<u>Lab</u>

Temperature measurement loop: *Questions 91 and 92*, **completed objectives due by the end of day 5**

<u>Exam</u>

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

Specific objectives for the "mastery" exam:
- Electricity Review: Calculate voltages and currents in an ideal AC transformer circuit
- Sketch proper wire connections showing how to simulate an RTD or thermocouple input to a temperature transmitter using simple electronic components
- Calculate temperatures or voltages in thermocouple and RTD circuits given access to thermocouple and RTD tables
- Calculate instrument input and output values given calibrated ranges
- Solve for a specified variable in an algebraic formula
- Determine the possibility of suggested faults in a Wheatstone bridge circuit given measured values (voltage, current), a schematic diagram, and reported symptoms
- Motor/relay/3phase/PLC Review: Calculate either the full-load current or the horsepower of an electric motor (either single- or three-phase) given the line voltage and one of the other parameters
- INST250 Review: Calculate C_v rating of control valve for liquid (non-cavitating) service
- INST263 Review: Determine effect of a fault in a selector or override control system

Recommended daily schedule

<u>Day 1</u>

Theory session topic: Thermocouples (continued)

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

<u>Day 2</u>

Theory session topic: Thermocouple and RTD applications

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

<u>Day 3</u>

Theory session topic: Non-contact pyrometers, temperature switches, calibration standards, and accessories

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

<u>Day 4</u>

Theory session topic: Review for exam

Questions 61 through 80; <u>answer questions 61-70</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

<u>Day 5</u>

Exam

How To . . .

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

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

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

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

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

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

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

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

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

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

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

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

file `howto`

General Values, Expectations, and Standards

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

Learning is the top priority in this program. Every circumstance, every incident, every day 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. If your efforts do not yield the expected results, only you can make it right.

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 means exercising self-discipline and persistence in your studies, 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.

Mastery 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 nearest deadline.

Communication means clearly conveying your thoughts and paying attention to what others convey. Remember that no one can read your mind, and so it is incumbent upon you to communicate any and all important information.

Teamwork means working constructively with your classmates so as to maximize their learning as well as your own.

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

Representation means your actions are a reflection of this program and not just of 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 hire.

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

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 provided you have signed the FERPA release form. You are welcome to see these records at any time, and are encouraged to track your own academic progress using the grade spreadsheet template.

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 if any of the following behaviors are demonstrated: false testimony (lying) to your instructor, cheating on any assignment or assessment, plagiarism (presenting another's work as your own), willful violation of a safety policy, theft, harassment, intoxication, or destruction of property. Such 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 241 Course Outcomes

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

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

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

- Sketch proper wire connections showing how to simulate an RTD or thermocouple input to a temperature transmitter using simple electronic components. [Ref: Program Learning Outcome #5]

- Calculate temperatures or voltages in thermocouple and RTD circuits given access to thermocouple and RTD tables. [Ref: Program Learning Outcome #7]

- Calculate flow rate and pressure drop for a nonlinear flow element given maximum flow specifications. [Ref: Program Learning Outcome #7]

- Determine suitability of different flow-measuring technologies for a given process fluid type. [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]

- Identify specific instrument calibration errors (zero, span, linearity, hysteresis) from data in an "As-Found" table. [Ref: Program Learning Outcome #7]

- Determine the possibility of suggested faults in simple circuits and Wheatstone bridge 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 working temperature-measurement loop consisting of an electronic temperature transmitter, signal wiring, and SCADA RTU programmed in a text-based programming language. [Ref: Program Learning Outcome #5]

- Construct and commission a working flow-measurement loop consisting of an electronic flow transmitter, signal wiring, and flow computer programmed in a text-based programming language. [Ref: Program Learning Outcome #5]

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

- Research equipment manuals to sketch a complete circuit connecting a loop controller to either a 4-20 mA transmitter or a 4-20 mA final control element, with all DC voltages and currents correctly annotated, all electrical sources and loads properly identified, given components randomly selected by the instructor. [Ref: Program Learning Outcomes #5 and #9]

- Calibrate an electronic RTD temperature transmitter to specified accuracy using industry-standard calibration equipment. [Ref: Program Learning Outcome #7]

- Calibrate an electronic thermocouple temperature transmitter to specified accuracy using industry-standard calibration equipment. [Ref: Program Learning Outcome #7]

- Accurately simulate a thermocouple signal using a millivoltage source. [Ref: Program Learning Outcome #7]

- Accurately simulate an RTD signal using a potentiometer. [Ref: Program Learning Outcome #7]

- Calculate flow rate and pressure drop for a nonlinear flow element given maximum flow specifications. [Ref: Program Learning Outcome #7]

- Edit text-based programming code for a flow computer. [Ref: Program Learning Outcome #5]

- Utilize command-line instructions in a Unix operating system environment. [Ref: Program Learning Outcome #5]

file `outcomes_INST241`

Sequence of second-year Instrumentation courses

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

(Only if 4th quarter was Summer: INST23x)

INST 200 -- 1 wk
Intro. to Instrumentation

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

Prerequisite for all INST24x, INST25x, and INST26x courses

Summer quarter

INST 233 -- 4 cr
Protective Relays *(elective)*

Jobshadow and/or Internship strongly recommended

Fall quarter

INST 240 -- 6 cr
Pressure/Level Measurement

INST 241 -- 6 cr
Temp./Flow Measurement

INST 242 -- 5 cr
Analytical Measurement

Winter quarter

INST 250 -- 5 cr
Final Control Elements

INST 251 -- 5 cr
PID Control

INST 252 -- 4 cr
Loop Tuning

Spring quarter

INST 260 -- 4 cr
Data Acquisition Systems

INST 262 -- 5 cr
Digital Control Systems

INST 263 -- 5 cr
Control Strategies

ENGT 134 -- 5 cr
CAD 1: Basics

Prerequisite for INST206

All courses completed?
No
Yes

INST 205 -- 1 cr
Job Prep I

INST 206 -- 1 cr
Job Prep II

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

Graduate!!!

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

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

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

Beginning in Summer

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`

<h1 style="text-align:center">Methods of instruction</h1>

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 your own words; outline missing important topic(s); unable to explain the outline or solution methods represented in written work
- **Full credit** = Every homework question answered, with any points of confusion clearly articulated; all important concepts from reading assignments accurately expressed in the outline and clearly articulated when called upon by the instructor to explain

The minimum expectation at the start of every student-instructor session is that all students have made a good-faith effort to complete 100% of their assigned homework. This does not necessarily mean all answers will be correct, or that all concepts are fully understood, because one of the purposes of the meeting between students and instructor is to correct remaining misconceptions and answer students' questions. However, experience has shown that without accountability for the homework, a substantial number of students will not put forth their best effort and that this compromises the whole learning process. Full credit is reserved for good-faith effort, where each student thoughtfully applies the study and problem-solving recommendations given to them (see Question 0).

| Sample rubric for post-assessments |

- **No credit** = Failure to comprehend one or more key concepts; failure to apply logical reasoning to the solution of problem(s); no contribution to the dialogue
- **Half credit** = Some misconceptions persist by the close of the session; problem-solving is inconsistent; limited contribution to the dialogue
- **Full credit** = Socratic queries answered thoughtfully; effective reasoning applied to problems; ideas communicated clearly and accurately; responds intelligently to questions and statements made by others in the session; adds new ideas and perspectives

The minimum expectation is that each and every student engages with the instructor and with fellow students during the Socratic session: posing intelligent questions of their own, explaining their reasoning when challenged, and otherwise positively contributing to the discussion. Passive observation and listening is not an option here – every student must be an active participant, contributing something original to every dialogue. If a student is confused about any concept or solution, it is their responsibility to ask questions and seek resolution.

If a student happens to be absent for a scheduled class session and is therefore unable to be assessed on that day's study, they may schedule a time with the instructor to demonstrate their comprehension at some later date (before the end of the quarter when grades must be submitted). These same standards of performance apply equally make-up assessments: either inspection of homework or a closed-book quiz for the pre-assessment, and either a Socratic dialogue with the instructor or another closed-book quiz for the post-assessment.

Lab sessions

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

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

Troubleshooting assessments must meet the following guidelines:

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

file `instructional`

Distance delivery methods

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

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

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

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

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

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

file `distance`

Metric prefixes and conversion constants

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

METRIC PREFIX SCALE

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

10^{2}	10^{1}	10^{-1}	10^{-2}
hecto	deca	deci	centi
h	da	d	c
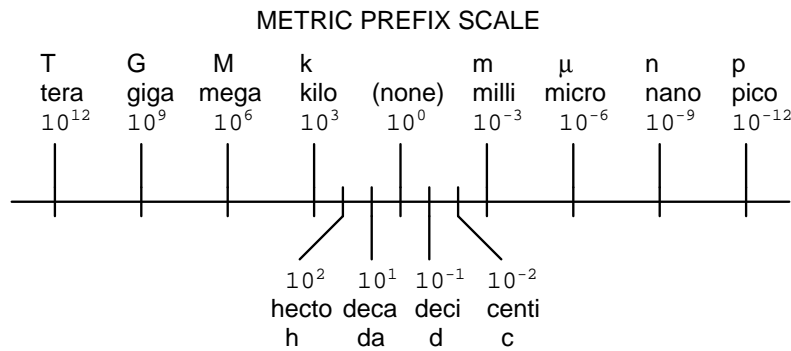
- **Conversion formulae for temperature**
- $^{o}F = (^{o}C)(9/5) + 32$
- $^{o}C = (^{o}F - 32)(5/9)$
- $^{o}R = {}^{o}F + 459.67$
- $K = {}^{o}C + 273.15$

Conversion equivalencies for distance

1 inch (in) = 2.540000 centimeter (cm)

1 foot (ft) = 12 inches (in)

1 yard (yd) = 3 feet (ft)

1 mile (mi) = 5280 feet (ft)

Conversion equivalencies for volume

1 gallon (gal) = 231.0 cubic inches (in^3) = 4 quarts (qt) = 8 pints (pt) = 128 fluid ounces (fl. oz.) = 3.7854 liters (l)

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

Conversion equivalencies for velocity

1 mile per hour (mi/h) = 88 feet per minute (ft/m) = 1.46667 feet per second (ft/s) = 1.60934 kilometer per hour (km/h) = 0.44704 meter per second (m/s) = 0.868976 knot (knot – international)

Conversion equivalencies for mass

1 pound (lbm) = 0.45359 kilogram (kg) = 0.031081 slugs

Conversion equivalencies for force

1 pound-force (lbf) = 4.44822 newton (N)

Conversion equivalencies for area

1 acre = 43560 square feet (ft^2) = 4840 square yards (yd^2) = 4046.86 square meters (m^2)

Conversion equivalencies for common pressure units (either all gauge or all absolute)

1 pound per square inch (PSI) = 2.03602 inches of mercury (in. Hg) = 27.6799 inches of water (in. W.C.) = 6.894757 kilo-pascals (kPa) = 0.06894757 bar

1 bar = 100 kilo-pascals (kPa) = 14.504 pounds per square inch (PSI)

Conversion equivalencies for absolute pressure units (only)

1 atmosphere (Atm) = 14.7 pounds per square inch absolute (PSIA) = 101.325 kilo-pascals absolute (kPaA) = 1.01325 bar (bar) = 760 millimeters of mercury absolute (mmHgA) = 760 torr (torr)

Conversion equivalencies for energy or work

1 british thermal unit (Btu – "International Table") = 251.996 calories (cal – "International Table") = 1055.06 joules (J) = 1055.06 watt-seconds (W-s) = 0.293071 watt-hour (W-hr) = 1.05506 x 10^{10} ergs (erg) = 778.169 foot-pound-force (ft-lbf)

Conversion equivalencies for power

1 horsepower (hp – 550 ft-lbf/s) = 745.7 watts (W) = 2544.43 british thermal units per hour (Btu/hr) = 0.0760181 boiler horsepower (hp – boiler)

Acceleration of gravity (free fall), Earth standard

9.806650 meters per second per second (m/s^2) = 32.1740 feet per second per second (ft/s^2)

Physical constants

Speed of light in a vacuum $(c) = 2.9979 \times 10^8$ meters per second (m/s) = 186,281 miles per second (mi/s)

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

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

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

Stefan-Boltzmann constant $(\sigma) = 5.67 \times 10^{-8}$ Watts per square meter-Kelvin^4 (W/m^2·K^4)

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

Properties of Water

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

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

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

Specific heat of water at 14^oC = 1.00002 calories/g·^{o}C = 1 BTU/lb·^{o}F = 4.1869 Joules/g·^{o}C

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

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

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

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

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

Properties of Dry Air at sea level

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

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

file `conversion_constants`

How to get the most out of academic reading:
- <u>Articulate your thoughts</u> as you read (i.e. "have a conversation" with the author). This will develop *metacognition*: active supervision of your own thoughts. Write your thoughts as you read, noting points of agreement, disagreement, confusion, epiphanies, and connections between different concepts or applications. These notes should also document important math formulae, explaining in your own words what each formula means and the proper units of measurement used.

- <u>Outline, don't highlight!</u> Writing your own summary or outline is a far more effective way to comprehend a text than simply underlining and highlighting key words. A suggested ratio is one sentence of your own thoughts per paragraph of text read. Note points of disagreement or confusion to explore later.

- <u>Work through all mathematical exercises</u> shown within the text, to ensure you understand all the steps.

- <u>Imagine explaining concepts you've just learned to someone else.</u> 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.

- <u>Write your own questions</u> based on what you read, as though you are a teacher preparing to test students' comprehension of the subject matter.

How to effectively problem-solve and troubleshoot:
- <u>Rely on principles, not procedures.</u> Don't be satisfied with memorizing steps – learn *why* those steps work. Each one should make logical sense and have real-world meaning to you.

- <u>Sketch a diagram</u> to help visualize the problem. <u>Sketch a graph</u> showing how variables relate. When building a real system, always prototype it on paper and analyze its function *before* constructing it.

- <u>Identify</u> what it is you need to solve, <u>identify</u> all relevant data, <u>identify</u> all units of measurement, <u>identify</u> any general principles or formulae linking the given information to the solution, and then <u>identify</u> any "missing pieces" to a solution. <u>Annotate</u> all diagrams with this data.

- <u>Perform "thought experiments"</u> to explore the effects of different conditions for theoretical problems. When troubleshooting, perform *diagnostic tests* rather than just visually inspect for faults.

- <u>Simplify the problem</u> 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). Often you can add or remove components in a malfunctioning system to simplify it as well and better identify the nature and location of the problem.

- <u>Work "backward"</u> from a hypothetical solution to a new set of given conditions.

How to manage your time:
- <u>Avoid procrastination.</u> Work now and play later, or else you will create trouble for yourself. Schedule your work appropriate to the *place* you're in as well: e.g. don't waste lab time doing things that could be done anywhere else, when there is work to be done that requires the lab.

- <u>Eliminate distractions.</u> Kill your television and video games. Study in places where you can concentrate.

- <u>Use your "in between" time productively.</u> 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 <u>persistence</u>. Persistent effort 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!

<u>file `question0`</u>

Question 1

Read and outline the "Reference Junction Compensation" subsection of the "Thermocouples" section of the "Continuous Temperature Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- Acknowledgement of previously learned concepts
- Descriptions of problem-solving strategies applied by the author

file i03990

Question 2

Read and outline the "Law of Intermediate Metals" subsection of the "Thermocouples" section of the "Continuous Temperature Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

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- Descriptions of problem-solving strategies applied by the author

file i03991

Question 3

Read and outline the "Software Compensation" subsection of the "Thermocouples" section of the "Continuous Temperature Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

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- Descriptions of problem-solving strategies applied by the author

file i03992

Question 4

Read and outline the "Extension Wire" subsection of the "Thermocouples" section of the "Continuous Temperature Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

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- Images copied from the text (or sketched by you) to illustrate concepts
- Acknowledgement of previously learned concepts
- Descriptions of problem-solving strategies applied by the author

file i03993

Question 5

Read and outline the "Side-Effects of Reference Junction Compensation" subsection of the "Thermocouples" section of the "Continuous Temperature Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- Acknowledgement of previously learned concepts
- Descriptions of problem-solving strategies applied by the author

file i03994

Question 6

Read and outline the "Burnout Detection" subsection of the "Thermocouples" section of the "Continuous Temperature Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- Acknowledgement of previously learned concepts
- Descriptions of problem-solving strategies applied by the author

file i03995

Question 7

The relationship between the amount of voltage produced by a thermocouple's measurement junction (E_{meas}), the voltage produced by the reference junction (E_{ref}), and the voltage received by the measuring instrument (E_{meter}) is stated by the following equation:
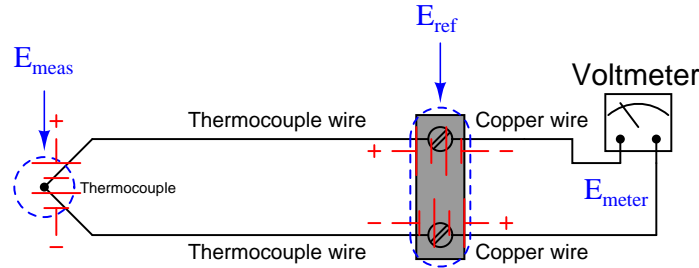
$$E_{meter} = E_{meas} - E_{ref}$$

In a *hardware-compensated* thermocouple measuring instrument, the reference junction's voltage is canceled by the addition of a variable voltage source inside the instrument which we will designate as E_{comp}. An alternative approach is to connect an external device called an *electronic ice-point* between the voltage-measuring instrument and the thermocouple, such that the "ice point" device adds the necessary voltage to compensate for the reference junction:
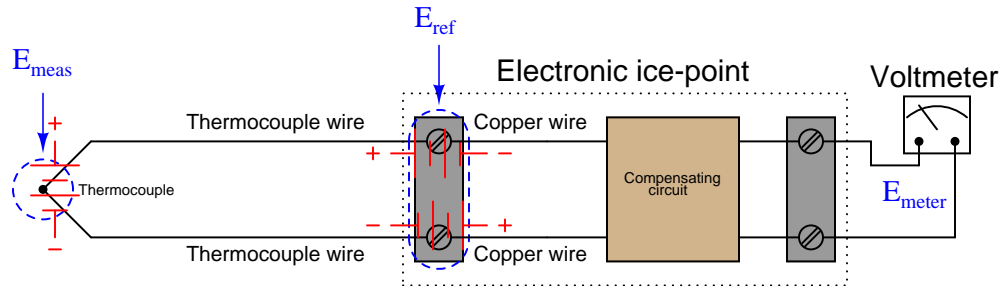
Re-write the thermocouple circuit equation to include this "compensating" voltage, and identify both the magnitude and the polarity this voltage must have in order to successfully cancel E_{ref}.

| Suggestions for Socratic discussion |

- Why can't we just somehow build the thermocouple circuit so it doesn't have a reference junction at all? That way we wouldn't have to concern ourselves with compensation for this junction!
- Should we use thermocouple extension wire to connect the voltmeter to the ice-point circuit, or is copper wire sufficient?
- Can we get away with using copper extension wire all the way to the thermocouple so long as we're using an ice-point circuit? Why or why not?

file i00385

Thermocouple-based temperature instruments work on the principle of measuring voltage output by a thermocouple:

Instrument in use
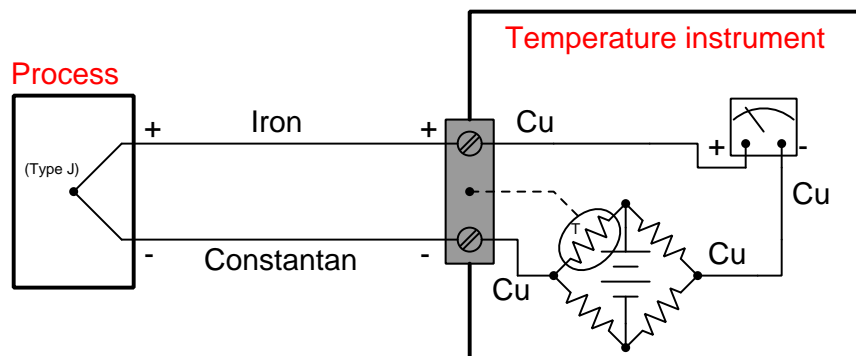
If we try to simulate a thermocouple by using a precision potentiometer circuit to send a precise millivolt signal to a temperature instrument, however, the instrument will not register the way we might expect. For instance, thermocouple tables for type J thermocouples tell us that 500 ^{o}F corresponds to a voltage signal of 14.110 mV. However, if we were to input this amount of signal voltage to a type J instrument, it would probably *not* register 500 ^{o}F:
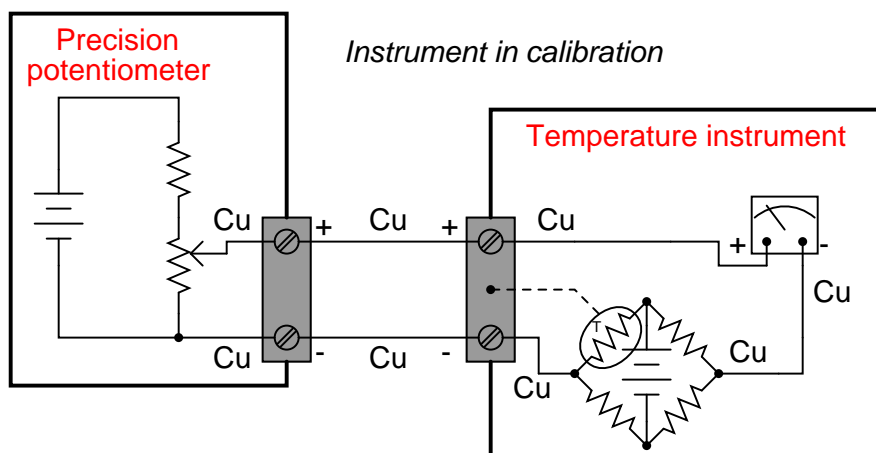
Describe what the problem is, and determine the amount of voltage we would have to "dial up" on the precision potentiometer in order to get the thermocouple instrument to register 500 ^{o}F, assuming an ambient temperature of 72 ^{o}F.

Suggestions for Socratic discussion

- Express in *general terms* how one could solve a problem such as this one. In other words, think of a way to express a general step-by-step solution you could give to someone in the form of an instruction list, to show them how much voltage they would need to input to a temperature instrument to make it "think" it was connected to a thermocouple of any given temperature.
- Should the thermistor in the compensation bridge possess a *positive* or a *negative* coefficient of resistance?

  file i00386

Determine the correct potentiometer millivoltage setting to generate the following temperature indications on the following instruments:
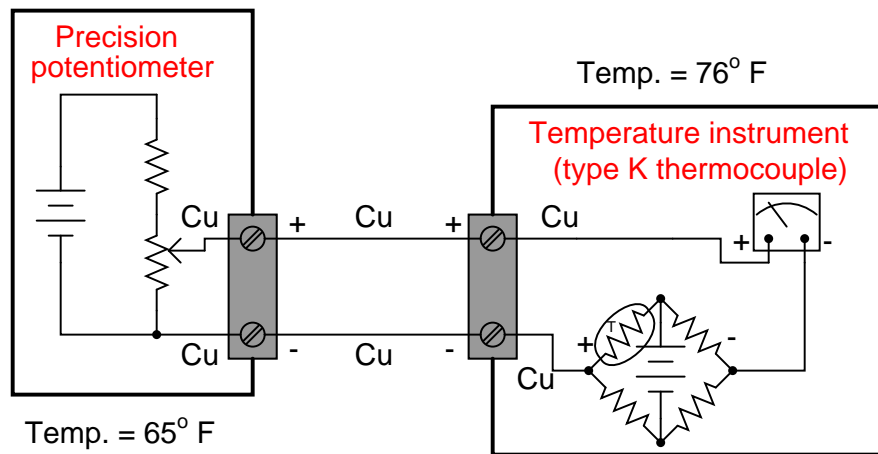
- 0° F ; Potentiometer setting = ???
- 300° F ; Potentiometer setting = ???
- 600° F ; Potentiometer setting = ???
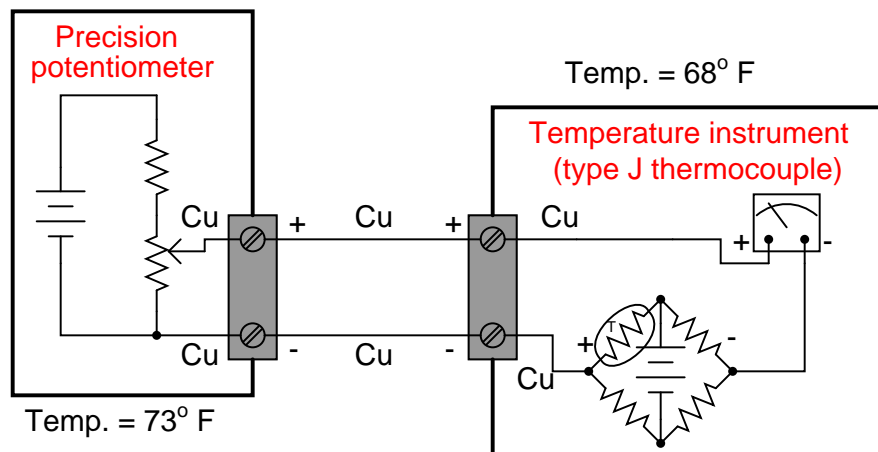
- 400° F ; Potentiometer setting = ???
- 600° F ; Potentiometer setting = ???
- 800° F ; Potentiometer setting = ???
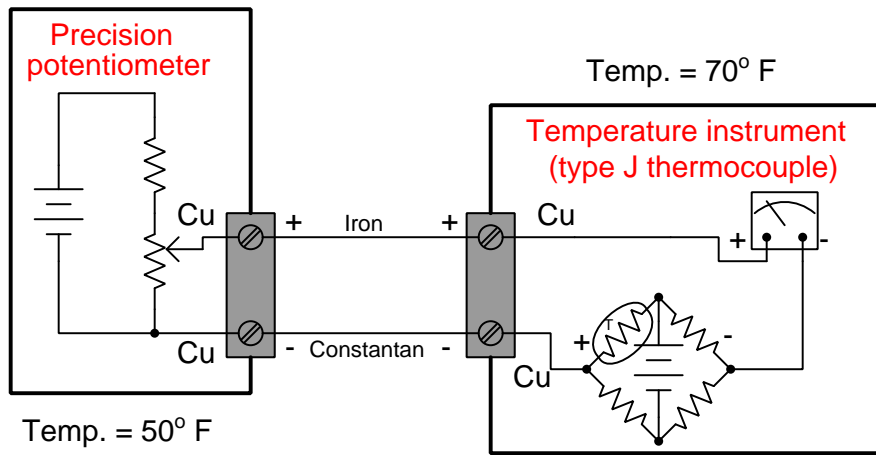
- 250° F ; Potentiometer setting = ???
- 500° F ; Potentiometer setting = ???
- 750° F ; Potentiometer setting = ???

Suggestions for Socratic discussion

- In each of these example circuits, only one of the ambient temperatures given is relevant. Identify which one that is, and explain why the other one doesn't matter.
- What would have to be different in each circuit for the irrelevant temperature to matter?
- Explain what you would have to alter in each circuit in order to disable the temperature instrument's cold junction compensation (CJC).

file i00388

Question 10

It is important for a thermocouple-based temperature instrument to have a *high input impedance*. What does this mean, and why is it important in a thermocouple circuit?

Modern digital voltmeter designs all exhibit high input impedance – high enough for measuring thermocouple junction voltage, at least. Suppose, though, you were asked to measure the output of a thermocouple *without* using any digital instruments. You have plenty of analog voltmeter movements available, but they all have input impedances that are too low for this task.

Describe how you could build your own super-high input impedance voltmeter using readily available components. Extra points for doing so without using an electronic circuit!
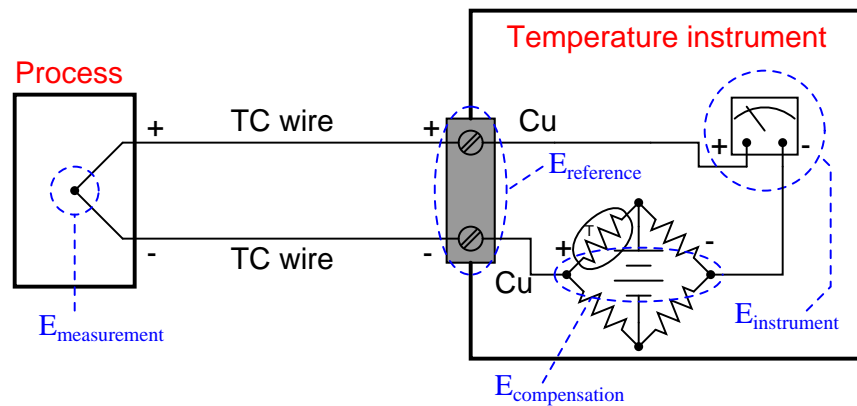
file i00394

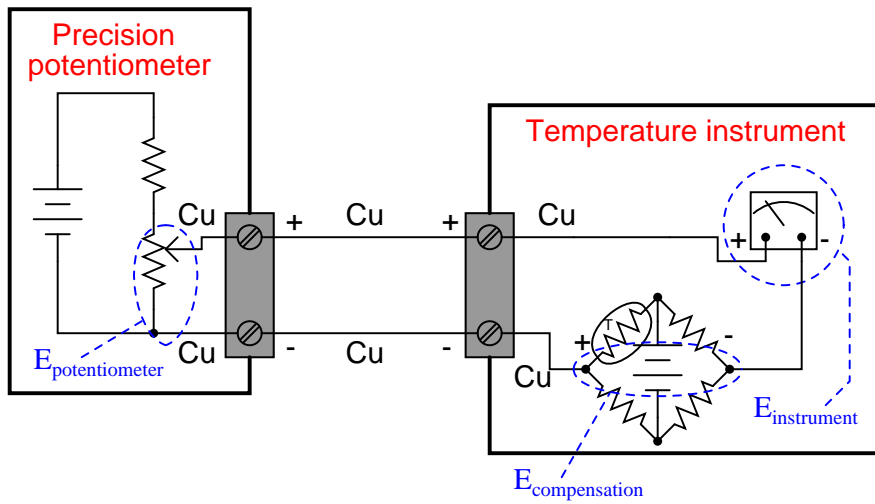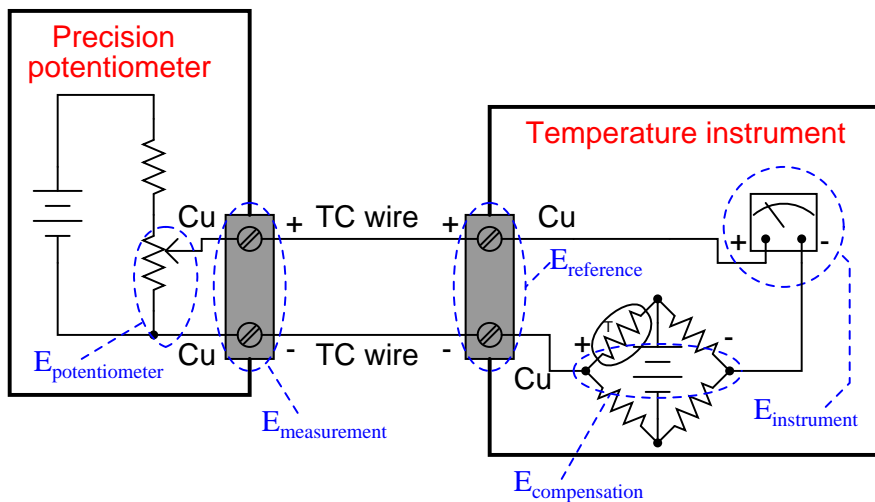Write an equation for each circuit shown, showing how all the voltages in each circuit relate to each other:


Equation:

Equation:

Precision potentiometer

Temperature instrument

Cu   +   Cu   +   Cu

$E_{potentiometer}$

Cu   -   Cu   -   Cu

$E_{instrument}$

$E_{compensation}$

Equation:

Precision potentiometer

Temperature instrument

Cu   +   TC wire   +   Cu

$E_{reference}$

$E_{potentiometer}$ Cu   -   TC wire   -   Cu

$E_{measurement}$

$E_{instrument}$
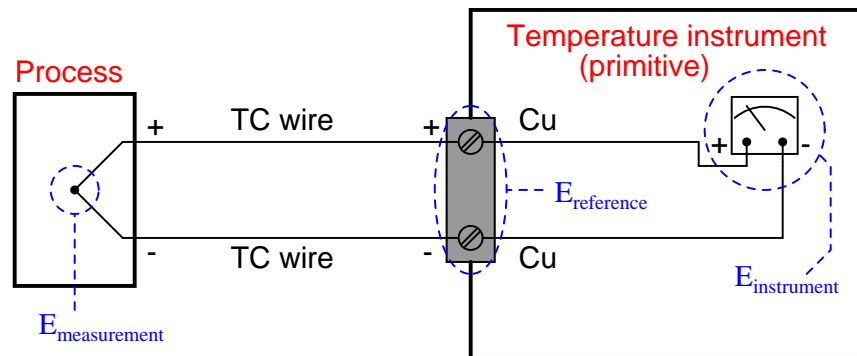
$E_{compensation}$

Equation:

Suggestions for Socratic discussion

- You should notice a definite progression in complexity from the first circuit to the last in this question. Why do you suppose these circuits were arranged in this order? How might this help you figure out the equation for a realistic calibration circuit (such as the last two) in the future if you do not have a reference at hand to remind you how thermocouple circuits work?

file i00387

28

The following diagram is a simplified schematic for a 2-wire, loop-powered, 4-20 mA analog temperature transmitter:

Loop-powered 4-20 mA temperature transmitter
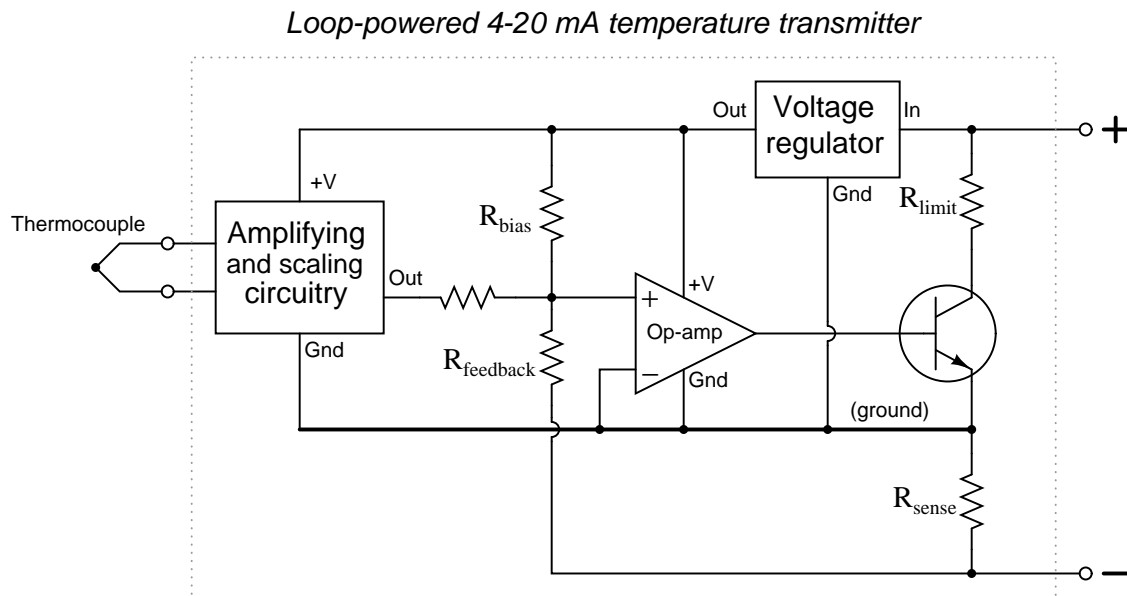
The rest of the circuit, of course, looks something like this:
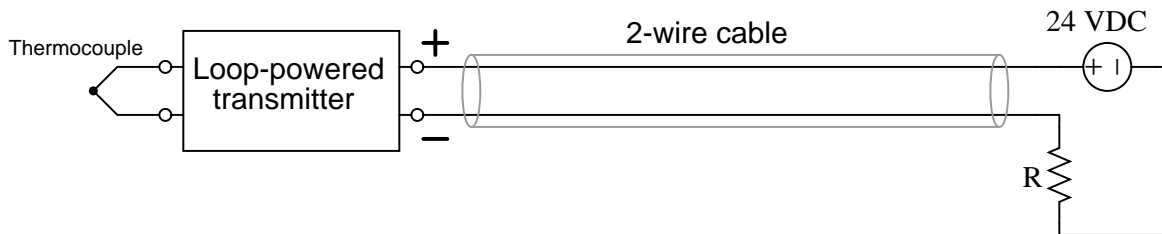
Calculate the amount of current through the emitter of the transistor inside the temperature transmitter given the following conditions:

- Calibrated temperature range = 50 to 250 degrees C
- Thermocouple temperature = 100 degrees C
- Loop power supply = 24.0 volts
- Loop resistance = 250 ohms
- Voltage regulator input current = 3.7 mA (constant)

Also, trace the directions of all currents in the temperature transmitter circuit using both conventional and electron flow notations.

file i00397

Question 13

The *HART* protocol was an early attempt at establishing a digital communications standard for field process instruments, designed as an extension of the already-popular 4 to 20 mA DC current signal standard. The basic idea of HART is that serial digital data could be encoded as bursts of high-frequency AC voltage superimposed on the DC voltage present in a 4-20 mA loop-powered circuit:
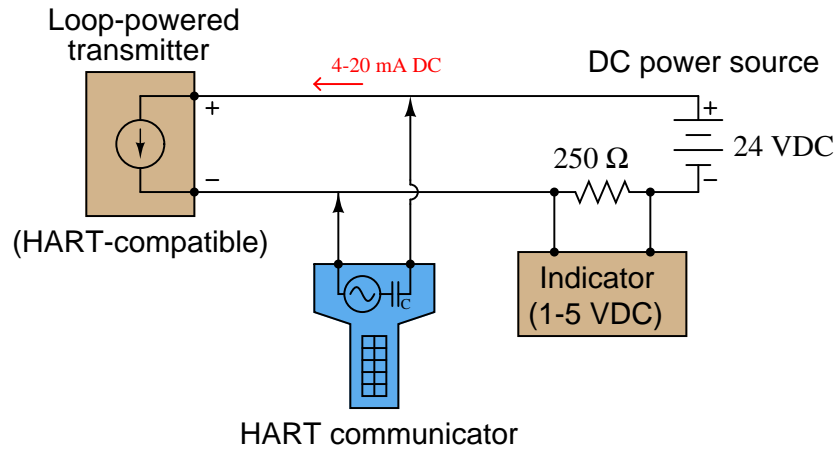
A microprocessor inside the loop-powered transmitter detects the digital data signals from the HART communicator as pulses of low-voltage AC dropped across the transmitter terminals. The transmitter, in turn, has the ability to send digital data out in the same format, being detected by the communicator as AC voltage pulses across its terminals.

Apply the Superposition Theorem to this circuit, showing the circuit as "seen" by the AC signals sent between the transmitter and communicator, and showing the circuit as "seen" by the DC signals sent between the transmitter and the indicator.

