Lab

Level measurement loop: *Questions 91 and 92*, **completed objectives due by the end of day 5, section 4**

Exam

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

- Electricity Review: Calculate voltages, currents, powers and/or resistances in a DC series-parallel circuit
- Determine suitability of different level-measuring technologies for a given process fluid type
- Calculate ranges for hydrostatic (DP) level-measuring instruments given physical dimensions and fluid densities
- Calculate buoyant force values for a displacer-type level-measuring instrument at different liquid levels
- 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: Determine status of PLC discrete output given input switch conditions and a simple RLL program listing
- INST251 Review: Determine the effect of a component change on the gain of a pneumatic controller mechanism
- INST263 Review: Determine the effect of a component fault or condition change in a cascade-, ratio-, or feedforward-controlled process

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**Recommended daily schedule**

Day 1

**Theory session topic:** Level measurement technologies and liquid densities
Questions 1 through 20; <u>answer questions 1-10</u> in preparation for discussion (remainder for practice)

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Day 2

**Theory session topic:** Hydrostatic level measurement
Questions 21 through 40; <u>answer questions 21-29</u> in preparation for discussion (remainder for practice)

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Day 3

**Theory session topic:** Displacer level measurement
Questions 41 through 60; <u>answer questions 41-49</u> in preparation for discussion (remainder for practice)

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Day 4

**Theory session topic:** Measuring liquid-liquid interfaces
Questions 61 through 80; <u>answer questions 61-69</u> in preparation for discussion (remainder for practice)

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

**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 240 Course Outcomes

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

- Calculate and annotate voltages and currents in a DC series-parallel circuit. [Ref: Program Learning Outcome #4]

- Calculate voltages, currents, powers, and/or resistances in a DC series-parallel circuit. [Ref: Program Learning Outcome #4]

- Convert between different pressure units (PSI, "W.C., bar. etc.) showing proper mathematical cancellation of units (i.e. the "unity fraction" technique). [Ref: Program Learning Outcome #7]

- Determine suitability of different level-measuring technologies for a given process fluid type. [Ref: Program Learning Outcome #5]

- Calculate pressure applied to a DP instrument given a pictorial diagram. [Ref: Program Learning Outcome #4]

- Calculate ranges for hydrostatic (DP) level-measuring instruments given physical dimensions and fluid densities. [Ref: Program Learning Outcome #4]

- Calculate buoyant force values for a displacer-type level-measuring instrument at different liquid levels. [Ref: Program Learning Outcome #4]

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

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

- Determine the possibility of suggested faults in series-parallel 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 lab work. [Ref: Program Learning Outcomes #1 and #2]

- Construct and commission a working pressure-measurement loop consisting of an electronic pressure transmitter, signal wiring, and indicator. [Ref: Program Learning Outcome #5]

- Construct and commission a working level-measurement loop consisting of an electronic level transmitter, signal wiring, and indicator. [Ref: Program Learning Outcome #5]

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

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

- Build a circuit to sense either pressure or vacuum using a differential pressure transmitter with HART communication capability, reporting the sensed variable on an analog meter chosen by the instructor,

setting the range values according to instructor specifications, capturing peak signal value using a digital multimeter, and capturing binary 0 and 1 bits using a digital oscilloscope. [Ref: Program Learning Outcome #5]

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

- Demonstrate the proper usage of a deadweight tester for generating precise pressures. [Ref: Program Learning Outcome #7]

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

- Demonstrate the proper usage of a manometer for measuring gas pressure. [Ref: Program Learning Outcome #7]

- Diagnose a random fault placed in another team's pressure measurement system by the instructor within a limited time using no test equipment except a multimeter, logically justifying your steps in the instructor's direct presence. [Ref: Program Learning Outcome #4]

- Diagnose a random fault placed in another team's level measurement system by the instructor within a limited time using no test equipment except a pressure gauge, logically justifying your steps in the instructor's direct presence. [Ref: Program Learning Outcome #4]

file `outcomes_INST240`

# Sequence of second-year Instrumentation courses

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

*(Only if 4th quarter was Summer: INST23x)*

Prerequisite for all INST24x, INST25x, and INST26x courses

**INST 200** -- 1 wk
Intro. to Instrumentation

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

## Summer quarter

**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

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

Prerequisite for INST206

**INST 205** -- 1 cr
Job Prep I

**INST 206** -- 1 cr
Job Prep II

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

**Graduate!!!**

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

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

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

### Beginning in Summer

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

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

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

**Spring quarter** (April–June)
- INST 206 -- 1 cr — Job Prep II
- INST 260 -- 4 cr — Data Acquisition Systems
- INST 262 -- 5 cr — Digital Control Systems
- INST 263 -- 5 cr — Control Strategies
- ENGT 134 -- 5 cr — CAD 1: Basics

*Graduation!*

### Beginning in Fall

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

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

**Spring quarter** (April–June)
- INST 206 -- 1 cr — Job Prep II
- INST 260 -- 4 cr — Data Acquisition Systems
- INST 262 -- 5 cr — Digital Control Systems
- INST 263 -- 5 cr — Control Strategies
- ENGT 134 -- 5 cr — CAD 1: Basics

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

*Graduation!*

### Beginning in Winter

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

**Spring quarter** (April–June)
- INST 205 -- 1 cr — Job Prep I
- INST 260 -- 4 cr — Data Acquisition Systems
- INST 262 -- 5 cr — Digital Control Systems
- INST 263 -- 5 cr — Control Strategies
- ENGT 134 -- 5 cr — CAD 1: Basics

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

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

*Graduation!*

### Beginning in Spring

**Spring quarter** (April–June)
- INST 200 -- 1 wk — Intro. to Instrumentation
- INST 260 -- 4 cr — Data Acquisition Systems
- INST 262 -- 5 cr — Digital Control Systems
- INST 263 -- 5 cr — Control Strategies
- ENGT 134 -- 5 cr — CAD 1: Basics

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

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

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

*Graduation!*

file sequence

9

# General tool and supply list

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

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

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

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

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

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

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

file `tools`

# Methods of instruction

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

## Inverted theory sessions

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

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

### Small sessions

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

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

### Large sessions

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

### Correspondence

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

In all formats, students are held accountable for completion of their homework, "completion" being defined as successfully interpreting the given information from source material (e.g. accurate outlines of reading or video assignments) and constructive effort to solve given problems. It must be understood in an inverted learning environment that students *will* have legitimate questions following a homework assignment, and that it is therefore unreasonable to expect mastery of the assigned subject matter. What is reasonable to expect from each and every student is a basic outline of the source material (reading or video assignments) complete with major terms defined and major concepts identified, plus a good-faith effort to solve every problem. Question 0 (contained in every worksheet) lists multiple strategies for effective study and problem-solving.

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**Sample rubric for pre-assessments**
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- **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).*

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

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

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

**Methods of instruction** (continued)

**Lab sessions**

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

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

**Troubleshooting assessments must meet the following guidelines:**

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

file `instructional`

## Distance delivery methods

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

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

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

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

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

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

file distance

# Metric prefixes and conversion constants

- **Metric prefixes**
- Yotta = $10^{24}$ Symbol: Y
- Zeta = $10^{21}$ Symbol: Z
- Exa = $10^{18}$ Symbol: E
- Peta = $10^{15}$ Symbol: P
- Tera = $10^{12}$ Symbol: T
- Giga = $10^{9}$ Symbol: G
- Mega = $10^{6}$ Symbol: M
- Kilo = $10^{3}$ Symbol: k
- Hecto = $10^{2}$ Symbol: h
- Deca = $10^{1}$ Symbol: da
- Deci = $10^{-1}$ Symbol: d
- Centi = $10^{-2}$ Symbol: c
- Milli = $10^{-3}$ Symbol: m
- Micro = $10^{-6}$ Symbol: $\mu$
- 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 | $\mu$ | n | p |
|---|---|---|---|---|---|---|---|---|
| tera | giga | mega | kilo | (none) | milli | micro | nano | pico |
| $10^{12}$ | $10^{9}$ | $10^{6}$ | $10^{3}$ | $10^{0}$ | $10^{-3}$ | $10^{-6}$ | $10^{-9}$ | $10^{-12}$ |

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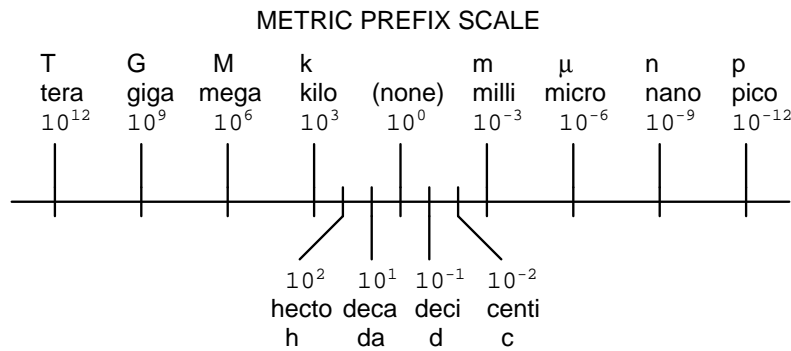
- **Conversion formulae for temperature**
- ${}^{o}\text{F} = ({}^{o}\text{C})(9/5) + 32$
- ${}^{o}\text{C} = ({}^{o}\text{F} - 32)(5/9)$
- ${}^{o}\text{R} = {}^{o}\text{F} + 459.67$
- $\text{K} = {}^{o}\text{C} + 273.15$

**Conversion equivalencies for distance**

1 inch (in) = 2.540000 centimeter (cm)

1 foot (ft) = 12 inches (in)

1 yard (yd) = 3 feet (ft)

1 mile (mi) = 5280 feet (ft)

## Conversion equivalencies for volume

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

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

## Conversion equivalencies for velocity

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

## Conversion equivalencies for mass

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

## Conversion equivalencies for force

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

## Conversion equivalencies for area

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

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

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

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

## Conversion equivalencies for absolute pressure units (only)

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

## Conversion equivalencies for energy or work

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

## Conversion equivalencies for power

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

## Acceleration of gravity (free fall), Earth standard

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

**Physical constants**

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

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

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 $= 32^o\text{F} = 0^o\text{C}$

Boiling point at sea level $= 212^o\text{F} = 100^o\text{C}$

Density of water at $4^o\text{C} = 1000$ kg/m$^3$ = 1 g/cm$^3$ = 1 kg/liter = 62.428 lb/ft$^3$ = 1.94 slugs/ft$^3$

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

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

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

Absolute viscosity of water at $20^o\text{C} = 1.0019$ centipoise (cp) = 0.0010019 Pascal-seconds (Pa·s)

Surface tension of water (in contact with air) at $18^o\text{C} = 73.05$ dynes/cm

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


**Properties of Dry Air at sea level**

Density of dry air at $20^o\text{C}$ and 760 torr = 1.204 mg/cm$^3$ = 1.204 kg/m$^3$ = 0.075 lb/ft$^3$ = 0.00235 slugs/ft$^3$

Absolute viscosity of dry air at $20^o\text{C}$ and 760 torr = 0.018 centipoise (cp) = $1.8 \times 10^{-5}$ Pascal-seconds (Pa·s)

file `conversion_constants`

**How to get the most out of academic reading:**
- Articulate your thoughts 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.

- Outline, don't highlight! 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.

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

- Imagine explaining concepts you've just learned to someone else. Teaching forces you to distill concepts to their essence, thereby clarifying those concepts, revealing assumptions, and exposing misconceptions. Your goal is to create the simplest explanation that is still technically accurate.

- Write your own questions 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:**
- Rely on principles, not procedures. 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.

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

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

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

- Simplify the problem and solve that simplified problem to identify strategies applicable to the original problem (e.g. change quantitative to qualitative, or visa-versa; substitute easier numerical values; eliminate confusing details; add details to eliminate unknowns; consider simple limiting cases; apply an analogy). 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.

- Work "backward" from a hypothetical solution to a new set of given conditions.

**How to manage your time:**
- Avoid procrastination. Work now and play later, 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.

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

- Use your "in between" time productively. Don't leave campus for lunch. Arrive to school early. If you finish your assigned work early, begin working on the next assignment.

**Above all, cultivate persistence.** 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!

file `question0`

Question 1

Read and outline the "Fluid Density Expressions" subsection of the "Fluid Mechanics" section of the "Physics" 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

**Suggestions for Socratic discussion**

- As the specific gravity of a liquid increases, does its "degrees API" density value increase or decrease?
- As the specific gravity of a liquid increases, does its "degrees Twaddell" density value increase or decrease?
- As the specific gravity of a liquid increases, does its "degrees Baumé (light)" density value increase or decrease?
- As the specific gravity of a liquid increases, does its "degrees Baumé (heavy)" density value increase or decrease?
- What value of specific gravity yields a *zero* degree API density figure?
- What value of specific gravity yields a *zero* degree Twaddell density figure?
- What value of specific gravity yields a *zero* degrees Baumé (light) density figure?
- What value of specific gravity yields a *zero* degrees Baumé (heavy) density figure?

file i03947

Question 2

Skim the "Continuous Level Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook to specifically answer these questions:

Explain what a *sightglass* is, and how it functions similar to a U-tube manometer.

Explain how a *float* may be used to measure liquid level in a vessel, both by hand and automatically.

Identify some potential problems exhibited by sightglasses and floats.

**Suggestions for Socratic discussion**

- Identify different strategies for "skimming" a text, as opposed to reading that text closely. Why do you suppose the ability to quickly scan a text is important in this career?

file i03940

Question 3

Skim the "Continuous Level Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook to specifically answer these questions:

Describe and explain the mathematical relationship between liquid density, liquid depth (or height), and hydrostatic pressure. How may we exploit this principle to measure liquid level in industrial processes?

Explain what a *bubbler* system is, and how it is used to measure liquid level. Why would anyone opt to use a bubbler instead of directly connecting a pressure sensor to the process vessel?

| Suggestions for Socratic discussion |

- Identify different strategies for "skimming" a text, as opposed to reading that text closely. Why do you suppose the ability to quickly scan a text is important in this career?
- You probably noticed a lot of math applied in these sections of the textbook. Identify some good learning strategies to apply when learning mathematically "dense" topics.

file i03941

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Question 4

Skim the "Continuous Level Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook to specifically answer these questions:

Describe what *Archimedes' Principle* is, and how it may be used to infer the level of a liquid.

Is a "displacement" type of liquid level sensor affected by changes in liquid density? Explain why or why not. Are they affected by changes in process fluid pressure? Explain why or why not.

| Suggestions for Socratic discussion |

- Identify different strategies for "skimming" a text, as opposed to reading that text closely. Why do you suppose the ability to quickly scan a text is important in this career?
- You probably noticed a lot of math applied in these sections of the textbook. Identify some good learning strategies to apply when learning mathematically "dense" topics.

file i03942

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Question 5

Skim the "Continuous Level Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook to specifically answer these questions:

Identify three different types of "echo" level measurement technologies, and explain how each one works to measure the level of solid or liquid material inside a vessel.

Are "echo" sensors affected by changes in process material density? Explain why or why not.

| Suggestions for Socratic discussion |

- Identify different strategies for "skimming" a text, as opposed to reading that text closely. Why do you suppose the ability to quickly scan a text is important in this career?

file i03944

Question 6

Skim the "Continuous Level Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook to specifically answer these questions:

Explain how the weight of a vessel may be measured to infer the level of process substance (solid or liquid) inside that vessel. Describe what sort of device is typically used to sense the vessel's weight.

Describe the special construction of vessels, pipes, and other structures in a weight-based level measurement system. Why are these special features necessary for accurate level measurement?

Is a "weight" type of liquid level sensor affected by changes in liquid density? Explain why or why not.

Suggestions for Socratic discussion

- Identify different strategies for "skimming" a text, as opposed to reading that text closely. Why do you suppose the ability to quickly scan a text is important in this career?

file i03943

Question 7

Skim the "Continuous Level Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook to specifically answer these questions:

Describe how electrical capacitance maybe used to infer the level of a process material inside a vessel.

Identify two different categories of capacitance probe, and explain why each type has its purpose in different process applications.

Is a capacitive level sensor affected by changes in liquid density? Explain why or why not.

Suggestions for Socratic discussion

- Identify different strategies for "skimming" a text, as opposed to reading that text closely. Why do you suppose the ability to quickly scan a text is important in this career?

file i03945

Question 8

Skim the "Continuous Level Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook to specifically answer these questions:

Explain how nuclear radiation may be used to detect the level of process fluid (or solids) inside a vessel.

Nuclear-type level sensors are often more expensive to install and maintain than other level-measurement technologies. Given this fact, explain why anyone would choose nuclear over more common technologies for sensing process fluid level.
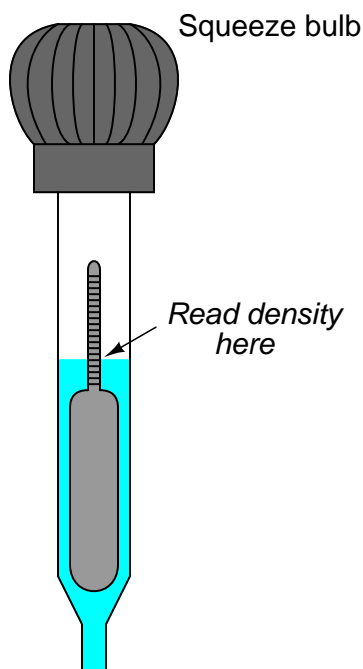
Suggestions for Socratic discussion

- Identify different strategies for "skimming" a text, as opposed to reading that text closely. Why do you suppose the ability to quickly scan a text is important in this career?

file i03946

Question 9

A type of density gauge called a *hydrometer* often used to measure the acid concentration in lead-acid battery electrolyte uses a weighted float with a graduated scale at the top, designed to be read at the interface between liquid and air:



Squeeze bulb

*Read density here*

Regarding the graduated scale at the top of the float, would the larger numbers (representing greater density) be located toward the top of the scale, or toward the bottom of the scale? Explain your answer.

Suggestions for Socratic discussion

- A good problem-solving technique to apply to this is *limiting cases*, where you imagine extreme variations to make the problem simpler to solve. How might you apply "limiting cases" to this particular problem?
- Hydrometers were traditionally used in the alcohol industries to measure the strength ("proof") of an alcohol sample. Why do you think this method works, since a hydrometer primarily measures *density*?
- High-accuracy hydrometers have thermometers built in so they can sense the temperature of the liquid sample. Explain what temperature has to do with density measurement by invoking a "thought experiment" to see how temperature affects the reading taken by a hydrometer.

file i00282

23

Question 10

Acetic acid has a specific gravity of $1.0492^{20/4}$. Explain what the superscript "20/4" means, and calculate how much hydrostatic pressure a vertical column of acetic acid 12.3 meters high is supposed to produce, in PSI at $20^o$ C.
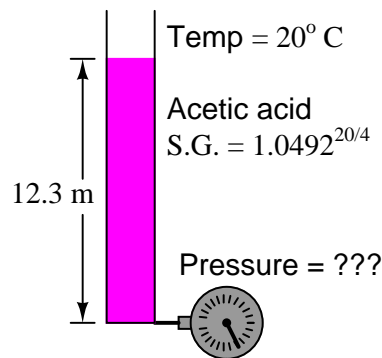


$P =$ _____ PSI

Suppose the pressure gauge connected to the bottom of this vessel registers 14.2 PSI instead of the value you calculated. Identify the likelihood of each specified fault shown in the table, considering each fault one at a time (i.e. no coincidental faults) to determine whether or not each fault could independently account for the discrepancy in pressure measurement.

| Fault | Possible | Impossible |
|---|---|---|
| Gauge has a zero error | | |
| Gauge has a span error | | |
| Gauge has a linearity error | | |
| Gauge has a hysteresis error | | |
| Liquid inside tank is denser than acetic acid | | |
| Level of liquid inside tank is less than what is shown in the diagram | | |

Suggestions for Socratic discussion

• Explain how we could determine what kind of calibration error this gauge had, if indeed its calibration was off at all.
• Identify some alternative level-measurement technologies which could be used to sense liquid level in this vessel, which aren't affected by changes in liquid density.

file i00231

24

A tank holding 13 feet of liquid exerts an hydrostatic pressure on the gauge mounted at the bottom:



13 feet    47.9 lb/ft$^3$
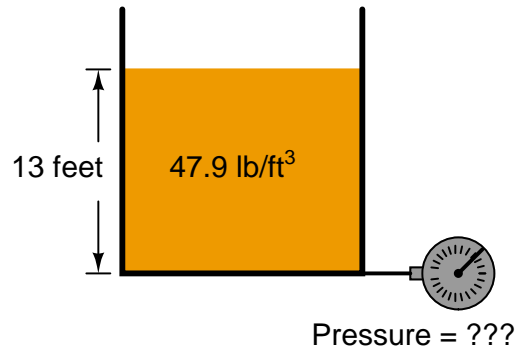
Pressure = ???

Calculate the magnitude of this hydrostatic pressure, in units of PSI:

$P =$ _____ PSI

file i02822

Question 12

Suppose we were to steadily pour a liquid into the leftmost vertical tube until it reaches a mark four inches from the bottom. Given the diameters of the other tubes, how high will the liquid level settle in each when all columns are in a condition of equilibrium (no liquid *flowing* through any part of the system)?
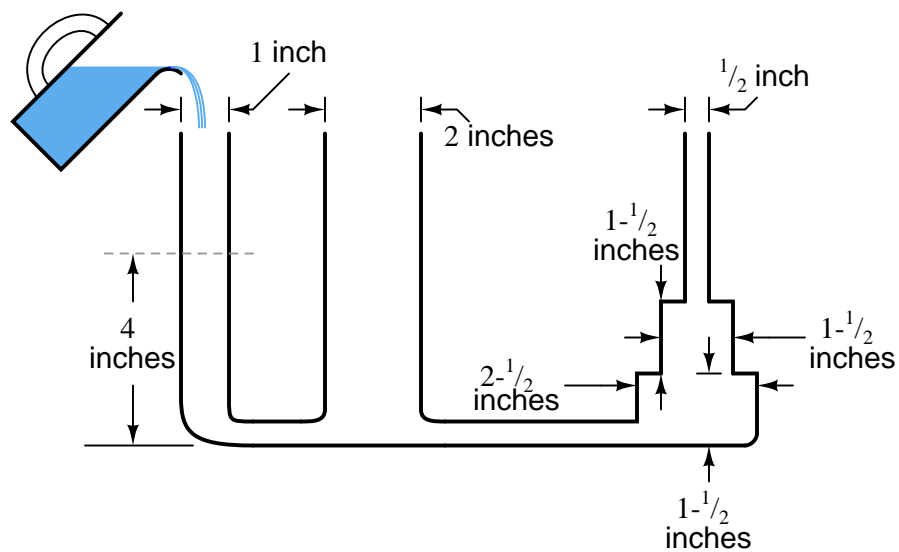


Now consider the same set of vertical tubes (same diameters, same step heights) connected at the bottom by an *inclined* pipe. If we were to pour a liquid into the leftmost vertical tube until it reaches a mark two inches from its bottom, how high will the liquid level settle in each column when all columns are in a condition of equilibrium?



file i00236

26
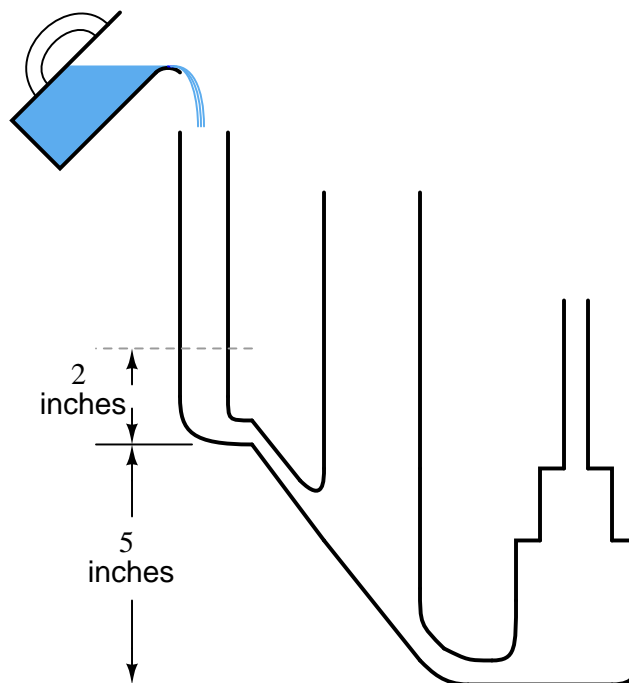
Question 13

A primitive kind of thermometer is called a *Galileo thermometer*, and it looks something like this:
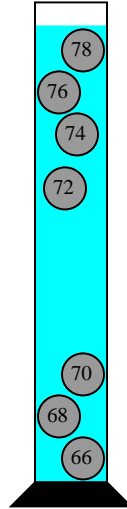


Ambient temperature is indicated by the whichever ball is floating mid-way inside the liquid container. In this case, the indicated temperature is 72$^o$ F. Explain the operating principle of this thermometer.

A simple form of *densitometer* is used to measure the concentration of anti-freeze additive in automotive engine coolant. It somewhat resembles a Galileo thermometer, and it is read the same way (by seeing how many of the balls float):
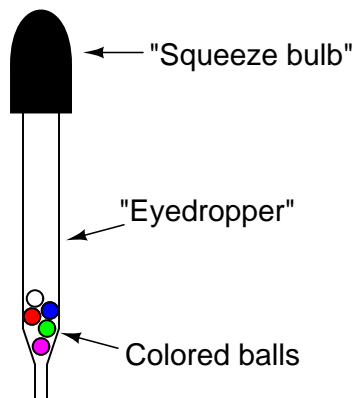


Explain how this instrument works, and how its operating principle relates to that of the Galileo thermometer.

file i00281

## Question 14

Water, at its maximum density (temperature of $3.98^o$ C, or approximately $4^o$ C), weighs 62.428 lb/ft$^3$. Based on this reference density, determine the specific gravities of the following liquids:

- Sea water: D = 63.99 lb/ft$^3$
- Mercury: D = 849 lb/ft$^3$
- Olive oil: D = 57.3 lb/ft$^3$
- Castor oil: D = 60.5 lb/ft$^3$
- Kerosene: D = 51.2 lb/ft$^3$
- Benzene: D = 56.1 lb/ft$^3$
- Acetone: D = 49.4 lb/ft$^3$
- Glycerin: D = 78.6 lb/ft$^3$
- Methanol (methyl alcohol): D = 49.41 lb/ft$^3$
- Ethanol (ethyl alcohol): D = 49.27 lb/ft$^3$
- Ethylene glycol (ethanediol): D = 69.22 lb/ft$^3$
- Gasoline: D = 41 lb/ft$^3$ to 43 lb/ft$^3$

file i00232

## Question 15

Toluene has a density of 0.8669 g/cm$^3$ at $20^o$ C. Calculate its density in units of pounds per cubic feet and its specific gravity (unitless).

file i00233

## Question 16

Which of these tubes will generate the most hydrostatic pressure, assuming they all contain the same type of liquid at precisely the same (vertical) height?
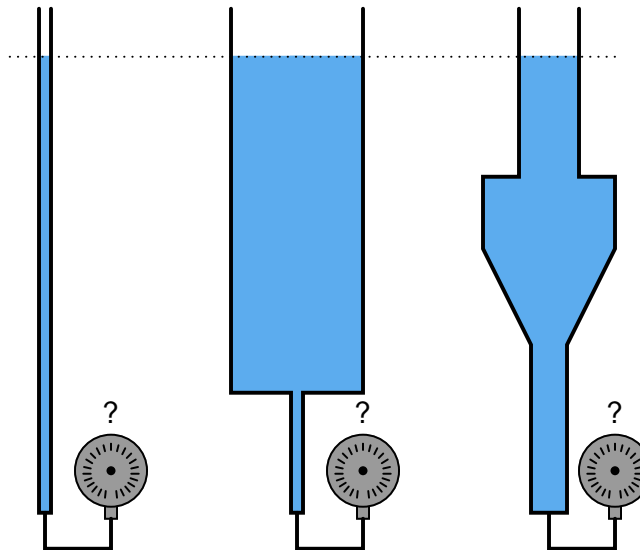


file i02953

*Specific gravity* is defined as the ratio of densities between a particular fluid and a reference fluid. For liquids, the reference fluid is water; for gases, the reference fluid is air.

For example, the density of olive oil is 57.3 lb/ft$^3$ and the density of water is 62.4 lb/ft$^3$. Calculating the ratio of these two densities yields the specific gravity of olive oil: 0.918. That is to say, the density of olive oil is 91.8% that of water.

A useful definition of specific gravity when performing hydrostatic pressure calculations for various liquids is the ratio of equivalent water column height to the height of a particular liquid. Using the specific gravity of olive oil (0.918) as an example, we could say that 0.918 units of water column height will generate the same hydrostatic pressure as 1 unit of olive oil height. The unit could be "inches," "centimeters," "millimeters," "cubits," or anything else:

$$0.918 \text{ unit W.C. pressure} = 1 \text{ unit olive oil pressure}$$

We may make a "unity fraction" from this equality, since we are dealing with two physically equal quantities: the amount of hydrostatic pressure generated by two vertical columns of different liquids.

$$\frac{0.918 \text{ unit W.C.}}{1 \text{ unit olive oil}} = \text{ unity}$$

Apply this "unity fraction" to the calculation of hydrostatic pressure at the bottom of a 20 foot tall storage tank filled to the top with olive oil, expressing that pressure in units of kPa. Show how the units cancel in your calculation(s), beginning with feet of olive oil and ending in kilo-Pascals (kPa):
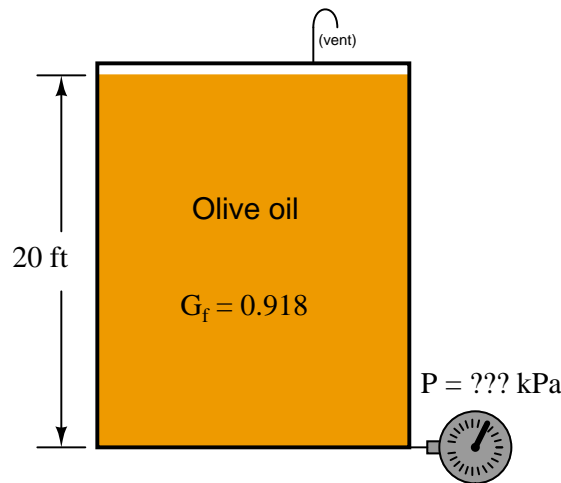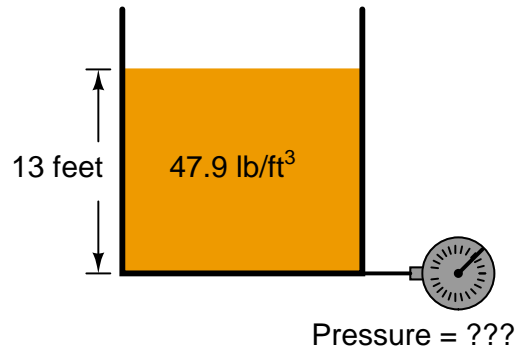


file i02956

## Question 18

A tank holding 13 feet of liquid exerts an hydrostatic pressure on the gauge mounted at the bottom:



13 feet    47.9 lb/ft$^3$

Pressure = ???

