



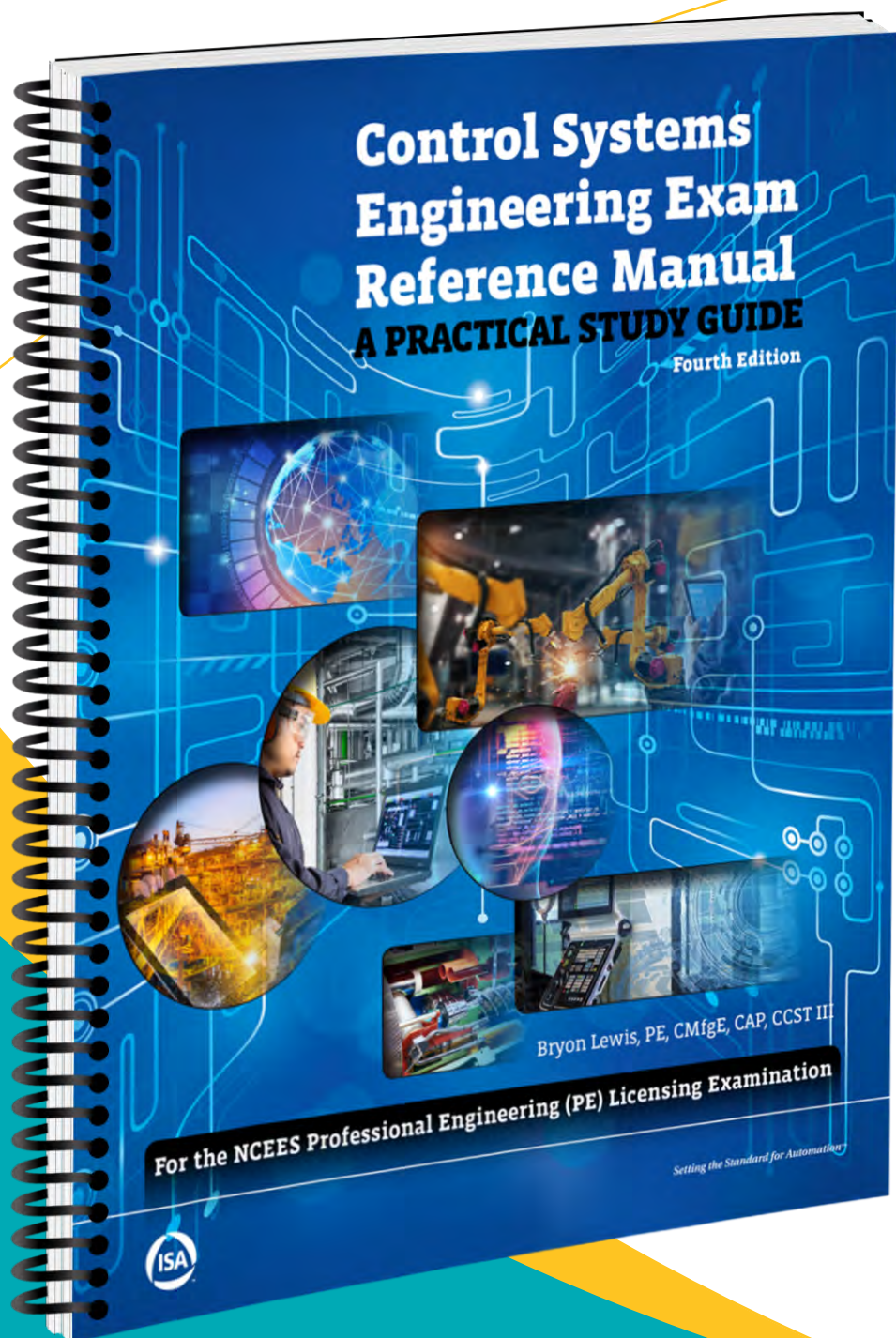
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Control Systems Engineering Exam Reference Manual

A Practical Study Guide

Fourth Edition

For the NCEES Professional
Engineering (PE) Licensing Examination

Bryon Lewis, PE (CSE), CAP, CCST III

Controls engineering encompasses a broad range of industries: power, paper and pulp, pharmaceuticals, manufacturing, water treatment, and chemical plants. Although this fourth edition addresses many different applications used by all these industries, it focuses on petrochemical applications.

The National Council of Examiners for Engineering and Surveying (NCEES) Professional Engineer (PE)/Control Systems Engineer (CSE) exam tends to be concentrated toward chemical and pharmaceutical plant design applications of code and control systems. The purpose of this book is to introduce new engineers to the depth of knowledge they will need to tackle the NCEES PE/CSE exam.



This is an excerpt from the book. Pages are omitted.

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Introduction to This Study Guide

This manual helps prepare the Professional Engineer (PE) candidate for the NCEES Practice of Engineering exam in the PE discipline option of control systems engineering (CSE). The CSE exam covers a broad range of subjects from the electrical, mechanical, and chemical engineering disciplines. This exam is not on systems theory, but on sound judgment of the application of process control systems and applicable codes. Basic process control systems (BPCSs) and safety instrumented systems (SISs) are presented in detail. Experience in engineering or designing process control systems is a necessity to pass this discipline of the NCEES Principles and Practice of Engineering exam.

Studying this manual and other reference materials recommended within it should adequately prepare the experienced engineer or designer to take the CSE exam. This manual presents many practical problems that may be presented on the CSE exam, with explanations and worked solutions. State and federal codes needed for the exam are reviewed, and standard documentation and design practices are demonstrated for the design of real-world plant control systems.

Most state licensing boards in the United States recognize the CSE exam; however, some states do not offer it. Check with your state licensing board to determine if it offers the CSE exam. If you live in a states that does not offer the CSE exam, you may choose to pursue licensing in another discipline (e.g., electrical, mechanical, or chemical engineering). You may also try to arrange to take the CSE exam in a neighboring state. More details about the exam content, application process, and study materials are presented later in this manual.

About the Author

Professional Engineer (PE)—Control Systems Engineering
Certified Manufacturing Engineer (CMfgE)—Integration and Control
Certified Automation Professional (CAP)
Certified Control System Technician Level III (CCST)
Certified Electronics Technician (CET)—Industrial Electronics
State of Texas Master Electrician



email: bryon.lewis@integrated.cc
profile: <http://www.linkedin.com/in/bryonlewis>



Bryon Lewis is a licensed PE in control systems engineering (CSE). He is a senior member of ISA and has held senior membership with SME. Lewis has over 30 years of experience in electrical, mechanical, instrumentation, and control systems. He holds letters of recommendation from Belcan Engineering, S & B Engineers and Constructors, Enron Corporation, and Lee College. Lewis' experience in diversified engineering and competitive projects is as follows:

- 12 years of engineering and design experience using AutoCAD 9 through 2014
- 16 years of field experience including start-up and troubleshooting and calibration of instruments
- Projects consist of compressor stations, and petrochemical and food process plants
- Turbine and compressor control systems, material handling systems, and burner management systems
- Development of P&IDs, MFDs, electrical power distribution systems, and control diagrams
- Engineering and implementation of Foxboro I/A and Honeywell DCS systems and security
- Network support including servers, workstations, routers, switches, and cabling
- Allen-Bradley automation and programmable logic controller (PLC) programming for the Allen-Bradley family of processors

Lewis has participated in projects for clients such as Shell Oil, Exxon, Diamond Shamrock, Eli Lilly Pharmaceuticals, Procter and Gamble (fault analysis), JVC America (solvent recovery project), Keebler Corporation, Mission Foods, Enron Transportation and Storage. He also worked at the Comanche Peak Steam Nuclear Station in 1987 and the powerhouse addition and computer grounding at the Johnson Space Center in 1985. If there are any questions, please contact Bryon Lewis at his email address.

1 Welcome to Control Systems Engineering

Licensing as Professional Engineer/Control Systems Engineer

A Professional Engineer (PE) license must be obtained to perform engineering work for the public and private sectors in the United States and most countries in the world. To protect the health, safety, and welfare of the public, the first engineering licensure law was enacted in 1907 in Wyoming. Now every state regulates the practice of engineering to ensure public safety by granting only Professional Engineers the authority to sign and seal engineering plans and offer their services to the public. *Individuals who do not have a PE license cannot use the title of engineer to advertise for engineering work.*

A control systems engineer (CSE) takes on responsibilities beyond those of most other disciplines of professional engineering. If a pump quits working, there is no water. If an electrical panelboard fails, there is no power. In plant control systems, a failure can mean absolute disaster. Without proper attention to these failures, the plant can explode, resulting in fatalities. The failure of systems can mean the loss of hundreds of thousands of dollars, and loss of product and production can cost millions of dollars. There may also be class action and environmental lawsuits into the billions of dollars.

This is why I have taken a complete plant design approach to show the vast exposure and experience needed to be a CSE. Just like the saying in the *Spiderman* movie, "With great power comes great responsibility." The CSE's job cannot be taken lightly. People's lives depend on CSEs knowing what they are doing and getting it right the first time. You cannot guess at control systems engineering. *You must know. Being a PE does not just mean answering a minimum number of questions on an 8-hour exam.*

The CSE cannot just say "the bottle is in place, now fill it." The CSE must ask questions such as:

1. Is the bottle in place?
2. Is the valve open?
3. Is fluid available to fill the bottle in the tank?
4. Is the pump running?
5. Is the fluid flowing?
6. Did the bottle fill?

7. Did the valve close?
8. Did the fluid stop flowing?
9. Did the pump stop?
10. Did something fail?

The CSE must be ready to handle abnormal conditions and upsets at any time. This will be a major part of the programming and a large part of the instrumentation, with increasing concern for safety and compliance with government regulations now requiring safety instrumented systems (SISs) to be installed.

Explosions can occur in petrochemical and other similar hazardous plants, even though the electrical and process systems are designed to be explosion-proof per National Fire Protection Association (NFPA), American National Standards Institute (ANSI)/International Society of Automation (ISA), American Petroleum Institute (API), Occupational Safety and Health Administration (OSHA), International Electrotechnical Commission (IEC), and other codes.

Why Become a Professional Engineer?

Being licensed as a PE is an important distinction that can enhance one's career options. Many engineering jobs require that a person have a PE license to work as an engineering consultant or senior engineer, testify as an expert witness, conduct patent work, work in public safety, or advertise to provide engineering services. Although you may never need to be registered for "legal" reasons, you may find that you must be a PE to be eligible for engineering management positions.

On average, a PE makes significantly more money than an unlicensed engineer. Even if your first job does not require a PE license, you may need a license later in your career. In today's economic environment, it pays to be in a position to move to new jobs and compete with others who have a PE license or are on a professional engineering track. It is also highly unlikely that a job requiring a PE license will be outsourced overseas.

The following excerpt is from the NCEES website.

What makes a PE different from an engineer?

- Only a licensed engineer may prepare, sign and seal, and submit engineering plans and drawings to a public authority for approval, or seal engineering work for public and private clients.
- PEs shoulder the responsibility for not only their work, but also for the lives affected by that work and must hold themselves to high ethical standards of practice.
- Licensure for a consulting engineer or a private practitioner is not something that is merely desirable; it is a legal requirement for those who are in responsible charge of work, be they principals or employees.

2 Exam General Information

State Licensing Requirements

Licensing of engineers is intended to protect the public health, safety, and welfare. State licensing boards have established requirements to be met by applicants for licenses that will, in their judgment, achieve this objective.

Licensing requirements vary somewhat from state to state but have some common features. In all states, candidates with a 4-year engineering degree from an Accreditation Board for Engineering and Technology (ABET)/Engineering Accreditation Commission (EAC) accredited program and 4 years of acceptable experience can be licensed if they pass the Fundamentals of Engineering (FE) exam and the Principles and Practice of Engineering exam in a specific discipline. References must be supplied to document the duration and nature of the applicant's work experience.

Eligibility

Some state licensing boards will accept candidates with engineering technology degrees, related-science (such as physics or chemistry) degrees, or no degree, with indication of an increasing amount of work experience. Some states will allow waivers of one or both exams (FE and PE) for applicants with many years (6–20) of experience. Additional procedures are available for special cases, such as applicants with degrees or licenses from other countries. Most states have abandoned the no-degree statute and will only accept as minimal, an accredited associate degree.

Note: Recipients of waivers may encounter difficulty in becoming licensed by “reciprocity” or “comity” in another state where waivers are not available. Therefore, applicants are advised to complete an ABET accredited degree and to take and pass the FE/Engineer in Training (EIT) exam. Some states require a minimum of 4 years of experience after passing the FE/EIT exam before allowing a candidate to sit for the PE (principles and practices) exam. Some states will not accept experience incurred before passing the FE/EIT exam as qualifying experience.

It is necessary to contact your licensing board for the up-to-date requirements of your state. Phone numbers and addresses can be obtained by calling the information operator in your state capital, or by checking the Internet at www.ncees.org or nspe.org.

Exam Schedule

The CSE exam is offered once per year, on the last weekend in October (typically on Friday). Application deadlines vary from state to state, but typically are about 3 or 4 months ahead of the exam date.

Requirements and fees vary among state jurisdictions. Enough time must be allotted to complete the application process and assemble the required data. PE references may take a month or more to be returned. The state board needs time to verify professional work history, references, and academic transcripts or other proof of the applicant's engineering education.

After accepting an applicant to take one of the exams, the state licensing board will notify him or her where and when to appear for the exam. The board will also describe any unique state requirements, such as allowed calculator models or limits on the number of reference books taken to the exam site.

Description of Exam

Exam Format

The NCEES Principles and Practice of Engineering exam (commonly called the *PE exam*) in control systems engineering (CSE) is an 8-hour, open-book exam administered in a 4-hour morning session and a 4-hour afternoon session. Each session contains 40 questions in a multiple-choice format.

Each question has a correct or “best” answer. Questions are independent, so an answer to one question has no bearing on the following questions.

All the questions are compulsory; applicants should try to answer all the questions. Each correct answer receives one point. If a question is omitted or the answer is incorrect, a score of zero will be given for that question. There is no penalty for guessing.

Exam Content – The NCEES 2019 Specifications

The subject areas of the CSE exam are described by the exam specification and are given in five areas. ISA supports CSE licensing and the exam for professional engineering. ISA is responsible for the content and questions in the NCEES exam. Refer to the ISA website (<http://www.isa.org>) for the latest information concerning the CSE exam.

For a copy of the latest PE/CSE exam format and content, visit NCEES at: <http://www.ncees.org>.

The following is an overview of the categories and content that might be included the exam. The NCEES website has the latest information on the exam, as the format and specifications change over the years.

I. Measurement – 20 Questions

- Sensors – 10 Questions
 - Sensor technologies applicable to general measurement (e.g., flow, pressure, level, temperature, counters, and motion)
 - Sensor technologies applicable to general analytical instruments and sampling systems (e.g., pH, ORP, density, O₂, conductivity, effects of sampling systems, and GC)
 - Grounding, shielding, segregation, and alternating current (AC) coupling
 - Sensor technologies applicable to fire and gas detection
 - Sensor technologies applicable to machinery monitoring and protection (e.g., vibration, bearing temperature, lube oil pressures, thrust, and speed)
 - Sensor characteristics (e.g., rangeability, accuracy and precision, temperature effects, response times, reliability, repeatability, maintenance, and calibration)
 - Sensor selection (e.g., plugging service, process severity, environmental effects and constraints, and costs)
 - Material compatibility
 - Installation details (e.g., process, pneumatic, electrical, location, maintenance, and calibration)
- Flow, Level, and Pressure Calculations – 8 Questions
 - Flow (e.g., element sizing, pressure-temperature compensation, and mass/volume)
 - Level
 - Pressure drop
- General Calculations – 2 Questions
 - Unit conversions
 - Velocity
 - Square root extraction and interpolation
 - Variables involved in wake frequency calculations (e.g., thermowell length/diameter, velocity, natural frequency, and wake frequency)

II. Control Systems – 20 Questions

- Drawings – 3 Questions
 - Drawings (e.g., process flow diagrams, piping and instrumentation diagrams— P&IDs, loop diagrams, Ladder Diagrams, logic drawings, cause-and-effects drawings, electrical drawings, schematics, and wiring diagrams)

3 Reference Materials for the Exam

Recommended Books and Materials to Take to the Exam

I have included a review of all subject material that is in the NCEES PE/CSE exam specifications and almost any data you may need to look up for questions on the exam.

The list of recommended books and materials for testing is provided to help you pass the CSE exam. Use the materials with which you are most comfortable. A substitution with the same material and information may be used.

The list of recommended books and materials for additional study can be helpful in the review of subjects and preparation for the exam. See the International Society of Automation (ISA) website (www.isa.org) for more books that may give you knowledge and deeper insight into various subjects in instrumentation and control systems.

Remember to keep the review simple. The test is not focused on control systems theory studies, but rather on general functional design. Again, keep your studies simple and practical; control systems theory will encompass only about 3% of the exam.


National Council of
Examiners for
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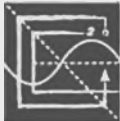
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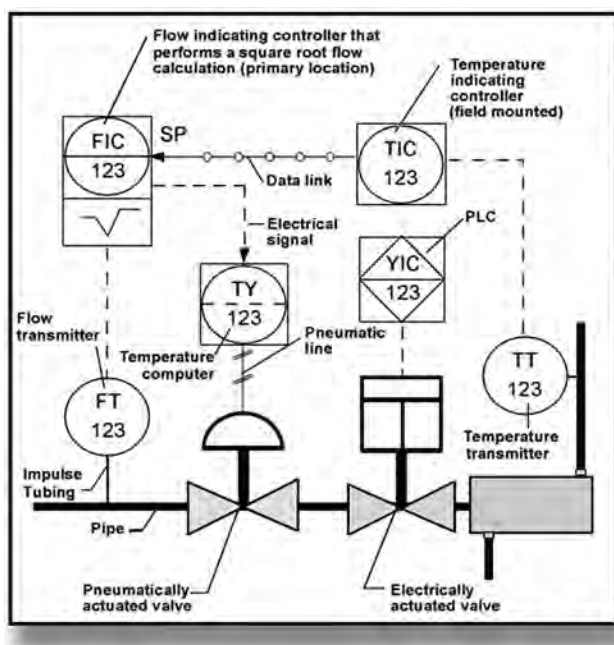
4 Measurement Standards and Terminology

Overview of Process Measurement, Control, and Calibration

The process control industry covers a wide variety of applications: petrochemical, pharmaceutical, pulp and paper, food processing, material handling, and even commercial applications. Experience designing process control systems is almost a necessity to pass the CSE PE exam.

Process control in a plant can include discrete logic, such as relay logic or a programmable logic controller (PLC); analog control, such as single-loop control or a distributed control system (DCS); and pneumatic, hydraulic, and electrical systems. The CSE must be versatile and have a broad range of understanding of the engineering sciences. The CSE is typically referred to as *instrumentation and electrical* (I&E), though the CSE must have in-depth knowledge of mechanical and process systems.

The CSE exam encompasses a broad range of subjects to ensure minimum competency. This book will review the foundations of process control and demonstrate the breadth and width of the CSE exam. It will then review the basic process control elements and their theory of operation, and then apply the elements to real-world applications. Next, this book reviews the calculations for sizing the elements, as well as the applicable laws, standards, and codes governing the installation of a process control system.



Process Signal and Calibration Terminology

The most important terms in process measurement and calibration are *range*, *span*, *zero*, *accuracy*, and *repeatability*. Let us start by first defining *span*, *range*, *lower range value* (LRV), *upper range value* (URV), *zero*, *elevated zero*, and *suppressed zero*.

Definition of the Range of an Instrument

The range is the region in which a quantity can be measured, received, or transmitted, by an element, controller, or final control device. The range can usually be adjusted and is expressed by stating the lower and upper range values.

Note 1: For example:

	Full Range	Adjusted Range	LRV	URV
a)	0 to 150°F	None	0°F	150°F
b)	−20 to 200°F	−10 to +180°F	−10°F	+180°F
c)	20 to 150°C	50 to 100°C	50°C	100°C

Note 2: Unless otherwise modified, input range is implied.

Note 3: The following compound terms are used with suitable modifications in the units: *measured variable range*, *measured signal range*, *indicating scale range*, *chart scale range*, etc. See Tables 4-1 and 4-2.

Note 4: For multirange devices, this definition applies to the particular range that the device is set to measure.

- **LRV** – The lowest value of the measured variable that a device is adjusted to measure
- **URV** – The highest value of the measured variable that a device is adjusted to measure

Note 5: The following compound terms are used with suitable modifications to the units: *measured variable lower range-limit*, *measured signal lower range-limit*, etc. See Tables 4-1 and 4-2.

Note 6: The following compound terms are used with suitable modifications to the units: *measured variable upper range-limit*, *measured signal upper range-limit*, etc. See Tables 4-1 and 4-2.

Definition of the Span of an Instrument

The span is the algebraic difference between the URVs and LRVs.



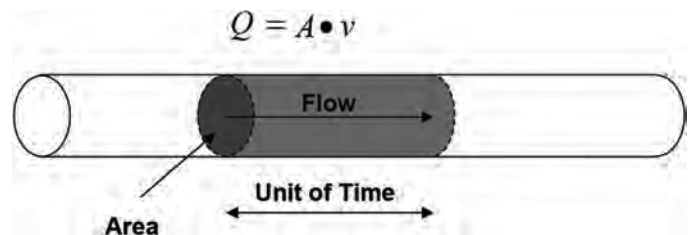
This is an excerpt from the book. Pages are omitted.

5 Fluid Mechanics in Process Control

Relationship of Pressure and Flow

In a pipe, the static pressure distributed across the pipe is even during no flow or deadheaded with pump. The pressure at both ends of the pipe is the same because the total energy in the system is at equilibrium. As the fluid flows, it is accelerated through the pipe. There is a pressure drop across the pipe. The static pressure is a measurement of the potential energy in the fluid. It is changed to the form of kinetic energy and is used up in the form of heat and vibration doing work on the pipe to overcome the friction of the pipe.

The higher the flow rate, the greater the pressure drop across the pipe. The work done to transfer the fluid through the pipe at higher flow rates becomes greater. Therefore, the pressure drop across the pipe increases as the velocity of the fluid increases through the pipe. The static pressure (available pressure) at the end of the pipe will be lower than the supply or pump pressure at the start of the pipe because work is being done on the pipe. The pump head energy is used up doing work on the pipe.



The DP measurement across the flow element acts a bit differently. Flow is measured in the units of DP (differential pressure). There is a pressure drop across the orifice element, and there will be additional pressure drop across the element as the flow rate (the fluid's velocity) increases. This is the same thing that is happening in the pipe, because more work is being done on the element as the velocity increases. However, remember that the pressure on the downstream side of the flow element drops as the velocity increases. How does the pressure for the flow measurement increase? It does not; there is an increase in DP , not in the static pressure.

We are measuring the DP across the element, and this is an inferred measurement of flow rate. Flow rate equals the velocity (distance per time) multiplied by the area of the pipe. We achieve the measurement of velocity using differential pressure. The difference between the upstream pressure and the downstream pressure across the element is a measurement of the difference in height in two different water columns. This difference in height is a direct proportional measurement of the velocity of the fluid flowing through the pipe.

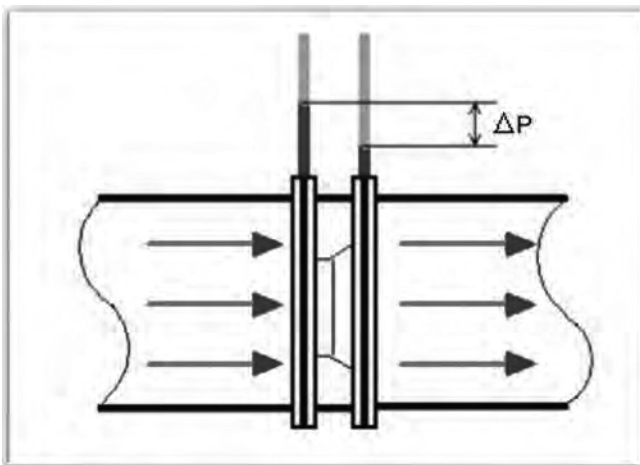
The pump endows potential energy into the fluid and accelerates the fluid upward into a measurable column of water. The water column is typically measured in feet of head pressure but can be measured in pounds per square inch (psi). The water is constantly “falling” down the pipe toward the other end of the pipe, and the pump must constantly accelerate the water upward against the pull of gravity to keep the water column up in the air. The potential energy endowed into the water column turns into kinetic energy as the water column falls.

The kinetic energy is used to overcome the resistance of the pipe and the work done on the pipe as the fluid flows to the other end. If there is energy left over in the fluid, it is again transformed into potential energy at the other end of the pipe, as an available pressure at the end of the pipe. This potential energy left over can now fall through a pipe, device, or piece of equipment and do work, finally resting at a state of equilibrium. At this point, all the energy endowed into the fluid by the pump will be used up.