Also, identify where in the circuit the communicator may be connected and still be able to "talk" with the smart instrument. What advantage(s) may there be in being able to connect the communicator at different points in the circuit?
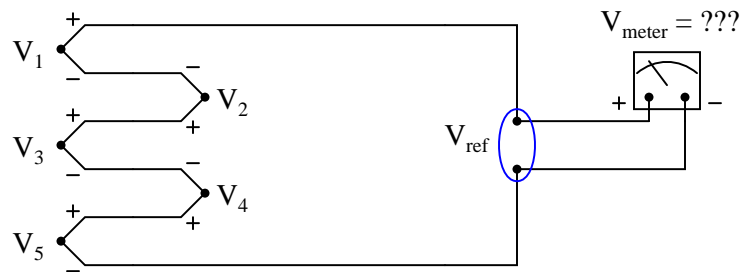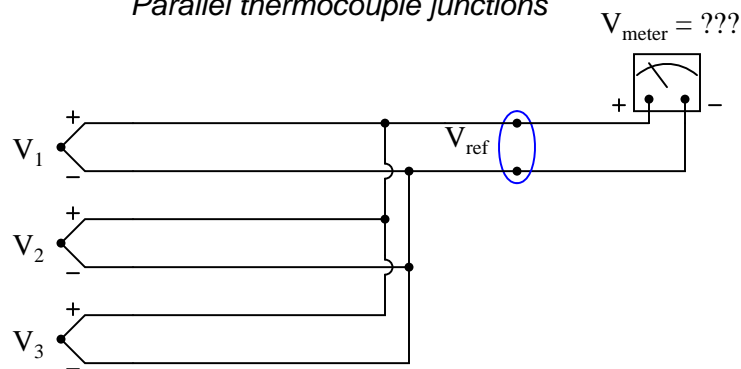
file i00400

Question 14

Write equations expressing the total voltage sensed by the indicating instrument, as functions of the voltages shown in the diagrams. Assume that all junctions form the same thermocouple type (e.g. all type J, all type K, etc.):

Series thermocouple junctions
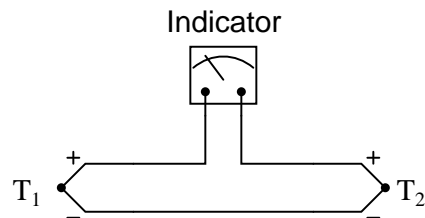

Parallel thermocouple junctions

file i00399

Question 15

*Differential* thermocouple circuits are used to measure the difference in temperature between two points:

Indicator

Does the indicating instrument require reference junction compensation or not? Explain your answer.

file i00401

Question 16

When using a thermocouple calibrator (simulator), where you simply set it to simulate a thermocouple at a specified temperature, is it important to use the correct thermocouple or extension wire to connect the calibrator with the transmitter, or is the wire type irrelevant?
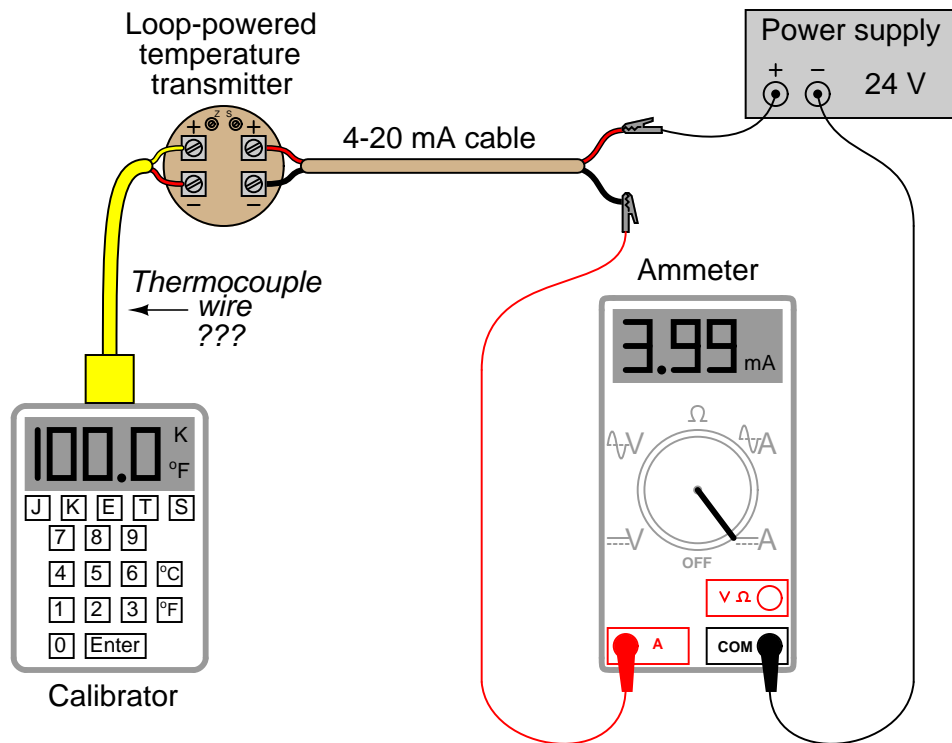
Be sure to explain your answer, based on the presence of dissimilar-metal junctions and junction-compensation circuitry in both the calibrator and transmitter.

file i00396

Question 17

Terminal blocks used in thermocouple circuits are designed to be *isothermal*. For example, the dual-terminal connection block found inside a thermocouple "head" box is a prime example of an isothermal block.
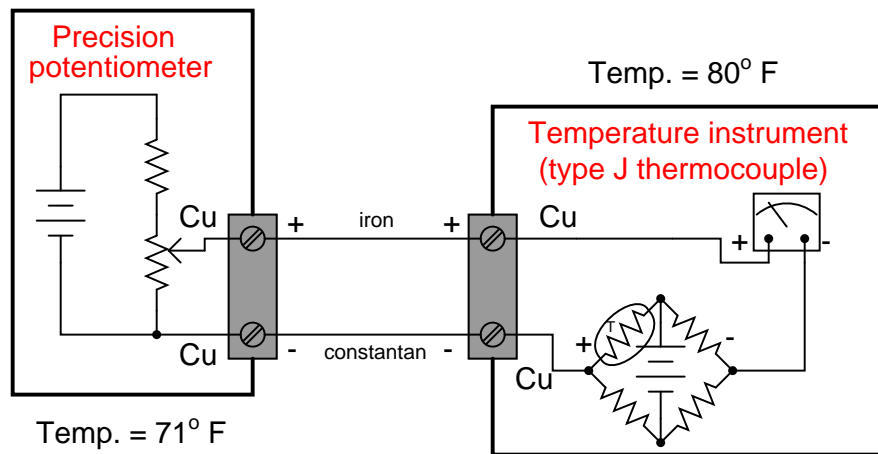
Explain what this term "isothermal" means, how it is physically designed, and also why it is an important feature.
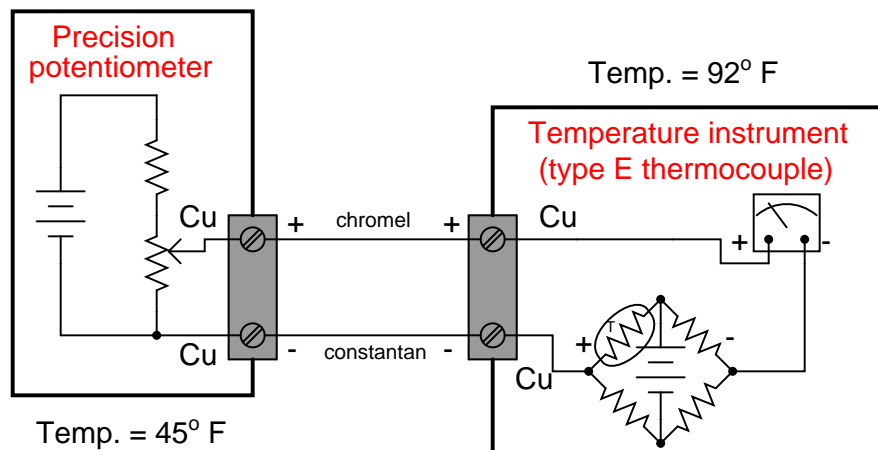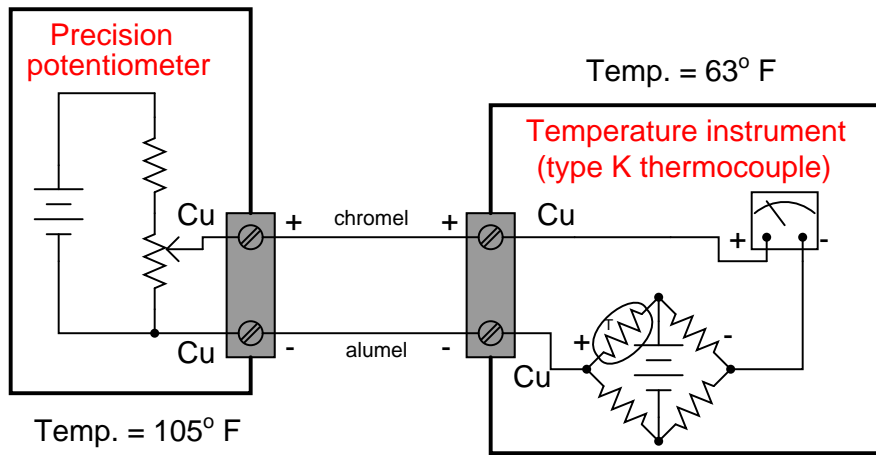
file i00402

Determine the correct potentiometer millivoltage setting to generate the following temperature indications on the following instruments:

Precision potentiometer

Temp. = 80° F

Temperature instrument (type J thermocouple)

Cu   +   iron   +   Cu   +   -

Cu   -   constantan   -   Cu   +   -

Temp. = 71° F

- -100° F ; Potentiometer setting = ???
- 150° F ; Potentiometer setting = ???
- 400° F ; Potentiometer setting = ???

Precision potentiometer

Temp. = 92° F

Temperature instrument (type E thermocouple)

Cu   +   chromel   +   Cu   +   -

Cu   -   constantan   -   Cu   +   -

Temp. = 45° F

- 0° F ; Potentiometer setting = ???
- 375° F ; Potentiometer setting = ???
- 750° F ; Potentiometer setting = ???
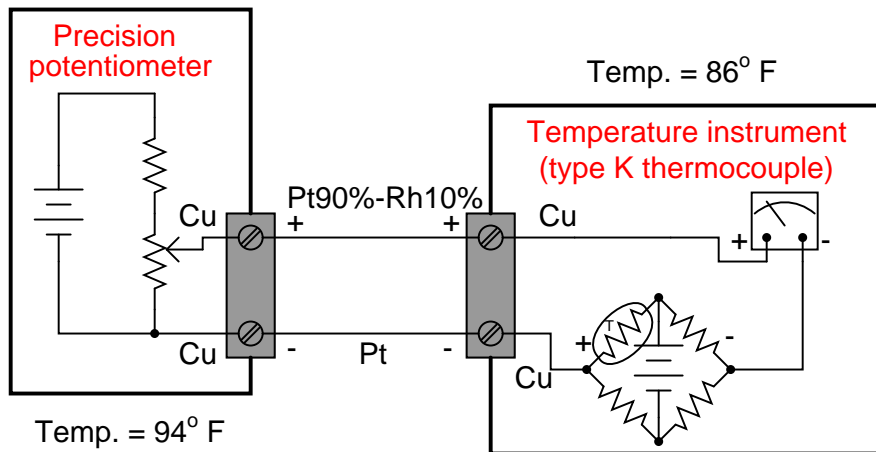
- -50° F ; Potentiometer setting = ???
- 975° F ; Potentiometer setting = ???
- 2000° F ; Potentiometer setting = ???

file i00422

Question 19

Suppose someone were to connect a precision potentiometer to a temperature instrument using thermocouple wire, except that they chose the wrong type of thermocouple wire:
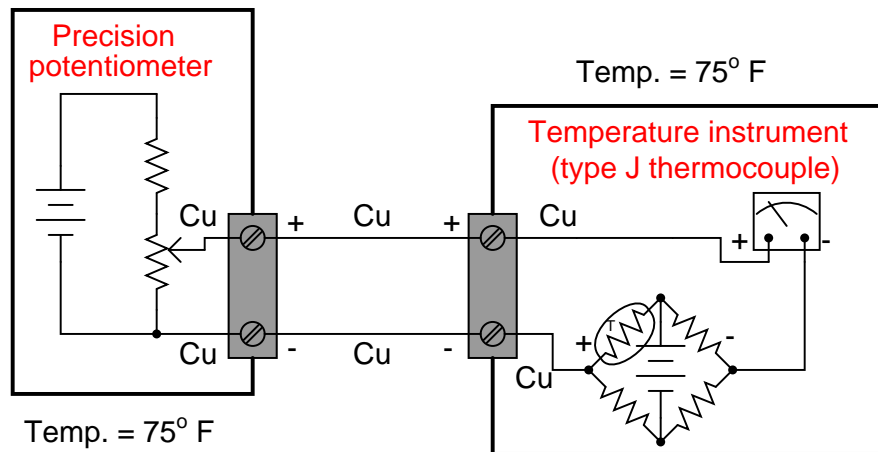

The instrument technician performing the calibration sets the potentiometer to an output of 20.871 millivolts, hoping to simulate a temperature of 1000° F for the temperature instrument to measure. However, since the wrong type of thermocouple wire is being used (type S instead of type K), the instrument will actually register something else.

Assuming the instrument is already properly calibrated, what temperature will it indicate with a potentiometer output of 20.871 mV and the indicated ambient temperatures?

file i00423

Determine the correct potentiometer millivoltage settings to generate the following temperature indications at the instrument:

Precision potentiometer

Temp. = 75° F

Temperature instrument
(type J thermocouple)

Cu   +   Cu   +   Cu

+   -

Cu   -   Cu   -

+   -

Cu

Temp. = 75° F

- -93° F ; Potentiometer setting = _____ mV
- 157° F ; Potentiometer setting = _____ mV
- 389° F ; Potentiometer setting = _____ mV
- 580° F ; Potentiometer setting = _____ mV

file i02976

Question 21

Read pages 10-13 of the Nuclear Regulatory Commission's "Three Mile Island – A Report to the Commissioners and to the Public" for an overview of the nuclear reactor power generating system, and pages 30-31 (Section 5 of the accident narrative) highlighting instrument technicians' roles on the day of the March 28, 1979 accident, then answer the following questions:

The normal operating temperature of water inside the reactor vessel is 575 ^{o}F, but yet the water does not boil even when the reactor is operating at full power. Explain how boiling is prevented with such a high operating temperature (see page 10), referencing a *steam table* and a *phase diagram* if necessary.

On pages 40-41 of the report, it states that measured reactor steam temperatures in excess of 600 degrees F at a measured pressure of 495 PSI were clues that the heat-generating reactor core was "uncovered" (no longer fully submerged in water inside the reactor vessel), because these figures imply *superheated* steam. Explain this reasoning, based on what you know about phase changes in general and steam in particular. Refer to a *steam table* and a *phase diagram* if necessary.

At the heart of the accident was a stuck-open pressure relief valve called a *PORV*. This open valve allowed cooling water to escape from the primary (reactor) coolant loop, eventually leading to a condition where about half of the reactor core (normally submerged in cooling water) was uncovered. Instrument technicians were sent to manually measure reactor core temperatures by taking electrical measurements off the "incore" thermocouple wires (pp. 30-31 of the Report). Based on what you know about thermocouples, explain exactly the steps these instrument technicians would have taken to obtain the temperature measurements.

According to the Report, what subsequent action(s) were taken following the instrument technicians' measurements?

Hint: the *Socratic Instrumentation* website contains a page where you may download public-domain textbooks, one of which is a set of steam tables published in 1920.
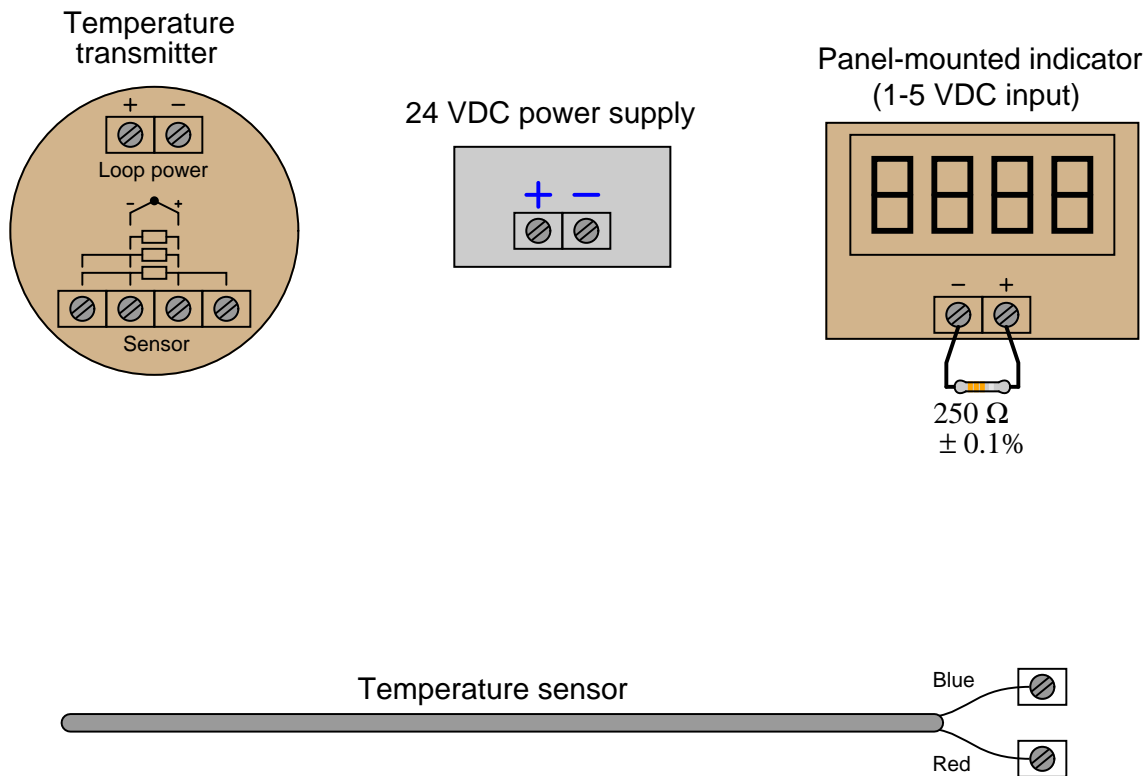

| **Suggestions for Socratic discussion** |

- Some of the millivoltage measurements taken of "incore thermocouples" by the technicians were "too low to be believable," and this is one of the reasons the high millivoltage measurements were dismissed. Based on what you know of thermocouples, is there any way a very hot thermocouple could produce unreasonably *small* millivoltage signals?
- Identify the ways in which heat is transferred from a nuclear reactor core to do useful work.
- Identify the point on a phase diagram for water where a pressurized-water reactor such as TMI is supposed to operate.
- An insightful paragraph from this report reads, *"Nuclear physics, as all science, is logical, and those instruments are speaking the truth to anyone logical enough to recognize it. Defeat awaits the individual who even subconsciously ascribes human qualitites like crankiness to functioning meters and thermocouples simply because they are bringing bad news. The answer in science is never to shoot the messenger."* (page 27). Discuss how you might very well encounter such attitudes on the job, and from whom these attitudes might come.
- On pages 42-43 of the report, it documents a "hydrogen burn" inside the concrete containment building, fueled by flammable hydrogen gas released by the overheated reactor through the stuck-open PORV. Explain how people were able to determine this was in fact a real explosion that occurred inside the building, and also identify what they assumed the instruments' readings meant when it first happened (i.e. not an explosion!).

file i03996

Question 22

Determine what type of temperature sensor is shown in this pictorial diagram, and then sketch wires showing how to correctly connect the sensor to the temperature transmitter:

Temperature
transmitter

+   −

Loop power

− +

Sensor

24 VDC power supply

+   −

Panel-mounted indicator
(1-5 VDC input)

−   +

250 Ω
± 0.1%

Temperature sensor

Blue

Red

Note what types of metal each of the connecting wires should be (e.g. copper, chromel, alumel, constantan, iron, platinum, etc.).
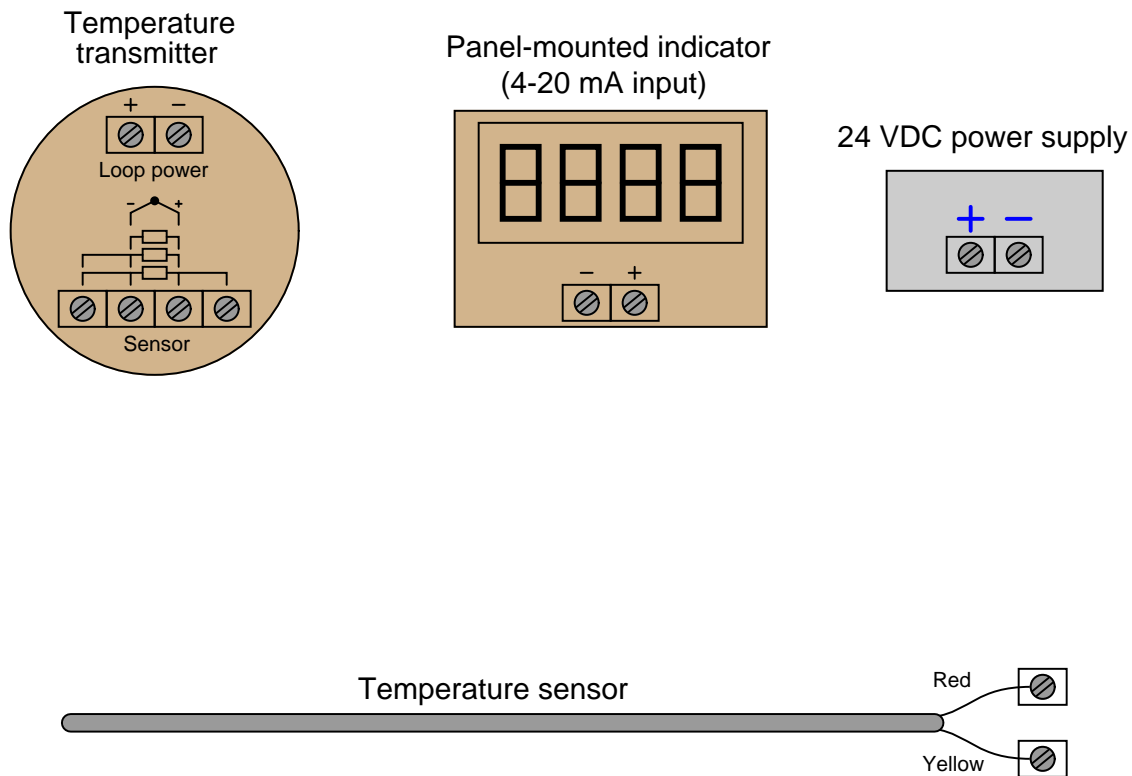
Suggestions for Socratic discussion

- A problem-solving technique useful for making proper connections in pictorial circuit diagrams is to first identify the directions of all DC currents entering and exiting component terminals, as well as the respective voltage polarity marks (+,−) for those terminals, based on your knowledge of each component acting either as an electrical *source* or an electrical *load*. Discuss and compare how these arrows and polarity marks simplify the task of properly connecting wires between components.
- Suppose the wire colors on the thermocouple were rubbed off, so you could not visually discern positive from negative. A tag on the thermocouple still tells you the type, though. Is there some other way we could determine thermocouple polarity?
- Suppose all labels and wire colors on the thermocouple were rubbed off, so you could not even tell what kind of sensor it was: thermocouple, RTD, or thermistor. Devise a simple test by which you could ascertain the identify of the temperature sensor.

file i03997

Question 23

Determine what type of temperature sensor is shown in this pictorial diagram, and then sketch wires showing how to correctly connect the sensor to the temperature transmitter:

Temperature
transmitter

+ −
Loop power

+

Sensor

Panel-mounted indicator
(4-20 mA input)

− +

24 VDC power supply

+ −

Temperature sensor

Red

Yellow

Note what types of metal each of the connecting wires should be (e.g. copper, chromel, alumel, constantan, iron, platinum, etc.).
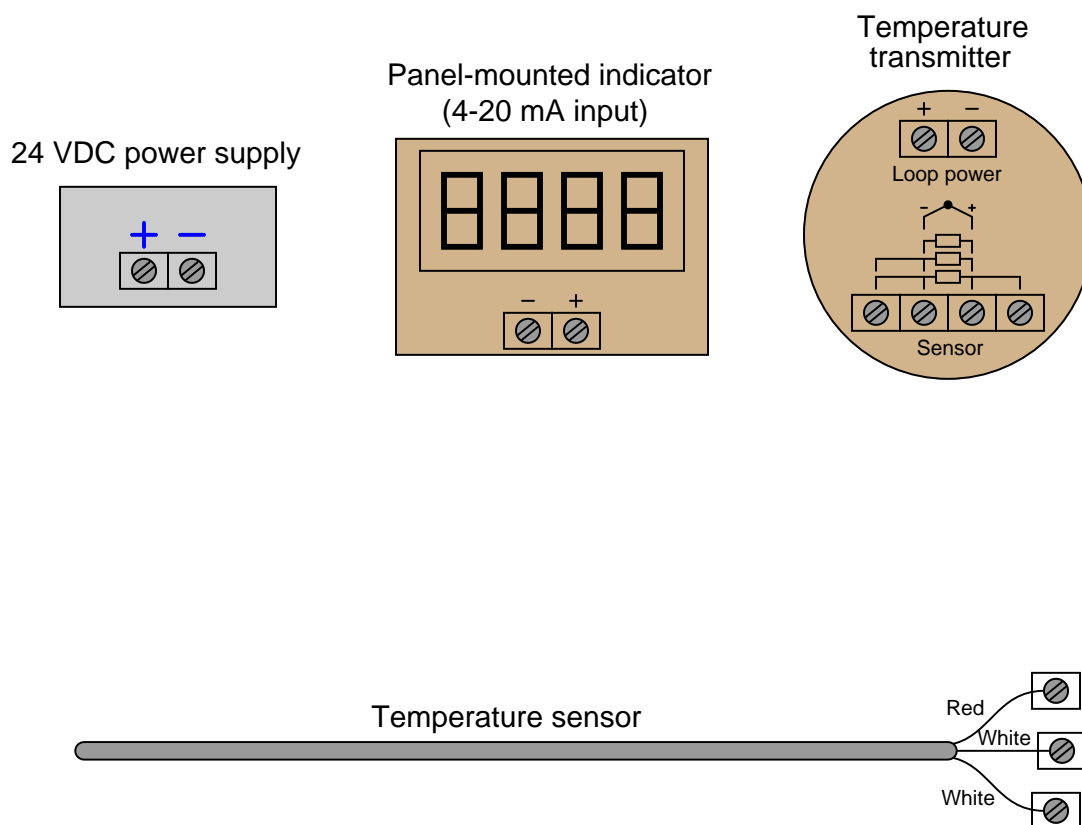
Suggestions for Socratic discussion

- A problem-solving technique useful for making proper connections in pictorial circuit diagrams is to first identify the directions of all DC currents entering and exiting component terminals, as well as the respective voltage polarity marks $(+,-)$ for those terminals, based on your knowledge of each component acting either as an electrical *source* or an electrical *load*. Discuss and compare how these arrows and polarity marks simplify the task of properly connecting wires between components.
- Explain why you used thermocouple-metal wires where you did, and why you used copper wires where you did.
- Suppose all labels and wire colors on the thermocouple were rubbed off, so you could not even tell what kind of sensor it was: thermocouple, RTD, or thermistor. Devise a simple test by which you could ascertain the identify of the temperature sensor.

file i03998

38

Question 24

Determine what type of temperature sensor is shown in this pictorial diagram, and then sketch wires showing how to correctly connect the sensor to the temperature transmitter:

Temperature transmitter

Panel-mounted indicator
(4-20 mA input)

24 VDC power supply

+   −

Loop power

+   −

Sensor

Temperature sensor

Red

White

White

Note what types of metal each of the connecting wires should be (e.g. copper, chromel, alumel, constantan, iron, platinum, etc.).
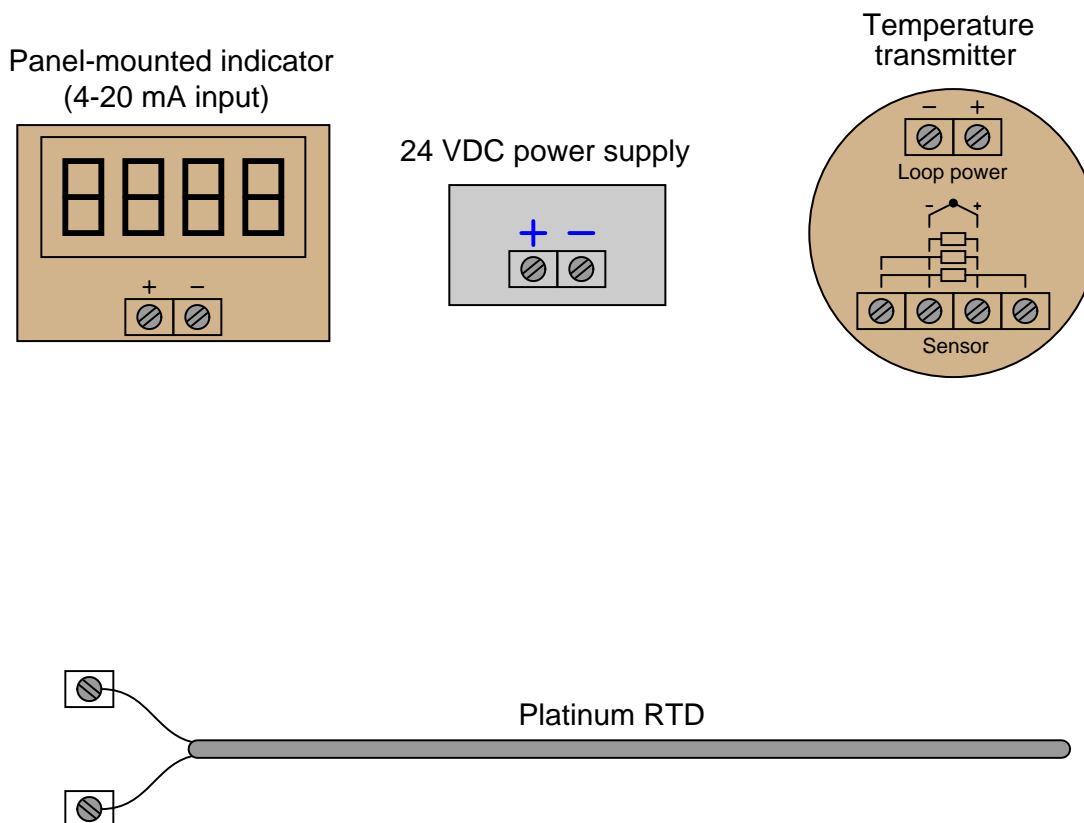
Suggestions for Socratic discussion

- A problem-solving technique useful for making proper connections in pictorial circuit diagrams is to first identify the directions of all DC currents entering and exiting component terminals, as well as the respective voltage polarity marks (+,−) for those terminals, based on your knowledge of each component acting either as an electrical *source* or an electrical *load*. Discuss and compare how these arrows and polarity marks simplify the task of properly connecting wires between components.
- Identify the possible result of connecting the DC loop power supply to the wrong + and − terminals on the temperature transmitter, explaining how we know this is bad for the circuit.
- Students very commonly mis-interpret the symbols drawn next to the input terminals of an RTD transmitter, especially the terminals which must be made common to each other at the sensor. One of the most popular misconceptions is to think that those terminals shown common to each other by the symbol are already joined together *inside the transmitter*. Explain why this interpretation cannot be true, based on how you know 3-wire and 4-wire RTD circuits are designed to work.

file i03999

Question 25

The sensor in this diagram is a platinum RTD. Sketch wires showing how to correctly connect this RTD sensor to the temperature transmitter so that the wire resistance is canceled and will produce absolutely no measurement error:

Panel-mounted indicator
(4-20 mA input)

24 VDC power supply

Temperature
transmitter

Platinum RTD

Note what types of metal each of the connecting wires should be (e.g. copper, chromel, alumel, constantan, iron, platinum, etc.).


Suggestions for Socratic discussion

- A problem-solving technique useful for making proper connections in pictorial circuit diagrams is to first identify the directions of all DC currents entering and exiting component terminals, as well as the respective voltage polarity marks $(+,-)$ for those terminals, based on your knowledge of each component acting either as an electrical *source* or an electrical *load*. Discuss and compare how these arrows and polarity marks simplify the task of properly connecting wires between components.
- Explain how and why the presence of *four* wires eliminates wire resistance errors.
- If we were connecting a "decade box" precision resistance to the transmitter for the purposes of simulating an RTD at temperature, would we still need to use four wires, or could we get away with using only two wires?
- Suppose all labels and wire colors on the RTD were rubbed off, so you could not even tell what kind of sensor it was: thermocouple, RTD, or thermistor. Devise a simple test by which you could ascertain the identify of the temperature sensor.

file i04000

Question 26

Suppose a precision voltage source ("precision potentiometer") is used to simulate a thermocouple signal into a temperature transmitter as such:
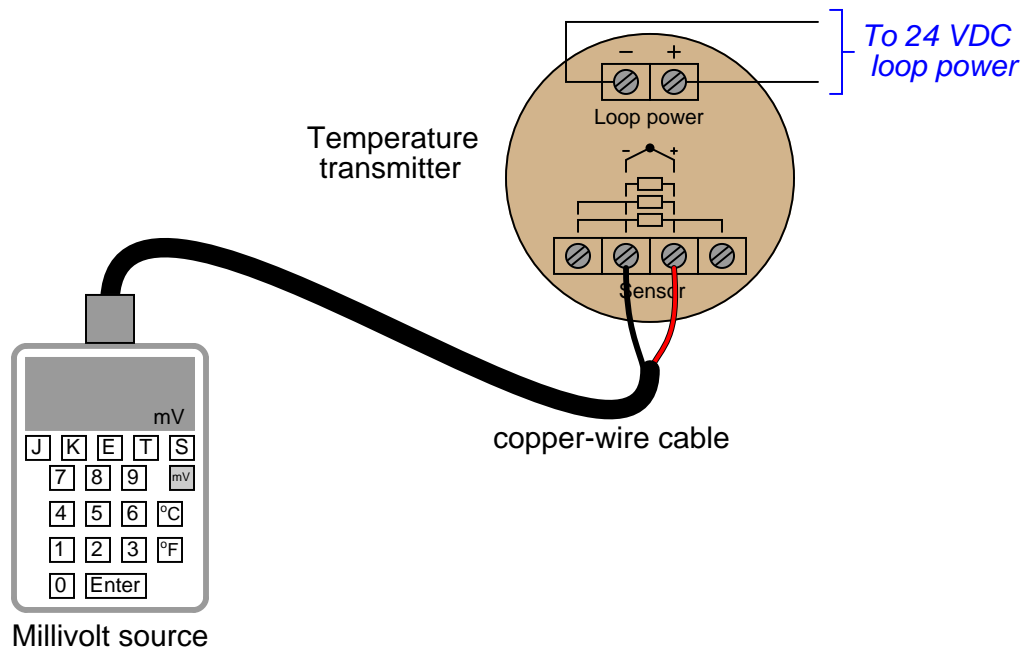
Calculate the amount of voltage this precision source would have to output in order to simulate the following thermocouple temperatures:

- Simulate 112 ^{o}F ; source voltage = _____

- Simulate 727 ^{o}F ; source voltage = _____

- Simulate 1380 ^{o}F ; source voltage = _____

Assume an ambient temperature near the transmitter of 75 ^{o}F, and a type K configuration with reference junction compensation active.

Examine the keypad of the calibration instrument being used here, and determine how this three-point calibration could be done much easier than looking up millivoltage values in thermocouple tables.
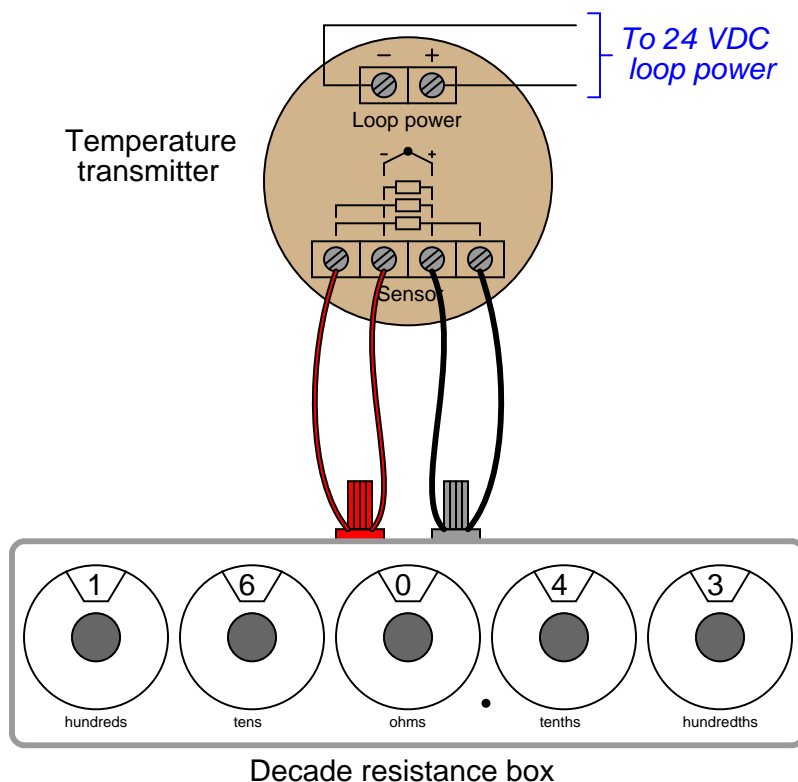
Suggestions for Socratic discussion

- Explain the relevance of compensation being "active" in the transmitter. How would our calibration differ if the compensation were turned off?
- What would happen if one of the wires inside the copper cable broke open during the calibration?
- How would the calibration procedure differ if type "KX" extension wires were used to connect the calibrator to the transmitter rather than copper wires?
- Does the *burnout mode* of a thermocouple transmitter matter during a calibration such as this?

file i04001

Question 27

Suppose a *decade box* resistance unit is used to simulate an RTD signal into a temperature transmitter as such:

To 24 VDC
loop power

− +

Loop power

Temperature
transmitter

Sensor

1 6 0 4 3

hundreds   tens   ohms   tenths   hundredths

Decade resistance box

Calculate the amount of resistance this decade box would have to be set to in order to simulate the following RTD temperatures:

- Simulate 84 ^{o}F ; resistance = _____

- Simulate 195 ^{o}F ; resistance = _____

- Simulate 357 ^{o}F ; resistance = _____

Assume a 100 ohm platinum ($\alpha = 0.00385$ Ω/Ω^oC) RTD configuration for the transmitter.

Suggestions for Socratic discussion

- Explain why *four* wires are being used here for this RTD transmitter calibration.
- If you consult a *table* for resistance values of a 100 ohm platinum RTD with an alpha value of 0.00385, you will find the numbers slightly disagree with those predicted by the equation. Explain why.
- Students very commonly mis-interpret the symbols drawn next to the input terminals of an RTD transmitter, especially the terminals which must be made common to each other at the sensor. One of the most popular misconceptions is to think that those terminals shown common to each other by the symbol are already joined together *inside the transmitter*. Explain why this interpretation cannot be true, based on how you know 3-wire and 4-wire RTD circuits are designed to work.

file i04002

Question 28

Suppose you walk up to this thermocouple, installed to measure the temperature of an enclosed process vessel, and connect a sensitive voltmeter to the terminals at the junction head:
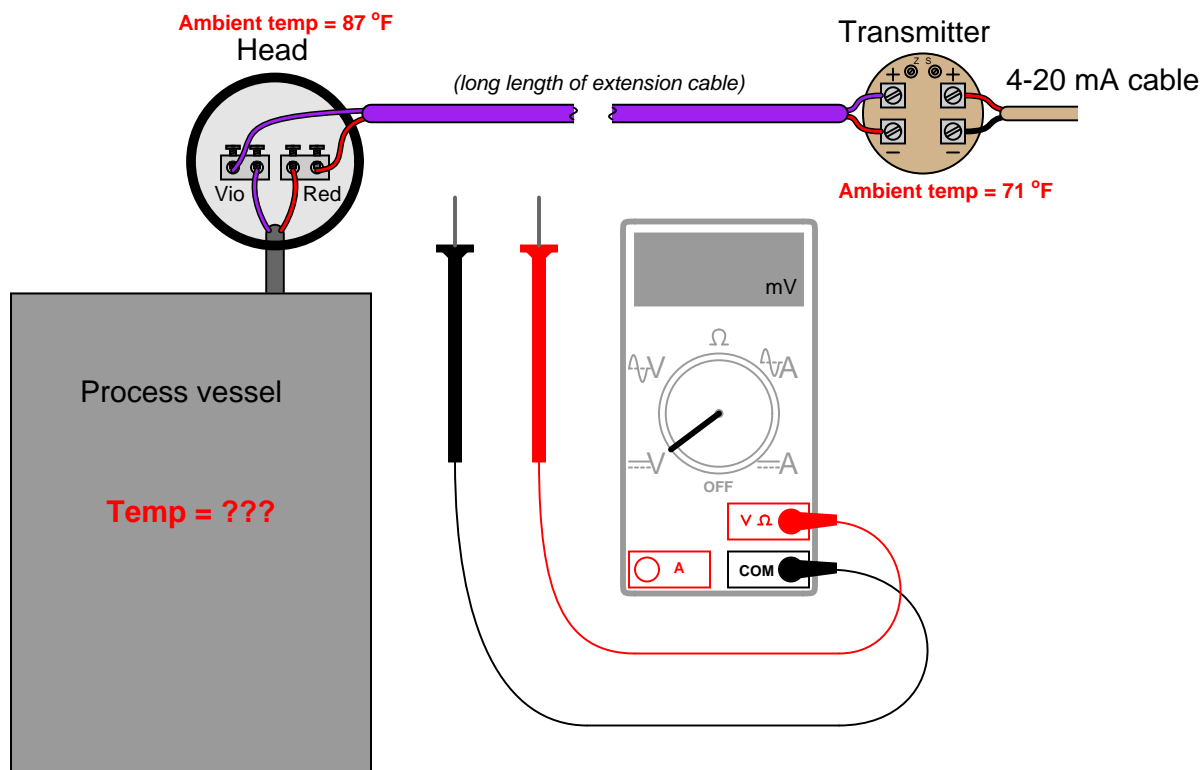
First, determine which lead of the voltmeter should contact which lead of the thermocouple (red to red?), then determine the temperature of the process vessel if the measured voltage is 15.830 mV.

Suggestions for Socratic discussion

- Will the transmitter's measurement of temperature be affected when the voltmeter probes touch the thermocouple leads? In other words, will this influence the temperature measurement for an operator (or an automatic controller) during your test?
- Suppose the technician touches the multimeter probe tips to the thermocouple wires directly, rather than to the copper terminals inside the junction head. Will this make any difference in the measurement? Explain why or why not.
- Suppose the technician mistakenly sets the multimeter up to measure *current* instead of voltage. Will this affect the transmitter's measurement of temperature when the meter probes touch the thermocouple leads?

file i04003

Question 29

Read the report "Improving Thermocouple Service Life in Slagging Gasifiers" written by James Bennett of the US Department of Energy (DOE) Albany Research Center (document DOE/ARC-2005-043), and answer the following questions:

What exactly does a *gasifier* do? What "feedstocks" does it input, and what products does it output? How do these facts make gasification a technology of interest for future energy production?

Identify the typical pressures and temperatures encountered in the interior of a slagging gasifier. Express these pressure and temperature ranges in *bar* and ${}^oF$, respectively.

What type of thermocouple has traditionally been applied to this service? Explain why this choice is more appropriate than some other thermocouple types.

How long have thermocouples typically lasted in this type of severe service, and how much does each one cost to replace?

One of the alternative temperature-measurement technologies cited in this report is the use of sapphire process probes with fiber-optic cables to conduct light to a remote location where it may be sensed. Explain how this novel temperature-measurement technology works, based on the description alone (and/or your own independent research on the topic).

An interesting style of thermocouple experimented with for gasifier applications is the so-called *open thermocouple*. Explain how this sensing device is constructed, and how it differs from a regular thermocouple.

Identify some of the specific modes of thermocouple failure (i.e. how exactly is it that they are failing?).

Explain how "bridging" inside a gasifier may lead to incorrect thermocouple EMFs (millivolt signals).