Calculate the magnitude of this hydrostatic pressure, in units of PSI:

$P = $ _____ PSI

file i02822

## Question 19

A vessel contains three different liquids of different specific gravities: glycerine, water, and olive oil. These three liquids settle at different levels in the vessel, so that there is a 3 foot deep layer of glycerine, a 2 foot deep layer of water, and a 4.5 foot deep layer of olive oil:



4.5 feet    Olive oil

2 feet    Water

3 feet    Glycerine
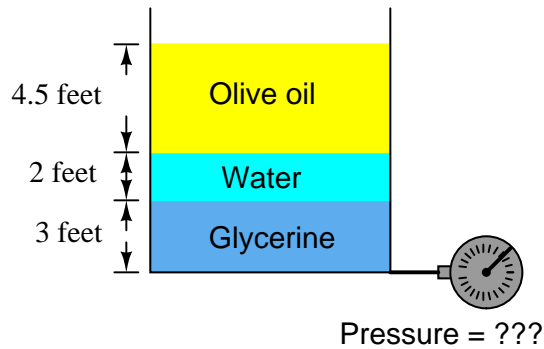
Pressure = ???

Calculate the total hydrostatic pressure at the bottom of the vessel, in units of PSI and kPa.
file i00235

Suppose the operator of this distillation process calls you to investigate a high-level alarm he is receiving on LAH-58. He doesn't think this should be happening, because LIC-38 registers a liquid level of 5'-1" in the bottom of the tower, which is a bit less than setpoint (5'-4"). Your first test is to measure the current signal from LT-38a, and you find that to be 10.67 mA (LT-38a is ranged 3'-0" to 8'-0"):
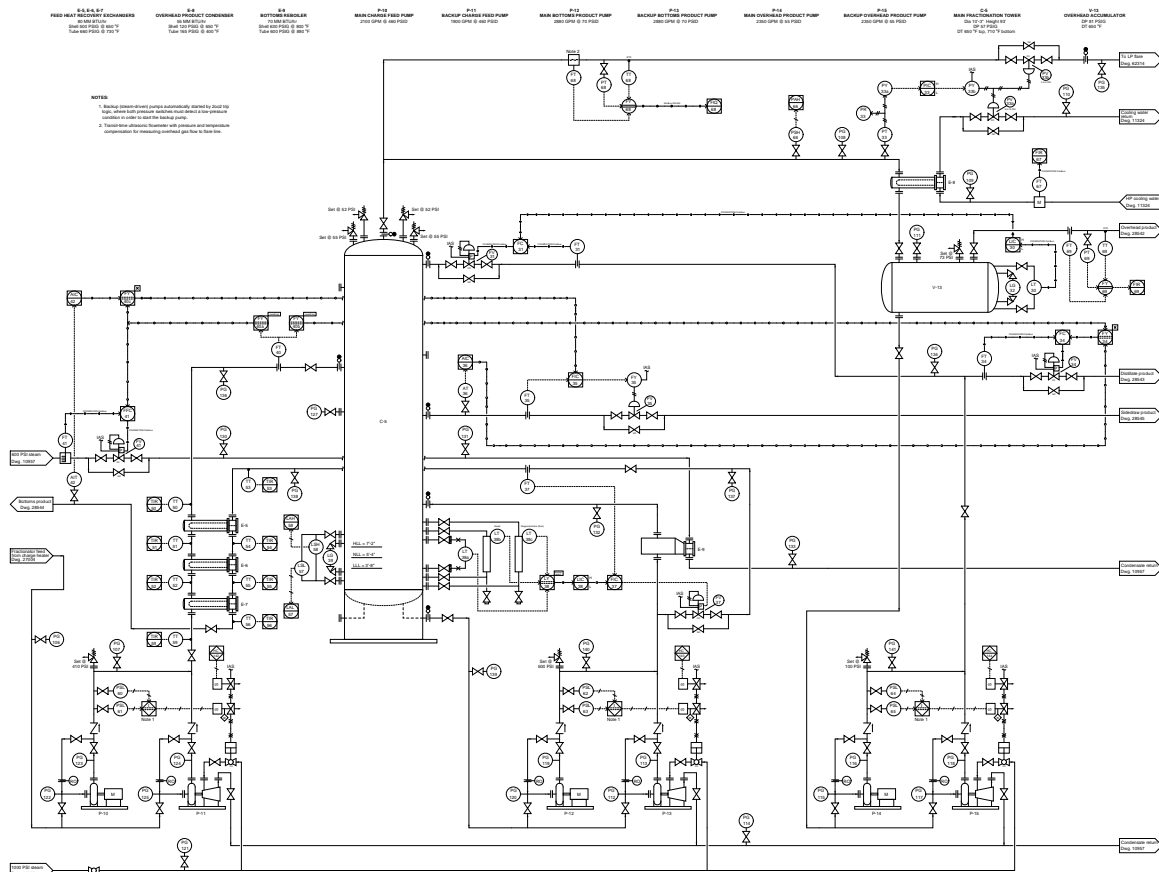


Identify which faults could account for this problem:

| Fault | Possible | Impossible |
|---|---|---|
| LSH-58 failed | | |
| LAH-58 failed | | |
| LSL-57 failed | | |
| LAL-57 failed | | |
| LT-38a calibration error | | |
| LIC-38 (input) calibration error | | |
| FIC-37 (input) calibration error | | |

file i03566

Question 21

Read and outline the "Pressure of a Fluid Column" subsection of the "Hydrostatic Pressure" section of the "Continuous Level 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 i03948

Question 22

Read and outline the "Bubbler Systems" subsection of the "Hydrostatic Pressure" section of the "Continuous Level 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
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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 i03949

Question 23

Read and outline the "Transmitter Suppression and Elevation" subsection of the "Hydrostatic Pressure" section of the "Continuous Level 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 i03950

Question 24

Read and outline the "Compensated Leg Systems" subsection of the "Hydrostatic Pressure" section of the "Continuous Level Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.
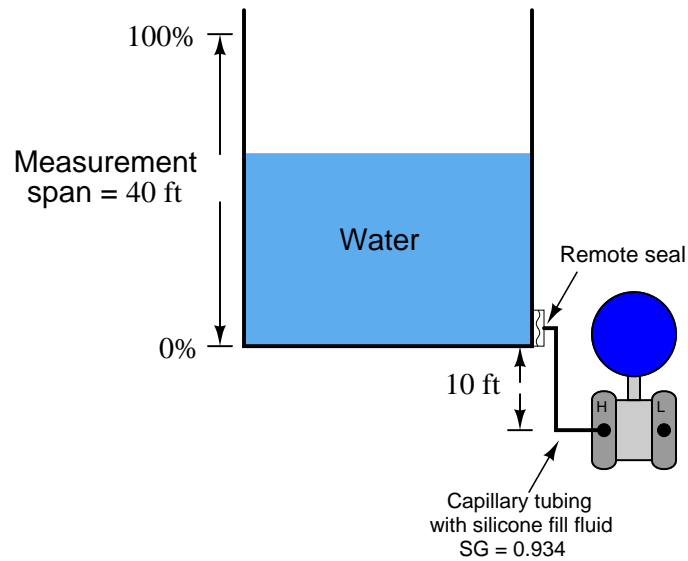
The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text 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 i03951

Question 25

Determine the LRV and URV points for a transmitter measuring water level in this vessel, with the $\Delta$P transmitter located 10 feet beneath the vessel and connected to it with capillary tubing and a remote seal filled with silicone fill fluid (SG = 0.934):



Be sure to show all your mathematical work so that your instructor will be able to check the conceptual validity of your technique(s). A good way to check to see if you're solving the problem correctly is to check that each and every one of your intermediate calculations (i.e. the results you get mid-way during the process to arrive at the final answer) has real physical meaning. **If you truly understand what you are doing, you will be able to identify the correct unit of measurement for every intermediate result and also be able to show where that number applies to the scenario at hand**.

---

| Suggestions for Socratic discussion |

- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.
- When calculating hydrostatic pressures, there are two common methods: one is to use the formula $P = \gamma h$ and another is to translate inches of vertical liquid height directly into PSI using the known relationship between water and PSI (1 PSI = 27.68 inches of water). Demonstrate both methods applied to this problem.
- Identify some realistic situations that would justify the use of a remote seal on a pressure transmitter.
- When using filled impulse lines (un-sealed), it is important to use a fill fluid denser than the fluid inside the process vessel. Is this a requirement when using a remote (sealed) diaphragm?
- Should the "low" side of the DP transmitter be vented or sealed?
- What would happen if a technician inserted a pipe plug into the formerly open "L" port of the transmitter, sealing it off from atmospheric pressure?
- What would happen if the capillary tube developed a leak?
- Explain why this level transmitter does not require a *compensating leg*.

file i00259

## Question 26

Determine the LRV and URV points for a transmitter measuring water level in this vessel, with the $\Delta P$ transmitter elevated 10 feet above the vessel bottom and connected to it with capillary tubing and a remote seal filled with silicone fill fluid (SG = 0.934):
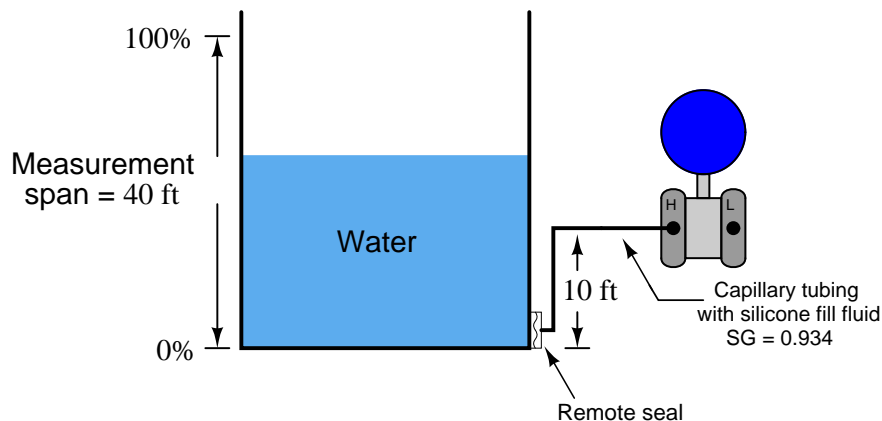


Also, explain why a remote seal is absolutely necessary in this installation. It would not be a good idea to simply connect the "high" port of the $\Delta P$ transmitter to the bottom of the vessel with a length of tubing as is permissible when the transmitter is either level with the bottom of the vessel or suppressed below the vessel's bottom!

Be sure to show all your mathematical work so that your instructor will be able to check the conceptual validity of your technique(s). A good way to check to see if you're solving the problem correctly is to check that each and every one of your intermediate calculations (i.e. the results you get mid-way during the process to arrive at the final answer) has real physical meaning. **If you truly understand what you are doing, you will be able to identify the correct unit of measurement for every intermediate result and also be able to show where that number applies to the scenario at hand**.

---

| Suggestions for Socratic discussion |

- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.
- When calculating hydrostatic pressures, there are two common methods: one is to use the formula $P = \gamma h$ and another is to translate inches of vertical liquid height directly into PSI using the known relationship between water and PSI (1 PSI = 27.68 inches of water). Demonstrate both methods applied to this problem.
- A good problem-solving technique is to imagine (perform a "thought experiment") the *converse* of a given question. Here, you were asked to explain why a remote seal is necessary. Present a thought experiment where you envision the opposite condition (e.g. the *lack* of a remote seal), and explain how this might help you to answer the initial question.
- Should the "low" side of the DP transmitter be vented or sealed?

file i00260

Question 27

The following storage vessel holds a liquid with a density of 60 lb/ft$^3$. The $\Delta$P transmitter is located 5 feet above the bottom of the vessel and has a remote seal with capillary tubing whose fill fluid has a specific gravity of 1.9. The desired level measurement range is 0 feet to 11 feet:
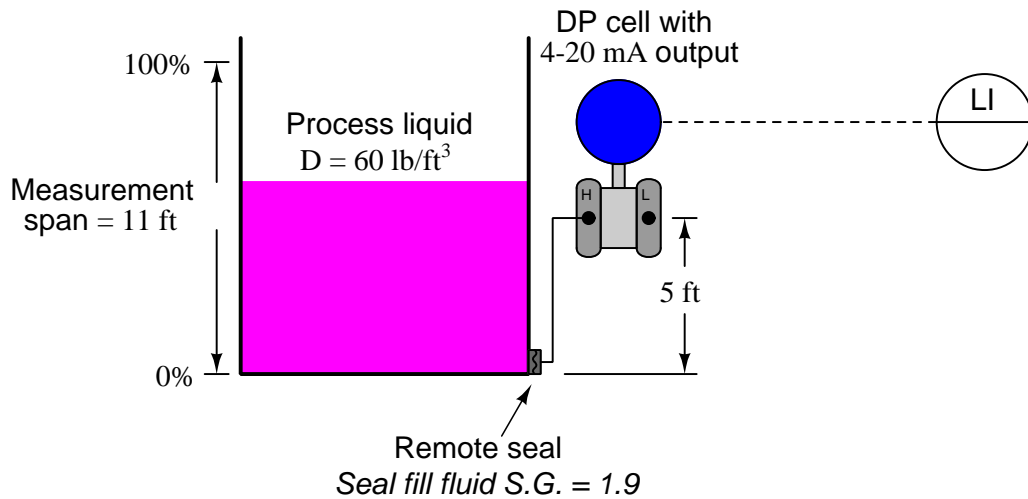


Assuming an electronic transmitter with an output range of 4 to 20 mA, and a calibration accuracy of $\pm$ 0.2% of span, complete the following calibration table for the transmitter:

| Process level (ft) | Percent of span (%) | $\Delta$ pressure sensed ("W.C) | Output signal ideal (mA) | Output signal min. (mA) | Output signal max. (mA) |
|---|---|---|---|---|---|
| | 0 | | | | |
| | 10 | | | | |
| | 25 | | | | |
| | 50 | | | | |
| | 75 | | | | |
| | 90 | | | | |
| | 100 | | | | |

Now, complete the following calibration table for the level indicator:

| Signal value (mA) | Percent of span (%) | Indication ideal (ft) | Indication min. (ft) | Indication max. (ft) |
|---|---|---|---|---|
| | 0 | | | |
| | 10 | | | |
| | 25 | | | |
| | 50 | | | |
| | 75 | | | |
| | 90 | | | |
| | 100 | | | |

Be sure to show all your mathematical work so that your instructor will be able to check the conceptual validity of your technique(s). A good way to check to see if you're solving the problem correctly is to check that each and every one of your intermediate calculations (i.e. the results you get mid-way during the process to arrive at the final answer) has real physical meaning. **If you truly understand what you are doing, you will be able to identify the correct unit of measurement for every intermediate result and also be able to show where that number applies to the scenario at hand**.
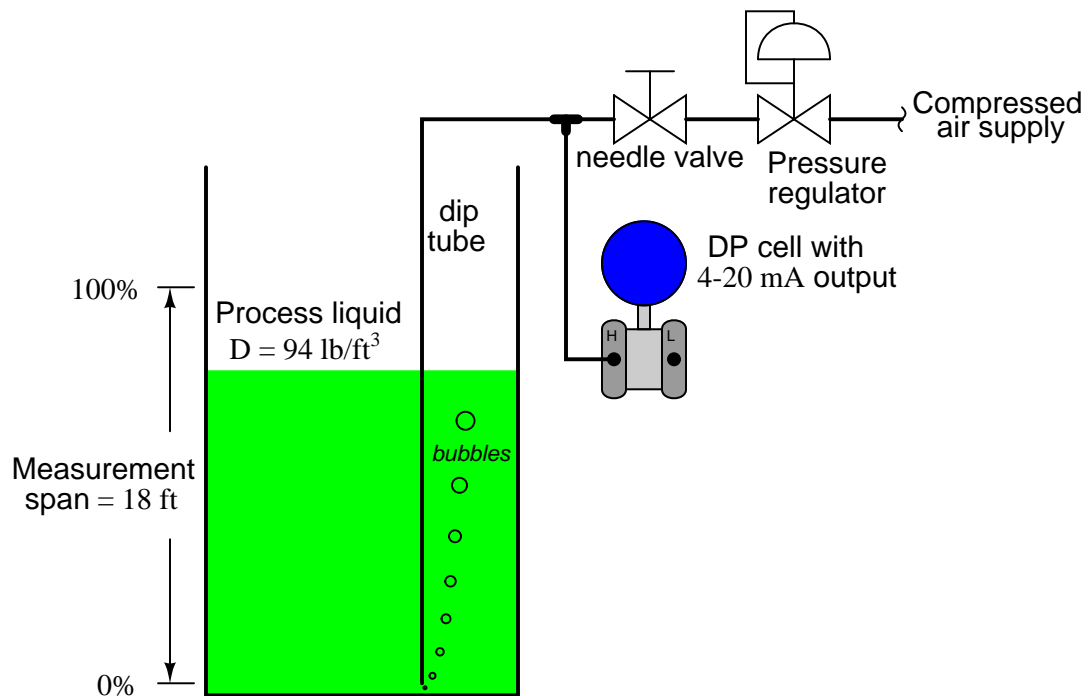
<div style="border:1px solid black; display:inline-block; padding:2px 6px;">**Suggestions for Socratic discussion**</div>

- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.
- Suppose this vessel were enclosed at the top, and a remote-sealed compensating leg connected from the transmitter's "L" port to the top of the vessel. How would this change the transmitter's necessary calibration? Would it require an adjustment in zero, span, linearity, or some combination of these?
- Given a 100% full vessel, calculate the amount of pressure that would be registered by a pressure gauge connected to the bottom of the vessel.
- Given a 100% full vessel, calculate the amount of pressure that would be registered by a pressure gauge connected to the capillary tube (at the remote seal).
- Given a 100% full vessel, calculate the amount of pressure that would be registered by a pressure gauge connected to the capillary tube (at the transmitter "H" port).

file i00261

Question 28

A liquid storage vessel holding a very corrosive liquid has its level measured by a *bubbler* system, whereby a transmitter measures the backpressure of air inside a "dip tube" inserted into the vessel:

Compressed air supply

needle valve  Pressure regulator

DP cell with 4-20 mA output

dip tube

100%

Process liquid
D = 94 lb/ft$^3$

bubbles

Measurement span = 18 ft

0%

Explain how this level measurement system works, and how it protects the DP cell from the corrosive effects of the process liquid.

Also, complete a calibration table for the differential pressure transmitter in this level measurement scenario, with a calibration tolerance of $\pm$ 0.5%. Assume that the lower range-value of the process (0% level) is exactly the same height as the bottom of the dip tube:

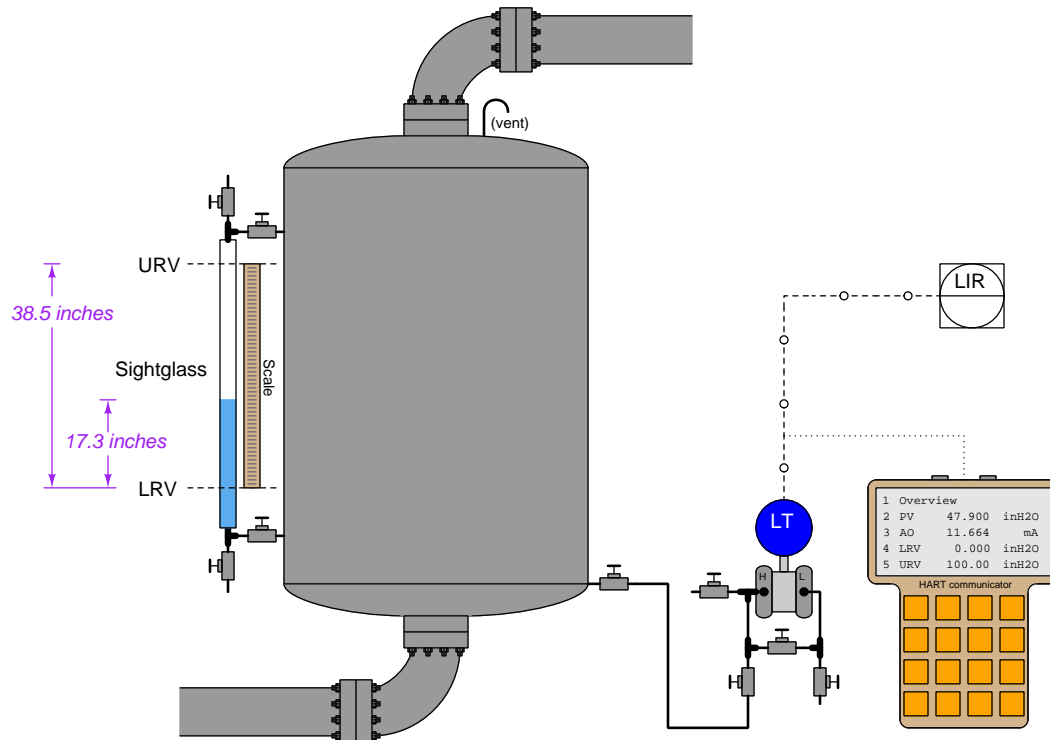| Process level (ft) | Percent of span (%) | $\Delta$ pressure sensed ("W.C) | Output signal ideal (mA) | Output signal min. (mA) | Output signal max. (mA) |
|---|---|---|---|---|---|
| | 0 | | | | |
| | 10 | | | | |
| | 25 | | | | |
| | 50 | | | | |
| | 75 | | | | |
| | 90 | | | | |
| | 100 | | | | |

Suggestions for Socratic discussion

- The dip tube (or "bubbler") system does indeed isolate the transmitter from the corrosive process liquid, but how can the dip tube itself survive? And, if the dip tube is able to survive in the corrosive liquid (just like the vessel), why can't we find a DP cell that can handle it directly without the isolation of a dip tube system?

- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.
- What is your recommendation for setting the position of the needle valve in this bubble tube system? Exactly how far open is "open enough," and more importantly for what reason?
- What would happen if the end of the dip tube were to become plugged with debris, blocking all flow?
- What would happen if the needle valve were to become plugged with debris, blocking all flow?
- What would happen if the pressure regulator were to become plugged with debris, blocking all flow?
- Add one or more hand valves to the tubing in this system to provide operators with a simple means of unblocking a plugged dip tube using high-pressure compressed air.
- Given a 100% full vessel, calculate the amount of pressure that would be registered by a pressure gauge connected to the bottom of the vessel.
- Given a 100% full vessel, calculate the amount of pressure that would be registered by a pressure gauge connected to the bottom of the dip tube.
- Given a 100% full vessel, calculate the amount of pressure that would be registered by a pressure gauge connected to the transmitter's "H" port.
- Given a 100% full vessel, calculate the amount of pressure that would be registered by a pressure gauge connected to the downstream side of the needle valve.
- Given a 100% full vessel, calculate the amount of pressure that would be registered by a pressure gauge connected to the upstream side of the needle valve.

file i00249

When installing a hydrostatic level transmitter on a working process, one must determine the proper lower- and upper-range values (LRV and URV) for the transmitter in order to properly register 0% at the LRV liquid level and 100% at the URV liquid level. If all fluid densities and physical dimensions are known in advance, this is a simple matter of a few mathematical calculations. However, sometimes it is difficult to know all the physical dimensions in advance, especially the elevation or suppression. Consider this example, assuming clean water as the process liquid and a static pressure of 0 PSIG inside the (vented) process vessel:

(vent)

URV

38.5 inches

Sightglass

Scale

17.3 inches

LRV

LIR

LT

```
1  Overview
2  PV      47.900   inH2O
3  AO      11.664      mA
4  LRV      0.000   inH2O
5  URV     100.00   inH2O
```
HART communicator

This "smart" transmitter has already been *calibrated* (i.e. *trimmed*) at the instrument shop to accurately register applied pressure and to accurately output its 4-20 mA signal, but its range values have not been customized to the installation. Reading off the sightglass's scale, we find a vertical distance of 38.5 inches between the LRV and URV points marked on the sightglass, and we also see the current liquid level is 17.3 inches above the marked LRV point. Using a HART communicator to interrogate this "smart" transmitter, we see that the registered pressure at this process condition is 47.9 inches of water column ("WC), which is greater than 17.3 inches registered by the sightglass due to the transmitter's *suppression*.

Based on this information alone, calculate the appropriate LRV and URV settings to program into the smart transmitter, so that it will output 4 mA when the process water level is at the LRV height and 20 mA when the water level is at the URV height:

LRV = _____ "WC (@ 4 mA)          URV = _____ "WC (@ 20 mA)

Also, determine the appropriate LRV and URV settings for the indicating recorder (LIR) so that it will register the same as the scale (in inches) alongside the sightglass:
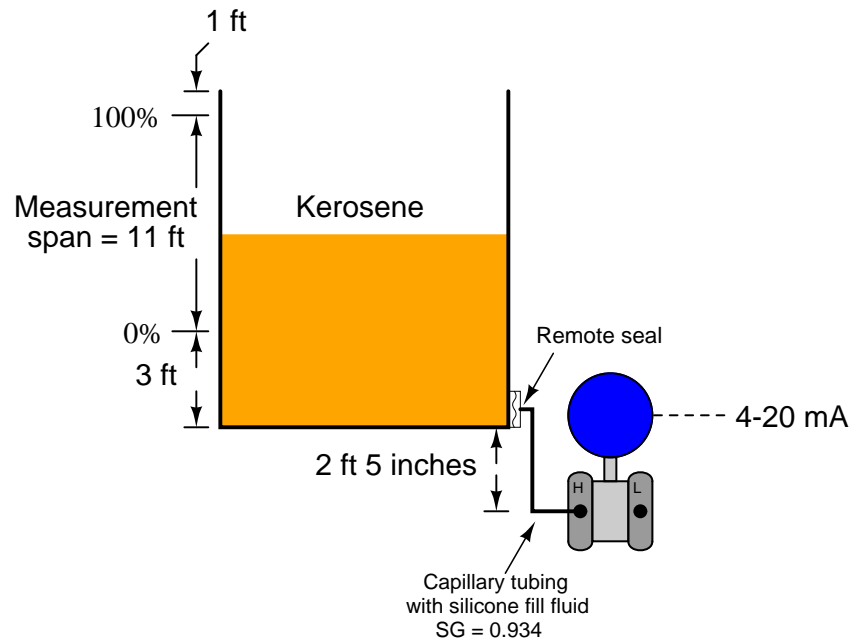
LRV = _____ inches (@ 4 mA)          URV = _____ inches (@ 20 mA)

file i02870

Calculate the proper LRV and URV pressures for the 4-20 mA loop-powered $\Delta$P transmitter in this level measurement scenario:



- LRV = _____ inches water column

- URV = _____ inches water column

Then, calculate the transmitter's output given the following process levels (assuming perfect transmitter calibration):

- Output = _____ mA with the kerosene level 4 feet up from the bottom of the tank (4 feet "fillage")
- Output = _____ mA with the kerosene level 6 feet down from the top of the tank (6 feet "ullage")

---

| Suggestions for Socratic discussion |

- Suppose the DP transmitter with the remote seal failed and had to be replaced. Unfortunately, you don't have another DP transmitter with a remote seal in stock to replace it. Could you use a DP transmitter *without* a remote seal for this application? If so, would its calibration have to be different from the remote-seal transmitter?
- Explain why this installation does not require a *compensating leg*.

file i00520

## Question 31

A water storage vessel is elevated by a tower structure, to provide a natural source of water pressure to all points of use below:
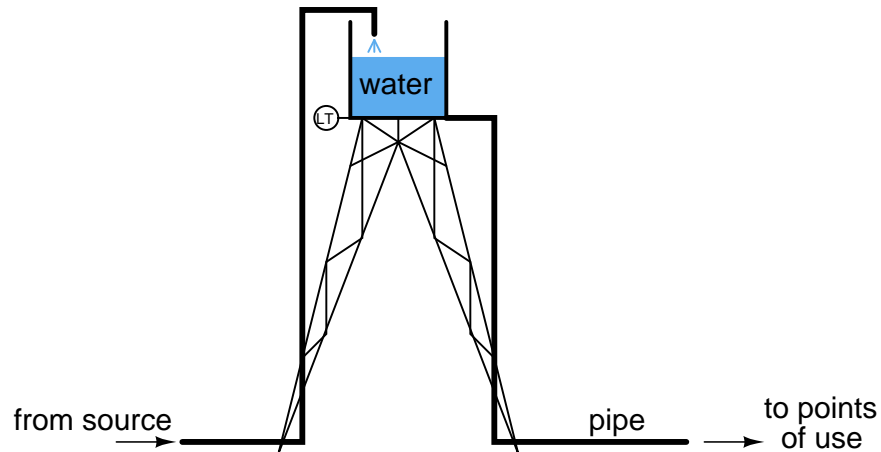


A pressure-sensing level transmitter is presently located at the base of the vessel, at the top of the tower structure, to measure water level inside the vessel. It has a calibrated range of 0 to 10 feet (0 to 120 inches W.C.). Unfortunately, the water inside the transmitter sometimes freezes in the winter months, preventing operation of the level measurement system. The water inside the storage vessel and the large pipes never freezes, because there is enough circulation as a result of water usage to raise the temperature and prevent ice crystals from forming.

It is decided to move the transmitter to ground level, at the base of the tower, so that it may be located inside a small, heated shelter where it will never freeze. By connecting the transmitter directly to the large water pipe carrying water from the vessel to the points of use, the hydrostatic pressure will still be measurable at this point:
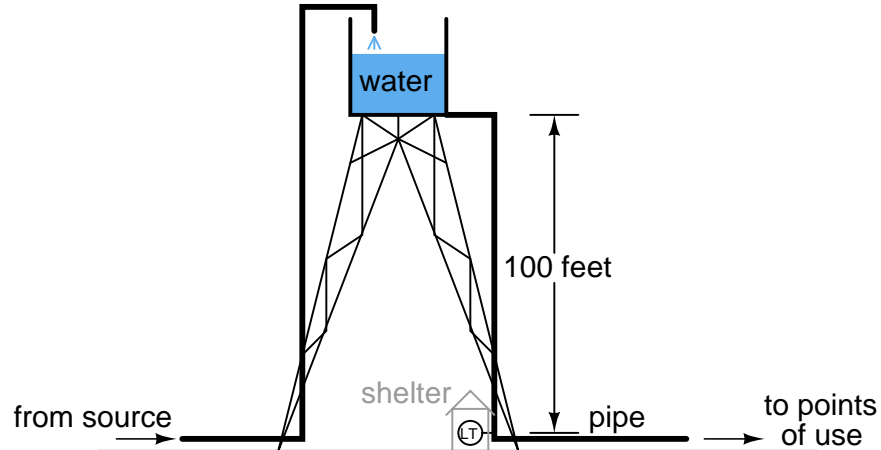


Calculate the new calibration points (lower and upper range-values) for the transmitter in its new location. Also calculate the water level in the vessel when the transmitter output is 13.7 mA, and the amount of hydrostatic pressure at that point in units of PSI.

