Control Systems Engineer

Control Systems Engineering Exam Reference Manual: A Practical Study Guide

Third Edition

For the NCEES Professional Engineering (PE) Licensing Examination

Bryon Lewis, PE, CMfgE, CET, CCST

ISA

Setting the Standard for Automation™

Control Systems Engineering Exam Reference Manual: A Practical Study Guide

Third Edition – A New Plant Design Approach

Controls engineering encompasses a broad range of industries: power, paper and pulp, pharmaceuticals, manufacturing and chemical plants. Although this third edition has been expanded to further include the many different applications used by all of the above, the book will focus on petrochemical applications.

The Professional Engineer – Control Systems Engineer (CSE) examination tends to be concentrated toward the application of chemical and pharmaceutical plant design applications of code and control systems. I have tried to introduce the new upcoming engineer to the depth of knowledge they will need to acquire in order to tackle very large projects that may present themselves in the future of their career.

I have tried to present a firsthand view of what a large plant looks like and how to break it down into small parts that are easily engineered and designed, while combining these many small parts into a large and complex working system that will run safe and smoothly.

The style of this book has a layout for reading on a computer. To maintain this easily read format when printing the book, use skip blank pages in your printer setup.

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Welcome to Control Systems Engineering

Licensing as a PE (Professional Engineer) / CSE (Control Systems Engineer)

A Professional Engineering license must be obtained to perform engineering work for the public and private sectors, in the United States and most countries in the world. In order 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 (PEs) the authority to sign and seal engineering plans and offer their services to the public. *The title of Engineer cannot be used to advertise for engineering work, without a PE license.*

The CSE (Control Systems Engineer) takes on responsibilities beyond those of most other disciplines of professional engineering. If the pump quits working, you just don't have water. If the electrical panelboard fails, you just replace the components. In plant control systems, a failure can mean absolute disaster. Plants explode and many people can die. Even the failure of systems can mean the loss of hundreds of thousands of dollars and up into the millions for loss of product and production. 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 vastness of exposure and experience needed to be a control systems engineer. Just like the saying in the Spiderman movie, "With great power comes great responsibility". The control systems engineer's job cannot be taken lightly. People's lives depend on you knowing what you are doing and getting it right the first time. You cannot guess at control systems engineering. *You must know! Being a Professional Engineer is not just answering a minimum of 54 questions on an eight hour examination.*

The CSE can't just say the bottle is in place, now fill it. The CSE has to ask questions like:

1. Is the bottle in place
2. Is the valve open
3. Is there 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 today and compliance with government regulations now requiring Safety Instrumented Systems (SIS) installed.

Explosions can occur in petrochemical and other similar hazardous plants, even though the electrical and process systems are designed explosion proof per NFPA, ANSI/ISA, API, OSHA, ISO and other codes.

A highly modular plant with complex motion controls and industrial networks using advanced diagnostics.

The In Singapore, ExxonMobil shown below, owns and operates a 592,000-barrel-per-day (bpd) refinery as one of the largest in the world. Singapore employs almost 3,000 people and Exxon resides in 200 countries.

The typical petrochemical plant will require around 1000 workers to build and will take years to complete. Most large petrochemical plants will have land coverage in the upward range of 2,000 to 7,500 acres.


Storage
HOAs
Screen
Process
HOAs
Screen

Why Become a Professional Engineer?

Being licensed as a Professional Engineer is an important distinction and can enhance your career options. Many engineering jobs require 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 need to be a PE to be eligible for engineering management positions.

On the average, PEs make significantly more money than unlicensed engineers. Even if your first job does not require a PE license, you may need it 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 was taken from the NCEES website: What makes a PE different from an engineer?

