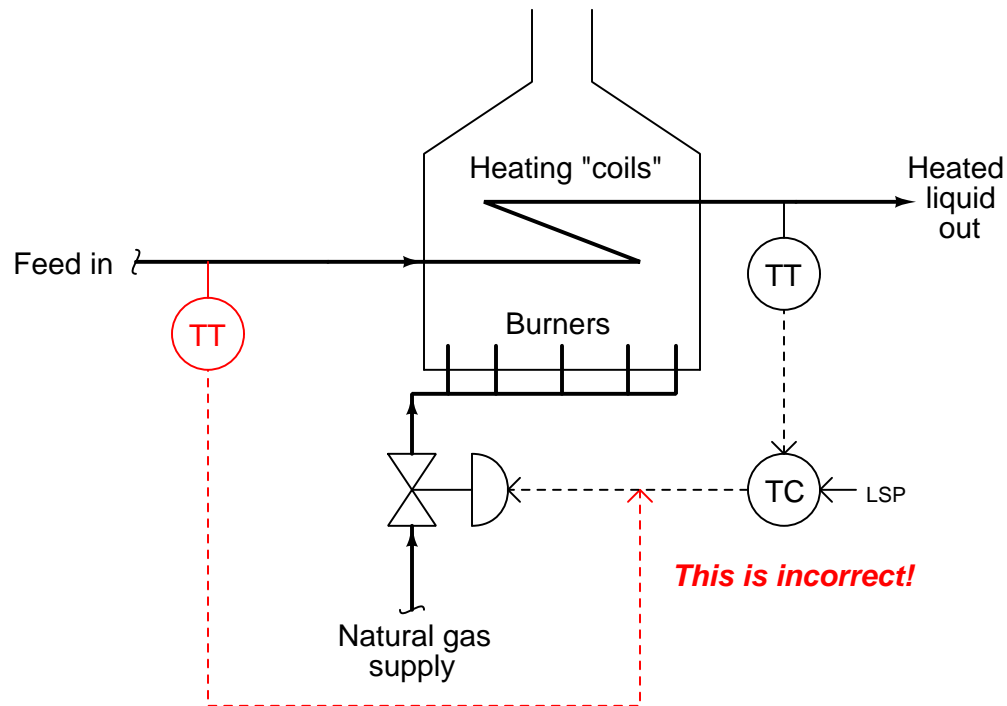
Answer 47

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

Answer 48

Place a steam flow transmitter on the outgoing steam line, then feed that steam flow signal "forward" to combine with the level controller's output to drive the feedwater valve.
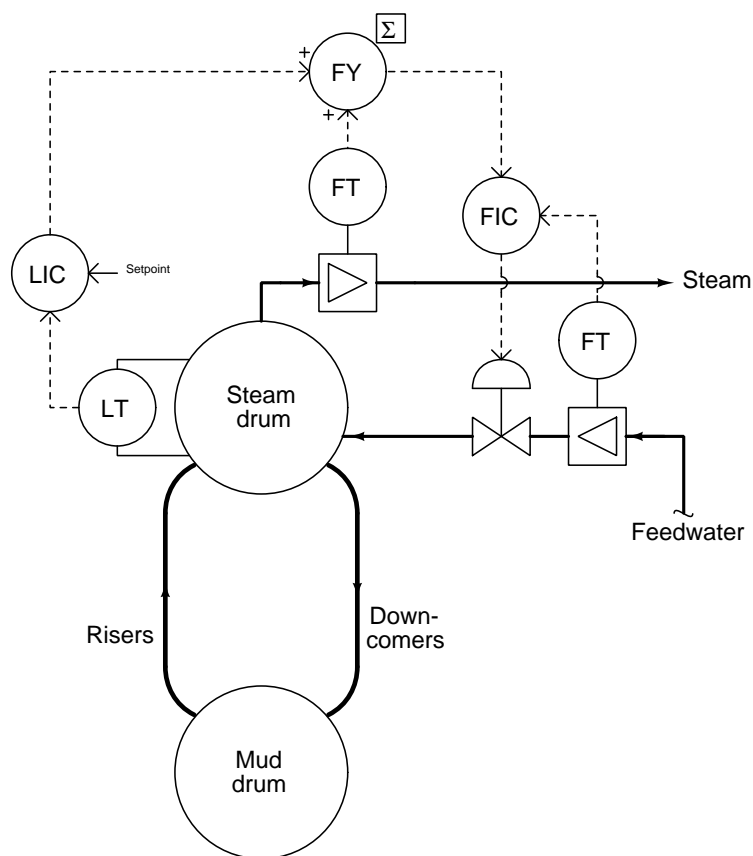
Answer 49