Suggestions for Socratic discussion

- Examine the graph of thermocouple readings over a 3-hour test period as shown in figure 10. Which slag thermocouple performed better as the sample warmed up? Which slag thermocouple performed better after the sample had reached 880 ${}^oC$?
- Explain how "syngas analysis" may be alternatively used to infer temperatures inside the gasifier, and why this technique is not suitable for all phases of gasifier operation.
- Explain chemical interactions between thermocouple wires and compounds inside the gasifier can lead to measurement errors, even before complete failure of the thermocouple.
- Explain what it means to *sequester* carbon dioxide gas from a process, and why this is important from the perspective of environmental impact.
- Under what operating conditions may a gasifier be *carbon-neutral* (i.e. no net release of carbon dioxide gas to the atmosphere)?
- Under what operating conditions may a gasifier be *carbon-negative* (i.e. it removes more carbon dioxide gas from the atmosphere than it releases)?
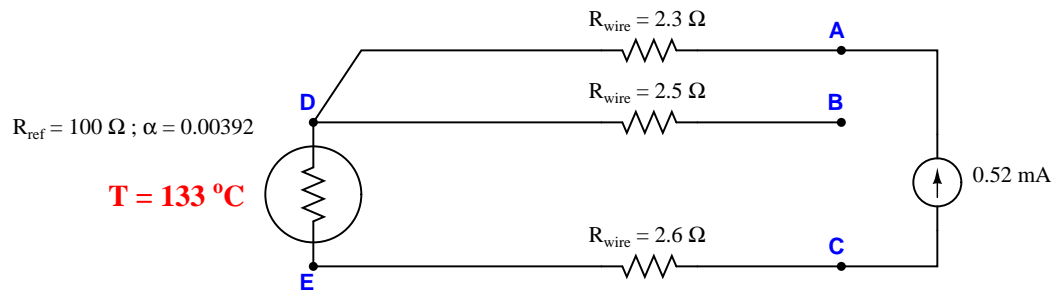
file i02484

44

Question 30

Calculate V_{BC} and V_{FG} in this two-wire RTD circuit:
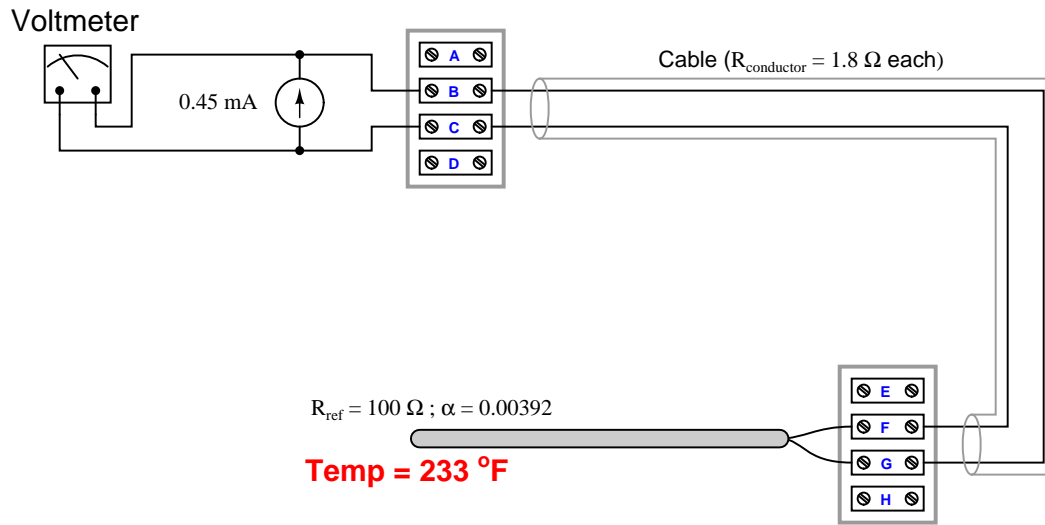
Question 31

Calculate V_{AC} and V_{BC} in this three-wire RTD circuit:

Question 32

Given the choice between these two wiring options (keeping the transmitter close to the process versus far away), which is best, and why?
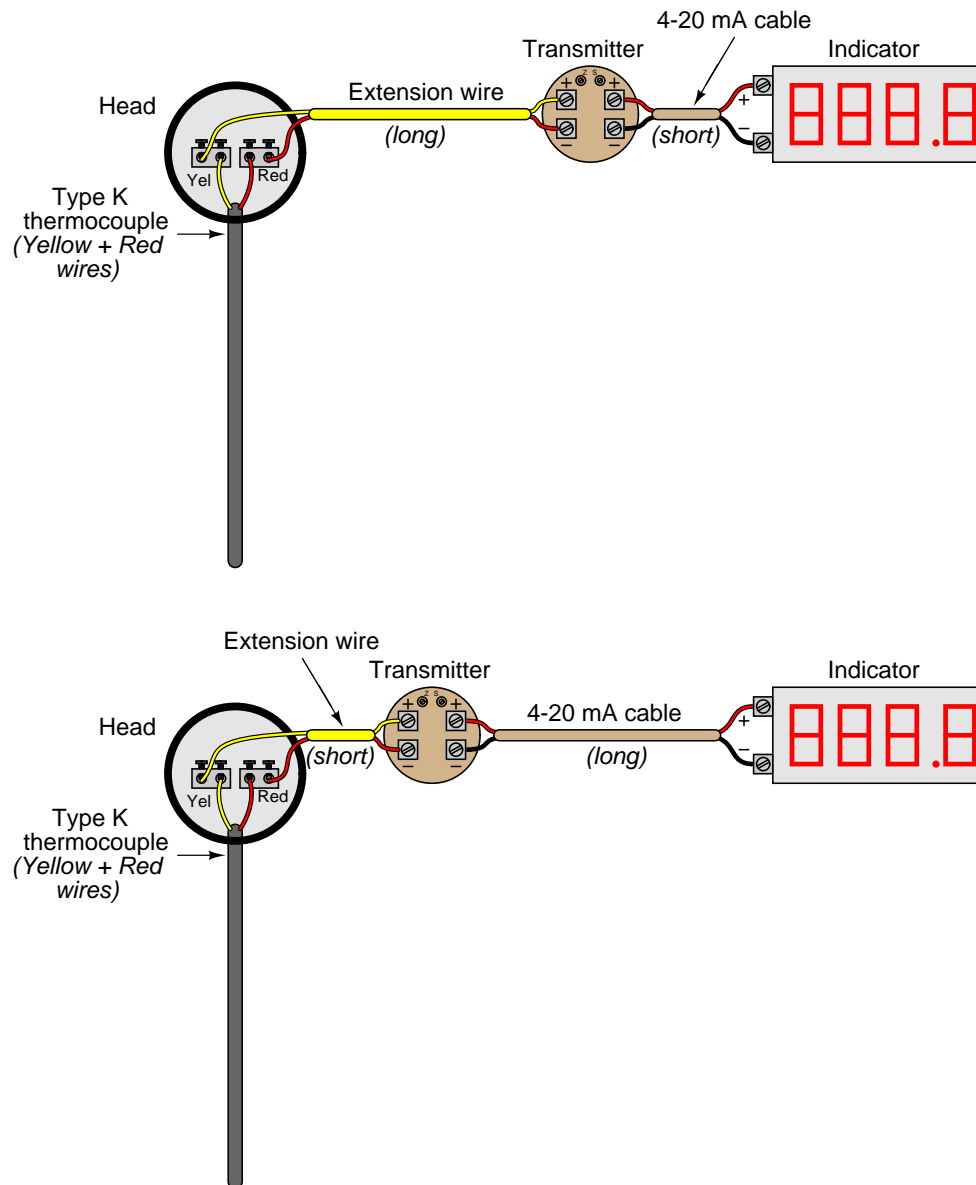
Suggestions for Socratic discussion

- If the longer wire in each case were *shielded*, how should we ground the shield for best results?
- How could we use a *loop calibrator* to "trick" the indicator into thinking the thermocouple was at some particular temperature when in fact it was not?

file i00392

46

Calculate V_{BC}, V_{EH}, and V_{FG} in this four-wire RTD circuit:

T$_{ambient}$ = 73 ^{o}F

0.7 mA

A Blk
B Brn
C Red
D Org

R$_{wire}$ = 1.34 Ω
(each conductor)

Blk   E Red
Brn   F Red
       G Wht
Red
Org   H Wht

100 Ω RTD, α = 0.00385

Temp = 473 ^{o}F
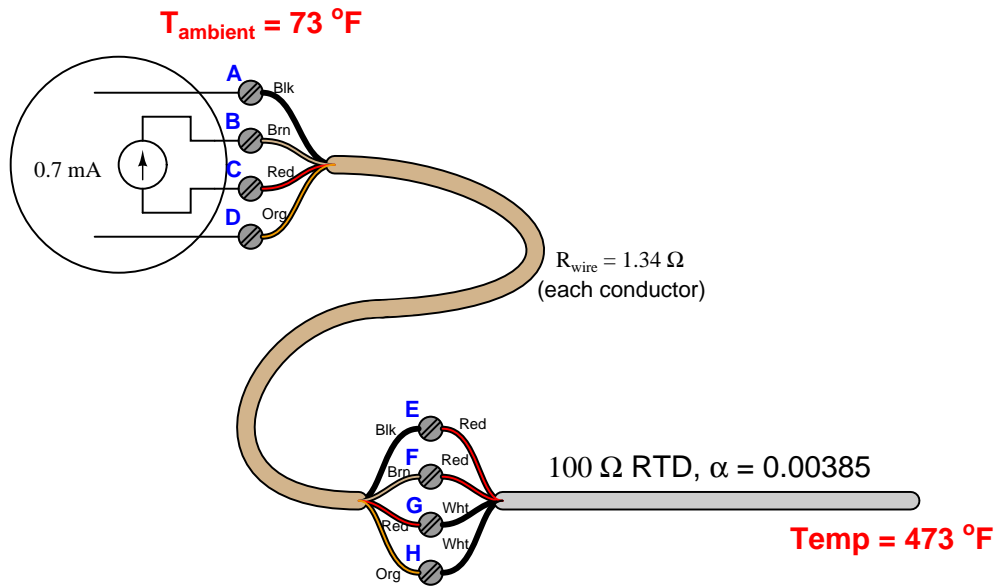
file i02315

Question 34

An RTD measures the temperature of saturated steam at the steam drum of a boiler:
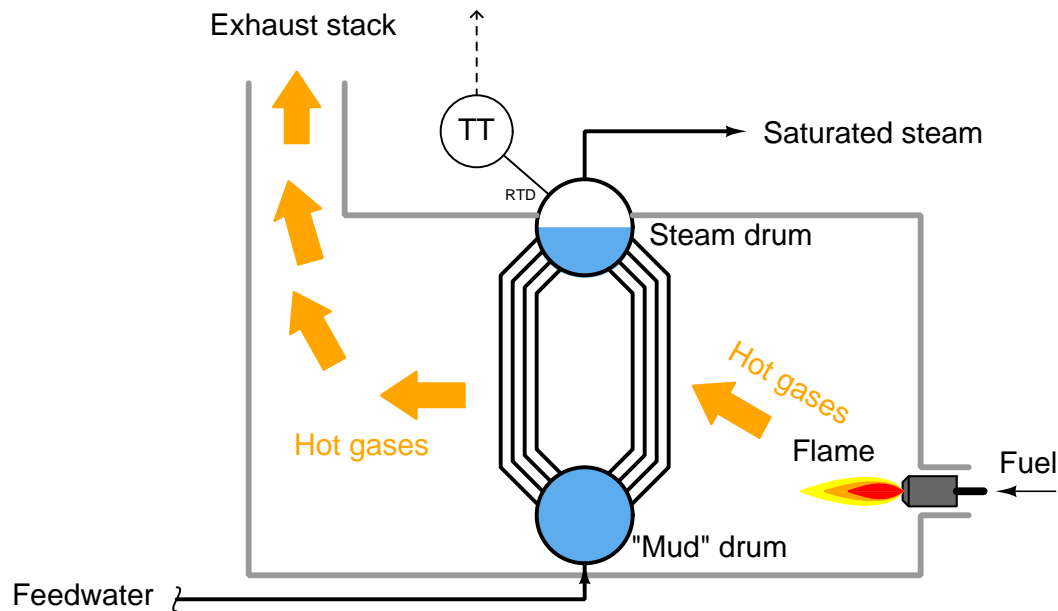
The RTD connects to a bridge circuit via three wires, to register temperature at a sensitive voltmeter mechanism in the control room:
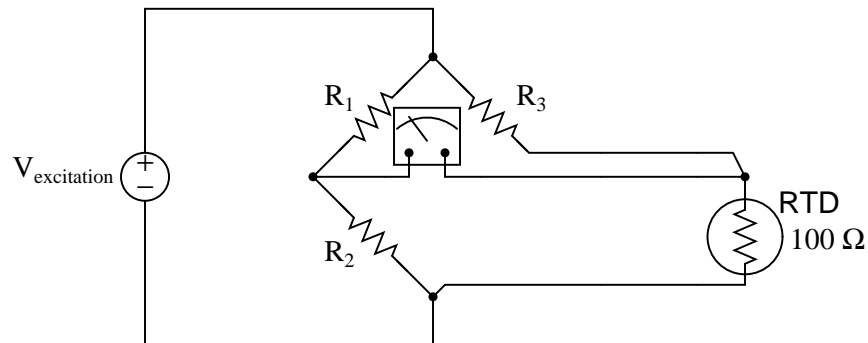
Suppose the boiler operator decides to increase the pressure of the boiler over a period of time. Identify the effects this pressure change will have on these voltage drops in the RTD circuit:

- V_{R1} will *increase*, *decrease*, or *stay the same*?
- V_{R2} will *increase*, *decrease*, or *stay the same*?
- V_{R3} will *increase*, *decrease*, or *stay the same*?
- V_{RTD} will *increase*, *decrease*, or *stay the same*?
- Explain the relationship between boiler pressure and boiler temperature:

file i04252

Question 35

Calculate the following voltage drops in this circuit assuming a thermocouple tip temperature of 718° F, perfect calibration of all other instruments in the loop (Temp. range = 500 to 1000° F; current range = 4 to 20 mA), and a DC power supply voltage of exactly 28 volts:
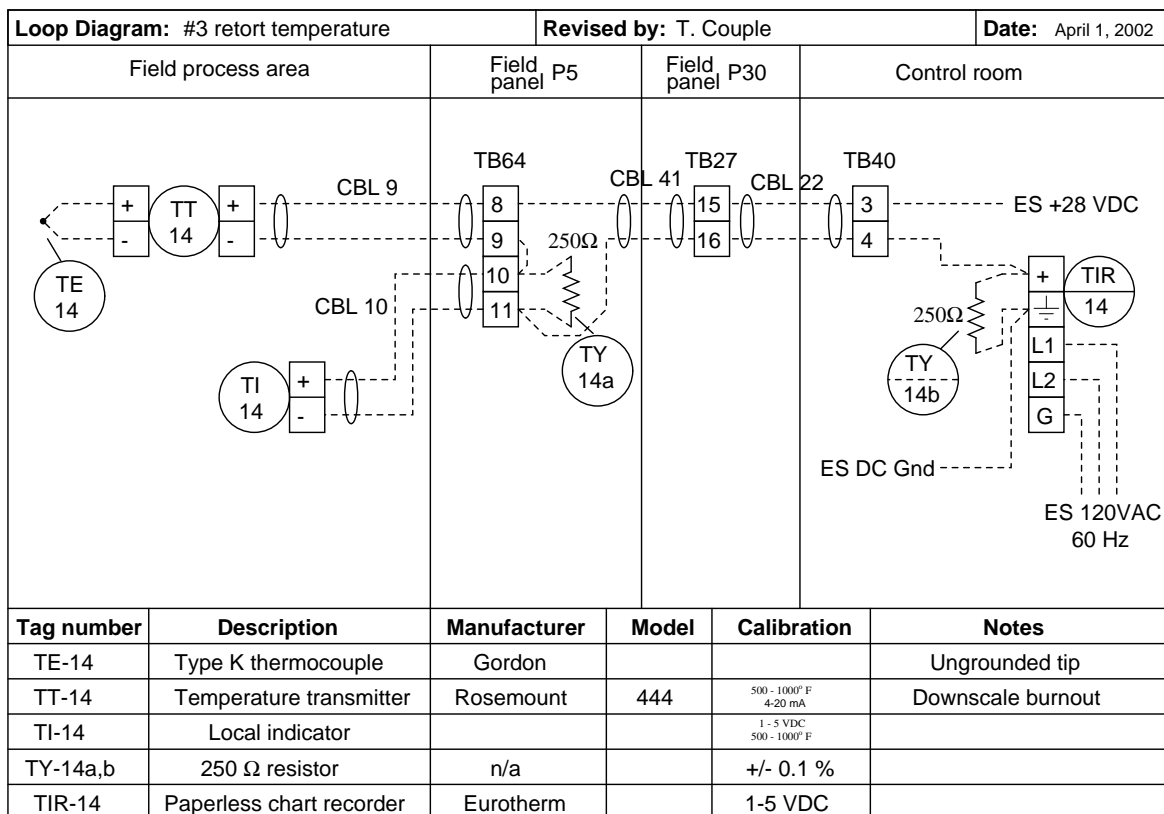

| Loop Diagram: #3 retort temperature | | | | Revised by: T. Couple | | Date: April 1, 2002 |

Tag number	Description	Manufacturer	Model	Calibration	Notes
TE-14	Type K thermocouple	Gordon			Ungrounded tip
TT-14	Temperature transmitter	Rosemount	444	500 - 1000º F / 4-20 mA	Downscale burnout
TI-14	Local indicator			1 - 5 VDC / 500 - 1000º F	
TY-14a,b	250 Ω resistor	n/a		+/- 0.1 %	
TIR-14	Paperless chart recorder	Eurotherm		1-5 VDC	

- Voltage between terminals TB64-8 and TB64-9 =

- Voltage between terminals TB64-10 and TB64-11 =

- Voltage between terminals TB27-15 and TB27-16 =

Also, determine where you could connect a *loop calibrator* device to substitute for the transmitter, and what mode the calibrator should be set to in order to control the loop current.

Suggestions for Socratic discussion

- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.
- Discuss the options we have for thermocouple tip styles, and how this particular thermocouple's tip characteristics compare with others.
- Explain what "downscale burnout" means and why this transmitter configuration might be significant.
- What exactly is a "paperless" chart recorder?
- What would happen in this system if the local indicator (TI-14) were to electrically fail open?

file i00393

Question 36

In this system, an Allen-Bradley SLC 500 PLC acts as a temperature controller, turning a cooling water solenoid valve on and off to modulate water flow to the heat-exchange jacket of a chemical reactor vessel. A thermocouple monitors the temperature of the fluids within the vessel. This diagram shows only the electrical connections (no piping, no other components represented) for simplicity:
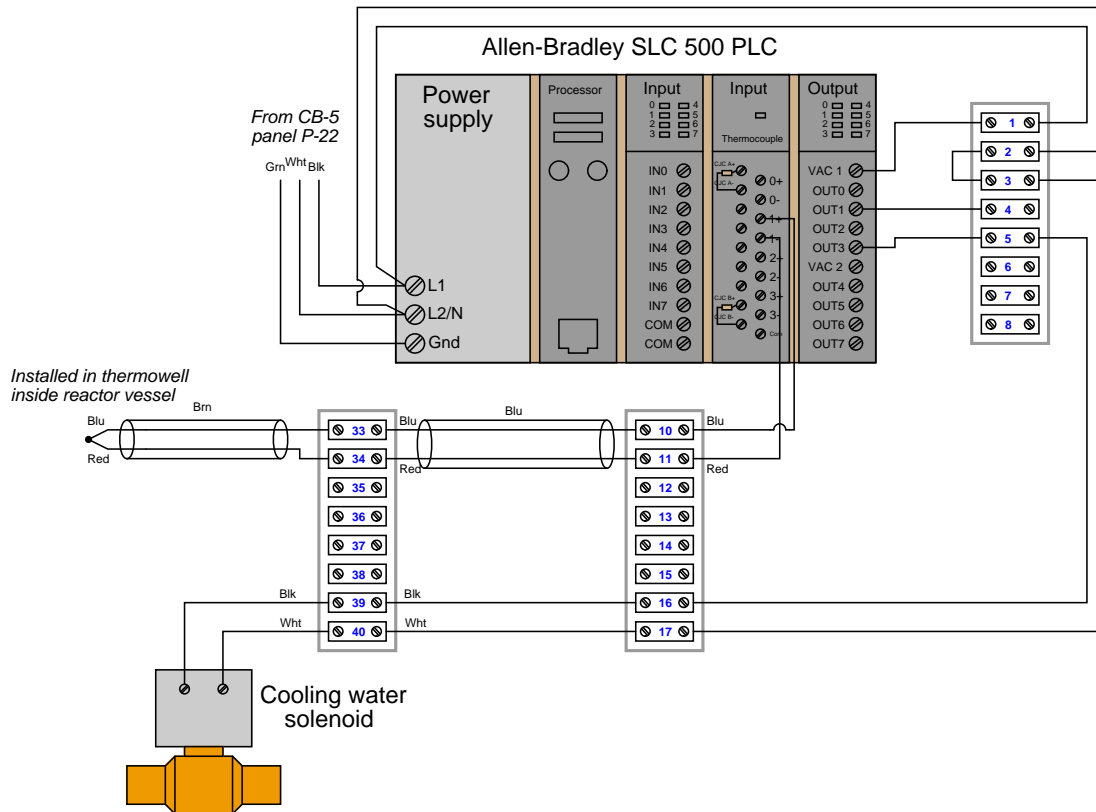
One day the operator of this reactor contacts you to say the reactor is overheating, based on the indication of a temperature gauge installed in the reactor near the PLC's thermocouple. The reactor temperature high/low setpoint values programmed in the PLC are 85 deg C and 80 deg C, respectively. The temperature gauge is registering 91 deg C and slowly climbing.

Identify some likely faults that could cause this situation to occur, and also identify what tests you would begin to conduct in order to diagnose the problem.

file i03112

50

Question 37

In this circuit, a type of temperature sensor called an *RTD* is used to generate a DC voltage signal that is read by a Programmable Logic Controller (PLC) – a specialized type of computer built to acquire and process information from industrial sensors – to be displayed on a graphic screen called a Human-Machine Interface (HMI):
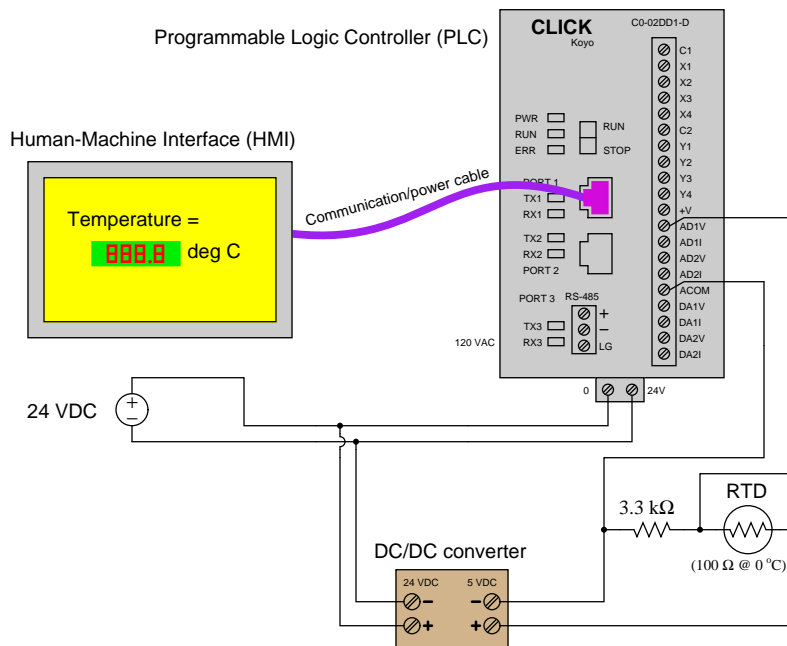
The electrical resistance of this RTD changes with temperature according to the following formula, with R being the RTD's resistance in ohms and T being the RTD's temperature in degrees Celsius:

$$R = 1000(1 + 0.00385T)$$

The analog input module of the PLC senses the voltage dropped across the 3.3 kΩ resistor, converting this signal into a digital number inside the PLC's memory directly representing volts DC. However, no human operator looking at the HMI display will know what "DC volts" is supposed to mean – he or she needs to see a display in units of *degrees Celsius*, not *volts*.

Fortunately, PLCs are *programmable*. That is, you as a technician can enter a mathematical formula into the memory of the PLC to convert the voltage value into a temperature value (in degrees C). Your task is to take the RTD formula shown above, combine it with the voltage divider formula you know from your studies of DC circuits, and write a custom formula for this application solving for T in terms of V:

$$T =$$

Suggestions for Socratic discussion

- A useful technique for double-checking your answer is to *work the problem backwards:* begin with your answer, working the problem in reverse to see if you arrive at the original (given) values. Explain how to apply this technique to double-checking your answer on this particular problem.
- Identify which fundamental principles of science, technology, and/or math apply to each step of your solution to this problem. In other words, be prepared to explain the reason(s) "why" for every step of your solution, rather than merely describing those steps.
- As the RTD temperature rises, does the voltage signal input to the PLC *increase* or *decrease*?

Question 38

An automotive performance shop is testing an engine they just built for a race car. The engine is removed from the car, attached to a dynamometer for measuring its horsepower and other performance parameters. For temperature measurement, a type K thermocouple has been attached to the metal block of the engine, thermocouple wires run all the way back to the control room where mechanics operate the dynamometer, and and a voltmeter connected to those thermocouple wires inside the control room (which happens to be at a temperature of 58 degrees F).

Before the engine is started up, the voltmeter reads 0.0 millivolts. The mechanics start up the engine, run it for several seconds, and then shut it down because they realized they forgot to hook up some other sensor for their main test. In that short run time, the voltmeter's indication increased to 0.089 millivolts.

How hot did the engine get in that short period of time?

Assuming the engine is made of 300 pounds of iron, and filled with 2.5 gallons of water (in the cooling system), how much heat did the engine absorb within its own mass during those few seconds of run time?
file i00971

Question 39

DANGER! *The following question will probably shatter your fundamental conceptions about how thermocouples work! If you find the topic confusing enough already, please turn the page and skip past this question!!*

Everything you thought you knew about thermocouples is wrong. Well, maybe not *everything*, but just the fundamental principle upon which they operate. In school you probably learned that the Seebeck effect depends on a junction of dissimilar substances, usually two different metals or metal alloys.

Wrong.

In point of fact, the Seebeck effect exists along the length of any *one* substance that is differentially heated. Take this length of copper wire for example, with one end held at the freezing point of water and the other end held at the boiling point of water:

Cold end   Copper wire   Hot end

0° F 212° F

                          − +
Seebeck voltage

The Seebeck coefficient (σ) is equal to the derivative of voltage (V) with respect to temperature (T):

$$\sigma = \lim_{\Delta T \to 0} \frac{\Delta V}{\Delta T}$$

$$\sigma = \frac{dV}{dT}$$

Different substances have different Seebeck coefficients. The following table shows several common examples:

Substance	σ @ 0° C	σ @ 100° C
Copper	1.72 μV / ^{o}C	2.23 μV / ^{o}C
Silver	1.42 μV / ^{o}C	1.84 μV / ^{o}C
Gold	2.3 μV / ^{o}C	2.0 μV / ^{o}C
Tungsten	1.9 μV / ^{o}C	6.7 μV / ^{o}C
Nickel	-7.0 μV / ^{o}C	-12.4 μV / ^{o}C
Kovar	0.20 μV / ^{o}C	0.19 μV / ^{o}C
Silicon	-408 μV / ^{o}C	-455 μV / ^{o}C

However, it is impossible to measure this voltage by connecting a real voltmeter across the ends of this copper wire. Explain why. Furthermore, explain how a *junction* of dissimilar materials may produce a thermal voltage that is easily measured.

file i02977

Question 40

Identify the problem(s) with this temperature measurement circuit:
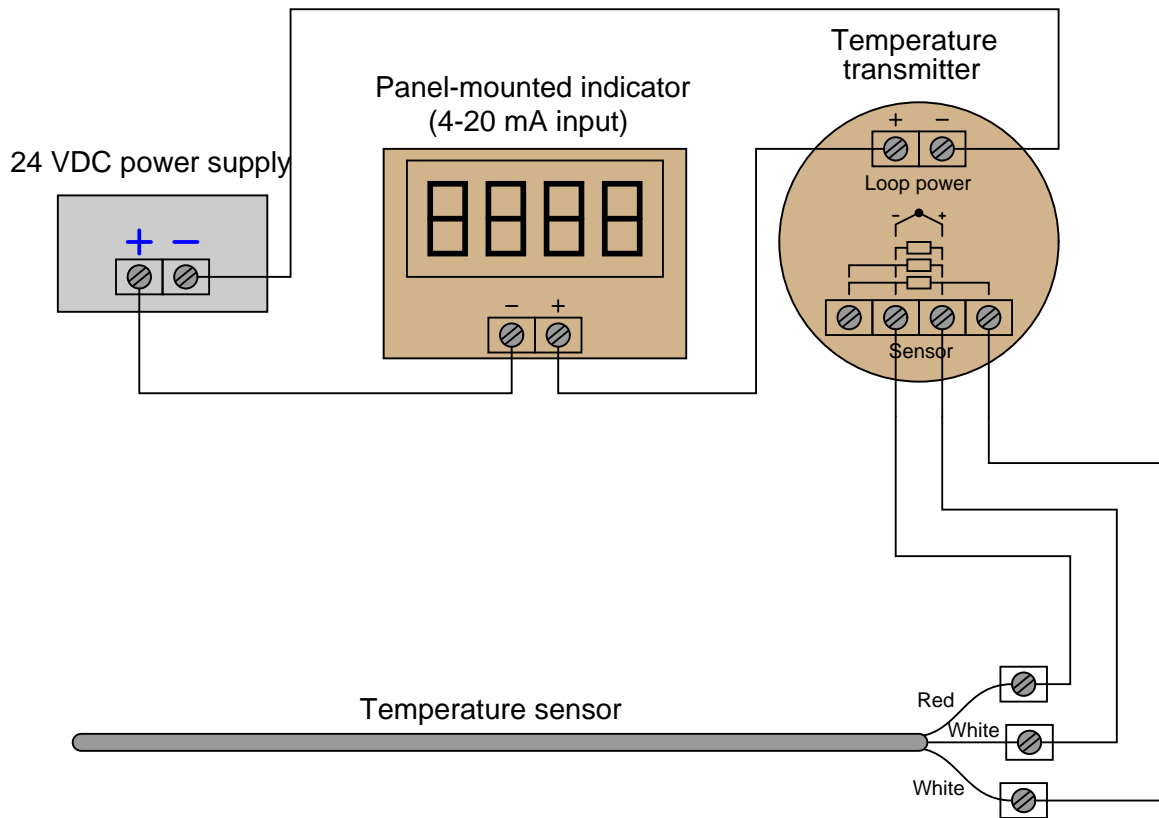
Question 41

Read and outline the "Non-Contact Temperature Sensors" section of the "Continuous Temperature Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- Acknowledgement of previously learned concepts
- Descriptions of problem-solving strategies applied by the author

file i04017

Question 42

Read and outline the "Temperature Switches" section of the "Discrete Process Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

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- Acknowledgement of previously learned concepts
- Descriptions of problem-solving strategies applied by the author

file i04004

Question 43

Explain what the following "ladder-logic" circuit does, and identify the meaning of each symbol in the diagram:
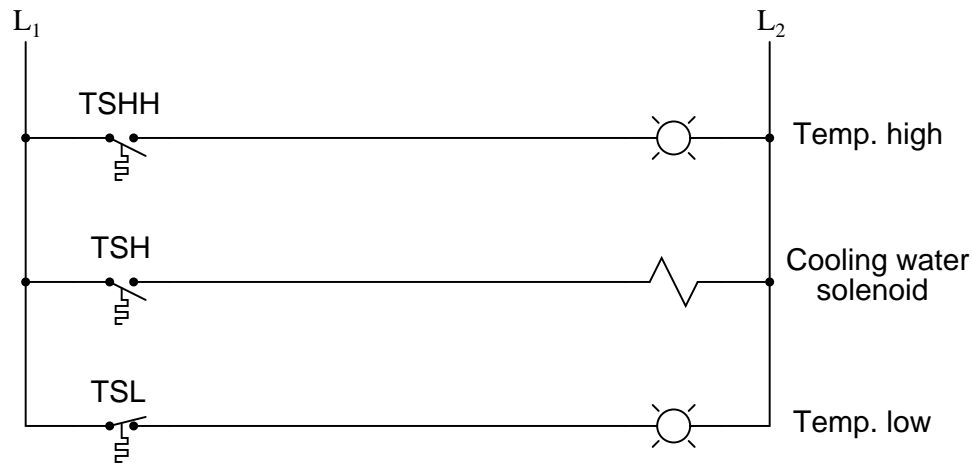
- Explain why the TSH uses a *normally-open* contact instead of a *normally-closed* contact.
- Explain why the TSL uses a *normally-closed* contact instead of a *normally-open* contact.
- Based on what we see in this diagram, determine whether the electric solenoid valve allows cooling water to flow when energized, or when de-energized.
- What do the designations "L1" and "L2" refer to in ladder-logic electrical diagrams?
- Suppose switch TSL has a trip setting of 105 ^{o}F (falling) and a deadband value of 2 ^{o}F. Explain how this switch will respond to a rising and falling temperature.
- Suppose we wished to have switch TSHH activate *two* different alarm lights instead of just one. Modify the circuit diagram accordingly.

file i00364

Question 44

The "Site Programmable Transmitter" (model SPT) manufactured by Moore Industries is an electronic device capable of receiving input from an RTD or thermocouple, and outputting a discrete switch contact signal useful as an alarm (in addition to outputting an analog 4-20 mA signal representing temperature measurement):
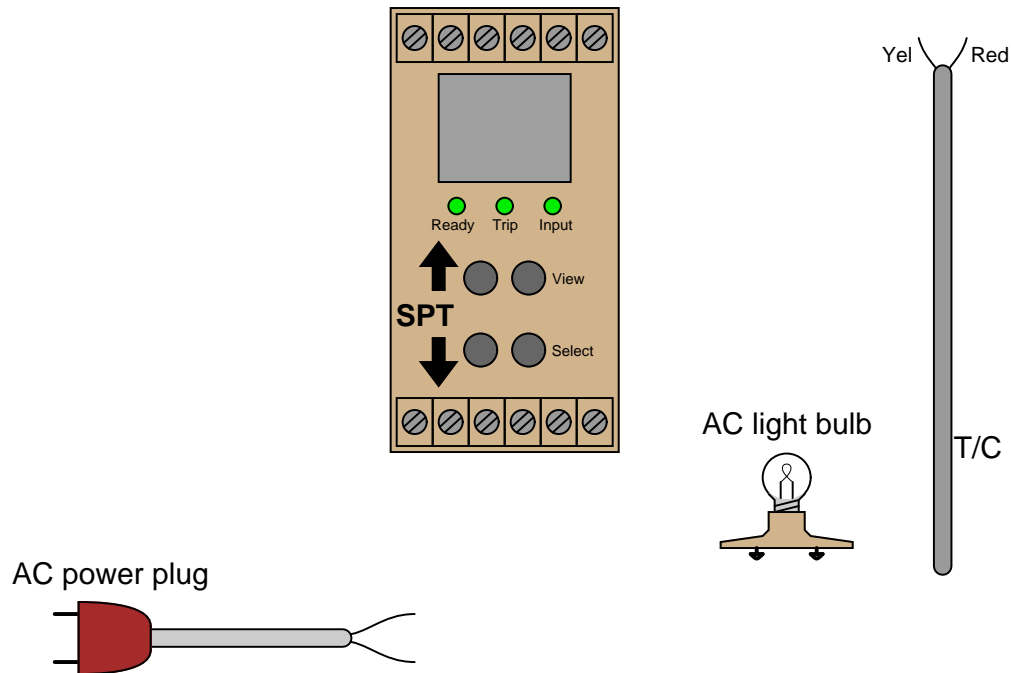
Based on analysis of this instrument's datasheet, sketch the necessary wire connections so that the light bulb will turn on when a certain temperature limit is exceeded. Also, determine what type of thermocouple is shown in the diagram.

<div style="border:1px solid; display:inline-block; padding:2px 6px;">Suggestions for Socratic discussion</div>

- Where is it appropriate to use copper wires in this circuit, and where should we use thermocouple or thermocouple extension wire?
- A cheaper alternative to the "SPT" is a simple temperature switch, such as the type directly actuated by a bi-metal spring. Justify the extra expense and complexity of an SPT unit, in terms of what it can do that a simple temperature switch cannot.

file i04009

Question 45

Read and outline the "Temperature Standards" subsection of the "Practical Calibration Standards" section of the "Instrument Calibration" chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

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- Images copied from the text (or sketched by you) to illustrate concepts
- Acknowledgement of previously learned concepts
- Descriptions of problem-solving strategies applied by the author

file i04006

Question 46

Read and outline the "Temperature Sensor Accessories" section of the "Continuous Temperature Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- Acknowledgement of previously learned concepts
- Descriptions of problem-solving strategies applied by the author

file i04007

Question 47

Read portions of the Rosemount datasheet for high-temperature thermocouple assemblies (document 00813-0401-2654) and answer the following questions:

Identify some of the different materials used in the construction of "protective tubes" (thermowells) offered by Rosemount for high-temperature measurement applications.

Ceramic thermowells may be damaged by a phenomenon called *thermal shock*. Explain what "thermal shock" is, how it may occur during thermocouple installation, and what precaution(s) to take to avoid this.

What are some of the factors to consider when selecting a thermowell material for a particular process application?

Explain what a *multipoint gradient* thermocouple assembly is, and what one might be used for.

Explain what *limit tolerance class* refers to, according to the DIN EN 60584-2 standard. Which class has a tighter tolerance, Class 1 or Class 2?

Suggestions for Socratic discussion

- Why should thermowells in high-temperature applications be inserted *vertically* rather than *horizontally* whenever possible?
- A section on page 6 of this document explains why type B thermocouples (where both wires are a platinum-rhodium alloy) tend to be more stable over time than type S or R thermocouples which both use pure platinum for one of their wires. Re-phrase this explanation in your own words, articulating why type B thermocouples are more stable than types R and S.

file i04010

In this process, steam heat is supposed to maintain the temperature of solvent in the tank at 105 ^{o}F:
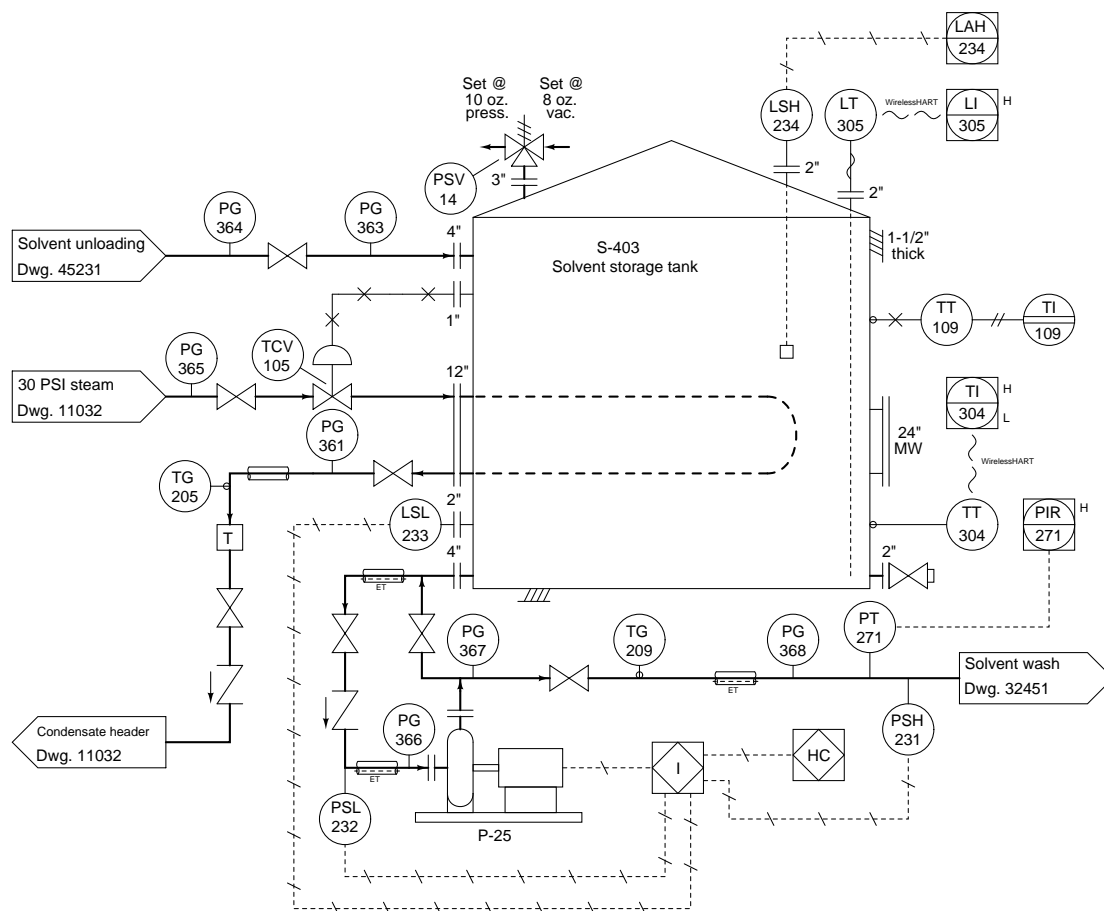
Suppose the steam pressure indicated by PG-365 is 30 PSIG, and we know that this steam is saturated (i.e. it's right at the boiling/condensing temperature for that pressure). Condensate (water) exits the heating loop at 145 ^{o}F as indicated by TG-205. PG-361 shows the condensate line to be at atmospheric pressure (0 PSIG).

Assuming a steam flow rate of 15 pounds per hour, calculate the approximate amount of time required to heat a new batch of solvent from ambient temperature (50 ^{o}F) up to 105 ^{o}F, if the stored volume of solvent is 4300 gallons, and the solvent happens to have a density of 57 lb/ft^3 and a specific heat of 0.73. Feel free to neglect details such as heat loss through the insulation of the tank wall, and simply treat this as a heat input / temperature rise thermodynamics problem.

file i00973

Question 49

The Stefan-Boltzmann Law of radiated energy tells us that the rate of heat lost by radiant emission from a hot object is proportional to the fourth power of the absolute temperature:

$$\frac{dQ}{dt} = e\sigma A T^4$$

Where,
$\frac{dQ}{dt}$ = Radiant heat loss rate, in watts (W)
e = Emissivity factor, unitless
σ = Stefan-Boltzmann constant (5.67×10^{-8} W / m^2 · K^4)
A = Surface area, in square meters (m^2)
T = Absolute temperature, Kelvin (K)

Algebraically manipulate this equation to solve for T in terms of all the other variables.
file i00421

Question 50

A radiation-style pyrometer measuring the temperature of a piece of glowing-hot steel coming out of a furnace at a steel mill produces a millivolt signal (at the thermopile sensing element) of 12.69 mV when the steel is at a temperature of 1400 ^{o}F. Calculate the approximate millivolt output signals at the following target temperatures:

- 1600 ^{o}F ; Output = _____ mV

- 800 ^{o}C ; Output = _____ mV

- 1000 K ; Output = _____ mV

file i00649

Question 51

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

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

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

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

file i00296

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

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.