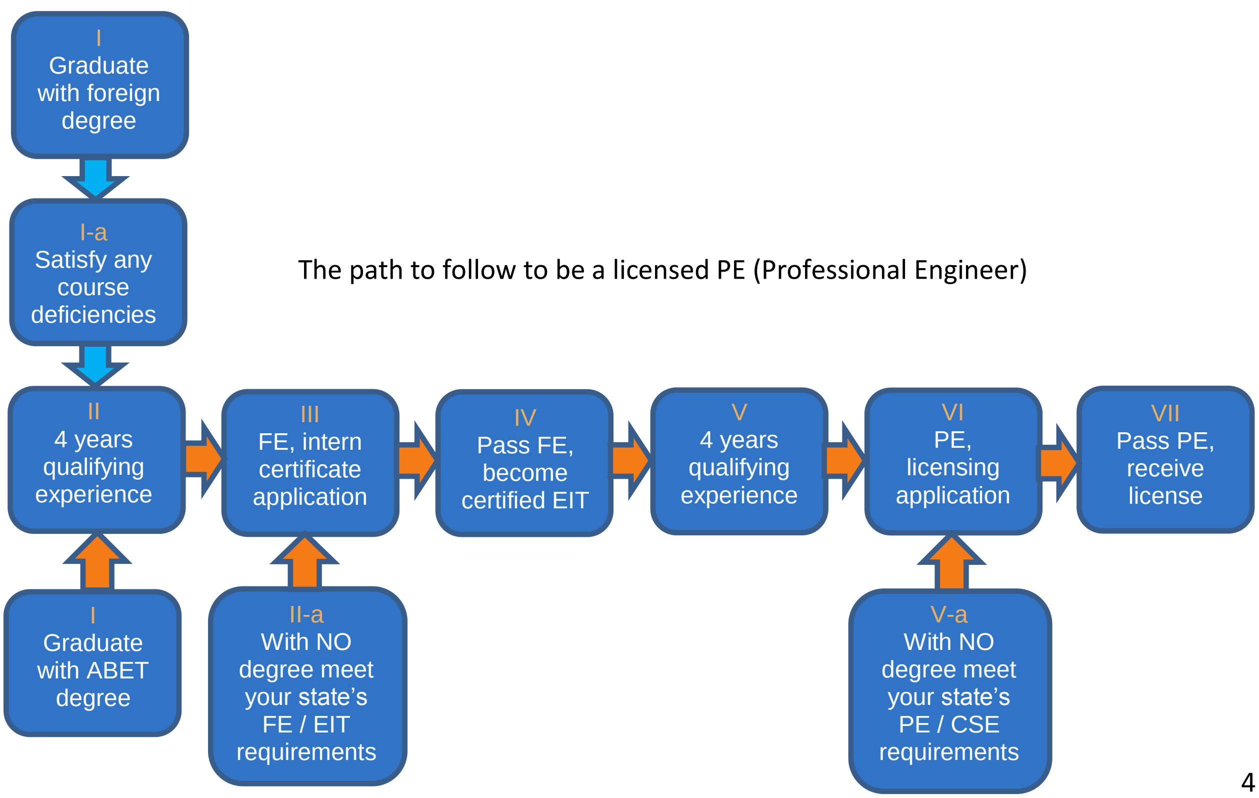
- Only a licensed engineer may prepare, sign and seal, and submit engineering plans and drawings to a public authority for approval, or seal engineering work for public and private clients.

- 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

- Licensure for engineers in government has become increasingly significant. In many federal, state, and municipal agencies, certain governmental engineering positions, particularly those considered higher level and responsible positions must be filled by licensed professional engineers.

Many states require that individuals teaching engineering must also be licensed. Exemptions to state laws are under attack, and in the future, those in education, as well as industry and government, may need to be licensed to practice. Also, licensure helps educators prepare students for their future in engineering.



The path to follow to be a licensed PE (Professional Engineer)

This is the third edition of this study manual

This review reference manual has been greatly expanded at the request of the NCEES CSE (Control Systems Engineer) PE examination committee chairman. It now includes new and expanded chapters on numerous control systems subjects.