Note: The image at the right shows that the pump must develop enough head to raise the fluid to the pipe’s top elevation plus enough head to overcome the friction loss of the piping (suction and discharge). We will also need to add head for any differential pressure across the valve and the orifice or head type meter.

The velocity of the fluid is measured as the fluid falls: $V^2 = 2gH$, where H is the height in feet (the head). The volumetric flow rate can then be an inferred measurement of the height of the water column. By knowing the size of the pipe, the coefficient of the orifice, and the properties of the fluid, we can accurately measure the volumetric flow rate of the fluid.

As the fluid flows through the opening of the orifice restriction, kinetic energy is transformed into potential energy in the form of a difference of water column on each side of the restriction orifice element. The height of the water column is the “scaled” velocity of the fluid through the pipe. Remember that the slower the fluid travels, the less work it has to do. The fluid has to accelerate through the small opening in the orifice to maintain the same mass flow rate through the pipe. Mass in must equal mass out.



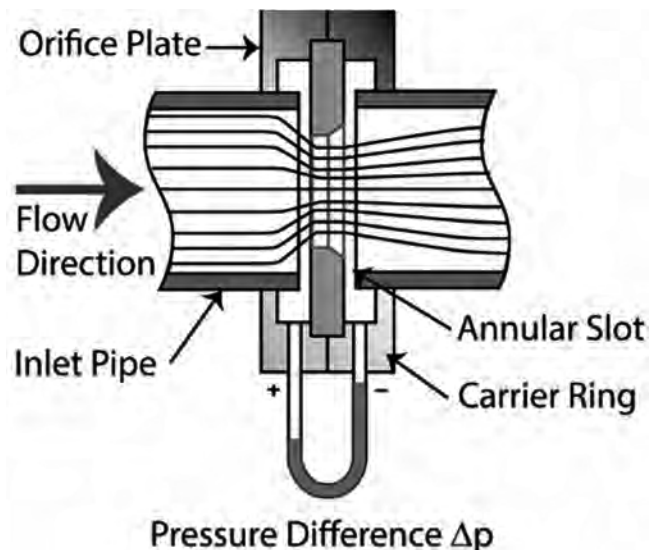
Energy is lost doing work on the orifice plate, and the pressure drops on the exit side of the orifice. This can be seen in the profile of the vena contracta of the fluid flowing and the DP across the orifice element. As the fluid exits the small opening into the much larger area of the pipe, the fluid decelerates and a portion of the kinetic energy endowed into the fluid by the pump is transformed back into potential energy. This potential energy can be seen in the form of a water column, of varying height, on the entry and exit sides of the orifice.

If the pipe were blocked at the exit end, the water would squirt out the taps on both sides of the orifice and the two water columns of equal height would become obvious. Again, as the fluid starts to accelerate through the pipe and through the orifice, the fluid's potential energy tends to change back into kinetic energy to do work. This means the water columns start to fall on both side of the orifice. The exit side will fall even more than the entrance side, because work is done on the orifice restriction element as the flow rate increases. The difference in height the column falls on the exit side compared to the upstream column is its scaled velocity of the flow rate. The higher the fluid's velocity, the more work is done on the orifice and the pressure drops even more on the exit side of the orifice. This gives a greater DP across the orifice. Note that as the pressure drops in the pipe due to increased velocity, the DP at the measurement meter becomes greater. This is because the total system pressure (total hydraulic head) is decreasing by doing work on the pipe, and the potential energy (pressure head) is being transformed back to kinetic energy (velocity head) to do the work.

The lower the fluid's velocity through the orifice, the higher the pressure on the exit side of the orifice. This means there is less difference between the pressure on the high side (entry side) water column and the low side pressure (exit side) water column. Therefore, there is less measured DP across the orifice when the fluid decelerates, even though the pressure increased on the exit side of the orifice and everywhere in the pipe system.

Note that as the fluid flow approaches a stop, the two water columns are almost even in height. The DP becomes almost nothing. The static pressure on the exit side of the orifice, which represents the potential energy in the fluid, becomes greater. The pipe system will try to reach equilibrium or uniform distribution of static pressure across the pipe system as the work across the pipe becomes less and less. The kinetic energy will change back into potential energy.

Remember that the total energy in the system equals the kinetic + potential + work done. As the fluid starts to accelerate down the pipe once again, the exit side water column starts to drop in height. The potential energy (pressure head) is once again being transformed back into kinetic energy (velocity head), to do work across the element and pipe. The distance in height the exit side water column falls compared to the height of the entry side water column is the *scaled* velocity of the flowing fluid.



Because we know the fluid's specific gravity (SG), we can now calculate the fluid's height as if it were a column of water. Remember ($F = m \cdot a$) and weight is a measure of the force exerted by the pull of gravity. Pressure equals (density • height) and force equals (pressure • area); therefore, the pressure measurement is a representation of the fluid's height.

6 Temperature Measurement and Calibration

Temperature Measurement Devices and Calibration

In the process industry, temperature measurements are typically made with thermocouples, resistance temperature detectors (RTDs), and industrial thermometers. Industrial thermometers are typically liquid (class I), vapor (class II), or gas (class III).

Standard Thermocouple Configurations

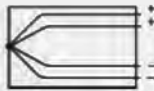
Single Grounded



Single Ungrounded



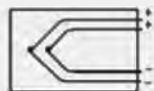
Dual Grounded Unisolated



Dual Ungrounded Unisolated



Dual Ungrounded Isolated



There are five major types of thermocouple configurations used in plants. They are shown to the left.

The first two thermocouples are welded or grounded, as shown, to the outside metal protective sheathing.

The last three thermocouples are ungrounded and should never touch the metal protective sheathing; otherwise, they are shorted to ground.

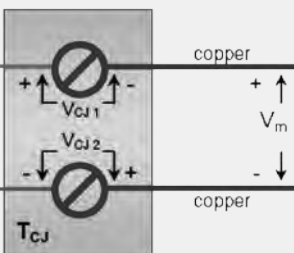
Thermocouple terminal junction blocks should be made of the same material as the thermocouple wire that is being connected to the terminal. This will prevent additional thermocouple junction points from being introduced into the temperature signal. Some companies use standard terminal strips, but they can cause an error in the signal.

Cold Junction Compensation in Thermocouple Temperature Measurements

Point of Measurement (Hot Junction)



Reference (Cold Junction)



$$V_m = V_{TC} - (V_{CJ1} + V_{CJ2}) = V_{TC} - V_{CJ}$$

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Thermocouple junctions are formed when connecting to the wire ends together or to a terminal block, so the total potential measured depends on the temperatures of those junctions as well as the junction at the measurement end of the thermocouple. Thermocouple voltages are relative values that must be measured with respect to a junction at a known temperature, called the *cold junction* or *reference junction*. Temperature should be measured with the cold junction at 0°C or 32°F.

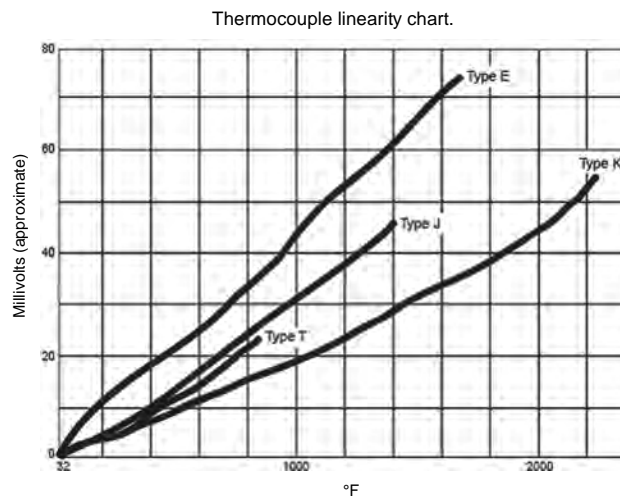
The connection diagram to the left shows a thermocouple used to measure the temperature at its hot junction. The cold junction (CJ) is connected to the wires that connect to the meter leads.



Thermocouple Extension Wiring

Thermocouples *should* be extended with thermocouple extension wire and thermocouple termination blocks, but can be extended with standard copper wire and standard terminal blocks if some error is acceptable. With all thermocouples, one side is positive (the color: yellow, white, purple, etc.) and the other side is negative (always red, except in some extension wires).

Thermocouple millivolt tables for the examination can be found in Table A1, “Thermocouple Table” (Type J), Table A2, “Thermocouple Table” (Type K), Table A3, “Thermocouple Table” (Type E), and Table A4, “Thermocouple Table” (Type T), in the Appendix, “Data Tables.”



Thermocouple makeup material and color code.

Thermocouple Type	Thermocouple Material	Range for Calibration °F	Useful Range °F	Thermocouple Colors
E	Chromel (+) Constantan (–)	–300 to 1830	200 to 1650	Purple Wire Jacket Purple (+) Red (–)
J	Iron (+) Constantan (–)	–320 to 1400	200 to 1400 (300 to 800)	Black Wire Jacket Black (+) Red (–)
K	Chromel (+) Alumel (–)	–310 to 2500	200 to 2300	Yellow Wire Jacket Yellow (+) Red (–)
R	Platinum 13% Rhodium (+) Platinum (–)	0 to 3100	1600 to 2640	Green Wire Jacket Black (+) Red (–)
S	Platinum 10% Rhodium (+) Platinum (–)	0 to 3200	1800 to 2640	Green Wire Jacket Black (+) Red (–)
T	Copper (+) Constantan (–)	–300 to 750	–310 to 660	Blue Wire Jacket Blue (+) Red (–)

Thermocouple — Worked Examples (How to Read the Thermocouple Tables)

Sample Problem: What is the millivolt (mV) output of a Type J thermocouple at 218°F and referenced to a 32°F electronic ice bath?

Find the nearest temperature in Table A1, “Thermocouple Table” (Type J), in the Appendix of this guide.

The nearest temperature in the first column is 210. Look at the column headers at the bottom of the chart. Find the column header labeled 8. Follow the column up to the row with the 210 value. Where they meet is a total of 210°F + 8°F = 218°F.

Read the value of mV. The answer is 5.45 mV.

Sample Problem: What is the millivolt (mV) output of a type K thermocouple at 672°F from the data given? Assume the thermocouple is linear.

Given:

$$670^{\circ}\text{F} = 14.479 \text{ mV}$$

$$672^{\circ}\text{F} = \text{mV}$$

$$680^{\circ}\text{F} = 14.713 \text{ mV}$$

Interpolate the mV value for the desired temperature as follows:

Interpolation:

$$\text{output mV} = \left[\left(\frac{\text{deg desired} - \text{deg lower value}}{\text{deg upper value} - \text{deg lower value}} \right) (\text{mV upper value} - \text{mV lower value}) \right] + \text{mV lower values}$$

Therefore, the output (mV) for 672°F:

$$14.526 = \left[\left(\frac{672 - 670}{680 - 670} \right) (14.713 - 14.479) \right] + 14.479$$

The output at 672°F is 14.526 mV.

This can be verified in Table A2, “Thermocouple Table” (Type K), in the Appendix.

Resistance Temperature Detector

The process control industry also uses RTDs for many applications, for example, when precise temperature measurement is needed, such as mass flow measurements or critical temperature measurements of motor bearings.

7 Pressure Measurement and Calibration

Pressure Measurement and Head Pressure

Pressure is typically measured in two different forms, pounds per square inch (psi) or head pressure. Head pressure is measured in inches or feet of water column (H_2O).

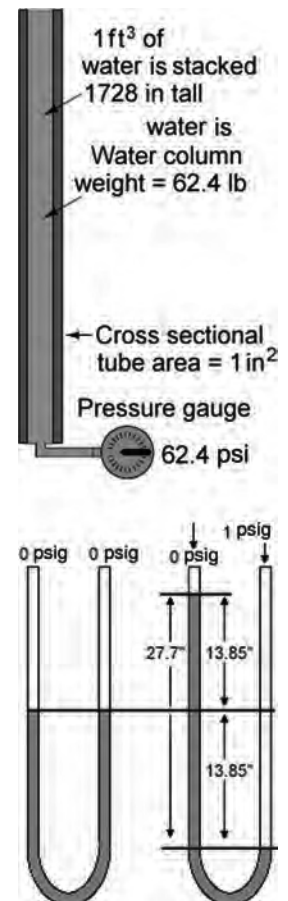
Head pressure is the measure of the potential energy or hydrostatic pressure in the system. Head pressure is independent of the tank's height or area. The transmitter measures head pressure. The transmitter measures the height from which the fluid is falling. The distance the fluid falls indicates the force generated ($F = ma$). The density of the fluid must be known to calibrate a pressure transmitter for a process, to obtain the fluid mass. The calibration process uses specific gravity (SG), the ratio of a known density of a fluid divided by the density of water (H_2O).

To illustrate these facts, we will start with 1 gal of water. The gallon of water equals 231 in³ and weighs approximately 8.334 lb at 60°F. Pressure is measured in psi. Only 1 in² of area is needed to calculate the height of the water and the force it is exerting. Remember that force divided by area equals pressure.

Divide the height of the column of water, 231 in, by the weight of 1 gal of water, 8.334 lb. The result will be 27.718 or 27.7 in of water per pound of water, over a 1 in² area. *Therefore, 27.7 in of H_2O equals 1 psi of head pressure, or 2.31 ft of H_2O equals 1 psi of head pressure.*

The SG of the fluid to be measured multiplied by the height of the tank in inches provides an equivalent value in inches of water. The transmitter can now be calibrated in inches of water, regardless of the fluid. If the tank's fluid has an SG equal to 0.8 and a height of 100 in, then the height in inches of H_2O will be:

$$(100 \text{ in of fluid} \cdot 0.8 \text{ SG} = 80 \text{ in of } H_2O)$$



Pressure transmitters are purchased in different sizes of measurement. They are in ranges of inches H₂O, psig (the *g* stands for *gauge pressure*), or psia (the *a* stands for *absolute pressure*). When the symbol psid (the *d* stands for *differential pressure*) is called for, a standard psig transmitter is used. Most industrial pressure transmitters are differential pressure transmitters. They act on differential forces applied to each side of the transmitter. The force is produced by the pressure in the system multiplied by the area of the diaphragm.



Applying Pressure Measurement and Signals – Worked Examples

Differential Pressure and Meter Calibration

Differential pressure or differential head pressure is used to calibrate transmitters for pressure, level, flow, and density measurements. The transmitter has a high side, marked with an *H*, and a low side, marked with an *L*. The low side will typically go to atmospheric pressure or to a fixed height wet-leg measurement. The high side will typically go to the tank, where the varying height of fluid is to be measured. When calibrating an instrument, remember: The low side is the negative scale, below zero, and the high side is the positive scale, above zero. The transmitter's sensor element is static in position or elevation, and therefore the transmitter itself is always equal to zero elevation. This will be discussed in detail in Chapter 8 on level measurement.

Transmitters can be purchased in ranges of 25 in H₂O, 250 in H₂O, 1000 in H₂O, 300 psi, and 2000 psi.

The formula for calibration is:

$$(\text{high side inches} \cdot \text{SG}) - (\text{low side inches} \cdot \text{SG}) = \text{lower or upper range value}$$

Note: The equation provides the lower range value (LRV) when the tank is empty or the pressure is at the minimum level and the upper range value (URV) when it is full or the pressure is at the maximum level.

Sample Problem: A pressure gauge is reading 25 psig. It is attached to a tank filled with a fluid. The bottom of the tank is 65 ft above the ground. The pressure gauge is 5 ft above the ground. The fluid has a specific gravity of 0.7. What is the level of the fluid in the tank?

First, convert the psig measurement to feet of head measurement.

$$25 \text{ psig} \cdot 2.31 \text{ ft per psi} = 57.75 \text{ ft of H}_2\text{O}$$

Next, find the elevation of the bottom of the tank in relation to the elevation of the pressure gauge. Tank bottom in feet – pressure gauge elevation in feet = the height in feet to the bottom of the tank

$$65 \text{ ft} - 5 \text{ ft} = 60 \text{ ft of head to the bottom of the tank}$$

Note: Head is always measured in the standard of inches or feet of water column (wc).

Multiply the head between the bottom of the tank and the pressure gauge times the SG to get the head equal to H₂O.

$$60 \text{ ft of fluid} \cdot 0.7 \text{ SG} = 42 \text{ ft H}_2\text{O to bottom of tank from the pressure gauge}$$

Next, subtract the height from the pressure gauge to the bottom of the tank in feet of H₂O from the total height of fluid in feet of in H₂O above the pressure gauge to find the height of the fluid in the tank in H₂O.

$$(57.75 \text{ ft of H}_2\text{O total head}) - (42 \text{ ft of H}_2\text{O below the tank}) = \text{feet of fluid in H}_2\text{O in the tank}$$

$$(57.75 \text{ ft total}) - (42 \text{ ft to bottom tank from the pressure gauge}) = 15.75 \text{ ft in H}_2\text{O in the tank}$$

Next, convert height in feet of H₂O to height of fluid with an SG of 0.7.

$$15.75 \text{ ft of H}_2\text{O} / 0.7 \text{ SG} = 22.5 \text{ ft of total height of the fluid column in the tank}$$

Pressure Change in a Pipe for a Given Flow Rate

On the CSE exam, you will be asked to correlate signals and measurements using flow, pressure and the output in 4–20 mA signals. A change in flow in a pipe will cause a change in the head pressure across the pipe and measurement element. If the flow decreases in the pipe, the pressure in the pipe will increase at any point along the pipe.

If the flow rate increases, the pressure in the piping system decreases. If the flow rate decreases, the pressure in the piping system increases. This is because the total head of the system remains constant due to the head pressure developed by the pump. The total energy head being endowed into the pump and piping system remains constant. This is the case with a pump at a constant speed; two pressure gauges, one at each end of the pipe; and a hand valve at the end of the pipe.

$$h_1 F_1^2 = h_2 F_2^2 \qquad h_1 \left(\frac{F_1}{F_2} \right)^2 = h_2$$

8 Level Measurement and Calibration

Applying Level Measurement and Calibration – Worked Examples

TUNED SYSTEM



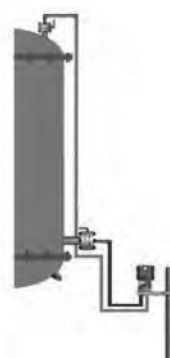
BALANCED SYSTEM



WET LEG



WET/DRY LEG



The Calibration Procedure

The level in a vessel or tank can be measured by many methods: differential pressure, displacement of volume, bubbler tube, capacitance, sonar, radar, and weight, to name a few. This book will focus on differential pressure, displacement of volume, and bubbler tube for the exam.

Remember: $(\text{high side inches} \cdot \text{SG}) - (\text{low side inches} \cdot \text{SG}) = \text{lower or upper range value}$

Example 1 – Open Tank

The low side of the transmitter is open to atmosphere. Atmospheric pressure is pushing on the low side. The high side of the transmitter is connected to the tank; it also has atmospheric pressure pushing on it. The atmospheric pressures on each side of the transmitter cancel out. In the example, the first line of math will be the lower range value (LRV) and the second line of math will be the upper range value (URV). The tank has 100 in of fluid with a specific gravity (SG) of 1.0. The calibrated *range* of the instrument will be 0–100 in of water or H₂O.

The *span* of the transmitter is: $100 \text{ in} \cdot 1.0 = 100 \text{ in}$



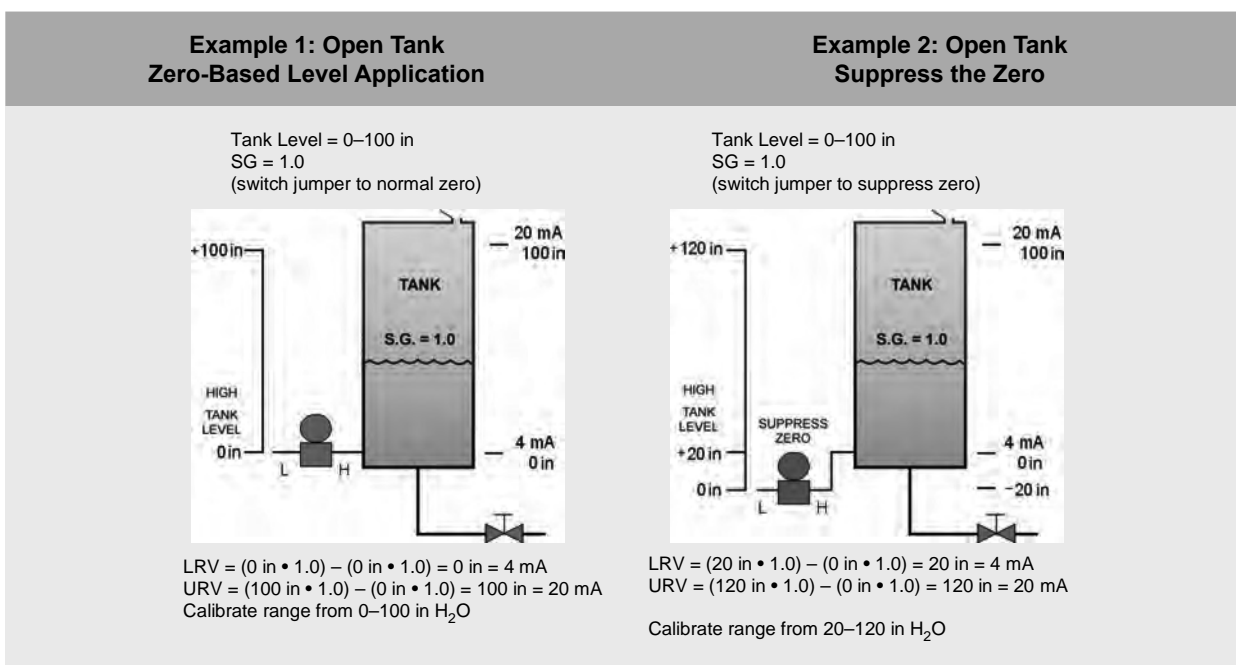


Example 2 – Open Tank, Suppress the Zero

The low side of the transmitter is open to the atmosphere. Atmospheric pressure is pushing on the low side. The high side of the transmitter is connected to the tank; it also has atmospheric pressure pushing on it. The atmospheric pressures on each side of the transmitter cancel out. In the example, the first line of math will be the LRV and the second line of math will be the URV.

The tank has a 100-inch level, and the tube dropping down below the tank adds 20 in of fluid height with an SG of 1.0. The calibrated range of the instrument will be 20–120 in of water or H₂O. Remember that the minimum measurement cannot be lower than the fixed tube height of 20 in. Suppress the zero with the hard wire jumper or set the variable in the transmitter and make 20 in a live zero for the instrument. In pneumatic instruments, a suppression kit must be installed.

The *span* of the transmitter is: $100 \text{ in} \cdot 1.0 = 100 \text{ in}$



Example 3 – Closed Tank, Elevate the Zero

The low side is connected to the top of the closed tank. The high side is connected to the bottom of the closed tank. The tank's pressure does not matter because the pressures in the low and high side lines cancel each other out. Because the tank is pressurized, a "wet leg" or "reference leg" must be used. This is the piping going from the low side of the transmitter to the top of the tank. It typically will be filled with some other type of product, such as glycol or silicon. This prevents moisture from accumulating in the line.

If moisture accumulates in the line, it will give an error in the transmitter reading. The wet leg has 100 in of fluid with an SG of 1.1. In the example, the first line of math will be the LRV and the

second line of math will be the URV. The tank has 100 in of fluid with an SG of 1.0. The calibrated *range* of the instrument will be -110 to -10 in of water or H₂O. Elevate the zero in the transmitter with the hard wire jumper or set the variable in the transmitter and make -110 in a live zero for the instrument. In pneumatic instruments, a suppression kit must be installed.

The *span* of the transmitter is: $100 \text{ in} \cdot 1.0 = 100 \text{ in}$

Example 4 – Closed Tank, Elevate the Zero (Transmitter below Tank)

The low side is connected to the top of the closed tank. The high side is connected to the bottom of the closed tank. The tank's pressure does not matter because the pressures in the low and high lines cancel each other out. The wet leg has 120 in of fluid with an SG of 1.1. The first line of math will be the LRV, and the second line of math will be the URV. The tank has 100 in of fluid, and the tube dropping down below the tank adds 20 in of fluid height with an SG of 0.8. The calibrated *range* of the instrument will be -116 to -36 in of water or H₂O. Remember that the minimum measurement cannot be lower than 20 in on the high side, due to the fixed 20-inch height of the tube dropping below the tank. **Elevate the zero** and make -116 in a live zero.

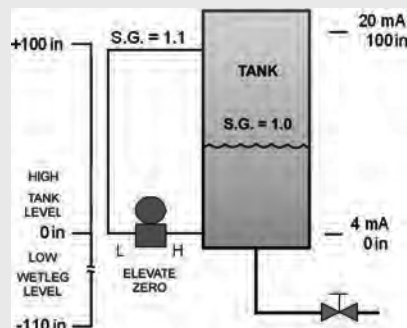
The *span* of the transmitter is: $100 \text{ in} \cdot 0.8 = 80 \text{ in}$

Remember: (high side inches • SG) – (low side inches • SG) = lower or upper range value

Note: The formula provides the LRV when the tank is empty and URV when it is full.