Answer 50

I'll let you research the meanings of functional diagram symbols.

Answer 51

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

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

Answer 52

If the two lag times are unequal, the feedforward response to a change in feed flow may either be too soon, or too late.

Follow-up question: given the lag times shown in the "manual test" trends, would the fuel gas adjustment be too soon or too late to compensate for a change in feed rate?

128

Answer 53

This is the correct solution, where the total load flow signal gets added to the *output* of the pressure controller, not to its *PV input*:
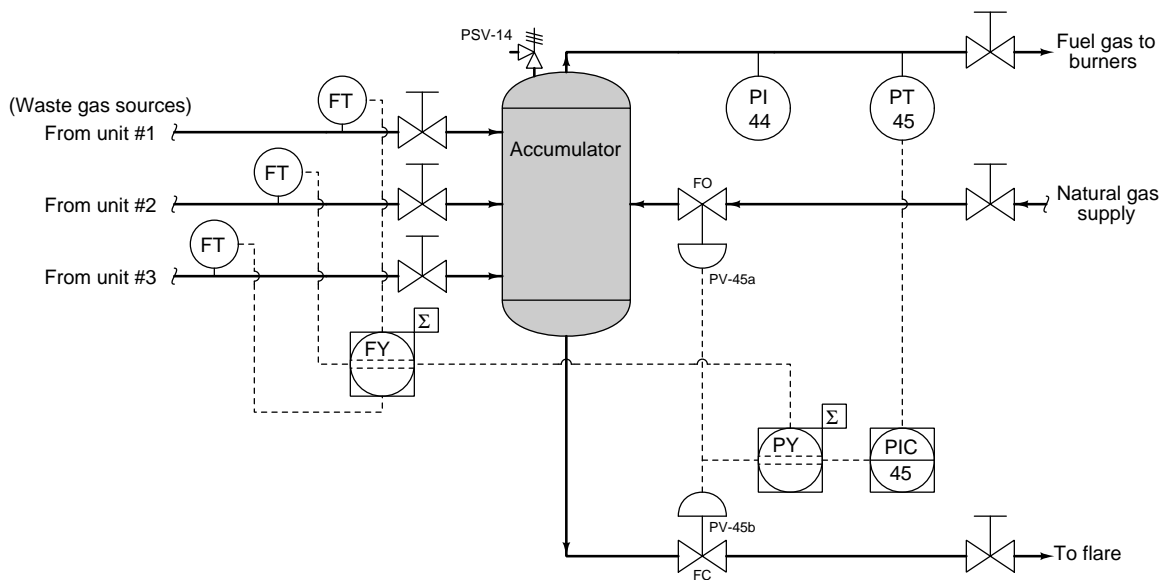
The reason for this is quite straightforward: we want the feedforward signal to directly contribute to the positions of the control valves, so that any change in waste gas flow immediately biases the control valves in order to pro-actively compensate. If the feedforward signal were to be added to the pressure controller's PV signal, it would cause the pressure controller to incorrectly