Finally, identify whether the transmitter move resulted in a shift of its *zero*, a shift in its *span*, or both.
file i00253

Question 32

The following storage vessel holds water. A pneumatic pressure transmitter located at the bottom infers water level by hydrostatic pressure (head). Determine the calibration range of this pressure transmitter in order to properly translate the range of vessel level (0 to 18 feet) into an output signal of 3 to 15 PSI. Please express the transmitter's calibration range in units of inches W.C. (inches of water column).
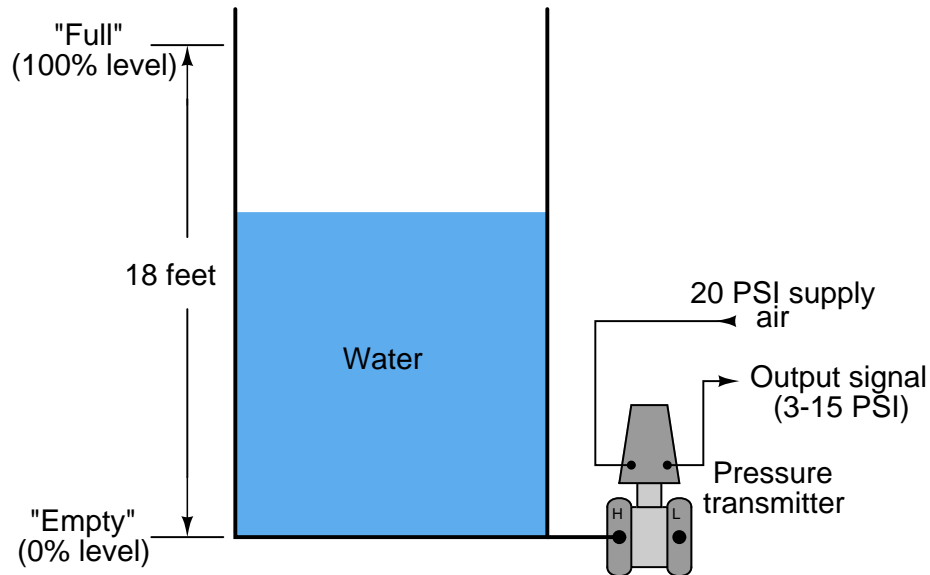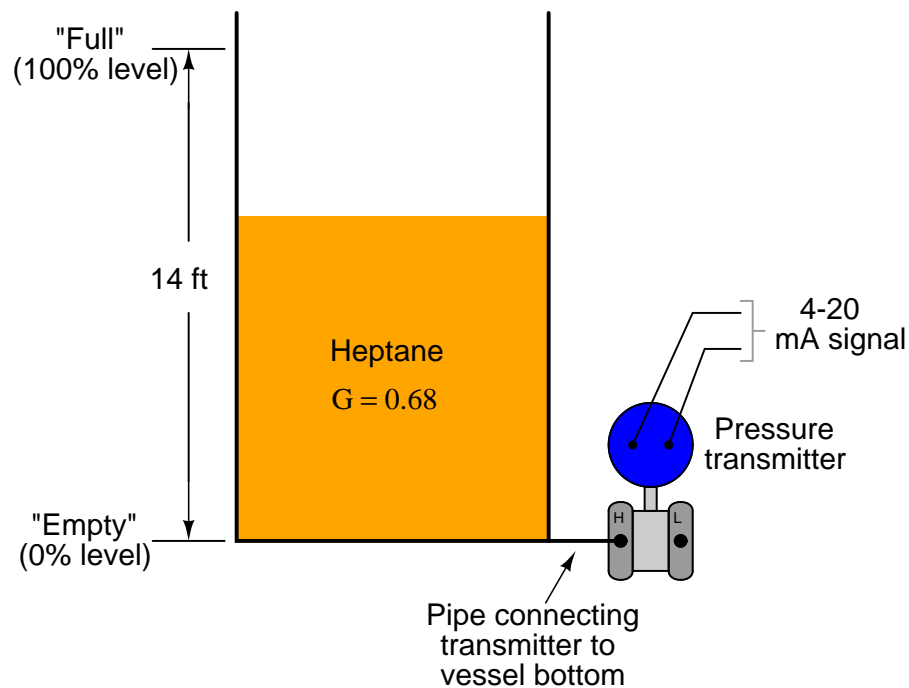


Then, determine the following (assuming the transmitter has been properly calibrated for the application):

- Transmitter output signal (PSI) at 12 feet of level
- Water level at 5.9 PSI signal output

file i00243

Question 33

The following storage vessel holds liquid heptane, a hydrocarbon with an approximate specific gravity of 0.68. A pressure transmitter located at the bottom infers heptane level by hydrostatic pressure (head). Determine the calibration range of this pressure transmitter in order to properly translate the range of vessel level (0 to 14 feet) into an output signal of 4 to 20 mA. Please express the transmitter's calibration range in units of inches W.C. (inches of water column).
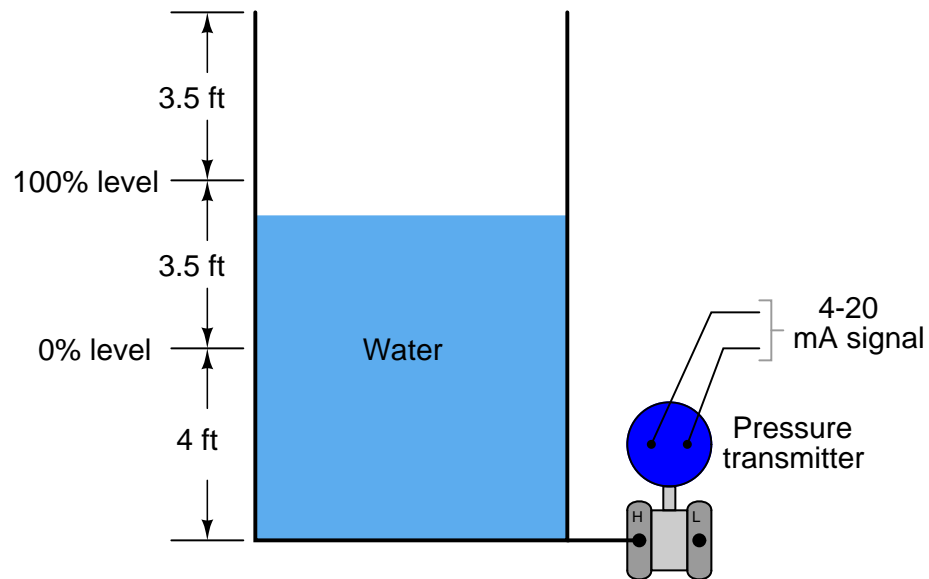


Then, determine the following (assuming the transmitter has been properly calibrated for the application):

- Transmitter output signal (mA) at 8 feet of level
- Heptane level at 5.7 mA signal output

file i00241

44

# Question 34

Suppose we wish to measure water level in this vessel, where the LRV and URV points are both between the extreme limits of "empty" and "full":
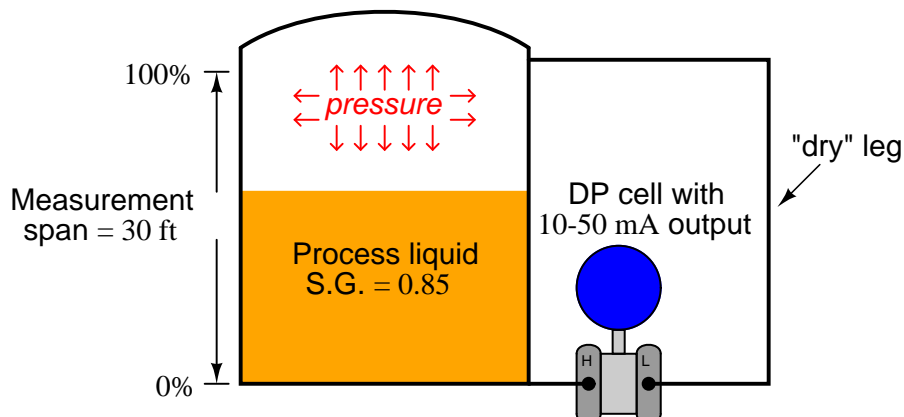


Complete the following calibration table for this level transmitter:

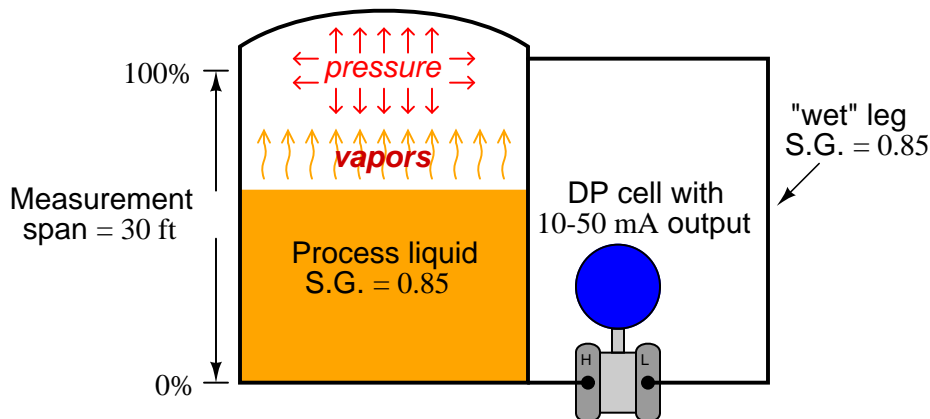| Process level (in) | Percent of span (%) | Hydrostatic pressure (PSI) | Output signal ideal (mA) |
|---|---|---|---|
| 0 | 0 | 1.732 | 4 |
| 10.5 | 25 | 2.111 | 8 |
| 21 | 50 | 2.490 | 12 |
| 31.5 | 75 | 2.869 | 16 |
| 42 | 100 | 3.248 | 20 |

file i02963

Calculate the 0%, 50%, and 100% calibration points for the $\Delta P$ transmitter to measure liquid level in this vessel, given a range of 0 to 30 feet and a specific gravity of 0.85. Note that the "low" side of the transmitter connects to the top of the vessel to compensate for vapor pressure inside the vessel. This tube is called a "dry leg" because there is no liquid inside of it:

100%

← pressure →
↑↑↑↑↑
↓↓↓↓↓

"dry" leg

Measurement
span = 30 ft

DP cell with
10-50 mA output

Process liquid
S.G. = 0.85

H    L

0%

| % of span | $\Delta P$ ("H$_2$O) | Output (mA) |
|---|---|---|
| 0 | | |
| 50 | | |
| 100 | | |

Now suppose the vessel is heated, and the liquid inside the vessel emits condensible vapors. These vapors will condense inside low-side tube leading to the $\Delta P$ transmitter which is cooler than the storage vessel, resulting in a "wet leg" instead of a "dry leg." In other words, the transmitter will now "see" a constant column of liquid (SG = 0.85) 30 feet high connected to its "low" process port:

100%

↑↑↑↑↑
← pressure →
↓↓↓↓↓
↑↑↑ vapors ↑↑↑

"wet" leg
S.G. = 0.85

Measurement
span = 30 ft

DP cell with
10-50 mA output

Process liquid
S.G. = 0.85

H    L

0%

Re-calculate the 0%, 50%, and 100% calibration points for the $\Delta P$ transmitter to measure liquid level in this vessel with a wet reference leg instead of a dry reference leg.

| % of span | $\Delta P$ ("H$_2$O) | Output (mA) |
|---|---|---|
| 0 | | |
| 50 | | |
| 100 | | |

Question 36

Purge systems may be used to detect hydrostatic pressure in a vessel even when there is no dip tube. For example, in this level measurement system, compressed air is used as a purge medium directly into the vessel where the transmitter tubing connects:
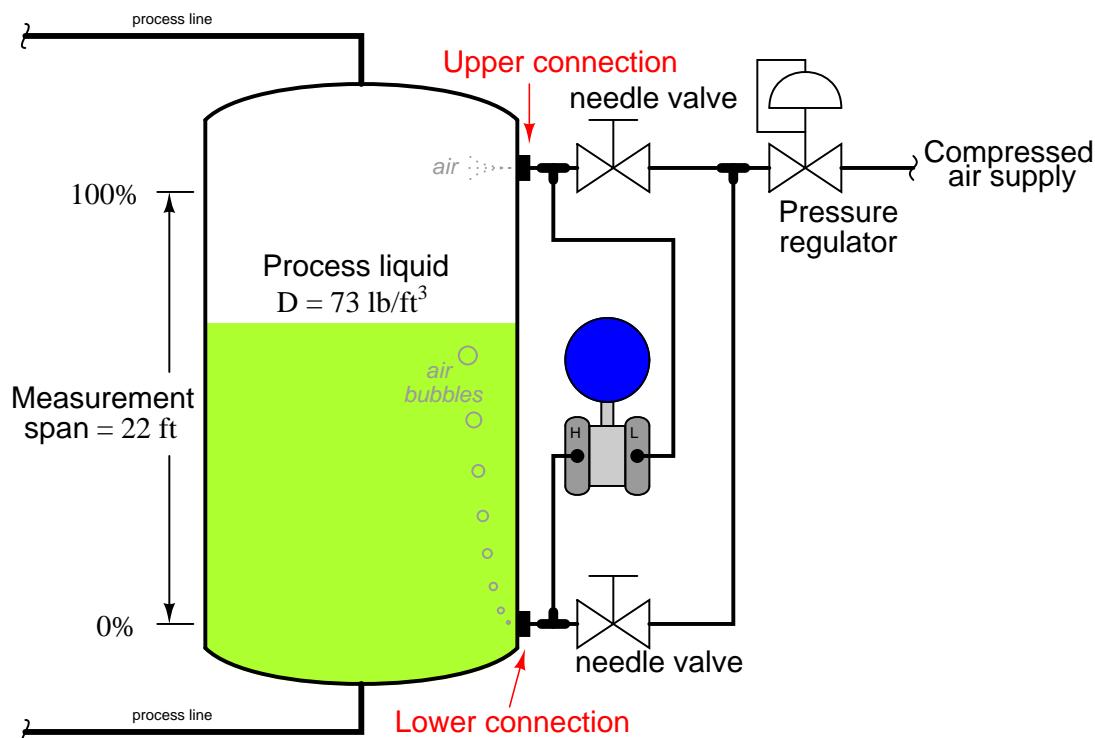


First, calculate the appropriate calibration range for the DP transmitter in this application.

Next, explain what would happen to the transmitter's output if the lower connection to the process vessel became plugged by debris (despite the cleaning action of the compressed air flowing through it). Alternatively, what if only the upper connection became plugged?

---

**Suggestions for Socratic discussion**

- Why would anyone choose to continuously *purge* the nozzles of a hydrostatic level transmitter when they could have easily chosen remote seals (diaphragms)?
- Is air always a safe purge fluid to use? If not, what are some valid alternatives?
- Suppose a slug of process liquid were to find its way into the "H" side impulse line leading up to the DP transmitter. How would this bit of liquid affect the transmitter's accuracy?
- Suppose a slug of process liquid were to find its way into the "L" side impulse line leading down to the DP transmitter. How would this bit of liquid affect the transmitter's accuracy?

file i00250

47

A *tank expert* system uses three pressure transmitters to measure level and density of a liquid in a large storage vessel. The three transmitters are labeled "top," "middle," and "bottom," as such:

Liquid storage vessel (vent) "Top"

Process liquid

LY
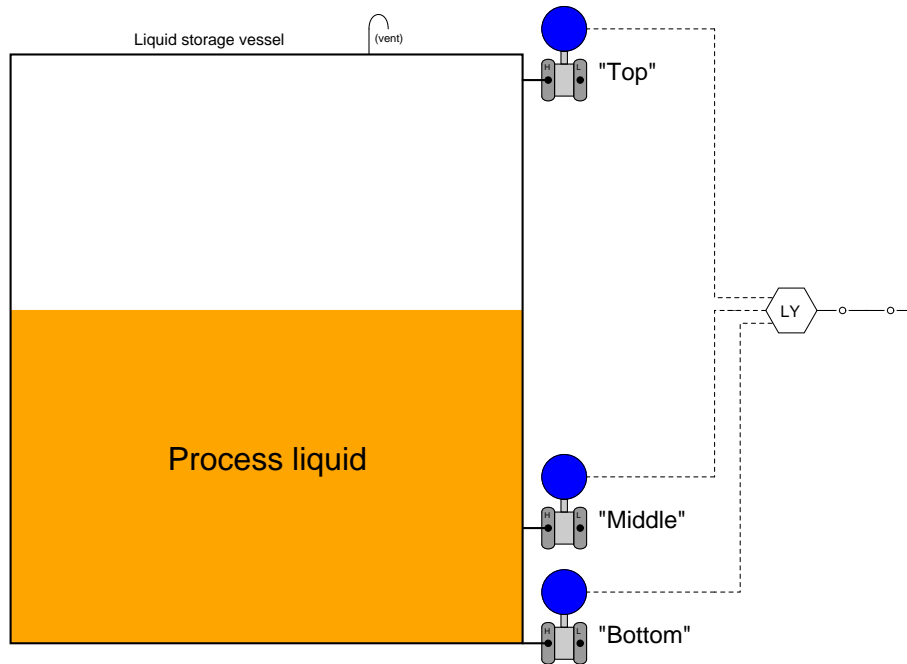
"Middle"

"Bottom"

Tank expert systems use a computer (LY in the diagram) to process data gathered from the three pressure transmitters, calculating both liquid density and liquid level. The distance between the "middle" and "bottom" pressure transmitters is known from installation and entered into this computer system as a constant value, to be used in the calculations. An important requirement of a tank expert system is that the liquid level must be above the "middle" pressure transmitter's location if density is to be calculated.

Suppose that a tank expert system has the "middle" transmitter located 10 feet above the bottom of the vessel, the "bottom" transmitter at the very bottom of the vessel, and the "top" transmitter at the very top. Supposing that the vessel is vented at the top (preventing any vapor pressure buildup) and is 40 feet tall, and the liquid level inside is 15 feet with a specific gravity of 0.86, what pressures will the three pressure transmitters report to the computer system under these conditions? In other words, what will be the "raw" data input to the computer system under these conditions?

file i00254

48

A tank expert system gives the following pressure indications from its three transmitters:

Liquid storage vessel

Measurement = 50 "W.C.

"Top"

Process liquid

*Level = ???*
*S.G. = ???*

Measurement = 220 "W.C.

"Middle"

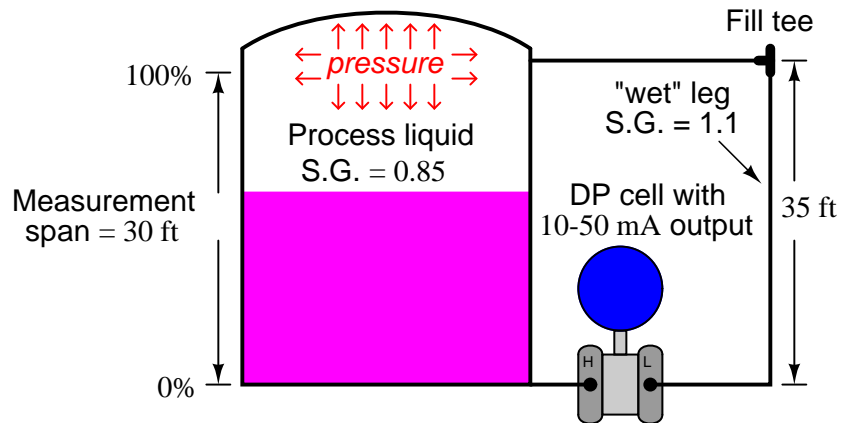10 feet

Measurement = 310 "W.C.

"Bottom"
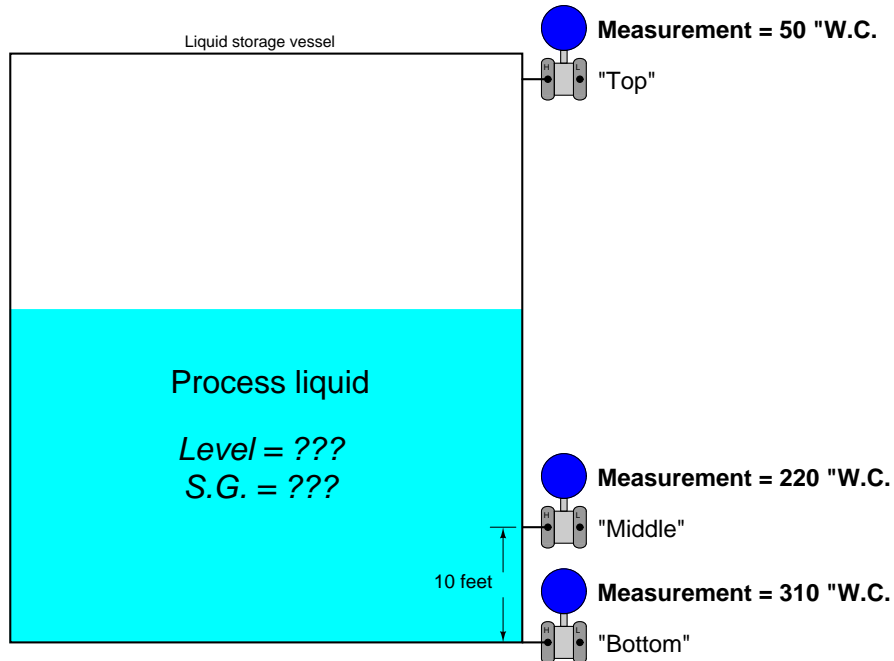
From these pressure measurements, determine the level of liquid in the vessel and its specific gravity. Also, write mathematical equations for calculating both these parameters given the three pressure sensor measurements.

file i00256

## Question 39

Calculate the 0%, 50%, and 100% calibration points for the $\Delta P$ transmitter to measure liquid level in this vessel, given a range of 0 to 30 feet and a process specific gravity of 0.85. Note the "wet" leg filled with fluid different than the process (SG = 1.1), 35 feet tall:



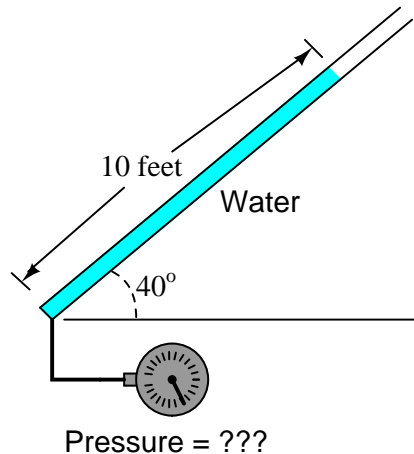| % of span | $\Delta P$ ("H$_2$O) | Output (mA) |
|-----------|----------------------|-------------|
| 0         |                      |             |
| 50        |                      |             |
| 100       |                      |             |

file i00263

## Question 40

A tube containing a 10 foot long column of water is angled $40^o$ from horizontal. Calculate the hydrostatic pressure at the bottom of this tube in units of inches water column ("W.C.) and also in units of atmospheres.



file i00234

## Question 41

Read and outline the "Buoyancy" subsection of the "Fluid Mechanics" section of the "Physics" 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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file i03954

## Question 42

*Ebony* wood is a very dense – so dense that it does not float in water. How much would a piece of ebony wood of D=75 lb/ft$^3$, 200 cubic inches in volume, weight when dry and when submerged in water?

What would the density of wood have to be in order for it to float in water?

Be sure to show all your mathematical work so that your instructor will be able to check the conceptual validity of your technique(s). A good way to check to see if you're solving the problem correctly is to check that each and every one of your intermediate calculations (i.e. the results you get mid-way during the process to arrive at the final answer) has real physical meaning. **If you truly understand what you are doing, you will be able to identify the correct unit of measurement for every intermediate result and also be able to show where that number applies to the scenario at hand**.

file i00268

## Question 43

Calculate the weight of an iron rod (D = 490.68 pounds per cubic foot), 5 feet long and 2 inches in diameter, as it hangs inside an empty vessel:
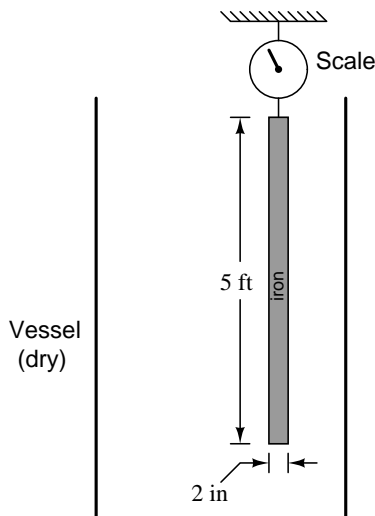


Next, calculate the amount of weight indicated by the scale as the vessel fills with water until 3 feet of the rod is submerged. Hint: the metal rod will be *displacing* a volume of water 3 feet in length and 2 inches in diameter.



Be sure to show all your mathematical work so that your instructor will be able to check the conceptual validity of your technique(s). A good way to check to see if you're solving the problem correctly is to check that each and every one of your intermediate calculations (i.e. the results you get mid-way during the process to arrive at the final answer) has real physical meaning. **If you truly understand what you are doing, you will be able to identify the correct unit of measurement for every intermediate result and also be able to show where that number applies to the scenario at hand**.
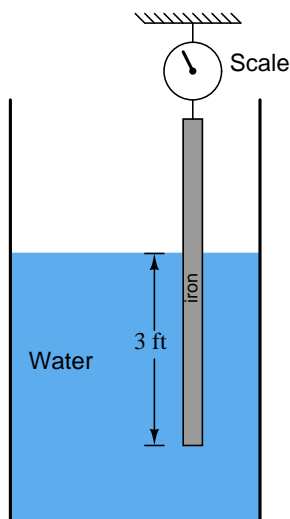
---

Suggestions for Socratic discussion

- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

- How would your weight calculations be affected if the rod were made of some material other than iron?
- How would your weight calculations be affected if the iron rod were a larger diameter but identical length?
- How would your weight calculations be affected if the liquid had a density different from water?

file i00275

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Question 44

Read and outline the "Buoyant-Force Instruments" and "Torque Tube" subsections of the "Displacement" section of the "Continuous Level 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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file i03952

Question 45

Read portions of Product Flier PF11.2:2390 for the Fisher model 2390 and 2500 displacement-type level transmitters ("Level-Trol"), and Instruction Manual "Form 5729" for the model 249W level sensor, both published by Fisher, and answer the following questions:

Describe what a *cage* is and how it relates to the construction of a displacement-style liquid level transmitter. Also describe what a *cageless* transmitter installation looks like.

Identify a page in at least one of these documents where the torque tube assembly is clearly shown. Do your best to describe how it functions.

Figure 10 found on page 9 of the Instruction Manual "Form 5729" for the model 249W level sensor shows how the displacer connects to the end of the displacer rod. A small piece of spring-steel wire called a "cotter spring" inserts into the displacer end piece to hold the displacer rod's ball into the socket of the end piece. Explain what could happen if this cotter spring is accidently omitted from the assembly, or is improperly inserted, such that the displacer rod is able to slip out of the end piece. How, exactly, will this affect the operation of the instrument?

---

Suggestions for Socratic discussion

- Suppose the displacer were removed from a Fisher "Level-Trol" instrument and replaced with one having the same weight and length but smaller diameter. How would this change the instrument's response to process liquid level?
- Suppose the displacer were removed from a Fisher "Level-Trol" instrument and replaced with one having the same weight and diameter but shorter length. How would this change the instrument's response to process liquid level?
- Suppose the torque tube were removed from a Fisher "Level-Trol" instrument and replaced with one having a stiffer spring constant. How would this change the instrument's response to process liquid level?
- Displacers are hollow, but filled with enough lead shot to prevent the displacer from ever floating. Explain how the instrument's response would be affected by a leak developing in the displacer, such that process fluid is able to fill it up.
- Describe a calibration procedure suitable for either type (caged or cageless) "Level-Trol" transmitter.

file i03953

Question 46

*Distillation* is a process of continuous boiling and condensing used to separate mixtures of different fluids. A practical example of distillation is the separation of crude oil into multiple gases and liquids (propane, butane, naphtha, hexane, etc.). Components with higher boiling points (typically denser fluids) collect at the bottom of the tower, while components with lower boiling points (typically lighter fluids) and gases collect at the top of the tower.

In this distillation tower, the "feed" fluid is a mixture of just three components, each separated from each other within the distillation tower and draw off as products at three different points. "Overhead" gases are drawn off the very top of the tower, "distillate" liquid is drawn out of an accumulation vessel near the top, and "bottom product" is drawn off the bottom of the tower. A displacer-style level transmitter (LT) senses the level of this "bottom product" liquid collecting at the tower's base:
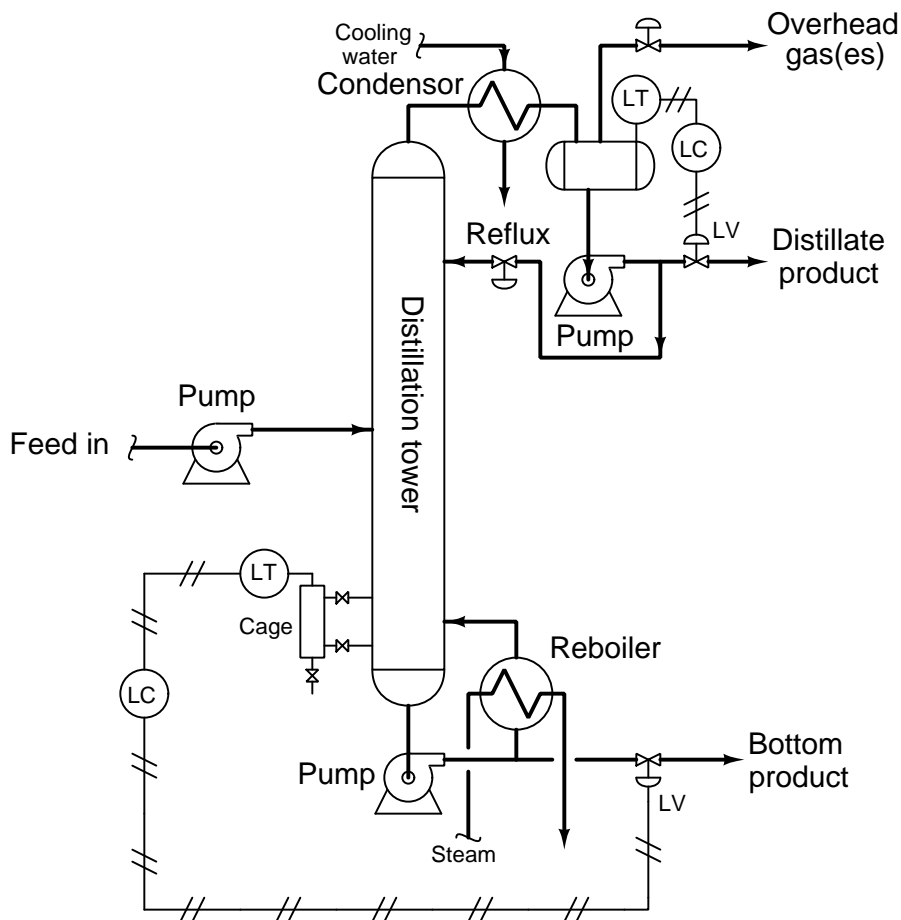


An instrument technician calculates the buoyant force for the displacer of this level instrument to be 0 pounds at 0% liquid level, and 3.75 pounds at 100% liquid level. Explain how you would check the calibration of this instrument while the distillation tower was running, using these figures.