Example 3: Closed Tank Elevate the Zero

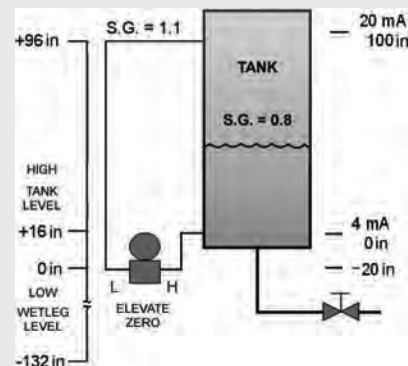
Tank Level = 0–100 in
SG = 1.0, Wet Leg: SG = 1.1
Height = 100 in
(switch jumper to elevate zero)



LRV = $(0 \text{ in} \cdot 1.0) - (100 \text{ in} \cdot 1.1) = -110 \text{ in} = 4 \text{ mA}$
URV = $(100 \text{ in} \cdot 1.0) - (100 \text{ in} \cdot 1.1) = -10 \text{ in} = 20 \text{ mA}$
Calibrate range from -110 in to -10 in H₂O

Example 4: Closed Tank Elevate the Zero (transmitter below tank)

Tank Level = 0–100 in
SG = 0.8, Wet Leg: SG = 1.1
Height = 120 in
(switch jumper to elevate zero)



LRV = $(20 \text{ in} \cdot 0.8) - (120 \text{ in} \cdot 1.1) = -116 \text{ in} = 4 \text{ mA}$
URV = $(120 \text{ in} \cdot 0.8) - (120 \text{ in} \cdot 1.1) = -36 \text{ in} = 20 \text{ mA}$
Calibrate range from -116 in to -36 in H₂O

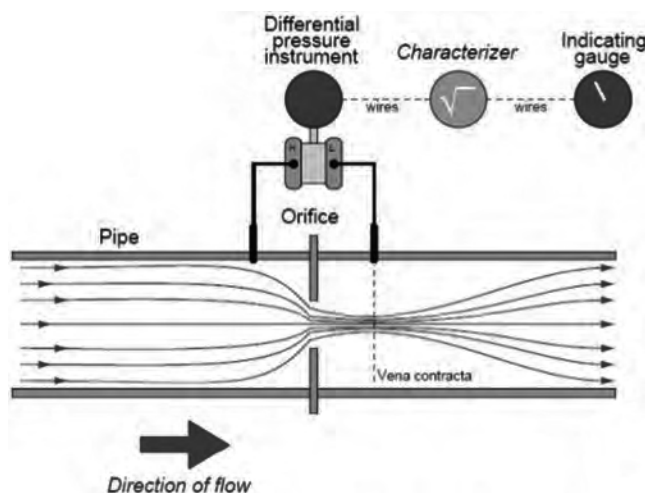
9 Flow Measurement and Calibration

Applying Flow Measurement Devices

Like level measurement, flow measurement is head pressure and zero elevation-based. Head pressure is the measure of the endowed potential energy (hydrostatic pressure) in the system. The transmitter measurement is from how high the fluid falls, it is velocity squared. The velocity is squared because the fluid is constantly being accelerated through the pipe, as potential energy is endowed into the fluid by the pump head pressure.

Head pressure is lost across an orifice element because energy loss is the product of energy flow multiplied by the resistance though which it flows (see figure at right).

Sizing of the orifice will be discussed in detail in the subsection titled “Orifice Tap Dimensions and Impulse Line Connections” later in this chapter. You should familiarize yourself with the different types of flowmeters, their applications, and their ISA symbols. The ISA piping and instrumentation diagram (P&ID) symbols are shown in the ISA Standard Flowmeter Symbols section below.



Refer to ANSI/ISA-5.1-2009, *Instrumentation Symbols and Identification*, for more symbols and standards.

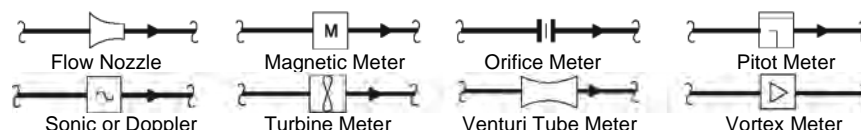
Turndown Ratio in a Flowmeter

The turndown ratio of a flowmeter is its ability to measure with acceptable accuracy the ratio of the maximum flow rate measurement to the minimum flow rate measurement. This is also known as the rangeability of the flowmeter. Turndown ratio is important when choosing a flowmeter technology for a specific application. If a gas flow to be measured will have a maximum measured flow rate of 1,000,000 scfm (standard cubic feet per minute) and a minimum measured flow rate

of 100,000 scfm, the meter must have a minimum turndown ratio of 10:1 (1,000,000/100,000). For example, if the meter had an advertised turndown ratio of 20:1 and a maximum flow rate measurement of 2,000,000 scfm, then the minimum measurable flow rate would be 100,000 scfm.

The turndown ratio of each type of meter is limited by the constraints of the manufacturing process and materials used, as well as practical application considerations. For example, orifice meters create a pressure drop in the measured fluid proportional to the square of the velocity.

ISA Standard Flow Meter Symbols



Flow Meter Applications Chart

Sensor	Rangeability	Accuracy	Advantages	Disadvantages
Orifice	3.5:1	2%–4% of full span	–Low cost –Extensive industrial practice	–High pressure loss –Plugging with slurries
Venturi	3.5:1	1% of full span	–Lower pressure loss than orifice –Slurries do not plug	–High cost –Line under 15 cm
Flow nozzle	3.5:1	2% full span	–Good for slurry service –Intermediate pressure loss	–Higher cost than orifice plate –Limited pipe sizes
Elbow meter	3:1	5%–10% of full span	–Low pressure loss	–Very poor accuracy
Annubar	3:1	0.5%–1.5% of full span	–Low pressure loss –Large pipe diameters	–Poor performance with dirty or sticky fluids
Turbine	20:1	0.25% of measurement	–Wide rangeability –Good accuracy	–High cost –Strainer needed, especially for slurries
Vortex shedding	10:1	1% of measurement	–Wide rangeability –Insensitive to variations in density, temperature, pressure, and viscosity	–Expensive
Positive displacement	10:1 or greater	0.5% of measurement	–High rangeability –Good accuracy	–High pressure drop –Damaged by flow surge or solids
Coriolis mass flow	100:1	0.05%–0.15% of measurement	–Very good accuracy	–Expensive

Pressure Tappings (Impulse Line Taps)

There are three standard positions for pressure tappings (also called *taps*), commonly named as follows:

1. *Corner taps* placed immediately upstream and downstream of the plate; convenient when the plate is provided with an orifice carrier incorporating tappings
2. *D and D/2 taps*, or *radius taps* or *vena contracta taps*, placed one pipe diameter upstream and half a pipe diameter downstream of the plate
3. *Flange taps* placed 25.4 mm (1 in) upstream and downstream of the plate, normally within specialized pipe flanges.

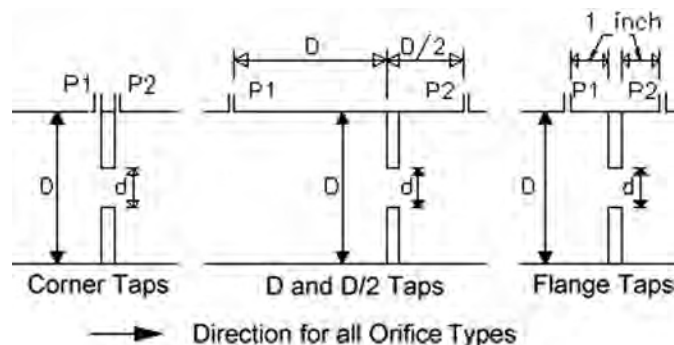
These types are covered by ISO 5167 and other major standards. Other types include:

- *2½D and 8D taps* or *recovery taps* placed 2.5 pipe diameters upstream and 8 diameters downstream, at which point the measured differential is equal to the unrecoverable pressure loss caused by the orifice
- *Vena contracta tappings* placed one pipe diameter upstream and at a position of 0.3 to 0.9 diameters downstream, depending on the orifice type and size relative to the pipe, in the plane of minimum fluid pressure

The measured differential pressure differs for each combination, so the coefficient of discharge used in flow calculations depends partly on the tapping positions.

The simplest installations use single tappings upstream and downstream, but in some circumstances these may be unreliable; they might be blocked by solids or gas bubbles, or the flow profile might be uneven so that the pressures at the tappings are higher or lower than the average in those planes. In these situations, multiple tappings can be used, arranged circumferentially around the pipe and joined by a piezometer ring, or in the case of corner taps, annular slots running completely around the internal circumference of the orifice carrier.

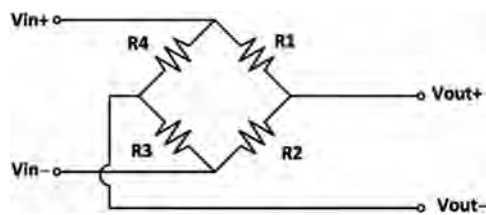
Orifice Tap Dimensions and Impulse Line Connections



10 Weight Measurement and Calibration

Weight Measurement Devices and Calibration

Weight measurements are typically made with load cells (strain gauges attached to metal bars). The bending moment of the bar causes the strain gauge to elongate, resulting in an increase of resistance in the strain gauge. This variable resistance is connected to a bridge circuit, and a voltage is measured across the bridge. The voltage is proportional to the weight applied to the measuring bar.



This strain gauge technology is used in measuring the weight in tanks, the weight in screw conveyors, and the weight on conveyor belts. The tare weight (tank weight) is nulled out and the voltage is set to zero or 0% in the bridge circuit. Then the maximum weight to be measured is applied. These weights are National Institute of Standards and Technology (NIST) certified. The span voltage is then calibrated to a maximum of 100%. This measurement is the net weight.

Note: Remember that all calibration processes should be repeated at least three times.

Load Cells

When outfitting a tank for batching, you must select a method for measuring the amounts of each ingredient added. A flowmeter or level meter may be the first device that comes to mind. However, the load cell might be the better solution.

A flowmeter may come in many forms, but it is usually an in-line device that measures the rate or flow of a fluid, either in volume or mass. On the other hand, a load cell is a device that allows for the contents of a tank or vessel to be weighed. This can be better than a level measurement, in cases such as pounds of sugar or pounds of flour.



Because a flowmeter is located in the tubing upstream from a tank, there is a difference between what the meter reads and what is truly in the tank. Programming changes can correct for the delays in measurement caused by this difference, but they can be imprecise and require frequent calibration.



However, because a load cell measures the weight of the tank itself, delays are minimized. Load cells offer a particular benefit when dealing with products that do not usually work well with flowmeters. Liquids with entrained air or bubbles may give meters trouble, but they are no problem for load cells. Even dry ingredients like powders can be measured just like liquid mass and volumes using load cells.

Load Cells for (Flow, Level, Force) Applications in Process

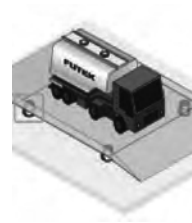
Mass Flowmeter



Batch Weighing



Weighbridge Measurements



Tank Dispensing



Silo Measurement



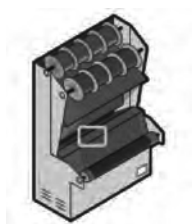
Automation Container Filling



Hydraulic/Pneumatic Press Force



Wire Tension Measurement



Robotic Tactile Sensing



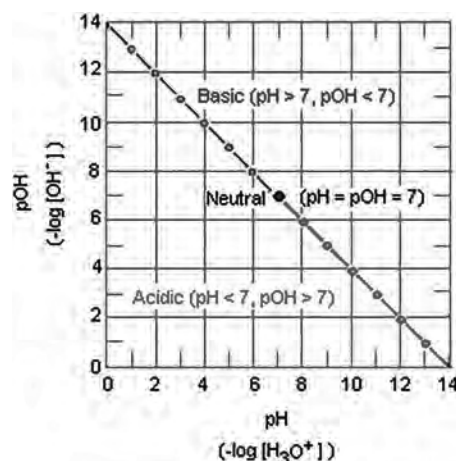
11 Process Analyzers

Electrical Conductivity and pH Correction

It is often useful to characterize an environment, such as a body of water, by measuring its pH and electrical conductivity (EC). pH is a measure of the acidity of the water or soil based on its hydrogen ion concentration and is mathematically defined as the negative logarithm of the hydrogen ion concentration:

$$\text{pH} = -\log[\text{H}^+]$$

The brackets around the H^+ symbolize *concentration*. The pH of a material ranges on a logarithmic scale from 1 to 14, where pH 1–6 are acidic, pH 7 is neutral, and pH 8–14 are basic. Lower pH corresponds with higher $[\text{H}^+]$, while higher pH is associated with lower $[\text{H}^+]$.



EC is a measurement of the dissolved material in an aqueous solution, which relates to the ability of the material to conduct electrical current through it. EC is measured in units called *Siemens per unit area* (e.g., *mS/cm*, or *milliSiemens per centimeter*), and the higher the dissolved material in a water or soil sample, the higher the EC will be in that material.

How Are pH and Electrical Conductivity Measured?

A meter and probe or litmus paper can be used to measure the pH of a sample. The more accurate and expensive of these methods is the meter and probe. pH meters are calibrated using special solutions, or buffers with a known pH value.

Electrical conductivity can be measured using a meter and probe as well. The probe consists of two metal electrodes spaced 1 cm apart (thus the unit of measurement is microSiemens or miliSiemens per centimeter, *uS/cm* or *mS/cm*). A constant voltage is applied across the electrodes, resulting in an electrical current flowing through the aqueous sample. Because the current flowing through the water is proportional to the concentration of dissolved ions in the water, the electrical conductivity can be measured. The higher the dissolved salt/ion concentration, the more conductive the sample and therefore the higher the conductivity reading.

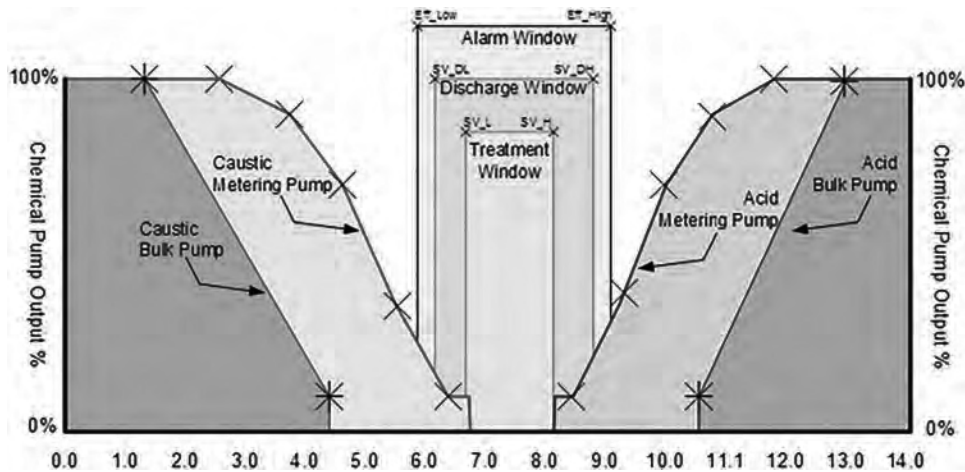
Control of pH Values in Processes

The process curve below shows the response of pH correction is not linear and cannot be controlled as such. Most pH “controllers” on the market are not truly pH controllers because they use simple on/off control or a linear control algorithm by using a standard proportional-integral-derivative (PID) algorithm, which is far too simple to account for the ever-changing control gain encountered with the logarithmic reaction of pH to control input.

A true pH controller *must* have the ability to control a logarithmic and nonlinear response such as the typical pH process correction response curve shown below.

The response of the process being corrected accelerates around a pH level equal to 7. Special pH controllers with adaptive gain and logarithmic algorithms are typically used. A window or hysteresis about the correction set point is typically used for control as shown below. This reduces hunting and causes the process to run continuously within acceptable tolerances. Chart recorders are typically used to document the pH correction before the process products are allowed to be discharged into rivers and sewage systems.

Typical pH correction control scheme.



Conventionally, in the controllers, 4 mA would correspond to 0 pH, and 20 mA to 14 pH. When such a device is connected to a 1/4 DIN panel mounted chart recorder, the pH value can be constantly monitored. If the process requires a stringent control and is also operating within a narrow band of set points, say 1 pH, the recording on the chart paper will not be well resolved. This is because in the conventional controller, the range of 14 pH is distributed over 16 mA. Therefore, for a 1 pH variation, the current varies only by approximately 1.15 mA.

Control of Conductivity

Electrical conductivity in water is a measure of the ion-facilitated electron flow through it. Water molecules dissociate into ions as a function of pH and temperature and result in a



12 Sensors for Fire and Rotating Equipment

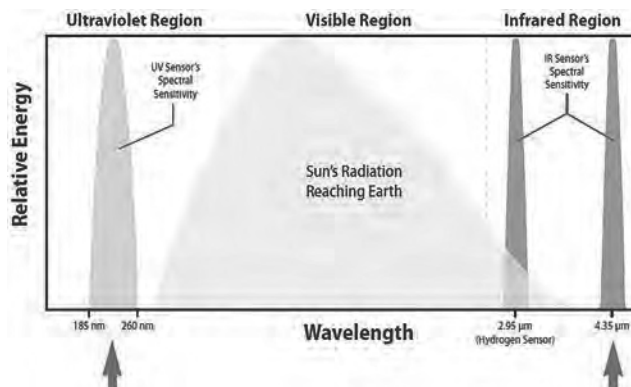
Sensors for Fire Protection and Flame Monitoring

Optical flame detectors have multiple applications in a variety of hazardous environments, ranging from industrial heating and drying systems and industrial gas turbines to petrochemical oil and gas facilities. They can reduce the risk in a given environment by quickly detecting an unwanted flame. Therefore, they are more reliable, especially in outdoor settings, where they can respond faster to the presence of a flame than a heat or a smoke detector can. In industry, two basic types of flame or fire detection are used:

1. Detection of fire and flames for protection, such as in a compressor building (fire prevention)
2. Detection of fire and flames for process monitoring, such as a flare or oven (burner management)

Fire Prevention

In fire prevention, fire and flames are detected using an ultraviolet (UV) sensor or infrared (IR) sensor. A resistance temperature detector (RTD) may be used in heating, ventilation, and air conditioning (HVAC) ductwork to detect fire in the ductwork. A UV/IR flame detector consists of UV and IR sensors that are combined in a single apparatus. UV sensors work by detecting the UV radiation emitted by the flame and are sensitive to a wide range of flammable fuels including hydrocarbons, sulfur, hydrazine, and ammonia.

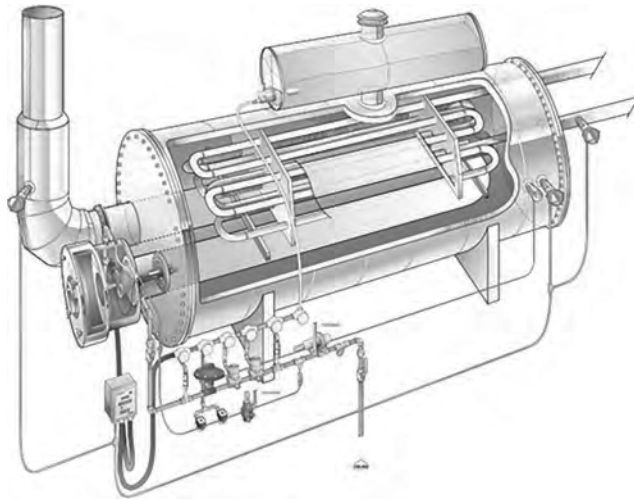


The main radiant emission band for hydrocarbon fueled fires ranges between 4.3 and 4.4 microns, μ . It is an infrared emission that the IR sensors can detect with ease. The energy released by the burning of the CO_2 , at a resonance frequency of 4.3 μ , enables the IR detector to discover the emission.

The ultimate benefit of having UV and IR sensors combined in a single device is that they share the same alarm source—a real hydrocarbon fire. As mentioned, each individual sensor operates separately, but adding advanced signal processing algorithms enables the combination of the two sensors to deliver outstanding flame detector performance to a wide range of flammable liquids, gases, and volatile solids. At the same time, the UV or IR sensors can individually provide enhanced false alarm rejection.

Burner Management System

In the oil and natural gas industry, various applications (e.g., tanks, line heaters, separators, dehydrators, amine reboilers, and flares) are used in the production and transportation of oil and natural gas. These applications require heat, which is used to facilitate the proper function of the application. To provide that heat, a burner is used within the application. Such applications typically use what is called a burner management system (BMS).



- **Auto-Relight**
 - The BMS quickly detects the flame absence in the combustion application, and can quickly reignite the burner flame or shut off the fuel source if there is a failure.
- **Temperature Control**
 - The BMS will manage temperature set points that are set by the user, ensuring that the burner flame is on only when needed.
- **Remote Monitoring and Control**
 - Most BMSs are compatible with remote monitoring and control technologies (i.e., telemetry). This allows the user to monitor and manage the BMS from the comfort of a control panel or control room.

13 Process Control Valves and Actuators

Process Control Valves

A wide variety of valve types exist. The most widely used types for process control systems and other industrial fluid applications are those that have linear stem and rotary spindle movement:

- Linear stem movement type valves include globe valves and slide valves.
- Rotary spindle type valves include ball valves, butterfly valves, plug valves, and their variants.

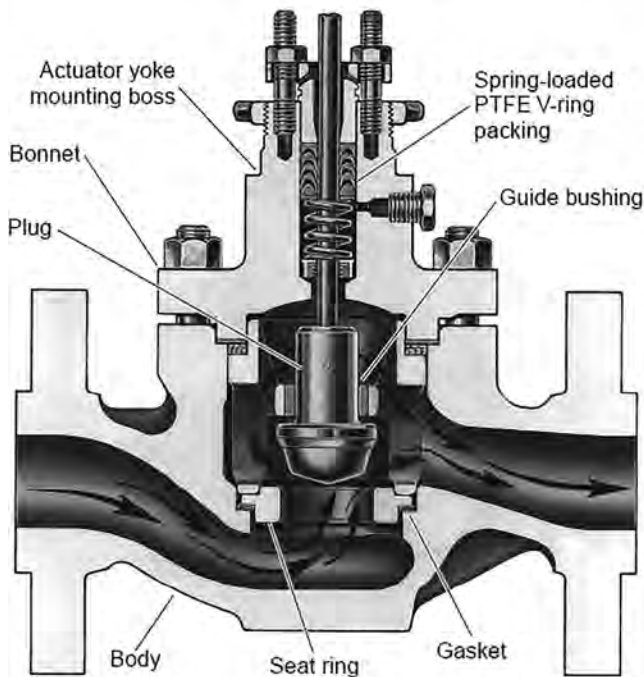
The first choice to be made is between two-port and three-port valves:

- Two-port valves “throttle” (restrict) the fluid passing through them.
- Three-port valves can be used to “mix” or “divert” liquid passing through them.

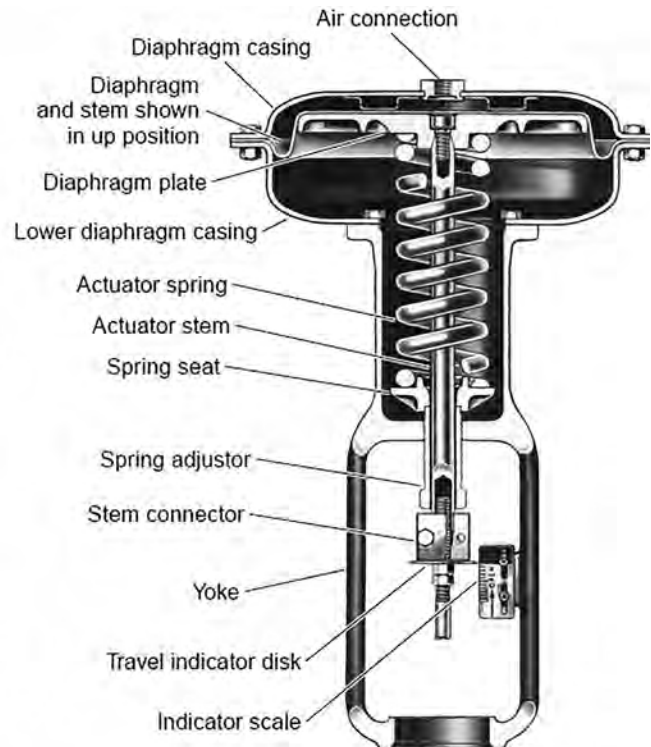
Globe valves are frequently used for control applications because of their suitability for throttling flow and the ease with which they can be given a specific “characteristic,” relating the valve opening to flow. For any given valve orifice size, the greater the differential pressure, the greater the flow rate. The maximum value of the valve flow coefficient C_v is defined as the number of US gallons of water per minute (at standard pressure and temperature) that will flow through a wide-open valve when there is a 1 psig pressure drop across the valve. The flow rate can be determined by the following equation:

$$1 \text{ gpm} = 1 C_v \cdot \sqrt{1 \text{ DP}_{\text{psig}}}$$

Control valve sizing will be discussed in detail for liquid, steam, gas, vapor, and two-phase applications in this section of the manual. We will also look at the accessories used on common valves and valve sizing limitations that must be considered. The style of the valve trim (internal makeup), the characteristics (the gain of the flow per signal), and the DP across the valve all affect whether the valve will function in the process piping loop. There may be limits of the maximum and minimum DP across the valve to adhere to. The DP can limit the flow through the valve and can cause excessive noise and even destruction of the valve.