see changes in pressure that were really changes in waste gas flow. Not only would this not achieve the desired effect, but it would also "lie" to the pressure controller, the result of which being it could never properly hold to setpoint!
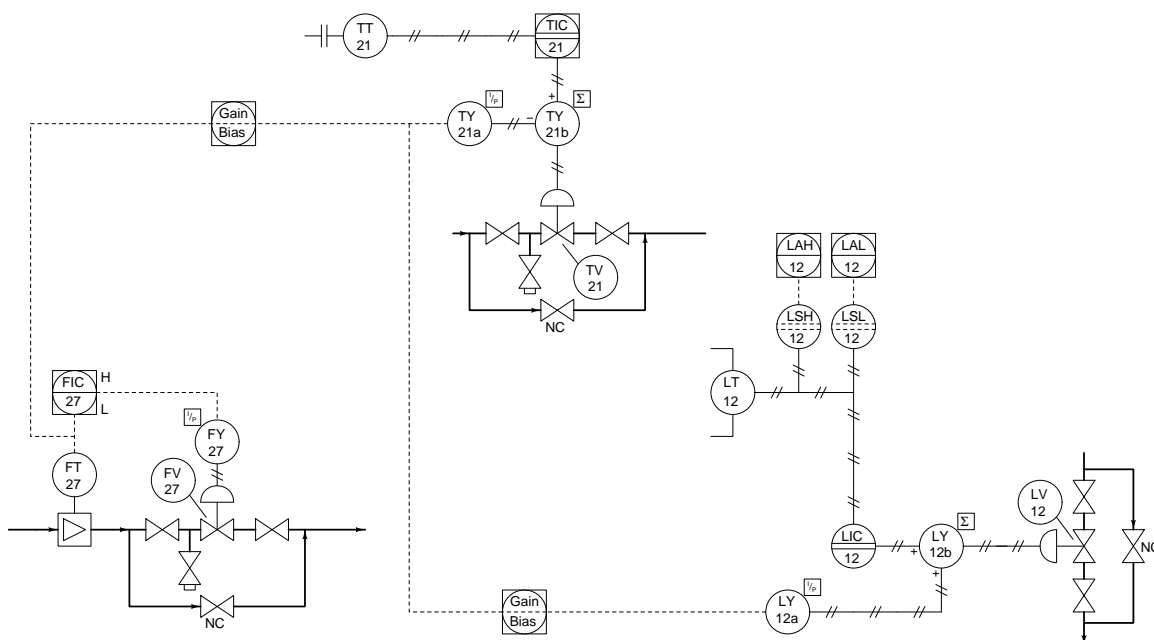
Answer 55
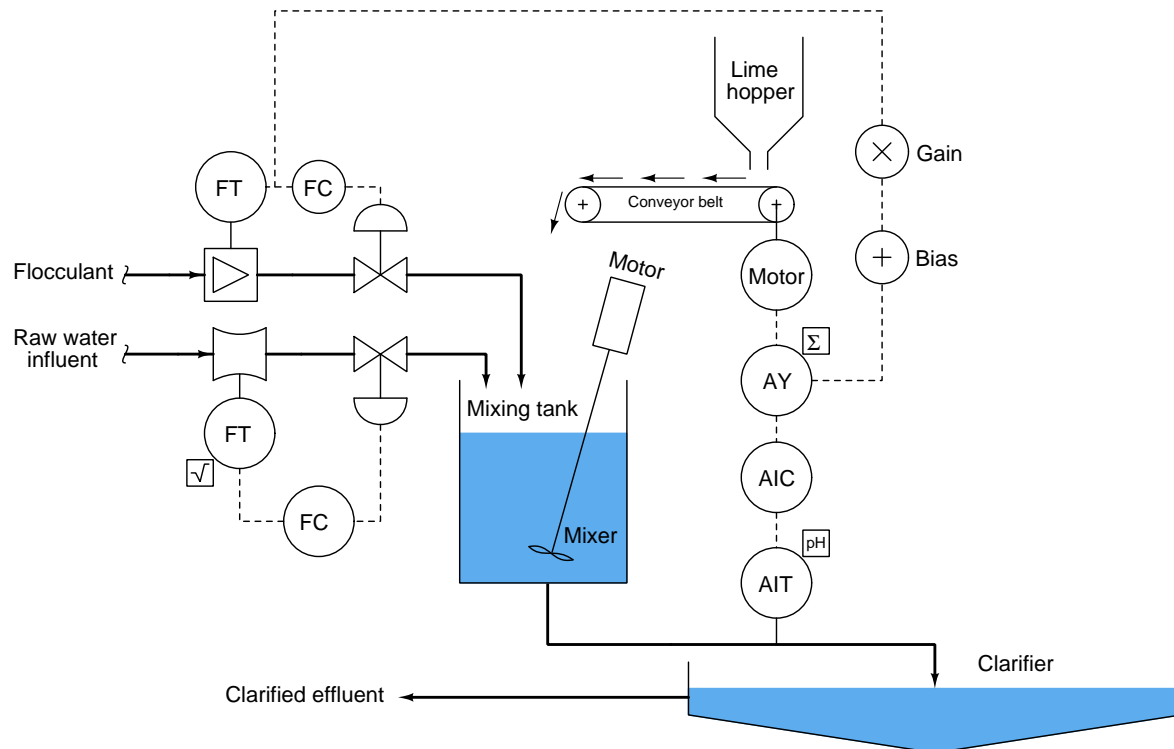
First, we must clearly understand what the loading effects will be (i.e. which direction the load changes will affect TIC-21 and LIC-12). Performing a thought experiment where we suddenly increase the amount of cold liquid feed into the stripper vessel (C-7), we see this will *decrease* temperature within that vessel which reduces the need for cooling water controlled by TIC-21 and drive the temperature (process variable for TIC-21) under setpoint. Increasing sour water flow into the vessel will also *increase* the level of liquid accumulated at the bottom which will demand an increased flow rate of stripped water leaving the vessel and heading toward the water treatment process, driving the liquid level (process variable for LIC-12) above setpoint.