---

| Suggestions for Socratic discussion |

- What safety concerns are there in this process that you would have to be aware of?
- What *standard* will you use for calibration (i.e. the thing you check the instrument's calibration against)?
- Are there any process-related factors that could skew the calibration accuracy of this instrument while it is in service?

Determine a basic 5-point (0%, 25%, 50%, 75%, and 100%) calibration table for the displacer level transmitter in this scenario:
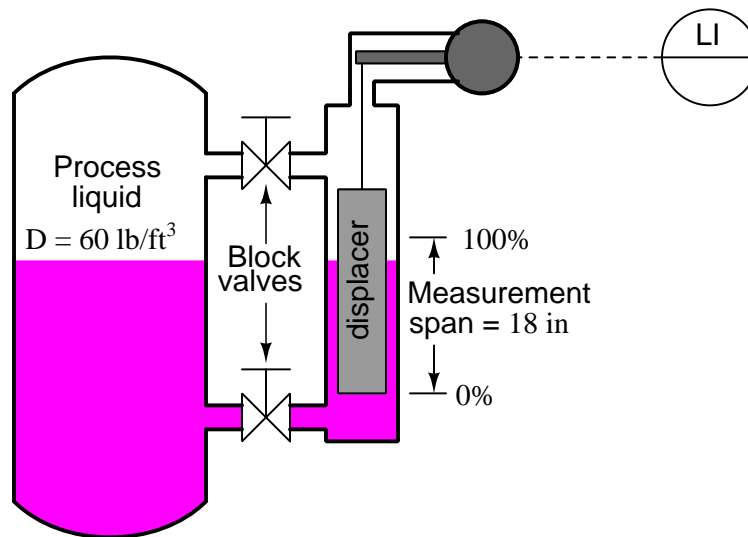
The cylindrical displacer weighs 8 pounds (dry) and has a diameter of 2.5 inches. The process liquid is at a temperature of 52 degrees F and has a density of 60 lb/ft$^3$. The 0% process liquid level (LRV) is even with the bottom of the displacer. Assume an electronic transmitter mechanism with an output range of 4 to 20 mA, and a calibration tolerance of ± 0.2% (of span).

| Process level (in) | Percent of span (%) | Buoyant force (lb) | Output signal ideal (mA) | Output signal min. (mA) | Output signal max. (mA) |
|---|---|---|---|---|---|
| | 0 | | | | |
| | 25 | | | | |
| | 50 | | | | |
| | 75 | | | | |
| | 100 | | | | |

Now, complete the following calibration table for the level indicator:

| Signal value (mA) | Percent of span (%) | Indication ideal (in) | Indication min. (in) | Indication max. (in) |
|---|---|---|---|---|
| | 0 | | | |
| | 25 | | | |
| | 50 | | | |
| | 75 | | | |
| | 100 | | | |

Be sure to show all your mathematical work so that your instructor will be able to check the conceptual validity of your technique(s). A good way to check to see if you're solving the problem correctly is to check that each and every one of your intermediate calculations (i.e. the results you get mid-way during the process to arrive at the final answer) has real physical meaning. **If you truly understand what you are doing, you will be able to identify the correct unit of measurement for every intermediate result and also be able to show where that number applies to the scenario at hand**.

- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.
- Calculate the apparent weight of the displacer in each of these process level conditions.

file i00688

Question 48

Determine a basic 5-point (0%, 25%, 50%, 75%, and 100%) calibration table for the displacer level transmitter in this scenario:
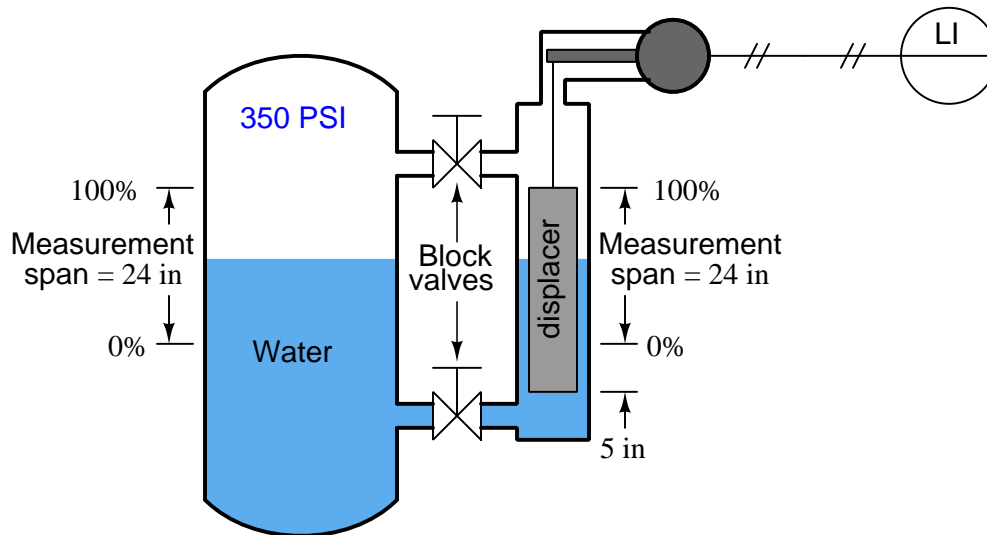


The cylindrical displacer weighs 10 pounds (dry) and has a diameter of 2 inches. The process liquid is water (density = 62.428 lb/ft$^3$). The 0% process liquid level (LRV) begins when the displacer is submerged 5 inches. Assume a pneumatic transmitter mechanism with an output range of 3 to 15 PSI, and a calibration tolerance of $\pm$ 1% (of span).

| Percent of span (%) | Buoyant force (lb) | Output signal ideal (PSI) | Output signal min. (PSI) | Output signal max. (PSI) |
|---|---|---|---|---|
| 0 | | | | |
| 25 | | | | |
| 50 | | | | |
| 75 | | | | |
| 100 | | | | |

Be sure to show all your mathematical work so that your instructor will be able to check the conceptual validity of your technique(s). A good way to check to see if you're solving the problem correctly is to check that each and every one of your intermediate calculations (i.e. the results you get mid-way during the process to arrive at the final answer) has real physical meaning. **If you truly understand what you are doing, you will be able to identify the correct unit of measurement for every intermediate result and also be able to show where that number applies to the scenario at hand**.

---

Suggestions for Socratic discussion

- What effect would accidently leaving the lower block valve closed have on this instrument upon process start-up?
- What effect would accidently leaving the upper block valve closed have on this instrument upon process start-up?
- Describe a complete *wet* calibration procedure for this level transmitter.
- Describe a complete *dry* calibration procedure for this level transmitter.
- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

Question 49

Read selected sections of the US Chemical Safety and Hazard Investigation Board's report (2005-04-I-TX) of the 2005 BP Texas City oil refinery explosion, and answer the following questions.

Describe in your own words how the situation progressed from the raffinate splitter tower start-up time to the explosion. How did instrumentation play a part in allowing this accident to happen?

Read pages 320-323 of the report, and identify the following:

• Explain why, based on the report and also what you know about displacer-style level transmitters, why LT-5100 was incapable of registering liquid levels greater than 100% of its measurement range.
• How was the specific gravity (density) of the process liquid for level transmitter LT-5100 important in the cause of the accident?
• Explain why level transmitter LT-5100 indicated *less than 100% level and falling* even though the transmitter cage was completely full of liquid ("flooded").
• Describe the role that instrument documentation played in the mis-calibration of level transmitter LT-5100.

Suggestions for Socratic discussion

• Page 34 of the report shows a simple P&ID of the raffinate section of the ISOM process. Identify the relevant instrumentation in this portion of the process and explain in your own words what happened on the day of the accident.
• 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 industry trend since this unfortunate event has been the installation of *redundant* level-sensing instruments for critical process vessels. Identify the characteristics an engineer might consider when choosing redundant level transmitters for a safety application in an oil refinery.
• Pages 329-330 of the report show some of the level instruments being inspected post-accident. Examine these photographs and try to explain how the instruments are supposed to function based on what you are able to see.

file i03955

A solid metal cube measuring exactly 1 inch on a side is submerged in an open container filled with water. The bottom of the cube is 24 inches down from the water's surface:
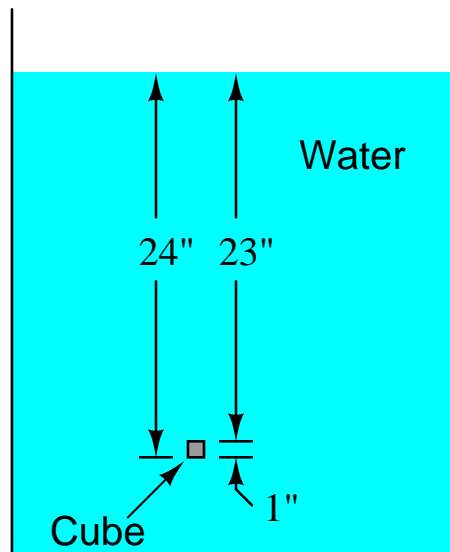


Based on your calculations of hydrostatic pressure (in PSI), determine the force applied to each side of the cube (in units of pounds), and the net, or *resultant* of these six forces (one force for each side of the cube).

Based on the figure for water density of 62.428 lb/ft$^3$, how much does one cubic inch of water happen to weigh?

file i00265

A solid metal cube measuring exactly 4 inches on a side is submerged in an open container filled with methanol. The bottom of the cube is 10 inches down from the methanol's surface:



Based on your calculations of hydrostatic pressure (in PSI), determine the force applied to each side of the cube (in units of pounds), and the net, or *resultant* of these six forces (one force for each side of the cube).
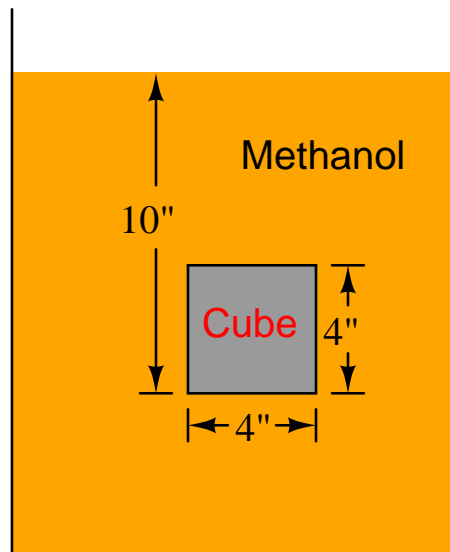
Based on the figure for methanol density of 49.41 lb/ft$^3$, how much does 64 cubic inches of methanol (a 4" × 4" × 4" cube) happen to weigh?

file i00266

Question 52

A king is given a shiny crown as a gift. The person giving the crown claims that it is made of pure, solid gold. It looks like gold, but the king – being wise to the ways of the world – knows that it might just be gold-plated tin or some other cheaper metal.

He hands his new crown over to a famous scientist to have it analyzed, with the command that the crown is not to be damaged in any way by the testing. The scientist ponders the task of determining the crown's composition nondestructively, and decides that a density measurement performed by weighing the crown both dry and submerged in water would suffice, since gold is substantially heavier than any cheap metal.

The crown weighs 5 pounds dry. When completely submerged in water, it weighs 4.444 pounds. Is it really made of solid gold?

file i00273

Determine a basic 5-point (0%, 25%, 50%, 75%, and 100%) calibration table for the displacer level transmitter in this scenario:

100%

Measurement
span = 24 in

0%

Water

Block
valves

displacer

100%

Measurement
span = 24 in

0%
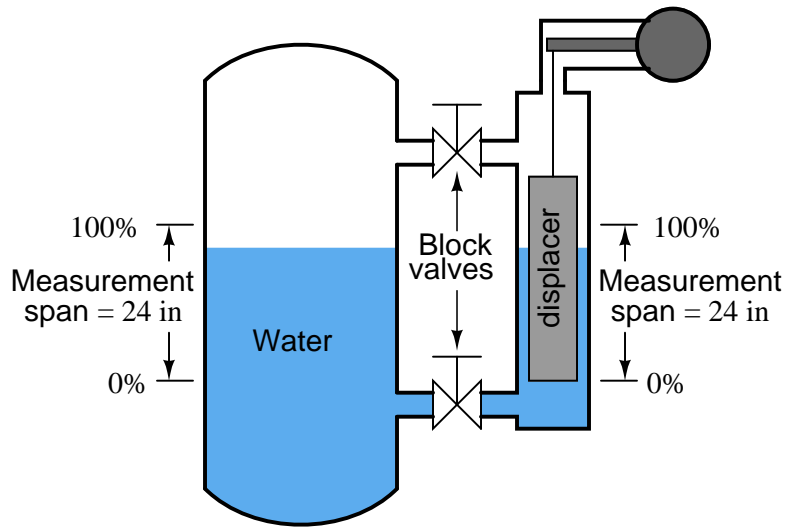
The cylindrical displacer weighs 10 pounds (dry) and has a diameter of 3 inches. The process liquid is water (density = 62.428 lb/ft$^3$). The 0% process liquid level (LRV) is even with the bottom of the displacer. Assume a pneumatic transmitter mechanism with an output range of 3 to 15 PSI, and a calibration tolerance of +/- 1% (of span).

| Process level (in) | Percent of span (%) | Buoyant force (lb) | Output signal ideal (PSI) | Output signal min. (PSI) | Output signal max. (PSI) |
|---|---|---|---|---|---|
|  | 0 |  |  |  |  |
|  | 25 |  |  |  |  |
|  | 50 |  |  |  |  |
|  | 75 |  |  |  |  |
|  | 100 |  |  |  |  |

file i00278

Determine a basic 5-point (0%, 25%, 50%, 75%, and 100%) calibration table for the displacer level transmitter in this scenario:

Process
liquid
$D = 55 \text{ lb/ft}^3$

Block
valves

displacer

100%

Measurement
span = 30 in

0%

100%

Measurement
span = 30 in

0%

The cylindrical displacer weighs 15 pounds (dry) and has a diameter of 3.5 inches. The process liquid has a density of 55 lb/ft$^3$. The 0% process liquid level (LRV) is even with the bottom of the displacer. Assume an electronic transmitter mechanism with an output range of 4 to 20 mA, and a calibration tolerance of +/- 0.2% (of span).

| Process level (in) | Percent of span (%) | Buoyant force (lb) | Output signal ideal (mA) | Output signal min. (mA) | Output signal max. (mA) |
|---|---|---|---|---|---|
| | 0 | | | | |
| | 25 | | | | |
| | 50 | | | | |
| | 75 | | | | |
| | 100 | | | | |

file i00279

A pressure transmitter with a remote seal measures the pressure of a gas inside a process vessel. A pressure gauge directly attached to the vessel registers 19.3 PSI. The transmitter is located 22 feet 5 inches below this point, with a capillary tube filled with fluid having a specific gravity of 0.94:

PG

19.3 PSI

Vessel

Capillary tube

22' 5"

PT

Fill fluid S.G. = 0.94
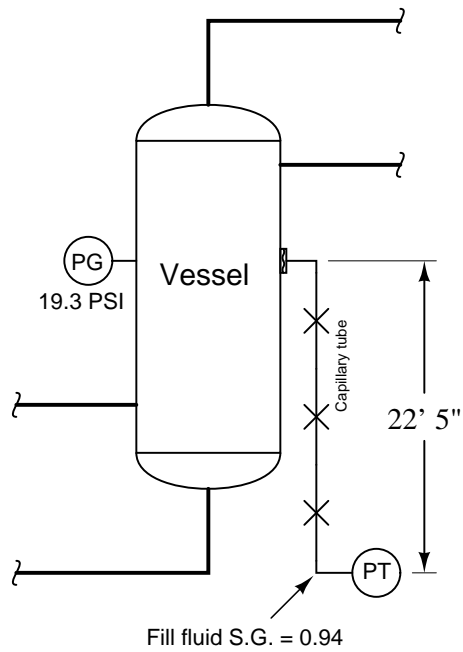
How much pressure will the transmitter register?

file i00240

65

## Question 56

An operator complains to you, claiming the sour water tank level indication shown by LIR-18 is unreasonably high (something like 6 inches more than it should be). You remove LT-18 and take it to the instrument shop to check its calibration on a bench, and find that it is well within tolerance:



Based on this information, what would be your next step? What sort of problem do you suspect there is – if any – in this system? Also, explained what you could have done differently as your first step, rather than to remove LT-18 from service immediately to check its calibration.

---

**Suggestions for Socratic discussion**
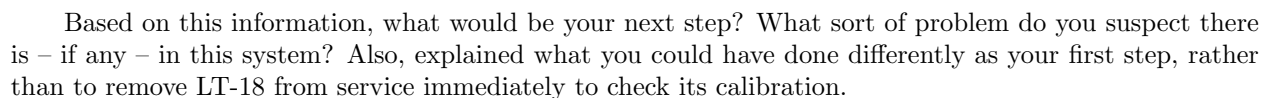
- Describe how you would connect the transmitter LT-18 to calibration equipment in the shop to check its calibration, given the type of transmitter that it is.
- Propose a *better* initial step you could have taken besides removing LT-18 for a calibration check in the shop.

file i03527

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## Question 57

A pure lead crown weighs 5 pounds dry. It's a crummy crown, I know, but fit for a lesser king. How much will it weigh when completely submerged in water? Assume a density of 11.35 g/cm$^3$ for pure lead.

file i00274

Question 58

Displacer-type instruments are often used to measure liquid level:
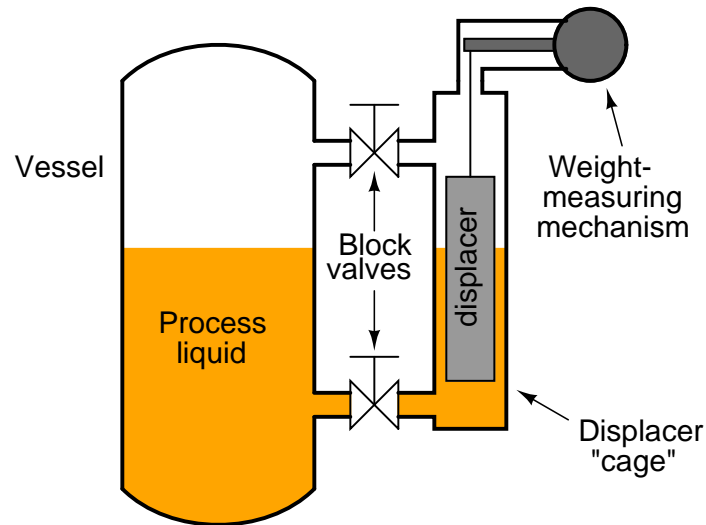


How might such an instrument be modified to measure liquid *density* instead?

Suggestions for Socratic discussion

- A problem-solving technique to employ here is examining the buoyant force equation to identify which physical quantities are fixed and which are variable in a standard level-measuring instrument, then asking ourselves which quantities would have to be fixed versus variable to turn this into a *density*-measuring instrument. Explore this technique to see if this helps you answer the question.

file i00280

Question 59

Calculate the following circuit parameters, assuming the transmitter has been calibrated to a range of 25 to 150 inches of water column (direct-acting, 4 to 20 mA output). Be sure to show all your calculations!

2.96 PSI
vapor pressure

"dry" leg

110"

Process liquid
S.G. = 0.85

H    L

A    120 Ω    B    + −    C

250 Ω

22 VDC
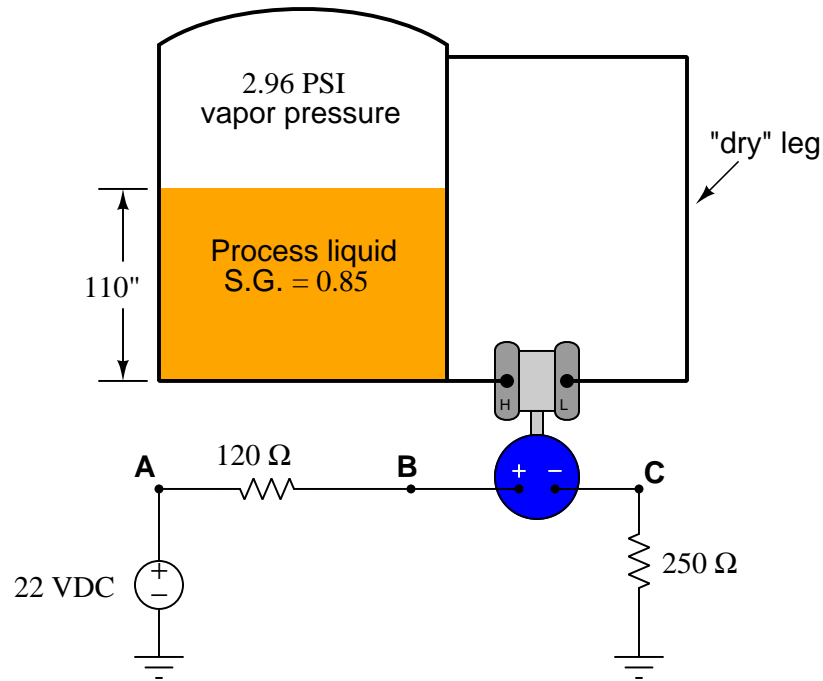
- $I =$ _____ mA

- $V_C =$ _____ V

- $V_{BC} =$ _____ V

- $V_B =$ _____ V

file i02906

In this biogas generation system, cow manure is used as a feedstock to produce methane gas ($CH_4$), which is then used to fuel an engine to turn a generator and make electricity. The waste heat from the engine is used to maintain the cascaded digesters ("reactors" R-101 and R-102) at optimal temperatures for anaerobic bacteria to digest the manure and produce biogas (approximately 105 $^o$F):
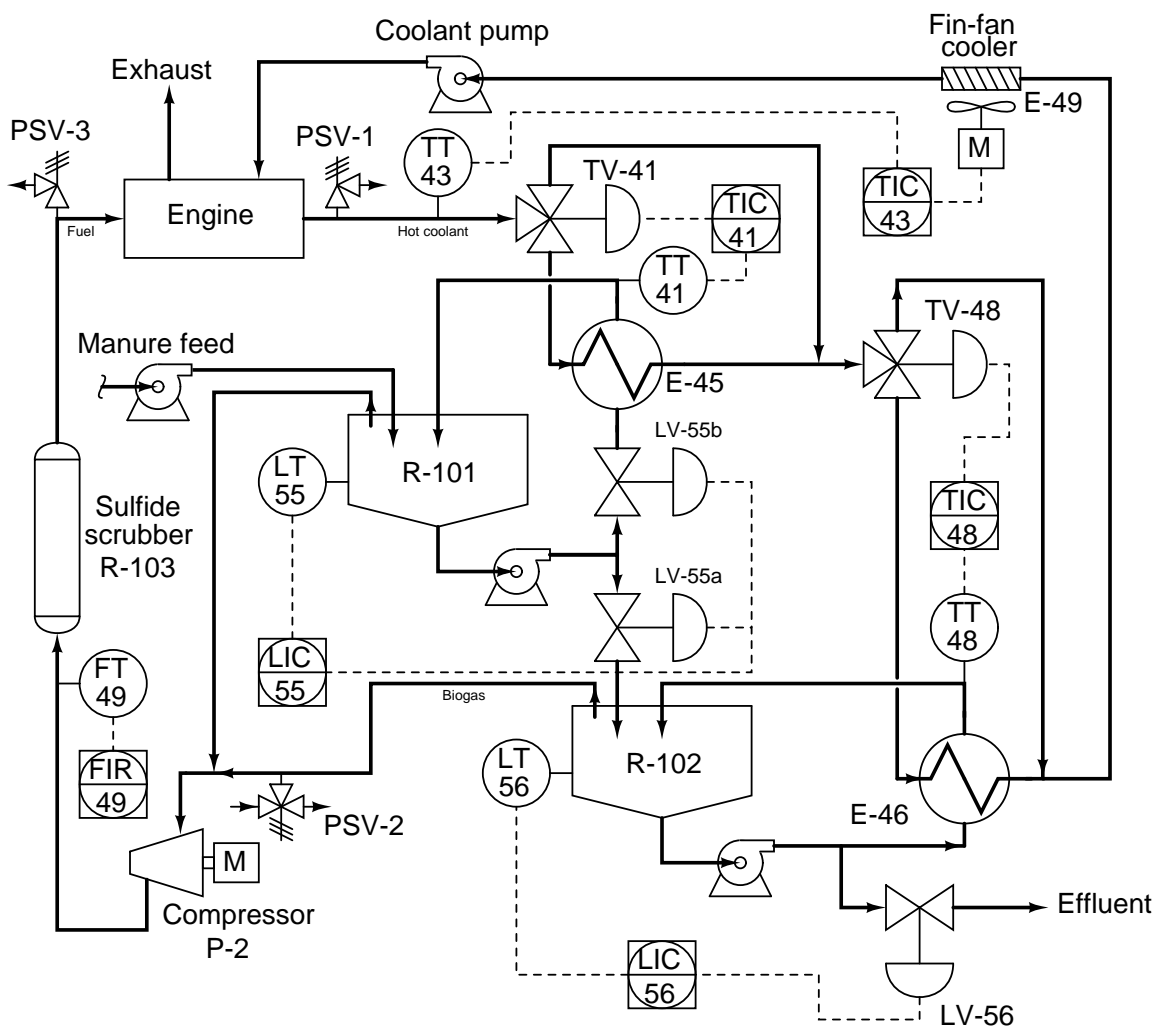


LIC-56 registers a manure level of 3 feet 10 inches, while the operator's manual gauge reading is only 3 feet 7 inches. The calibrated range of LT-56 is 0 to 4 feet. Your first step is to measure current in the cable connecting LT-56 and LIC-56, and there your digital multimeter (DMM) registers 19.33 mA.

Based on this information, determine at least two potential problems in this system. Also, determine whether or not a hydrostatic (DP) level transmitter would be suitable for measuring manure level in R-102.

file i03526

Question 61

Read and outline the "Interface Problems" subsection of the "Level Gauges (Sightglasses)" section of the "Continuous Level Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook relevant to *liquid-liquid interface measurement.*

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 i03956

Question 62

It is possible to measure the level of a liquid-liquid interface by means of a float:
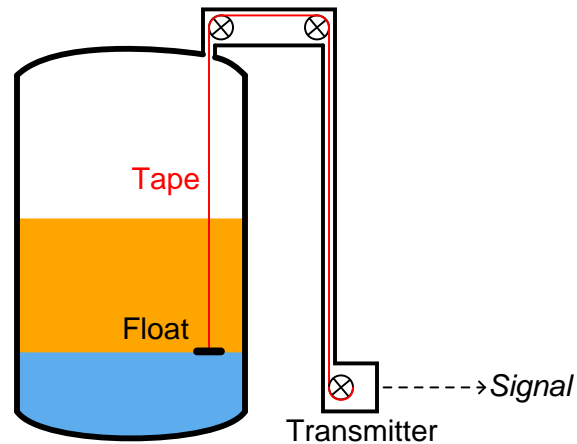


Explain what characteristic(s) the float must have in order to successfully hover at the interface level. Also, describe some potential advantages this technique enjoys over interface methods based on hydrostatic pressure.

Question 63

Read and outline the "Hydrostatic Interface Level Measurement" subsection of the "Hydrostatic Pressure" section of the "Continuous Level 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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- 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

Make special note of the "thought experiment" problem-solving technique applied to the solution of calibration points for liquid-liquid interface level instruments.
file i03957

Question 64

Read and outline the "Displacement Interface Level Measurement" subsection of "Displacement" section of the "Continuous Level 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

Make special note of the "thought experiment" problem-solving technique applied to the solution of calibration points for liquid-liquid interface level instruments.
file i03959

Calculate values for the following calibration table, for a transmitter measuring liquid level interface (specific gravities = 0.8 and 1.0), with a calibration tolerance of ± 1% and a 4-20 mA output range. Be sure to specify which port on the ΔP transmitter to apply the calibration pressure:



| Interface level (ft) | Percent of span (%) | Δ pressure sensed ("W.C) | Output signal ideal (mA) | Output signal min. (mA) | Output signal max. (mA) |
|---|---|---|---|---|---|
| | 0 | | | | |
| | 10 | | | | |
| | 25 | | | | |
| | 50 | | | | |
| | 75 | | | | |
| | 90 | | | | |
| | 100 | | | | |

Be sure to show all your mathematical work so that your instructor will be able to check the conceptual validity of your technique(s). A good way to check to see if you're solving the problem correctly is to check that each and every one of your intermediate calculations (i.e. the results you get mid-way during the process to arrive at the final answer) has real physical meaning. **If you truly understand what you are doing, you will be able to identify the correct unit of measurement for every intermediate result and also be able to show where that number applies to the scenario at hand**.

---

### Suggestions for Socratic discussion

- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.
- How will this level transmitter respond if the gas pressure inside this vessel were to increase?
- How will this level transmitter respond if the gas pressure inside this vessel were to decrease?
- How will this level transmitter respond if the overflow pipe were to be blocked off, so no light liquid could exit the vessel?
- How will this level transmitter respond if the heavier fluid's density were to increase, yet the interface level remain the same?

- How will this level transmitter respond if the lighter fluid's density were to increase, yet the interface level remain the same?

  <u>file i00310</u>

74

Question 66

Calculate values for the following calibration table, for a transmitter measuring liquid level interface (specific gravities = 0.75 and 1.2), with a calibration tolerance of $\pm\, 0.1\%$. Be sure to specify which port on the $\Delta$P transmitter to apply the calibration pressure:



| Interface level (in) | Percent of span (%) | $\Delta$ pressure sensed ("W.C) | Output signal ideal (mA) | Output signal min. (mA) | Output signal max. (mA) |
|---|---|---|---|---|---|
| | 0 | | | | |
| | 10 | | | | |
| | 25 | | | | |
| | 50 | | | | |
| | 75 | | | | |
| | 90 | | | | |
| | 100 | | | | |

Be sure to show all your mathematical work so that your instructor will be able to check the conceptual validity of your technique(s). A good way to check to see if you're solving the problem correctly is to check that each and every one of your intermediate calculations (i.e. the results you get mid-way during the process to arrive at the final answer) has real physical meaning. **If you truly understand what you are doing, you will be able to identify the correct unit of measurement for every intermediate result and also be able to show where that number applies to the scenario at hand**.
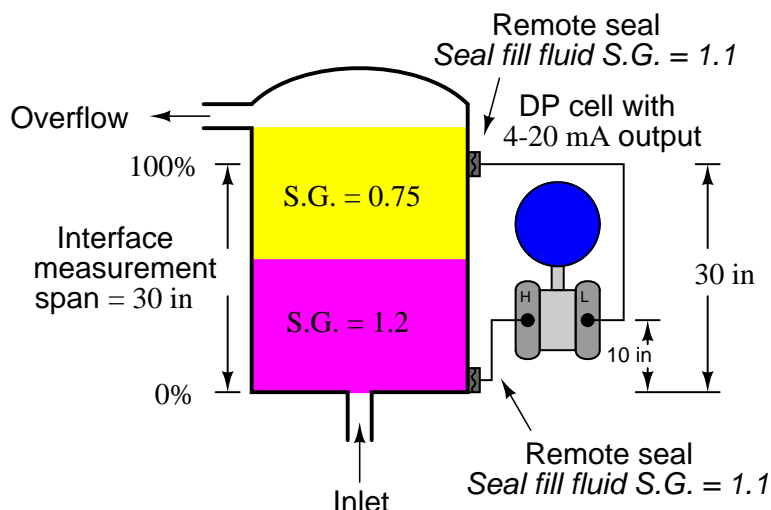
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| **Suggestions for Socratic discussion** |
|---|

- Does the position of the transmitter within the 30 inch span matter? For example, would the calibration be affected if the transmitter were re-located just 5 inches higher, without moving the remote seals? Why or why not?
- Suppose the process vessel were not filled all the way up to the overflow point. How would this change affect the accuracy of the level transmitter? Would it register falsely low, falsely high, or would it still register as it should?
- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

file i00311

Calculate values for the following calibration table, for a displacer-type level transmitter measuring liquid level interface (densities = 50 lb/ft$^3$ and 70 lb/ft$^3$), with a calibration tolerance of $\pm$ 1%:



| Interface level (in) | Percent of span (%) | Buoyant force (lbs) | Output signal ideal (PSI) | Output signal min. (PSI) | Output signal max. (PSI) |
|---|---|---|---|---|---|
| | 0 | | | | |
| | 10 | | | | |
| | 25 | | | | |
| | 50 | | | | |
| | 75 | | | | |
| | 90 | | | | |
| | 100 | | | | |

Assume the following displacer characteristics:

- Shape: *cylindrical*
- Length = 11 inches
- Diameter = 1.5 inches
- Dry weight = 2.7 lbs

Be sure to show all your mathematical work so that your instructor will be able to check the conceptual validity of your technique(s). A good way to check to see if you're solving the problem correctly is to check that each and every one of your intermediate calculations (i.e. the results you get mid-way during the process to arrive at the final answer) has real physical meaning. **If you truly understand what you are doing, you will be able to identify the correct unit of measurement for every intermediate result and also be able to show where that number applies to the scenario at hand**.