Cross sectional view of a globe valve showing the basic structure



Typical arrangement of a spring and diaphragm type actuator

Considerations When Sizing a Control Valve

The following should be considered when sizing and selecting process control valves for a project.

$$1 \text{ gpm} = 1 C_v \cdot \sqrt{\frac{1 \text{ DP}_{\text{psig}}}{1 \text{ SG}}}$$

Flow Coefficient C_v

The use of the flow coefficient, C_v , first introduced by Masoneilan in 1944, quickly became accepted as the universal yardstick of valve capacity. So useful has C_v become that practically all discussions of valve design and characteristics or flow behavior now employ this coefficient. By definition, the valve flow coefficient is the number of US gallons per minute of water that will pass through a given flow restriction with a pressure drop of 1 psi.

For example, a control valve with a maximum flow coefficient of $C_v = 12$ has an effective port area in the full open position such that it passes 12 gpm of water with 1 psi pressure drop. Basically, it is a capacity index on which the engineer can rapidly and accurately estimate the required size of a valve restriction for desired flow in any fluid system. The flow is dependent on other variables as well, and there may be limitations of the maximum DP that can be applied across the valve.

Specific Gravity

In the flow formulas, the specific gravity (SG) is a square root function; therefore, small differences in gravity will have a minor effect on valve capacity. If the SG is not known accurately, a reasonable assumption will suffice. The use of SG equal to 0.9, for example, instead of SG equal to 0.8, will cause an error of less than 5% in valve capacity. $\text{Sqrt}[1/(0.9-0.8)] = 3.16\%$ error in flow.

Operating Conditions

The selection of a correct valve size, as determined by formula, is always premised on the assumption of full knowledge of the actual flowing conditions. Frequently, one or more of these conditions is arbitrarily assumed. The evaluation of these arbitrary data determines the final valve size.

No formulas, only good common sense combined with experience, can solve this problem. There is no substitute for good engineering judgment.

Most errors in sizing are due to incorrect assumptions as to actual flowing conditions. The tendency is to make the valve too large and to be on the “safe” side (commonly referred to as *oversizing*). A combination of several of these “safety factors” can result in a valve so greatly oversized it tends to be troublesome.

ISA Standard Valve Symbols



Valve (generic)



Globe Valve



Butterfly Valve



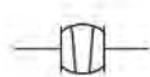
Ball Valve



Gate Valve



Saunders Valve



Plug Valve



Characterized Ball Valve



Pneumatic Pinch Valve



Pressure-Relief
or Safety Valve



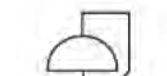
Angle Valve



Three-Way Valve



Check Valve (generic)



Pressure Regulator
Valve



Ball Check Valve



Diaphragm Valve

14 Pressure-Relief Valves and Rupture Disks

Pressure-Relief Valves and Pressure Safety Valves

Gases and steams can be compressed. When gas reaches the disk in a valve, it compresses and builds up pressure before escaping through the valve. This compression can cause system pressure to build up rapidly. A liquid-type relief valve does not open fast enough to relieve gas or steam pressure. A gas system requires a valve that can open completely under excess pressure, or a pressure safety valve.

Pressure safety valve (PSV) and *pressure-relief valve (PRV)* are commonly used terms to identify pressure-relief devices on a vessel. These terms are often used interchangeably; depending on the project or company standards, pressure-relief devices may be identified as *safety valves* or as *relief valves*, or sometimes even as *safety relief valves*.

Although used freely and interchangeably, these terms differ:

- *Pressure-relief valve* is the term used to describe a relief device on a liquid-filled vessel. For such a valve, the opening is proportional to the increase in the vessel pressure. Therefore, the opening of the valve is not sudden but gradual, if the pressure is increased gradually.

Note: Do not throttle pressure-relief valves.

- *Pressure safety valve* is the term used to describe a relief device on a compressible fluid or gas-filled vessel. For this type of valve, the opening is sudden. When the set pressure of the valve is reached, the valve opens almost fully.

A PRV should not be used to control the pressure out of a pump. The PRV will chatter, and the hammering action caused by the pulsations will quickly destroy the valve. A proportional control valve should be used for this application. Contact the manufacturer for more information about this application.

Environmental Protection Agency Regulations

Many environmental protection agencies worldwide have been tightening regulations on hazardous material emissions. In the United States, for example, the Environmental Protection Agency (EPA) has been issuing new and stricter regulations for several types of industries, ranging from food and beverage to nuclear power plants. There are regulations for refineries, with specific sections for each type of plant unit, such as fluid catalytic cracking units, catalytic reforming units, utilities, storage, and water treatment. The requirements for refineries and other types of industries are similar, with the main difference being the tolerated amounts for each type of pollutant released. The more stringent rules established by the new EPA regulations issued in September 2015 and by other environmental agencies can be generalized with three simple requirements:

1. Provide indication and location where a pressure-relief device (PRD) event occurs through electronic monitoring.
2. Measure the time and duration of the PRD event for recording and reporting of emissions releases from:
 - A. Protected vessel
 - B. Rupture disc
 - C. Relief valve
 - D. Bypass valve
3. Notify the operator of the event so corrective action can occur.

Also, the EPA expects “flare operation at all times during the process of gas being sent to the flare,” so quick identification of a PRD release is not optional. In general, newer and more stringent rules apply not only to normal operation, but also to start-up/shutdown periods, where there have historically been more leniencies. These start-up/shutdown periods are often when process upsets are most likely to occur, so compliance with these new regulations can be demanding.

Plants must comply with environmental regulations by law. Failing to do so can cause serious damage to the environment and personnel. It can also cause explosions and serious damage to plant equipment. In addition, lack of compliance can result in expensive fines, production disruptions, and bad publicity. But there is another compelling reason to monitor and curb fugitive emissions: leakages caused by PRD malfunctions can waste large amounts of valuable products, along with the energy required to produce such products.

Regulation Details

Every national and international government has its own rules to control and monitor emissions of pollutants. In the United States, the Clean Air Act (CAA) is the key federal law regulating air emissions from stationary and mobile sources. Among other things, this law authorizes the EPA to establish national ambient air quality standards to protect public health and public welfare by regulating emissions of hazardous air pollutants. CAA Section 111(b) requires the EPA to set and

15 Review of Feedback Control Fundamentals

Compare Open-Loop Control to Closed-Loop Control

Open-Loop Example – A Mathematical Analysis

Most industries today use closed-loop control. It offers a faster and tighter response. That is, it can maintain the desired set point of a process almost exactly. Its output is almost perfect (exactly what is desired). Let us examine an everyday application, speed control of an automobile. Look at Figure 15-1. There are a desired speed (R); a controller, mechanical accelerator pedal mechanism or microprocessor controller and electronics, that provides a signal to the engine and transmission (u); a disturbance, the slope of the road (w); and a desired output, the actual speed of the automobile (Y).

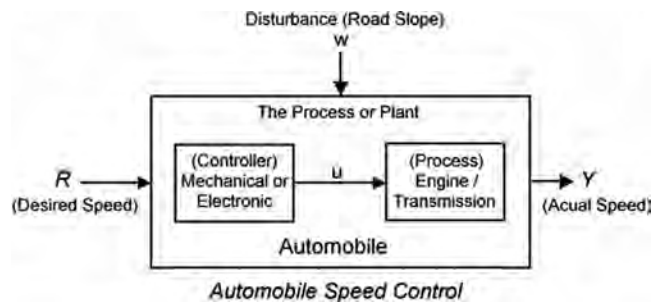


Figure 15-1

First let us examine open-loop control and its drawbacks. Open-loop control is cheap and can work in a circumstance where the output can vary, that is, the output can be in a range of speeds and does not have to be exact for the conditions of the process. This may not always be desirable. Look at Figure 15-2. Here we have variable R , desired speed, and variable Y_o , output speed of the open-loop.

The automobile uses a mechanical linkage with an accelerator pedal to send a signal to the engine and transmission, which will control the speed of the automobile. The mechanical linkage combined with the accelerator pedal has a gain of $1/10$. The accelerator pedal and mechanical linkage gain of $1/10$ adds to the automobile's output speed. The road has a slope. This slope subtracts from the automobile's response of desired set-point speed (R), with a gain of 0.5 . When the slope of the road is zero (for a level surface), the disturbance does not affect the output speed.

When the slope is greater than zero, for example, 1% or 10% grade, the automobile's actual speed is less than the desired speed. This can be seen when driving down a road and holding the accelerator pedal at a constant position. You will slow down going up a hill or slope (the rise versus the run or Y/X).

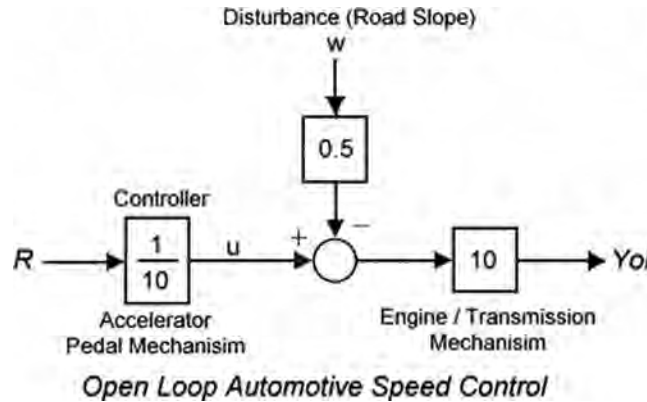


Figure 15-2

where

R = desired or reference speed in miles per hour

u = throttle angle in degrees (sets engine speed)

Y_{ol} = actual open-loop speed of the automobile in miles per hour

w = road grade in percent

The set point (desired speed) is multiplied by the gain of the controller ($1/10$). The output of the controller is called the *manipulated variable* (u). The system disturbance, which models the effect of slope in the road, is multiplied by a gain of 0.5 and is subtracted from the manipulated variable. The manipulated variable, which is the throttle angle of the carburetor, sets the engine speed. The process final correction control device or element is the engine and transmission, which has a gain of 10. The manipulated variable, minus the system disturbance multiplied by a gain of 0.5, is then multiplied by the final control device or element gain of 10 to set the value of the final output, which is the actual speed of the process or plant (Y_{ol}). In this case, the process or plant is the automobile.

Let us look at the math to prove what is happening in the system.

The open-loop output speed is given by:

$$\begin{aligned}
 u &= R \left(\frac{1}{10} \right) \\
 Y_{ol} &= (u - 0.5w)10 \\
 Y_{ol} &= \left(\frac{R}{10} - 0.5w \right) 10 \\
 Y_{ol} &= R - 5w
 \end{aligned}$$



16 Review of Frequency Response Fundamentals

Electrical Application – A First-Order System

Frequency response is a way to analyze what the output of the process or plant will be. We can calculate the output (e.g., volts or watts in power) for a given system gain and input (e.g., volts) at some frequency. Remember the capacitance reactance is varying with the change in frequency ($X_C = 1/2\pi f_C$). First, we will look at where the transfer function comes from. See Figure 16-1.

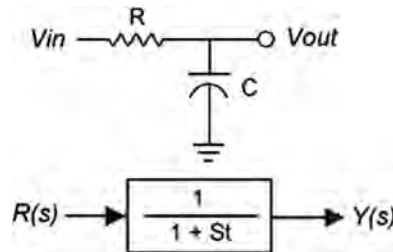


Figure 16-1

We will now derive the transfer function for this first-order system, where $R(S)$ is the input signal at some frequency and $Y(S)$ is the output voltage with some phase angle and amplitude.

Current equals the voltage drop across the resistor divided by the resistor value.

where

I = Current

V_R = Voltage across resistor

R = Resistor

C = Capacitor

$$I = \frac{V_R}{R}$$

$$I = \frac{V_{in} - V_{out}}{R}$$

Current also equals the drain out of the capacitor, from the voltage across the capacitor.

$$I = C \frac{dV_{out}}{dt}$$

Substitute voltage drop divided by resistance for amps (I) and set the two equations equal to each other.

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

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

$$s = \frac{d}{dt}$$

$$V_{in} - V_{out} = RCS(V_{out})$$

$$V_{in} = V_{out} + RCS(V_{out})$$

$$V_{in} = (1 + RCS)V_{out}$$

$$\frac{V_{in}}{1 + RCS} = V_{out}$$

$$\frac{1}{1 + RCS} = \frac{V_{out}}{V_{in}}$$

$$t = RC$$

The transfer function is equal to the gain of the system.

$$\frac{1}{1 + St} = \frac{V_{out}}{V_{in}}$$

Use the transfer function to calculate the voltage out of the system.

$$V_{in} \left(\frac{1}{1 + St} \right) = V_{out}$$

We have derived the transfer function for this first-order system. We can now plug in an input voltage and an angular frequency and calculate the attenuation of the output signal and the phase angle of the output signal.

Bode Plot of First-Order System

Make a Bode plot for a circuit with the following components.

resistor = $1000 \, \Omega$

capacitor = $2.65 \, \mu\text{F}$

17 Control Theory and Controller Tuning

The process control industry covers a wide variety of applications: petrochemical, pharmaceutical, power generation, water treatment, pulp and paper, food processing, material handling, and even commercial applications.

Process control in a plant can include discrete logic, such as relay logic or a programmable logic controller (PLC); analog control, such as single-loop control or a distributed control system (DCS); pneumatic systems; hydraulic systems; and electrical systems. The control systems engineer must be versatile and understand a broad range of control subjects as applied to controller applications, configuration, and tuning, as well as analysis and understanding of loop gain and stability.

This section will review the foundations of process control theory and its applications. Some of this material may be on the CSE exam. I have tried to keep the studies to a minimum and reduce the math for the problems to a form in which you can just plug in the values and get the answer you need for the exam.

We will cover degrees of freedom, process loop gain and applications, filtering of noise in process variable (PV) signals, open- and closed-loop tuning, damping of the system, time constants, overshoot of process set points, and checking for stability of a system transfer function.

Degrees of Freedom in Process Control Systems

In an unconstrained system, the number of independent variables required to completely specify the state of the system at a given moment must be defined. If the system has constraints, that is, kinematic or geometric relations between the variables, each such independent relation reduces by one the number of degrees of freedom (DOF) of the system.

$$\begin{aligned}\text{process variables} - (\text{equations} + \text{constraints}) &= \text{DOF} \\ \text{DOF} &= \text{minimum number of process controllers required}\end{aligned}$$

Example 1: An Airplane

Variables	
Altitude	1
Latitude	1
Longitude	$\frac{1}{3}$
Minus Constraints	0
Minus Equations	$\frac{0}{3}$
DOF =	3



$$\text{DOF} = 3 - (0 + 0) = 3$$

Three controllers are needed, one for each variable.

Example 2: A Train

Variables	
Altitude	1
Latitude	1
Longitude	$\frac{1}{3}$
Minus Constraints	
Altitude	1
Latitude	1
Minus Equations	$\frac{0}{1}$
DOF =	1

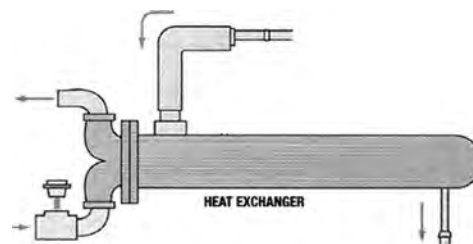


$$\text{DOF} = 3 - (2 + 0) = 1$$

One controller is needed; one for longitude only.

Example 3: A Hot Water Heat Exchanger

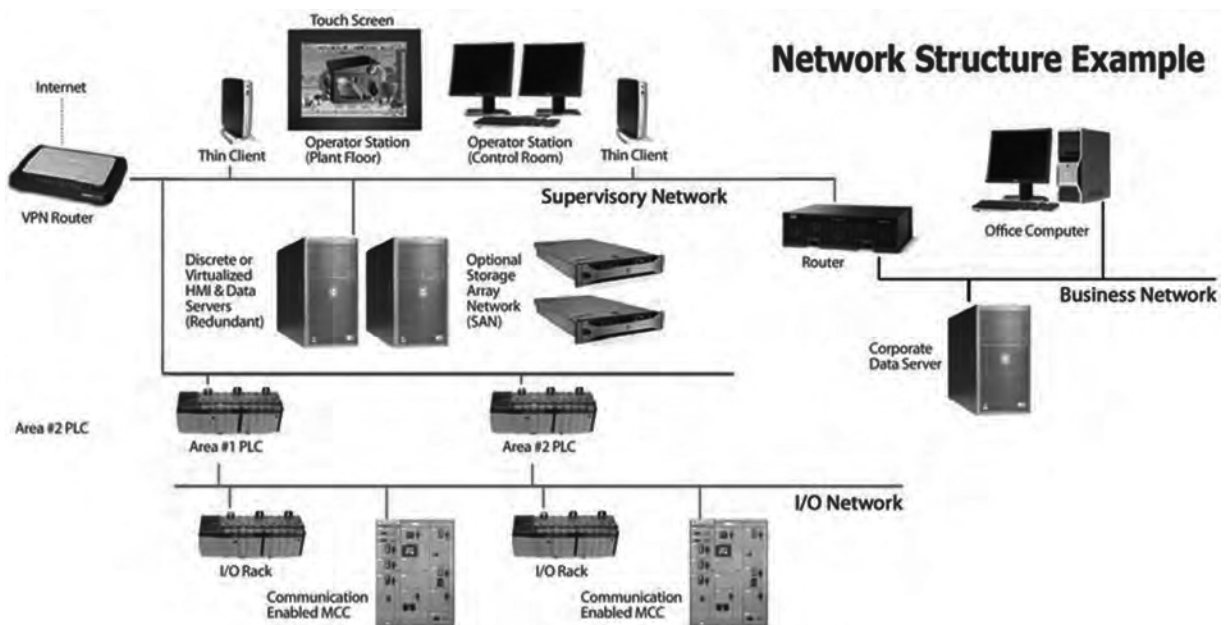
Variables	
W_s (flow rate of steam)	1
W_{CW} (flow rate of cold water)	1
W_{HW} (flow rate of hot water)	1
Q (quantity of steam in cubic feet)	1
P_s (supply pressure of steam)	1
T_{CW} (temperature of cold water)	1
T_{HW} (temperature of hot water)	$\frac{1}{7}$
Minus Constraints or Constants	
Q (quantity of steam)	1
P_s (supply pressure of steam)	1
T_{CW} (temperature of cold water)	$\frac{1}{3}$



18 Communications and Control Networks

Overview of Corporate and Plant Networks

On the CSE exam, there may be a few questions on fieldbus, intelligent devices, and networks. We will briefly review the highlights of these subjects. For more information on fieldbus, contact your local distributor.



Fieldbus is a digital, two-way, multidrop communication link among intelligent control devices that replaces the 4–20 mA analog standard devices. *The key to fieldbus is that the device is digital, not analog.* There are numerous protocols on the international market. FOUNDATION Fieldbus, PROFIBUS, AS/i, ControlNet, DeviceNet, Modbus, and HART are the most popular in the process industry.

The most popular types of fieldbus typically use EIA-485 protocol with token passing and 31.25 kbps on a single twisted pair wire that can be run up to 1900 m. They can have 32 segments and 1024 intelligent devices per network.

The connected intelligent devices are not calibrated; the data is scaled in software. Intelligent devices may deliver from 1 up to 12 or more data variables of information from one instrument. The data is delivered in data packets to the intelligent control device or master. With FOUNDATION

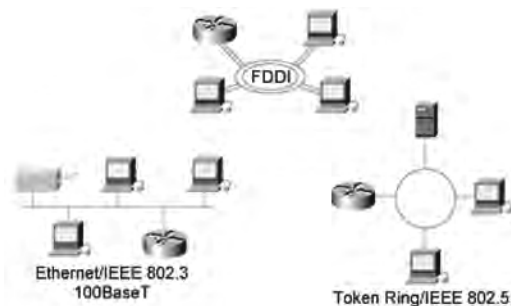
Fieldbus, any intelligent device can be the controller. More than likely, the valve may be selected as the intelligent controller that will be responsible for the PID calculation for its control loop.

Intelligent devices must be configured when first installed. This is done through Electronic Device Description Language or Field Device Tool. Most of the intelligent devices are plug-and-play. PROFIBUS devices can even be changed out without reconfiguring the device once it is initially configured. The configuration data is stored by the master controller and is then automatically downloaded to the new device on connection to the network.

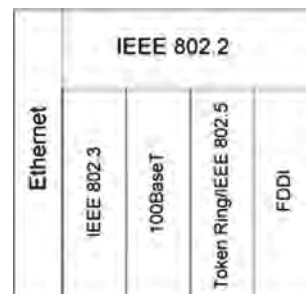
Networks can be connected by wire or fiber-optic cable, or can be wireless. There are three major categories of networks: LAN (local area network), WAN (wide area network), and MAN (metropolitan area network). The LAN is typically limited to 100 m (or 330 ft per segment) and 1024 nodes.

Industrial instruments typically communicate through a version of one of the three communication network protocols:

1. In a *fieldbus network*, they use one of the previously mentioned networks.
2. In a *serial network*, they use EIA/RS-232, EIA/RS-485, or EIA/RS-488.
3. In an *Ethernet network*, they use Ethernet/IEEE 802.3, Token Ring/IEEE 802.5, and the fiber distributed data interface (FDDI). A fiber backbone for the control system usually uses IEEE 802.1Q. This is a 1-gigabit Ethernet network.



Three typical Ethernet networks.



Ethernet protocols.

If the device communicates through Ethernet protocol, it typically has a *media access control* (MAC) address. Like a social security number, this number is unique to each device. For a device on one network to talk to a device on another network using a different protocol, a *protocol converter* or *gateway* is needed.

Open System Interconnect and TCP/IP Network Layer Model

Seven Layers of Networking in the Open System Interconnect Model

The network layers in the Open System Interconnect (OSI) model enable us to break down functional steps in communication by program protocols. You can think of protocols as the different steps in an assembly line. Computers communicate with each other through encapsulating or

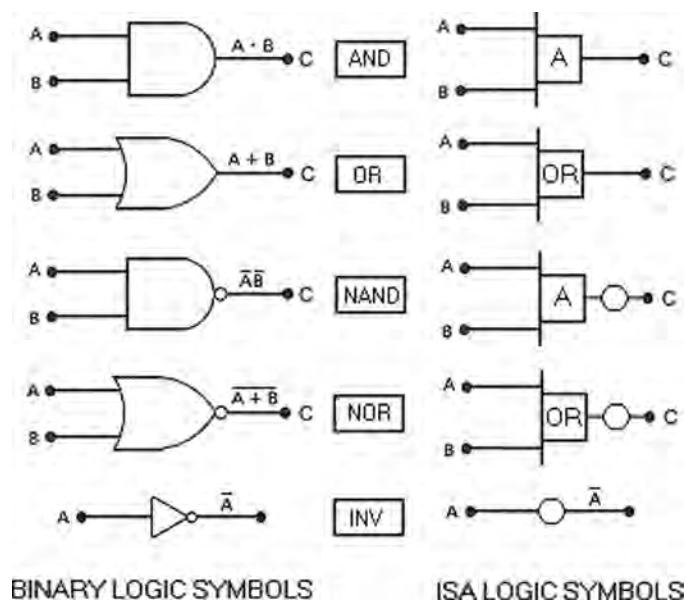
19 Digital Logic in Control Systems

Overview of Digital Logic

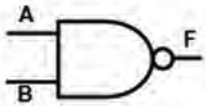
Discrete control plays a vital role in the process control industry. Discrete control is used for material handling, lockouts, and safety controls of systems, indicators, alarms, and switching applications. Discrete control usually takes the form of Relay Ladder Logic (RLL) or digital logic combined with some type of mechanical apparatus. The programmable logic controller (PLC) is the workhorse of the industry today and is covered on the CSE exam with International Society of Automation (ISA) binary logic and Relay Ladder Logic.