The purpose of feedforward control is to preemptively move a final control element in response to a change in load, such that the loading effects will be canceled and the feedback control system need not correct for it. In this case, we will need to take the flow signal output by FT-27 and use that flow signal to negatively bias control valve TV-21 (i.e. reducing cooling water flow as the cold feed flow increases) and positively bias control valve LV-12 (i.e. increasing stripped water flow as feed flow increases).

Perhaps the most significant obstacle to implementing feedforward control in these two loops is the fact that both feedback control loops are entirely pneumatic, while FT-27 outputs an electronic signal. The "summing" functions necessary to add the feedforward signal to the control valve signals (TV-21 and LV-12) will need to be pneumatic summer instruments, and the electronic feedforward signal from FT-27 will need to enter an I/P converter to change it to a pneumatic signal. An alternative plan, of course, would be to upgrade both controllers (TIC-21 and LIC-12) to electronic instead of pneumatic in order to make the feedforward strategy much easier to implement.

This diagram shows what the feedforward strategy would look like, with the process vessels and piping removed for simplicity:

Answer 56

Answer 57

Answer 58

Answer 59

Answer 60

Answer 61

Answer 62

Answer 63

Answer 64

The *lead/lag* relay introduces an adjustable lead or an adjustable lag into the feedforward signal, the purpose being to equalize the fuel flow's lag time with the feed flow lag time. By advancing or delaying the fuel flow response to changes in feed flow, we can make sure that the feedforward effect "arrives" at the process variable (outlet temperature) at just the right time to compensate for the change in feed.
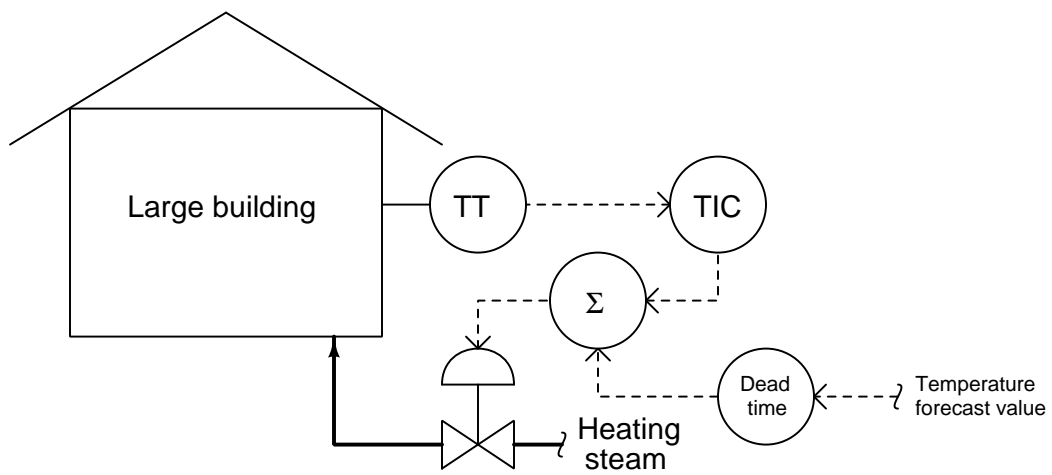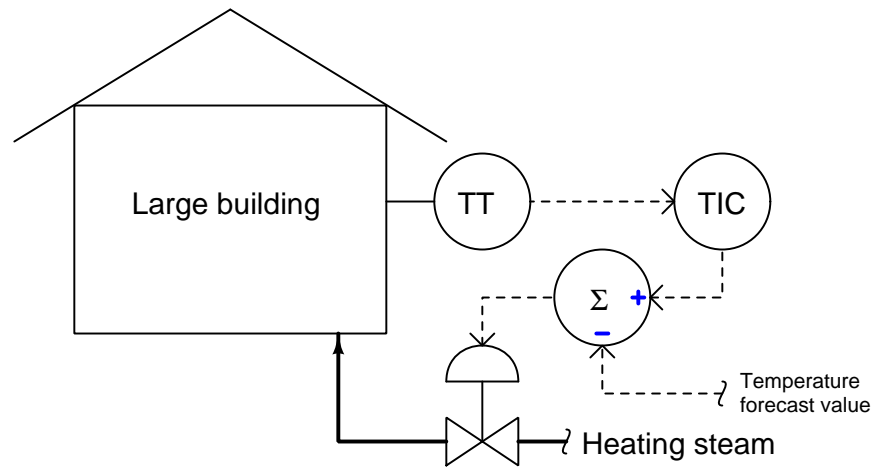
Answer 65

Answer 66