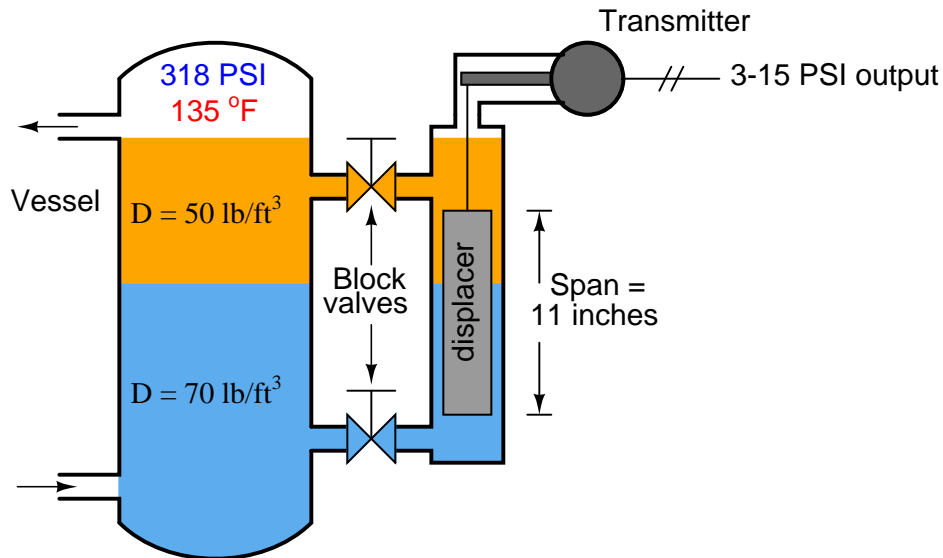---

| **Suggestions for Socratic discussion** |

- How will this level transmitter respond if the gas pressure inside this vessel were to increase?
- How will this level transmitter respond if the gas pressure inside this vessel were to decrease?

- How will this level transmitter respond if the total liquid level were to decrease below the top of the displacer?
- Does it matter for the calibration of the instrument whether or not the displacer is solid or hollow? For example, suppose a technician were to exchange a solid displacer for the original (hollow) displacer – would he or she have to recalibrate the instrument?
- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

file i00687

Question 68

Calculate values for the following calibration table, for a displacer-type level transmitter measuring liquid level interface (specific gravities = 0.9 and 2.0), with a calibration tolerance of ± 1%:



| Interface level (in) | Percent of span (%) | Buoyant force (lbs) | Output signal ideal (PSI) | Output signal min. (PSI) | Output signal max. (PSI) |
|---|---|---|---|---|---|
| | 0 | | | | |
| | 10 | | | | |
| | 25 | | | | |
| | 50 | | | | |
| | 75 | | | | |
| | 90 | | | | |
| | 100 | | | | |

Assume the following displacer characteristics:

- Shape: *cylindrical*
- Length = 15 inches
- Diameter = 2 inches
- Dry weight = 4.5 lbs

Be sure to show all your mathematical work so that your instructor will be able to check the conceptual validity of your technique(s). A good way to check to see if you're solving the problem correctly is to check that each and every one of your intermediate calculations (i.e. the results you get mid-way during the process to arrive at the final answer) has real physical meaning. **If you truly understand what you are doing, you will be able to identify the correct unit of measurement for every intermediate result and also be able to show where that number applies to the scenario at hand**.

Suggestions for Socratic discussion

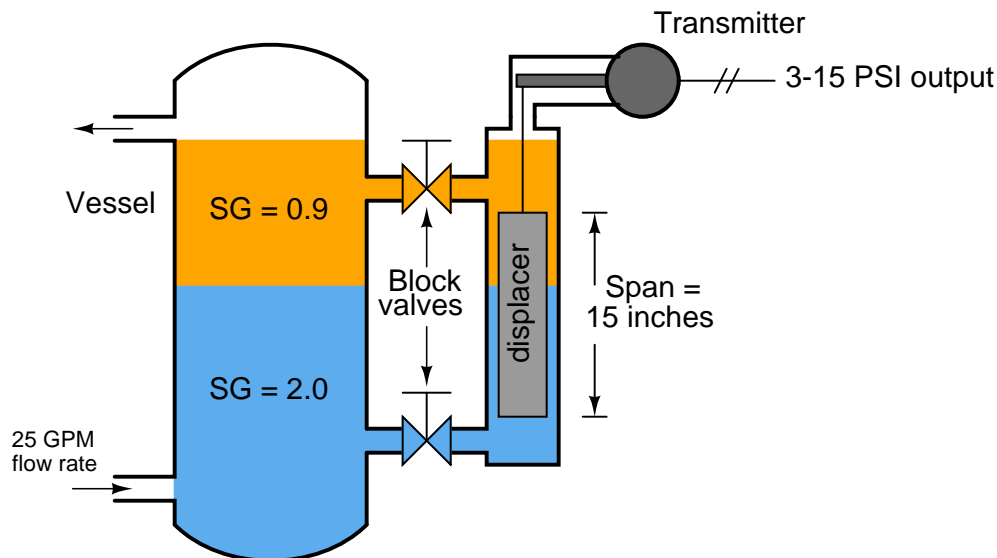- Two technicians are arguing about the operation of a displacer-type level transmitter. One thinks that static pressure inside the process vessel affects accuracy, while the other technician thinks it doesn't. Who is correct, and why?

- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

file i00314

---

Question 69

Three level-sensing instruments measure the same liquid level at the bottom of this fractionation tower (LT-38a, LT-38b, and LT-38c), but their measurements do not agree. An operator calls you to investigate, showing you on the control system display how LT-38a registers 34.8%, LT-38b registers 35.1%, and LT-38c registers 40.4%. According to the P&ID, LT-38a is hydrostatic (sensing pressure through two remote seals), LT-38b is a radar instrument (sensing liquid level by the reflection time of a radar wave inside a cage), and LT-38c is magnetostrictive (sensing the position of a float inside of another cage). The indicating controller (LIC-38) shows a level of 35.1%:
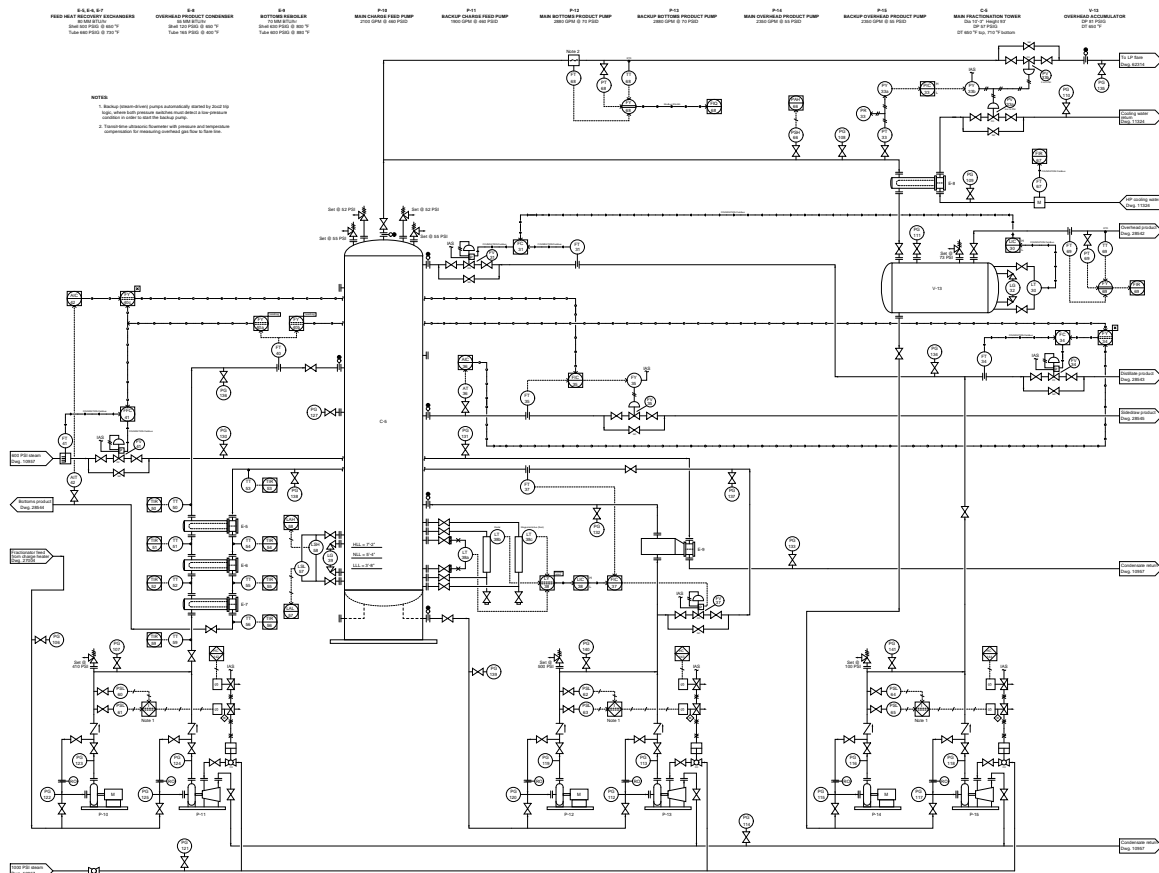


Based on the information you have, identify a condition that could account for the discrepancy in these transmitter indications, and also determine what your first diagnostic step will be.

---

| Suggestions for Socratic discussion |

- Why do you suppose three different instruments are used to measure the same liquid level in this application?
- Identify the function of LY-38.

file i01200

79

Calculate the height of glycerine ($\gamma = 78.6$ lb/ft$^3$) in a vertical tube if there is 21 PSI of hydrostatic pressure at the bottom of the tube:
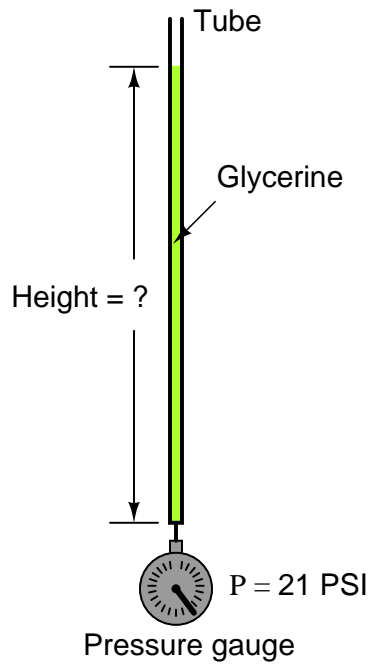


Glycerine height = _____ ft

Also, calculate the height of castor oil ($\gamma = 60.5$ lb/ft$^3$) necessary to generate the exact same amount of pressure:

Castor oil height = _____ ft
file i02951

The following illustration shows a rather strange manometer, one with two different liquids inside, coupled by a hand valve:
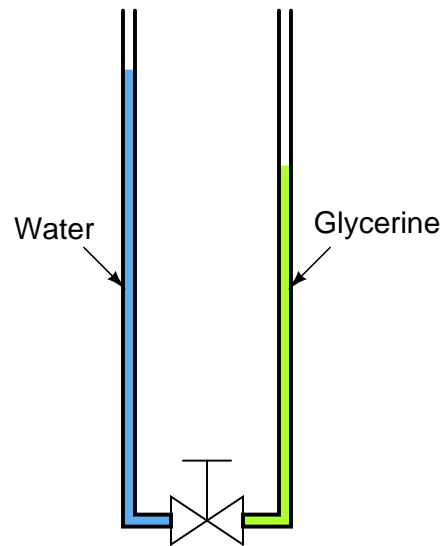


If the two columns of liquid are just right, they will remain at their respective (different) heights when the valve is opened. Unlike a normal manometer where the two liquid columns always equalize to the same height when vented, this manometer is "content" to rest at different heights. Explain why.

Also, calculate two possible heights that will balance each other, given the liquids of water and glycerine.
file i02952

*Stilling wells* are very useful accessories to many types of liquid level measurement gauges, including float and ultrasonic. However, if used on a liquid-liquid interface level measurement application, care must be taken to ensure the stilling well is always submerged:
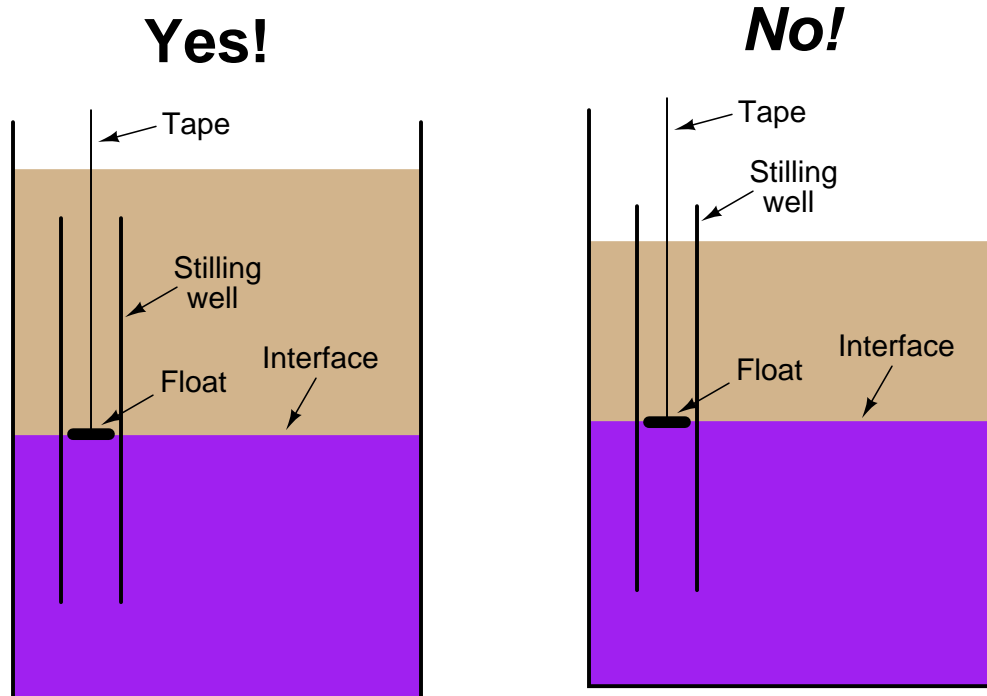


Explain why a stilling well might be used in a liquid level measurement system, and also why it needs to be completely submerged if being used to measure the level of an interface.

file i00315

Question 73

Steam drum water level measurement is actually a form of interface level measurement, because high-pressure steam is significantly denser than air under ambient conditions:
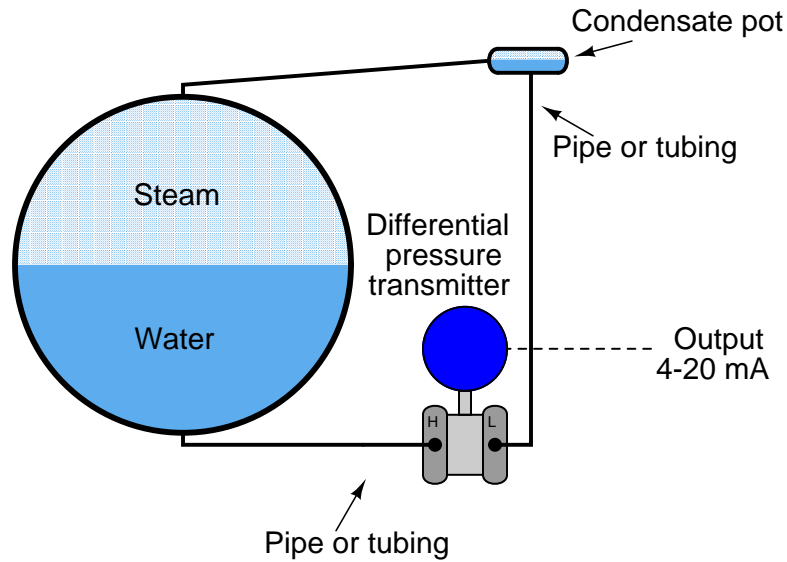


Making this situation even more complex is the fact that the densities of both the water and the steam change as boiler pressure and temperature change. Identify what happens to water density and steam density as both pressure and temperature increase, and explain why.

file i00316

Calculate the amount of pressure applied to each side of the differential pressure transmitter (in units of PSI) when there is 9 feet of liquid level in the process vessel. Note the pressure gauge at the top of the vessel registering the amount of vapor pressure inside:



Pressure gauge
(reads 68 PSIG)

100%

← pressure →

Process liquid
$G_f = 1.15$

"dry" leg

Measurement
span = 16 ft

0%

H     L
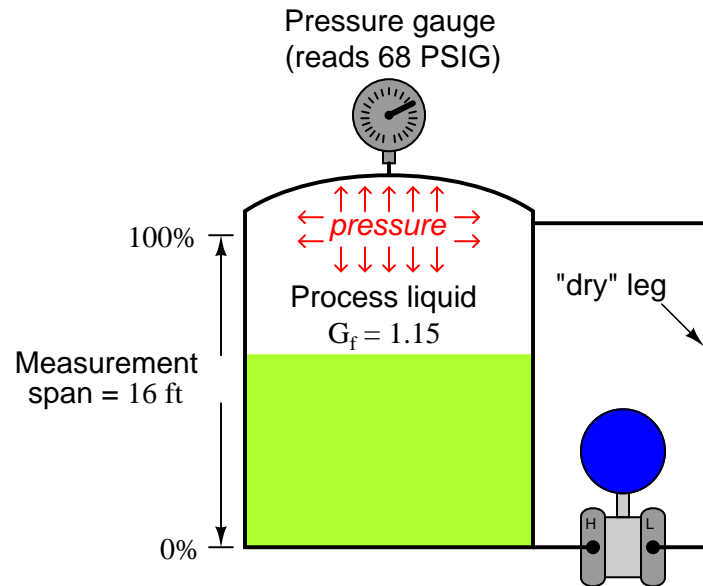
$P_{high} =$ _____ PSIG                    $P_{low} =$ _____ PSIG

Also, calculate the *differential* pressure seen by the transmitter (in units of PSI):

$\Delta P =$ _____ PSID

file i02950

84

In this process, water is separated from an oil stream by gravity. The oil floats to the top of the vessel where it exits, while the water settles to the bottom and is drained off periodically by opening a hand valve. A hydrostatic level transmitter detects the height of the oil/water interface and lets the human operator know when to open up the water drain valve:
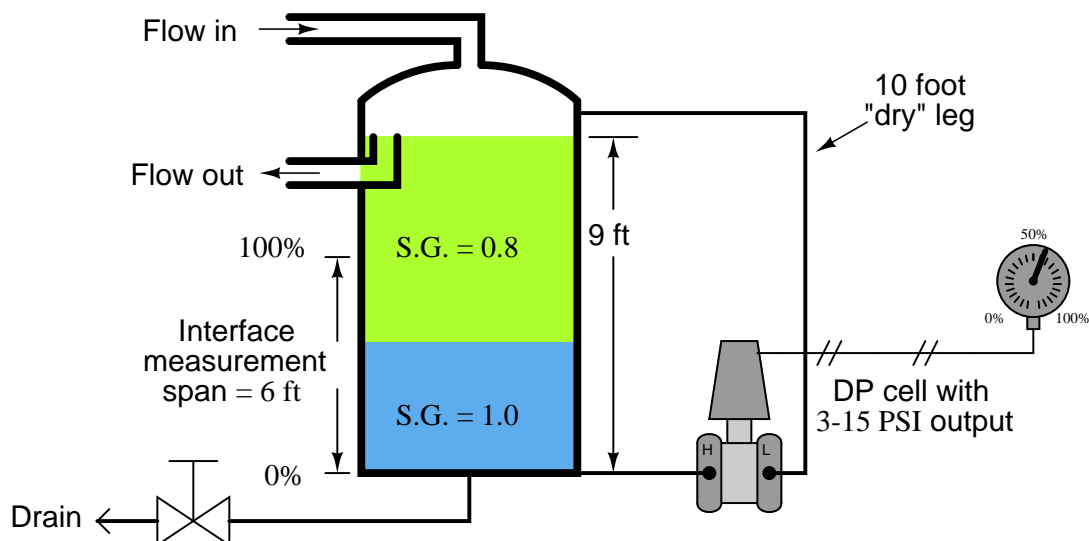


Calculate values for the following calibration table, such that the transmitter will register the height of the oil/water interface from 0 to 6 feet off the bottom of the vessel. Note that the oil/air interface is held at a constant 9 feet of level by the position of the overflow tube. Assume a vapor pressure inside the vessel of 2.53 PSI and a transmitter calibration tolerance of +/- 0.25%:

| Interface level (ft) | Percent of span (%) | $\Delta$ pressure sensed ("W.C) | Output signal ideal (PSI) | Output signal min. (PSI) | Output signal max. (PSI) |
|---|---|---|---|---|---|
| | 0 | | | | |
| | 10 | | | | |
| | 25 | | | | |
| | 50 | | | | |
| | 75 | | | | |
| | 90 | | | | |
| | 100 | | | | |

---

| Suggestions for Socratic discussion |

- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.
- How will this level transmitter respond if the gas pressure inside this vessel were to increase?
- How will this level transmitter respond if the gas pressure inside this vessel were to decrease?
- How will this level transmitter respond if the overflow pipe were to be blocked off, so no light liquid could exit the vessel?
- How will this level transmitter respond if some liquid enters the otherwise "dry" compensating leg?

file i00309

Question 76

Fill a tall glass with water, then take a straw and gently blow air through the straw so that bubbles slowly escape from the straw's end. Try this with the straw submerged at different levels within the water:
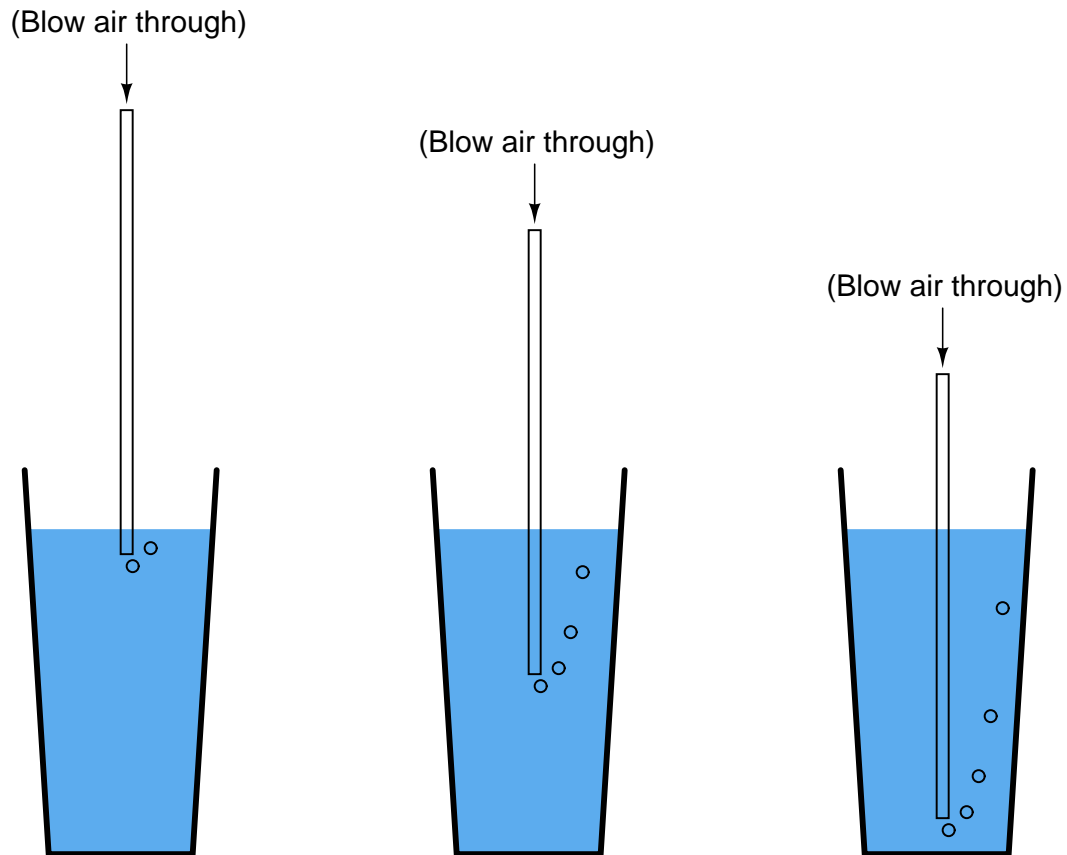


Note how much pressure it takes to blow bubbles out the end of the tube at these different levels by sensing the air pressure within your mouth as you blow (the tension on your cheeks from the air pressure within).

Explain what causes the required air pressure to vary with straw depth, and elaborate on how this principle might be used to measure the level of liquids in a vessel using compressed air and a "bubble tube."

file i02955

A tank expert system gives the following pressure indications from its three transmitters:



Liquid storage vessel

**Measurement = 0 "W.C.**

"Top"

Process liquid

*Level = ???*
*S.G. = ???*

**Measurement = 165.6 "W.C.**

"Middle"

10 feet

**Measurement = 276 "W.C.**

"Bottom"
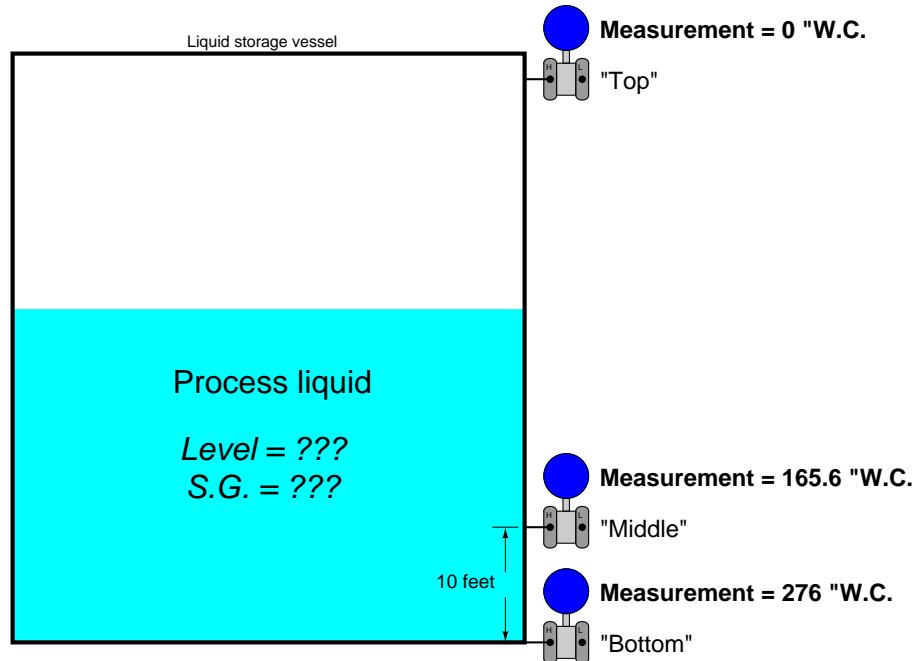
From these pressure measurements, determine the level of liquid in the vessel and its specific gravity. Be sure to explain how you obtained your answers!

file i00255

# Question 78

Determine a basic 5-point (0%, 25%, 50%, 75%, and 100%) calibration table for the level transmitter in this scenario. Assume a calibration tolerance of +/- 0.5%:



| Process level (in) | Percent of span (%) | Differential pressure ("W.C.) | Output signal ideal (PSI) | Output signal min. (PSI) | Output signal max. (PSI) |
|---|---|---|---|---|---|
| 0 | 0 | −64 | 6 | 5.88 | 6.12 |
| 12.5 | 25 | −51.5 | 12 | 11.88 | 12.12 |
| 25 | 50 | −39 | 18 | 17.88 | 18.12 |
| 37.5 | 75 | −26.5 | 24 | 23.88 | 24.12 |
| 50 | 100 | −14 | 30 | 29.88 | 30.12 |

file i00322

Calculate values for the following calibration table, for a transmitter measuring liquid level interface (densities = 50 lb/ft$^3$ and 70 lb/ft$^3$), with a calibration tolerance of ± 1% and a 4-20 mA output range:



| Interface level (in) | Percent of span (%) | $\Delta$ pressure sensed ("W.C) | Output signal ideal (mA) | Output signal min. (mA) | Output signal max. (mA) |
|---|---|---|---|---|---|
| | 0 | | | | |
| | 10 | | | | |
| | 25 | | | | |
| | 50 | | | | |
| | 75 | | | | |
| | 90 | | | | |
| | 100 | | | | |

Suppose the level indicator reads 6.3 inches of interface level while operators report a sightglass indication of 5.7 inches interface level. Using a multimeter, you measure 12.29 mA output by the transmitter. Based on this information, where would you say the fault lies?