Digital Logic Gate Symbols

Familiarize yourself with the following binary logic table and its functions. ISA binary logic is the same in function as digital logic, although the symbols are slightly different. Familiarize yourself with ISA-5.2-1976 (R1992), *Binary Logic Diagrams for Process Operations*. ISA logic is used in the CSE exam. Look at some examples of its use, such as in ISA's *Control Systems Engineer Study Guide*.

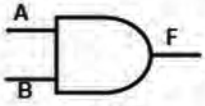


Digital Logic Gate Truth Tables



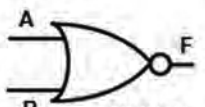
Inputs		Output
A	B	F
0	0	1
1	0	1
0	1	1
1	1	0

NAND




Inputs		Output
A	B	F
0	0	0
1	0	0
0	1	0
1	1	1

AND



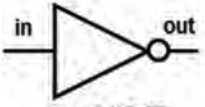
Inputs		Output
A	B	F
0	0	1
1	0	0
0	1	0
1	1	0

NOR



Inputs		Output
A	B	F
0	0	0
1	0	1
0	1	1
1	1	1

OR

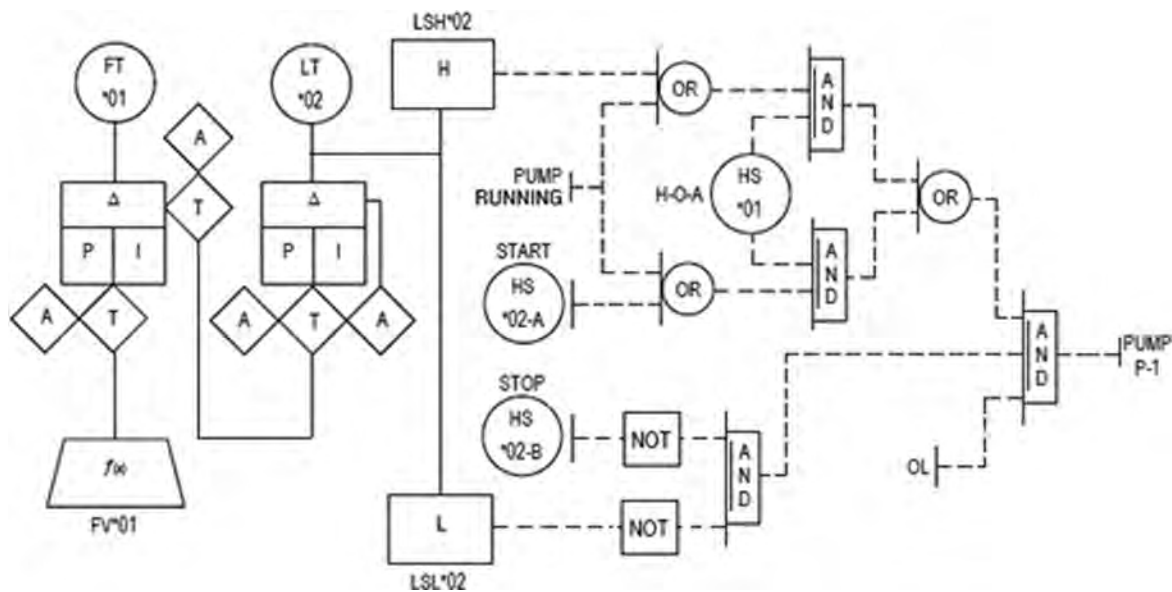


Input	Output
I	F
0	1
1	0

NOT

ISA Binary Logic

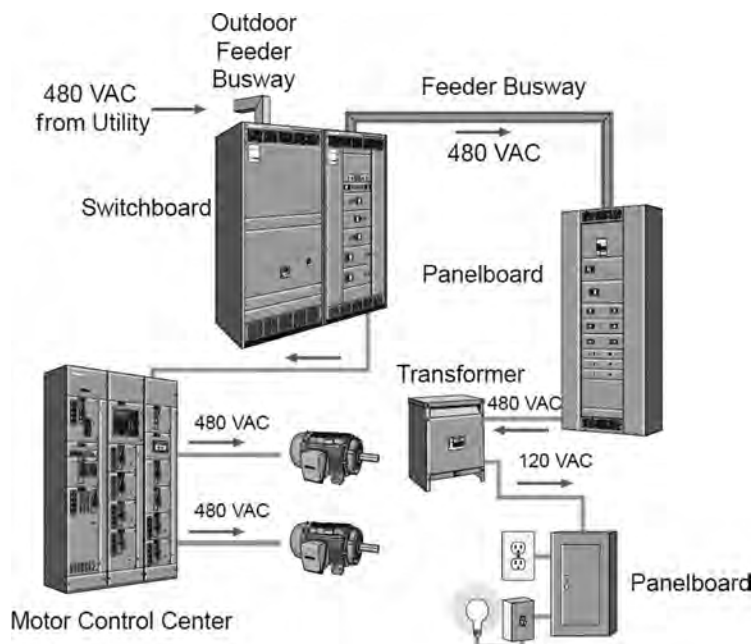
This is an example of the use of ISA logic symbols and SAMA (Scientific Apparatus Makers Association) symbols. Familiarize yourself with ISA-5.2-1976 (R1992), *Binary Logic Diagrams for Process Operations*.



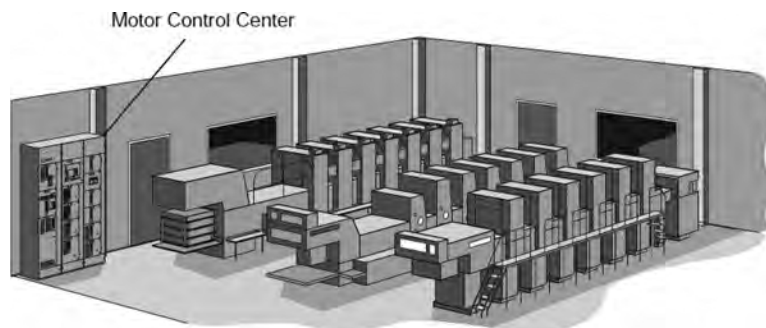
20 Motor Control and Logic Functions

The figures below show how a motor control center (MCC) is implemented in a plant electrical system.

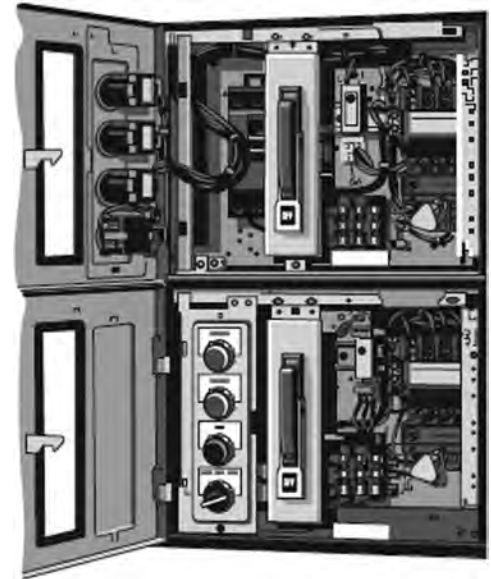
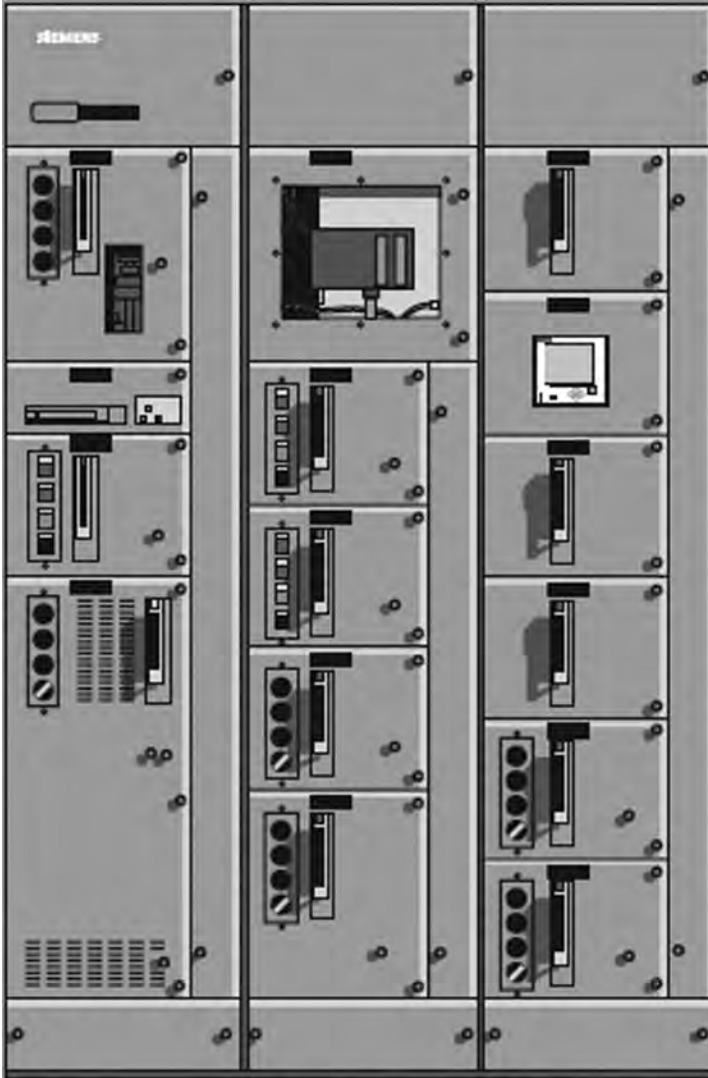
Plant Electrical System



Motor Control Center (MCC)



Typical MCC Design



This is a typical MCC found in most plants. It is a modular and expandable unit. The smaller squares are the motor starter compartments (see right unit).

The compartments are called *buckets*, and the wiring can be quickly disconnected and the bucket removed and replaced for fast repair and turn-around during shutdowns and design expansions.

The buckets typically slide in or plug into a vertical busbar with spring-clamped contacts, this is called *stab-in design*. But some buckets are wired to the busbar. They take up different vertical dimensions based on the motor starter size. These dimensions are called *space factors*.

The MCC can come with 42 circuit panelboards, small power transformers, variable frequency drives (VFDs), heater and lighting contactors, breakers, and switches. Spare units and blank covers (called *spaces*) are available for future expansion and can also be installed.

Most MCCs today are equipped with a programmable logic controller (PLC) or human-machine interface (HMI) and a communications network for controlling the MCC remotely as well as power usage monitoring. The networks are typically DeviceNet or Ethernet or an older technology such as Modbus RS-485 serial networks.



21 Analog Circuits in Control Systems

Overview of Analog Signals

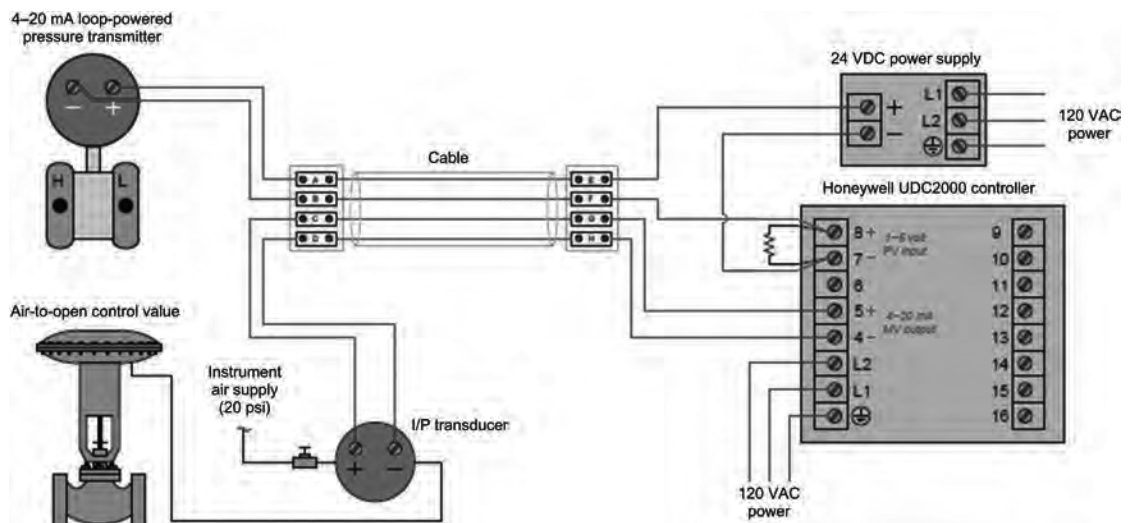
On the CSE exam, there may be a few questions on International Society of Automation (ISA) symbols for electrical and pneumatic systems. Study the following ISA standards publications:

- ANSI/ISA-5.1-2009, *Instrumentation Symbols and Identification*
- ISA-5.2-1976 (R1992), *Binary Logic Diagrams for Process Operations*
- ISA-5.3-1983, *Graphic Symbols for Distributed Control/Shared Display Instrumentation, Logic, and Computer Systems*
- ISA-5.4-1991, *Standard Instrument Loop Diagrams*

The author of this book considers this information a required subject. Many problems can arise in dealing with the above standards. You will be tested on details, so do not feel comfortable with your company's standards. Only the ISA standard is correct. There may be exam questions from the documentation text, not just the symbols.

Typical Analog Loop Wiring Diagram

Most instrumentation operates on what is called a 4–20 mA loop or a *loop-powered system*. The signal is sent as a 4–20 mA current loop (4 mA to 20 mA) because the signal does not degrade

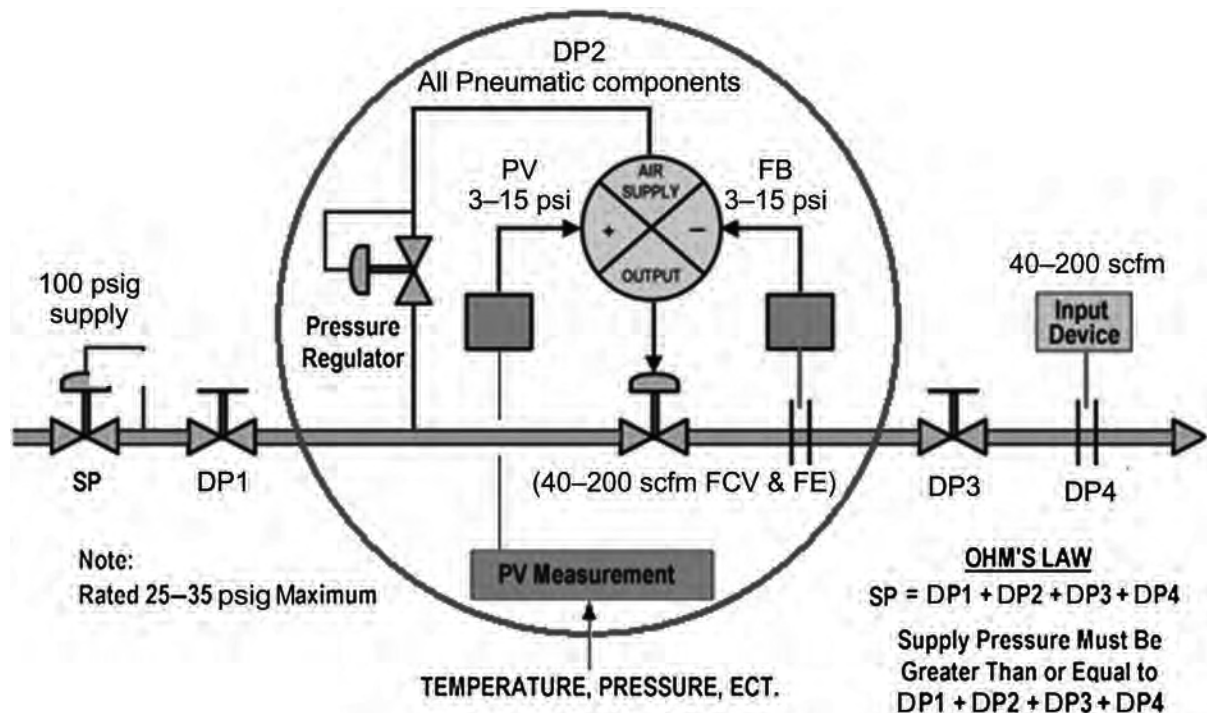


with changes in voltage or resistance in the signal wires. The 4–20 mA analog signal is also immune to electrical noise. Any noise that is injected into the signal loop, such as electromagnetic interference and radio frequency interference, is typically cancelled out by the data acquisition card or input signal card electronic circuitry by design using common mode rejection amplifiers.

It is important to understand that this is a current-based signal and *not* voltage-based! Ohm's law applies to the total voltage drops in the system and will have to be considered when designing your current loops in the plant control system.

See the equivalent schematic of a transmitter below. The transmitter acts as a current pump or a current sourcing device, not a voltage regulator. The measurement or control signal (4–20 mA) is directly proportional to the measurement process variable or controller percentage output.

A pneumatic analogy of the electronic transmitter and process variable transmission signal that is not affected by pressure drops in the signal line by varying hand valves DP1 or DP3 or length of pipe.



A standard 4–20 mA electronic current transmitter with a process variable transmission signal that is not affected by voltage (pressure) drops in the signal line.

22 Overview of Motion Controller Applications

Motion Control Systems

The basic architecture of a motion control system contains:

- A motion controller to move something to a desired position or set and maintain the velocity of a system component or fluid. Motion controllers typically use closed-loop feedback, but not always.
- A drive or amplifier to transform the control signal from the motion controller into a higher power electrical current or voltage that is presented to the actuator.
- An actuator such as a hydraulic pump, air cylinder, linear actuator, or electric motor for output of motion.
- One or more feedback sensors, such as optical encoders, resolvers, or Hall effect devices, to return the position or velocity of the actuator to the motion controller in order to close the position or velocity control loops.
- Mechanical components to transform the motion of the actuator into the desired motion, including gears, shafting, ball screws, belts, linkages, and linear and rotational bearings.

Common control functions include:

- Velocity control.
- Position (point-to-point) control: There are several methods for computing a motion trajectory. These are often based on the velocity profiles of a move, such as a triangular profile, trapezoidal profile, or an S-curve profile.
- Pressure or force control.
- Electronic gearing (or cam profiling).

Stepper Motors

A stepper motor is a brushless, synchronous electric motor that converts digital pulses into mechanical shaft rotation.

Every revolution of the stepper motor is divided into a discrete number of steps, in many cases 200 steps, and the motor must be sent a separate pulse for each step. The stepper motor can only take one step at a time, and each step is the same size. Because each pulse causes the motor to rotate a precise angle, typically 1.8° , the motor's position can be controlled without any feedback mechanism. As the digital pulses increase in frequency, the step movement changes into continuous rotation, with the speed of rotation directly proportional to the frequency of the pulses. Stepper motors are used every day in both industrial and commercial applications because of their low cost, high reliability, high torque at low speeds, and simple, rugged construction that operates in almost any environment.

Closed-Loop Stepper Motor

Modern motion controllers can include the ability to run stepper motors with encoder feedback, resulting in true closed-loop motion control. This mode of motor control is similar to standard three-phase brushless servo motor control, where the three phases are offset 120 electrical degrees. With steppers, the motor has two phases offset by 90 electrical degrees. The benefits of closed-loop control with stepper motors include greatly improved velocity smoothness and reduced power consumption (compared to open-loop steppers) and much higher torque at low velocity (compared with traditional three-phase brushless servomotors).

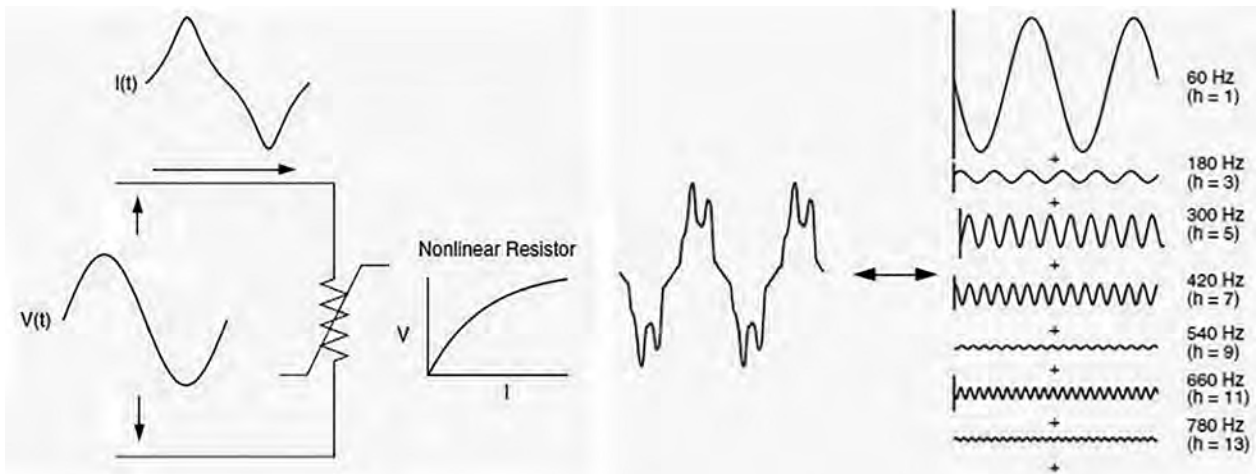
Stepper Motor Advantages

1. The rotation angle of the motor is proportional to the input pulse.
2. The motor has full torque at standstill (if the windings are energized).
3. Precise positioning and repeatability of movement because good stepper motors have an accuracy of 3%–5% of a step and this error is noncumulative from one step to the next.
4. Excellent response to starting/stopping/reversing of the motor.
5. Very reliable because there are no contact brushes in the motor. Therefore, the life of the stepper motor is simply dependent on the life of the bearing.
6. The stepper motor's response to digital input pulses provides open-loop control, making the motor simpler and less costly to control.
7. It is possible to achieve very low speed synchronous rotation with a load that is directly coupled to the shaft.
8. A wide range of rotational speeds can be realized as the speed is proportional to the frequency of the input pulses.
9. Linear motion control with lead screw or worm gears.

23 Electrical Systems and Power Quality

Filtering Power and Harmonics

Harmonic distortion is caused by nonlinear devices in the power system. A nonlinear device is one in which the current is not proportional to the applied voltage. The figure below illustrates this concept by the case of a sinusoidal voltage applied to a simple nonlinear resistor in which the voltage and current vary according to the curve shown. While the applied voltage is perfectly sinusoidal, the resulting current is distorted. Increasing the voltage by a few percent may cause the current to double and take on a different wave shape. This is the source of most harmonic distortion in a power system.



Input for power supply or drive.

Line harmonics due to nonlinear resistance

The figure above illustrates that any periodic, distorted waveform can be expressed as a sum of sinusoids. When a waveform is identical from one cycle to the next, it can be represented as a sum of pure sine waves in which the frequency of each sinusoid is an integer multiple of the fundamental frequency of the distorted wave. This multiple is called a *harmonic* of the fundamental.

There are notable exceptions to this, such as half-wave rectifiers and arc furnaces when the arc is random. Although they may cause interference with low-power electronic devices, they are usually not damaging to the power system.

Harmonic Neutralizing Transformers

Odd harmonics generate heat and a much larger magnitude of rms voltage compared to average voltage. A 24 VAC control circuit transformer may output up to 32 or 45 VAC rms when connected to a plant electrical grid that has very large silicon-controlled rectifier (SCR) heat controllers. The harmonics are reflected in the voltage and then re-induced in the output of the current from the transformer windings.

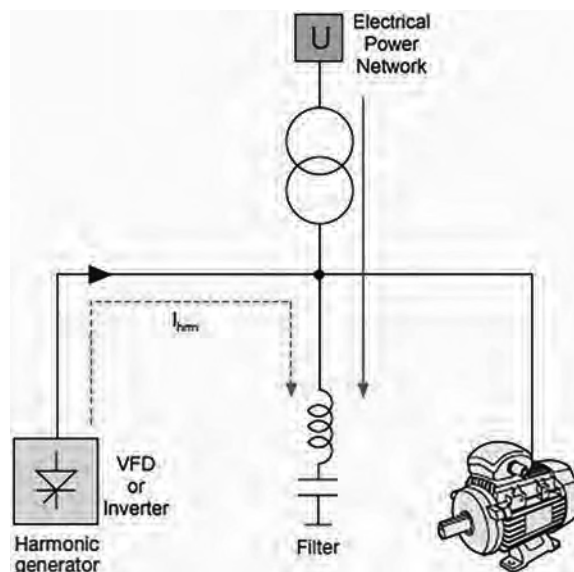
These harmonics cause annoying and troublesome breaker trips and the blowing of fuses in control circuits because of the heating effect. Harmonics can also cause problems on control signal lines. A harmonic neutralizing transformer can reduce and remove most harmonics through cancellation of the distorted waveforms with waveforms 180° out of phase. This results in a very clean waveform.