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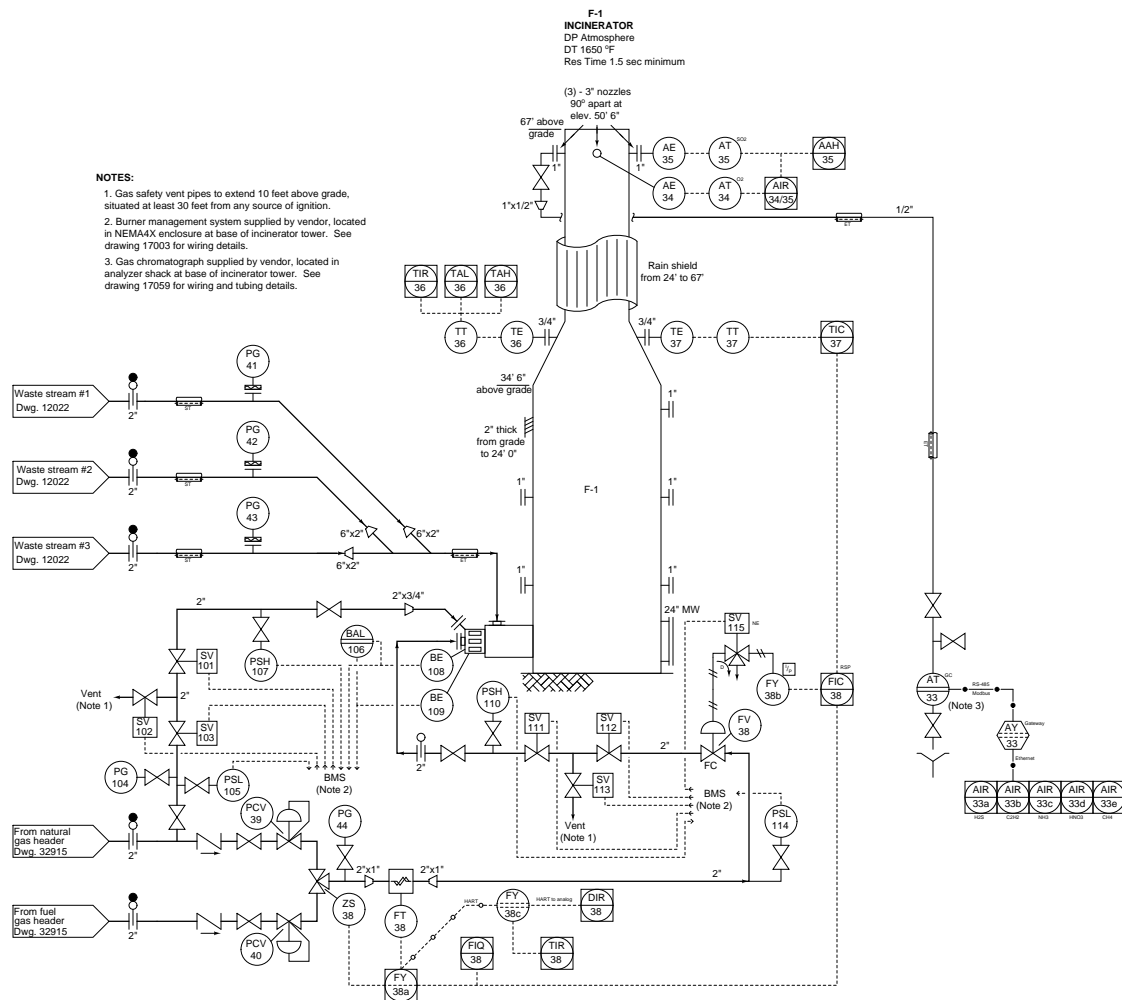
Fault	Possible	Impossible
TT-37 miscalibrated (reading too low)		
TT-37 miscalibrated (reading too high)		
TIC-37 in manual mode		
TIC-37 in auto mode		
FIC-38 in manual mode		
FIC-38 in auto mode		
FIC-38 in cascade mode		
FT-38 miscalibrated (reading too low)		

file i03529

Question 53

Calculate the pressure of gas inside an enclosed vessel using the Ideal Gas Law, if the vessel volume is 1500 liters, the vessel and gas temperature is 125 ^{o}F, and the molecular quantity of gas inside the vessel is 80 moles. Express this pressure in units of atmospheres and also kPaG (kilopascals, gauge pressure).
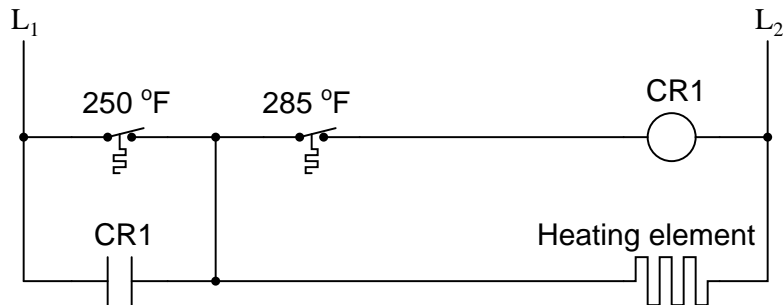
Suggestions for Socratic discussion

- The "Ideal Gas Law" is called *ideal* for a reason – it does not perfectly describe the behavior of real gases. Identify some scenarios where the Ideal Gas Law may yield erroneous results.

file i04014

Question 54

Two temperature switches sense the temperature inside an electrically-heated oven, each one with its own "trip" value. Examine the schematic diagram for the control circuit, and then explain how it is supposed to function:

Suppose relay contact CR1 were to fail open. Identify the effect this fault would have on the operation of the temperature control circuit.

Suggestions for Socratic discussion

- This type of control system is sometimes called *differential gap*. Explain why this label is appropriate for describing the system's operation.
- Sketch a modified version of this circuit whereby the same temperature switches and relay control power to a three-phase electric heating element powered by 480 VAC.
- Explain the effect(s) of the vertical wire connecting between the two temperature switches were to fail open.
- Explain the effect(s) of the 285 ^{o}F temperature switch failing open.
- Explain the effect(s) of the 285 ^{o}F temperature switch failing shorted.
- Explain the effect(s) of the 250 ^{o}F temperature switch failing open.
- Explain the effect(s) of the 250 ^{o}F temperature switch failing shorted.

file i04005

Question 55

Suppose two temperature-measuring instruments are measuring the exact same process temperature, providing redundant indications inside a control room:
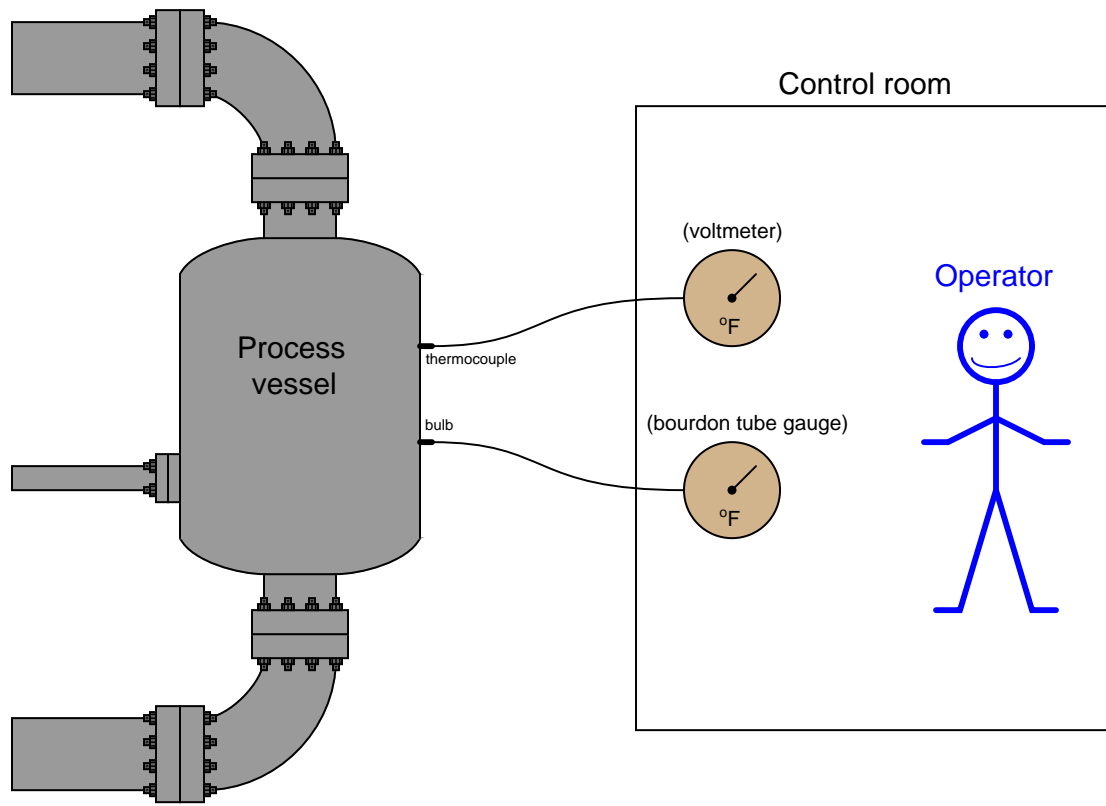
Both instruments are rather primitive: the thermocouple indicator is nothing more than an analog milli-voltmeter movement, and the filled-bulb system is a Class V arrangement with a simple bourdon tube pressure gauge mechanism used as the temperature indicator.

Now, suppose that the operator accidently bumps the thermostat in the control room, causing the control room's ambient temperature to increase by 20° F. Assuming the process vessel temperature remains the same, describe the effect of elevated control room temperature on both temperature indicators, being sure to explain *why* for both cases.
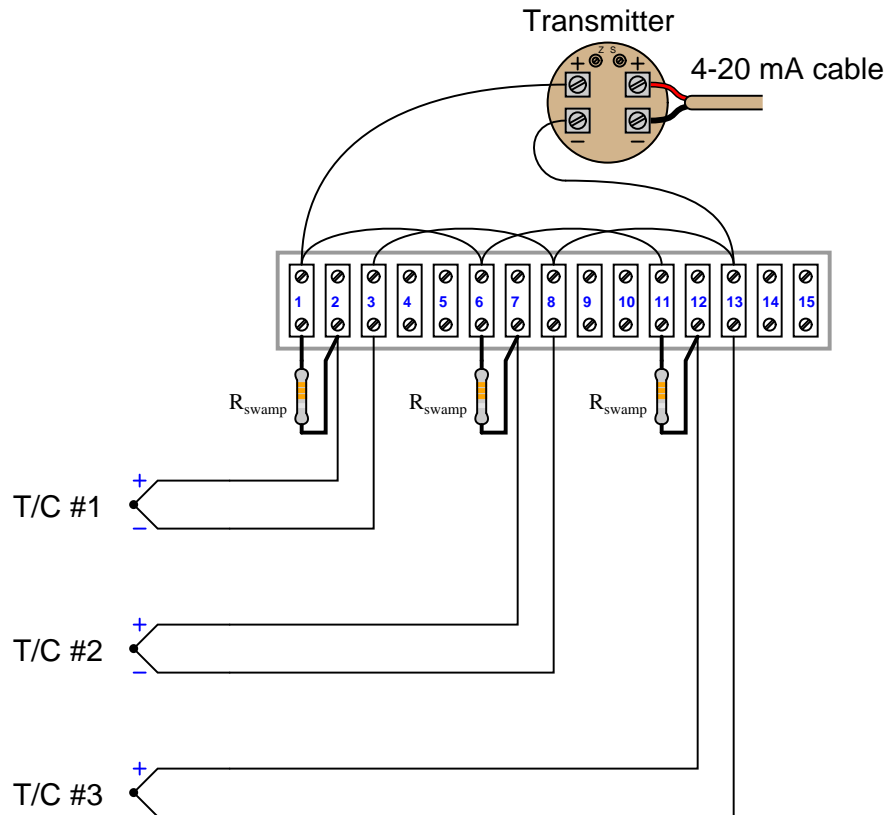

Suggestions for Socratic discussion

- Some Class V filled-bulb temperature instruments are *compensated* to eliminate calibration errors resulting from changes in ambient temperature. Explain how such a "compensating" mechanism might function – how exactly would it sense and then compensate for room temperature?

  file i02969

Question 56

A technique to measure *average* temperature using multiple sensors involves paralleling multiple thermocouples, using "swamping resistors" to join them to a single transmitter:

First, explain what the purpose of these swamping resistors is – why not just simply parallel the three thermocouples directly? Second, determine what will happen if one of these swamping resistors were to fail open.

| Suggestions for Socratic discussion |

- Describe a practical application where we might need to have an *average* temperature measurement of three different locations than a single-point measurement.
- Where should thermocouple wire be used in this circuit, and where is it appropriate to use copper wire?
- Will the presence of these swamping resistors impact the reference junction compensation? Why or why not?

file i02354

Question 57

Read the datasheet for "The WORM" flexible temperature sensor marketed by Moore Industries and answer the following questions:

Explain how this sensor design ensures good thermal contact with the thermowell.

Identify some of the sensor types available in this product line.

Note which specific types of thermocouple sensor offered in this sensor respond fastest to changes in process temperature, and explain why.

Note the accuracy specified for RTD sensors, and compare this to the accuracy specifications you've seen for thermocouples.

file i04008

Question 58

Determine the following test point voltages (all with reference to ground) at the following temperatures, for the following 4-wire RTD circuit:
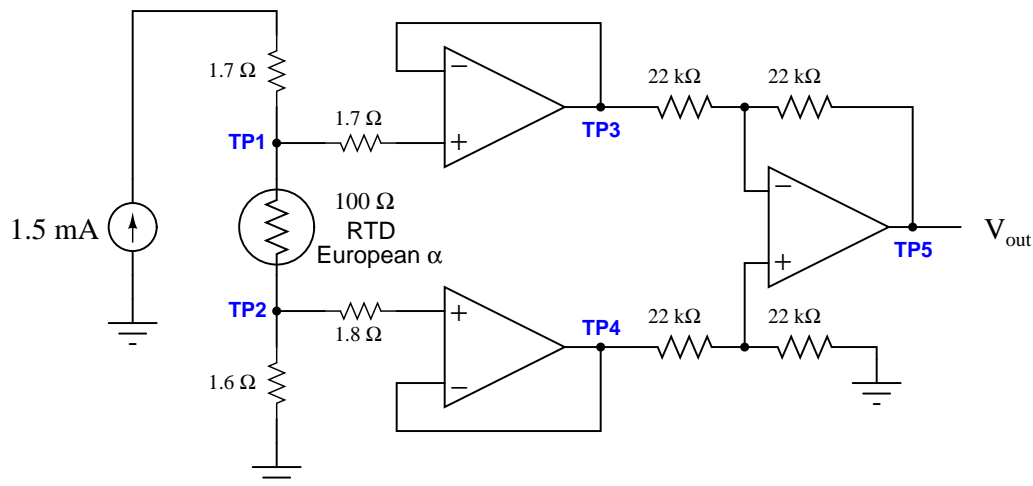
- Voltage at TP1 (V_{TP1}), with RTD at 0° C = _____ V
- Voltage at TP2 (V_{TP2}), with RTD at 10° F = _____ V
- Voltage at TP3 (V_{TP3}), with RTD at 12° C = _____ V
- Voltage at TP5 (V_{TP5}), with RTD at -20° C = _____ V

file i00652

Question 59

Question 60

Question 61

Identify any general principles applicable to the topics within this course, and describe where you applied some of these principles. Examples include:

- Conservation of Energy
- Conservation of Mass
- Negative feedback
- Electrical principles:
- Unit conversion and dimensional analysis
    → Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL)
    → Ohm's Law
    → Properties of series and parallel networks
    → Capacitance and Inductance
    → Transformers
    → Filtering networks
    → Semiconductor switching

Next, identify any problem-solving strategies applicable to the problems you faced in this course, and describe where you applied them. Examples include:

- Performing "thought experiments"
- Re-drawing a complex diagram in simpler form
- Annotating a diagram to show relevant quantities
- Simplifying the problem, and solving that simpler version first
- Collecting data and analyzing for patterns

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

- One useful strategy is to maintain a *journal* of all you've learned in a course of study. Explore ways you could take the work you're already doing to prepare for homework (daily discussions with your instructor) and turn this into a journal or even a weblog ("blog") for your own reflection and eventual use as a portfolio to showcase your capabilities to employers.
- Where exactly are the practice problem worksheets located on the *Socratic Instrumentation* website?
- Peruse the "feedback questions" for this (and/or past) course sections to identify any questions related to areas you would like to strengthen.

file i00999

Question 62

Determine how either of the potentiometers may be connected to the temperature transmitter in order to simulate a 4-wire RTD:
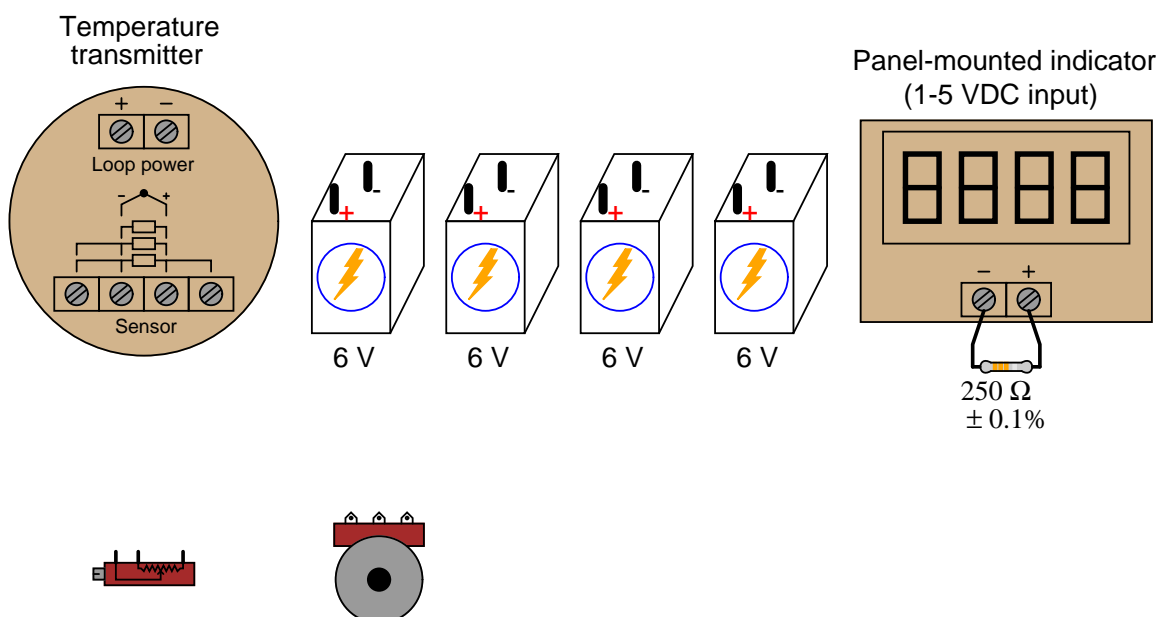
- Students very commonly mis-interpret the symbols drawn next to the input terminals of an RTD transmitter, especially the terminals which must be made 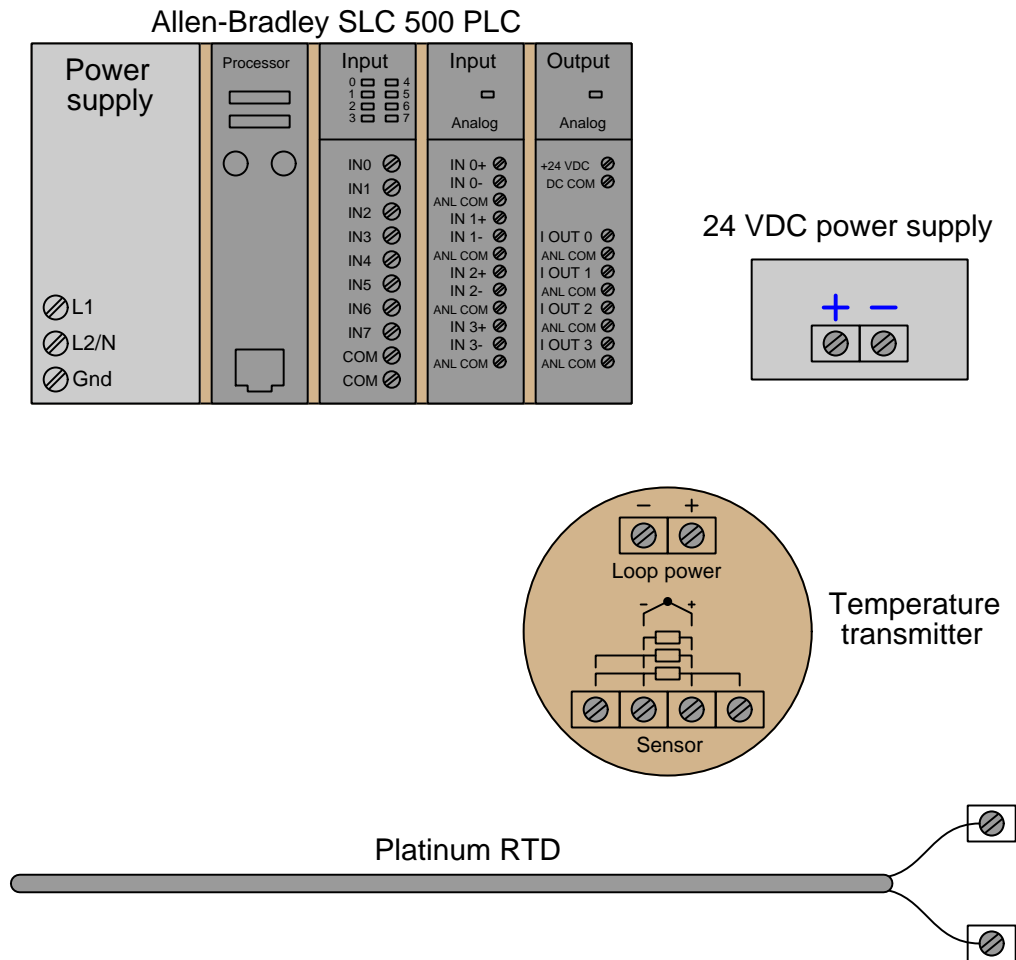common to each other at the sensor. One of the most popular misconceptions is to think that those terminals shown common to each other by the symbol are already joined together *inside the transmitter*. Explain why this interpretation cannot be true, based on how you know 3-wire and 4-wire RTD circuits are designed to work.
- A problem-solving technique useful for making proper connections in pictorial circuit diagrams is to first identify the directions of all DC currents entering and exiting component terminals, as well as the respective voltage polarity marks (+,−) for those terminals, based on your knowledge of each component acting either as an electrical *source* or an electrical *load*. Discuss and compare how these arrows and polarity marks simplify the task of properly connecting wires between components.
- Perhaps the most difficult part of this problem is deciding how to connect the potentiometer to the transmitter. One way to help you solve this problem is to apply the technique of *simplifying* the problem so that it is easier to solve, then use that solution as a starting point for the final solution of the given (complex) problem. Show how you would first simplify the given problem here, and what that simple(r) solution would look like.

file i03567

69

Question 63

Connect the necessary wires so that this temperature transmitter sends a 4-20 mA current signal to channel 1 of the analog input card on the PLC, assuming the temperature transmitter will be configured for a *3-wire RTD* sensor:

Allen-Bradley SLC 500 PLC

24 VDC power supply

Temperature transmitter

Platinum RTD

Suggestions for Socratic discussion

- Students very commonly mis-interpret the symbols drawn next to the input terminals of an RTD transmitter, especially the terminals which must be made common to each other at the sensor. One of the most popular misconceptions is to think that those terminals shown common to each other by the symbol are already joined together *inside the transmitter*. Explain why this interpretation cannot be true, based on how you know 3-wire and 4-wire RTD circuits are designed to work.
- What type(s) of wire should be used to connect the RTD to the input terminals on the transmitter? Should platinum wires be used (to match the RTD's wire type) or may regular copper wires be used?

file i03430

Question 64

Read portions of the Moore Products model 33 "Nullmatic" pneumatic temperature transmitter service manual and answer the following questions:

Identify the upper operating temperature limit of this instrument, and compare this against common thermocouples.

Describe a typical calibration procedure for this transmitter.

Determine whether this is a *force-balance* or a *motion-balance* instrument, based on an examination of its cut-away diagram.

| Suggestions for Socratic discussion |

- Explain how the "zero" adjustment works in this temperature transmitter.
- Explain how the span of this temperature transmitter could be altered.
- Identify at least one fault that could cause the pneumatic output of this instrument to saturate low (below 3 PSI)
- Identify at least one fault that could cause the pneumatic output of this instrument to saturate high (above 15 PSI)
- If the ambient temperature of this instrument increases, what effect (if any) will it have on the output signal?
- If you were to classify this filled-bulb instrument by number, which one would it be (e.g. Class I, II, III, V)?

file i04016

Question 65

A company named GlassPoint designed and built a rather ingenious solar-powered steam generating system for enhanced oilfield recovery cost-competitive to natural gas in regions with plentiful direct sunshine. Their website in 2011 claimed these performance figures:

- Steam pressure = 2500 PSIG
- Steam temperature = 750 degrees Fahrenheit
- Steam volume = 90 barrels of boiler feedwater consumption per day, per acre of collection area

Based on these performance metrics, answer the following questions:

Is this saturated steam or superheated steam? How can you tell?

Calculate the water flow rate in units of gallons per minute (per acre of collection). Hint: one "barrel" is equal to 42 gallons. Assume the unit operates for 12 hours each day, not 24 hours since the sun does not shine at night.
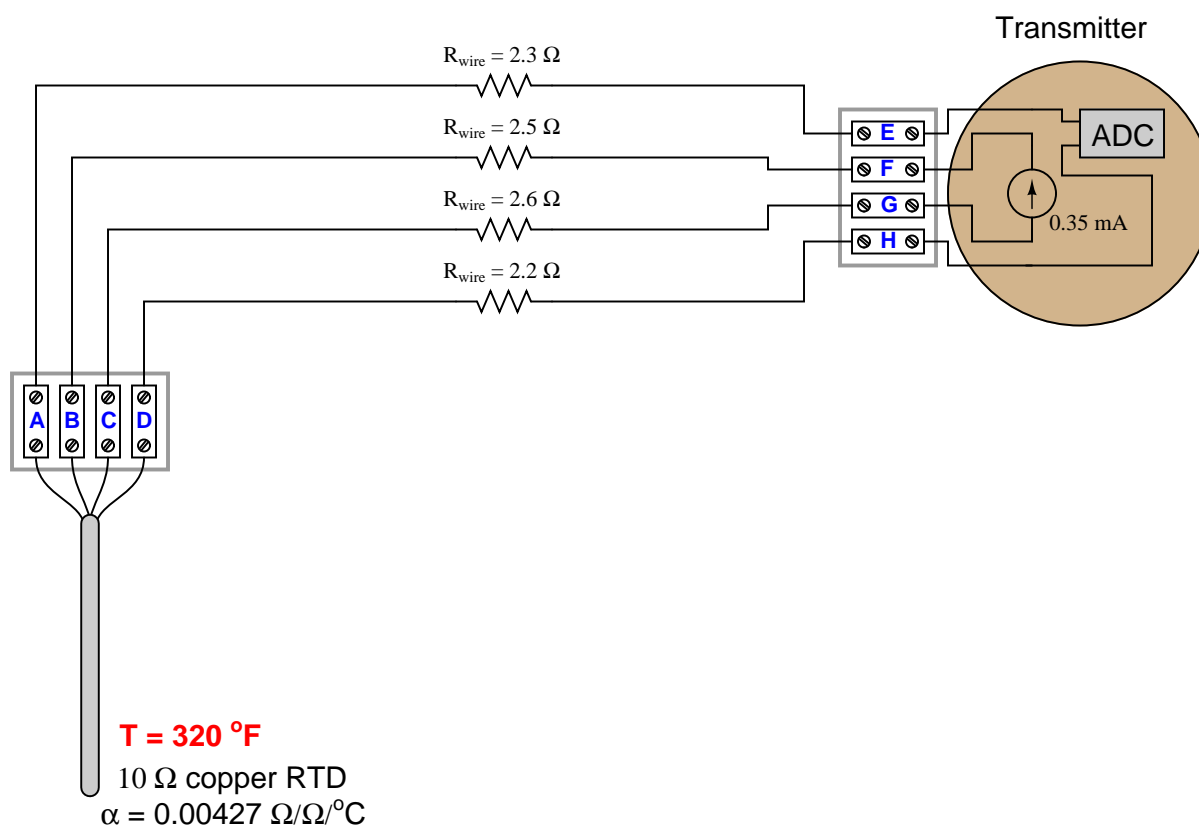
Calculate the heat output rate in units of BTU per minute per acre of collection, assuming the boiler feedwater starts at an ambient temperature of 70 degrees Fahrenheit.

Calculate the heat output rate in units of horsepower per acre of collection.

file i02899

Question 66

Calculate V_{BC}, V_{EH}, and V_{FG} in this four-wire RTD circuit, assuming the RTD transmitter uses a 0.35 mA current source to "excite" the RTD circuit:

Transmitter

$R_{wire} = 2.3\ \Omega$

$R_{wire} = 2.5\ \Omega$

$R_{wire} = 2.6\ \Omega$

$R_{wire} = 2.2\ \Omega$

E

F

G

H

ADC

0.35 mA

A B C D

T = 320 °F
10 Ω copper RTD
$\alpha = 0.00427\ \Omega/\Omega/°C$

Note: reference a *table* for this RTD to determine its resistance at the specified temperature.

Also, determine which of the four wires should be colored red, and which should be colored white.

Suggestions for Socratic discussion

- Does it matter to the accuracy of this system that the four wires have unequal resistances?
- Which of the two requested voltages have the same value, and why?
- When you look at the table of resistance values for a 10 ohm copper RTD, you will note it differs from platinum RTDs in terms of its "10 ohm" reference temperature. What is the reference temperature for a 10 ohm copper RTD?

file i02316

Question 67

Read selected portions of the US Chemical Safety and Hazard Investigation Board's analysis of the 1998 chemical manufacturing incident at the Morton International manufacturing facility in Paterson, New Jersey (Report number 1998-06-I-NJ), and answer the following questions:

Based on the incident summary and key findings presented on pages 1 through 5, summarize how the process is supposed to work and then describe what went wrong to produce the explosion.

A graph on page 31 of the report contrasts *heat production* of the chemical reaction versus *heat removal* of the process cooling system. Identify where the "danger" point is on this graph, and explain why it is dangerous based on your knowledge of specific heat and heat transfer.

The chemical reactions involved in this process were primarily *exothermic*. Explain what this term means, and why it is important to the cause of this accident.

| Suggestions for Socratic discussion |

- Identify some of the discrepancies found in Morton's MSDS datasheet for the Yellow 96 dye product (page 3) and explain how MSDS datasheets (more commonly known now as SDS datasheets) are generally useful.
- Explain why the "heat removal" graph is a linear function, based on your knowledge of heat transfer equations.
- Pick any point on the "heat removal" graph and explain how the temperature of the kettle will naturally proceed from that temperature, based on a comparison of heat generation versus heat removal rates. Identify the *two* points on this graph where the temperature will settle at an equilibrium value.
- Identify the shape of the "heat removal" graph if the dominant mode of heat transfer were *radiation* instead of conduction/convection.

file i04011

Question 68

Read selected portions of the US Chemical Safety and Hazard Investigation Board's analysis of the 1998 chemical manufacturing incident at the Morton International manufacturing facility in Paterson, New Jersey (Report number 1998-06-I-NJ), and answer the following questions:

Pages 14 and 16 of the report describe the construction of the "kettle" batch process used by Morton to produce "Yellow 96" dye. Page 16 in particular shows a simplified P&ID of the batch process. Based on what you find in this section of the report, identify and explain all the modes of heat addition to and heat removal from the process vessel. Also identify all measurement instrumentation for the kettle.

An important factor leading to this event was a failure to heed established *Management of Change* (MOC) procedures, as described on page 7, on pages 45-46, and also on pages 57-58. Explain what "Management of Change" refers to and why it is important for process safety.

Supposing the kettle was heated by a flow of saturated steam at 15 PSIG boiler pressure at a mass flow rate of 3 pounds per minute and cooling to become condensate (water) at atmospheric pressure and 200 degrees F, calculate the amount of heat transferred to the kettle by this steam, in units of BTU per minute.

Hint: the *Socratic Instrumentation* website contains a page where you may download public-domain textbooks, one of which is a set of steam tables published in 1920.

Suggestions for Socratic discussion

- An important safety policy at many industrial facilities is something called *stop-work authority*, which means any employee has the right to stop work they question as unsafe. Explain how stop-work authority could have been applied to this particular incident.
- Explain why the transition from a 1000 gallon kettle to a 2000 gallon kettle resulted in diminished heat-removal capacity, based on what you know about thermodynamics.
- If the pressure of the saturated steam used to heat the kettle increased, would this result in more heat delivered to the kettle, less heat delivered to the kettle, or the same amount of heat delivered to the kettle?
- Do you suppose most of the heat transferred in the "condenser" took place via *specific* (sensible) heat or via *latent* heat?

file i04012

Question 69

Once upon a time, an instrument technician (and BTC graduate!) stumbled upon this temperature measurement circuit at a biopharmaceutical manufacturing facility, used to measure the temperature of storage freezers:

4-20 mA to indicator

Loop
RTD
+excit
+
+sense
−
-sense
-excit

4-conductor cable

Wht
Wht
Red
Red

RTD
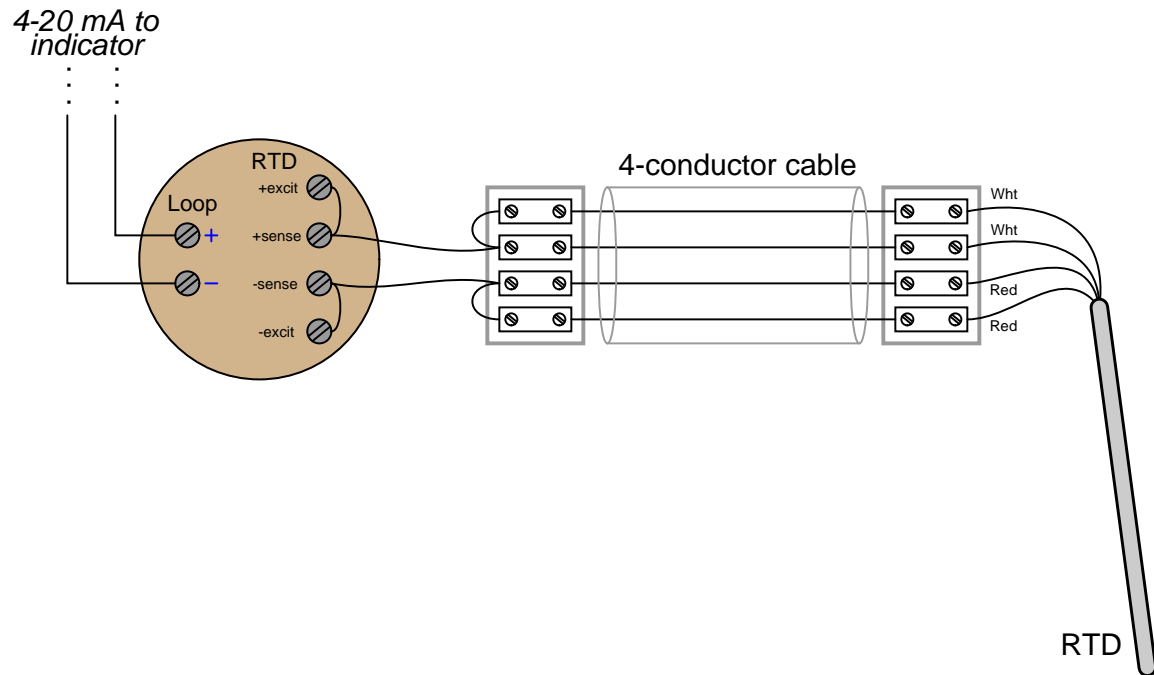
Identify the type of calibration error introduced by this improper wiring (e.g. zero shift, span shift, linearity, hysteresis), and also explain how the wiring error may be corrected for improved measurement accuracy.

file i03740

Question 70

Read "Case Number 1" (pages 1-4) of the US Chemical Safety and Hazard Investigation Board's safety bulletin on "Management of Change" (Bulletin number 2001-04-SB) discussing the 1998 coker fire at the Equilon refinery in Anacortes (Washington), and answer the following questions:

Explain in general terms what happened in the Coker unit of the refinery following a power outage, that led to this accident. Specifically, identify how temperature measurement played a crucial role in the decision to drain the coke drum.

Identify how the temperature sensors would have had to be built differently in order to provide better information to operations about the status of the coke drum under these abnormal conditions. Explain why their existing design was adequate to measure temperature under normal operating conditions.

Page 2 describes how a similar incident (though not lethal) occurred in 1996. Describe the follow-up to that incident, and how better "Management of Change" (MOC) procedures might have prevented the 1998 disaster.

A significant number of industrial accidents may be traced back to insufficient or non-existent MOC policies. Identify some of the reasons MOC might not be adequately applied at an industrial facility, and what you as a technician might be able to do to increase the likelihood MOC procedures are respected.
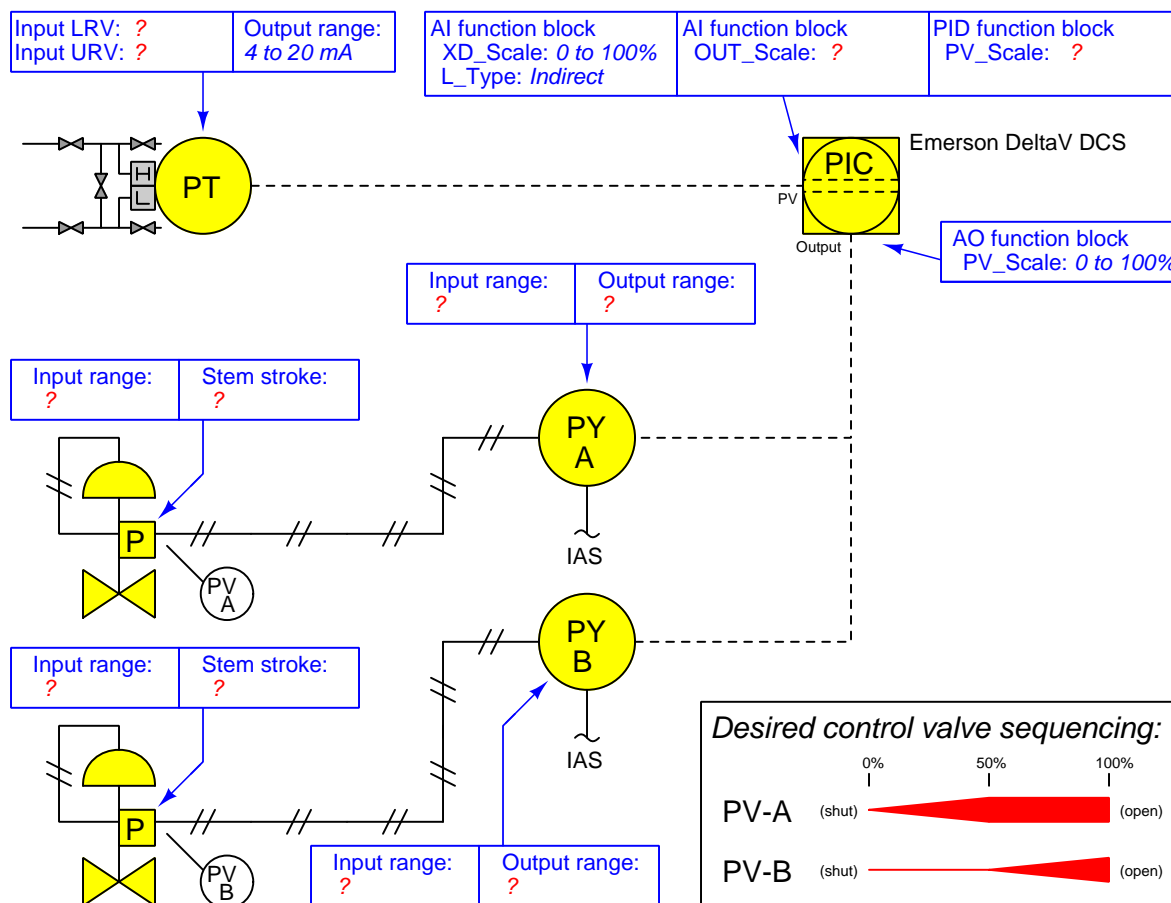

Suggestions for Socratic discussion

- An important safety policy at many industrial facilities is something called *stop-work authority*, which means any employee has the right to stop work they question as unsafe. Explain how stop-work authority could have been applied to this particular incident.
- An ironic hazard within many chemical processing operations is that of a *power failure*. This seems odd at first, because we typically associate the lack of electrical power with safety (lock-out, tag-out) rather than with danger. However, a chemical processing operation may become very dangerous when electrical service is disrupted. Try to generalize why this is, based on this particular case at the Equilon refinery and/or on any industrial accident examples you may be familiar with.
- The report notes that "heat transfer calculations" would have shown a much longer cooling time necessary than what operators assumed. Identify which heat transfer equations might apply to this type of scenario, identifying the important variables dictating rate of cooling for the coke drum.

file i04253

Question 71

Suppose you are asked to configure the instruments in this pressure control loop to sense and display process pressure over a range of 0 to 150 kPa, with the loop controller actuating two split-ranged control valves in a progressive sequence:

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

Suggestions for Socratic discussion

- Suppose the controller displayed a pressure of 80 kPa when the actual process pressure was 87 kPa PSIG. First, identify *two* possible locations in this loop for a calibration error that would account for this discrepancy. Then, assuming only one fault, explain how you could positively determine the location of this calibration error with a single diagnostic test.
- Suppose valve PV-A was 100% open and PV-B was 60% open when the controller output displayed 75%. First, identify *three* possible locations in this loop for a calibration error that would account for this discrepancy. Then, assuming only one fault, explain how you could positively determine the location of this calibration error with no more than two diagnostic tests.

file i02081

Question 72

The reference manual for the Rosemount model 3144 temperature transmitter states that the default (factory) configuration for this transmitter is for the *failure mode* to be "high". Explain what this means, and why the "failure mode" is an important parameter for a thermocouple instrument.

Also, comment on the "NAMUR" signal levels differentiating a saturated condition from a detected failure, and why this standard might be important in a control system.

Suggestions for Socratic discussion

- Are NAMUR signals used only for temperature instruments, or for other types of instruments as well (e.g. pressure, level, flow)?

file i04015

Question 73

Suppose you measured the output of a type J thermocouple inserted into a process vessel and read 12.53 millivolts on your digital multimeter. Knowing the ambient temperature at the connection point (using a portable thermometer) is 54 degrees Fahrenheit, how hot is the tip of the thermocouple inside the process vessel?

Suppose you measured the output of a type E thermocouple inserted into a process pipe and read 23.85 millivolts on your digital multimeter. Knowing the ambient temperature at the connection point (using a portable thermometer) is 33 degrees Celsius, how hot is the tip of the thermocouple inside the pipe?

file i03734

Question 74

Suppose you wish to simulate a type S thermocouple at a temperature of 2670 degrees Fahrenheit for a temperature transmitter with reference junction compensation enabled. Knowing the ambient temperature at the transmitter (using a portable thermometer) is 73 degrees Fahrenheit, how many millivolts must you send to the transmitter's input terminals?