If your problem-solving included the thought, *"We need to speed up the feed temperature's effect to bring it into step with the valve's effect"* then you have made a very common mistake. I will leave it to you to determine why it is impossible for us to speed up the feed temperature's effect on the process using dynamic compensation in the control system.

Answer 67

AIC-28 is the primary (master) pH controller, while FFC-23 is the cascaded secondary (slave) flow controller. FFC-23 also acts as the summer where the "wild" feedforward ammonia vapor flow signal from FT-24 may preemptively call for changes in acid flow rate. The lead/lag unit, FY-23, of course is the dynamic compensation portion of the feedforward control.

Answer 68

In this faulty system, the flocculant *valve position* is being used as the feedforward signal rather than the actual flocculant *flow rate*. Plus, there is one more (major) error which I will leave to you to find!

Answer 69

Answer 70

133

Answer 71

FT-40's signal is fed forward into two control loops: FFC-41 (Flow Ratio Controller #41) which controls the flow of heating steam to the reboiler, and FC-34 (Flow Controller #34) which controls the flow of distillate (overhead) product exiting the system. The concept here is that additional feed flow into the fractionator demands additional heat applied to the reboiler as well as additional heat removed from the system in the form of overhead product drawn away from the fractionator.

We see dynamic compensation applied to this feedforward signal in the form of lead/lag functions FY-40a and FY-40b. FY-40a applies lead/lag to the reboiler steam flow controller while FY-40b applies lead/lag to the distillate product flow controller. The concept here is that changes in feed flow, while demanding commensurate changes in reboiler steam flow and distillate product flow, will not impose a loading effect with the same lag time as an immediately fed-forward command to change steam and distillate flow rates. Therefore, these lead/lag functions must add some lag time to the feedforward signal (essentially delaying its effect) so that it does not over-compensate immediately following a change in feed flow rate.