Filtering Harmonics in Power Systems

Passive Filter

Capacitor banks can be used combined with inductors to limit the effects of the harmonics on a network. Actually, the combination capacitor–inductor constitutes a filter for harmonics. To avoid the negative effects of resonance, it is necessary to insert an inductor in series with a capacitor. By attaching an inductor and a capacitor in proper configuration to the electrical network, harmonics can be drained to the grounding system or be cancelled out in three-phase configurations at resonance frequency in the n^{th} order of the current harmonic to be eliminated. The bandwidth of the n^{th} order of harmonic frequencies (multiples) will be based on the quality of the filter components. This is a band stop filter for the 60 Hz fundamental frequency and a band pass for the n^{th} order of harmonic frequencies.

In this way, the assembly (inductor–capacitor) presents a very low reactance in correspondence with the harmonic (or harmonics) to be eliminated, which shall circulate in the filter assembly without affecting the whole network. In a single-phase circuit, the harmonics will be drained to ground through the current-limiting effect of the reactive components. In a three-phase system, the current will sum to zero.



Passive filter—capacitor connected in series with an inductor.

24 Emergency Standby Systems

NEC Article 700 – Emergency Systems

The requirements of Article 700 apply only to the wiring methods for “emergency systems” that are essential for safety to human life and are required by federal, state, or municipal governments or other agencies having jurisdiction. When normal power is lost, emergency systems shall be able to supply standby power in 10 s or less.

NEC Article 701 – Legally Required Standby Systems

Legally required standby systems provide electric power to aid in firefighting, rescue operations, control of health hazards, and similar operations. When normal power is lost, legally required systems shall be able to supply standby power in 60 s or less, instead of the 10 s or less required of emergency systems.

NEC Article 702 – Optional Standby Systems

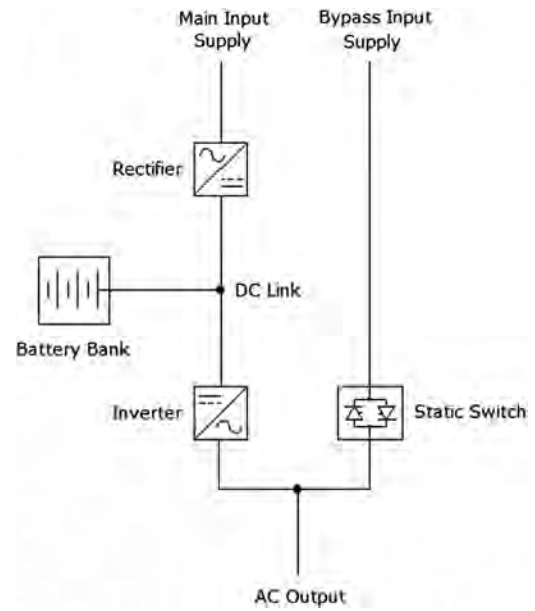
Optional standby systems are intended to protect public or private facilities or property where life safety does not depend on the performance of the system. These systems are typically installed to provide an alternate source of electric power for such facilities as industrial and commercial buildings, farms, and residences, and to serve loads that, when stopped during any power outage, could cause discomfort, serious interruption of the process, or damage to the product or process. Optional standby systems are intended to supply on-site generated power to selected loads either automatically or manually.

Uninterruptible Power Supply

An uninterruptible power supply (UPS), also called *uninterruptible power source* or *battery/flywheel backup*, is an electrical apparatus that provides emergency power to a load when the input power source, typically the main power, fails. A UPS differs from an auxiliary or emergency power system or standby generator in that it will provide nearly instantaneous protection from input power interruptions by supplying energy stored in batteries, supercapacitors, or flywheels. The on-battery runtime of most UPSs is relatively short, only a few minutes to a few hours (maybe up

to 8 h), but sufficient to properly shut down a system in an orderly manner or start a standby power source such as a backup generator.

A UPS is typically used to protect hardware such as computers, data centers, telecommunication equipment, or other electrical equipment where an unexpected power disruption could cause injuries, fatalities, serious business disruption, or data loss. UPS units range in size from those designed to protect a single computer without a video monitor (around 200 VA rating) to large units powering entire data centers or buildings. The world's largest UPS, the 46-megawatt Battery Electric Storage System, in Fairbanks, Alaska, powers the entire city and nearby rural communities during outages.



Backup Generator

The natural gas, propane, or diesel generator is the most widely used alternative source of power in facilities today. Its ability to provide continuous power as long as it has a supply of fuel makes it well suited for providing both long- and short-term backup power.

Most generator-based systems are designed to automatically provide power to designated loads in the event of an interruption in service. When power is lost, the generator automatically starts. Once the generator comes up to speed, a switch automatically transfers the load from utility power to the output of the generator. Depending on the size of the generator, this transfer typically takes place in 30 s or less. When utility company power is restored, the load is transferred back and the generator shuts down.

Note: The phase rotation of the utility power and backup generator must be observed. If the direction of their rotations is not the same, pumps, fans, and other mechanical three-phase equipment may spin in the wrong direction. With make-before-break switches, this will cause a short circuit.

Building Monitoring and Controls System Implementation

The implementation of an advanced building monitoring and controls system (BMCS) incorporating fault-tolerant design, system redundancy, and system integration in data center infrastructure is critical to maintaining the goal of 100% uptime. Fault-tolerant design encompasses designing the BMCS to fail critical systems “on” in the event of a control system malfunction. Fault-tolerant design ensures that the system’s cooling capabilities are not lost because the BMCS malfunctioned or lost power and shut essential mechanical equipment down.

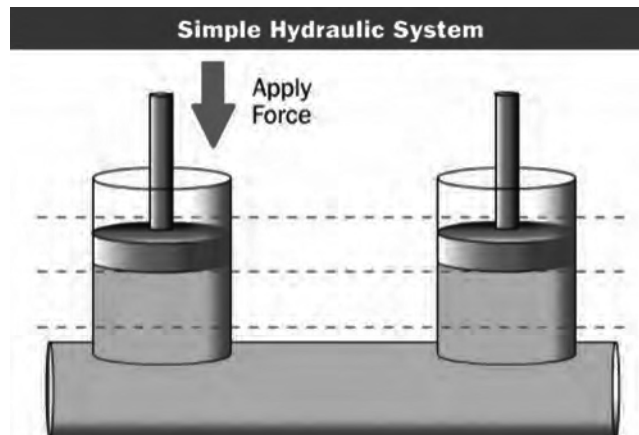
25 Hydraulics and Pneumatics

Fluid Power Systems

Fluid power is the use of fluids under pressure to generate, control, and transmit power. Fluid power is subdivided into hydraulics using a liquid such as mineral oil or water, and pneumatics using a gas such as air or other gases. Compressed-air and water-pressure systems were once used to transmit power from a central source to industrial users over extended geographic areas; fluid power systems today are usually within a single building or mobile machine.

Hydraulic Systems

The basic idea behind any hydraulic system is very simple: Force that is applied at one point is transmitted to another point using an incompressible fluid. The fluid is almost always an oil of some sort. The force is almost always multiplied in the process. The picture below shows the simplest possible hydraulic system:



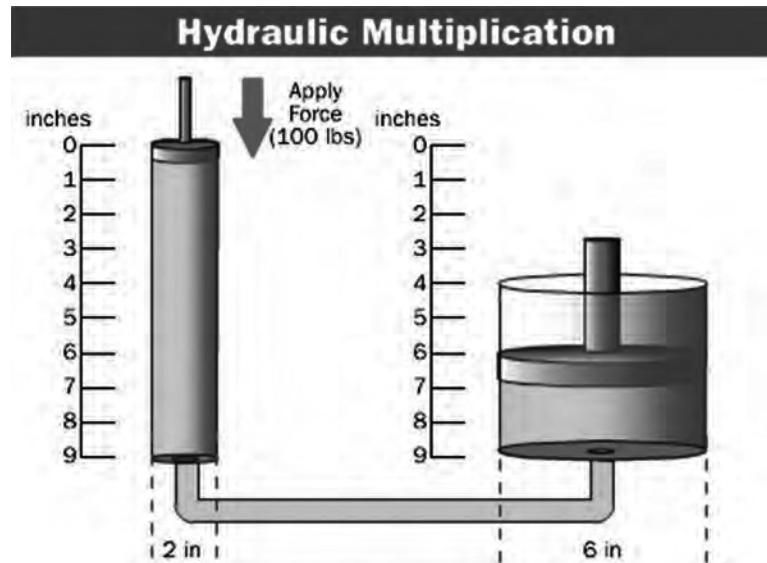
A simple hydraulic system consisting of two pistons and an oil-filled pipe connecting them.

If you apply a downward force to one piston (the left one in this drawing), then the force is transmitted to the second piston through the oil in the pipe. Because oil is incompressible—the efficiency is very good—almost all the applied force appears at the second piston.

The great thing about hydraulic systems is that the pipe connecting the two cylinders can be any length and shape, which enables installers to snake it through all sorts of things separating

the two pistons. The pipe can also fork, so that one *master cylinder* can drive more than one **slave** cylinder if desired.

In a hydraulic system, all you do is change the size of one piston and cylinder relative to the other to make a hydraulic amplifier, as shown in the next image. This is called *hydraulic multiplication*. The piston on the right has a surface area nine times greater than the piston on the left. When force is applied to the left piston, it will move nine units for every one unit that the right piston moves, and the force is multiplied by nine on the right-hand piston.



To determine the **multiplication factor**, start by looking at the size of the pistons. Assume that the piston on the left is 2 in in diameter (1-inch radius), while the piston on the right is 6 in in diameter (3-inch radius). The area of the two pistons is π multiplied by r^2 . The area of the left piston is therefore 3.14, while the area of the piston on the right is 28.26.

The piston on the right is nine times larger than the piston on the left. What that means is that any force applied to the left-hand piston will appear nine times greater on the right-hand piston. So if you apply a 100-pound downward force to the left piston, a 900-pound upward force will appear on the right. The only catch is that you will have to depress the left piston 9 in to raise the right piston 1 in.

Pneumatic Systems

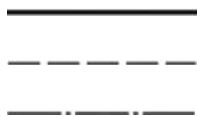
Pneumatics is a branch of technology that deals with the study and application of pressurized gas to produce mechanical motion. Pneumatic systems used extensively in industry are commonly powered by compressed air or compressed inert gases. A centrally located and electrically powered compressor powers cylinders, air motors, and other pneumatic devices. A pneumatic system controlled through manual or automatic solenoid valves is selected when it provides a lower cost, more flexible, or safer alternative to electric motors and actuators.



26 Fluid Power Schematic Symbols

Hydraulic and Pneumatic Circuit Design

Lines



Connecting pressure lines (usually representing plastic tubing for pneumatic [air] lines with low pressures, metal piping for hydraulic [fluid] lines with high pressure)

continuous line for flow line

dashed line for pilot, drain

envelope for long and short dashes around two or more component symbols.

Circular



large circle – pump, motor

small circle – measuring devices

semicircle – rotary actuator

Square



one square – pressure control function

two or three adjacent squares – directional control

Diamond



diamond – fluid conditioner (filter, separator, lubricator, heat exchanger)

Miscellaneous Symbols



spring

slow restriction

Triangle



solid – direction of hydraulic fluid flow

open – direction of pneumatic flow

Pump and Compressor Symbols

(Turn rotary torque from an AC or DC electric motor into pressure in a hydraulic or pneumatic system)

Fixed Displacement Hydraulic Pump

-  unidirectional
-  bidirectional

Variable Displacement Hydraulic Pump

-  unidirectional
-  bidirectional

Compressor



Motor Symbols

Fixed Displacement Hydraulic Motor

-  unidirectional
-  bidirectional

Variable Displacement Hydraulic Motor

-  unidirectional
-  bidirectional

Pneumatic Motor

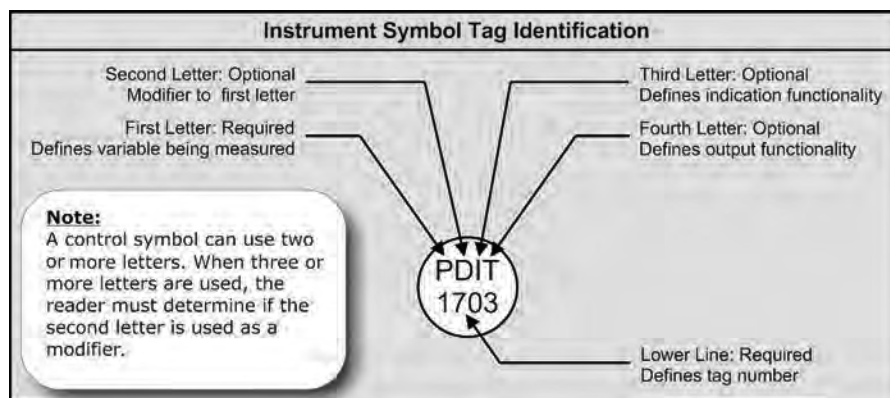
-  unidirectional
-  bidirectional

Rotary Actuator Symbol

-  hydraulic
-  pneumatic

27 ISA Standards for Documentation

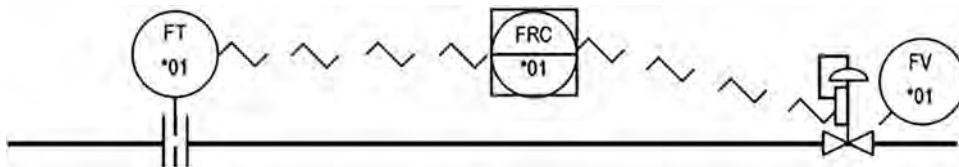
ISA Instrument or Function Symbol—ANSI/ISA-5.1-2009



	Primary Location Normally Accessible to operator	Field Mounted	Auxiliary Location Normally Accessible to operator	Behind the Panel Normally Inaccessible to Operator
Discrete Instrument				
Shared Display, Shared Control				
Computer Function				
Programmable Logic Control				
	Instruments Sharing Common Housing	Instrument with long Tag Number	Interlock Logic	Convert Such As Current to Pressure
More Common Symbols				

ISA Line-Type Symbols—ANSI/ISA-5.1-2009

B.9.5 Shared display, shared control, and wireless instrumentation:

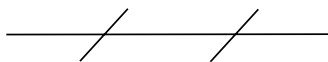


Standard Line Types—ANSI/ISA-5.1-2009

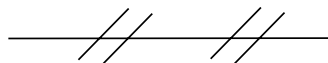
1. Instrument Supply or Connected to Process



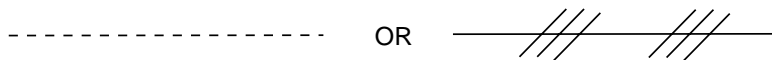
2. Undefined Signal



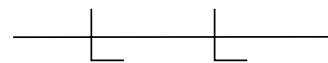
3. Pneumatic Signal



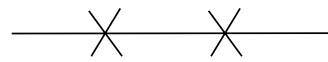
4. Electric Signal



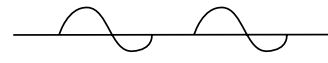
5. Hydraulic Signal



6. Capillary Signal



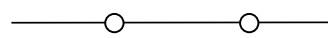
7. Electromagnetic or Sonic Signal (Guided)



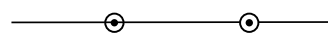
8. Electromagnetic or Sonic Signal (Not Guided)



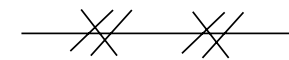
9. Internal Systems Link (Software or Data Link)



10. Mechanical Link



11. Pneumatic Binary



12. Electrical Binary



28 Overview of Safety Instrumented Systems

Overview of Process Safety and Shutdown

On the CSE exam, there will be questions on safety instrumented systems (SISs) and safety integrity levels (SILs). We will discuss some of the calculations and data you may encounter on the test.

SISs

US Occupational Safety and Health Administration (OSHA) law incorporates as a guideline that “good engineering practice” will be used in evaluating and engineering SISs. This means that the program follows the codes and standards published by such organizations as the American Society of Mechanical Engineers (ASME), American Petroleum Institute (API), American National Standards Institute (ANSI), National Fire Protection Association (NFPA), American Society for Testing and Materials (ASTM), National Board of Boiler and Pressure Vessel Inspectors (NBBI), and International Society of Automation (ISA). Other countries have similar requirements.

ANSI/ISA-S84.00.01-2003, (IEC 61511 Mod), *Application of Safety Instrumented Systems for the Process Industries*, (referred to as IEC 61511/ISA-84 in this book) addresses the application of SISs to take a process to a safe state when predetermined conditions are violated, such as set points for pressure, temperature, and level. Its objective is to define requirements for SISs. SISs are also called *emergency shutdown systems*, *safety shutdown systems*, and *safety interlock systems*. SISs provide safety control functions and complement the basic process control system (BPCS), which provides normal process control. IEC 61511/ISA-84 address the entire life cycle for SISs, and compliance with the standard requires a significant effort.

Complying with IEC 61511/ISA-84

OSHA endorsed IEC 61511/ISA-84 as a “national consensus standard” in a March 23, 2000, OSHA letter to ISA. This letter states that the standard is considered “a recognized and generally accepted good engineering practice” for SISs. Paragraph (d)(3)(ii) of the process safety management (PSM) standard specifies, “The employer shall document that equipment complies with recognized and generally accepted good engineering practices.” The letter states that in evaluating whether an employer’s engineering practices with respect to SISs comply with PSM, OSHA would consider, among other factors, whether the employer meets the requirements of IEC 61511/ISA-84.

In the letter, OSHA states that it is also important to note that there are a large percentage of processes that are not covered by PSM, which may include SISs covered by the standard. OSHA states that *“the employer may be in violation of the General Duty Clause, Section 5(a)(1) of the OSH Act, if SISs are utilized that do not conform with IEC 61511/ISA-84, and hazards exist related to the SISs that could seriously harm employees”*. Consequently, this means that companies must comply with IEC 61511/ISA-84, not only for PSM-covered processes, but also for other processes that use SISs where hazards to personnel may be present.

Regardless of regulatory requirements, IEC 61511/ISA-84 is an internationally recognized standard and represents good engineering practice.

Other Codes Related to SIS

- NFPA 85 – *Boiler and Combustion Systems Hazard Code*
- NFPA 86 – *Standard for Ovens and Furnaces*
- IEC 61508 – *Functional Safety: Safety-Related Systems*
- IEC 61511 – *Functional Safety: Safety Instrumented Systems for the Process Industry Sector*
- ANSI/ISA S84.01 – *Application of Safety Instrumented Systems for the Process Industries*

ISA and OSHA Letter Defining the Requirements for Implementation of SIS

- Standard Number: 1910.119

This letter constitutes OSHA’s interpretation only of the requirements discussed and may not be applicable to any situation not delineated within the original correspondence.

November 29, 2005

Ms. Lois M. Ferson
Manager of Standards Services
ISA
67 Alexandria Drive
P.O. Box 12277
Research Triangle Park, NC 27709

Dear Ms. Ferson:

Thank you for your October 25, 2004 letter to the Occupational Safety and Health Administration (OSHA), on behalf of the Instrumentation, Systems, and Automation Society (ISA), regarding a consensus standard jointly issued by the American National Standards Institute (ANSI) and ISA that may be applied under OSHA’s Process Safety Management (PSM) standard, 29 CFR 1910.119. We apologize for the delay in our response.

29 Overview of NEC/NFPA and Other Codes

NFPA 30	2003	National Fire Protection Association	Flammable and Combustible Liquids Code	49 CFR 192
NFPA 54	2002	National Fire Protection Association	National Fuel and Gas Code	24 CFR 3280
NFPA 58	2001	National Fire Protection Association	Standard for Liquefied Petroleum Gases	49 CFR 173
NFPA 58	2004	National Fire Protection Association	Standard for the Storage and Handling of Liquefied Petroleum Gases	49 CFR 192.11(b)
NFPA 59	2004	National Fire Protection Association	Standard for the Storage and Handling of Liquefied Petroleum Gases at Utility Gas Plants	49 CFR 192.11(b)
NFPA 70	2005	National Fire Protection Association	National Electrical Code	49 CFR 192.189(c)
NFPA 101	2000	National Fire Protection Association	Life Safety Code	59 CFR 130
UL 50	1995	Underwriters Laboratories	Standard for Enclosures for Electrical Equipment	46 CFR 111.81-1(d)

List of NFPA Codes (Be Familiar with These Codes)

The CSE exam will include code questions. We covered American Society of Mechanical Engineers (ASME) in Chapter 14 pressure-relief valves and safety rupture disks. We will now talk about the codes for the installation, maintenance, and operation of control systems in manufacturing and process plants. Our focus will be on the installation of electrical systems.

Here are the major codes the CSE exam may cover:

NFPA 30 – *Flammable and Combustible Liquids Code*

NFPA 70 NEC – *National Electrical Code* (be extremely familiar with this code)

NFPA 70E – *Standards for Electrical Safety in the Workplace*

NFPA 77 – *Static Electricity* (very important in the application of loading stations)

NFPA 79 – *Industrial Machinery* (electrical code specifically focusing on industrial controls for machinery)

NFPA 407 – *Aircraft Fuel Servicing*

NFPA 780 – *Lightning Protection* (protection of equipment and tanks from damage and explosion)

NFPA 496 – *Purged and Pressurized Systems* (used extensively in petrochemical production)

All the above listed standards are referred to and may be required by the word “shall” to meet the federally required compliance. 49 CFR 195.405(a) (API Standard 2003 *Protection Against Ignitions Arising Out of Static, Lightning, and Stray Currents*) and 49 CFR 192 (NFPA 30, *Flammable and Combustible Liquids Code*) are both required by the NEC, NFPA 70.

NFPA 70 – NEC

Be familiar with the NEC (NFPA 70) *National Electrical Code Handbook*, or a book of equal information. Most, if not all, the information and tables required for performing the calculations on the CSE exam are in this manual. The handbook contains information needed for motors, hazardous locations, National Electrical Manufacturers Association (NEMA) classifications, and temperature group ratings. The NEC handbook contains information about group classifications and auto-ignition temperature ratings of flammable gases and vapors (reprints from NFPA 497M).

Most states require an inspection of plant installations by a local electrical inspector (authority having jurisdiction—AHJ). In Article 100 of the 2014 NEC, the term *authority having jurisdiction* is defined as “an organization, office, or individual responsible for enforcing the requirements of a code or standard, or for approving equipment, materials, an installation, or a procedure.”

The following is a list of tables that may be used on the CSE exam.

- Table 310-16 Conductor ampacities in raceways, cable or earth
- Table 430-147 Motor currents for single-phase motors
- Table 430-150 Motor currents for three-phase motors
- 500-2 List of TYPE X, Y, Z purging of enclosures (in handbook only)
- 500-3 Special precautions, group classifications of gases and vapors
- 500-3 List of gases and vapors, with their group ratings (in handbook only)
- 504-X Intrinsically Safe Systems (review this section)
- 504-50 Handbook, diagrams of intrinsically safe barriers
- 725 Class 1, Class 2, Class 3 Remote Control Circuits
- 800 Communications Circuits
- Chapter 9—Table 8 Conductor properties and DC resistance
- Chapter 9—Table 9 AC resistance for 600-volt cables

Voltage Drop Calculations

Voltage drop will also probably be on the CSE exam. Voltage drop is just Ohm’s law.

$$V_D = \left(\frac{2 \cdot L}{1000} \right) \cdot I \cdot R \text{ (from NEC table); for DC}$$

30 Equations for Pumping, Piping, and Sizing Motors

Find Pipe Diameter with Velocity of Flow Known

$$ID \text{ (in)} = \sqrt{\frac{\text{gpm} \cdot 0.4085}{\text{velocity (ft/s)}}}$$

$$ID \text{ (in)} = \sqrt{\frac{\text{acfm} \cdot 3.0558}{\text{velocity (ft/s)}}}$$

Find Flow Velocity with Pipe Diameter Known

$$\text{velocity (ft/s)} = \frac{\text{gpm} \cdot 0.4085}{ID^2 \text{ (in)}}$$

$$\text{velocity (ft/s)} = \frac{\text{acfm} \cdot 3.0558}{ID^2 \text{ (in)}}$$

Change acfm to scfm with Standard Temperature and Pressure Correction

$$\text{scfm} = \text{acfm} \left(\frac{14.7}{14.7 + \text{psig}} \right) \left(\frac{460 + T_{\text{deg F}}}{520} \right)$$

Note: scfh equals scfm times 60 (acfm equals scfm when both are at 60°F and 14.696 psia)

Change scfm to acfm with Standard Temperature and Pressure Correction

$$\text{acfm} = \frac{\text{scfm}}{\left(\frac{14.7}{14.7 + \text{psig}} \right) \left(\frac{460 + T_{\text{deg F}}}{520} \right)}$$

where

T = temperature

Find the Reynolds Number for the Flow

$$R_e = \frac{3160 \cdot \text{flow rate (gpm)} \cdot SG}{\text{Pipe ID (in)} \cdot \text{Viscosity (cSt)}} \quad \textbf{Note: for liquids}$$



$$R_e = \frac{7740 \cdot \text{Velocity (ft/s)} \cdot \text{Pipe ID (in)}}{\text{Viscosity (cSt)}} \quad \text{Note: for liquids}$$

$$R_e = \frac{6.316 \cdot \text{Flow Rate (lb/h)}}{\text{Pipe ID (in)} \cdot \text{Viscosity (cSt)}} \quad \text{Note: for gases and steam}$$

Calculate the Piping Head Losses to Size a Control Valve

Calculate the pump head needed for a piping system.