Suppose you wish to simulate a type T thermocouple at a temperature of 155 degrees Celsius for a temperature transmitter with reference junction compensation enabled. Knowing the ambient temperature at the transmitter (using a portable thermometer) is 20 degrees Celsius, how many millivolts must you send to the transmitter's input terminals?

file i03733

How many reference junctions does this thermocouple circuit have, and where exactly are they located?
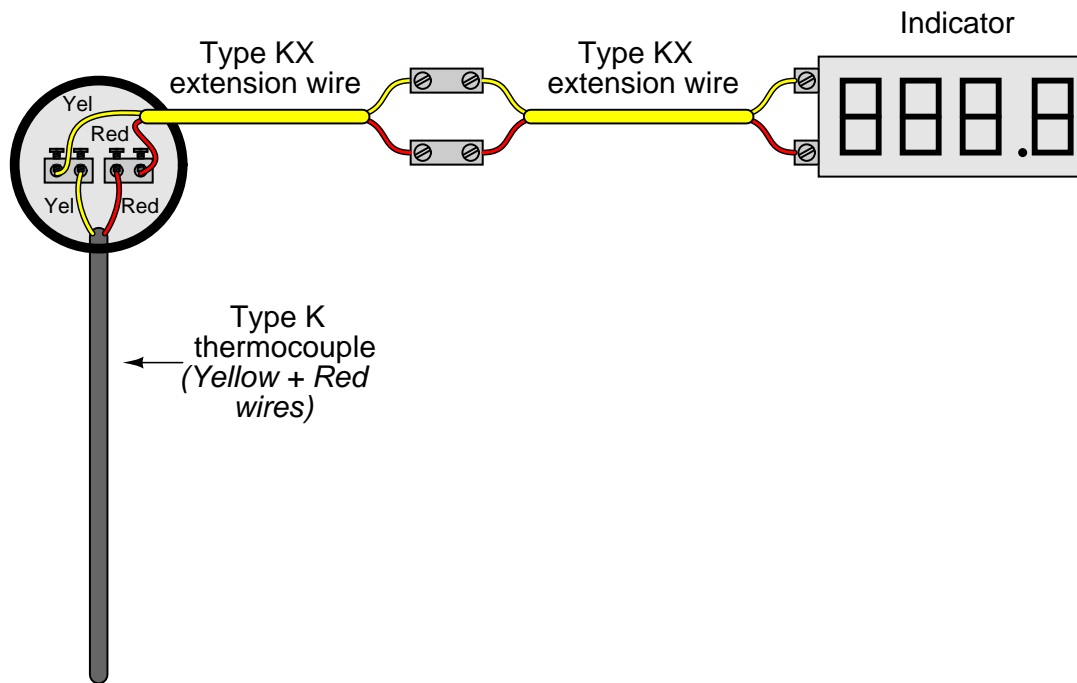
Indicator

Type KX
extension wire

Type KX
extension wire

Yel

Red

Yel   Red

Type K
thermocouple
*(Yellow + Red
wires)*

file i02972

79

Determine the correct potentiometer millivoltage settings to generate the following temperature indications at the instrument:

Precision potentiometer

Temp. = 70° F

Temperature instrument (type J thermocouple)

Cu + Cu + Cu

Cu - Cu -

Cu

+ -

+ -

Temp. = 70° F
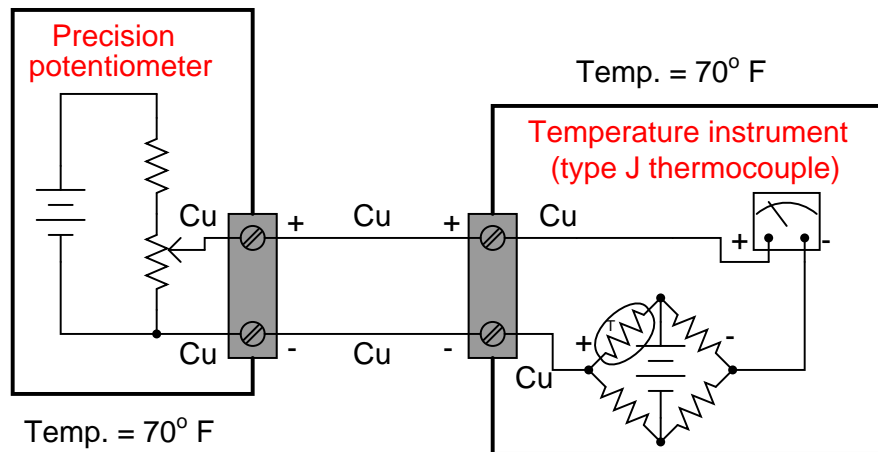
- 0° F ; Potentiometer setting = _____ mV
- 229° F ; Potentiometer setting = _____ mV
- 454° F ; Potentiometer setting = _____ mV
- 641° F ; Potentiometer setting = _____ mV

file i00651

80

An RTD measures the temperature of saturated steam at the steam drum of a boiler:
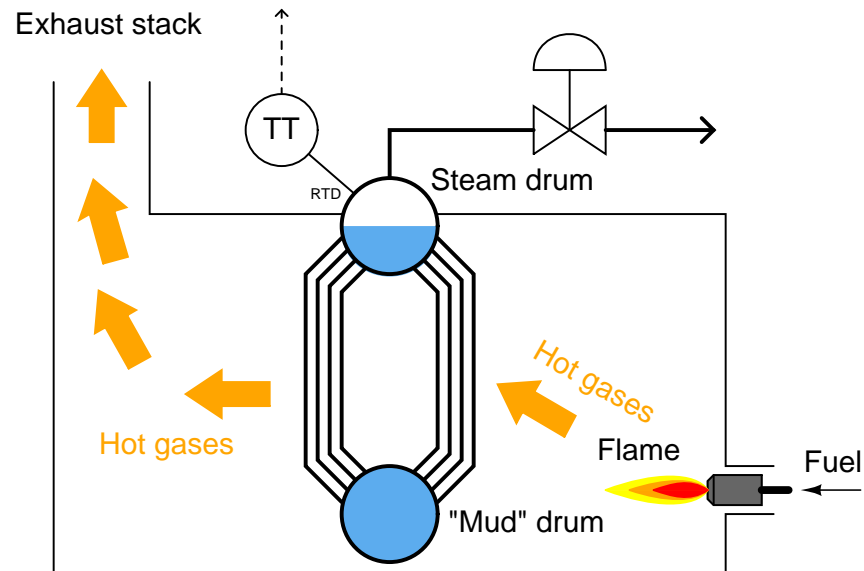
The RTD connects to a bridge circuit via three wires, to register temperature at a sensitive voltmeter mechanism in the control room:
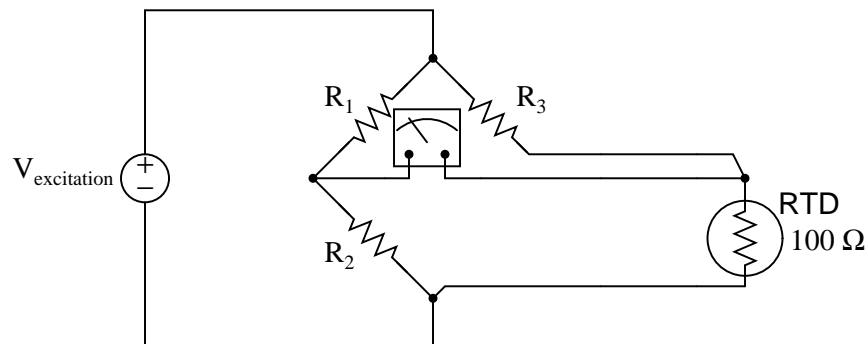
Suppose the boiler operator decides to decrease the pressure of the boiler over a period of time. Identify the effects this pressure change will have on these voltage drops in the RTD circuit:

- V_{R1} will *increase*, *decrease*, or *stay the same*?
- V_{R2} will *increase*, *decrease*, or *stay the same*?
- V_{R3} will *increase*, *decrease*, or *stay the same*?
- V_{RTD} will *increase*, *decrease*, or *stay the same*?
- Explain the relationship between boiler pressure and boiler temperature:

  file i00653

Question 78

Suppose we needed to measure the temperature of a batch "reactor" vessel at a biopharmaceutical manufacturing facility. We know the temperature of this particular vessel may range between 20° F and 300° F, and we also know we need the temperature measurement to be as precise and accurate as possible at all points within this range.

Choose the best temperature sensing element for this application from the list below, and then explain *why* it will provide the best accuracy for this application:

- 100 ohm platinum RTD
- Type S thermocouple
- Type J thermocouple
- Class III filled-bulb (with pneumatic transmitter)

file i00650

Industrial operations using large quantities of steam often distribute it at different pressures, much like an electrical utility system distributing power at several different voltages:
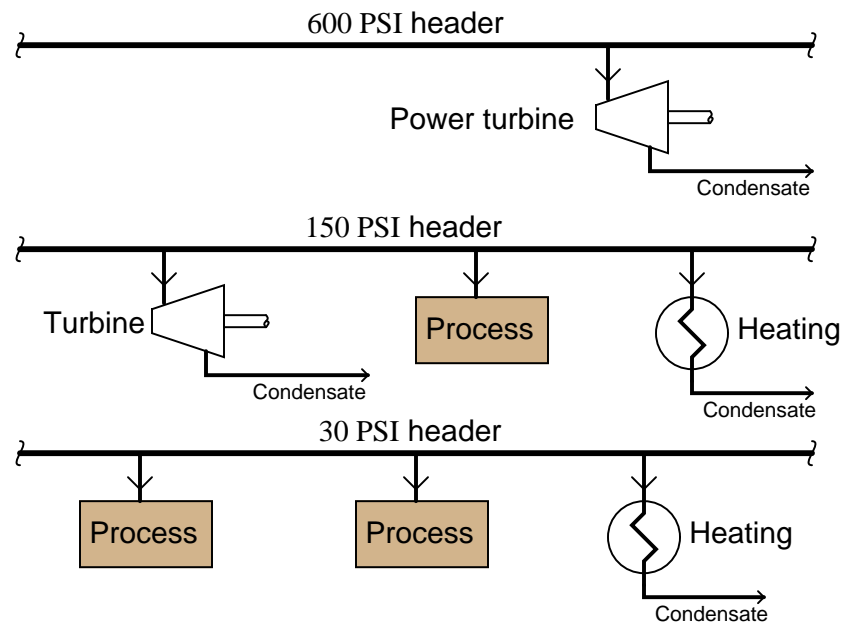
It may not always be practical to have a separate boiler (or set of boilers) for each header pressure (e.g. one boiler outputting 600 PSI, one outputting 150 PSI, and one outputting 30 PSI). So, often there is a need to "let down" high-pressure steam to a lower pressure.

Although it is possible to simply use control valves to throttle high-pressure steam into a lower-pressure headers, this would be a waste of energy. Such a strategy would be analogous to using resistive voltage dividers to step high voltage down to lower values in an electric power system:

A very inefficient way to get different steam pressures!
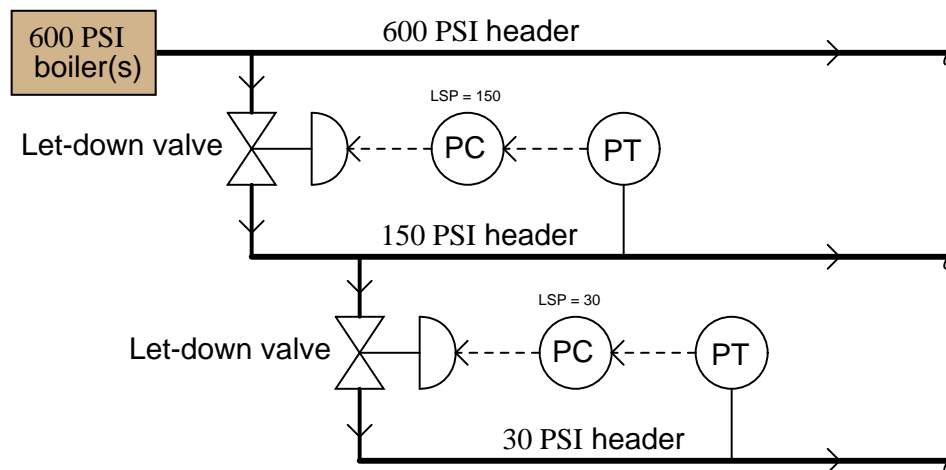
An improvement over the plain let-down strategy is to use special *desuperheating* valves instead of normal throttling valves. Desuperheating is a process whereby water is sprayed into the throttled steam:

A better way to get different steam pressures!
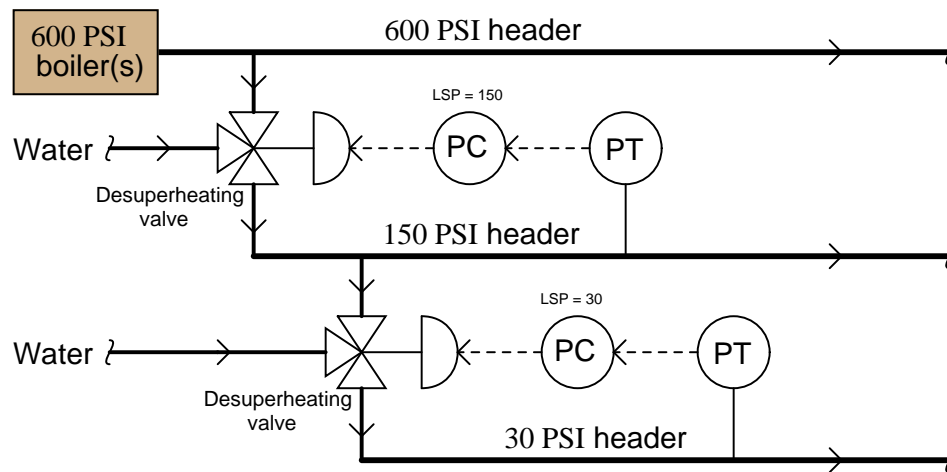
Desuperheaters may be thought of as the steam equivalent of electrical transformers: a much more efficient means of reducing pressure (voltage) than throttling with a restrictive (resistive) element. Explain how desuperheating works, and why the electrical transformer analogy is appropriate.

file i01801

Question 80

One simple way to build a "reference junction compensation" circuit is to use a bridge with a thermistor (temperature-sensitive resistor) in one arm like this:
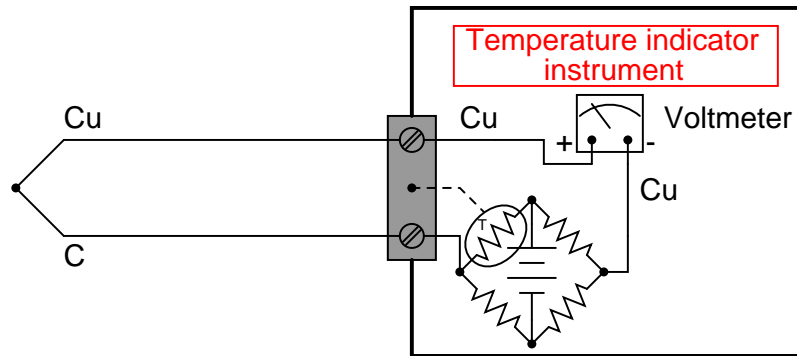
As the terminal block warms up and cools down, the resistance of the thermistor will change, altering the balance of the bridge to add the appropriate amount of voltage in series with the meter circuit to cancel out the millivoltage generated by the thermocouple wires connecting with copper wires at the terminal block (the "reference junction").

Given the type of thermocouple shown here (type T, with copper and constantan wires), the voltmeter's polarity, the orientation of the battery in the bridge circuit, and the thermistor's location in the bridge circuit, does the thermistor have to have a *positive* temperature coefficient (resistance increases as temperature increases) or a *negative* temperature coefficient (resistance decreases as temperature increases)?

Hint: begin your solution to the problem by properly identifying the source of the problem itself – determine the polarity of the reference junction voltage, so you will know which way the bridge's output voltage must be oriented to cancel it out.

Suggestions for Socratic discussion

- What type of temperature coefficient does an RTD have?
- Suppose the thermistor did not have the right *magnitude* of temperature coefficient (i.e. it's "alpha" value was wrong). Would this affect the system's *zero*, *span*, or both?
- If we must use a thermistor to compensate for the reference junction of a thermocouple, then why use a thermocouple to sense process temperature at all? Why not just use a thermistor located at the process and be done with it?
- If the thermistor fails open, will it drive the voltmeter upscale or downscale?
- If the thermistor fails shorted, will it drive the voltmeter upscale or downscale?

file i00384

Calculate the amount of voltage dropped across the RTD element in this circuit, the amount of voltage output by the operational amplifier, and the amount of temperature measurement error based on the discrepancy between those two voltages:
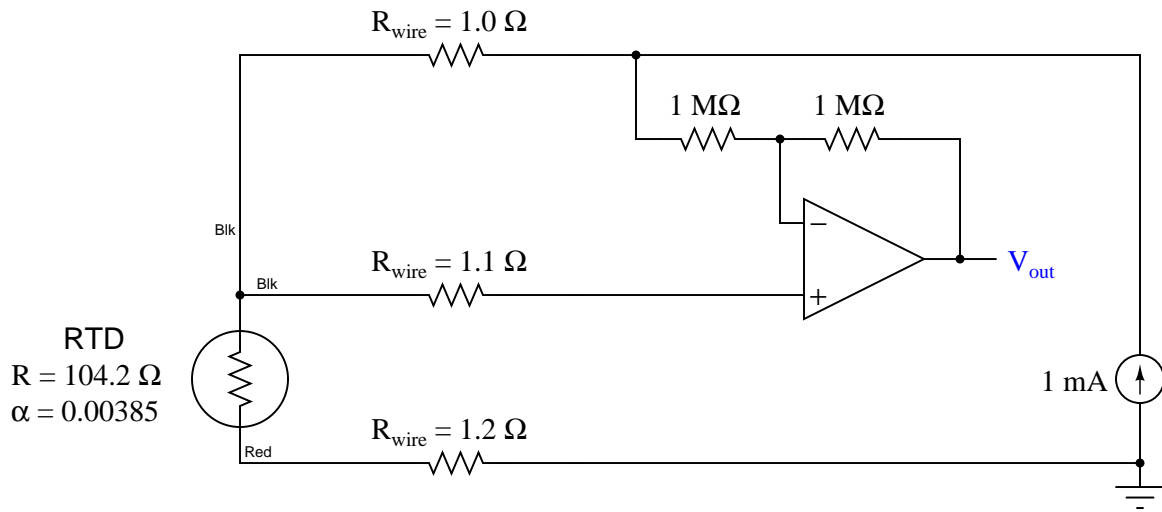
$V_{RTD} = $ _____

$V_{out} = $ _____

Temp. error = _____

Note: the RTD in this circuit is a "100 ohm" platinum sensor, but its actual resistance at this temperature is 104.2 Ω.

Note: in order to simplify your analysis, you may assume the current through the 1 MΩ resistors to be zero. The actual current is so small as to be negligible.

file i00041

Question 82

Suppose the voltmeter in this bridge circuit is "pegged" in the *positive* direction. A test using a digital multimeter (DMM) shows the voltage between test points **B** and **E** to be 7.2 volts:
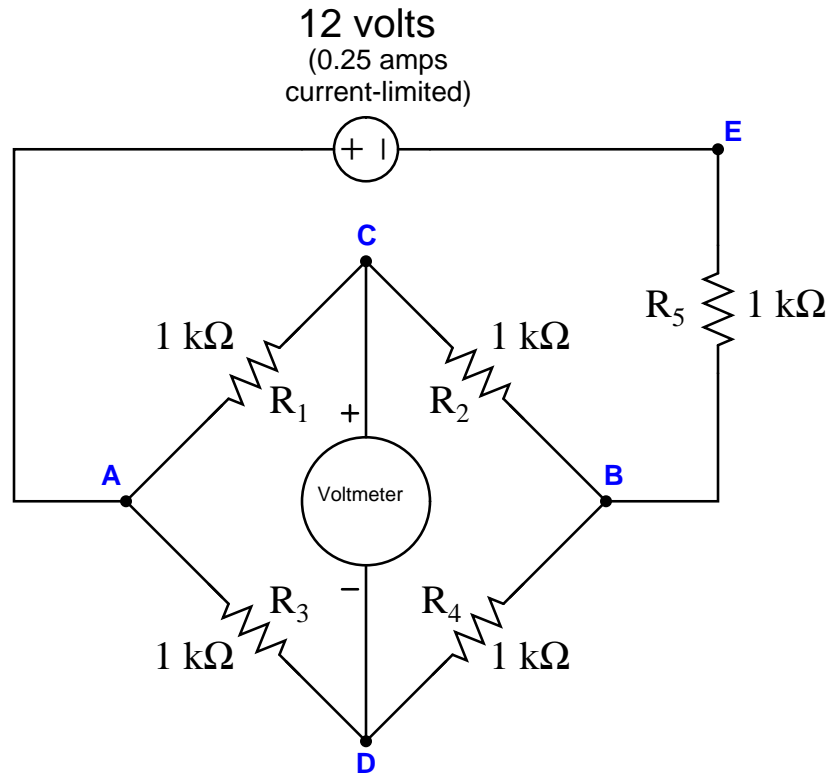
Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

Fault	Possible	Impossible
R_1 failed open		
R_2 failed open		
R_3 failed open		
R_4 failed open		
R_5 failed open		
R_1 failed shorted		
R_2 failed shorted		
R_3 failed shorted		
R_4 failed shorted		
R_5 failed shorted		
Voltage source dead		

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

<u>file i02702</u>

87

Question 83

Suppose an instrument technician connects a multimeter (set to measure millivolts DC) to the ends of a thermocouple cable, the other end of the cable terminating in a thermocouple junction inserted into a hot process.

Assuming the multimeter registers 25.841 millivolts, with an ambient temperature of 53 degrees Fahrenheit at the connection point where the technician is at, and type N thermocouple cable throughout, determine the process temperature in degrees Celsius. Be sure to show all your work (including all values taken from a thermocouple table)!

Question 84

This solvent storage tank is kept heated to 95 degrees F by a steam heat exchanger inside the tank. Steam is admitted to the exchanger "loop" through temperature control valve TCV-105, and exits the loop through a steam trap:
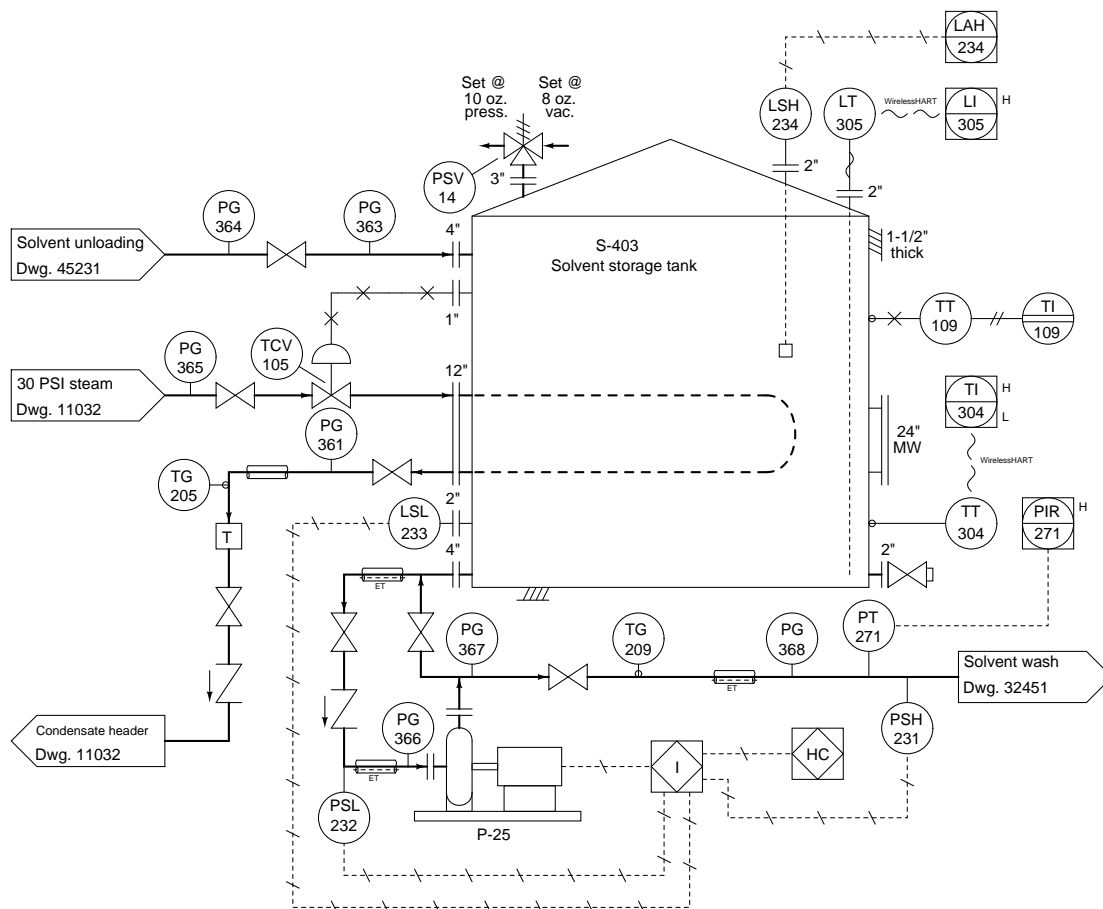
Suppose one day you notice that pressure gauge PG-361 registers 22 PSI while temperature gauge TG-205 registers 234 degrees F. Based on this information, determine whether the fluid in that pipe is *steam* (vapor) or *water* (liquid). Be sure to explain how you were able to make this determination.

file i00043

Certain types of non-contact pyrometers output a DC voltage proportional to the fourth power of the target's absolute temperature, in accordance with the Stefan-Boltzmann equation. Suppose one of these pyrometers is rated to output 30.0 mV at a target temperature of 3750 Kelvin.

Calculate the target temperature corresponding to an output voltage of 14.3 millivolts, both in Kelvin and degrees Fahrenheit.

$T_{target} = $ _____ K = _____ ^{o}F

file i00044

Question 86

A heat exchanger is used to pre-heat a flow of liquid acetone before it enters a process reactor. The heating medium is steam, entering the exchanger at 160 PSIA and 480 °F, then leaving the exchanger at 120 PSIA and 400 °F:
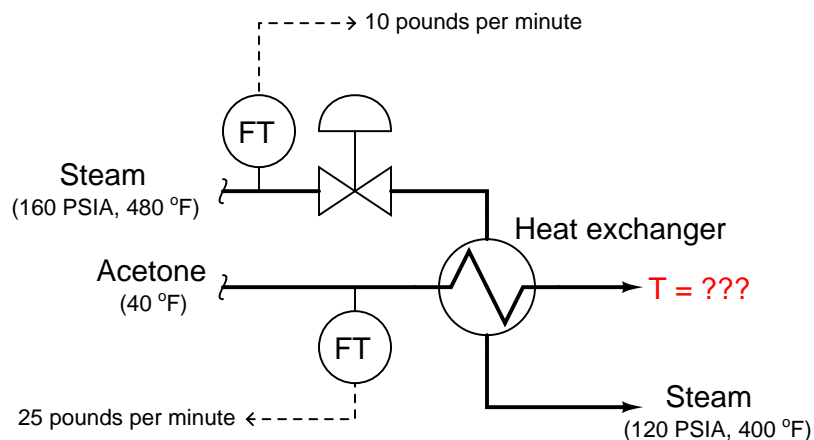
Assuming a steam flow rate of 10 pounds per minute, an acetone flow rate of 25 pounds per minute, and no heat lost to the surrounding environment, calculate:

- The rate of heat exchanged between the steam and the acetone, in BTU/hour (hint: use the enthalpy values found in a *steam table*)

- The exiting temperature of the acetone, assuming $c = 0.521$

Hint: the *Socratic Instrumentation* website contains a page where you may download public-domain textbooks, one of which is a set of steam tables published in 1920.
file i03974

An instrument technician desires to simulate a thermocouple signal using a precision voltage reference and a voltage divider network of her own making:
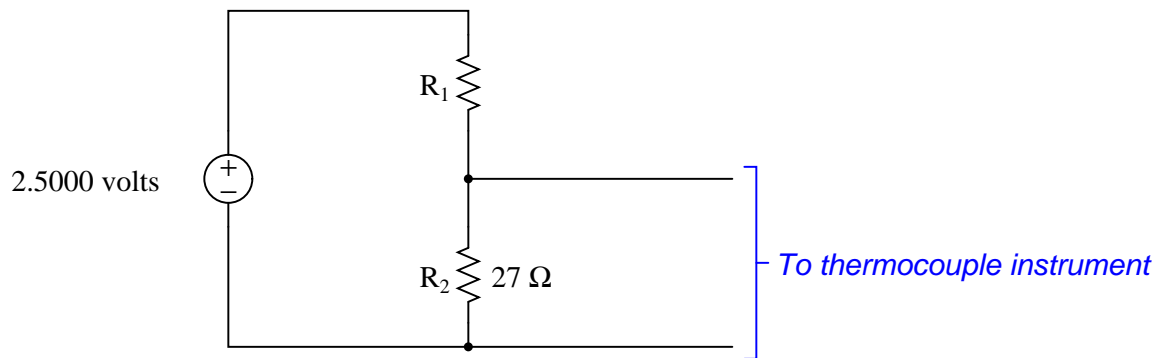
Calculate the necessary value for resistor R_1 in order to generate a millivoltage signal simulating a type J thermocouple at 607 degrees Fahrenheit. Assume the instrument receiving this signal has reference junction compensation enabled, and is at an ambient temperature of 71 degrees Fahrenheit.

$R_1 = $ _____

file i03738

Question 88

An interesting method of electrical *heat tracing* is to pass a very large electric current through the walls of the pipe itself, using the metal pipe as a large resistor. The heat dissipated by the "resistor" will maintain the pipe's temperature high enough to avoid solidification of the liquid inside it.

In order to achieve such a high current, a step-down power transformer is used to convert industrial line power (typically 240 VAC or 480 VAC) into low-voltage, high-current power used to resistively heat the pipe. Assuming the use of 480 VAC power (single-phase), determine the step-down ratio necessary to deliver 1500 watts of heating power to a pipe exhibiting an end-to-end electrical resistance of 0.75 ohms.

file i00856

In this heat exchanger system, a hot oil (called "Therminol") is used to heat up a chemical fluid product. The oil is heated in a boiler located somewhere else in the plant, with the cooled oil returned to the boiler for re-heating.

Suppose an operator decides to close valve B slightly in this heat exchanger process, and that all other input variables to this system (e.g. Therminol oil supply pressure, oil supply temperature, etc.) remain unchanged:

Valve B

Cold feed

Valve C

Valve D

Cooled Therminol return to boiler

Therminol oil supply from boiler unit
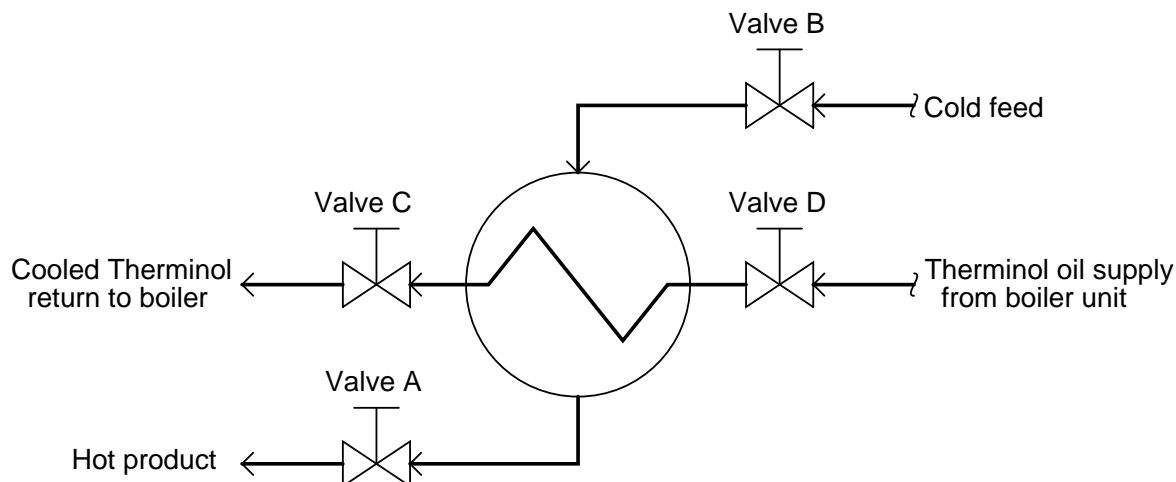
Valve A

Hot product

Identify the effects of this one valve position change on all the following variables in the system. Simply place a "check" mark in the appropriate box for each variable:

Action	Increase	Decrease	Remains constant
Product flow rate			
Product inlet temperature			
Product outlet temperature			
Therminol flow rate			
Therminol return temperature			
Heat exchange rate			

file i03478

Question 90

Suppose a voltmeter registers 0 volts between test points **C** and **B** in this series-parallel circuit:
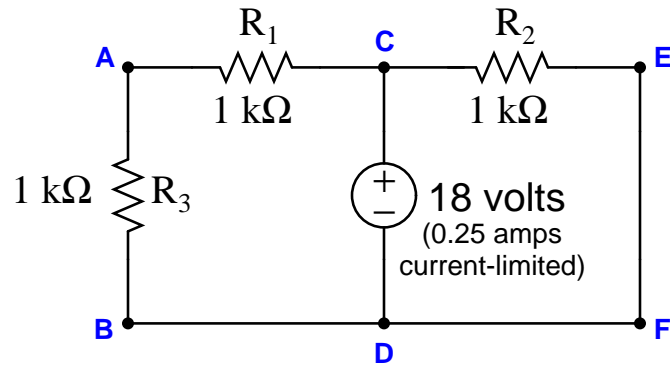
Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

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

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

<u>file i03153</u>

Lab Exercise – introduction

Your task is to build, calibrate, document, and program a temperature measurement system consisting of an electronic temperature transmitter connected to one of the analog inputs of a data acquisition module (DAQ) for a SCADA RTU (Remote Terminal Unit) node. The particular SCADA system we will be using has been designed specifically for BTC Instrumentation students. It is called *caSCADA* and it is based on a single-board computer running the Linux operating system. In this lab exercise you will be configuring the RTU node to receive a temperature transmitter's 4-20 mA analog signal and properly condition that data for visual display on a remote computer. This will involve editing some of the programming code written in the "C" language. Your instructor will assign the temperature to be measured, as well as the specific channel(s) to use on the caSCADA system for your loop.

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 (do *first!*)	mastery	–	–	–	–	
Final loop diagram and system inspection	mastery					– – – –
T/C signal simulation (± 1% of span accuracy)	mastery					– – – –
RTD signal simulation (± 1% of span accuracy)	mastery					– – – –
Linux command-line usage	mastery					– – – –
Editing and running caSCADA code	mastery					– – – –
Safety and professionalism	deduction					
Lab percentage score	proportional					– – – –
Decommission and lab clean-up	(ungraded)	–	–	–	–	

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

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

Meet with your instructor prior to any project construction, presenting the design as a prototype sketch. *Analyze the circuit represented in your prototype sketch, being sure to annotate the diagram with all expected voltages and currents, and identifying all electrical sources and loads. Be prepared to identify the effects of specific faults your instructor may propose in this circuit, applying principles such as series and parallel network properties, Kirchhoff's Laws, and Ohm's Law.* Read the lab exercise documentation in its entirety and discuss with your teammates prior to this meeting, where you may ask questions and clarify expectations with the instructor. Be prepared to answer questions from your instructor about this lab exercise, especially regarding any unique safety or procedural details described in the documentation.

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.

T/C signal simulation

Simulate a thermocouple signal to the input of your transmitter for a temperature randomly selected by the instructor, based on thermocouple tables and measured ambient temperature, demonstrating that the system displays within $\pm$ 1% of that temperature.

RTD signal simulation

Simulate an RTD signal to the input of your transmitter for a temperature randomly selected by the instructor, based on RTD tables or formulae, demonstrating that the system displays within $\pm$ 1% of that temperature.

Linux command-line usage

Demonstrate proper use of Linux commands described in the lab exercise documentation as called upon by the instructor.

Editing and running caSCADA code

Edit your team's caSCADA source code file and recompile to express your transmitter's output in a unique range (and/or unit) specified by the instructor.

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, 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 without the instructor's presence so long as that work does not disturb the learning environment for other students.

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

Lab Exercise – team meeting, prototype sketch, and planning the system

An important first step in completing this lab exercise is to **meet with your instructor** as a team to discuss safety concerns, team performance, achievement expectations, 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. This team meeting will also be an opportunity to clarify expectations on all lab project objectives, so everyone on the team knows exactly what is being asked of them. *Completely read the lab exercise documentation and discuss it with your teammates prior to meeting with the instructor.*

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 diagram must show all connections between components. It need not be exhaustive in detail, but it must show enough for the instructor to determine if all components will function properly and safely. *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!*

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 first step should be selecting proper field instruments from the instrument storage area to use in building your system. In this particular lab, you are looking for an electronic temperature transmitter, either "smart" or analog. The Rosemount model 644/3044/3144/3244 transmitters are good examples of smart transmitters, while the Rosemount model 444 is a good example of an analog transmitter. Note that analog transmitters are built *either* thermocouple or RTD input. Since you will need to calibrate *both* types in this lab activity, this will require two different analog transmitters! If you choose to use a "smart" transmitter, however, you need only select one because digital temperature transmitters are usually configurable for both RTD and thermocouple input.

The next step should be finding appropriate documentation for your temperature transmitter. Nearly every instrument in the lab is documented electronically at the manufacturer's website, so your best resource is the Internet (and/or your Instrumentation Reference where a variety of instrument manuals have been downloaded for you). Use this documentation to identify how to properly connect and calibrate the transmitter.

After locating a suitable instrument and its associated documentation, you should qualitatively test it prior to installing it in your system. For an analog thermocouple transmitter, you may simply short (jumper) the thermocouple input terminals to make the transmitter "think" it is measuring ambient temperature. For an analog RTD transmitter, you may connect a 100 Ω resistor to the RTD input terminals to make it "think" it is measuring the freezing point of water. For a digital ("smart") transmitter, first use a HART communicator to configure it for either 2-wire RTD or thermocouple input, then proceed with these tests. If the transmitter fails to respond properly, tag it with a label explaining what it does (or what it fails to do).

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 – loop diagram and system inspection

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

Construction Standards

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

Documentation Standards

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

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

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

Common mistakes:

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

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

Lab Exercise – building the system

Each RTU contains power circuitry and terminal blocks set up to marshal analog signals from field instruments to a data acquisition device. A generic loop diagram (shown in the following question of this worksheet) shows how any field device may connect to the DAQ. Your final loop diagram will simply be a customized version of this generic diagram provided to you near the end of this worksheet.

Each loop has a pre-assigned loop number, kept on file by the instructor to ensure each loop is uniquely labeled. Your transmitter and its signal wiring should be labeled with the loop number to distinguish it from other loops.

Common mistakes:

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

Building a functioning system should take no more than one full lab session (3 hours) if all components are readily available and the team is working efficiently!

Lab Exercise – instrument calibration and signal simulation

Each team must calibrate the transmitter to ensure it interprets temperature accurately and outputs an accurate current, and also scale the SCADA system channel to register in the proper engineering units (e.g. a temperature transmitter ranged for 0 to 200 degrees F should actually register 0 to 200 deg F back at the SCADA system display). Instructions for programming the caSCADA system with the proper range for your measurement loop are explained later in this document. Each team should choose a temperature range that covers room temperature, but is something *other* than 0 to 100 degrees so they get practice setting range points on the controller to values other than the default (0 to 100%). Teams using a "smart" temperature transmitter may need to "trim" both the input and output of their transmitter, then set the range (LRV and URV points). Teams using an analog transmitter must apply LRV and URV electrical signals to the transmitter's input while adjusting the "zero" and "span" potentiometers on the transmitter.

As in all cases where an instrument must be calibrated, you will need to check the instrument's response against one or more *standards*. In this case, the standard we will use is either millivoltage (thermocouple) or resistance (RTD) applied to the input of the temperature transmitter using a thermocouple/RTD simulator, while we use a multimeter to measure the transmitter's electronic output signal in DC milliamps:
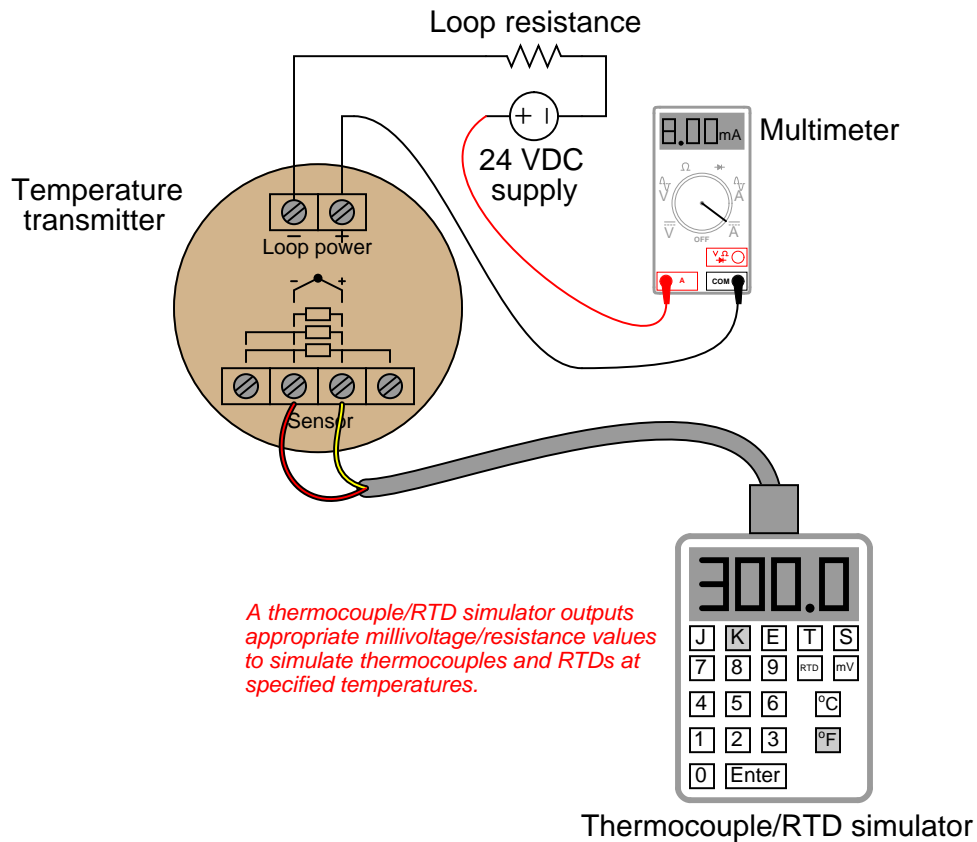
This calibration may be performed at the calibration bench or other work-table, or in the field. Refer to the simulator's documentation for more information on how to make proper wire connections to the transmitter being calibrated. This is especially helpful when simulating 3- or 4-wire RTD sensors.