---

| Suggestions for Socratic discussion |

- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

  file i00686

Question 80

In this density measurement system, what will the output of the transmitter be when the vessel is filled with clean water?

needle valve

Inert gas supply

needle valve

Pressure regulator

dip tube

dip tube

H L

ΔP transmitter

10 inches

Transmitter calibration:

10" W.C. = 4 mA

20" W.C. = 20 mA
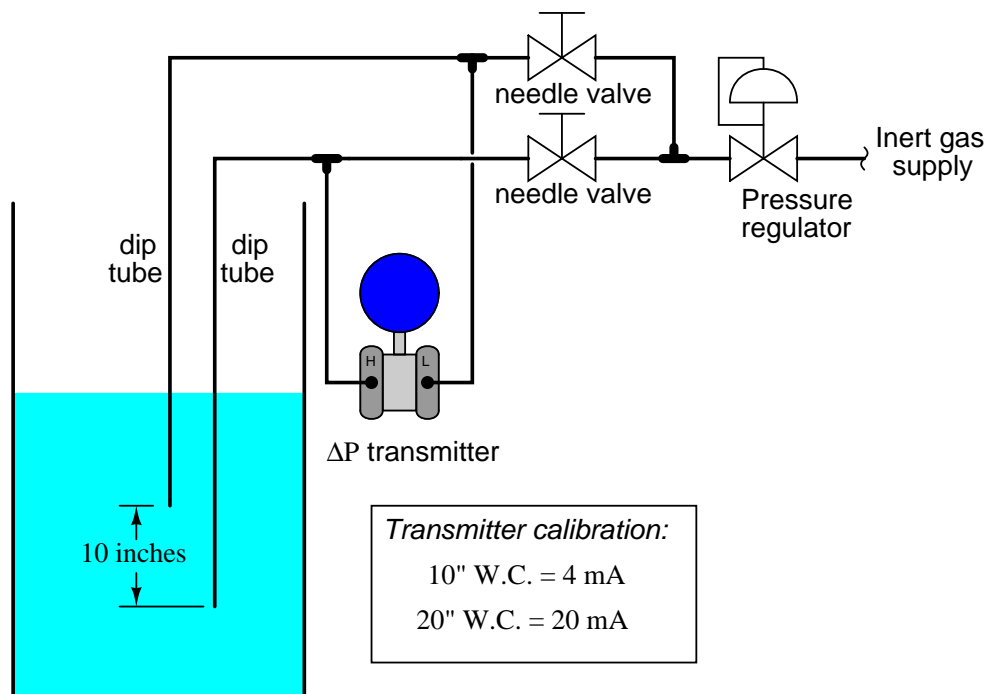
What will the output of the transmitter be when the vessel is filled with carbon tetrachloride (D = 99.573 lb/ft$^3$)?

Finally, specify the density measurement range in units of *specific gravity*.
file i00284

In this circuit, an electronic differential pressure transmitter with a 4-20 mA output signal connects to a local pressure indicator and to a remote pressure indicator. Your task is to figure out how to connect the loop calibrator to force the remote indicator (only) to register a pressure of 300 PSI, without interrupting or otherwise affecting the transmitter's signal to the local indicator:
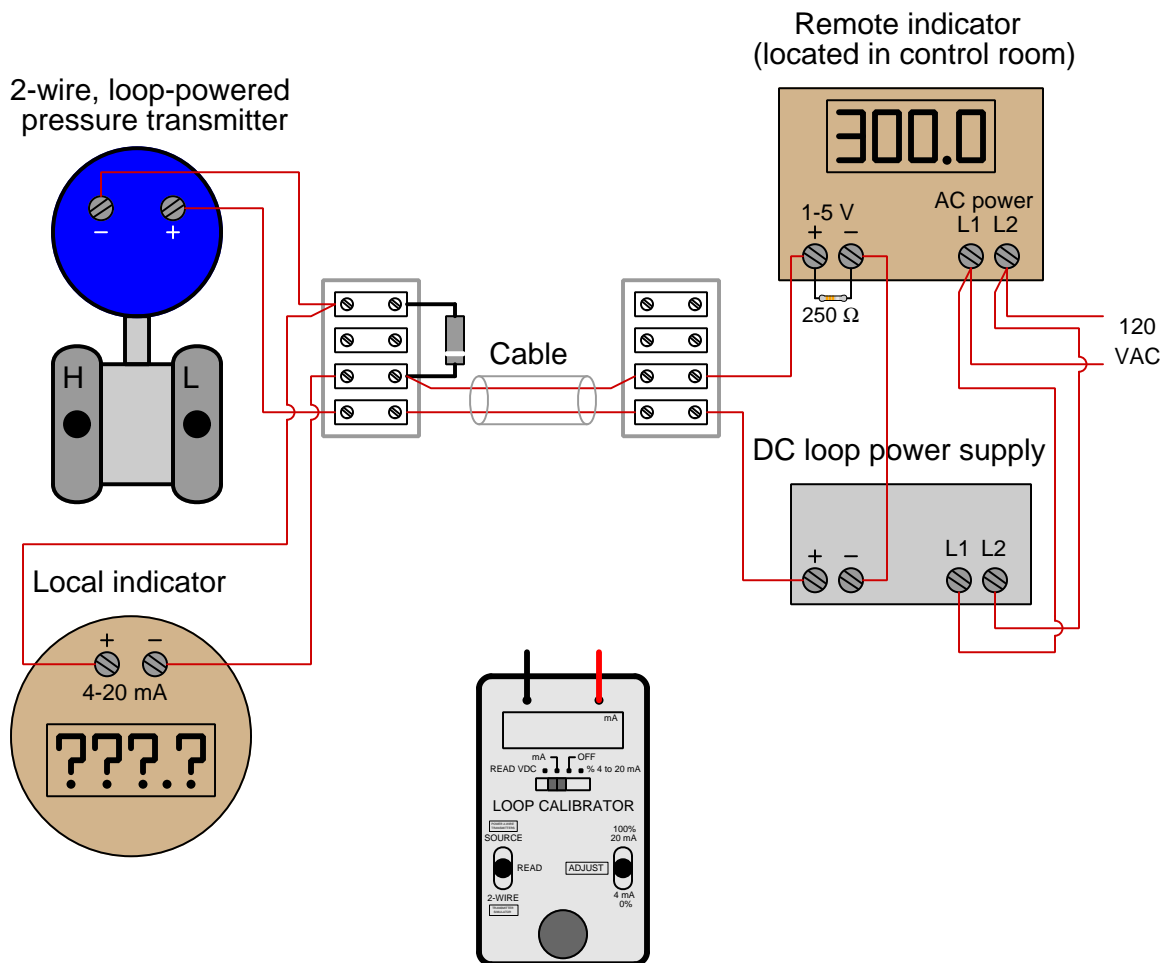


Sketch your solution, showing both the loop calibrator's test lead connections and the mode it must be set to (*source*, *read*, or *simulate*). Assume a transmitter calibration of −10 PSI to +440 PSI.

Note: there is more than one correct answer to this question!
file i00627

91

Suppose a level measurement system is "stuck" at one measurement value of approximately 40% even when the process liquid level rises and falls between 20% and 80% of range (as indicated by the sightglass):

Isolation valve    Fill valve

43 PSI    Vessel

20 PSI air supply

*Cal: 10 to 150 "H$_2$O*

LT

LI

Isolation valve

(vent)

L    H

Equalizing valve

Block valve    Block valve
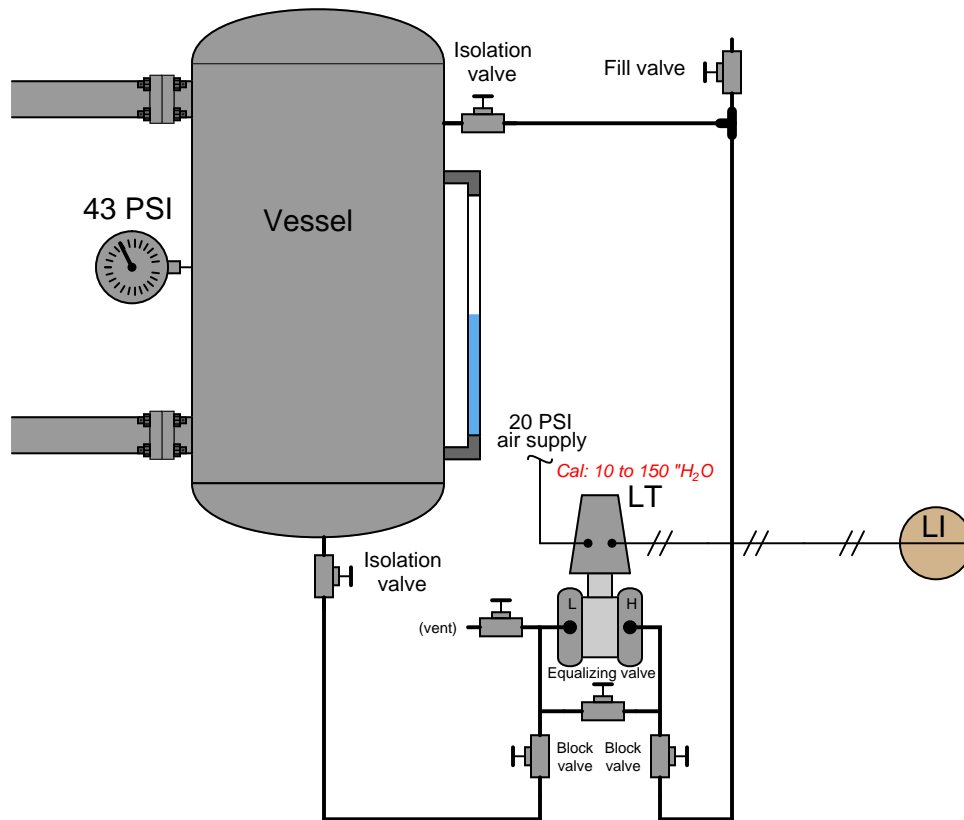
An instrument technician removes the cover from the pneumatic transmitter and momentarily presses the baffle against the nozzle. The level indicator in the control room does not respond at all, but remains fixed at about 40%.

Identify the likelihood of each possible fault in this list by checking boxes in the table – whether the fault is "probable" (worth considering as a cause of this system's trouble) or is "unlikely" (either completely ruled out as a cause, or just not worth considering at this point in the diagnosis) – following the results of the technician's test:

| Fault | Probable | Unlikely |
|---|---|---|
| Plugged isolation valve | | |
| Plugged equalizing valve | | |
| Fill fluid lost in "wet" leg | | |
| Low supply air pressure | | |
| Transmitter restrictor (orifice) clogged | | |
| Indicator pointer stuck | | |
| Transmitter nozzle clogged | | |
| 3-15 PSI signal tubing plugged | | |
| Transmitter out of calibration | | |

file i00030

## Question 83

Calculate the resistance of the strain gauge in this unbalanced bridge circuit, given the voltmeter's indication of 5.8 millivolts (A positive and B negative):
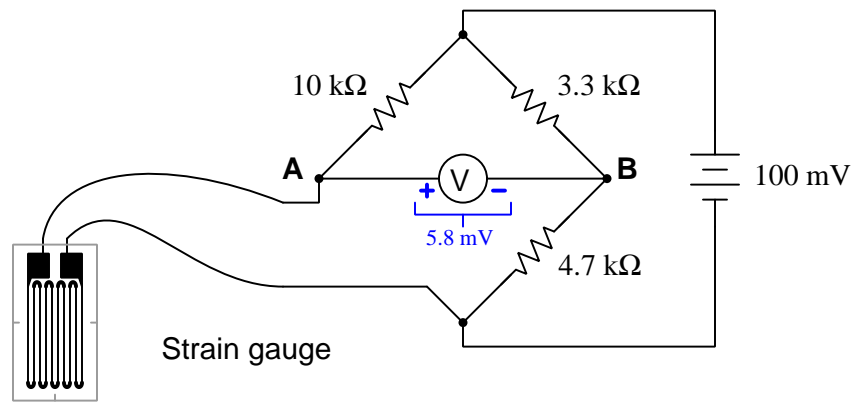


$R_{strain} =$ _____

Question 84

    An electronic differential pressure transmitter with remote (chemical) seals is used to measure the level of liquid in this pressurized vessel. The specific gravity of fill fluid in both remote seals is 0.934. The range of liquid level measurement is 0 to 24 feet, and the output signal range is 4 to 20 mA. Assume a calibration tolerance of +/- 0.25 percent. Complete the following table of values for this transmitter. Show the equations used to calculate all values given the percentage of span $(x)$:



| Process level (ft) | Percent of span (%) | $\Delta$ pressure sensed ("W.C) | Output signal ideal (mA) | Output signal min. (mA) | Output signal max. (mA) |
|---|---|---|---|---|---|
| | 0 | | | | |
| | 10 | | | | |
| | 25 | | | | |
| | 50 | | | | |
| | 75 | | | | |
| | 90 | | | | |
| | 100 | | | | |

**Equations used:**

Process level =

Pressure sensed =

Output signal (ideal) =

Output signal (min.) =

Output signal (max.) =

<u>file i00033</u>

Explain how the following dip tube system measures the *density* of the liquid inside the vessel rather than the *level*. Assume the liquid level never drops below the upper dip tube, and that the difference in height between the two dip tubes is fixed at 12 inches (1 foot):
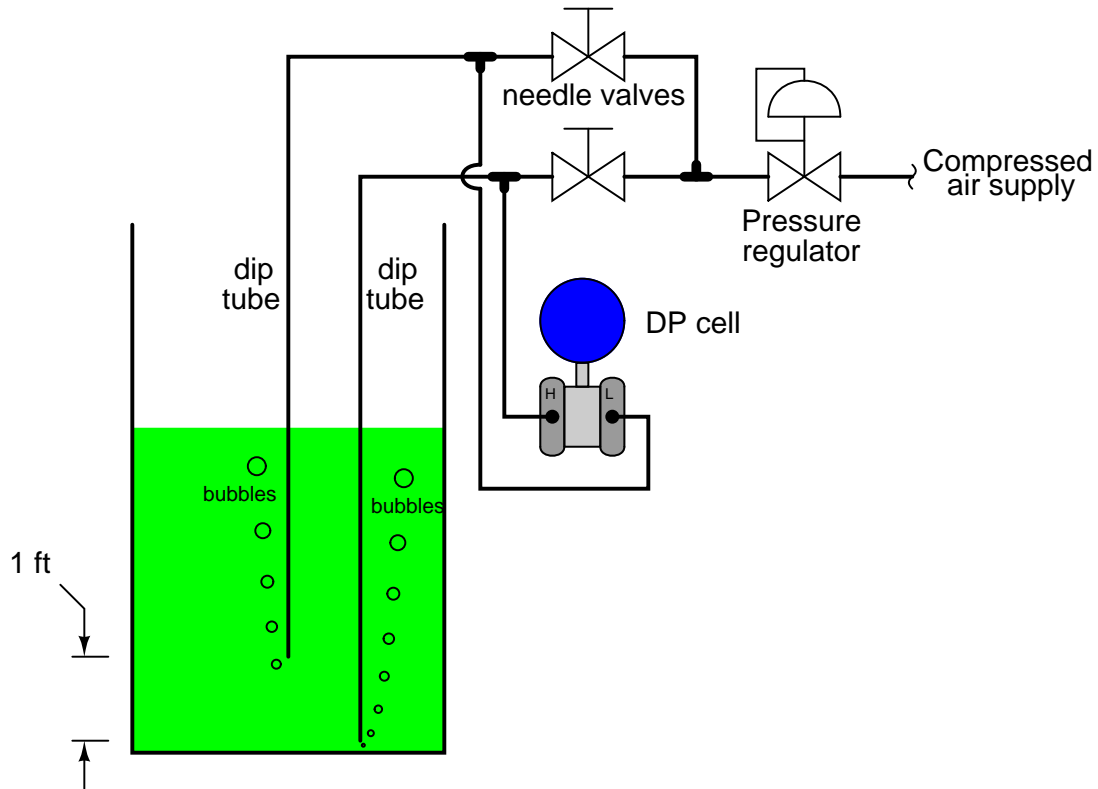


Furthermore, calculate the differential pressure sensed by the DP transmitter for a liquid with a density of 58 pounds per cubic foot.

A pine "2 × 6" board (actually 1.5 inches thick and 5.5 inches wide), 10 feet long, floats in water. Its density is 26 lb/ft$^3$. How far will it sink into the water while floating? Hint: the board will float so that its "6 inch" dimension is parallel to the water's surface:
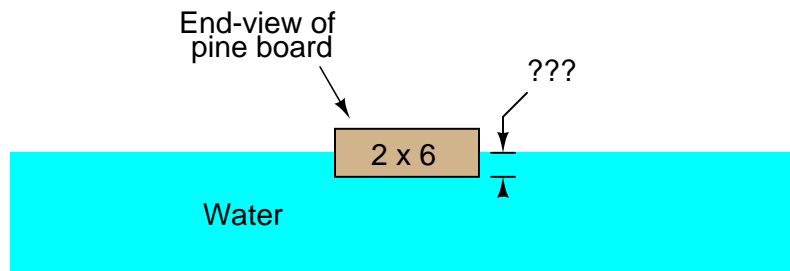


Hint: try the following "thought experiments" first. Imagine a completely weightless board (wood density = 0.0 lb/ft$^3$) and determine the depth of submersion into the water. Then, imagine a board whose density is exactly equal to that of water (wood density = 62.428 lb/ft$^3$) and determine the depth of submersion. Finally, imagine a board with a density exactly equal to half that of water (31.214 lb/ft$^3$) and determine its depth of submersion. Do you see a pattern?

Next, write an equation describing the percentage of submersion for an object given its density ($D_o$) and the density of the liquid ($D_l$).

file i00270

## Question 87

The cylindrical displacer in this level transmitter weighs 6.5 pounds (dry) and has a diameter of 1.75 inches. The process liquid has a specific gravity of 1.25. The 0% process liquid level (LRV) is even with the bottom of the displacer, and the URV is even with the top:
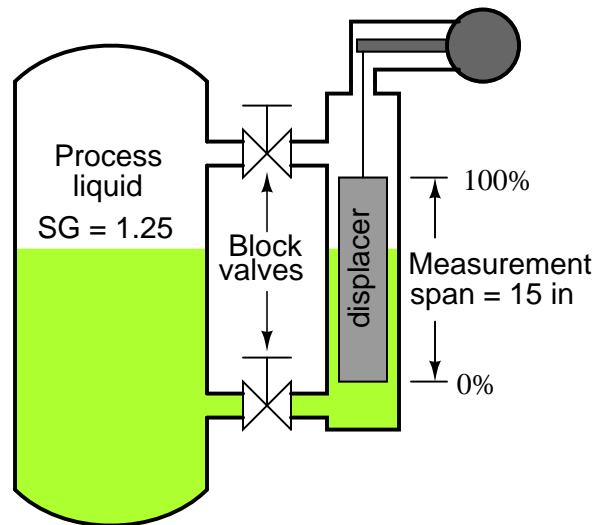


Calculate the amount of upward force you would have to apply to the displacer during a "dry" calibration to simulate a 50% full condition.

Calculate the depth of *water* the displacer would have to be submerged during a "wet" calibration to simulate a 50% full condition.

Question 88

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



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

| Fault | Possible | Impossible |
|:---:|:---:|:---:|
| $R_1$ failed open | | |
| $R_2$ failed open | | |
| $R_3$ failed open | | |
| $R_1$ failed shorted | | |
| $R_2$ failed shorted | | |
| $R_3$ failed shorted | | |
| Voltage source output too high | | |

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 i03233

Small relays often come packaged in clear, rectangular, plastic cases. These so-called "ice cube" relays have either eight or eleven pins protruding from the bottom, allowing them to be plugged into a special socket for connection with wires in a circuit. Note the labels near terminals on the relay socket, showing the locations of the coil terminals and contact terminals:

(top views)

Relay

Relay socket
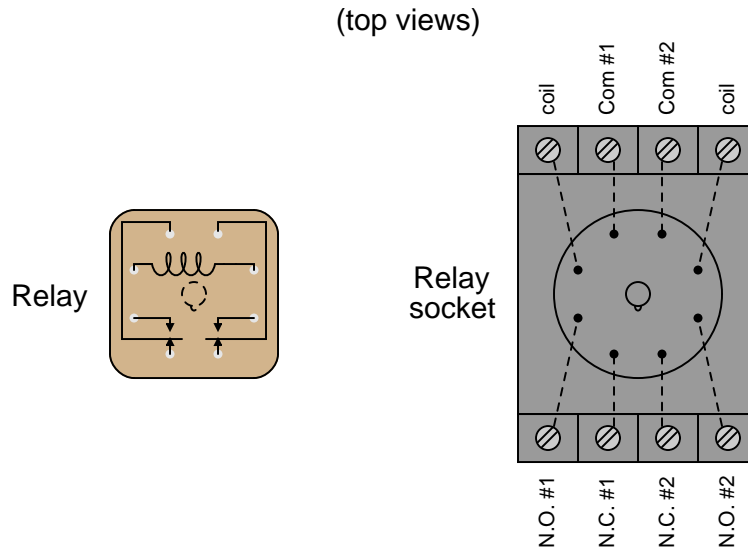
Draw the necessary connecting wires between terminals in this circuit, so that actuating the normally-open pushbutton switch sends power from the battery to the coil to energize the relay, with one of the relay's normally-open contacts turning the lamp on. The pushbutton switch should not carry any lamp current, just enough current to energize the relay coil:

Battery

Relay
(plugged into socket)

N.O.
switch

Lamp

file i03212
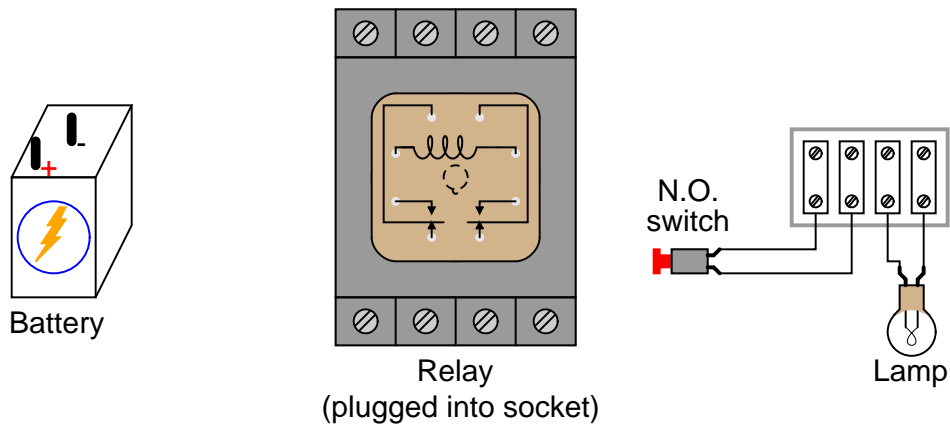
Question 90

Suppose the voltmeter in this circuit is "pegged" in the negative direction (i.e. it registers a strong *negative* voltage beyond its normal measurement range). A test using a digital multimeter (DMM) shows the voltage between test points **D** and **B** to be 6 volts:
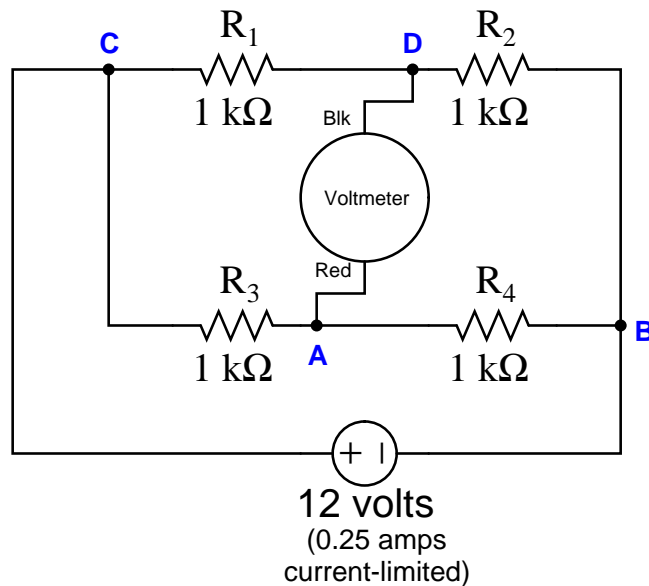


Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

| Fault | Possible | Impossible |
|---|---|---|
| $R_1$ failed open | | |
| $R_2$ failed open | | |
| $R_3$ failed open | | |
| $R_4$ failed open | | |
| $R_1$ failed shorted | | |
| $R_2$ failed shorted | | |
| $R_3$ failed shorted | | |
| $R_4$ failed shorted | | |
| Voltage source dead | | |

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

file i00329

Question 91

**Lab Exercise – introduction**

Your task is to build, document, and troubleshoot an electronic liquid level measurement system. Transmitter options include an echo-based level transmitter (either radar or ultrasonic) or a hydrostatic (pressure-based) level transmitter. The transmitter must connect to an electronic indicator, recorder, or indicating controller, and its measurements of liquid level must agree to within 1% of the level shown by a sightglass mounted on the vessel. Water held in a vertical tube is the suggested process variable to measure, but other liquid level variables are open for consideration, though. Alternatives to the standard level-measurement lab are authorized by instructor permission only.

Part of this lab exercise is using a *liquid manometer* as a standard pressure-verification instrument. Another part is the correct identification of common pipe and tube fittings. If using a hydrostatic transmitter, a 3-valve or a 5-valve manifold must be attached for isolation and testing purposes.

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 | – | – | – | – | |
| Circuit design challenge | mastery | | | | | – – – – |
| Final loop diagram and system inspection | mastery | | | | | – – – – |
| Loop ranging ($\pm$ 1% of span accuracy) | mastery | | | | | – – – – |
| Manometer usage | mastery | – | – | – | – | |
| Pipe and tube fitting identification | mastery | – | – | – | – | |
| Troubleshooting | mastery | | | | | – – – – |
| *Safety and professionalism* | deduction | | | | | |
| *Lab percentage score* | proportional | | | | | – – – – |
| Decommission and lab clean-up | (ungraded) | – | – | – | – | |

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

**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.

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**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.

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**Circuit design challenge**

Build a circuit with a HART differential pressure transmitter responding properly to applied pressure/vacuum, using an analog multimeter to register the transmitter's analog signal and a digital oscilloscope to register the transmitter's digital (HART) signal.

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**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.

---

**Loop ranging**

Set the lower- and upper-range values of the "smart" transmitter according to values randomly chosen by the instructor, and also set the range values in the indicating device so that any operator will see the actual process variable value shown in real-world units of measurement (e.g. PSI). The indicator's reading must match the true process variable by $\pm$ 1%.

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**Manometer usage**

Demonstrate the proper use of a liquid manometer as a trusted pressure-measuring instrument, ideally as your calibration standard when "trimming" a pressure-sensing instrument.

---

**Pipe and tube fitting identification**

Correctly identify a random set of pipe and tube fittings selected by the instructor, noting material type (e.g. brass, black iron, stainless steel), fitting name, and fractional-inch size.

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**Troubleshooting**

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

**Lab 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 instrument selection**

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

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

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

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

When selecting a transmitter for this lab exercise, pay close attention to its measurement range. If using a ΔP transmitter, the range will need to be in *inches of water* appropriate to the expected height of liquid inside the vessel. If using an echo-based transmitter, the measurement limits of the transmitter must be respected. Note that many echo-based instruments cannot reliably sense liquid level that is too close to the measurement head, which places an upper limit on liquid level.

Consult documentation from the manufacturer's website to identify how to properly mount, plumb, and calibrate the transmitter. Your instructor will check to see you have located and are familiar with the equipment manual(s).

After locating a suitable instrument and its associated documentation, you should qualitatively test it prior to installing it in your system. For a differential pressure transmitter, this entails applying a low air pressure (blowing air using your mouth is usually adequate) to the "high" pressure port and measuring the transmitter's 4-20 mA electronic output signal to see if it responds to the application of pressure. If the transmitter fails to respond properly, tag it with a label explaining what it does (or what it fails to do). Ultrasonic and non-contact radar transmitters may be tested by elevating them above the floor and checking to see they reliably indicate sensor-to-floor distance. Guided-wave radar transmitters cannot be reliably dry-tested.

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

**Lab Exercise – circuit design challenge**

Connect a loop-powered "smart" differential pressure transmitter (4-20 mA output with HART communication ability) to a DC voltage source and an analog meter such that the meter will indicate a increasing signal when a certain stimulus is applied to the transmitter, setting the transmitter's pressure measurement range as specified by the instructor. Additionally, connect a digital oscilloscope to this circuit and use it to capture one of the digital messages communicated between the transmitter and the HART communicator. All electrical connections must be made using a terminal strip (no twisted wires, crimp splices, wire nuts, spring clips, etc.) "Alligator" clips are permitted for making connections to battery terminals only.

This exercise tests your ability to correctly identify pressure port functions on a differential pressure transmitter, to navigate a "smart" instrument's parameters using a communicator, to properly interpret terminal connections on a field instrument for signal and power, to use an analog multimeter to measure 4-20 mA loop current, to use a DMM to capture peak signal amplitude, to use a digital oscilloscope to capture FSK data, and to interpret that FSK-encoded digital data.
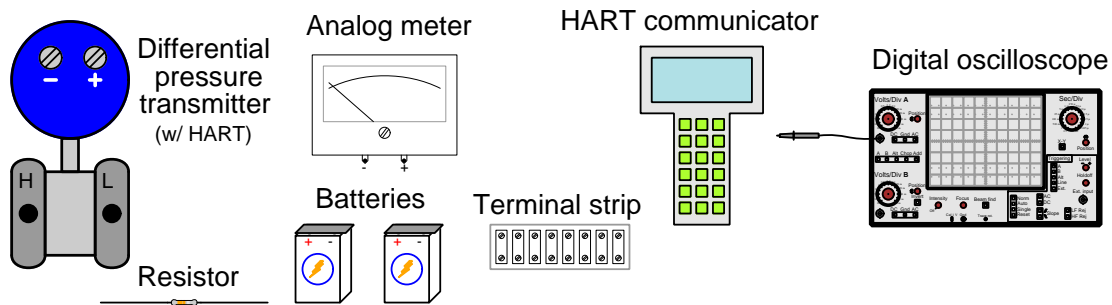


The following components and materials will be available to you: assorted 2-wire 4-20 mA HART differential pressure **transmitters** calibrated to ranges 0-30 PSI or less, equipped with Swagelok compression tube connectors at the "high" and "low" ports ; lengths of **plastic tube** with ferrules pre-swaged ; **terminal strips** ; lengths of **hook-up wire** ; 250 Ω (or approximate) **resistors** ; analog **meters** ; **batteries** ; **HART communicator** ; digital **oscilloscope**. You must provide your own tools and digital multimeter (DMM) as well as a copy of this page for your instructor to mark objectives.

**SEQUENCE:** (1) Instructor chooses criteria; (2) You build, power, and test circuit; (3) Instructor verifies all objectives satisfied.

**Transmitter range** (instructor chooses):      LRV = _____      URV = _____

**Meter options** (instructor chooses):      ____ Voltmeter (1-5 VDC)   *or*   ____ Ammeter (4-20 mA)

**Signal increases with...** (instructor chooses):      ____ Positive pressure   *or*   ____ Vacuum (suction)

**HART signal captured** (instructor verifies):      ____ (peak FSK signal voltage read on DMM)

**HART signal captured** (instructor verifies):      ____ (correctly read FSK "0" and "1" bits on scope)

Study references: the "Analog Electronic Instrumentation" chapter of *Lessons In Industrial Instrumentation*, particularly the sections on loop-powered transmitters and current loop troubleshooting. Also, the "Basic Concept of HART" subsection of the "The HART Digital/Analog Hybrid Standard" section of the "Digital Data Acquisition and Networks" chapter of the same book. Your DMM manual will provide instructions on capturing peak signal values.