"Tuning" any feedforward system requires that you disable any feedback control (so that you will be monitoring pure feedforward action) and then introduce intentional load changes to watch the feedforward compensation. This means de-tuning FFC-41 (i.e. setting its PID parameters for minimum effect) and watching changes in reboiler temperature as the feed flow (load) is changed, as well as de-tuning FC-34 and watching for changes in overhead accumulator (V-13) liquid level. Under-compensation should be corrected by increasing feedforward gain, while over-compensation should be corrected by decreasing that gain. Lag time and the lead/lag ratio should be adjusted such that there is minimal over/under compensation transients following a load change.
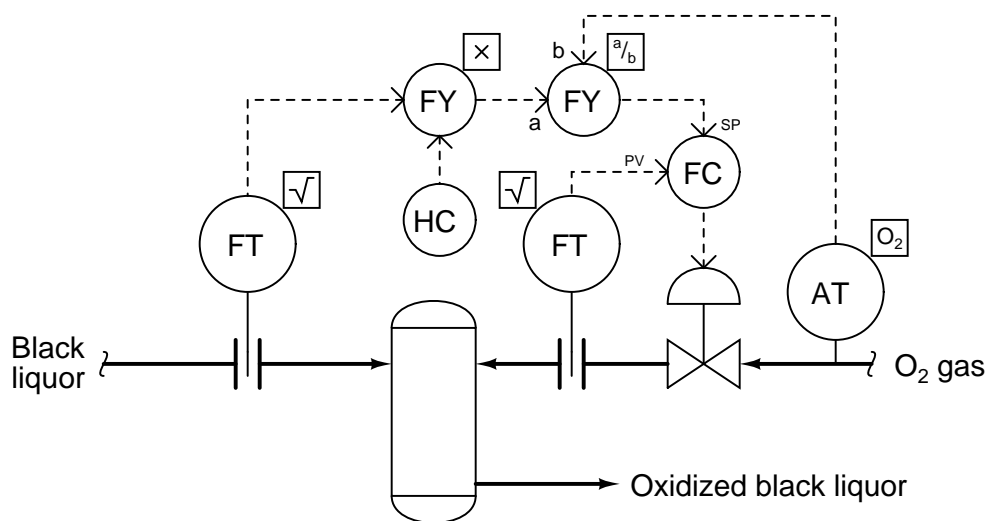
Answer 72

The multiplier relay provides the flow controller with an actual *mass flow rate* signal for the coal. The dead + lag time relay "models" the mill and separator, so that the flow controller sees a virtual representation of fuel flow going out the separator and to the burner.

This ingenious application of lag and dead time function blocks in a control system provides an *inferred* variable of coal dust flow rate to the burners, where no suitable flowmeter exists to measure that quantity. Measuring mass flow rate of coal chunks is easy with a weighfeeder, but extraordinarily difficult when the coal is in powdered form and fluidized by a moving air stream. By adding the appropriate amount of lag time and dead time after the weighfeeder's mass flow signal, the flow controller "sees" the equivalent of powdered coal dust flow as it enters the burner, and so may be tuned to control this lagging and dead-timed quantity better than if it only "saw" the instantaneous flow rate of coal into the ball mill.

Answer 73

The optimal solution uses a *divider* function block rather than a summer, so that the feedforward oxygen analyzer's signal will have the proper multiplicative effect on oxygen flow to the reactor if the oxygen purity becomes weakened:

If oxygen concentration were to fall from 100% to 50% (for example), we would need *twice* the flow rate of oxygen to the reactor than previously, not just an additional sum of oxygen flow.

Answer 74

Answer 75

Answer 76

Answer 77

Answer 78

Answer 79

Answer 80

Answer 81

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

Answer 82

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

Answer 83

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

Answer 84

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

Answer 85

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

Answer 86

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

Answer 87

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

Answer 88

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

Answer 89

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

Answer 90

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

Answer 91

Answer 92

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

Answer 93

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