Document the accuracy of your transmitter's sensor trim before and after adjustment in this table, at five different points throughout its sensing range using these two tables:
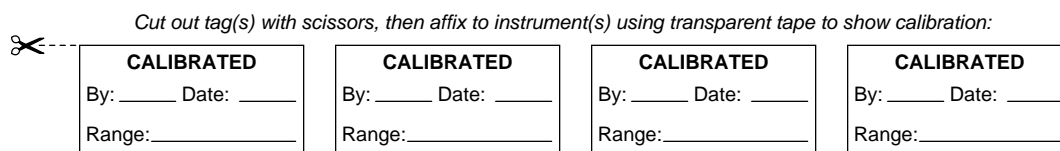
As-Found calibration table

Applied temperature	Output signal (actual)	Output signal (ideal)	Error (% of span)

As-Left calibration table

Applied temperature	Output signal (actual)	Output signal (ideal)	Error (% of span)

$$\text{Error as \% of span} = \left(\frac{\text{Actual} - \text{Ideal}}{\text{Span}} \right) (100\%)$$

When finished calibrating your team's transmitter, be sure to place a calibration tag on it showing the range and the date it was calibrated. A set of calibration tags are shown here which you may cut out and tape to the transmitter after completing your calibration:

Cut out tag(s) with scissors, then affix to instrument(s) using transparent tape to show calibration:

✂ - - - -

CALIBRATED	**CALIBRATED**	**CALIBRATED**	**CALIBRATED**
By: _____ Date: _____	By: _____ Date: _____	By: _____ Date: _____	By: _____ Date: _____
Range:_____	Range:_____	Range:_____	Range:_____

After each team calibrates their transmitter and installs it in the working system, each student on the team must then individually demonstrate their understanding of the electrical signals generated by thermocouples and RTDs by manually simulating appropriate signals at the input of the transmitter to make it register random temperatures called out by the instructor. The purpose of doing this is to ensure each student understands how thermocouples and RTDs actually work, and are familiar with the purpose and use of thermocouple and RTD tables.

For example, if a team calibrates and installs a type J thermocouple transmitter with a range of 0 to 150 degrees Fahrenheit, the instructor will choose a different temperature value within that range (e.g. 102, 93, 77, 128 ^{o}F) for each student on the team to simulate using simple electrical equipment (no thermocouple/RTD simulators allowed here!). Each student passes the "T/C signal simulation" objective when they are able to successfully simulate a specified temperature using nothing more than a multimeter and a low-voltage source (e.g. a DC power supply connected to a voltage divider circuit). Each student passes the "RTD signal simulation" objective when they are able to successfully simulate a specified temperature using nothing more than a multimeter and a low-range variable resistance (e.g. a potentiometer, or a decade resistance box). The instructor checks to see that the temperature value specified appears on the SCADA system display to within ± 1% of transmitter span.

The following illustrations show the general scheme of thermocouple ("T/C") and RTD signal simulation. Resistor values shown in these illustrations are examples only, and may need to be modified for your particular application. *Invest the necessary time for all team members to thoroughly understand how and why these potentiometer networks function as thermocouple and RTD simulators.* A convenient way to determine necessary values for R_1 and R_2 is to set up a computer spreadsheet or use circuit simulation software to experiment with different R_1 and R_2 values to get the desired range of adjustment from your potentiometer. This adjustment range must be reasonable for your temperature transmitter, and be narrow enough that your potentiometer will yield sufficiently fine resolution which is especially important if it only has a 3/4 turn movement range:

Please note that a thermocouple temperature transmitter is easily damaged by providing it with excessive signal voltage. These instruments are designed to receive MILLI-VOLT signals, and so your voltage divider circuit must be designed in such a way that it cannot generate any signal exceeding the transmitter's maximum rating. Be sure to research your transmitter model's maximum input signal voltage value before designing the voltage divider circuit!!
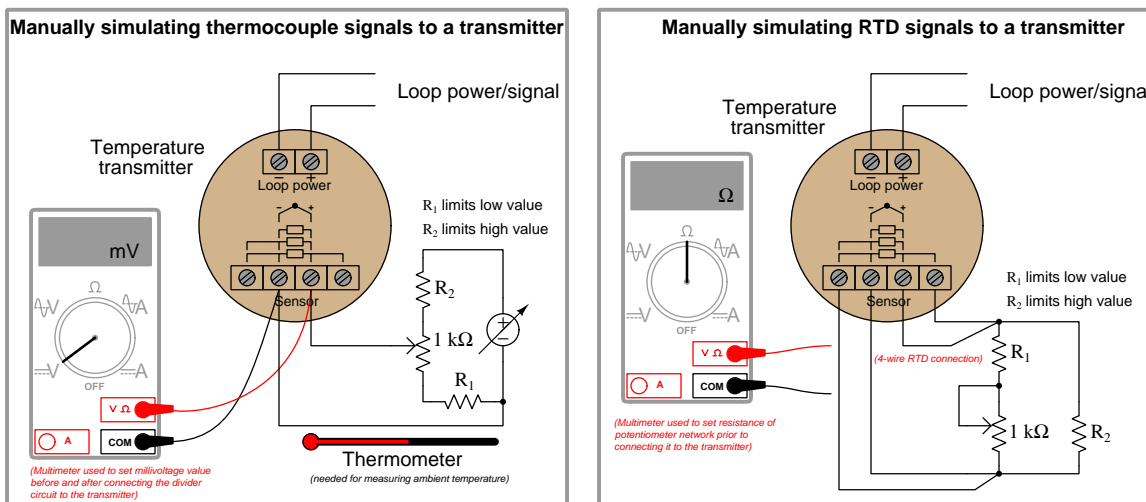
It is recommended that you use a terminal strip rather than a solderless "breadboard" to construct your potentiometer networks, due to the unstable contact resistance typical of breadboards. Use the "relative" function on your DMM's resistance scale to "zero out" the electrical resistance of your meter's test leads when using it to set the resistance of your RTD-simulating network. If your DMM supports a "high resolution" mode for millivoltage measurement, you should use that mode when setting the voltage signal of your thermocouple-simulating network. For RTD and thermocouple simulation alike, adjustments should be made with the simulation circuit disconnected from the transmitter, to avoid interference between the transmitter and the multimeter.

Students typically find the accurate simulation of thermocouple signals to be more challenging than RTD signals, since RTDs simply manifest a certain amount of resistance at each temperature, while thermocouple signals vary with the process (measured) temperature *and* the ambient temperature at the transmitter terminals. For more information on the simulation of thermocouple signals, refer to the "Thermocouples" section of the "Continuous Temperature Measurement" chapter of *Lessons In Industrial Instrumentation*.

Common mistakes:

- Applying excessive voltage to the input of a thermocouple or RTD transmitter. Remember that thermocouples only output small amounts of voltage, in the low millivolt range. I have seen students **destroy** thermocouple transmitters by applying as little as 1.5 volts to its input terminals, thinking that would be a safe amount of voltage for the transmitter!!! To avoid this mistake, set the millivolt signal of your simulating circuit *before* connecting it to the input of your transmitter.
- Neglecting to accurately measure the ambient temperature when manually simulating a thermocouple signal (in order to look up the correct reference junction millivoltage).
- Mis-interpreting rows and columns in the thermocouple/RTD table when looking up millivoltage or resistance values.
- Trying to make potentiometer adjustments while connected to the transmitter's input terminals. This is especially true for RTD simulation, where the transmitter's excitation current to the RTD interferes with the multimeter's resistance measurement.
- Choosing a calibration ("trim") range that is substantially less than the final range of measurement when installed. As a general rule, you should trim the sensor of the transmitter to cover the broadest range of measurement possible with your calibration equipment.
- Ignoring the mathematical signs (+ or −) of error calculations.
- Neglecting to place a calibration tag on the transmitter after calibrating it.

Calibrating your team's transmitter should take no more than one full lab session (3 hours) if the team is working efficiently!

Notes on using SSH for remote administration

Each caSCADA RTU is based on single-board computer running Linux operating system software, located inside an electrical enclosure without convenient physical access. Attaching a keyboard and monitor is impractical, therefore you will need to log in to this computer through some other means.

Fortunately, a digital communication protocol has been developed to permit remote access of Unix-based operating systems called *SSH*, which stands for *Secure SHell*. Any computer running an SSH client program is able to log into any Linux computer running an SSH server program. Any personal computers running a Unix-based operating system (e.g. FreeBSD, Linux, Apple's OS X) have SSH clients built in.

Microsoft Windows operating systems do not have native SSH client software, but one available for free download is `Bitvise`. Another one is called `PuTTY`. For the really ambitious there is even a complete Linux terminal emulation package for Microsoft Windows called `Cygwin`. Any of these programs will suffice, but the easiest to download, install, and use is `Bitvise`. Be sure you download and install the *client* software for `Bitvise`, and not the *server* software (which should already be installed and running on the single-board Linux computer)!

The following screenshot shows `Bitvise` running on a Windows XP machine, communicating with a model of single-board computer called a "Raspberry Pi":
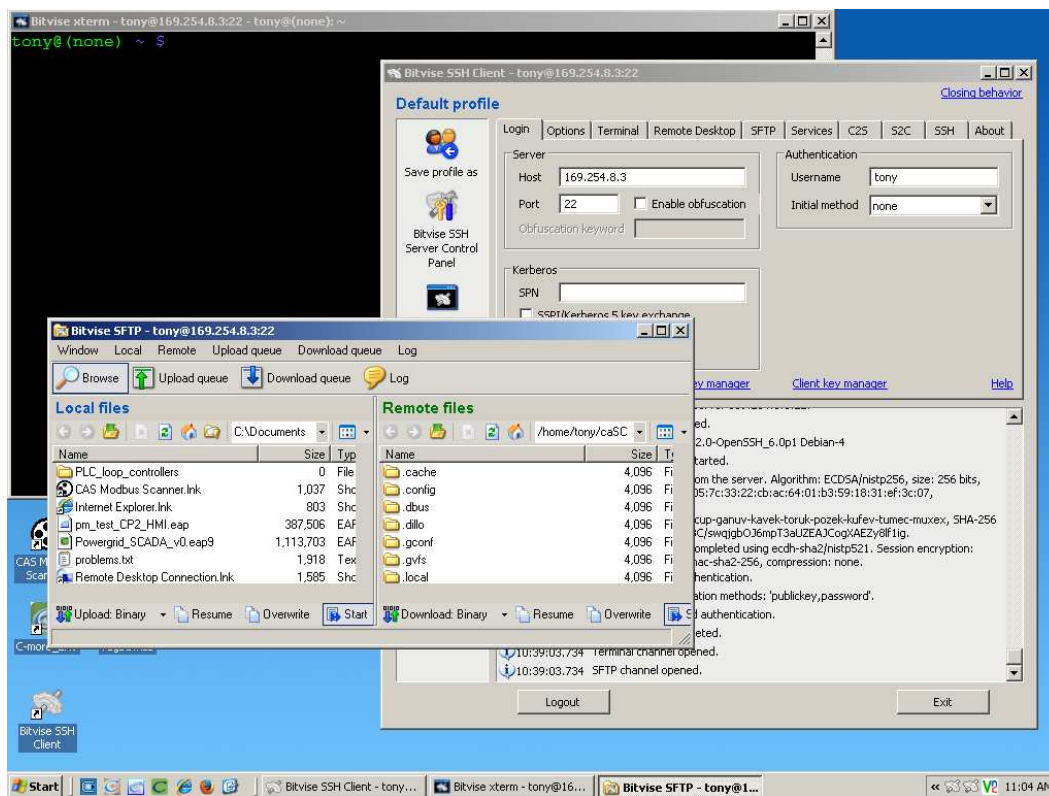
Three windows appear in this screenshot: the `Bitvise` client through which the login connection is established (you must enter the RTU computer's IP address and Linux user name, then later enter the Linux password for that user account), the `Bitvise` SFTP window for file transfer between the two computers, and the `xterm` terminal window (the one with the black background and colorful prompt) where you may enter typed commands to the RTU computer. Since Linux is a multi-user operating system, many people can log into the RTU using their own individual Windows PCs, even under the same user name! All you need is a network connection to the RTU and its IP network address.

Lab Exercise – Linux command-line usage

The caSCADA telemetry system is built on the foundation of a single-board computer running the Linux operating system. Linux is a very robust alternative to Microsoft Windows, and it happens to be entirely free. To use this operating system, you will need to become familiar with typing text-based commands into a *command-line interface* and reading the results given back to you by the computer, rather than pointing and clicking with a mouse. Linux does support mouse-based user interfaces, but the text-based interface is more efficient from the perspective of processing power and memory and so it is what we will use here.

If you have ever used the `cmd` ("command") window on a Microsoft operating system to run utilities such as `ping` or `ipconfig` for network troubleshooting, you are already familiar with what a command-line interface is. Here is an example of the Linux command `ifconfig` (similar to the Windows command `ipconfig`) being run in the command-line interface:

```
tony@(none) ~ $ ifconfig
eth0      Link encap:Ethernet  HWaddr b8:27:eb:ba:f9:0d
          inet addr:169.254.8.3  Bcast:169.254.255.255  Mask:255.255.0.0
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:77541 errors:0 dropped:385 overruns:0 frame:0
          TX packets:23178 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:10964517 (10.4 MiB)  TX bytes:4455164 (4.2 MiB)

lo        Link encap:Local Loopback
          inet addr:127.0.0.1  Mask:255.0.0.0
          UP LOOPBACK RUNNING  MTU:16436  Metric:1
          RX packets:2 errors:0 dropped:0 overruns:0 frame:0
          TX packets:2 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:0
          RX bytes:100 (100.0 B)  TX bytes:100 (100.0 B)

tony@(none) ~ $
```

The dark blue text (`~ $`) is called the *prompt*, which shows me which directory on the computer's filesystem I'm currently viewing and working under. The green text to the left of the prompt tells me I'm logged into the Linux operating system under the username `tony` with an undefined domain name. In a fully configured system, the domain might be something like `btc.edu` or `RTU_MC1`. The white text `ifconfig` is the command I typed (pressing the Enter key at the end), and the two "paragraphs" of text following that line are the results of running the `ifconfig` command. In this particular example it tells me details about the two network interfaces operational on this computer: one Ethernet interface (`eth0`) and one called a "loopback" (`lo`).

There are a great multitude of typed commands available within the command-line environment of the Linux operating system. We will only need to use a few to do our work with the caSCADA system. The next several pages showcase those commands you should learn in order of their importance.

`ls`

The `ls` command lists the contents of a directory, or folder, on the computer's filesystem. Here is an example of the `ls` command being issued by myself (`tony`) while working in my "home" directory (`/home/tony` which is abbreviated as `~`):

```
tony@(none) ~ $ ls
caSCADA   Desktop   letter.txt   pistore.desktop
tony@(none) ~ $
```

The two dark blue listings (`caSCADA` and `Desktop`) are both directories within my home directory (called "subdirectories"). Think of these as folders in which we may store files. The white listing (`letter.txt`) is a file. The light blue listing (`pistore.desktop`) is a *link* to a file of the same name located in a completely different directory. In the Microsoft Windows world, a link is called a *shortcut*.

`ls -l`

This is the same command, issued with the `-l` option. Many Linux commands have options you may specify, each one preceded by a dash. In this case, the `-l` option instructs the `ls` command to provide a *long* (i.e. more detailed) listing of the same files and directories. It should be noted that the `l` symbol is a lower-case letter L, and not the number 1.

```
tony@(none) ~ $ ls -l
total 12
drwxr-xr-x 2 tony tony 4096 Oct  7 20:48 caSCADA
drwxr-xr-x 2 tony tony 4096 Jun 19  2013 Desktop
-rw-r--r-- 1 tony tony   39 Oct  9 20:29 letter.txt
lrwxrwxrwx 1 tony tony   44 Jun 19  2013 pistore.desktop -> /usr/share/indiecity/pistore/pistore.des
ktop
tony@(none) ~ $
```

Here we see how the "long" listing provides much more detail. The series of 10 characters starting each line tell us what type of listing each line is and who has permission to use it (`d` for *directory*, `l` for *link*, a dash symbol for regular files, `w` for *write* permission, `r` for *read* permission, and `x` for *executable* permission). We can also tell the owner and group of each listing (`tony`), the size of the file in *bytes*, and the last date and time that listing was changed.

You will use the `ls` and `ls -l` commands frequently to see which files and directories are accessible to you.

cd

The cd ("change directory") command moves you from one directory to another. This is analogous to clicking on folder symbols in a Microsoft Windows environment. Here we see the ls command issued to list all the items in my home directory (~), then the cd command issued to descend into the caSCADA directory, then the ls command issued one more time to list all the files contained in the caSCADA directory:

```
tony@(none) ~ $ ls
caSCADA  Desktop  letter.txt  pistore.desktop
tony@(none) ~ $ cd caSCADA
tony@(none) ~/caSCADA $ ls
cascada.h                 f_channel_03.c  f_channel_12.c  f_channel_21.c  f_channel_30.c
cascada_poll.c            f_channel_04.c  f_channel_13.c  f_channel_22.c  f_channel_31.c
cascada_poll_simulate.c   f_channel_05.c  f_channel_14.c  f_channel_23.c  LICENSE.txt
cascada.tar               f_channel_06.c  f_channel_15.c  f_channel_24.c  Makefile
data.html                 f_channel_07.c  f_channel_16.c  f_channel_25.c  poll
data.txt                  f_channel_08.c  f_channel_17.c  f_channel_26.c  README.txt
f_channel_00.c            f_channel_09.c  f_channel_18.c  f_channel_27.c  simulate
f_channel_01.c            f_channel_10.c  f_channel_19.c  f_channel_28.c  write_datahtml.c
f_channel_02.c            f_channel_11.c  f_channel_20.c  f_channel_29.c  write_datatext.c
tony@(none) ~/caSCADA $
```

Note how the dark blue prompt changed from ~ to ~/caSCADA after issuing the cd command. This is a reminder to you, the user, of which directory you are currently "in" as you do your work in the command-line environment.

If we wish to go back up one directory level, we invoke the command cd ../ and it will take you there. If you wish to return to your home directory, simply invoke cd without any options or arguments and you will go back home regardless of your present location.

nano
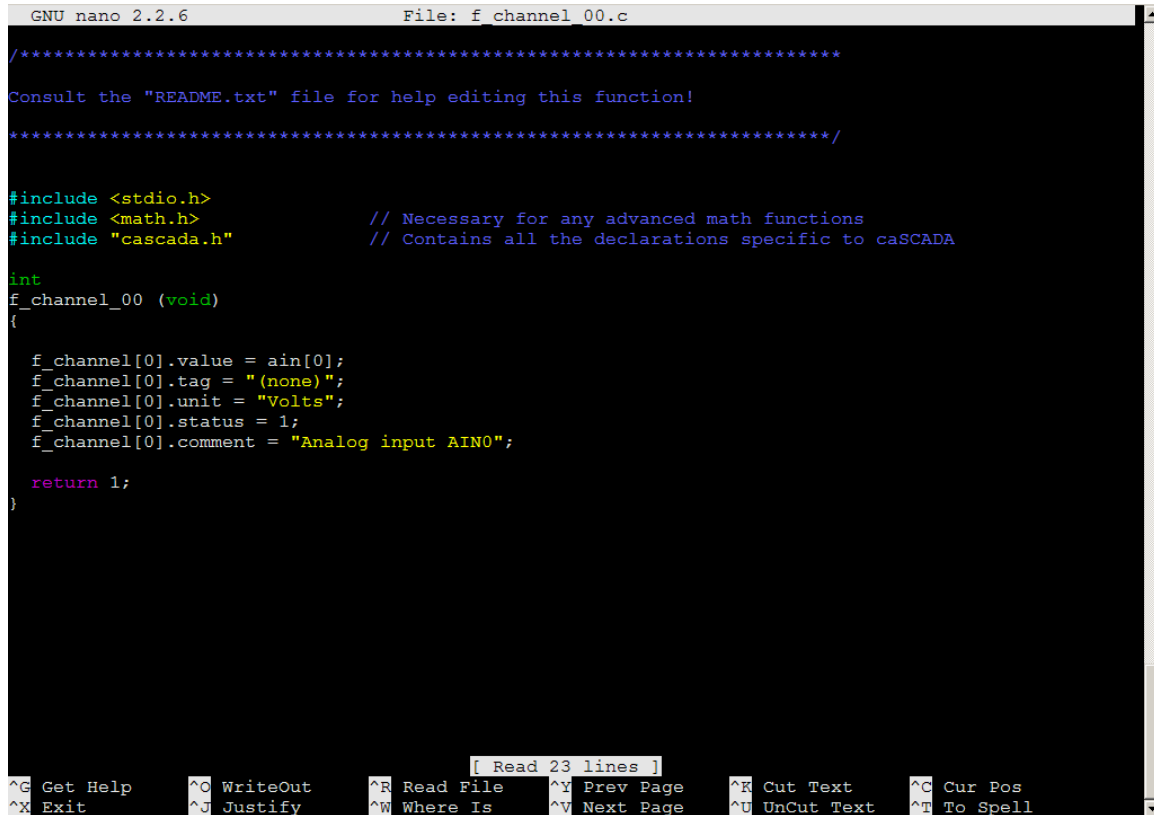
One of the most important applications you will use when using Linux is a *text editor*, used to create and modify plain-text files. You may think of a text editor as being a kind of simplified word processor because it doesn't offer any means of formatting the text to look nice on paper. However, text editors are powerful tools for programming because most offer *syntax-sensitive coloring* to render certain programming instructions in different colors to make them easier to identify.

nano is a popular text editor found on practically all Linux operating systems. It is fast and easy to learn, which is why I'm recommending it to you. To start this program, simply type nano at the command prompt and you will get a mostly blank screen with some key-command reminders at the bottom, like this:

```
  GNU nano 2.2.6                    New Buffer                              ▲








































^G Get Help     ^O WriteOut     ^R Read File    ^Y Prev Page    ^K Cut Text     ^C Cur Pos
^X Exit         ^J Justify      ^W Where Is     ^V Next Page    ^U UnCut Text   ^T To Spell     ▼
```
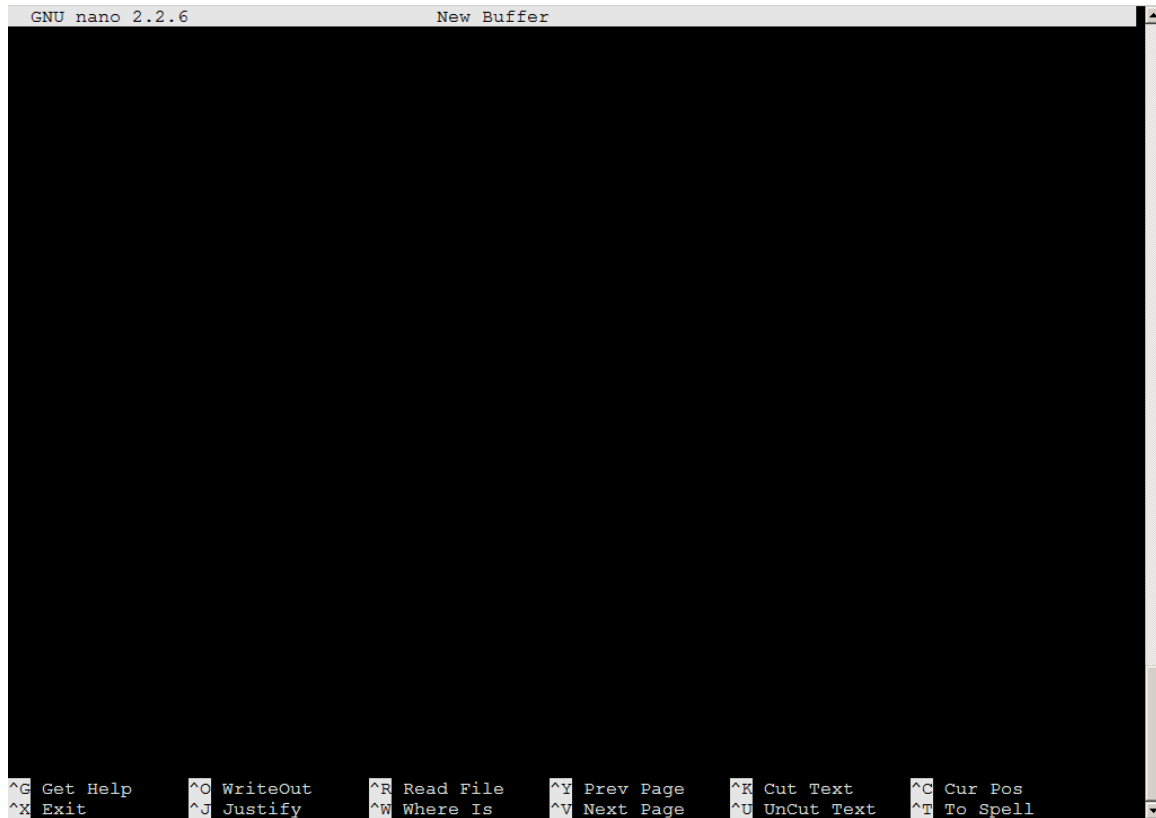
Most of the screen is blank because nano hasn't been told to open any file, and therefore there is no content to view. This is like starting up Microsoft Word (a heinous monstrosity of a program) with a blank page, before we have typed anything. The inverse-colored symbols at the bottom of the screen show you common nano commands, such as viewing a help menu (^G which means holding the "Ctrl" key down while pressing the "G" key), or writing your edits to a file (^O), or exiting the nano text editor (^X) entirely.

If we wish to use `nano` to edit a particular file within our current directory instead, we would simply type `nano` at the prompt followed by the name of the file we wish to edit. Here we see the results of typing `nano f_channel_00.c` at the command-line prompt:

```
  GNU nano 2.2.6                    File: f_channel_00.c

/************************************************************************

Consult the "README.txt" file for help editing this function!

************************************************************************/


#include <stdio.h>
#include <math.h>                // Necessary for any advanced math functions
#include "cascada.h"             // Contains all the declarations specific to caSCADA

int
f_channel_00 (void)
{

   f_channel[0].value = ain[0];
   f_channel[0].tag = "(none)";
   f_channel[0].unit = "Volts";
   f_channel[0].status = 1;
   f_channel[0].comment = "Analog input AIN0";

   return 1;
}




                              [ Read 23 lines ]
^G  Get Help    ^O  WriteOut    ^R  Read File   ^Y  Prev Page   ^K  Cut Text    ^C  Cur Pos
^X  Exit        ^J  Justify     ^W  Where Is    ^V  Next Page   ^U  UnCut Text  ^T  To Spell
```

The file named **f_channel_00.c** is one of the files containing programming code to instruct the caSCADA system what to do. This particular file controls the information for channel 0 in the caSCADA system. You will be editing a source file much like this one when you do your configuration work for the caSCADA system, just for a different channel number. The various colors rendered by `nano` as it views the contents of this file have different meanings in the C programming language, and make the code easier to comprehend than if it were all shown in white.

Once you are viewing the contents of a file, you may use the arrow keys, page up/down keys, Enter key, Delete key, Backspace key, and all the alpha-numeric keys on your keyboard to write and edit text into this file. When complete, you use the command Ctrl-X to save and exit from `nano`.

The *concatenate* command, abbreviated `cat`, simply reads the contents of a text file and prints it all to the screen in the command-line environment. In this example we see the `cat` command used to print the contents of a file named `data.txt` residing within the `caSCADA` directory we have navigated to:

```
tony@(none) ~/caSCADA $ cat data.txt
F_CH #   TAG              VALUE          UNIT          COMMENT
0        (none)           4.2372         Volts         Analog input AIN0
1        (none)           3.8622         Volts         Analog input AIN1
2        (none)           1.6518         Volts         Analog input AIN2
3        (none)           1.5448         Volts         Analog input AIN3
4        (none)           2.1167         Volts         Analog input AIN4
5        (none)           1.6125         Volts         Analog input AIN5
6        (none)           2.9682         Volts         Analog input AIN6
7        (none)           1.3455         Volts         Analog input AIN7
8        (none)           1.6593         Volts         Analog input AIN8
9        (none)           3.5525         Volts         Analog input AIN9
10       (none)           1.8980         Volts         Analog input AIN10
11       (none)           1.4140         Volts         Analog input AIN11
12       (none)           4.6203         Volts         Analog input AIN12
13       (none)           3.9976         Volts         Analog input AIN13
14       (none)           0.0000         (none)        (none)
15       (none)           0.0000         (none)        (none)
16       (none)           0.0000         (none)        (none)
17       (none)           0.0000         (none)        (none)
18       (none)           0.0000         (none)        (none)
19       (none)           0.0000         (none)        (none)
20       (none)           0.0000         (none)        (none)
21       (none)           0.0000         (none)        (none)
22       (none)           0.0000         (none)        (none)
23       (none)           0.0000         (none)        (none)
24       (none)           0.0000         (none)        (none)
25       (none)           0.0000         (none)        (none)
26       (none)           0.0000         (none)        (none)
27       (none)           0.0000         (none)        (none)
28       (none)           0.0000         (none)        (none)
29       (none)           0.0000         (none)        (none)
30       (none)           0.0000         (none)        (none)
31       (none)           0.0000         (none)        (none)
tony@(none) ~/caSCADA $
```

We could have easily viewed the contents of the `data.txt` file using a text editor program such as `nano`, but `cat` is faster and more convenient if all we want to do is *look* at what the file contains and not edit (change) it. While `cat` is useful for viewing caSCADA's `data.txt` file, it may be used to view the contents of *any* plain-text file.

If you choose to learn more about the Linux, you will find that a great many details of the operating system are represented by and controlled by plain-text files. Knowing how to edit those files with a text editor and view those files using `cat` are nothing less than survival skills for Linux users.

Using the `cat` command to display the contents of the `data.txt` file is something you will undoubtedly find yourself doing as you work with the caSCADA system: this file happens to show all the conditioned data in the caSCADA system. As you can see here, the `data.txt` file shows us the last-recorded view of all analog input voltages being read by the data acquisition unit (DAQ), and later when we've customized the C programming code for our instrument loops this same file will show us the signals scaled and presented as real-world measurements.

```
who
```

Linux is a *multi-user* operating system, which means multiple people may log into one computer at any given time, either with individual login names or even under the same name! Microsoft Windows, by contrast, was designed to support only one user at a time. The `who` command gives a listing of all the users logged into the Linux operating system:

```
tony@(none) ~ $ who
root     tty2         2015-10-09 21:28
tony     pts/0        2015-10-09 21:29 (169.254.15.90)
tony@(none) ~ $
```

Here we see two users logged in: one named `root` and the other named `tony`. The green text preceding each command-line prompt tells us who we are (`tony`). If we had any doubt, we could issue the command `whoami` which will reply back with *our* user name.

The `root` user is sometimes called the *super-user* because of their unlimited privileges. The `root` user can delete or edit any file, in any directory, at any time. As far as the Linux operating system is concerned, `root` is God. Therein lies a lesson: never sign into a Linux system as `root` unless you are absolutely, one hundred percent sure of what you are doing.

The text `tty2` tells us that the `root` user is logged into the system at a keyboard that is directly plugged into the RTU computer. "`tty`" comes from the old days of *teletype* machines which were the equivalent of modern computer keyboards. The text `pts/0` (which stands for "pseudo terminal slave") tells us that the user (`tony`) is logged into the system through a *network* connection. The four dot-separated numbers shown in parentheses (`169.254.15.90`) shows the IP network address of the other computer from which `tony` is logging in.

You will probably do most of your work on the caSCADA system via network connection to your own personal computer. Free software is available for your download that lets any Microsoft Windows PC remotely log into any Linux computer using the *SSH* (Secure SHell) protocol. This detail will be discussed later in this document.

All the work you will be doing on the caSCADA system will be through the user account `btc` (password also `btc`). This account will already be set up for you on each RTU's computer.

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Linux is also a *multi-tasking* operating system, like Microsoft Windows. This means it has the ability to execute multiple programs at once. Single-processor computers manage this feat by switching attention really fast between all the running programs, giving the illusion that they're all running simultaneously.

Each running program is called a *process* (not to be confused with the term "process" as it applies to industrial instrumentation). Any user may view running processes on a Linux system by invoking the `ps` command, although this command (without any options) doesn't provide much information.

`ps -e`

If we run the command `ps -e` we will see a very long list of *every* process running in the operating system, including the `ps` command itself:

```
1909 ?        00:00:00 dbus-daemon
1970 ?        00:00:38 ntpd
1975 ?        00:00:01 ntpd
2034 ?        00:00:04 thd
2045 tty1     00:00:00 getty
2046 tty2     00:00:00 getty
2047 tty3     00:00:00 getty
2048 tty4     00:00:00 getty
2049 tty5     00:00:00 getty
2050 tty6     00:00:00 getty
2051 ?        00:00:00 getty
2053 ?        00:00:00 console-kit-dae
2120 ?        00:00:00 polkitd
2151 ?        00:00:03 flush-179:0
2266 ?        00:10:06 simulate
3340 ?        00:00:00 kworker/0:2
3903 ?        00:00:00 kworker/0:1
3964 ?        00:00:00 sshd
3972 ?        00:00:00 sshd
3979 ?        00:00:00 sshd
3980 ?        00:00:00 sshd
3987 ?        00:00:00 sshd
3988 ?        00:00:00 sftp-server
3989 pts/1    00:00:01 bash
4074 pts/1    00:00:00 ps
tony@(none) ~ $
```

The list shown here is so long that it doesn't even fit the whole screen!

`ps -u` *username*

A more useful invocation of the `ps` command shows us all the processes that have been run under a specified user name. Here, we will view all the processes running under the user name `tony` by entering the command as `ps -u tony` (using the `-u` "user" option):

```
tony@(none) ~ $ ps -u tony
  PID TTY          TIME CMD
2266 ?        00:10:06 simulate
3979 ?        00:00:00 sshd
3987 ?        00:00:00 sshd
3988 ?        00:00:00 sftp-server
3989 pts/1    00:00:01 bash
4076 pts/1    00:00:00 ps
tony@(none) ~ $
```

Each line displayed by the `ps` command begins with a number, which is the *Process ID number*, or *PID* (not to be confused with "PID" control for industrial instrumentation!). This number will become very useful to us for the next command.

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kill

From time to time it may be necessary for a user to halt a running process, especially one that runs without a live user interface. This is done using the `kill` command, which works by specifying the process ID number (PID) of the process you wish to terminate.

The following illustration shows how to kill a running process called `simulate`, which happens to be one of the processes used in the caSCADA telemetry system. First, we see the `ps` command being used to list all the processes started by the user `tony` so we can identify its PID, then the `kill` command being invoked to halt that one process, then the `ps` command used again to prove the `simulate` process is no longer running:

```
tony@(none) ~/caSCADA $ ps -u tony
  PID TTY          TIME CMD
 2266 ?        00:10:07 simulate
 3979 ?        00:00:00 sshd
 3987 ?        00:00:01 sshd
 3988 ?        00:00:00 sftp-server
 3989 pts/1    00:00:02 bash
 4183 pts/1    00:00:00 ps
tony@(none) ~/caSCADA $ kill 2266
tony@(none) ~/caSCADA $ ps -u tony
  PID TTY          TIME CMD
 3979 ?        00:00:00 sshd
 3987 ?        00:00:01 sshd
 3988 ?        00:00:00 sftp-server
 3989 pts/1    00:00:02 bash
 4184 pts/1    00:00:00 ps
tony@(none) ~/caSCADA $
```

You will be doing this many times as you work with the caSCADA system, because processes such as `simulate` run in the "background" (i.e. they don't prompt the user for any input, nor do they report any information to the command-line display). When you make changes to the caSCADA software, you will need to "compile" those edits into an executable file that Linux can run, kill the version of that program currently running, and start up your newly modified version.

As part of this lab exercise you will be asked to demonstrate the use of several of these commands, to ensure you are fluent enough in their use to work with the caSCADA system.

Common mistakes:

• Not practicing the use of these commands.

Lab Exercise – editing and running caSCADA code

The caSCADA system has been developed for the express purpose of teaching students how to write their own programming code in the C computer language, while at the same time building a working telemetry (SCADA) system measuring real-world data.

Each student team will be given a different piece of the caSCADA software (called a *function*) to modify for their own purposes. Each team's function resides in its own file ending with the extension `.c` which identifies it as a source code file written in the C language, just like a filename extension of `.txt` identifies the contents of a file as ASCII *text*, or a filename ending in `.pdf` identifies that file as an *Adobe PDF* document. Students will use a text editor to modify their source file, then they will use another program in the Linux operating system called a *compiler* to translate that source code into instructions that Linux can directly execute. After that, they will run their compiled program and monitor how well it performs the intended task.

Like much of the software found on Linux (including all the essential parts of the Linux operating system itself), caSCADA is an *open-source* project. This means all the source code files are available for perusal and modification. This is very different from most of the software that Microsoft Windows users are familiar with, which is generally "closed" and therefore cannot be modified by the end-user.

Most open-source software projects provide a text file called `README` or `README.txt` describing details about the project. caSCADA is no exception to this rule: in the `caSCADA` directory you will find such a file describing how the system works, complete with examples of how to modify the function code to perform practical conditioning on real-world data.

Here is a step-by-step summary of your program development cycle:

(1) Use a text editor (one easy-to-use editor is named `nano`) to modify the source file for the channel you've been assigned. For example, if you are assigned caSCADA channel number 6, then you will need to edit the file named `f_channel_06.c` and then save those changes before exiting the text editor.

(2) Next, re-compile the executable file by issuing a `make` command followed by the name of the executable you wish to create. The `make` command invokes the compiler software for you, handling a bunch of technical details along the way, to make this task simpler. You have only two options here: either run `make poll` to compile the executable called `poll` which gathers real data from the LabJack DAQ unit, or run `make simulate` to compile the executable called `simulate` which generates random data (useful in the absence of a LabJack DAQ) for your function to process.

(3) Use the `ps` command to check for currently-running instances of the executable. If your user name is *btc*, for example, you will want to run `ps -u btc`. If one or more are running, halt them using the `kill` command. *There should never be more than one of* `poll` *or* `simulate` *running at any given time, and neither should you have* `poll` *and* `simulate` *running at once – just one or the other, that's all!*

(4) Start up a new instance of that process by typing the name of the executable (either `poll` or `simulate` depending on what you want to do) preceded by `./` and followed by an ampersand symbol (`&`). For example, if you just compiled the `simulate` executable file, you would run it by typing `./simulate &` at the command prompt. To run the `poll` executable, type `./poll &` at the command prompt. Remember, you only need *one* of these running at any given time. Running multiple instances of `poll` and/or `simulate` will write possibly conflicting data to the data files.

(5) Read the contents of the `data.txt` file to see how the data is being displayed. I recommend typing `cat data.txt` to do this. If a console-based web browser such as `lynx` is installed in the Linux computer, you may alternatively use it to view the contents of the `data.html` file which will produce results that are better-formatted for easier viewing than the plain text file. Both the `poll` and the `simulate` process updates both data files with fresh values once per second. If everything is working as planned, you're done! If not, go back to step 1 to fix your function and repeat all these steps.

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You will find the caSCADA channel functions to be fairly easy to understand, even if you have never done any computer programming before. For example, here is a listing of the default code for the source file `f_channel_10.c`:

```c
/***********************************************************
Consult the "README.txt" file for help editing this function!
***********************************************************/

#include <stdio.h>
#include <math.h> // Necessary for any advanced math functions
#include "cascada.h" // Contains all the declarations specific to caSCADA

int
f_channel_10 (void)
{

  f_channel[10].value = ain[10];
  f_channel[10].tag = "(none)";
  f_channel[10].unit = "Volts";
  f_channel[10].status = 1;
  f_channel[10].comment = "Analog input AIN10";

  return 1;
}
```

The only code you'll have to edit here is what falls between the curly brace characters ({ and }): that is to say, the lines of code assigning values to each element of the `f_channel[10]` data structure. The first of these lines assigns `f_channel[10].value` to be equal to analog input 10 on the LabJack. If AIN10 on the LabJack happens to measure 4.307 volts, another portion of caSCADA will place that value into the external variable `ain[10]`, and when the `f_channel[10]` function is called by the main program the first line copies that value 4.307 into the variable `f_channel[10].value` where another portion of the caSCADA program will displayed it a file named `data.txt` (as well as in another file named `data.html`. The lines assigning text (between quotation marks) to the `.tag`, `.unit`, and `.comment` elements are for free-form text. The `.status` element is normally set to a value of 1 (which means "good" status), but may be set to other values at your discretion.

As written, this default function doesn't do much other than directly display channel 10's value in volts and applies some text labels. This is where your work becomes important: your task will be to modify the code for your channel to make it do something more useful, like scale the analog input's voltage value into a real-world measurement complete with appropriate units. This lab exercise is focused on *temperature*, and so your modified channel function will have to scale the received voltage signal into a temperature measurement expressed in *degrees* F, C, R, or Kelvin.

You are welcome to make your function code as simple or as sophisticated as you desire. Multiple examples are shown in the `README.txt` file located with the other source files on the RTU computer. The following code segment shows a simple version of the `f_channel_10.c` source file written to scale analog input number 3's 1-to-5-volt DC signal into a *pressure* measurement range of 0 to 75 PSI using a $y = mx + b$ equation where $m = 18.75$ and $b = -18.75$:

```
int
f_channel_10 (void)
{

  f_channel[10].value = (ain[3] * 18.75) - 18.75;
  f_channel[10].tag = "PT-42";
  f_channel[10].unit = "PSI";
  f_channel[10].status = 1;
  f_channel[10].comment = "Receiver tank pressure";

  return 1;
}
```

A good way for each student on a team to get experience programming a different mathematical function without having to re-range their team's transmitter each time is to re-program the function for a different unit of temperature measurement on the exact same calibrated range. For example, one student programs caSCADA to read out in degrees Fahrenheit, another in degrees Celsius, another in degrees Rankine, and another in Kelvin, but each and every one of these uses the exact same transmitter range. This objective could even be checked by the instructor at the same time as the RTD or thermocouple simulation objective, with the student applying a simulated RTD/thermocouple signal to the transmitter and showing that simulated temperature displayed in a unique unit on the caSCADA display (i.e. the contents of the live `data.txt` or `data.html` file.

If you would like to learn more about the mathematical and algorithmic capabilities offered by the C programming language, an excellent resource is the book *The C Programming Language* written by the inventors of C: Brian W. Kernighan and Dennis M. Ritchie. Many other C programming tutorials and references may be found on the internet as well. Suffice it to say, you can program each function to do almost *anything* to and with the channel data. You may even program your function to read the values, statuses, and text fields of other channels, since all default channel variables are "global" (also called *external*) and therefore accessible to all portions of the caSCADA software.

C is a professional-grade programming language, which means that although the caSCADA system was written for use as a student learning system, anyone wishing to extend the capabilities of caSCADA beyond its intended use is welcome and able to do so because the C language is sufficiently capable for practically any task. The fact that caSCADA is an *open-source* software project means anyone has the freedom to sample the C programming code and modify it to their heart's content without the need to request permission from the original developer. This is the real beauty of open-source software: it gives you both the right and the means to *learn* from the code and *extend* that code well beyond its original intent.

Common mistakes:

- Syntax errors resulting from incorrect characters added to the code, or necessary characters deleted from it. *Pay close attention to the color highlighting presented by the text editor (*`nano`*), as this often reveals such errors.*
- Failing to follow all steps of the programming development cycle (e.g. neglecting to recompile edited source code using the `make` command, failing to kill the old (running) version and re-start the new version).
- Running multiple instances of `poll` and/or `simulate` on the same RTU. This will cause conflicting data to be written and re-written to the `data.txt` file. The most common cause of this problem is when multiple students log in to the same caSCADA RTU and attempt to test their code simultaneously.
- Leaving a HART communicator connected to the transmitter's 4-20 mA circuit, which will result in the caSCADA system picking up on bursts of FSK data. This will make the signal appear to "jump" around.
- Not using ISA-standard tag names for each channel.