Note: Feet of head in system (h_{sys}) equals height plus head loss in the pipe plus head loss in the fittings plus head across the meter element plus head across the control valve plus head for pressure in the vessel.

The head for the pump is all in feet of head. This head must be in feet of head at the maximum operating flow rate.

$$h_{\text{sys}} = h_{\text{elevation}} + h_{\text{pipe}} + h_{\text{fitting}} + h_{\text{meter}} + h_{\text{valve}} + h_{\text{vessel}}$$

Head Losses for Piping System (h_{pipe})

The Darcy–Weisbach equation for piping head loss in feet of head loss across the piping system is:

$$h_{\text{pipe}} = f \left(\frac{\text{Length (ft)}}{\text{Pipe ID (ft)}} \right) \cdot \frac{V^2 (\text{ft/s})}{2 \cdot g} = f \left(\frac{\text{Length (ft)} \cdot 12}{\text{Pipe ID (in)}} \right) \cdot \frac{V^2 (\text{ft/s})}{64.34}$$

Moody friction factor formula for Darcy - Weisbach equation

Note: $e = 0.00015$ for steel pipes

$$f = 0.0055 + 0.0055 \left[20,000 \left(\frac{e \cdot 12}{\text{Pipe ID (in)}} \right) + \frac{10^6}{Re} \right]^{\frac{1}{3}}$$

where

h_{pipe} = head drop across pipe system

f = friction factor of pipe

V = velocity in feet per second

e = relative roughness of pipe

Head Losses for Hand Valves and Fittings (h_{fitting})

Use this formula to obtain head loss of fittings and hand valves. Then add this head loss to the piping head loss obtained by the Darcy–Weisbach equation for the total piping system head loss as:

$$h_{\text{fitting}} = K \cdot \frac{V^2 (\text{ft/s})}{2 \cdot g} = K \cdot \frac{V^2 (\text{ft/s})}{64.34}$$

where K is computed as: **Note:** L_e and D are in feet, so $D (\text{ft}) = d (\text{in})/12$.

31 Calculating Volume in Tanks

The following calculations are for obtaining the volume of cylindrical and irregularly shaped tanks.

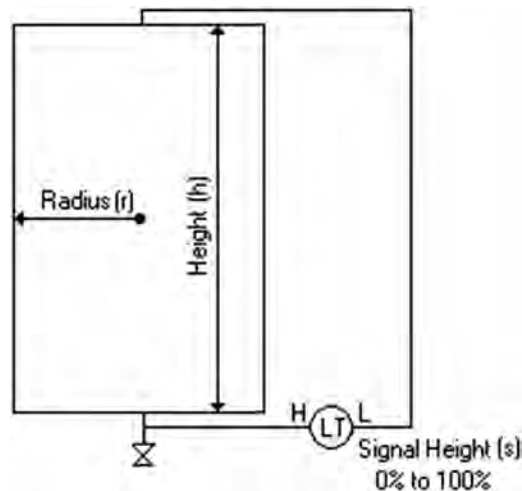
See Chapter 8, “Level Measurement and Calibration,” for the level transmitter calibration.

This section is for information only. All units are in inches. This topic will not be on the CSE exam.

Note: All measurements for calculations are in units of inches. Diameter (D) = h in these examples.

(Hint: Multiply the tank diameter (h) by the percentage level signal to get y , and then calculate the formula.)

Cylindrical Tanks Upright



$$y = h \cdot s = \text{height} \cdot 0.00 \text{ to } 1.00 \text{ (\% of signal from transmitter)}$$

$$V_{\text{gal}} = (\pi \cdot r^2 \cdot y) / 231 \text{ in}^3$$

where

y = height of process fluid in inches

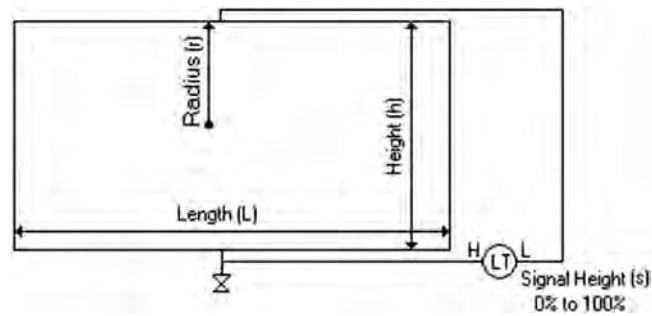
h = tank height in inches

V = volume in gallons

r = radius of tank in inches

s = percent height of process variable

Cylindrical Tanks on Side

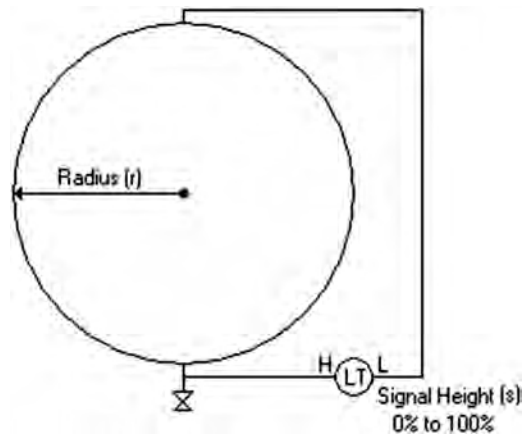


$$y = h \cdot s = \text{height} \cdot 0.00 \text{ to } 1.00 \text{ (\% of signal from transmitter)}$$

$$V_{\text{gal}} = \text{length} \cdot \left[r^2 \cdot \cos^{-1} \left(1 - \frac{y}{r} \right) + \sqrt{(2r - y)y} \cdot (y - r) \right] / 231 \text{ in}^3$$

Important Note: The (\cos^{-1}) or (arccos) or (acos) function must return radians, *not* degrees. All measurements for the calculations are in units of inches.

Spherical Tanks



$$y = h \cdot s = \text{height} \cdot 0.00 \text{ to } 1.00 \text{ (\% of signal from transmitter)}$$

$$V_{\text{gal}} = \frac{1}{3} \pi (3r - y) y^2 / 231 \text{ in}^3$$

32 Exam Sample Questions

Sample Questions

1. At 433°F, a type J thermocouple with a 32°F reference junction (ice bath) will produce an output in millivolts (mV) that is most nearly equal to:
 - A. 9.04 mV
 - B. 10.51 mV
 - C. 12.05 mV
 - D. 17.79 mV
2. The flow of water in a 6-inch pipe is measured with an orifice plate and differential pressure transmitter. At a flow rate of 200 gpm, the differential pressure is 35 in of water. At a flow rate of 312 gpm, the differential pressure will be approximately equal to:
 - A. 16.4 in wc
 - B. 32.5 in wc
 - C. 85.4 in wc
 - D. 100 in wc
3. A tank level is measured using a differential pressure transmitter and a bubbler tube. The tank is vented to atmosphere. The bubbler tube is 1 ft from the bottom of the tank, and the tank wall is 20 ft high. A 0–10 psig differential pressure gauge, accurate to 0.25% of full scale, is connected to the bubbler tube connection at the high side of the transmitter. The low-pressure side is connected to the tank top. With the tank containing liquid with a specific gravity (SG) of 1.1 and the level in the tank at 16 ft, the gauge reading in pounds per square inch (psi) is most nearly equal to:
 - A. 4.80
 - B. 9.35
 - C. 13.00
 - D. 7.10
4. Which of the following practices is important in routing optic cable?
 - A. Laying cable in trays with high-horsepower motor wiring should be avoided.
 - B. Conduit fittings that require small radius bends should be avoided.
 - C. Overhead runs on messenger wires should be limited to 75 ft.
 - D. Underground fiber-optic runs must be covered with concrete.

5. Compared to a control loop with no dead time (pure time delay), a control loop with an appreciable dead time tends to require:
- A. Less proportional gain and less integral action
 - B. More proportional gain and less integral action
 - C. More proportional gain and more integral action
 - D. Less proportional gain and more integral action
6. The definition and classification of hazardous areas for the purpose of wiring and electrical equipment is found in codes published by:
- A. National Fire Protection Association
 - B. International Society of Automation
 - C. Electric Power Research Institute
 - D. Occupational Safety and Health Administration
7. Given the following data for liquid flow:
Flow rate: 0–200 gpm
Water at: 125°F and 75 psia
Pipe size: 4-inch, schedule 40
- The orifice bore for a pressure differential range of 100 in of water is most nearly equal to:
- A. 2.33 in
 - B. 3.50 in
 - C. 1.50 in
 - D. 0.75 in
8. A control valve is to be sized for the following conditions:
Liquid flow: 50 gpm
Specific gravity: 0.81
Inlet pressure: 240 psig
Delta pressure drop of across the valve: 10 psi
- The required flow coefficient (C_v) for the valve will most nearly be:
- A. 10.4
 - B. 14.2
 - C. 22.0
 - D. 35.5
9. A control valve is to be sized for the following service conditions, saturated steam:
Maximum flow rate: 30,000 lb/h
 P_1 (upstream pressure): 40 psia
 P_2 (downstream pressure): 30 psia

33 Guide to the Fisher Control Valve Handbook

The *Fisher Control Valve Handbook* from Emerson is a supplement book with many worked examples.

Purchasing this book or printing it out is highly recommended.

The handbook can help aid in study for the CSE exam. The information and tables in the *Fisher Control Valve Handbook* will be constantly referenced. I have repeated the most common data from the book needed for the CSE exam. The book is not required, but it is recommended and may be downloaded in PDF format from the Fisher Controls public website at the following address:

<https://www.emerson.com/documents/automation/control-valve-handbook-en-3661206.pdf>

If you wish to obtain a hard copy of the handbook, the *Fisher Control Valve Handbook* can be acquired for free, or for about \$20, from your local instrumentation supplier. The book is also available from Brown's Technical Book Shop, 1517 San Jacinto, Houston, Texas, 77002. <http://www.browntechnical.org>.

I suggest tabbing the handbook for quick reference.

Important Sections to Review

- Chapter 3 – Valve and Actuator Types
- Chapter 5 – USA Regulatory Requirement for Fugitive Emissions
- Chapter 5 – Control Valve Selection (and sizing)

Important Pages to Possibly Tab

Valve and Materials Selection

- Chart for Test Frequency for Valves Leaking 500 ppm
- Sliding-Stem Valve Environmental Packing Selection
- Rotary Valve Environmental Packing Selection
- Designations for the High Nickel Alloys

Pressure-Temperature Ratings for Standard Class

- Cast Carbon Steel (ASTM A216 Grade WCC)
- Cast Chromium-Molybdenum Steel (ASTM A217 Grade WC9)
- Cast Chromium-Molybdenum Steel (ASTM A217 Grade C5)
- Cast Type 304L Stainless Steel (ASTM A351 Grade CF3)
- Cast Type 316 Stainless Steel (ASTM A351 Grade CF8M)
- Cast Type 317 Stainless Steel (ASTM A479 Grade UNS S31700)
- Cast Iron (ASTM A126)
- Cast Bronze Valves (ASTM B61 and B62)

Valve Trim Material Temperature Limits

Ambient Temperature Corrosion information

Elastomer Information

Application of Valves for Liquid Level Systems

Application of Valves for Flow Control Processes

Actuator Sizing Methods

- Typical Packing Friction Values
- Actuator Force Calculations
- Typical Rotary Shaft Valve Torque Factors (V-Notch Ball Valve)
- Typical Rotary Shaft Valve Torque Factors (High-Performance Butterfly Valve)
- Packing Selection Guidelines for Sliding-Stem Valves (100 ppm)
- Packing Selection Guidelines for Rotary Valves (500 ppm)

Valve Sizing Methods

- Valve Sizing Procedure
- Abbreviations and Terminology
- Equation Constants
- Determining q_{MAX} (the Maximum Flow Rate)
- Determining P_{MAX} (the Allowable Sizing Pressure Drop)
- Liquid Sizing Sample Problem
- Sizing Coefficients (C_v , X_T) for Single-Ported Globe Valve Bodies
- Sizing Coefficients (C_v , X_T) for Rotary Shaft Valve Bodies

Electrical Apparatus

- NEMA Enclosure Ratings and Definitions
- Hazardous Location Classification
- IEC Temperature Codes (Temperature Ratings)
- NEMA and IEC Enclosure Rating Comparison



Appendix and Data Tables

Table A1 – Thermocouple Table: Type J

Table A2 – Thermocouple Table: Type K

Table A3 – Thermocouple Table: Type E

Table A4 – Thermocouple Table: Type T

Table A5 – Platinum 100 Ohm Resistance Temperature Detector Table in Ohms

Table A6 – Properties of Water Specific Gravity and Pounds per Hour to Gallons per Minute Conversion

Table A7 – Properties of Water: Specific Volume and Density

Table A8 – Properties of Water: Kinematic Viscosity Centistokes

Table A9 – Properties of Saturated Steam

Table A10 – Valve Selection: Materials and Applications

Valve Terms

Selecting Your Valve

Valve Types and Descriptions

Valve Selection Overview: Service Application Chart

Valve Selection Detailed: Service Application Chart

Valve Types: Advantages and Disadvantages

Standard Control Valve Body Materials

Valve Seat Leakage Bubbles per Minute

Valve Trim Material Temperature Limits

Valve Service Temperature Limits for Nonmetallic Materials

Valve Stem Packing Friction Values – Typical

Valve Stem Packing Temperature – Pressure

Valve Seating Shutoff Pressure

Abbreviations and Terminology

Table A11 – Properties and Sizing C_v Coefficients for Fisher ED Globe Valves

Table A12 – Properties and Sizing C_v Coefficients for Fisher Rotary Valves

Table A13 – Numerical Constants for Control Valve Sizing Formulas

Table A14 – Critical Pressure and Temperature of Elements

Table A15 – Standard Pipe Dimensions and Data

Table A16 – NEC Wire Ampacity Table 310.16

Table A17 – NEC Conductor Properties and Impedance

Table A18 – NEC Full-Load Motor Currents

Table A19 – NEC Grounding and Bonding Conductors

Table A20 – Specific Gravity and Gas Constants: Some Common Gases

Table A21 – Specific Gravity: Common Fluids

Table A22 – Kinematic Viscosity: Common Fluids

Table A23 –Absolute Viscosity: Common Liquids

Table A24 –Absolute Viscosity Common Gases

Table A25 – Density of Elements in English and Metric Units

Table A26 – Metric Conversion Tables

Table A27 – Standard Conditions and Gas Laws

Table A28 – Head Loss in Piping Systems

Table A29 – Maximal Flow Velocity in Pipes

Table A30 – Pressure Vapor Chart of Common Liquids



Table A1 – Thermocouple Table: Type J**Thermoelectric Voltage in Millivolts**

°F	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	°F	°F	0	1	2	3	4	5	6	7	8	9	10	°F
-340					-8.095	-8.085	-8.074	-8.063	-8.052	-8.041	-8.030	-340	300	7.949	7.979	8.010	8.041	8.071	8.102	8.133	8.163	8.194	8.225	8.255	300
-330	-8.030	-8.019	-8.008	-7.996	-7.985	-7.973	-7.962	-7.950	-7.938	-7.927	-7.915	-330	310	8.255	8.286	8.317	8.347	8.378	8.409	8.439	8.470	8.501	8.532	8.562	310
-320	-7.915	-7.903	-7.890	-7.878	-7.866	-7.854	-7.841	-7.829	-7.816	-7.804	-7.791	-320	320	8.562	8.593	8.624	8.654	8.685	8.716	8.747	8.777	8.808	8.839	8.869	320
-310	-7.791	-7.778	-7.765	-7.752	-7.739	-7.726	-7.713	-7.699	-7.686	-7.672	-7.659	-310	330	8.869	8.900	8.931	8.962	8.992	9.023	9.054	9.085	9.115	9.146	9.177	330
-300	-7.659	-7.645	-7.632	-7.618	-7.604	-7.590	-7.576	-7.562	-7.548	-7.534	-7.519	-300	340	9.177	9.208	9.238	9.269	9.300	9.331	9.362	9.392	9.423	9.454	9.485	340
-290	-7.519	-7.505	-7.491	-7.476	-7.462	-7.447	-7.432	-7.417	-7.403	-7.388	-7.373	-290	350	9.485	9.515	9.546	9.577	9.608	9.639	9.669	9.700	9.731	9.762	9.793	350
-280	-7.373	-7.357	-7.342	-7.327	-7.312	-7.296	-7.281	-7.265	-7.250	-7.234	-7.219	-280	360	9.793	9.823	9.854	9.885	9.916	9.947	9.977	10.008	10.039	10.070	10.101	360
-270	-7.219	-7.203	-7.187	-7.171	-7.155	-7.139	-7.123	-7.107	-7.090	-7.074	-7.058	-270	370	10.101	10.131	10.162	10.193	10.224	10.255	10.285	10.316	10.347	10.378	10.409	370
-260	-7.058	-7.041	-7.025	-7.008	-6.991	-6.975	-6.958	-6.941	-6.924	-6.907	-6.890	-260	380	10.409	10.440	10.470	10.501	10.532	10.563	10.594	10.625	10.655	10.686	10.717	380
-250	-6.890	-6.873	-6.856	-6.839	-6.821	-6.804	-6.787	-6.769	-6.752	-6.734	-6.716	-250	390	10.717	10.748	10.779	10.810	10.840	10.871	10.902	10.933	10.964	10.995	11.025	390
-240	-6.716	-6.699	-6.681	-6.663	-6.645	-6.627	-6.609	-6.591	-6.573	-6.555	-6.536	-240	400	11.025	11.056	11.087	11.118	11.149	11.180	11.211	11.241	11.272	11.303	11.334	400
-230	-6.536	-6.518	-6.500	-6.481	-6.463	-6.444	-6.426	-6.407	-6.388	-6.370	-6.351	-230	410	11.334	11.365	11.396	11.426	11.457	11.488	11.519	11.550	11.581	11.612	11.642	410
-220	-6.351	-6.332	-6.313	-6.294	-6.275	-6.256	-6.236	-6.217	-6.198	-6.179	-6.159	-220	420	11.642	11.673	11.704	11.735	11.766	11.797	11.828	11.858	11.889	11.920	11.951	420
-210	-6.159	-6.140	-6.120	-6.101	-6.081	-6.061	-6.042	-6.022	-6.002	-5.982	-5.962	-210	430	11.951	11.982	12.013	12.044	12.074	12.105	12.136	12.167	12.198	12.229	12.260	430
-200	-5.962	-5.942	-5.922	-5.902	-5.882	-5.862	-5.842	-5.821	-5.801	-5.781	-5.760	-200	440	12.260	12.290	12.321	12.352	12.383	12.414	12.445	12.476	12.506	12.537	12.568	440
-190	-5.760	-5.740	-5.719	-5.699	-5.678	-5.657	-5.637	-5.616	-5.595	-5.574	-5.553	-190	450	12.568	12.599	12.630	12.661	12.691	12.722	12.753	12.784	12.815	12.846	12.877	450
-180	-5.553	-5.532	-5.511	-5.490	-5.469	-5.448	-5.426	-5.405	-5.384	-5.363	-5.341	-180	460	12.877	12.907	12.938	12.969	13.000	13.031	13.062	13.093	13.123	13.154	13.185	460
-170	-5.341	-5.320	-5.298	-5.277	-5.255	-5.233	-5.212	-5.190	-5.168	-5.146	-5.125	-170	470	13.185	13.216	13.247	13.278	13.308	13.339	13.370	13.401	13.432	13.463	13.494	470
-160	-5.125	-5.103	-5.081	-5.059	-5.037	-5.015	-4.992	-4.970	-4.948	-4.926	-4.903	-160	480	13.494	13.524	13.555	13.586	13.617	13.648	13.679	13.709	13.740	13.771	13.802	480
-150	-4.903	-4.881	-4.859	-4.836	-4.814	-4.791	-4.769	-4.746	-4.724	-4.701	-4.678	-150	490	13.802	13.833	13.864	13.894	13.925	13.956	13.987	14.018	14.049	14.079	14.110	490
-140	-4.678	-4.655	-4.633	-4.610	-4.587	-4.564	-4.541	-4.518	-4.495	-4.472	-4.449	-140	500	14.110	14.141	14.172	14.203	14.233	14.264	14.295	14.326	14.357	14.388	14.418	500
-130	-4.449	-4.425	-4.402	-4.379	-4.356	-4.332	-4.309	-4.286	-4.262	-4.239	-4.215	-130	510	14.418	14.449	14.480	14.511	14.542	14.573	14.603	14.634	14.665	14.696	14.727	510
-120	-4.215	-4.192	-4.168	-4.144	-4.121	-4.097	-4.073	-4.050	-4.026	-4.002	-3.978	-120	520	14.727	14.757	14.788	14.819	14.850	14.881	14.911	14.942	14.973	15.004	15.035	520
-110	-3.978	-3.954	-3.930	-3.906	-3.882	-3.858	-3.834	-3.810	-3.786	-3.761	-3.737	-110	530	15.035	15.065	15.096	15.127	15.158	15.189	15.219	15.250	15.281	15.312	15.343	530
-100	-3.737	-3.713	-3.688	-3.664	-3.640	-3.615	-3.591	-3.566	-3.542	-3.517	-3.493	-100	540	15.343	15.373	15.404	15.435	15.466	15.496	15.527	15.558	15.589	15.620	15.650	540
-90	-3.493	-3.468	-3.443	-3.419	-3.394	-3.369	-3.344	-3.320	-3.295	-3.270	-3.245	-90	550	15.650	15.681	15.712	15.743	15.773	15.804	15.835	15.866	15.897	15.927	15.958	550
-80	-3.245	-3.220	-3.195	-3.170	-3.145	-3.120	-3.095	-3.070	-3.044	-3.019	-2.994	-80	560	15.958	15.989	16.020	16.050	16.081	16.112	16.143	16.173	16.204	16.235	16.266	560
-70	-2.994	-2.969	-2.943	-2.918	-2.893	-2.867	-2.842	-2.817	-2.791	-2.766	-2.740	-70	570	16.266	16.296	16.327	16.358	16.389	16.419	16.450	16.481	16.512	16.542	16.573	570
-60	-2.740	-2.714	-2.689	-2.663	-2.638	-2.612	-2.586	-2.560	-2.535	-2.509	-2.483	-60	580	16.573	16.604	16.635	16.665	16.696	16.727	16.758	16.788	16.819	16.850	16.881	580
-50	-2.483	-2.457	-2.431	-2.405	-2.379	-2.353	-2.327	-2.301	-2.275	-2.249	-2.223	-50	590	16.881	16.911	16.942	16.973	17.003	17.034	17.065	17.096	17.126	17.157	17.188	590
-40	-2.223	-2.197	-2.171	-2.145	-2.118	-2.092	-2.066	-2.040	-2.013	-1.987	-1.961	-40	600	17.188	17.219	17.249	17.280	17.311	17.341	17.372	17.403	17.434	17.464	17.495	600
-30	-1.961	-1.934	-1.908	-1.881	-1.855	-1.828	-1.802	-1.775	-1.749	-1.722	-1.695	-30	610	17.495	17.526	17.556	17.587	17.618	17.649	17.679	17.710	17.741	17.771	17.802	610
-20	-1.695	-1.669	-1.642	-1.615	-1.589	-1.562	-1.535	-1.508	-1.482	-1.455	-1.428	-20	620	17.802	17.833	17.863	17.894	17.925	17.955	17.986	18.017	18.048	18.078	18.109	620
-10	-1.428	-1.401	-1.374	-1.347	-1.320	-1.293	-1.266	-1.239	-1.212	-1.185	-1.158	-10	630	18.109	18.140	18.170	18.201	18.232	18.262	18.293	18.324	18.354	18.385	18.416	630
0	-1.158	-1.131	-1.104	-1.076	-1.049	-1.022	-0.995	-0.967	-0.940	-0.913	-0.886	0	640	18.416	18.446	18.477	18.508	18.538	18.569	18.600	18.630	18.661	18.692	18.722	640
0	-0.886	-0.858	-0.831	-0.803	-0.776	-0.749	-0.721	-0.694	-0.666	-0.639	-0.611	0	650	18.722	18.753	18.784	18.814	18.845	18.876	18.906	18.937	18.968	18.998	19.029	650
10	-0.611	-0.583	-0.556	-0.528	-0.501	-0.473	-0.445	-0.418	-0.390	-0.362	-0.334	10	660	19.029	19.060	19.090	19.121	19.152	19.182	19.213	19.244	19.274	19.305	19.336	660
20	-0.334	-0.307	-0.279	-0.251	-0.223	-0.195	-0.168	-0.140	-0.112	-0.084	-0.056	20	670	19.336	19.366	19.397	19.428	19.458	19.489	19.520	19.550	19.581	19.612	19.642	670
30	-0.056	-0.028	0.000	0.028	0.056	0.084	0.112	0.140	0.168	0.196	0.225	30	680	19.642	19.673	19.704	19.734	19.765	19.795	19.826	19.857	19.887	19.918	19.949	680
40	0.225	0.253	0.281	0.309	0.337	0.365	0.394	0.422	0.450	0.478	0.507	40	690	19.949	19.979	20.010	20.041	20.071	20.102	20.132	20.163	20.194	20.224	20.255	690
50	0.507	0.535	0.563	0.592	0.620	0.649	0.677	0.705	0.734	0.762	0.791	50	700	20.255	20.286	20.316	20.347	20.378	20.408	20.439	20.469	20.500	20.531	20.561	700
60	0.791	0.819	0.848	0.876	0.905	0.933	0.962	0.991	1.019	1.048	1.076	60	710	20.561	20.592	20.623	20.653	20.684	20.715	20.745	20.776	20.806	20.837	20.868	710
70	1.076	1.105	1.134	1.162	1.191	1.220	1.249	1.277	1.306	1.335	1.364	70	720	20.868	20.898	20.929	20.960	20.990	21.021	21.052	21.082	21.113	21.143	21.174	720
80	1.364	1.392	1.421	1.450	1.479	1.508	1.537	1.566	1.594	1.623	1.652	80	730	21.174	21.205	21.235	21.266	21.297	21.327	21.358	21.389	21.419	21.450	21.480	730
90	1.652	1.681	1.710	1.739	1.768	1.797	1.826	1.855	1.884	1.913	1.942	90	740	21.480	21.511	21.542	21.572	21.603	21.634	21.664	21.695	21.726	21.756	21.787	740
100	1.942	1.972	2.001	2.030	2.059	2.088	2.117	2.146	2.175	2.205	2														