**Lab Exercise – building the system**

After getting your prototype sketch approved by the instructor, you are cleared to begin building your system. Transmitters attach to 2-inch pipes using special brackets and U-bolts. These brackets and U-bolts are located along with the transmitters in the instrument storage area. Feel free to use 1/4 inch plastic tubing for all the pneumatic signal connections, and be sure not to exceed the rated supply pressure (as documented in the transmitter's manual).

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

It is recommended that you use a different electronic indicator or indicating controller as the display unit on this lab exercise, to give yourself wider exposure to the controller/indicator options in our lab facility. For example, if in the previous lab exercise your team used a panel-mount electronic indicating controller, consider using a PLC or a DCS as the electronic indicator in this lab exercise.

**Common mistakes:**

- Neglecting to consult the manufacturer's documentation for field instruments (e.g. how to connect pneumatic signal lines, how to calibrate them).
- Mounting the field instrument(s) in awkward positions, making it difficult to reach tube connectors or to remove covers when installed.
- Mounting the transmitter above the LRV point, rather than below (to avoid loss of impulse line liquid fill when the vessel's level is drained to the LRV point).
- Improper pipe/tube fitting installation (e.g. trying to thread tube fittings into pipe fittings and vice-versa).
- Applying Teflon tape to tube fitting threads; failing to apply Teflon tape to pipe fitting threads.
- Over-tightening tube fittings (remember, no more than 1-1/4 turns when installing a new ferrule set, and no more than "snug" when re-making the 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!

It is relatively easy to construct a "process vessel" for measuring water level in, by using inexpensive PVC plastic piping and fittings:
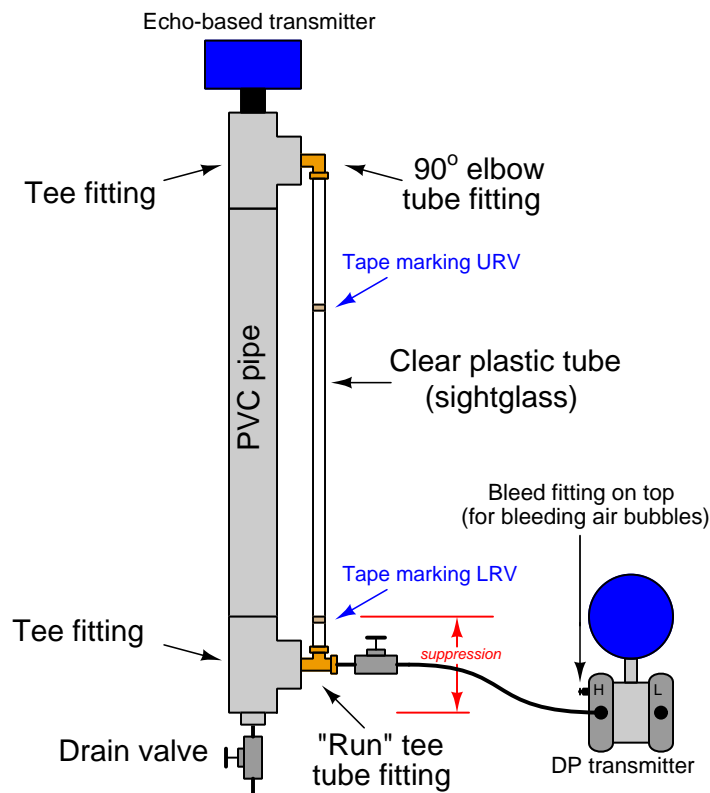


Water is poured in the top, through the open tee fitting, and is drained through a valve at the bottom (preferably a 1/4 turn ball valve).

Even with an instrument valve manifold on the $\Delta P$ transmitter, a shutoff valve is advisable between the process vessel connection and the transmitter to facilitate removal of the transmitter and manifold without having to drain the vessel. Note how the $\Delta P$ transmitter is mounted lower than the LRV mark on the sightglass: this is intentional, as it maintains a liquid fill throughout the impulse line even when the vessel is at its lowest liquid level. If the transmitter is mounted above this point, the possibility exists for that liquid fill to dribble out of the impulse line if ever the vessel's level goes too low, and this loss of liquid fill will cause calibration errors!

**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 – loop diagram and system inspection**

Each team's system will undergo an inspection simultaneous 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 – instrument ranging and manometer usage**

Each student must set the level measurement range of their team's transmitter, the LRV and URV points determined by the instructor (pieces of tape or zip-ties placed on the process vessel sightglass). Transmitters must be ranged without the benefit of filling and draining the actual process vessel as part of the procedure, because in industry we usually do not have the luxury of altering the liquid's actual level as part of our instrument commissioning. Each student will have the LRV and URV points individually set by the instructor.

Prior to ranging the transmitter, it should be *calibrated* against a trusted standard. For non-contact echo-based instruments this may be done using the floor as a reference, raising the instrument above floor level and checking its height using a tape measure or ruler. For pressure-based instruments sensing liquid level by the principle of hydrostatic pressure, a *manometer* may be most appropriate. In either case, you are expected to demonstrate the proper use of a manometer to measure low air pressures, so if this happens to work well as a calibration standard for your team's transmitter it makes sense to perform the calibration while demonstrating the use of the manometer.

One method for generating the low air pressures required for this calibration is to use a special low-range pressure regulator as shown here:

## Typical calibration setup for a low-range electronic pressure transmitter
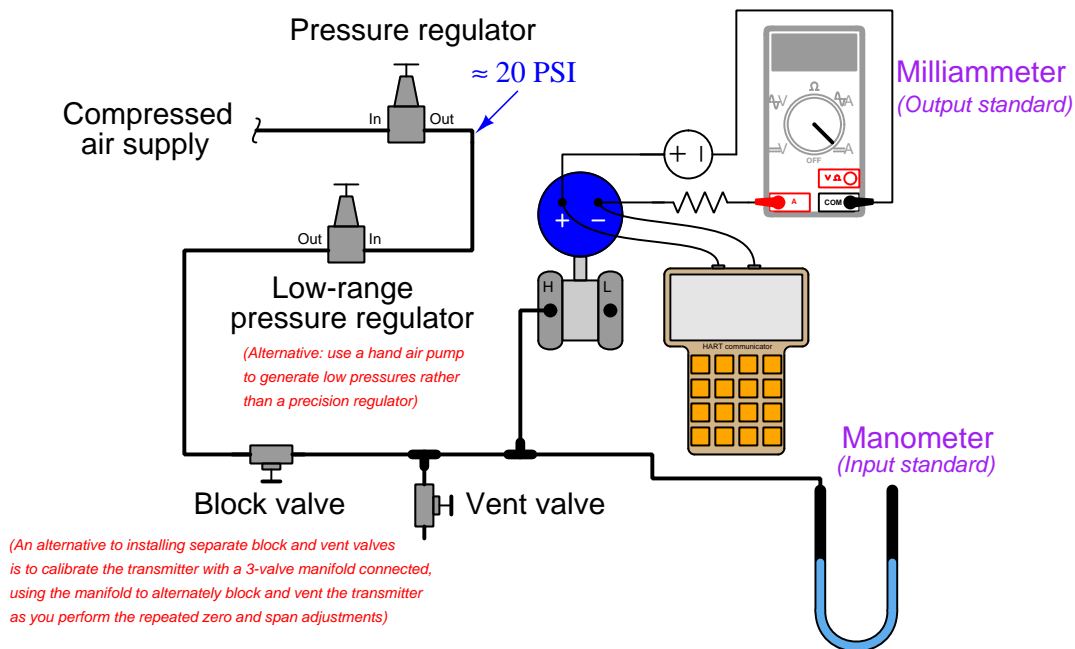
If the low-range pressure regulator does not reliably generate low enough pressures, you may throttle both the block and vent valves, using them as a sort of "pressure divider" (analogous to two resistors throttling current to make a voltage divider) to apply a lower pressure to the manometer and DP transmitter than the regulator outputs:
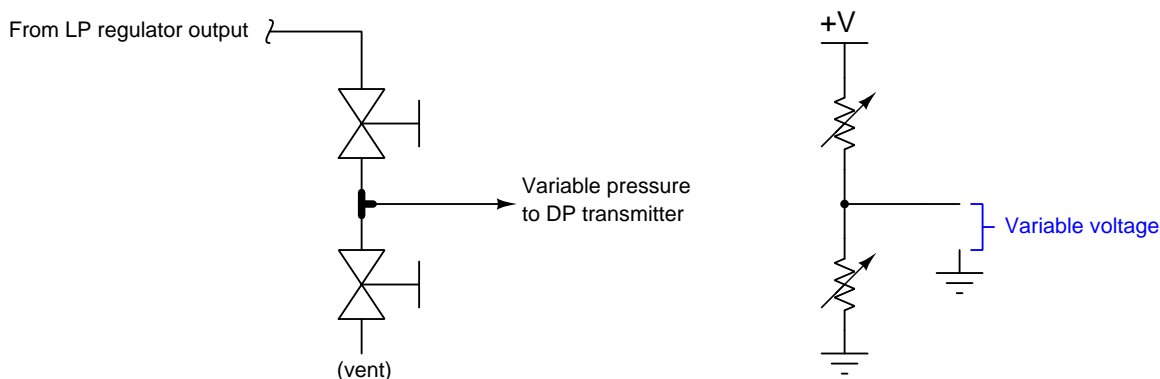


An alternative method for generating very low air pressures is to use a small-volume air pump (e.g. a bicycle tire pump works well for this purpose) connected to a chamber of large volume, such that each stroke of the pump results in a tiny increment of pressure increase applied to the manometer and DP transmitter:

## Alternative source of low-pressure air for calibration
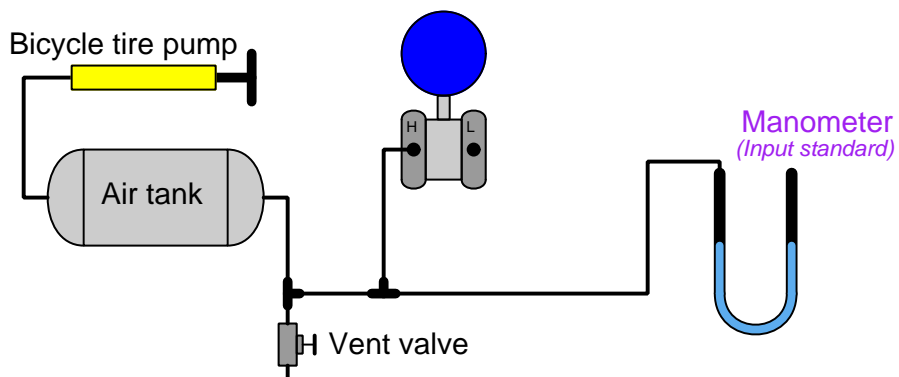


As with all modern "smart" transmitters, you need only *calibrate* the transmitter against trusted pressure and current standards once, and after that you may *re-range* the LRV and URV points as many times as you wish by typing values into the HART communicator. It is recommended that you work as a team to calibrate your transmitter at the same time you complete the "Manometer usage" objective. After that, each student on the team completes their "Loop ranging" objective individually.

The span of your instrument's range will be dictated by the distance between the LRV and URV points chosen by your instructor, and the zero of your instrument's range (its LRV) will be dictated by the location of the LRV point and the transmitter's mounting height (i.e. the amount of *suppression*). Your electronic indicator (or recorder, or indicating controller) must display the process vessel's level in units of *inches*, with the indication showing "0" when the vessel's liquid level is at the LRV point.
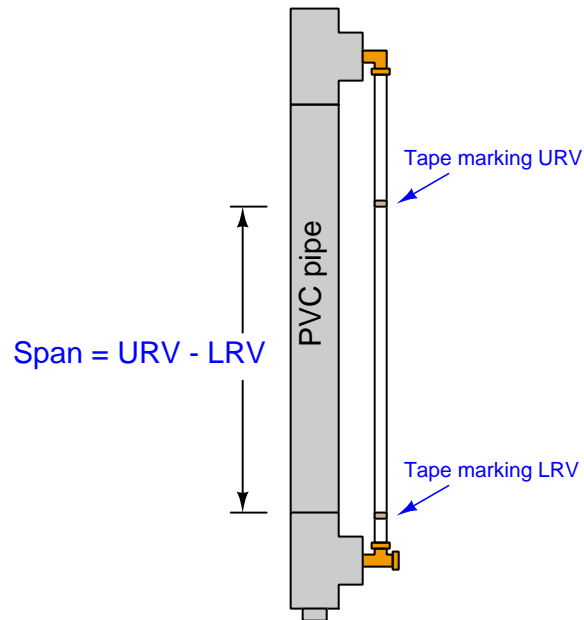


You must use whatever liquid level happens to be in the vessel at the time of transmitter installation as a reference for setting the zero, because this represents the kind of realism you will face on the job: operators are unlikely to let you interrupt production by significantly altering the amount of level in their process vessel just to range a level transmitter. If the transmitter is correctly calibrated (against a trusted standard) and field-ranged to match the liquid level, it should reliably indicate liquid level at any point within the set range.

It would be easy to set the LRV and URV points of your smart transmitter if you had the freedom to drain and fill the vessel at will: simply drain the vessel to the LRV point, then set the transmitter's LRV to the live pressure value indicated on the HART communicator's display; next, fill the vessel to the URV point, then set the transmitter's URV to the pressure value indicated. However, since you will not be allowed to do this, you must devise your own procedure for accurately setting the smart transmitter's LRV and URV while the liquid level is at some point not of your choosing. **(Hint: you will need to use a tape measure!)** *The instructor will ask you to explain your procedure, and why it works.*

The accuracy of your calibration will be checked by the instructor, filling and emptying your process vessel while checking the indicator to make sure it reads 0 inches at the LRV level and full height at the URV level. *Again, you are not allowed to fill and empty the vessel as part of your ranging procedure, but only the instructor is allowed to do this as a final check of your work!*

**Common mistakes:**

- Applying excessive air pressure to a manometer, and blowing all the liquid out of it (when using a regulator as the calibration air pressure source)!
- Improper pipe/tube fitting installation (e.g. trying to thread tube fittings into pipe fittings and vice-versa).
- Mounting the transmitter above the LRV point, rather than below (to avoid loss of impulse line liquid fill when the vessel's level is drained to the LRV point).
- Neglecting to drain all liquid out of the transmitter prior to applying air pressure at the calibration bench (this will likely blow liquid into the tubes, causing calibration errors).
- Neglecting to bleed all air out of the impulse line and transmitter body when installing the transmitter at the liquid process vessel (this will cause zero- and span-shift errors).

# Notes on instrument ranging

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

The reason this is an issue at all is because loop controllers operating on 4-20 mA analog signals don't "know" what those signals are supposed to represent unless someone configures the controller with the proper range reflecting real-world conditions. For example, if a student is assigned a temperature transmitter with a range of 300 to 800 degrees Fahrenheit, not only does the transmitter have to output 4 mA when sensing 300 $^o$F and output 20 mA when sensing 800 $^o$F, but the controller must display an indication of 300 $^o$F when it receives a 4 mA signal from the transmitter, and display an indication of 800 $^o$F when it receives a 20 mA signal from the transmitter. None of this happens on its own – the student must range the transmitter for 300-800 $^o$F input (and 4-20 mA output) as well as range the controller to display 300-800 $^o$F over its 4-20 mA input scale. A typical loop is shown here with all instrument ranges displayed:
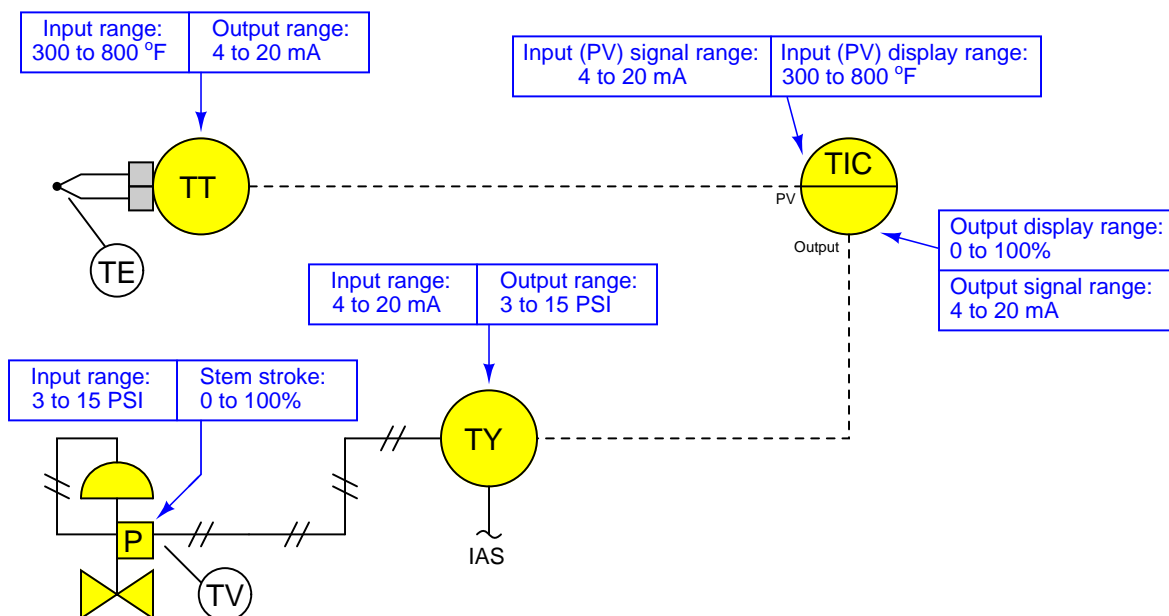


Analog (non-"smart") transmitters, I/P transducers, and valve positioners are ranged using "zero" and "span" adjustments, typically screws or nuts. The ranging of analog instruments is discussed in the "Instrument Calibration" chapter of the *Lessons In Industrial Instrumentation* textbook.

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

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

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

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

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

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

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

- Allen-Bradley PLC5, SLC500, and MicroLogix controllers: process variable scaling parameters are typically located either in a "Scale" instruction (SCL) or a "Scale with Parameters" instruction (SCP). In either case, the instruction takes the raw count value from the input channel's analog-to-digital converter and scales it into the desired process variable display range. A YouTube video on our BTCInstrumentation channel shows how to do this for the networked MicroLogix PLCs in the lab using the SCP instruction. *Note: SCP instruction parameters may be edited online. For this reason, downloading edits is not necessary for the MicroLogix PLCs in our lab. In fact, it is very important that you <u>not</u> save or download the PLC program, because doing so may alter the PLC's network address and lead to communication problems. Just make the changes while the PLC is in "Run" mode and then exit the program:*
  - → (SCL instruction) = *Rate* and *Offset* values scale the signal according to the slope-intercept formula $y = mx + b$, where *Rate* is $10000m$ and *Offset* is $b$
  - → (SCP instruction LRV) = *Scaled Min.*
  - → (SCP instruction URV) = *Scaled Max.*

- Allen-Bradley Logix5000 controller: process variable scaling parameters are located in the "PID" instruction (PID):
  - → LRV = *.MINS*
  - → URV = *.MAXS*

- caSCADA "`pid`" control program: process variable scaling parameters are located in one of the source code files which must be modified using a text editor program, then recompiling the `pid` program so the new parameters may take effect. This control program may be initiated from the Linux command line by typing `./pid` and pressing the Enter key, after which a set of instructions will appear on the screen showing the default LRV and URV range values, and which file to find these parameters within. After editing and saving this file, you will need to type `make` at the Linux command line and press Enter to recompile the program. Finally, type `./pid` and press Enter to initiate the recompiled program.
   - → LRV = *pid[0].LRV*
   - → URV = *pid[0].URV*

file ranging

**Lab Exercise – pipe and tube fitting identification**

Part of this lab exercise is to properly identify the following types of pipe and instrument tube fittings from memory (without the aid of a pictorial reference) and to explain how pipe fittings and tube fittings seal fluid pressure differently. Note that synonyms are separated by slash marks (e.g. "street/run"):

**Pipe fittings**

- Thread sizes: 1/8 inch NPT, 1/4 inch NPT, 3/8 inch NPT, and 1/2 inch NPT
- Fitting type: tee (female, branch, and street/run)
- Fitting type: elbow (female $45^o$, female $90^o$, and street)
- Fitting type: cross
- Fitting type: nipple
- Fitting type: coupling
- Fitting type: reducing coupling
- Fitting type: reducing bushing
- Fitting type: reducing adapter/expander
- Fitting type: union
- Fitting type: cap
- Fitting type: plug
- Fitting type: flange

**Instrument tube fittings**

- Tube sizes: 1/8 inch, 1/4 inch, 3/8 inch, and 1/2 inch
- Fitting components: nut and ferrule(s)
- Fitting type: straight connector (male and female)
- Fitting type: elbow connector (male and female)
- Fitting type: union (straight and reducing)
- Fitting type: tee (union, branch, run)
- Fitting type: union elbow
- Fitting type: union cross
- Fitting type: bulkhead union
- Fitting type: cap
- Fitting type: plug

As you closely inspect pipe fitting threads, you will notice those threads have a tapered profile such that they "wedge" against each other when tightened. Pipe fittings form leak-proof seals by the close fit of these male and female threads. Some form of pipe-sealing tape, or semi-liquid compound (often called *pipe dope*) must be applied to the threads prior to engagement. The pipe thread sealant fills in any gaps that might exist between the roots and crests of the threads as well as lubricates the threads so that the metal pieces do not "gall" against each other when tightened.

A close inspection of tube fittings reveals a different sealing method: the threads on a tube fitting are straight rather than tapered, since their only function is to provide the nut a place to engage with the fitting. The actual fluid sealing takes place inside the fitting, between the conical profile of the *ferrule* compressed on the tube and the conical bore of the tube fitting where the ferrule seats. This cone-shaped mating of ferrule and bore forms a pressure-tight seal requiring no sealant, which is why we never apply Teflon tape or other pipe sealant to any portion of a tube fitting.

For more information on tapered pipe and tube fittings, refer to the "Instrument Connections" chapter of your *Lessons In Industrial Instrumentation* textbook.

A good way to prepare for this assessment is by working together as a team to identify random fittings in the pipe/tube drawers while referencing a manual such as the Parker and Swagelok fitting manuals contained in your Instrumentation reference. The aspect of this assessment students find most challenging is identifying pipe thread sizes by sight. Some black-iron pipe fittings have the fractional size (e.g. 1/2", 3/8", 1/2") cast into the fitting itself, which is probably your best guide to learning these thread sizes.

**Lab Exercise – troubleshooting**

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

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

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

Failure to correctly identify both the general location and nature of the fault within the allotted time, and/or failing to demonstrate rational diagnostic procedure to the supervising instructor will disqualify the effort, in which case the student must re-try with a different fault. Multiple re-tries are permitted with no reduction in grade.

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

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

**Common mistakes:**

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

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

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

**Lab Exercise – decommissioning and clean-up**

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

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

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

**Return the following components to their proper storage locations:**

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

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

file i01293

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

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



TE 205

0-1500°F

TB-15   TB-11   0-1500°F

Yel 1 TT 205 + Red    Red 3 Wht/Blu    Wht/Blu 1 Red    Red 7
Red 2 − Blk    Blk 4 Blu    Blu 2 Blk    Blk 22 TIC 205

Cable TT-205    Cable 3, Pr 1    Cable TT-205    21
TY 205a    Red 19
18

TB-15   TB-11

I/P    Red 5 Wht/Org    Wht/Org 3 Red    H Blk
Out  TY 205b + Red    Red 5    Wht/Org 3 Red    Wht
Tube TV-205    − Blk    Blk 6 Org    Org 4 Blk    N

S

Cable TY-205b    Cable 3, Pr 2    Cable TY-205b

TV 205

AS 20 PSI
Valve #15
Column #8

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 |



0-50 PSI ↑

H
L
PT 73
+
−
Red
Blk

Cable PT-73

**TB-52**
Red | 1 | Red
Blk | 2 | Blk

Cable 4, Pr 1

**TB-80**
Red | 11 | Red
Blk | 12 | Blk

Cable PT-73

Red | 11 | Red
Blk | 12 | Blk

**Card 4 Channel 6 Analog input**

PIC 73   0-50 PSI ↑

Tube PV-73

PV 73

I/P   O
PY 73
+
−
S
Red
Blk

AS 20 PSI

Cable PV-73

**TB-52**
Red | 15 | Red
Blk | 16 | Blk

Cable 4, Pr 8

**TB-80**
Red | 29 | Red
Blk | 30 | Blk

Cable PV-73

Red | 11 | Red
Blk | 12 | 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 |
| | | | | | | |

| Loop Diagram: Sludge tank level control | | Revised by: I. Leaky | Date: April 1, 2008 |
|---|---|---|---|

| Process area | Bulkhead panel B-104 | Control panel CP-11 |
|---|---|---|



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

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

| Process area | Field panel FP-25 |

**Process area:**

H / L — FT 18
+ / − Red / Blk
0-75 GPM

Cable FT-18

P — A / Loop + / Loop − / Supply
Red / Blk
IAS 20 PSI

Cable FV-18

FV 18

**Field panel FP-25:**

Red — 21 — Blu
Blk — 22 — Blu
Red — 11 — Blu
Blk — 12 — Blu

10 — 800 mA — Blu

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

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

FC 18 — L2/N — L1
Ethernet

FIR 18
(Located in main control room)

PS-1
+ 24 VDC 1 amp
−
120 VAC
L1 / N / ⏚
Blk / Wht / Grn

1A / 1A
1 / 2 / 3 / 4
Blk / Wht / Grn

ES 120 VAC
From field panel disconnect

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

**Lab Exercise – loop diagram and system inspection**

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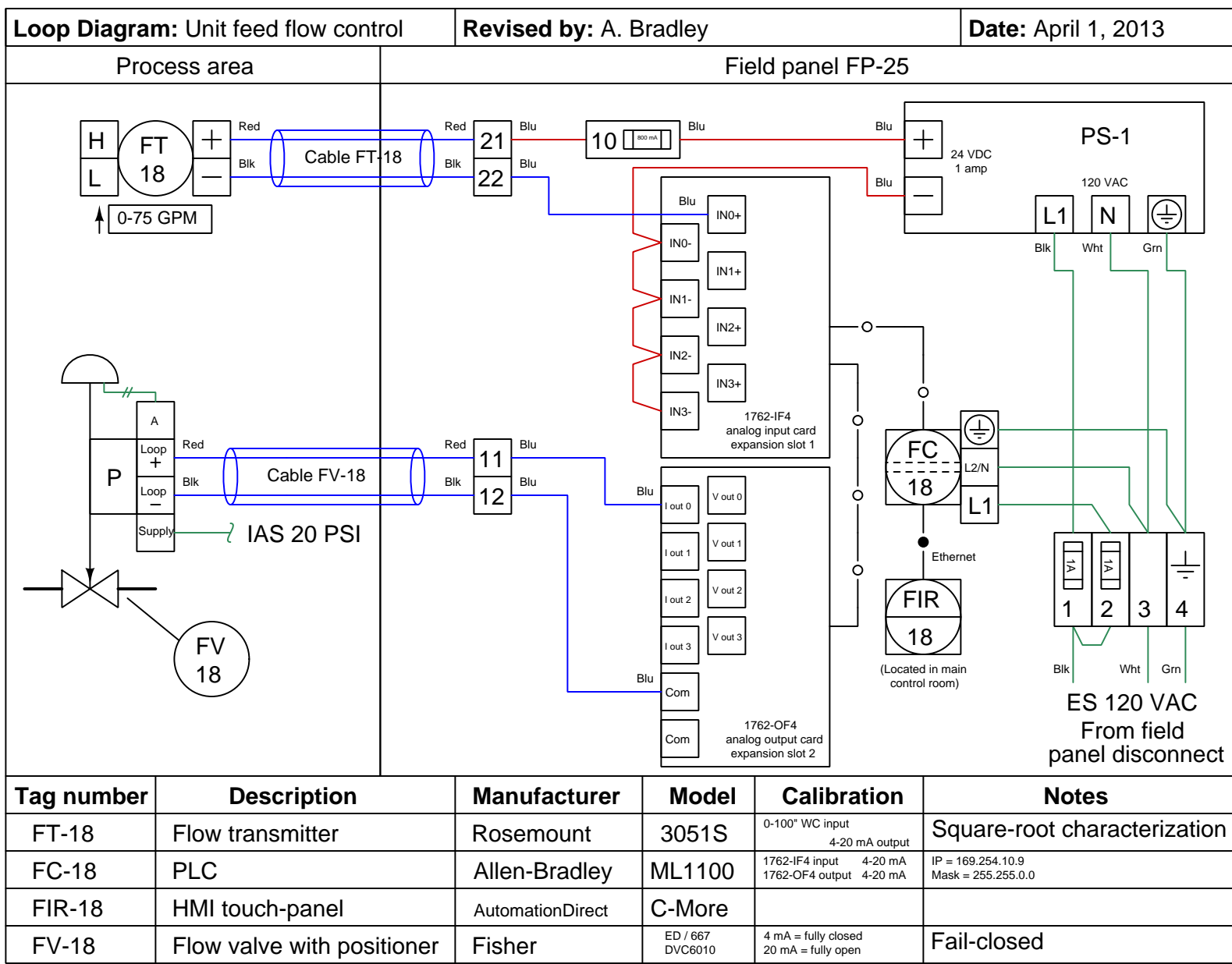hat the instructor sees when inspecting each and every panel and connection. *Please note that the "Lessons In Industrial Instrumentation" textbook describes good practices for construction and documentation.*

**Construction Standards**

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

**Documentation Standards**

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

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

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

**Common mistakes:**

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

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

file i00654

**Answers**

Answer 1

Answer 2

Answer 3

Answer 4

Answer 5

Answer 6

Answer 7
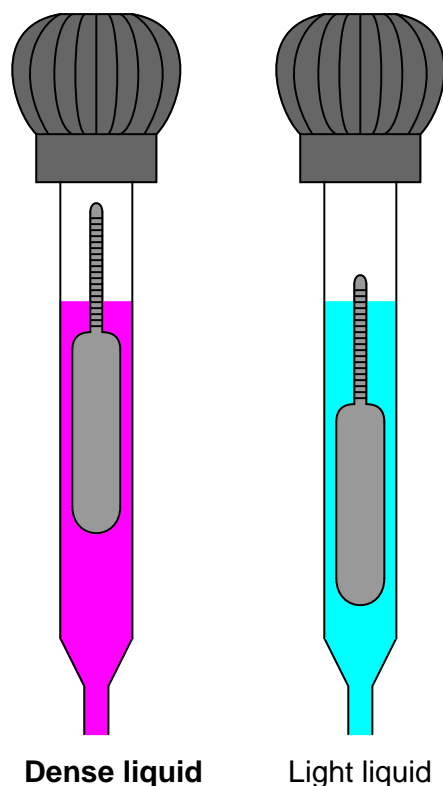
Answer 8

Answer 9

The larger numbers (greater density) would be located at the *bottom* end of the scale, because liquids of greater density will cause the float to rise higher. Liquids of low density will cause the float to sink further (with the liquid interface resting near the top of the scale).