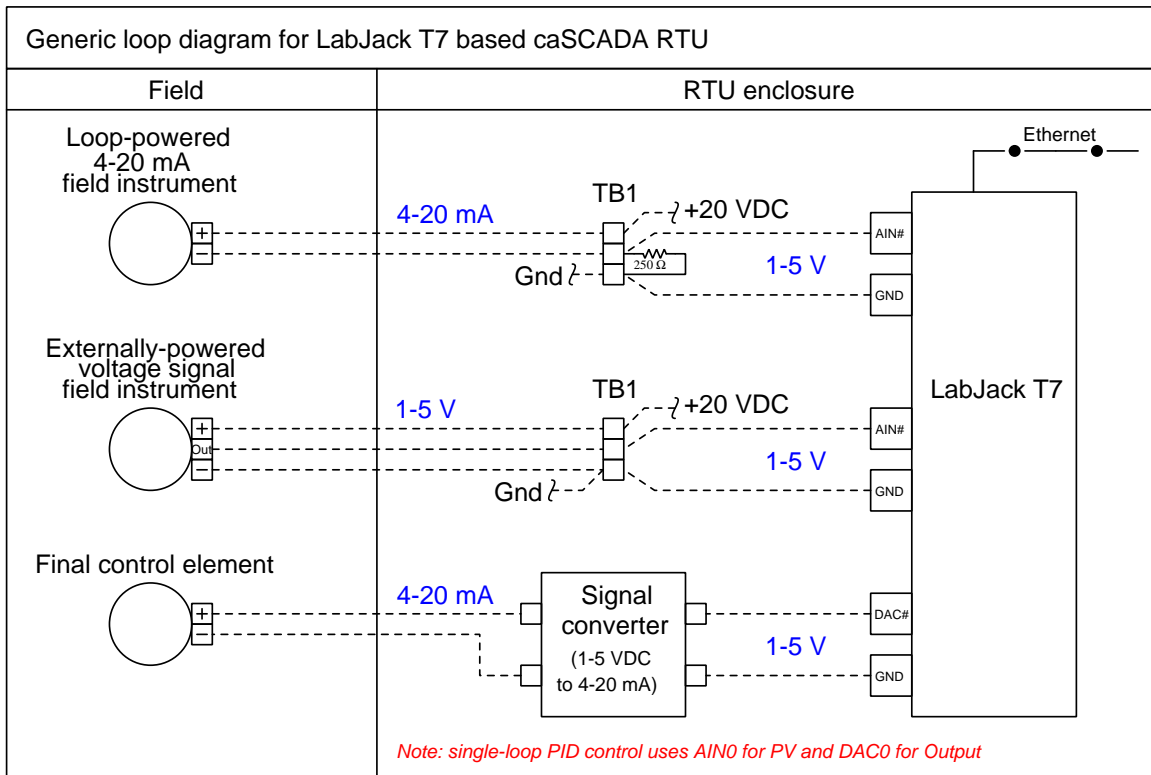file i00378

RTU component layout

An "RTU" is a *Remote Terminal Unit* in a SCADA system serving as the interface between field instruments and a central control/display unit called the "MTU" (*Master Terminal Unit*). In our caSCADA system, the MTU is just a laptop computer viewing data generated by the single-board Linux computer in each RTU. Each RTU uses a LabJack data acquisition unit to sense analog signals sent by field transmitters and a single-board computer to condition and present that data in the form of digital data files readable by the MTU. Communication takes place via a wireless access point (WAP) router:
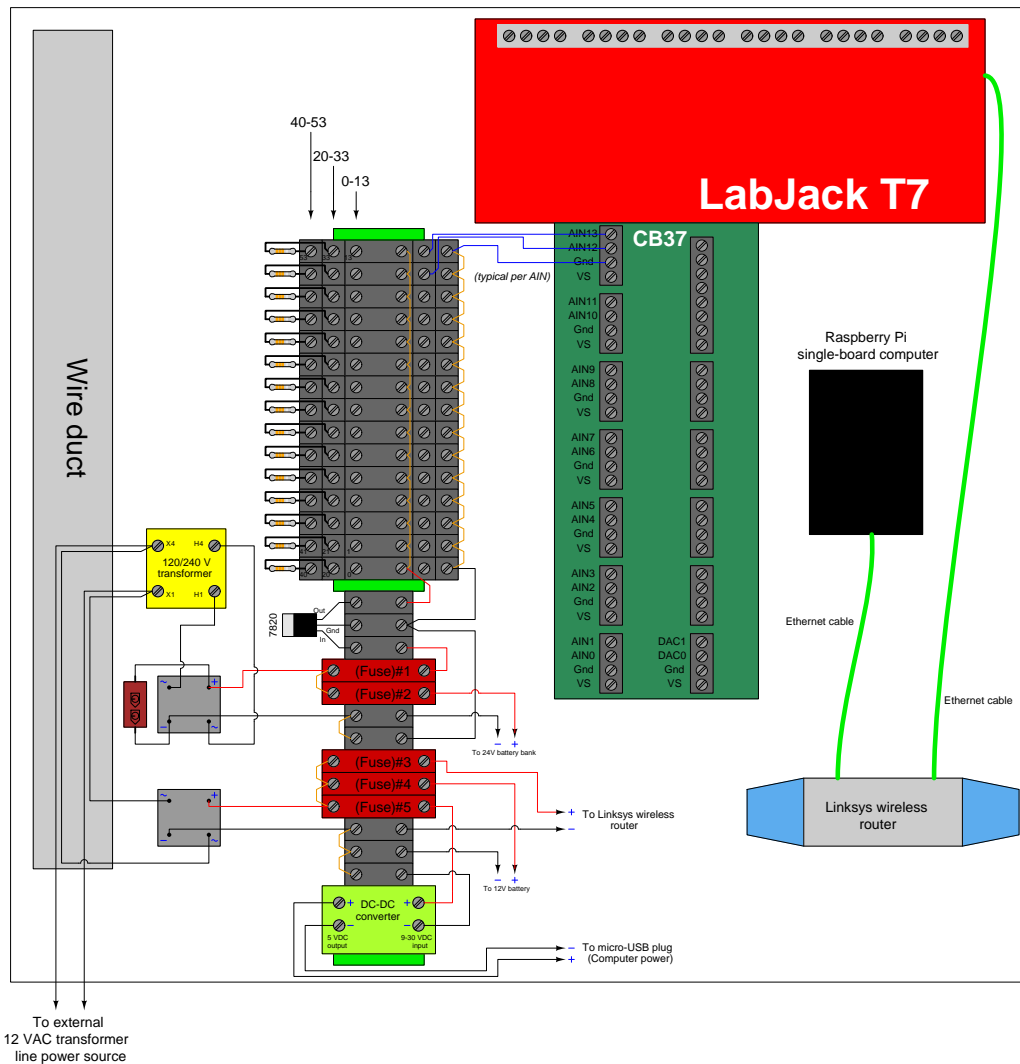
Each RTU enclosure is weatherproof, and equipped with a set of batteries to maintain DC power to all the system components in the event of an external AC power failure.

The upper level of terminals on the triple-level blocks should all be jumpered together because this is the 20 VDC "bus" used to power all field instruments. The lower level of terminals should also be jumpered together because they comprise the negative side ("Common" or "GND") of that same 20 VDC loop power supply.

Sample loop diagrams

Generic loop diagram for LabJack T7 based caSCADA RTU

*Note: single-loop PID control uses AIN0 for PV and DAC0 for Output*

A set of triple-height terminal blocks marshall field instrument signals to the DAQ input terminals, with the three terminals of each block represented in the above diagram. The top-most terminal is the + DC power supply bus, the middle terminal connects to the LabJack DAQ input channel, and the bottom terminal is the − DC power (GND) supply bus. Both current-based and voltage-based instrument signals may be accepted by the DAQ. In the case of 4-20 mA loop instruments, a precision 250 Ω resistor is connected in such a way to provide a 1-5 VDC signal for the DAQ to sense. If the field instrument outputs a voltage signal instead (which is actually quite common for RTU loops in remote installations relying on solar power) then the resistor is omitted and the LabJack AIN directly reads that instrument's output voltage.

The LabJack DAQ also provides two analog *output* channels (DAC0 and DAC1) for analog control of a final control element. In a caSCADA system these output channels are connected to an external signal converter, and the resulting 4-20 mA output signal may be used to drive an I/P transducer, electronic valve positioner, or VFD.

When using a caSCADA system for PID loop control, the Process Variable (PV) input is input channel AIN0 and the Manipulated Variable output is output channel DAC0. The PID control application may be invoked by entering `./pid` at the command line.

Electrical power diagram
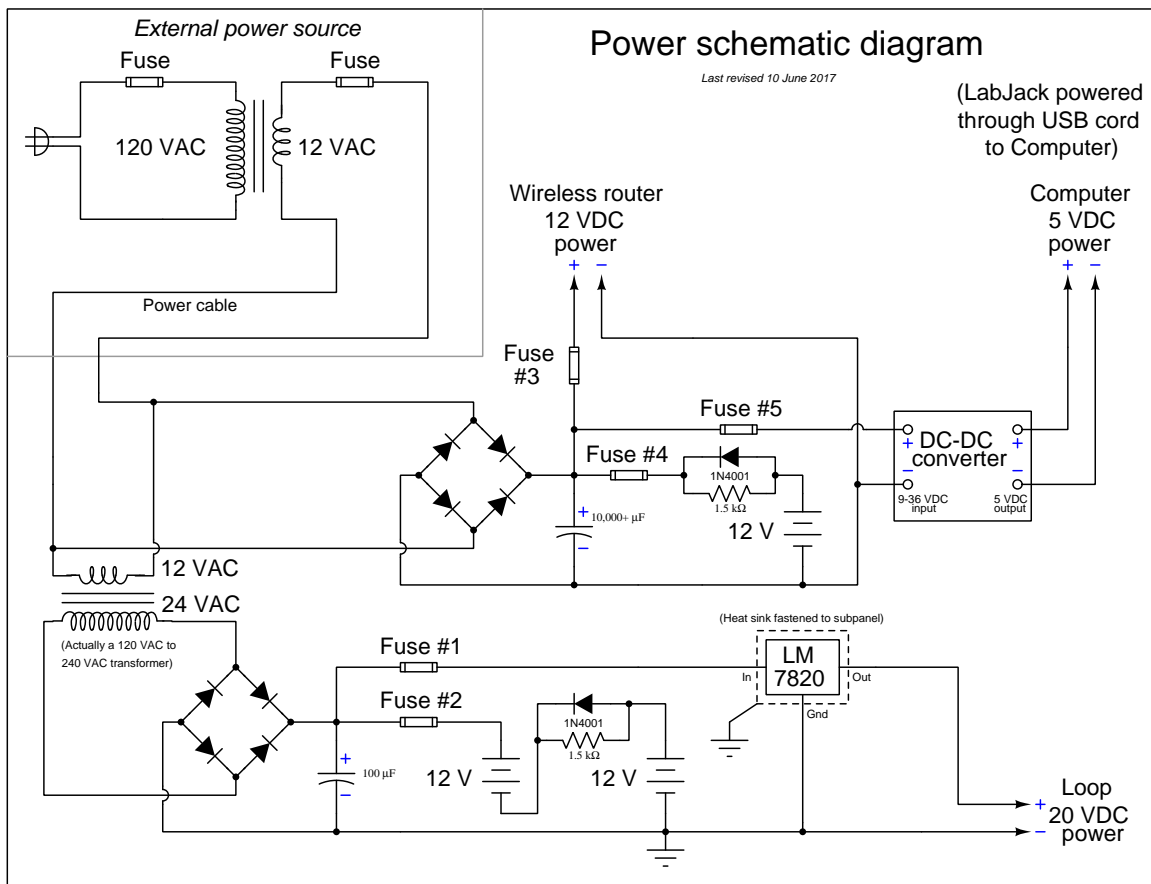
Power is sent to each RTU box at 12 volts AC, from a transformer located near a 120 VAC power source. This keeps the field power cable at a safe, low voltage (similar to outside sprinkler control systems and walkway lighting).

Internal to each RTU is a dual-voltage DC system: 12 volts (regulated down to 5 VDC) for running the Linux-based computer, LabJack DAQ, and Linksys WRT54GL wireless router; and 20 volts for powering the field instruments. Lead-acid batteries provide back-up power for the RTU to continue running in the event of a power outage. The resistor-diode network limits battery charging current to a bare minimum, while providing full current capacity in the discharge direction (in the event of an AC line power outage).

24 volts is a more customary DC supply voltage for loop-powered field instruments, but the LabJack model T7 DAQ has an absolute maximum input voltage of 20 VDC. Thus, the loop supply voltage is limited to this value to avoid the potential for damage to the LabJack in the event of a shorted instrument cable which would apply full power supply voltage to the DAQ input.

RTU power system testing procedure

You must follow this procedure when first commissioning a new RTU. When working with an existing RTU, you may follow the same procedure to test the continuing health of the DC power system.

(1) Test the external 12 VAC transformer by itself: when plugged into a 120 volt AC source, does it output at least 12 volts AC?

(2) Open up all fuses (#1 through #5) to ensure no device will become powered until you intend so.

(3) Connect this external 12 VAC transformer's output to the RTU as shown in the diagrams and apply power. Check the output of both bridge rectifiers for proper DC voltage magnitude and polarity. Due to the filter capacitors the DC voltage magnitudes will register greater than the AC voltage magnitudes feeding each of the bridge rectifiers.

(4) Ensure the batteries are wired to the proper terminal blocks and fuse holders, and measure DC voltage magnitudes and polarities at the battery-side of each open fuse. This ensures the batteries are properly connected.

(5) Close fuses #2 and #4. This connects the two battery banks to their respective charging sources. Re-measure the voltage magnitudes at the battery-side of each closed fuse. You should read slightly higher voltage now than in the previous step, because the batteries are charging.

(6) Ensure all power plugs are removed from the caSCADA electronic devices: the LabJack DAQ unit, the RTU computer, and the Linksys wireless router. Prepare to measure DC voltage at the ends of those power plugs.

(7) Close fuse #3 and measure DC voltage magnitude and polarity at the Linksys router's power plug. Check the router's documentation for the proper DC polarity of the plug's shell and tip to see that the polarity is correct. If all is well, plug the power cable into the router and check to see that it powers up. Re-measure voltage magnitude at fuse #3 to see that the router is receiving adequate voltage while powered (i.e. under load).

(8) Close fuse #5 and measure DC voltage magnitude and polarity at the RTU computer's micro-USB power plug. Check online for the "pinout" specification of a micro-USB power plug to see that the polarity is correct. If the pins on the micro-USB plug are too small to safely probe using your multimeter, you may check DC voltage at the stripped end of that cable where it lands at the terminal block, and verify correct voltage and polarity according to the colors of that cable's wires. If all is well, plug the power cable into the RTU computer and check to see that it powers up.

(9) Plug the B-style USB cable into the LabJack. It receives power through the RTU computer and should power up immediately. Re-measure voltage magnitude at fuse #5 to see that both the RTU computer and LabJack units are receiving adequate voltage while powered (i.e. under load).

(10) Close fuse #1 to apply 20 VDC power to the field instrument terminal blocks. Measure DC voltage magnitude and polarity between terminals 13 and 53 to ensure 20 VDC is supplied all the way to the end of the terminal block section.

(11) At this point in time you may initialize the caSCADA system MTU (a laptop PC) and test the system for proper data. A procedure for this is given on the following page.

(12) Unplug the external 12 VAC transformer from its line power source, and re-measure all DC supply voltages to ensure all devices are receiving adequate voltage under battery power alone.

(13) Repeat these DC voltage measurements at one-hour intervals to check the health of the batteries.

RTU data system testing

You must follow this procedure when first commissioning new devices for an RTU.

(1) Ensure that the proper IP addresses are all written on labels affixed to each of the networked devices in the RTU: the LabJack DAQ unit, the Linksys wireless router, and the single-board computer.

(2) Set the IP address and subnet mask of your personal computer to appropriate values for the Ethernet device you wish to connect to. For each octet of the subnet mask with the value "255" the octet of your PC's IP address must match the IP addresses of all devices in the RTU. For each octet of the subnet mask with the value of "0" the octet of your PC's IP address must be different from any device in the RTU. This will prepare your PC for direct Ethernet cable connection to the device you intend to configure.

(3) Plug your computer into the Linksys router using an Ethernet cable, and set the router's IP address and subnet mask and name using a web browser. Follow the instructions given in the manual for the router. The router's name should make sense to any user of the system. In an area with multiple RTUs, the name should be specific enough to clearly identify which RTU it is.

(4) Plug your computer into the LabJack DAQ using an Ethernet cable, and set the DAQ's IP address and subnet mask using the software provided by LabJack for this task. Follow the instructions given in the LabJack manual.

(5) Plug an HDMI monitor and USB keyboard into the single-board computer, and log in directly to set its IP address and subnet mask. To check its current settings, use the `ifconfig` command (similar to the `ipconfig` command in Microsoft Windows). If the settings are not correct, you may change them by editing the file `/etc/network/interfaces`. This requires "root" privileges. Lines of text in this `interfaces` file follow this pattern:
   - The line specifying the `eth0` interface must read `iface eth0 inet static`
   - Prior to the `eth0` line must be a line that reads `auto eth0`
   - The "address" line contains the IP address (e.g. `address 169.254.8.3`)
   - The "netmask" line contains the subnet mask (e.g. `netmask 255.255.0.0`)

(6) Unplug the Ethernet cable from your personal computer and wirelessly connect to the Linksys router. The router will automatically assign an appropriate IP address to your computer's wireless card, as routers are designed to do.

(7) Use the `ping` command in your computer to test network connectivity with each device in the RTU. This command is simply the word "ping" followed by the IP address of the device you wish to ping. For example, `ping 169.254.8.1` will test to see whether your computer has connectivity with the device bearing the IP address 169.254.8.1.

(8) Once all devices have been proven to ping successfully, you may use an SSH client program in your personal computer (e.g. `Bitvise`) to log into the RTU computer. The login account is simply `btc` with the password `btc`.

(9) Once you are logged in to the Linux operating system, you may try compiling the caSCADA code and then running it (either `poll` process or the `pid` process) to test its ability to communicate with the DAQ unit.
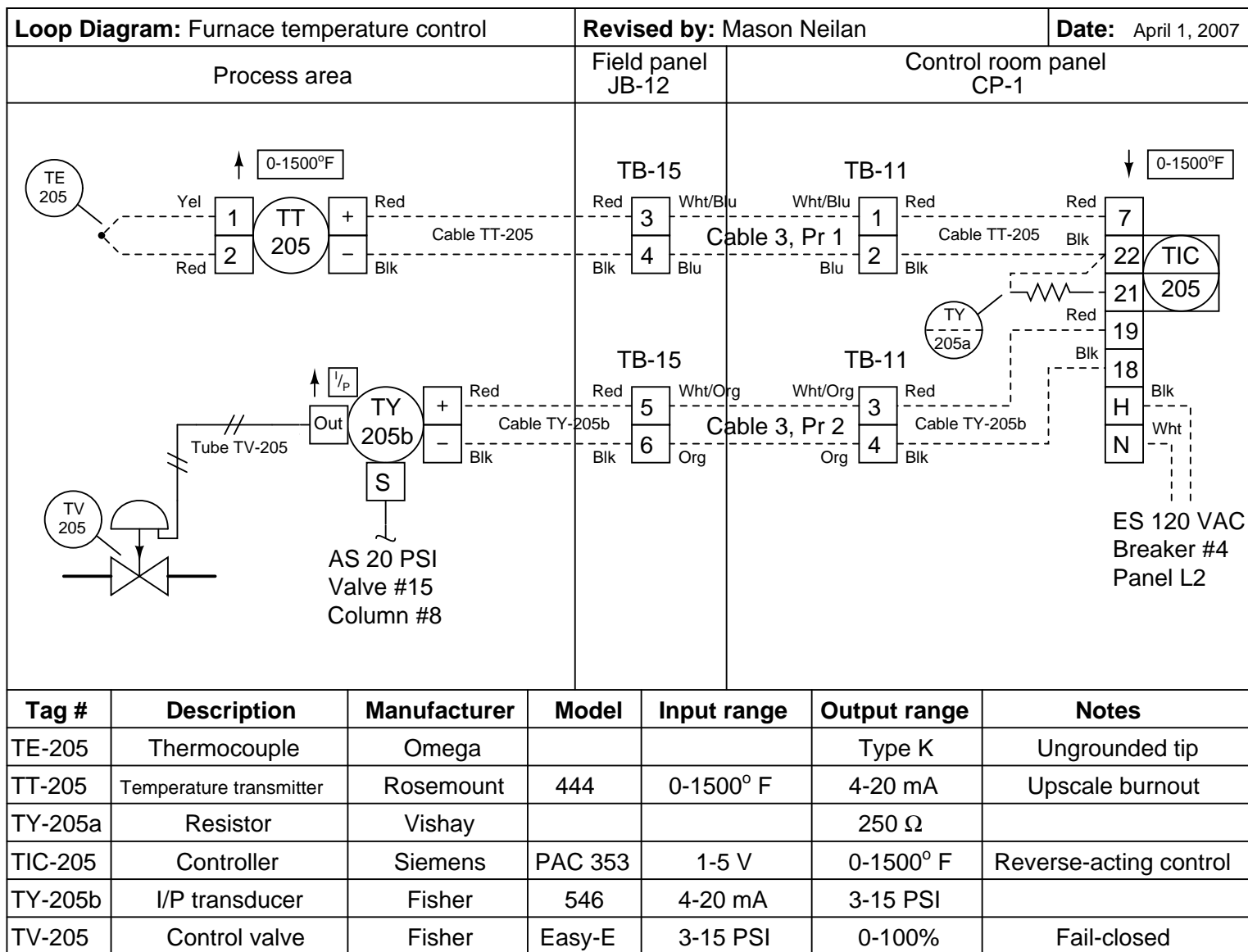
Preparing the "Raspberry Pi" single-board computer for use in the caSCADA system

To initially configuring a Raspberry Pi to be used in the caSCADA system, there are several things which must be done:
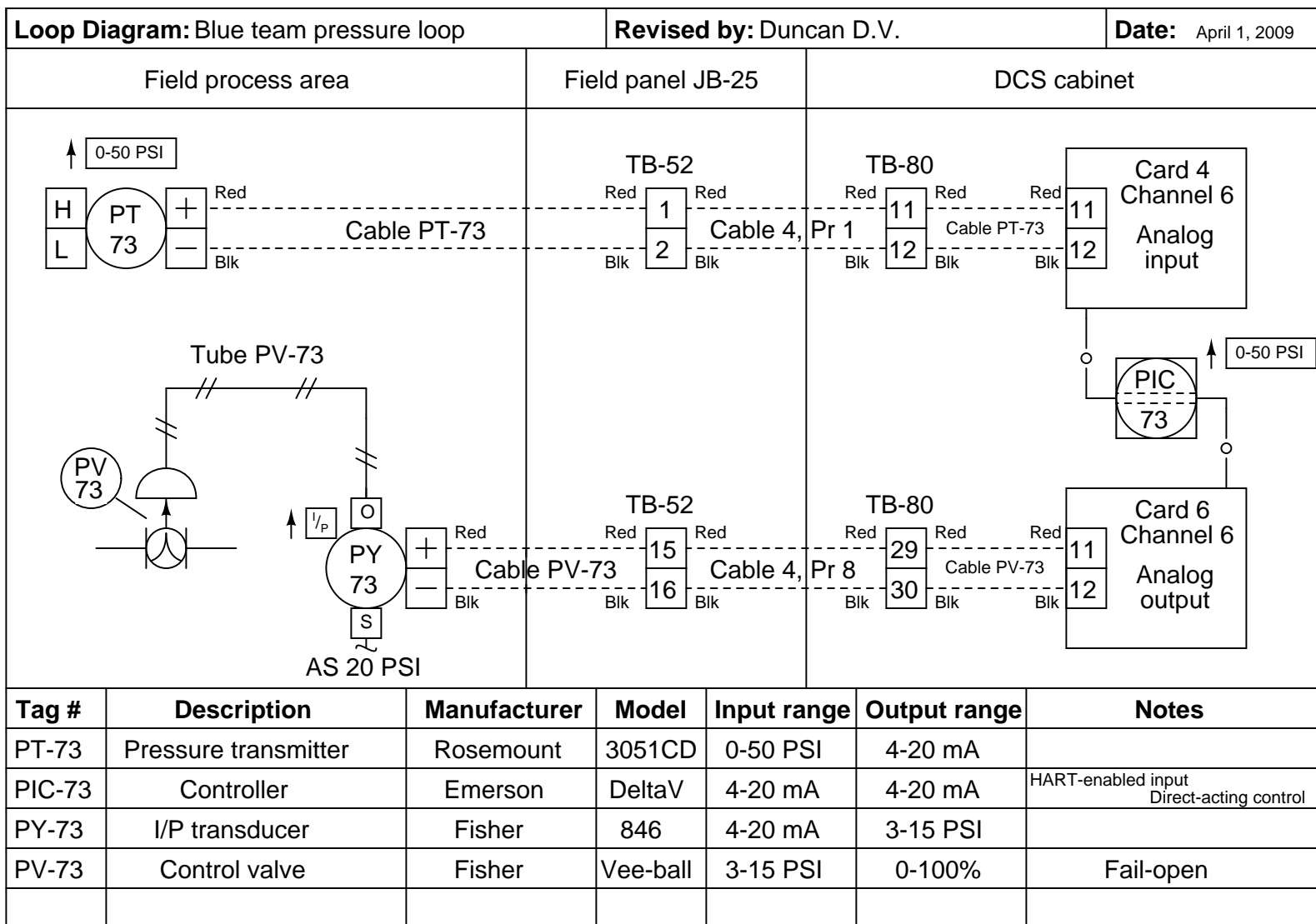
- Log in as the default user (name = `pi` and password = `raspberry`)

- Use the `sudo` and `passwd` commands to reset the root account's password to your liking (e.g. `sudo passwd root`). There are several tasks for which root privileges are necessary, so it's convenient to be able to log into the root account and do that work there, rather than have to preface all those commands typed under the `pi` login user with the "`sudo`" qualifier.

- Use the `raspi-config` utility to set the system's hostname, configure the keyboard for US mapping (as British "UK" mapping is the default!), and also enable the `ssh` server which will be essential for remote login and system administration.

- Add a new user account called `btc`.

- Feel free to edit the hidden file named `.profile` in the `/home/btc` directory with any special instructions to be executed at login. For example, you may add lines containing the `echo` shell command to print messages to the screen for the user once they log in (e.g. `echo "Welcome to the fish hatchery RTU"`).

- Set the current time and date using the `date` command. The format is MMDDhhmmCCYY. For example, 3:21 PM on November 5, 2016 would be set by issuing the command `date 110515212016`.

- Navigate to the `/etc/network` directory and edit the file named `interfaces` to set all the required IP address and netmask information to give the Raspberry Pi a static IP address for use in the caSCADA system. Lines of text in this `interfaces` file follow this pattern:
  - The line specifying the `eth0` interface must read `iface eth0 inet static`
  - Prior to the `eth0` line must be a line that reads `auto eth0`
  - The "address" line contains the IP address (e.g. `address 169.254.8.3`)
  - The "netmask" line contains the subnet mask (e.g. `netmask 255.255.255.0`)

- Install the `cascada.tar` archive file in the `/home/btc` directory, and then use the command `tar xvf cascada.tar` to unpack that archive file.

- Install the latest `libmodbus` library archive file in the `root` directory, then uncompress it (`gunzip libmodbus*.gz`) and unpack the archive (`tar xvf libmodbus*tar`) and then descend into the new `libmodbus` directory to build it. This library is absolutely necessary for caSCADA to run, as it contains all the code necessary to read and write Modbus device registers over a TCP/IP network. Build and install the new software using the commands `./configure ; make ; make install ; ldconfig`. Check the general header file repository (located in the directory `/usr/include/`) to see if the installation script successfully copied the file named `modbus.h` there. In the versions of `libmodbus` I've installed, I have had to copy the `modbus.h` file to the `/usr/include` directory manually.

- Install the latest `ncurses` library archive file in the `root` directory, then uncompress it (`gunzip ncurses*.gz`) and unpack the archive (`tar xvf ncurses*tar`) and then descend into the new `ncurses` directory to build it. This library is necessary to run the `lynx` web browser, as well as the graphic interface for the caSCADA `pid` controller process. Build and install the new software using the commands `./configure ; make ; make install ; ldconfig`.

- Install the latest `lynx` text-based web browser software archive file in the `root` directory, then uncompress it (`gunzip lynx*.gz`) and unpack the archive (`tar xvf lynx*tar`) and then descend into the new `lynx` directory to build it. Build and install the new software using the commands `./configure ; make ; make install ; ldconfig`.

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- Navigate to the `/home/btc` directory and edit the file `cascada_poll.c` with the correct IP address to establish a Modbus/TCP connection with the LabJack DAQ unit in your RTU. The function establishing the address will be easy to find in this file, as it calls out the IP address in standard four-octet format. Just edit the IP address that's shown, and the caSCADA `poll` software will be able to communicate with that LabJack DAQ.

- Try running `make` in the `/home/btc` directory to verify all the caSCADA software components successfully compile.

  file i02566

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

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

0-1500°F

TE 205
Yel 1
Red 2
TT 205
+ Red
− Blk

Cable TT-205

TB-15
Red 3 Wht/Blu
Blk 4 Blu

Cable 3, Pr 1

TB-11
Wht/Blu 1 Red
Blu 2 Blk

Cable TT-205

0-1500°F

7 Red
22 Blk
TIC 205
TY 205a
21
19 Red
18 Blk

TY 205b
I/P
Out
+ Red
− Blk
S

Tube TV-205

AS 20 PSI
Valve #15
Column #8

TV 205

TB-15
Red 5 Wht/Org
Blk 6 Org

Cable TY-205b | Cable 3, Pr 2

TB-11
Wht/Org 3 Red
Org 4 Blk

Cable TY-205b

H Blk
N Wht

ES 120 VAC
Breaker #4
Panel L2

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

Field process area

0-50 PSI

H
L
PT 73
+ Red
− Blk

Cable PT-73

Field panel JB-25

TB-52
Red | Red
1
Cable 4, Pr 1
2
Blk | Blk

DCS cabinet

TB-80
Red | Red | Red
11
Cable PT-73
11
12
12
Blk | Blk | Blk

Card 4
Channel 6
Analog input

0-50 PSI
PIC 73

Tube PV-73

PV 73

I/P

O
PY 73
+ Red
−
Blk
S

AS 20 PSI

Cable PV-73

TB-52
Red | Red
15
Cable 4, Pr 8
16
Blk | Blk

TB-80
Red | Red | Red
29
Cable PV-73
11
30
12
Blk | Blk | Blk

Card 6
Channel 6
Analog output

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

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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

H
L
LT 24
Out
In

(vent)

A.S. 21 PSI

14

Tube LT-24b

C
LIC 24
D

Supply

A.S. 21 PSI

LV 24

Tube LV-24

Tube LV-24   Tube LV-24

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

Sample Loop Diagram (using PLC, with electronic positioner installed on valve)

Loop Diagram: Unit feed flow control	**Revised by:** A. Bradley	**Date:** April 1, 2013
Process area	Field panel FP-25	

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

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

Lab Exercise – loop diagram and system inspection

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

Construction Standards

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

Documentation Standards

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

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

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

Common mistakes:

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

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

file i00654

Answer 1

Answer 2

Answer 3

Answer 4

Answer 5

Answer 6

Answer 7

Partial answer:

$$E_{meter} = E_{meas} - E_{ref} + E_{comp}$$

Answer 8

In the calibration circuit, there is not a trace of thermocouple wire to be found. Instead, all wires are made of copper. This presents a problem for us because the temperature instrument has a reference junction compensation circuit built in, which at this point is compensating for a reference junction millivoltage that doesn't exist. The instrument actually "sees" the series combination of the potentiometer's output voltage ($E_{potentiometer}$) and its own internally-generated compensation voltage ($E_{compensation}$), not the potentiometer voltage by itself. This is why we cannot simply set the potentiometer to the millivoltage corresponding to our calibration temperature point and adjust the instrument to read the same.

I'll let you figure out exactly how to work around this problem!

Answer 9

Partial answer:

- **Type K**
- 300° F ; Potentiometer setting = 5.116 mV

- **Type J**
- 400° F ; Potentiometer setting = 10.006 mV

- **Type J**
- 750° F ; Potentiometer setting = 21.280 mV

When any electrical instrument is said to have a high input impedance, it means that it draws very little current from the source of voltage it is measuring. This is true for any ideal voltmeter: that it measure voltage without "loading" the source of voltage by drawing substantial amounts of current from it. It usually means that the instrument has a high DC resistance, but the word "impedance" implies other forms of opposition to electric current as well (namely capacitive and inductive reactance – specific types of opposition to alternating current).

It is important for a thermocouple-based temperature instrument not to draw much current from the thermocouple it connects to, because thermocouple wires typically have greater electrical resistance per length than copper wires of similar gauge. If there is substantial current in the thermocouple circuit, voltage will be dropped along the wire lengths, resulting in a measurement error:

Voltage dropped along wire lengths
due to current in the circuit
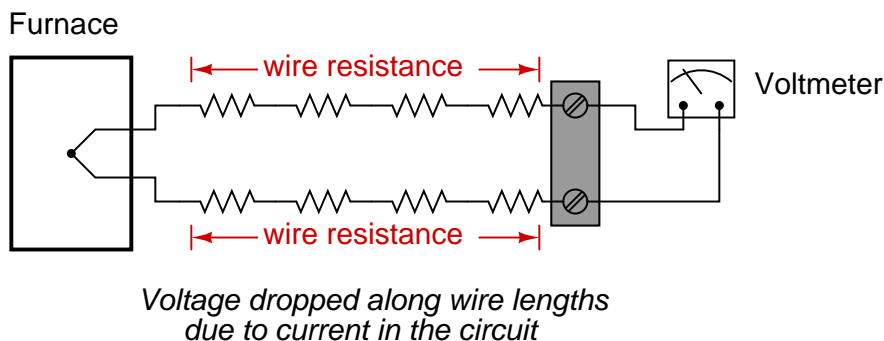
One way would be to build an operational amplifier ("op-amp") buffer circuit to power an analog voltmeter movement. Operational amplifiers typically have input impedances in the millions or billions of ohms (the TL082, an inexpensive, general-purpose JFET-input op-amp, has a typical input impedance of $10^{12} \, \Omega$, or 1 *trillion* ohms!). The circuit would look like this:
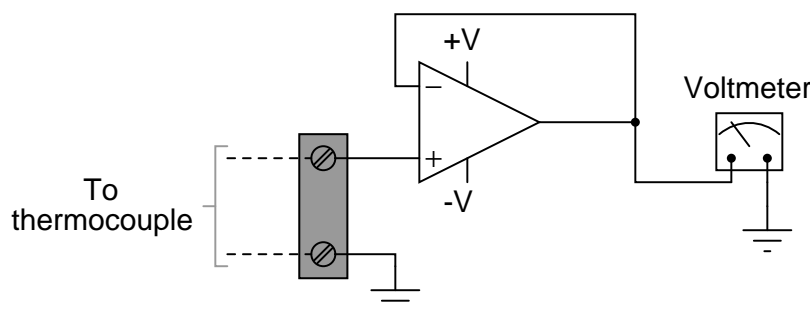
The op-amp senses the thermocouple's voltage signal and duplicates that voltage level at its output terminal, where it powers the meter movement. The current necessary for powering the meter movement comes from the DC power supply (+V/-V) powering the op-amp, and not from the thermocouple, so the thermocouple circuit does not become "loaded" by the meter. Another benefit of this strategy is that the op-amp buffer can easily be made into a precision amplifier, permitting the use of a larger-range voltmeter:
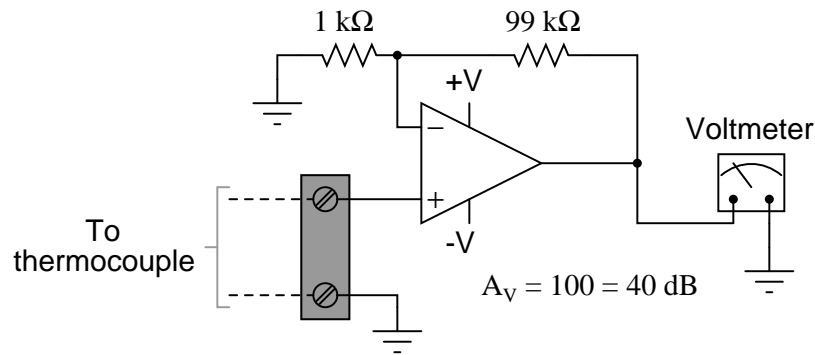
*Analog voltmeter registers 1 volt
for every 10 millivolts produced
by the thermocouple*

A non-electronic solution to this problem of building a high-impedance voltmeter is the classic "null-balance" or "potentiometric" voltmeter circuit, whereby an adjustable voltage source is used to balance the incoming signal voltage to be measured, with a highly sensitive "null" meter movement indicating when the two voltages are equal. Then, a regular analog voltmeter reads how much voltage the adjustable voltage source is set for in this condition of balance:
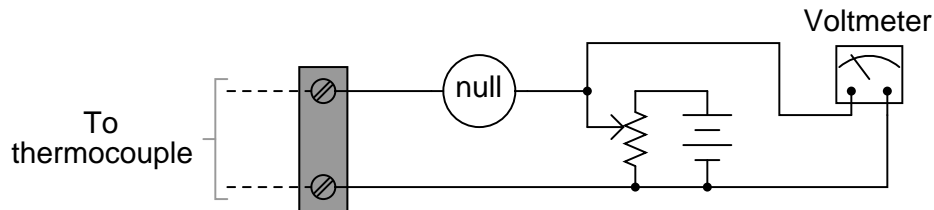
*When the "null" meter registers precisely zero,
then the potentiometer is outputting the same
voltage as the thermocouple, and the voltmeter
will register that voltage.*

In the balanced condition, the voltmeter movement's current requirements are supplied by the DC voltage source (battery), not the thermocouple. In fact this type of circuit (null-balance, or "potentiometric") is the *only* type of voltage-measuring instrument hypothetically capable of attaining *infinite* input impedance. Its simplicity and high theoretical input impedance makes it an elegant solution to the measurement problem.
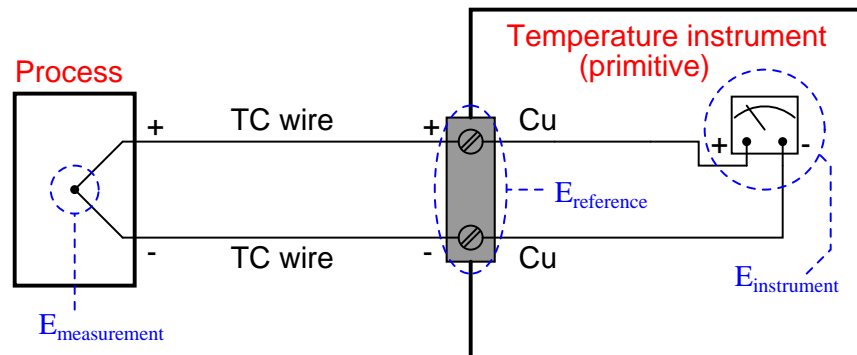
Equation: $E_{measurement} - E_{reference} = E_{instrument}$
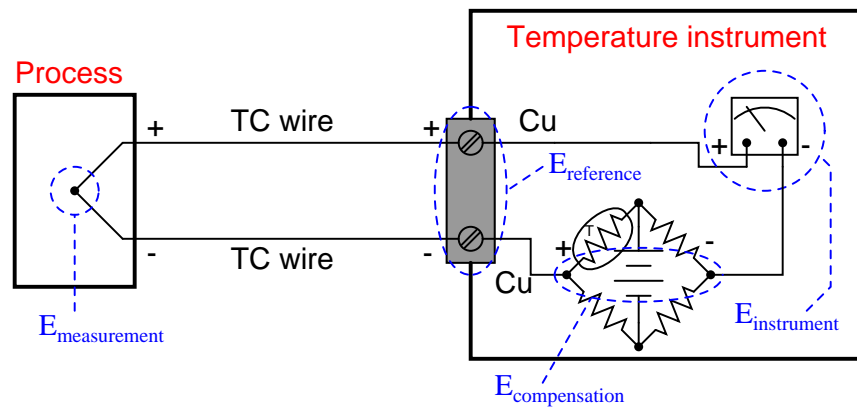
Equation: $E_{measurement} - E_{reference} + E_{compensation} = E_{instrument}$
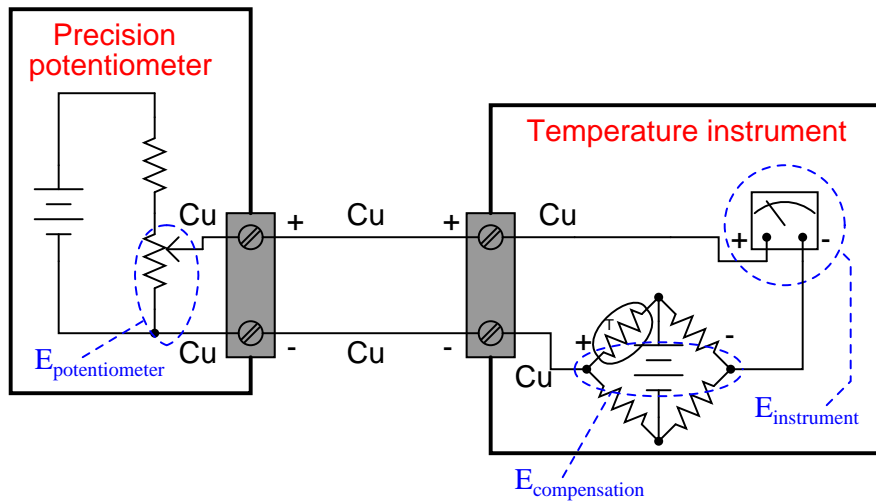
Equation: $E_{potentiometer} + E_{compensation} = E_{instrument}$
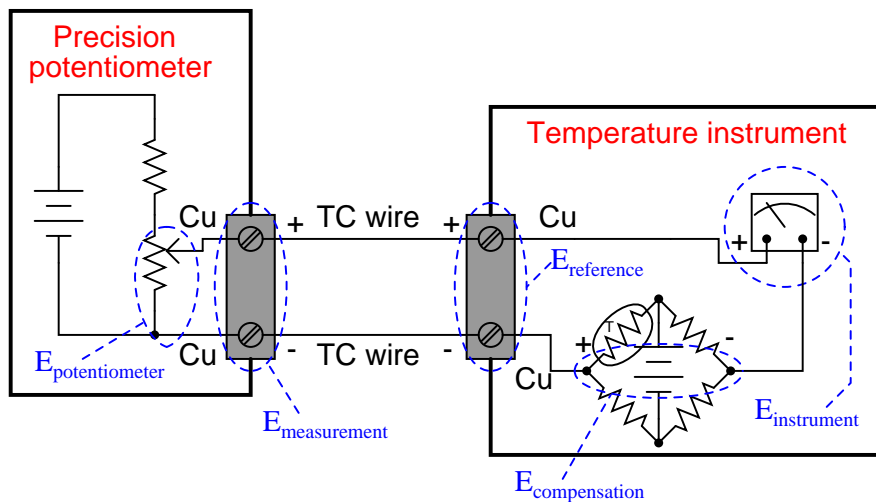
Equation: $E_{potentiometer} + E_{measurement} - E_{reference} + E_{compensation} = E_{instrument}$

To make this really simple: if you desire to know the proper potentiometer setting for generating an indication on any thermocouple-based instrument, just look up the millivoltage for the desired temperature, and subtract the millivoltage corresponding to the temperature at the point where either (A) copper wires join to a compensated instrument, or (B) where thermocouple wires join to an internally-copper, uncompensated, calibration device (assuming the temperature at the calibration device is the same as the temperature of the measuring instrument).