**Table A5 – Platinum 100 Ohm Resistance
Temperature Detector Table in Ohms**

°F	°C	Ω
0	–17.78	93.04
5	–15.00	94.12
10	–12.22	95.21
15	–9.44	96.31
20	–6.67	97.39
25	–3.89	98.48
30	–1.11	99.57
32	0.00	100.00
35	1.67	100.65
40	4.44	101.73
45	7.22	102.82
50	10.00	103.90
55	12.78	104.98
60	15.56	106.07
65	18.33	107.15
70	21.11	108.22
75	23.89	109.31
80	26.67	110.38
85	29.44	111.45
90	32.22	112.53
95	35.00	113.61
100	37.78	114.68
105	40.56	115.76
110	43.33	116.83
115	46.11	117.90
120	48.89	118.97
125	51.67	120.04
130	54.44	121.11
135	57.22	122.17
140	60.00	123.24
145	62.78	124.31
150	65.56	125.37
155	68.33	126.44
160	71.11	127.50
165	73.89	128.56
170	76.67	129.62

Table A10 – Valve Selection: Materials and Applications

Valve Selection Guide for Application

Valve Terms
<ul style="list-style-type: none"> • Breaking pressure – The minimum pressure required to produce flow through a valve. • Duty cycle – 100% duty cycle is defined as continuous operation without any damage occurring. For intermittent duty cycle (<100%), alternate energized and de-energized state at regular intervals to cause the valve to completely cool down to room temperature. • Flow pattern – A diagram showing how flow can be directed using a particular valve. • Normally closed – Valve stays closed in a de-energized state; opens when energized. • Normally open – Valve stays open in a de-energized state; closes when energized. • Pressure differential or pressure drop – The difference between the inlet and the outlet pressure through a valve. The outlet pressure is lower than the inlet pressure due to the restriction caused by the valve. • Three-way valve – A valve with three ports. Depending on the particular valve, all three ports may be open, two ports may be open, or all ports may be closed. • Two-way valve – A valve with a single inlet port and a single outlet port.

Selecting Your Valve
<ol style="list-style-type: none"> 1. Choose a valve type depending on your application. This manual contains two valve application selection charts: Valve Selection Overview: Service Application Chart and Valve Selection Detailed: Service Application Chart. 2. Consider your fluid type (liquid, gas, or solid) and its characteristics to determine compatible valve materials. PTFE withstands many harsh or corrosive chemicals. For safety reasons, always use metal valves for pressurized gases. 3. Determine the temperature, pressure, and flow rate under which your valve will be operating. In general, metal valves withstand higher temperatures and pressures than plastic valves. 4. For solenoid valves, consider the response time and the length of time the valve will be energized. Continuous (100%) duty solenoid valves are best for frequent on/off cycling. Choose normally closed or normally open depending on the state the valve will be in most often. 5. Consider your maintenance requirements. Ball valves resist plugging and are easiest to service.

Valve Types and Descriptions

■ Angle-Seat Valves

Valves that utilize an ultracompact actuator to move a piston back and forth within the valve body. On/off control and continuous control designs are available for gases, steam, and liquids. The construction of the body causes extremely high flow rates, particularly in comparison to conventional globe valves.

■ Ball Valves

Designed primarily for on/off service. These valves contain a ball with a hole through it. A handle or electric actuator rotates the ball 90°, turning the flow on or off. Use plastic ball valves for liquid applications only.

**Table A15 – Pipe Standard Dimensions and Data**

Carbon Steel Pipes – Working Pressure							
Nominal Size (in)	Pipe Outside Diameter OD (in)	Schedule Number or Weight	Wall Thickness, t (in)	Inside Diameter, d (in)	Working Pressure ASTM A53 B to 400°F		
					Manufacturing Process	Joint Type	psig
1/4	0.540	40ST	0.088	0.364	CW	T	188
		80XS	0.119	0.302	CW	T	871
3/8	0.675	40ST	0.091	0.493	CW	T	203
		80XS	0.126	0.423	CW	T	820
1/2	0.840	40ST	0.109	0.622	CW	T	214
		80XS	0.147	0.546	CW	T	753
3/4	1.050	40ST	0.113	0.824	CW	T	217
		80XS	0.154	0.742	CW	T	681
1	1.315	40ST	0.133	1.049	CW	T	226
		80XS	0.179	0.957	CW	T	642
1-1/4	1.660	40ST	0.140	1.380	CW	T	229
		80XS	0.191	1.278	CW	T	594
1-1/2	1.900	40ST	0.145	1.610	CW	T	231
		80XS	0.200	1.500	CW	T	576
2	2.375	40ST	0.154	2.067	CW	T	230
		80XS	0.218	1.939	CW	T	551
2-1/2	2.875	40ST	0.203	2.469	CW	W	533
		80XS	0.276	2.323	CW	W	835
3	3.500	40ST	0.216	3.068	CW	W	482
		80XS	0.300	2.900	CW	W	767
4	4.500	40ST	0.237	4.026	CW	W	430
		80XS	0.337	3.826	CW	W	695
6	6.625	40ST	0.280	6.065	ERW	W	696
		80XS	0.432	5.761	ERW	W	1209
8	8.625	30	0.277	8.071	ERW	W	526
		40ST	0.322	7.981	ERW	W	643
		80XS	0.500	7.625	ERW	W	1106
10	10.75	30	0.307	10.136	ERW	W	485
		40ST	0.365	10.020	ERW	W	606
		XS	0.500	9.750	ERW	W	887
		80	0.593	9.564	ERW	W	1081

Table A19 – NEC Grounding and Bonding Conductors

Table 250.66 Grounding-Electrode Conductor for Alternating Current Systems

Size of Largest Ungrounded Service-Entrance Conductor or Equivalent Area for Parallel Conductors (AWG/kcmil)		Size of Grounding-Electrode Conductors (AWG/kcmil)	
Copper	Aluminum or Copper-Clad Aluminum	Copper	Aluminum or Copper-Clad Aluminum
2 or smaller	1/0 or smaller	8	6
1 or 1/0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250	4	2
Over 3/0 through 350	Over 250 through 500	2	1/0
Over 350 through 600	Over 500 through 900	1/0	2/0
Over 600 through 1100	Over 900 through 1750	2/0	3/0
Over 1100	Over 1750	3/0	250

Notes:

- Where multiple sets of service-entrance conductors are used as permitted in 230.40.
Exception No. 2: The equivalent size of the largest service-entrance conductor shall be determined by the largest sum of the areas of the corresponding conductors of each set.
- Where there are no service-entrance conductors, the grounding-electrode conductor size shall be determined by the equivalent size of the largest service-entrance conductor required for the load to be served.

Table 250.122 Minimum Size Equipment Grounding Conductors for Grounding Raceway and Equipment

Rating or Setting of Automatic Overcurrent Device in Circuit Ahead of Equipment, Conduit, etc., Not Exceeding (Amperes)	Size (AWG or kcmil)	
	Copper	Aluminum or Copper-Clad Aluminum*
15	14	12
20	12	10
30	10	8
40	10	8
60	10	8
100	8	6
200	6	4
300	4	9
400	3	1
500	2	1/0
600	1	2/0
800	1/0	3/0
1000	2/0	4.0
1200	3/0	250
1600	4/0	350
2000	250	400
2500	350	600
3000	400	600
4000	500	750
5000	700	1200
6000	800	1200

Note: Where necessary to comply with 250.4(A)(5) or (BX4), the equipment grounding conductor shall be sized larger than given in this table. See installation restrictions in 250.120.

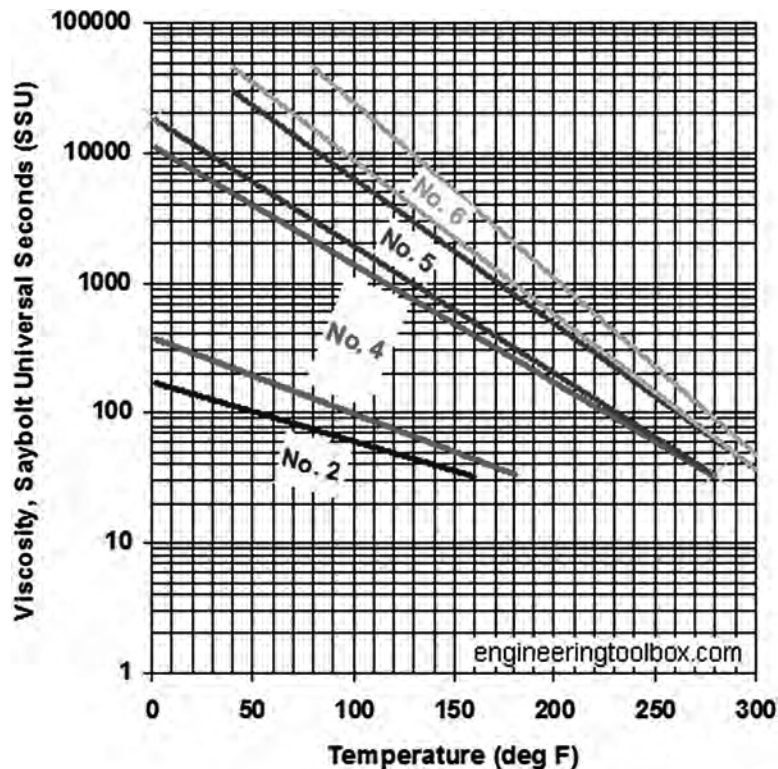
Table A21 – Specific Gravity: Common Fluids

Product	Temperature		Specific Gravity SG or G_f
	°F	°C	
Acetaldehyde CH_3CHO	61	16.1	0.79
	68	20	0.76
Acetic acid 5% – vinegar	59	15	1.006
Acetic acid – 10%	59	15	1.014
Acetic acid – 50%	59	15	1.061
Acetic acid – 80%	59	15	1.075
Acetic acid – concentrated	59	15	1.055
Acetic acid anhydride $(\text{CH}_3\text{COO})_2\text{O}$	59	15	1.087
Acetone CH_3COCH_3	68	20	0.792
Alcohol – allyl	68	20	0.855
Alcohol – butyl-n	68	20	0.81
	158	70	0.78
Alcohol – ethyl (grain) $\text{C}_2\text{H}_5\text{OH}$	68	20	0.789
	104	40	0.772
Alcohol – methyl (wood) CH_3OH	68	20	0.79
Alcohol – propyl	68	20	0.804
	32	0	0.817
Aluminum sulfate 36% solution	60	15.6	1.055
Ammonia	0	–17.8	0.662
Aniline	68	20	1.022
	32	0	1.035
Automotive crankcase oils SAE-5W/10W/20W/30W/40W/50W	60	15.6	0.88–0.94
Automotive gear oils SAE-75W/80W/85W/90W/140W/150W	60	15.6	0.88–0.94
Beer	60	15.6	1.01
Benzene (benzol) C_6H_6	32	0	0.899
	60	15.6	0.885
Bone oil	60	15.6	0.918
Boric acid H_3BO_3	46.4	8	1.014
	59	15	1.025
Bromine	32	0	2.9
Butane-n	60	15.6	0.584
Butyric acid	68	20	0.959
Calcium chloride 5%	65	18.3	1.040
Calcium chloride 25%	60	15.6	1.23
Carbolic acid (phenol)	65	18.3	1.08
Carbon tetrachloride CCl_4	68	20	1.594
Carbon disulfide CS_2	32	0	1.293
	68	20	1.263
Castor oil	68	20	0.96
	104	40	0.95

Table A22 – Kinematic Viscosity: Common Fluids (continued)

Fluid	Temperature		Kinematic Viscosity	
	°F	°C	Centistokes (cSt)	Seconds Saybolt Universal (SSU)

Viscosity - Saybolt Universal Seconds (SSU) versus temperature for typical fuel oils is indicated in the diagram below:



Fuel oil 1	70	21.1	2.39–4.28	34–40
	100	37.8	–2.69	32–35
Fuel oil 2	70	21.1	3.0–7.4	36–50
	100	37.8	2.11–4.28	33–40
Fuel oil 3	70	21.1	2.69–5.84	35–45
	100	37.8	2.06–3.97	32.8–39
Fuel oil 5A	70	21.1	7.4–26.4	50–125
	100	37.8	4.91–13.7	42–72
Fuel oil 5B	70	21.1	26.4	125–
	100	37.8	13.6–67.1	72–310
Fuel oil 6	122	50	97.4–660	450–3M
	160	71.1	37.5–172	175–780
Gas oils	70	21.1	13.9	73
	100	37.8	7.4	50
Gasoline a	60	15.6	0.88	
	100	37.8	0.71	
Gasoline b	60	15.6	0.64	
	100	37.8		
Gasoline c	60	15.6	0.46	
	100	37.8	0.40	
Glycerin 100%	68.6	20.3	648	2950
	100	37.8	176	813

Table A25 – Density of Elements in English and Metric Units

Element or Compound	Density – lb/ft ³ 14.7 psia and 60°F		Density – kg/m ³ 1013 mbar and 15.6°C		Mol. Wt. M _r
	Liquid	Gas	Liquid	Gas	
Acetic acid, CH ₃ -CO-OH	65.7		1052.4		66.1
Acetone, CH ₃ -CO-CH ₃	49.4		791.3		58.1
Acetylene, C ₂ H ₂		0.069		1.11	26.0
Air, O ₂ + N ₂		0.0764		1.223	29.0
Ammonia, NH ₃		0.045		0.72	17.0
Argon, A		0.105		1.68	39.9
Benzene, C ₆ H ₆	54.6		874.6		78.1
Butane, C ₄ H ₁₀		0.154		2.47	58.1
Carbon dioxide, CO ₂		0.117		1.87	44.0
Carbon monoxide, CO		0.074		1.19	28.0
Carbon tetrachloride, CCl ₄	99.5		1593.9		153.8
Chlorine, Cl ₂		0.190		3.04	70.9
Ethane, C ₂ H ₆		0.080		1.28	30.1
Ethyl alcohol, C ₂ H ₅ OH	49.52		793.3		46.1
Ethylene, CH ₂ =CH ₂		0.074		1.19	28.1
Ethyl ether, C ₂ H ₅ -O-C ₂ H ₅	44.9		719.3		74.1
Fluorine, F ₂		0.097		1.55	38.0
Helium, He		0.011		0.18	4.00
Heptane, C ₇ H ₁₆	42.6		682.4		100.2
Hydrogen, H ₂		0.005		0.08	2.02
Hydrogen chloride, HCl		0.097		1.55	36.5
Isobutane, (CH ₃) ₂ CH-CH ₃		0.154		2.47	58.1
Isopropyl alcohol, CH ₃ -CHOH-CH ₃	49.23		788.6		60.1
Methane, CH ₄		0.042		0.67	16.0
Methyl alcohol, H-CH ₂ OH	49.66		795.5		32.0
Nitrogen, N ₂		0.074		1.19	28.0
Nitrous oxide, N ₂ O		0.117		1.87	44.0
Octane, CH ₃ -(CH ₂) ₆ -CH ₃	43.8		701.6		114.2
Oxygen, O ₂		0.084		1.35	32.0
Pentane, C ₅ H ₁₂	38.9		623.1		72.2
Phenol, C ₆ H ₅ OH	66.5		1065.3		94.1
Phosgene, COCl ₂		0.108		1.73	98.9
Propane, C ₃ H ₈		0.117		1.87	44.1
Propylene, CH ₂ =CH-CH ₃		0.111		1.78	42.1
Refrigerant 12, CCl ₂ F ₂		0.320		5.13	120.9
Refrigerant 22, CHClF ₂		0.228		3.65	86.5
Sulfur dioxide, SO ₂		0.173		2.77	64.1
Water, H ₂ O	62.34		998.6		18.0

Table A27 – Standard Conditions and Gas Laws

Standards and Conditions	Laws of Gases
Standard conditions (US customary gases) are: 14.69 psia and 68°F	Universal gas equation
Standard conditions (US customary liquids) are: 14.69 psia and 60°F	$P_v = mRTZ$
Normal conditions (metric) are: 1.013 bar and 0°C and 4°C water	where
Note: In the <i>Masoneilan Control Valve Sizing Handbook</i> , the metric factors are: 1.013 bar and 15.6°C.	<i>English units</i> P = press in pounds per foot squared v = volume in cubic feet m = mass in pounds R = gas constant = $\frac{1545}{M_r}$
Specific gravity of air SG = 1 @ standard condition for gases	
Specific gravity of water = 1 @ std. cond. for liquids	<i>Metric units</i> P = press in pascals v = volume in cubic meters m = mass in kilograms R = gas constant = $\frac{8314}{M_r}$
1 US gallon of water = 8.3378 lb @ standard. condition	
1 cubic foot of water = 62.34 lb @ standard condition (= density)	
1 cubic foot of water = 7.48 gal	
1 cubic foot of air = 0.076 lb @ standard condition (= air density)	
Air specific volume = 1/density = 13.1 cubic ft /lb	Gas expansion (perfect gas)
Air molecular weight M_r = 29	$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$
SG of any gas = density of gas/0.076	
SG of any gas = molecular weight M of gas/29	Velocity of sound, C, in feet per second
	$C = 223 \sqrt{\frac{k(T + 460)}{M_r}}$
	Velocity of sound, C, in meters per second
	$C = 91.2 \sqrt{\frac{k(T + 273)}{M_r}}$


Table A28 – Head Loss in Piping Systems
Friction Losses in Pipe Fittings: Resistance Coefficient K
Head loss in fittings, h_f : $h_f = [K \cdot v^2/2g]$
Head loss in pipe, h_p : $h_p = f \cdot [L \text{ (in ft)} / D \text{ (in ft)}] \cdot [v^2/2g]$ **Note:** f = Moody friction factor for pipe

Head loss flowmeter, h_o : $h_o = [\text{inH}_2\text{O}/12]$ in feet

Head loss in piping and fittings: $h_L = h_p + h_f + h_o + h_v$
Head loss for valve $h_v = h_L \cdot (0.15 \text{ to } 0.4)$ **Note:** Verify valve works for percentage pressure drop.

Head required for pump in feet = $h_p + h_f + h_o + h_v$ + any working vessel pressure in feet

		LD	Nominal Pipe Size in Inches											
			1/2	3/4	1	1-1/4	1-1/2	2	2-1/2-3	4	6	8-10	12-16	18-24
Fitting			K Value											
Angle valve		55	1.48	1.38	1.27	1.21	1.16	1.05	0.99	0.94	0.83	0.77	0.72	0.66
Angle valve		150	4.05	3.75	3.45	3.30	3.15	2.85	2.70	2.55	2.25	2.10	1.95	1.80
Ball valve		3	0.08	0.08	0.07	0.07	0.06	0.06	0.05	0.05	0.05	0.04	0.04	0.04
Butterfly valve								0.86	0.81	0.77	0.68	0.63	0.35	0.30
Gate valve		8	0.22	0.20	0.18	0.18	0.15	0.15	0.14	0.14	0.12	0.11	0.10	0.10
Globe valve		340	9.2	8.5	7.8	7.5	7.1	6.5	6.1	5.8	5.1	4.8	4.4	4.1
Plug valve branch flow		90	2.43	2.25	2.07	1.98	1.89	1.71	1.62	1.53	1.35	1.26	1.17	1.08
Plug valve straightaway		18	0.48	0.45	0.41	0.40	0.38	0.34	0.32	0.31	0.27	0.25	0.23	0.22
Plug valve 3-way Thru-Flow		30	0.81	0.75	0.69	0.66	0.63	0.57	0.54	0.51	0.45	0.42	0.39	0.36
Standard elbow	90°	30	0.81	0.75	0.69	0.66	0.63	0.57	0.54	0.51	0.45	0.42	0.39	0.36
	45°	16	0.43	0.40	0.37	0.35	0.34	0.30	0.29	0.27	0.24	0.22	0.21	0.19
	long radius 90°	16	0.43	0.40	0.37	0.35	0.34	0.30	0.29	0.27	0.24	0.22	0.21	0.19
Close return bend		50	1.35	1.25	1.15	1.10	1.05	0.95	0.90	0.85	0.75	0.70	0.65	0.60
Standard tee	Thru-Flow	20	0.54	0.50	0.46	0.44	0.42	0.38	0.36	0.34	0.30	0.28	0.26	0.24
	Thru-Branch	60	1.62	1.50	1.38	1.32	1.26	1.14	1.08	1.02	0.90	0.84	0.78	0.72
90 bends, Pipe bends, Flanged elbows, Butt-welded elbows	r/d = 1	20	0.54	0.50	0.46	0.44	0.42	0.38	0.36	0.34	0.30	0.28	0.26	0.24
	r/d = 2	12	0.32	0.30	0.28	0.26	0.25	0.23	0.22	0.20	0.18	0.17	0.16	0.14
	r/d = 3	12	0.32	0.30	0.28	0.26	0.25	0.23	0.22	0.20	0.18	0.17	0.16	0.14
	r/d = 4	14	0.38	0.35	0.32	0.31	0.29	0.27	0.25	0.24	0.21	0.20	0.18	0.17
	r/d = 6	17	0.46	0.43	0.39	0.37	0.36	0.32	0.31	0.29	0.26	0.24	0.22	0.20
	r/d = 8	24	0.65	0.60	0.55	0.53	0.50	0.46	0.43	0.41	0.36	0.34	0.31	0.29
	r/d = 10	30	0.81	0.75	0.69	0.66	0.63	0.57	0.54	0.51	0.45	0.42	0.39	0.36
	r/d = 12	34	0.92	0.85	0.78	0.75	0.71	0.65	0.61	0.58	0.51	0.48	0.44	0.41
	r/d = 14	38	1.03	0.95	0.87	0.84	0.80	0.72	0.68	0.65	0.57	0.53	0.49	0.46
	r/d = 16	42	1.13	1.05	0.97	0.92	0.88	0.80	0.76	0.71	0.63	0.59	0.55	0.50
	r/d = 18	45	1.24	1.15	1.06	1.01	0.97	0.87	0.83	0.78	0.69	0.64	0.60	0.55
	r/d = 20	50	1.35	1.25	1.15	1.10	1.05	0.95	0.90	0.85	0.75	0.70	0.65	0.60
Miter bends	a = 0°	2	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.02
	a = 15°	4	0.11	0.10	0.09	0.09	0.08	0.08	0.07	0.07	0.06	0.06	0.05	0.05
	a = 30°	8	0.22	0.20	0.18	0.18	0.17	0.15	0.14	0.14	0.12	0.11	0.10	0.10
	a = 45°	15	0.41	0.38	0.35	0.33	0.32	0.29	0.27	0.26	0.23	0.21	0.20	0.18
	a = 60°	25	0.68	0.63	0.58	0.55	0.53	0.48	0.45	0.43	0.38	0.35	0.33	0.30
	a = 75°	40	1.09	1.00	0.92	0.88	0.84	0.76	0.72	0.68	0.60	0.56	0.52	0.48
	a = 90°	60	1.62	1.50	1.38	1.32	1.26	1.14	1.08	1.02	0.90	0.84	0.78	0.72

Note: Fittings are standard with full openings.


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