**Dense liquid**          Light liquid

This is why people float better when swimming in the Great Salt Lake of Utah than they do swimming in fresh water (or even ocean water, which is not nearly as salty). Salt(ier) water is denser than fresh(er) water, which means a person's body need not sink as deeply to displace enough weight of water to remain buoyant.

If a person tried to swim in a vat of alcohol, where the liquid density is quite a bit less than water, they would probably drown because it would be much more difficult to achieve buoyancy. This, however, might be a dream come true for some . . .

Answer 10

The 20/4 superscript means is that acetic acid is this much denser at $20^o$ C than water is at $4^o$ C.

Answer 11

$P = \underline{\textbf{4.324}}$ PSI
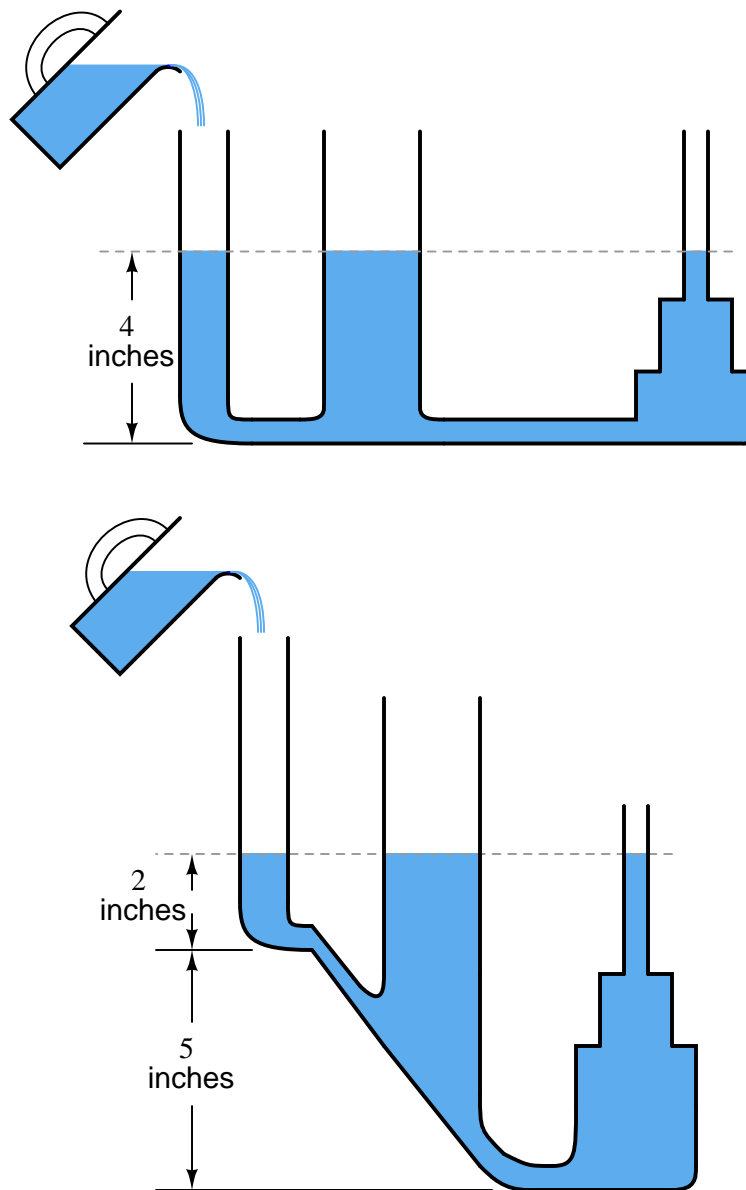
A Galileo thermometer works on the principle of liquid density changing with temperature. As the liquid density changes with ambient temperature, different balls will achieve neutral buoyancy.

For the densitometer, more balls will float as the fluid becomes denser. This equates to a "stronger" concentration of antifreeze in the coolant mixture.

## Answer 14

- Sea water: 1.025
- Mercury: 13.6
- Olive oil: 0.918
- Castor oil: 0.969
- Kerosene: 0.820
- Benzene: 0.899
- Acetone: 0.791
- Glycerin: 1.26
- Methanol: 0.7915
- Ethanol: 0.7892
- Ethylene glycol: 1.109
- Gasoline: 0.657 to 0.689

## Answer 15

Specific gravity = 0.8669 (same as density in units of $g/cm^3$)

The units of grams and cubic centimeters are *defined* in such a way that their density quotient in relation to pure water is 1. This is similar to the Celsius temperature scale, similarly *defined* at the $0^o$ and $100^o$ points by the freezing and boiling points of pure water, respectively.

To calculate the density of toluene in units of pounds per cubic feet, simply multiply the density of water ($62.428$ lb/ft$^3$) by the specific gravity of toluene (0.8669):

$(62.428$ lb/ft$^3)(0.8669) = 54.12$ lb/ft$^3$

## Answer 16

This is a "trick" question: they all generate the exact same amount of hydrostatic pressure.

The principle at work here is the relationship between *vertical* height and hydrostatic pressure. Cross-sectional area of the liquid column is irrelevant! Only column height, liquid density, and the gravitational pull of the Earth matter when calculating hydrostatic pressure. Since all three of these variables are precisely the same in this scenario, the hydrostatic pressures must likewise be precisely the same.

## Answer 17

$$\left(\frac{20 \text{ ft olive oil}}{1}\right)\left(\frac{0.918 \text{ ft W.C.}}{1 \text{ ft olive oil}}\right)\left(\frac{12 \text{ inches}}{1 \text{ ft}}\right)\left(\frac{6.895 \text{ kPa}}{27.6807 \text{ inches W.C.}}\right) = 54.88 \text{ kPa}$$

## Answer 18

$P = \underline{\mathbf{4.324}}$ PSI

Answer 19

Hydrostatic pressure due to 3 feet of glycerine (SG = 1.26)

(1.26)(3 feet)(12 in / 1 ft)(1 PSI / 27.6807 "W.C.) = 1.639 PSI

Hydrostatic pressure due to 2 feet of water (SG = 1.00)

(1.00)(2 feet)(12 in / 1 ft)(1 PSI / 27.6807 "W.C.) = 0.867 PSI

Hydrostatic pressure due to 4.5 feet of olive oil (SG = 0.918)

(0.918)(4.5 feet)(12 in / 1 ft)(1 PSI / 27.6807 "W.C.) = 1.791 PSI

Total hydrostatic pressure = 1.639 PSI + 0.867 PSI + 1.791 PSI = 4.297 PSI = 29.6 kPa

Answer 20

| Fault | Possible | Impossible |
|---|---|---|
| LSH-58 failed | √ | |
| LAH-58 failed | √ | |
| LSL-57 failed | | √ |
| LAL-57 failed | | √ |
| LT-38a calibration error | | √ |
| LIC-38 (input) calibration error | | √ |
| FIC-37 (input) calibration error | | √ |

It is highly unlikely that LT-38a is at fault because the controller (LIC-38) receives the median-selected signal from *three* different level transmitters. In order for the 10.67 mA signal to be incorrect, at least one of the other two level transmitters (LT-38b or LT-38c) would also have to be experiencing the same calibration error! In other words, this scenario would require coincidental faults, which are highly unlikely.

Answer 21

Answer 22

Answer 23

Answer 24

Answer 25

Answer 26

Answer 27

**Partial answer:**

| Process level (ft) | Percent of span (%) | Δ pressure sensed ("W.C) | Output signal ideal (mA) | Output signal min. (mA) | Output signal max. (mA) |
|---|---|---|---|---|---|
| | 0 | | | | |
| | 10 | | | 5.568 | |
| | 25 | −82.28 | | | |
| 5.5 | 50 | | | | |
| | 75 | | 16 | | |
| | 90 | | | | |
| | 100 | +12.87 | | | |

| Signal value (mA) | Percent of span (%) | Indication ideal (ft) | Indication min. (ft) | Indication max. (ft) |
|---|---|---|---|---|
| 4 | 0 | 0 | −0.022 | 0.022 |
| | 10 | | | |
| 8 | 25 | | | |
| | 50 | | | 5.522 |
| 16 | 75 | | | |
| | 90 | | | |
| 20 | 100 | 11 | 10.978 | |

Answer 28

**Partial answer:**

| Process level (ft) | Percent of span (%) | Δ pressure sensed ("W.C) | Output signal ideal (mA) | Output signal min. (mA) | Output signal max. (mA) |
|---|---|---|---|---|---|
| 0 | 0 | | | | |
| | 10 | | | | |
| | 25 | 81.31 | 8 | | |
| | 50 | | | | 12.08 |
| | 75 | | | | |
| | 90 | | | 18.32 | |
| 18 | 100 | 325.24 | | | |

Answer 29

**Partial answer:** (Transmitter range values only)

LRV = **30.6** "WC (@ 4 mA)          URV = **69.1** "WC (@ 20 mA)

Answer 30

Note: a weight density ($\gamma$) of 51.2 lb/ft$^3$ is assumed for kerosene.

- LRV = **56.62** "WC = 2.046 PSI
- URV = **164.9** "WC = 5.959 PSI

- Output = **5.455** mA with the kerosene level 4 feet up from the bottom of the tank (4 feet "fillage")
- Output = **12.73** mA with the kerosene level 6 feet down from the top of the tank (6 feet "ullage")

---

Answer 31

Lower range-values: 100 feet W.C. input (1200 inches W.C.) = 4 mA output
Upper range-values: 110 feet W.C. input (1320 inches W.C.) = 20 mA output

Water level in vessel at 13.7 mA = 6.0625 feet ; applied pressure = 45.98 PSI

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Answer 32

Lower range-values (LRV): 0 inches W.C. input = 3 PSI output

Upper range-values (URV): 216 inches W.C. input = 15 PSI output

- Transmitter output signal (PSI) at 12 feet of level = 11 PSI
- Water level at 5.9 PSI signal output = 4.35 feet

---

Answer 33

Lower range-values (LRV): 0 inches W.C. input = 4 mA output

Upper range-values (URV): 114.24 inches W.C. input = 20 mA output

- Transmitter output signal (mA) at 8 feet of level = 13.14 mA
- Heptane level at 5.7 mA signal output = 1.4875 feet

---

Answer 34

| Process level (in) | Percent of span (%) | Hydrostatic pressure (PSI) | Output signal ideal (mA) |
|---|---|---|---|
| 48 | 0 | 1.734 | 4 |
| 58.5 | 25 | 2.113 | 8 |
| 69 | 50 | 2.493 | 12 |
| 79.5 | 75 | 2.872 | 16 |
| 90 | 100 | 3.251 | 20 |

Answer 35

**Dry leg:**

| % of span | $\Delta P$ (”$H_2O$) | Output (mA) |
|---|---|---|
| 0 | 0 | 10 |
| 50 | 153 | 30 |
| 100 | 306 | 50 |

**Wet leg:**

| % of span | $\Delta P$ (”$H_2O$) | Output (mA) |
|---|---|---|
| 0 | -306 | 10 |
| 50 | -153 | 30 |
| 100 | 0 | 50 |

Answer 36

DP range = 0 to 308.8 ”WC = 0 to 11.15 PSID

If the lower process connection were blocked by debris, the transmitter's output signal would increase, quite possibly to a magnitude greater than 100%. Just the opposite would happen if the upper process connection plugged.

Answer 37

"Top" pressure = 0 ”W.C.
"Middle" pressure = 51.6 ”W.C.
"Bottom" pressure = 154.8 ”W.C.

Answer 38

The "Top" transmitter's measurement of 50 inches water column tells us that the vessel is pressurized. This figure will be important to include in our level calculations later.

The difference between "Bottom" and "Middle" pressure transmitter measurements is solely a function of liquid density, since the vertical distance between the two transmitters is fixed and any vapor pressure buildup (50 "W.C., as indicated by the "Top" transmitter) adds equally to *both* transmitters' indications. In this case, the difference between 310 inches water column and 220 inches water column is 90 inches of water column:

$$(310 \text{ "W.C.}) - (220 \text{ "W.C.}) = 90 \text{ "W.C.}$$

If the process liquid were water (S.G. = 1), the pressure difference would be 120 inches of water column, not 90, because the two transmitters are located 10 feet apart from each other. Thus, the density of this liquid is substantially less than that of water:

$$\text{Specific gravity} = (90 \text{ "W.C. } / 120 \text{ "W.C.}) = 0.75$$

To calculate liquid level (height), we must first subtract the measured vapor pressure (50 "W.C.) from the "Bottom" pressure transmitter's indication, so that we are left with the pressure due to liquid head alone:

$$\text{Hydrostatic pressure} = (310 \text{ "W.C.}) - (50 \text{ "W.C.}) = 260 \text{ "W.C.}$$

Dividing this hydrostatic pressure by the specific gravity yields the liquid column height:

$$(260 \text{ "W.C.})/(0.75 \text{ "W.C. } / \text{ in}) = 346.67 \text{ inches or } 28.89 \text{ feet}$$

Equations for calculating specific gravity and liquid level (let $x$ be the distance between the middle and bottom pressure transmitters in units of inches, and all pressures in units of inches water column):

$$\text{Specific Gravity} = \frac{P_{bottom} - P_{middle}}{x}$$

$$\text{Liquid level} = \frac{P_{bottom} - P_{top}}{\text{Specific Gravity}}$$

$$\text{Liquid level} = x \frac{P_{bottom} - P_{top}}{P_{bottom} - P_{middle}}$$

Answer 39

| % of span | $\Delta P$ ("H$_2$O) | Output (mA) |
|-----------|-----------------------|-------------|
| 0 | -462 | 10 |
| 50 | -309 | 30 |
| 100 | -156 | 50 |

Answer 40

**Partial answer:**

What matters here is the *vertical* height of the water column, not the angled length. Essentially, this is nothing more than a problem in trigonometry: to find the length of the side opposite the 40$^o$ angle, given a hypotenuse of 10 feet (120 inches).

Answer 41

Answer 42

Dry weight = 8.681 pounds. Submerged weight = 1.455 pounds.

For *any* object to float in water, its density must be less than that of water (62.428 lb/ft$^3$).

Answer 43

Dry weight = 53.52 pounds

Submerged (by 3 feet) weight = 49.44 pounds

Answer 44

Answer 45

Answer 46

Don't forget to contact the operator(s) for this process, and either have that operator put the level controller in manual mode, or you do it yourself! The distillation tower bottom product level will have to be manually controlled for the duration of your calibration test.

Answer 47

| Process level (in) | Percent of span (%) | Buoyant force (lb) | Output signal ideal (mA) | Output signal min. (mA) | Output signal max. (mA) |
|---|---|---|---|---|---|
| | 0 | | | | 4.032 |
| | 25 | | 8 | | |
| | 50 | 1.534 | | | |
| 13.5 | 75 | | | | |
| | 100 | | | 19.968 | |

| Signal value (mA) | Percent of span (%) | Indication ideal (in) | Indication min. (in) | Indication max. (in) |
|---|---|---|---|---|
| 4 | 0 | 0 | −0.036 | 0.036 |
| | 25 | | | |
| | 50 | 9 | | 9.036 |
| 16 | 75 | | | |
| | 100 | | 17.964 | |

## Answer 48

**Partial answer:**

| Percent of span (%) | Buoyant force (lb) | Output signal ideal (PSI) | Output signal min. (PSI) | Output signal max. (PSI) |
|---|---|---|---|---|
| 0 | 0.5675 | 3 | | |
| 25 | | | 5.88 | |
| 50 | 1.929 | | 8.88 | |
| 75 | | | | 12.12 |
| 100 | 3.291 | | | 15.12 |

## Answer 49

## Answer 50

Force pushing up on cube's bottom face: 0.867 lb
Force pushing down on cube's top face: 0.831 lb
Average force pushing horizontally on each of the cube's four other faces: 0.849 lb

Resultant force = 0.0361 lb (upward) = weight of 1 in$^3$ of water @ 62.428 lb/ft$^3$.

## Answer 51

Force pushing up on cube's bottom face: 4.575 lb
Force pushing down on cube's top face: 2.745 lb
Average force pushing horizontally on each of the cube's four other faces: 3.660 lb

Resultant force: 1.830 lb (upward) = weight of 64 in$^3$ of methanol @ 49.41 lb/ft$^3$.

## Answer 52

First, determine the specific gravity of the crown. If it weighs 5 pounds dry and 4.444 pounds submerged, then the weight of the displaced water must be 0.556 pounds. A crown weighing 5 pounds, and having a volume equivalent to 0.556 pounds of water, must have a density approximately 9 times that of water (5 / 0.556 $\approx$ 9). We can say it has a specific gravity of 9, or say that it has a density of 9 g/cm$^3$.

Pure gold has a specific gravity of almost 19, so this crown cannot be made of pure, solid gold. It is most likely made of copper (D = 8.96 g/cm$^3$) or tin (D = 7.31 g/cm$^3$), plated with gold.

According to legend, this is how Archimedes came up with his principle relating displacement to buoyant force.

## Answer 53

| Process level (in) | Percent of span (%) | Buoyant force (lb) | Output signal ideal (PSI) | Output signal min. (PSI) | Output signal max. (PSI) |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 3 | 2.88 | 3.12 |
| 6 | 25 | 1.532 | 6 | 5.88 | 6.12 |
| 12 | 50 | 3.064 | 9 | 8.88 | 9.12 |
| 18 | 75 | 4.597 | 12 | 11.88 | 12.12 |
| 24 | 100 | 6.129 | 15 | 14.88 | 15.12 |

Answer 54

| Process level (in) | Percent of span (%) | Buoyant force (lb) | Output signal ideal (mA) | Output signal min. (mA) | Output signal max. (mA) |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 4 | 3.968 | 4.032 |
| 7.5 | 25 | 2.297 | 8 | 7.968 | 8.032 |
| 15 | 50 | 4.593 | 12 | 11.968 | 12.032 |
| 22.5 | 75 | 6.890 | 16 | 15.968 | 16.032 |
| 30 | 100 | 9.187 | 20 | 19.968 | 20.032 |

Answer 55

The transmitter will measure 28.4 PSI, due to the added pressure of the fluid inside the capillary tube.

Answer 56

It is entirely possible that everything is normal in this scenario – no instrument faults and no unusual process conditions!

Answer 57

We know that an object's dry weight divided by the difference between dry and submerged weights gives us the specific gravity, or density in units of g/cm$^3$. If the lead crown's dry weight is 5 pounds and its specific gravity is 11.35, then the weight of the water it will displace when submerged is:

(5 lb)/(11.35) = 0.441 lb

Subtracting this figure of 0.441 pounds from the dry weight of 5 pounds should give us the submerged weight:

5 lb - 0.441 lb = 4.559 lb

Answer 58

Answer 59

- $I = \underline{\textbf{12.77}}$ mA

- $V_C = \underline{\textbf{3.192}}$ V

- $V_{BC} = \underline{\textbf{17.28}}$ V

- $V_B = \underline{\textbf{20.47}}$ V

Answer 60

The current value agrees with the indication at LIC-56, and so the problem is not with LIC-56. This leaves the transmitter (miscalibrated, plugged impulse line), a change in process density (assuming a hydrostatic DP transmitter) or the operator's manual measurement of manure level.

Hydrostatic (DP-based) level measurement is appropriate for R-102, assuming either remote seal(s) or purging. Otherwise, solids in the manure will surely plug up the transmitter's impulse line(s) over time.

Answer 61

Answer 65

**Partial answer:**

| Interface level (ft) | Percent of span (%) | $\Delta$ pressure sensed (”W.C) | Output signal ideal (mA) | Output signal min. (mA) | Output signal max. (mA) |
|---|---|---|---|---|---|
| 0 | 0 | | | | |
| | 10 | | | | 5.76 |
| | 25 | | | | |
| | 50 | | 12 | | |
| 4.5 | 75 | | | | |
| | 90 | | | | |
| | 100 | 43.2 (Low side) | | 19.84 | |

Follow-up question: why do you suppose it is a good idea to keep the wet leg filled with a fluid with such a high specific gravity (1.2)? Why not just let it flood with the lighter fluid (SG = 0.8) or even fill it with water (SG = 1.0)?

Answer 66

**Partial answer:**

| Interface level (in) | Percent of span (%) | $\Delta$ pressure sensed (”W.C) | Output signal ideal (mA) | Output signal min. (mA) | Output signal max. (mA) |
|---|---|---|---|---|---|
| | 0 | 10.5 L | | | |
| | 10 | | 5.6 | | |
| 7.5 | 25 | | | | |
| | | 3.75 L | | | |
| | 75 | | | 15.984 | |
| | 90 | | | | 18.416 |
| 30 | 100 | | | | |

Note: the letter "L" following the differential pressure value represents that amount of positive pressure applied to the *low* port of the transmitter.

Answer 67

**Partial answer:**

| Interface level (in) | Percent of span (%) | Buoyant force (lbs) | Output signal ideal (PSI) | Output signal min. (PSI) | Output signal max. (PSI) |
|---|---|---|---|---|---|
|  | 0 |  | 3 |  |  |
|  | 10 |  |  | 4.08 |  |
| 2.75 | 25 |  |  |  |  |
|  | 50 | 0.6750 |  |  |  |
|  | 75 |  |  |  | 12.12 |
| 9.9 | 90 |  |  |  |  |
|  | 100 | 0.7874 |  |  |  |

Answer 68

**Partial answer:**

| Interface level (in) | Percent of span (%) | Buoyant force (lbs) | Output signal ideal (PSI) | Output signal min. (PSI) | Output signal max. (PSI) |
|---|---|---|---|---|---|
| 0 | 0 |  |  |  | 3.12 |
|  | 10 |  |  | 4.08 |  |
|  | 25 |  |  |  |  |
|  | 50 | 2.469 |  |  |  |
| 11.25 | 75 |  |  |  |  |
|  | 90 |  |  |  |  |
|  | 100 |  | 15 |  |  |

Answer 69

One easy diagnostic step would be to change the setpoint of controller LIC-38 (in automatic mode) by 5% or 10%, to see if *all three* transmitters indicate a change in level or only the two in closest agreement.

Answer 70

Glycerine height = **38.46** ft

Castor oil height = **49.96** ft

Answer 71

19 inches of water and 15 inches of glycerine will balance one another in this manometer. These are not the only column heights that will self-balance. In fact, any ratio of 19:15 will work because the ratio of water's density to glycerine's density is 15:19.

Answer 72

If not completely submerged, the interface level in the well might not match the interface level in the rest of the vessel. Here are two examples of how this might happen:



. . . or . . .
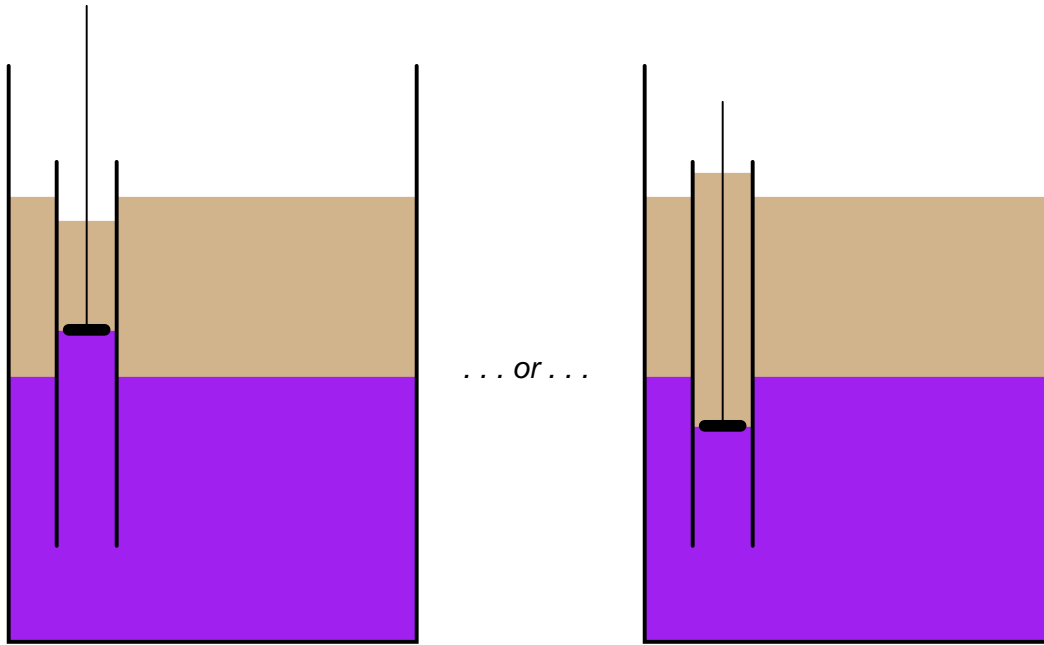
Challenge question: describe a simple way to modify the stilling well pipe so that it does not have to be fully submerged to avoid these false interface measurement problems.

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Answer 73

As boiler temperature increases, the water density decreases. For saturated steam conditions (i.e. water and steam in direct contact with each other in the same vessel), pressure and temperature are directly related. So, as temperature in the steam drum increases, pressure must also. This increase in pressure causes the steam to become denser as the steam molecules become packed closer together.

Just to give you an example of how significant these density changes are at high pressure (e.g. power generation boilers), consider the following values:

- Boiling (saturated) water density at 2,425 PSIG = 35.49 lb/ft$^3$
- Saturated steam density at 2,425 PSIG = 7.33 lb/ft$^3$
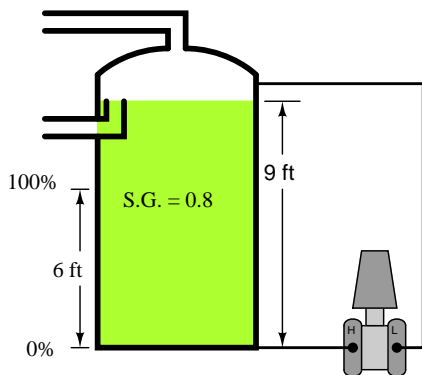
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Answer 74

$$P_{high} = \textbf{72.487} \text{ PSIG} \qquad\qquad P_{low} = \textbf{68} \text{ PSIG}$$
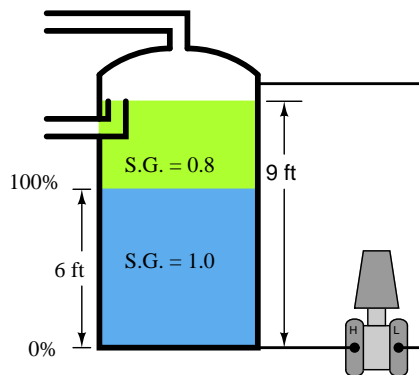
$$\Delta P = \textbf{4.487} \text{ PSID}$$

Answer 75

Here are the two "thought experiment" scenarios pictured to arrive at the LRV and URV pressure values:



$P_{LRV} = (9 \text{ ft})(12 \text{ in/ft})(0.8) = 86.4 \text{ "WC}$

$P_{URV} = (6 \text{ ft})(12 \text{ in/ft})(1.0) + (3 \text{ ft})(12 \text{ in/ft})(0.8) = 100.8 \text{ "WC}$

| Interface level (ft) | Percent of span (%) | $\Delta$ pressure sensed ("W.C) | Output signal ideal (PSI) | Output signal min. (PSI) | Output signal max. (PSI) |
|---|---|---|---|---|---|
| 0 | 0 | 86.4 | 3 | 2.97 | 3.03 |
| 0.6 | 10 | 87.84 | 4.2 | 4.17 | 4.23 |
| 1.5 | 25 | 90.0 | 6 | 5.97 | 6.03 |
| 3 | 50 | 93.6 | 9 | 8.97 | 9.03 |
| 4.5 | 75 | 97.2 | 12 | 11.97 | 12.03 |
| 5.4 | 90 | 99.36 | 13.8 | 13.77 | 13.83 |
| 6 | 100 | 100.8 | 15 | 14.97 | 15.03 |

Answer 76

Answer 77

The "Top" transmitter's indication of 0 inches water column tells us that the vessel is vented, or at least there is no vapor pressure buildup in it. This makes the task of determining level and density from the other two pressure measurements that much easier.

Determining specific gravity would be the best step to do first, before trying to determine liquid level. Once the liquid's density is known, its level may be easily calculated from the "Bottom" transmitter's pressure measurement.

With 10 feet of vertical distance separating the "Bottom" and "Middle" transmitters, there should be 120 inches (10 feet × 12 inches/foot) of water column pressure *difference* between the two transmitters' measurements if the liquid in question had a specific gravity equal to 1, like water. In this case, though, there is a pressure difference of only 110.4 inches between the two measurements:

(276 "W.C.) - (165.6 "W.C.) = 110.4 "W.C.

The discrepancy between 120 inches water column and 110.4 inches water column is due to one factor and one factor only: the liquid's density. We may find the density by dividing the actual pressure difference by the expected pressure difference assuming a density equal to water:

Specific gravity = (110.4 "W.C. / 120 "W.C.) = 0.92

Therefore, the liquid held in this vessel has a specific gravity of 0.92, meaning that its density is 92% that of water. Knowing the liquid density, we calculate the liquid level by re-working the liquid column pressure equation to solve for height:

$$P = hG$$

$$\frac{P}{G} = h$$

Where,
$P$ = hydrostatic pressure in inches water column
$h$ = liquid column height in inches
$G$ = specific gravity of liquid

(276 "W.C.)/(0.92 "W.C. / in) = 300 inches

So, the answer for liquid level is 300 inches, or 25 feet.

Answer 78

| Process level (in) | Percent of span (%) | Differential pressure ("W.C.) | Output signal ideal (PSI) | Output signal min. (PSI) | Output signal max. (PSI) |
|---|---|---|---|---|---|
| 0 | 0 | -64 | 6 | 5.88 | 6.12 |
| 12.5 | 25 | -51.5 | 12 | 11.88 | 12.12 |
| 25 | 50 | -39 | 18 | 17.88 | 18.12 |
| 37.5 | 75 | -26.5 | 24 | 23.88 | 24.12 |
| 50 | 100 | -14 | 30 | 29.88 | 30.12 |

Answer 79

**Partial answer:**

| Interface level (in) | Percent of span (%) | Δ pressure sensed ("W.C) | Output signal ideal (mA) | Output signal min. (mA) | Output signal max. (mA) |
|---|---|---|---|---|---|
| 0 | 0 | 28.83 | | 3.84 | |
| | 10 | | 5.6 | | 5.76 |
| 2.75 | 25 | 29.71 | | 7.84 | |
| | 50 | | 12 | | 12.16 |
| | 75 | 31.48 | | 15.84 | |
| 9.9 | 90 | | 18.4 | | 18.56 |
| | 100 | | 20 | 19.84 | |

---

Answer 80

When the vessel is holding clean water, the transmitter output will be 4 mA.

When the vessel is holding carbon tetrachloride, the transmitter output will be 13.52 mA.

LRV = 1.0 ; URV = 2.0 (specific gravity)

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Answer 81

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

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Answer 82

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

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Answer 83

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

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Answer 84

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

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Answer 85

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

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Answer 86

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

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Answer 87

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

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Answer 88

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

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Answer 89

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

Answer 90

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

Answer 91

Answer 92

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