Answer 12

$I_E = 4.3$ mA
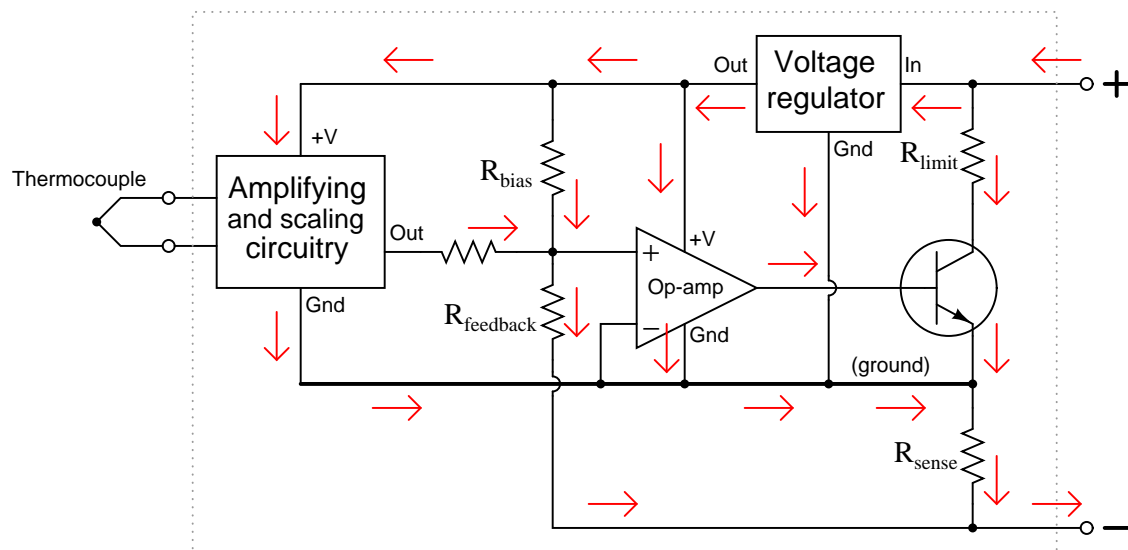
All arrows drawn in the direction of conventional flow

Follow-up question: how would the transmitter circuit respond to an increase in temperature sensed by the thermocouple? How about a decrease in loop power supply voltage (24 volts → 20 volts)?

Challenge question: it is important for instrument accuracy that we make R_{bias} and $R_{feedback}$ resistors rather large in value. Explain why.

Circuit as it appears to AC (HART) signals sent by the communicator:
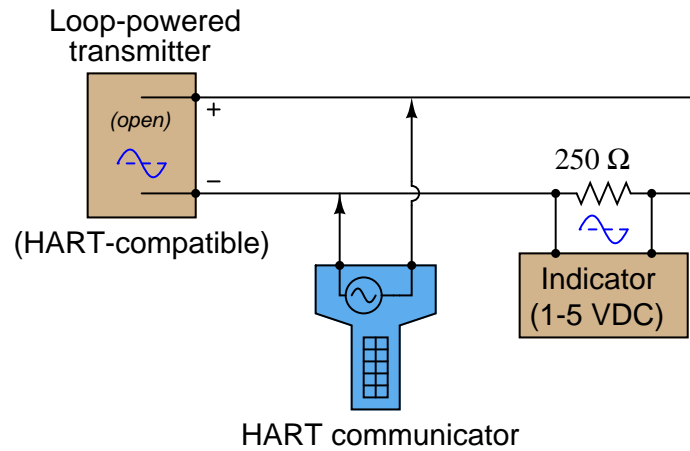
Circuit as it appears to DC (4-20 mA) signals:
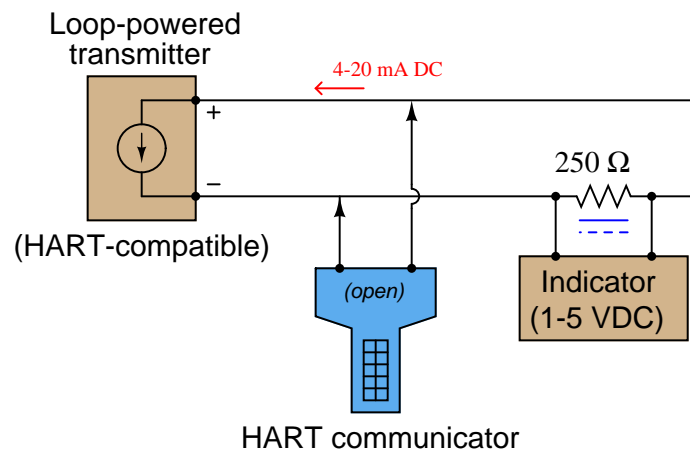
The communicator may be connected *anywhere* that places it in parallel with the transmitter terminals, from the transmitter itself all the way back to the control panel where the indicator is located!

Challenge question: a HART communicator will be able to communicate with the smart field instrument if it is connected directly in parallel with the 250 Ω loop resistor, even though this is technically not in parallel with the transmitter terminals. Explain why this works!

Series:

$$V_{meter} = (V_1 + V_3 + V_5) - (V_2 + V_4 + V_{ref})$$

Parallel:

$$V_{meter} = \frac{V_1 + V_2 + V_3}{3} - V_{ref}$$

Follow-up question: explain why *swamping resistors* are often added to paralleled thermocouples to improve the accuracy of their temperature averaging:

Parallel thermocouple junctions with "swamping" resistors
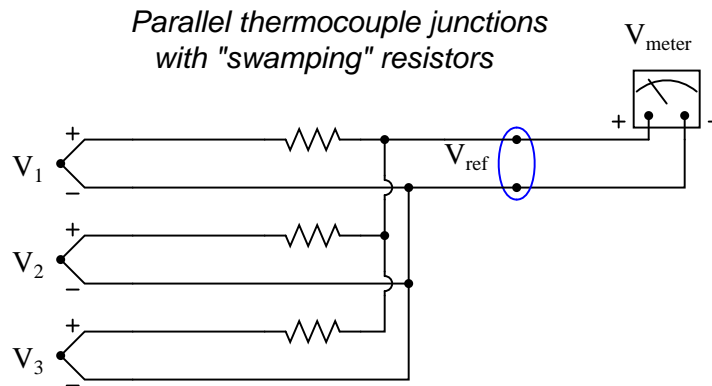
Answer 15

No reference junction compensation is needed at the indicator, because no reference junction exists there. In effect, the thermocouple at T_2 serves as a "reference" junction to the thermocouple at T_1.

A practical application for a differential thermocouple is in a solar heating system for a house. During the day time, solar energy will ensure that the collector is at a greater temperature than the house which it warms. At night, however, when the sun is not shining, the collector will be colder than the house. In this state, you do *not* want the circulating pump (or blower) to run, for that would transfer heat out of the warm house and dissipate it through the cold collector. A differential thermocouple could tell you (by the polarity of its voltage) which was warmer: the collector or the house. Then, an op-amp comparator circuit could disable the circulating pump to prevent heat loss through the collector at night.


Answer 16

Ideally, we may use any type of connection wire we wish so long as both the calibrator and the transmitter are at the exact same temperature! If the temperatures are not the same, we must be sure to use the correct type of thermocouple wire (or extension wire) to connect the calibrator to the instrument.
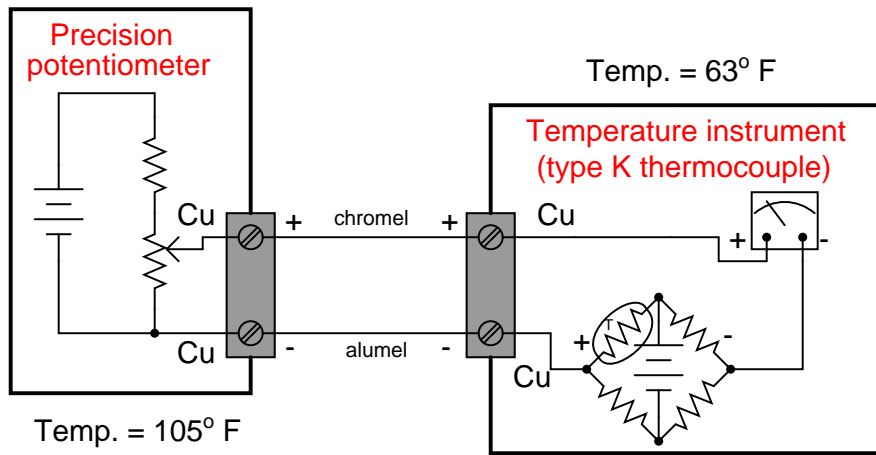

Answer 17

The metal blocks into which thermocouple wires go to connect are usually made of heavy brass, and they are physically secured to a thick ceramic (electrically insulating) base. This helps ensure the two connection points are held to the same temperature.
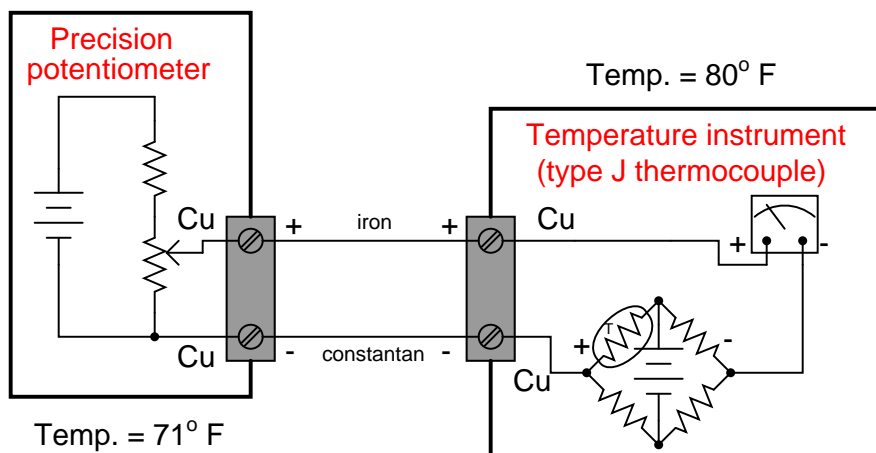
- -100° F ; Potentiometer setting = -4.598 mV (or, 4.598 mV connected in reverse polarity)
- 150° F ; Potentiometer setting = 2.307 mV
- 400° F ; Potentiometer setting = 9.920 mV
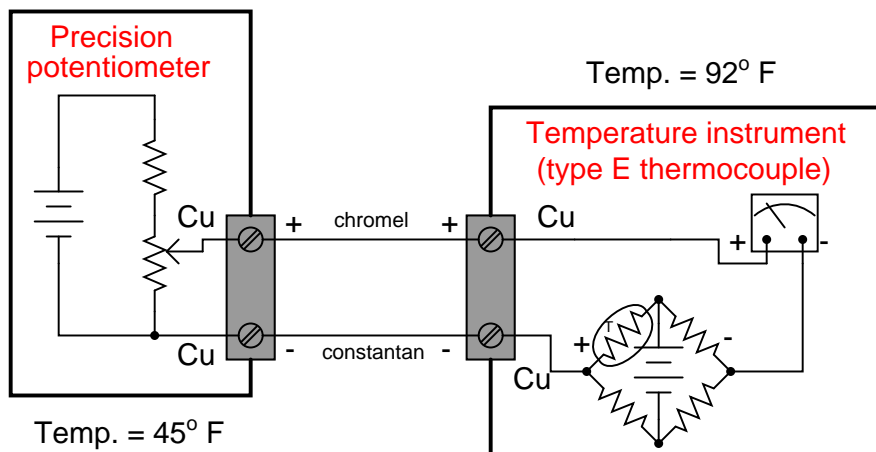
- 0° F ; Potentiometer setting = -1.452 mV (or, 1.452 mV connected in reverse polarity)
- 375° F ; Potentiometer setting = 12.298 mV
- 750° F ; Potentiometer setting = 28.431 mV

Precision potentiometer

Temp. = 63° F

Temperature instrument (type K thermocouple)

Cu   +   chromel   +   Cu

Cu   -   alumel   -   Cu

Temp. = 105° F

- -50° F ; Potentiometer setting = -3.364 mV (or 3.364 mV connected in reverse polarity)
- 975° F ; Potentiometer setting = 20.028 mV
- 2000° F ; Potentiometer setting = 43.231 mV

Answer 19

The instrument will register 993.5° F.

Answer 20

- -93° F ; Potentiometer setting = **-4.540** mV
- 157° F ; Potentiometer setting = **2.400** mV
- 389° F ; Potentiometer setting = **9.466** mV
- 580° F ; Potentiometer setting = **15.353** mV

Answer 21

Hint: according to a saturated steam table, the vapor pressure of water near 575 °F is approximately 1280 PSIG.

Answer 22

Partial answer:

The sensor is a type T thermocouple.

Answer 23

Partial answer:

The sensor is a type K thermocouple.

Answer 24

Partial answer:

The sensor is a three-wire RTD.

Answer 25

Partial answer:

   The sensor is a two-wire RTD.

Answer 26

Partial answer:

• Simulate 727 ^oF ; source voltage = <u>14.856 mV</u>

Answer 27

Partial answer:

• Simulate 357 ^oF ; resistance = <u>169.51 Ω (calculated)</u>   <u>168.68 Ω (according to table)</u>
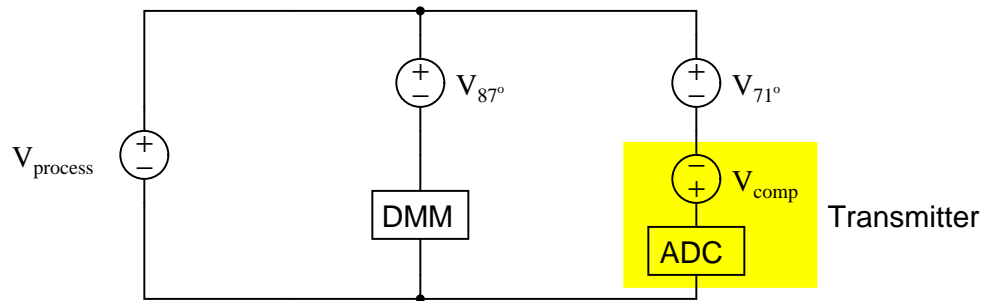

Answer 28

Partial answer:

   The *red* test lead of the meter (+) should contact the *violet* wire of the thermocouple. The *black* test lead of the meter (−) should contact the *red* wire of the thermocouple.

   An equivalent circuit diagram shows the relationship between the thermocouple measurement junction (in the process), the two reference junctions formed where thermocouple wire meets copper wire, the digital multimeter, and the temperature transmitter:

Equivalent circuit with digital multimeter (DMM) connected:

   If your answer was 480 ^oF or 481 ^oF, you made a common mistake, which is correctable by close examination of the above diagram!

Answer 29

Answer 30

   $V_{BC} = 66.285$ mV $V_{FG} = 64.665$ mV (calculations based on RTD table)

   $V_{BC} = 66.318$ mV $V_{FG} = 64.698$ mV (calculations based on RTD formula)

Answer 31

$V_{AC} = 81.526$ mV $V_{BC} = 80.330$ mV (calculations based on RTD table)

$V_{AC} = 81.659$ mV $V_{BC} = 80.463$ mV (calculations based on RTD formula)

Answer 32

Thermocouple signals are very small, and the input impedance of a thermocouple transmitter is typically large, making it susceptible to electrical interference. Given this fact, it is better to minimize the length of the noise-gathering signal path (the thermocouple wire). Also, thermocouple wire (even extension-grade wire) is more expensive than similar-gauge copper, which makes long lengths of copper cheaper than long lengths of thermocouple wire.

Answer 33

$V_{BC} = 136.479$ mV $V_{EH} = 134.603$ mV $V_{FG} = 134.603$ mV (calculations based on RTD table)

$V_{BC} = 137.904$ mV $V_{EH} = 136.028$ mV $V_{FG} = 136.028$ mV (calculations based on RTD formula)

Answer 34

- V_{R1} will **stay the same**
- V_{R2} will **stay the same**
- V_{R3} will **decrease**
- V_{RTD} will **increase**
- Explain the relationship between boiler pressure and boiler temperature:
  Boiler pressure and boiler temperature are directly related: as pressure increases, temperature also increases.

Answer 35

- Voltage between terminals TB64-8 and TB64-9 = 22.512 volts

- Voltage between terminals TB64-10 and TB64-11 = 2.744 volts

- Voltage between terminals TB27-15 and TB27-16 = 25.256 volts

Hint: if you are having difficulty analyzing this circuit, try re-drawing it in schematic form (all current-carrying components in a straight line to show their series connections).

Answer 36

Possible faults include (but are not limited to):

- PLC program halted (with output O:3/3 stuck in the "off" state)
- Discrete output O:3/3 channel bad (open TRIAC)
- Short-circuit in thermocouple cable, causing it to register ambient temperature (low)
- Failed thermocouple input I:2.1 channel, registering low temperature
- 120 VAC power to PLC failed (e.g. breaker CB-5 tripped)
- Cooling water supply failed
- Solenoid valve stuck shut
- Open wire fault between solenoid valve and PLC output card

Answer 37

Here are the two formulae you need to begin with:

$$R = 1000(1 + 0.00385T)$$

$$V = V_{source}\left(\frac{R}{R_{total}}\right)$$

In this particular application, we can "flesh out" the voltage divider formula a bit more with numerical values:

$$V = 5\left(\frac{3300}{3300 + R}\right)$$

After combining and manipulating these two formulae, your final formula should look something like this:

$$T = \frac{4300V - 5000}{19.25 - 3.85V}$$

Answer 38

The voltmeter's indication of 0.089 millivolts is the difference between the measurement junction's temperature and the ambient temperature of the control room (58 ^{o}F). Since the millivoltage for a type K thermocouple at 58 degrees F is 0.575 mV, and the thermocouple's temperature is 0.089 mV greater than that, the thermocouple must be outputting 0.664 mV, which equates to **62 degrees F**.

As for the amount of heat required to raise the engine to this new temperature, it is a matter of specific heat calculations: one incorporating the iron engine block's mass and the water's mass.
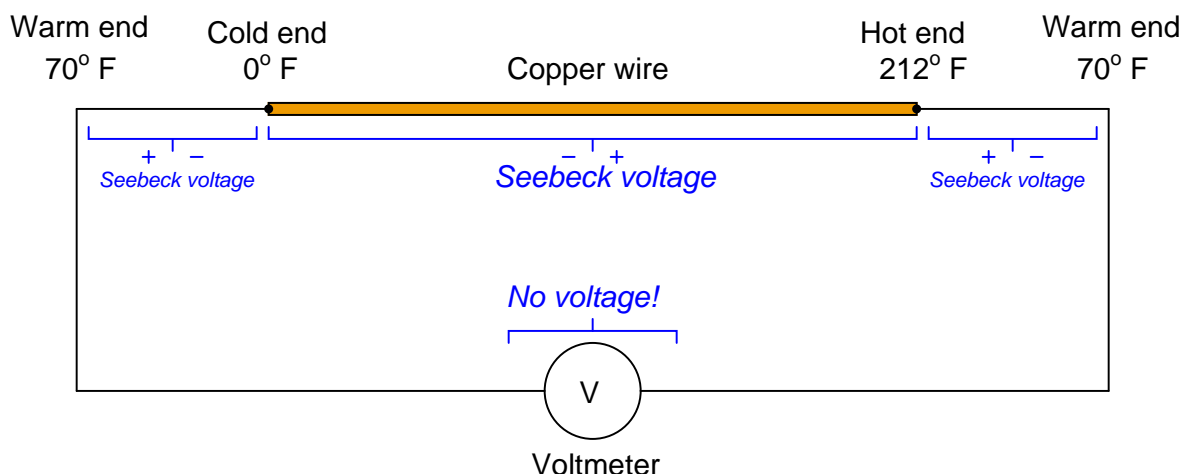
$$Q = mc\Delta T$$

$$Q = m_{iron}c_{iron}\Delta T + m_{water}c_{water}\Delta T$$

2.5 gallons of water is equivalent to 20.85 pounds of water. The temperature rise from 58 ^{o}F to 62 ^{o}F is 4 ^{o}F. Therefore:

$$Q = (300)(0.108)(4) + (20.85)(1)(4) = \textbf{213.0 BTU}$$

Answer 39

In connecting a room-temperature voltmeter to the ends of the copper wire, we form two more temperature gradients: one from freezing to room temperature, and the other from boiling to room temperature. Those gradients produce Seebeck voltages directly opposed to the Seebeck voltage across the length of the copper wire, resulting in a complete cancellation and zero voltage registered by the voltmeter.

Warm end 70° F   Cold end 0° F   Copper wire   Hot end 212° F   Warm end 70° F

+ −   Seebeck voltage

− +   *Seebeck voltage*

+ −   Seebeck voltage

No voltage!

V

Voltmeter

In other words, from one voltmeter lead to the other, we see a net temperature gradient of zero (from room temperature to room temperature) along the same material (copper), resulting in a net Seebeck voltage of zero.

A *junction* of two different metals, on the other hand, produces two unequal Seebeck voltages given the same temperature gradient from end to end along each wire:

Seebeck voltage (copper)
+   −

Hot end   Copper wire   Warm end

Silver wire

Warm end

+   −
Seebeck voltage (silver)
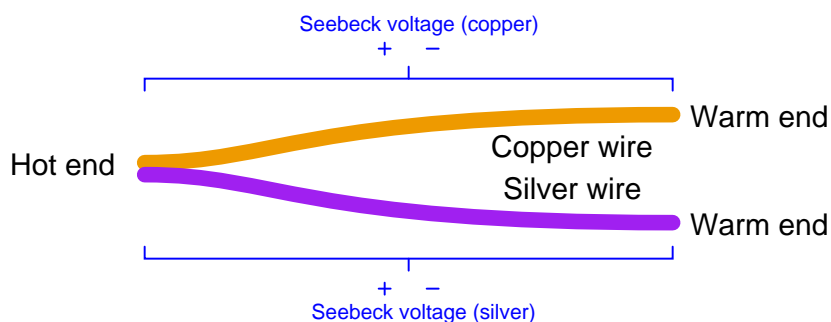
We can measure the net Seebeck voltage between the two cold wire ends because they are both at the same temperature as our meter leads. No temperature gradient exists at the connection point between the thermocouple leads and the meter leads, so no Seebeck voltage is generated here to add to the circuit's net voltage.

Answer 40

The indicator is wired backwards, and the RTD is connected to the wrong three terminals on the transmitter. A corrected diagram is shown here:
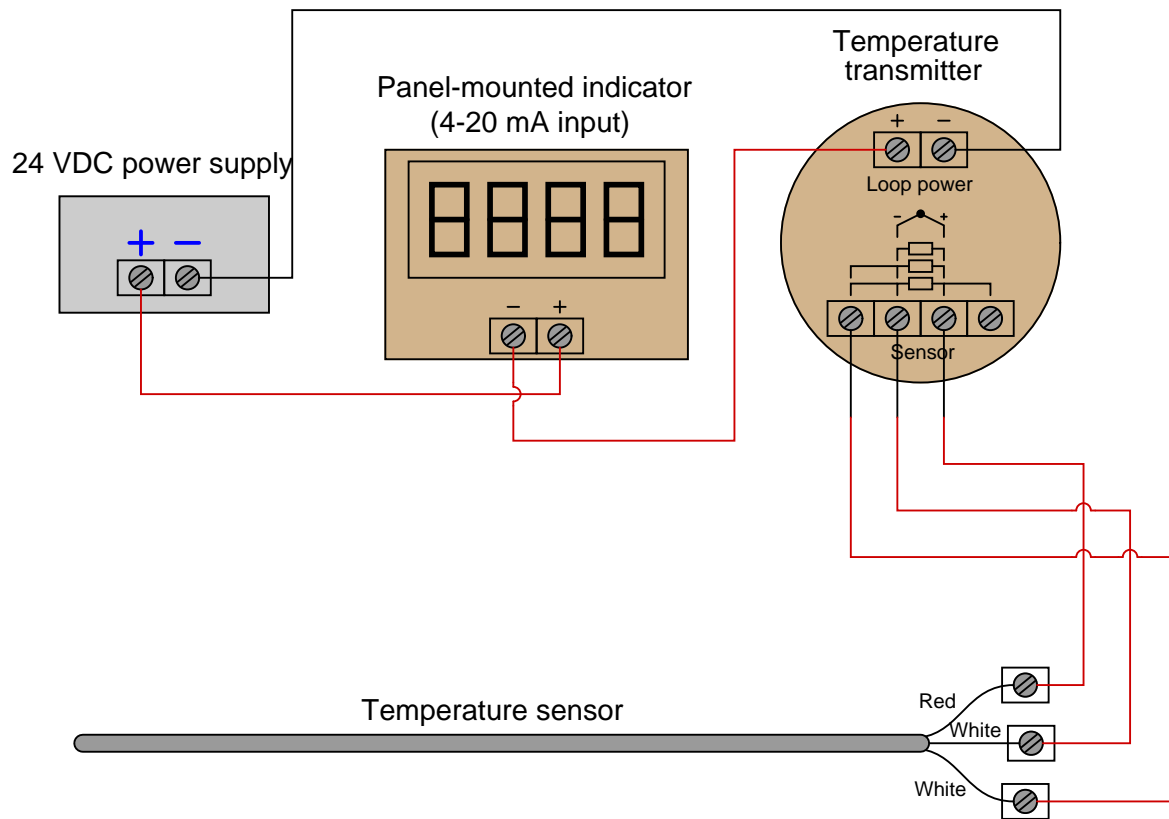
Answer 41

Answer 42

Answer 43

This is an automatic cooling system with high and low temperature alarms.

Answer 44

Answer 45

Answer 46

Answer 47

Answer 48

I won't reveal the solution in its entirety here, but this problem essentially breaks down into a few simple parts:

- Figuring out how much heat will be required to raise the solvent's temperature
- Figuring out how fast heat is delivered by the steam at the given mass flow rate
- Dividing <u>required heat</u> (BTU) by <u>heat rate</u> (BTU/hr) to solve for <u>time</u> (hr)

Determining heat rate delivered by the steam is most easily done using a *steam table*.

Answer 49

$$T = \sqrt[4]{\frac{\left(\frac{dQ}{dt}\right)}{e\sigma A}}$$

Answer 50

- 1600 ^{o}F ; Output = **<u>19.09</u>** mV
- 800 ^{o}C ; Output = **<u>14.77</u>** mV
- 1000 K ; Output = **<u>11.14</u>** mV

Answer 51

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

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

Answer 52

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

Answer 53

$P = 1.422$ atmospheres $= 42.8$ kPaG

Answer 54

The temperature should cycle between 250 and 285 degrees F, with the relay "latching" the heating element on even after the lower-temp switch contacts open. This is sometimes called a *differential gap* control system because the process variable bounces back and forth within a "gap" established by two setpoint values.

If contact CR1 fails open, the relay cannot latch. Thus, the heater will turn off any time the lower-temperature switch trips. The result of this will be a much more rapid cycling, with the temperature centered somewhere around 250 degrees.
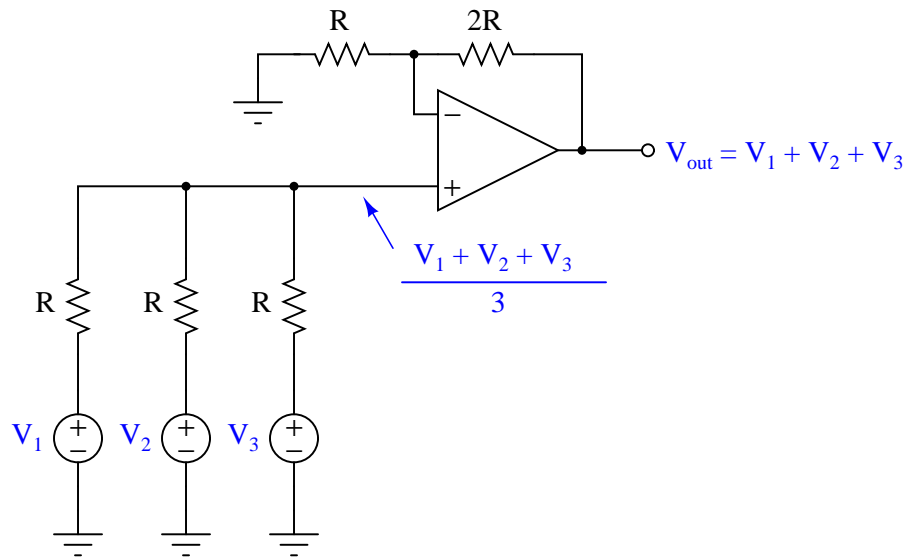
Answer 55

The thermocouple-based instrument's indication will *decrease* by approximately 20° F, while the Class V filled system's indication will *increase* slightly.

Answer 56

A circuit to jog your memory on this concept is the *noninverting summer*, designed to sum (add) three analog voltage signals:

At the noninverting input of the opamp is a set of three resistors functioning as a *passive averager*, to input the average of the three sources' voltage values to the opamp's noninverting input. It is this "averaging" resistor network which has relevance to the thermocouple circuit shown in the question. Swamping resistors are necessary to "even out" the otherwise disparate thermocouple wire resistances, so that the voltage signal received is a more fairly-weighted average that it would be otherwise.

If a swamping resistor happens to fail open, that thermocouple no longer has any effect on the average. In other words, the output voltage signal becomes the average of the remaining two thermocouples.

Answer 57

The WORM uses a long coil spring to maintain positive pressure contact between the sensor and the bottom of the thermowell.

Available sensor types include type J and K thermocouples, as well as 100 ohm and 1000 ohm platinum RTDs (both having α values of 0.00385) – shown on page 4.

Fastest thermocouple is the grounded-tip style, with a time constant of 2 seconds (page 4). By contrast, ungrounded thermocouples exhibit a typical time constant of 4.5 seconds.

RTD accuracy is stated as $\pm$ 0.12% at 0 ^{o}C (page 4). Typical thermocouple accuracies range plus or minus a couple of degrees Celsius.

Answer 58

Remember these simplifying assumptions of negative feedback opamp circuits:

- Negative feedback will force the output voltage to whatever value is necessary to maintain the differential input voltage at zero.
- Input terminals on the opamp(s) draw negligible current.

Voltages at TP1 and TP2 (with reference to ground) may be calculated simply by evaluating voltage drops in the series RTD circuit. Voltage at TP3 with reference to ground will be identical to that at TP1, since the upper opamp simply functions as a voltage follower. TP5 is the output of this differential amplifier circuit, representing the difference between potentials sensed at inputs TP1 and TP2 (i.e. the voltage dropped by the RTD). The reason why the output voltage is a negative quantity (with respect to ground) is because the differential amplifier's noninverting input sees a lower voltage than its inverting input.

For each of the voltage calculations, you will need to reference an RTD table to find the proper RTD resistance values. While it is possible to use a formula to approximate RTD resistance based on temperature, a table will give you more accurate answers because a table accounts for all nonlinearities of the RTD, while the formula assumes a perfectly linear characteristic.

- Voltage at TP1 (V_{TP1}), with RTD at 0° C ($R_{RTD} = 100.0$ Ω) = **0.1524** V
- Voltage at TP2 (V_{TP2}), with RTD at 10° F ($R_{RTD} = 95.21$ Ω) = **0.0024** V (**2.4** mV)
- Voltage at TP3 (V_{TP3}), with RTD at 12° C ($R_{RTD} = 104.68$ Ω) = **0.1594** V
- Voltage at TP5 (V_{TP5}), with RTD at -20° C ($R_{RTD} = 92.16$ Ω) = **-0.1382** V

Answer 59

Answer 60

Answer 61

Answer 62

Answer 63

Answer 64

Partial answer:

This is a direct *force-balance* instrument.

Answer 65

Partial answer:

This is definitely superheated steam, because its temperature is well above the boiling point for water at 2500 PSIG (approximately 670 ^{o}F, as my steam table shows water at 2526 PSIA to boil at 670 ^{o}F).

Your calculated value for water flow rate should be 5.25 gallons per minute, or 43.79 pounds per minute.

Heat output = approximately 1249.9 horsepower per acre of collection area.

Answer 66

$V_{BC} = 5.326$ mV $V_{EH} = 5.326$ mV $V_{FG} = 7.111$ mV (calculations based on RTD table)
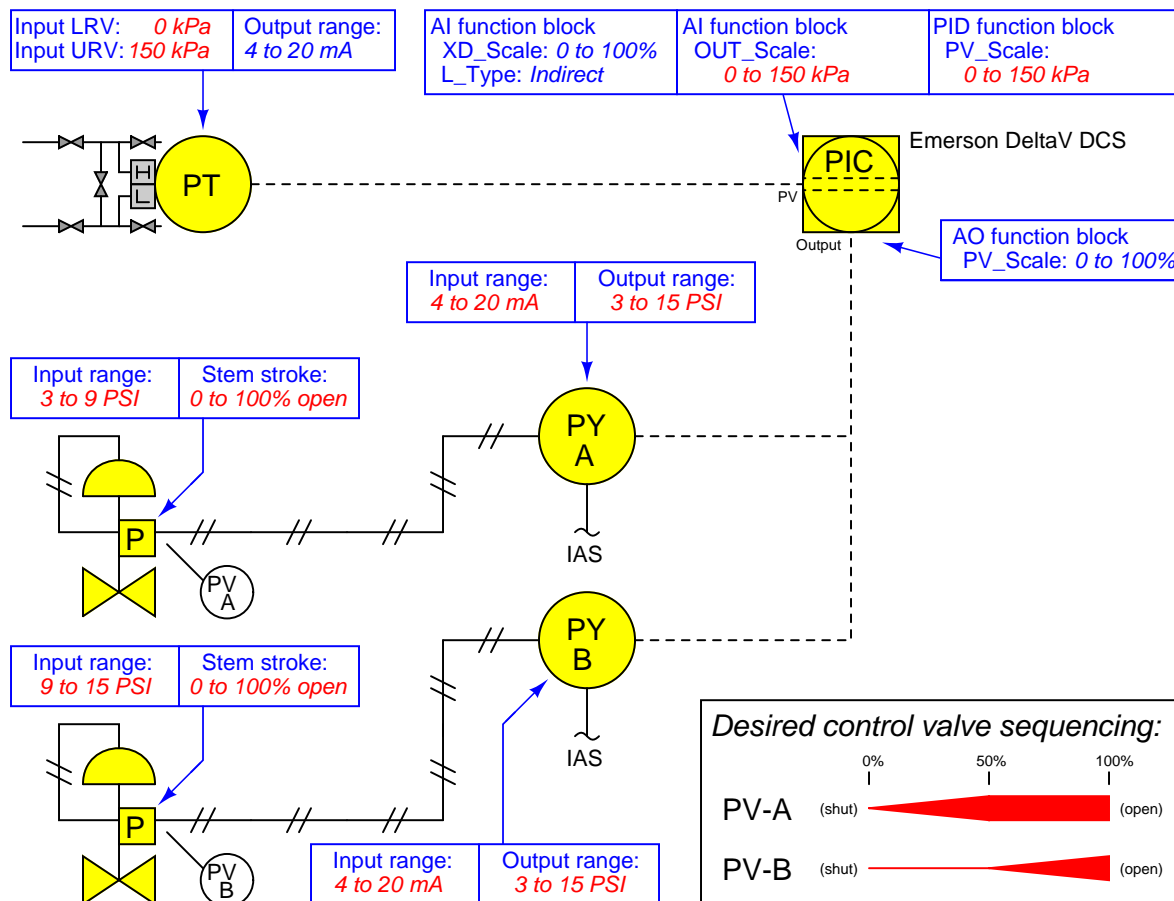
Answer 67

Answer 68

Heat transfer rate to kettle (assuming quantities given here in the question, not anywhere in the USCSB report) is equal to 2987.1 BTU/minute.

Answer 69

Answer 70

Answer 71

This ranges shown here for split-ranging the two control valves do not constitute the only possible range values that will work!

Try to identify what *other* I/P and control valve positioner range values will also yield the desired split-range sequencing.

Answer 72

Hint: what Rosemount refers to as a "failure mode" encompasses the more specific concept of "burnout".

Answer 73

Type J thermocouple: $T = 469$ °F

Type E thermocouple: $T = 361$ °C

Answer 74

Type S thermocouple: $V = 15.037$ mV

Type T thermocouple: $V = 6.166$ mV

Answer 75

This circuit only has one reference junction, if you count the two terminal connections at the indicator as a single junction. The junction mid-way between the thermocouple head and the indicator is not a reference junction because it is not a junction of dissimilar metals.

Answer 76

- 0° F ; Potentiometer setting = **-1.962** mV
- 229° F ; Potentiometer setting = **4.707** mV
- 454° F ; Potentiometer setting = **11.615** mV
- 641° F ; Potentiometer setting = **17.370** mV

Answer 77

- V_{R1} will **stay the same**
- V_{R2} will **stay the same**
- V_{R3} will **increase**
- V_{RTD} will **decrease**
- Explain the relationship between boiler pressure and boiler temperature:

Boiler pressure and boiler temperature are directly related: as pressure decreases, temperature also decreases.
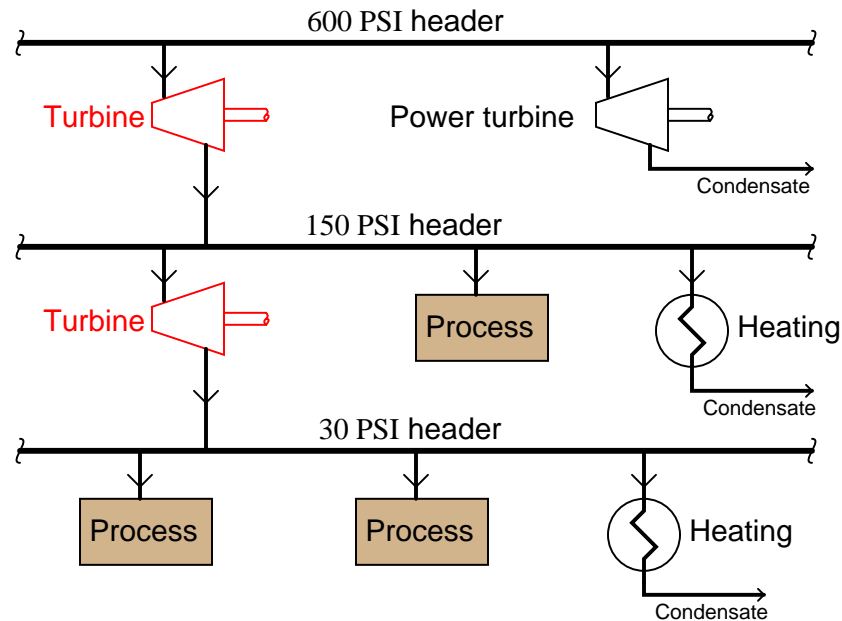
Answer 78

The **RTD** would be the best choice, due to the superior linearity of this sensing element compared to the others. Also, RTDs do not suffer the problem of reference junction compensation like thermocouples do, or the various mechanical sources of error like filled bulbs do.

Answer 79

The water injected in a desuperheating valve gains heat energy from the superheated let-down steam, producing a greater volume of steam at a lower pressure (and lower temperature), much like an electrical transformer steps down voltage with a corresponding *increase* in current. Desuperheaters exchange temperature for volume, much like transformers exchange voltage for current (or vice-versa).

Challenge question: explain why turbines make efficient steam pressure let-down devices:

*Using steam turbines as pressure let-down devices*

Answer 80

First, let's determine the polarity of the reference junction's voltage, caused by a joining of constantan (C) and copper (Cu) wires at the lower terminal. Since we know that copper is the positive wire in a copper-constantan junction, we know that the polarity of the bottom terminal's millivoltage will be positive on the right and negative on the left. The polarities are shown here both with +/- symbols and also with curved arrows (the arrow tip being positive):
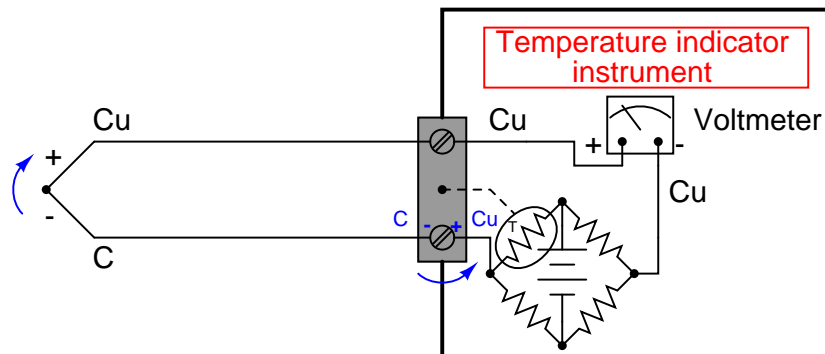
To counter this millivoltage, the bridge circuit's output must be positive on the left and negative on the right:
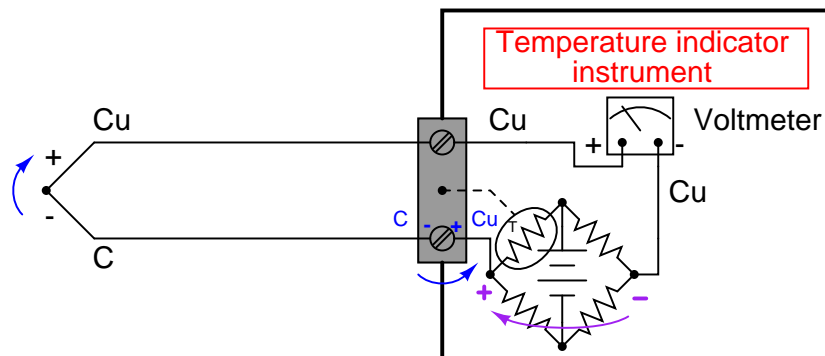
We know that the warmer the reference junction becomes, the more voltage it will produce. Thus, the bridge must also produce more countering voltage as the thermistor increases in temperature. For the left terminal of the bridge circuit to become more positive (and the right terminal, conversely, to become more negative), given a battery orientation that is positive "up" and negative "down," the thermistor must *decrease* in value. Therefore, we need a thermistor that has a **negative temperature coefficient**.

Thermocouples still have value as primary sensing elements for temperature because their operating temperature range far exceeds that of thermistors, and they tend to be more rugged as well.

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

Answer 93

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