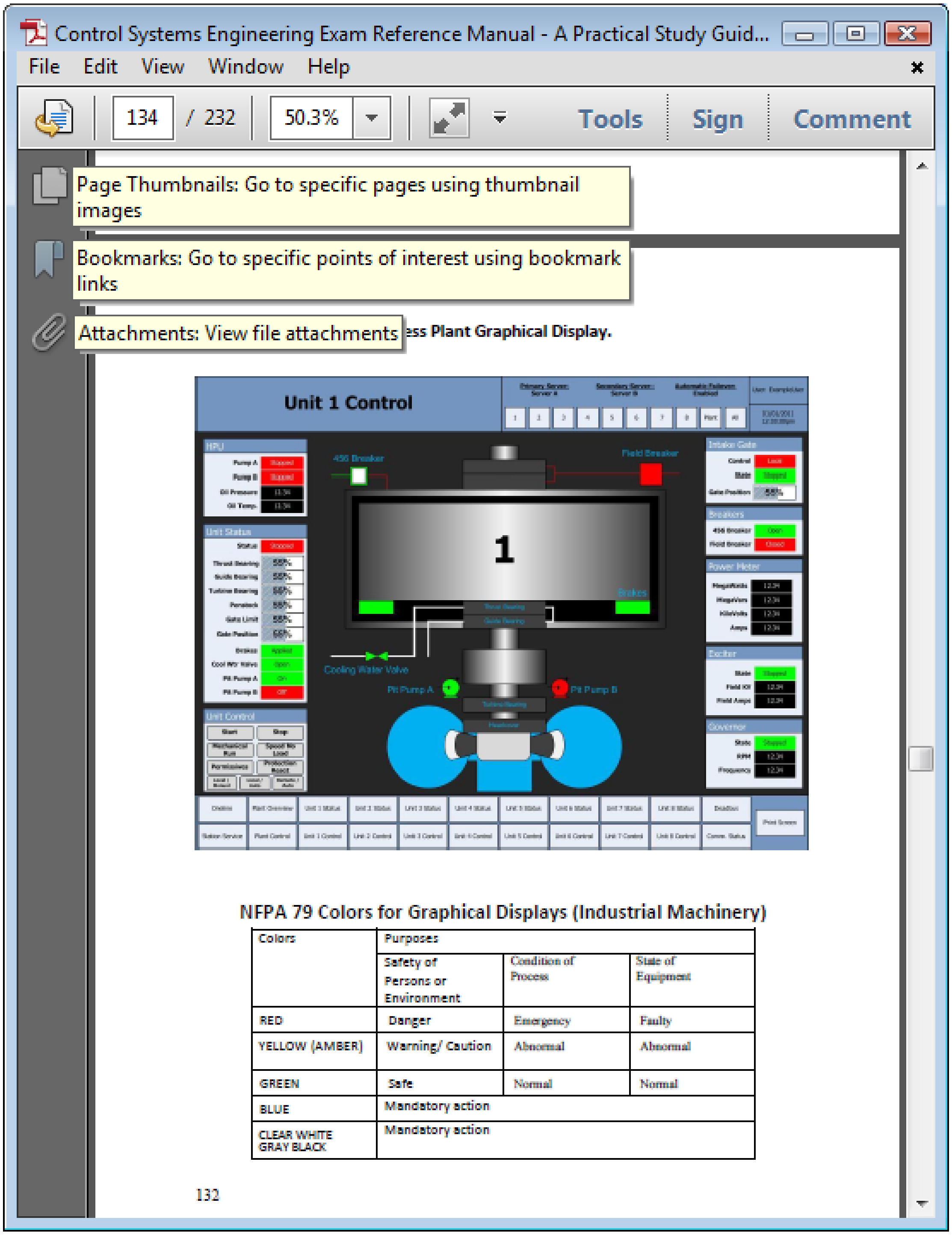
I have taken a complete systematic approach to understanding how to design a complete plantwide control system, for multiple processes, as might be encountered throughout the control engineer's career.

The new and expanded sections include:

- Updated NCEES PE (CSE) option examination content
- Expanded section on pressure measurement and calibration
- Expanded section on flow measurement and calibration
- Expanded section on weight and load cell applications
- New section on process analyzers
- Expanded section on process control valve sizing, applications and how to size them for installed real world flow control systems
- Expanded section on pressure relief and safety valves, their applications and federal regulations and requirements for installation
- Expanded section on process control modes
- Expanded section on discrete control subjects
- Expanded section on analog control signals
- New section on electrical systems and power quality
- New section on overview of conveying systems
- Expanded section on ISA standards for documentation
- Expanded section on SIS safety instrumented systems, explanation of OSHA requirements, definitions and their application and calculations for installations
- New section on overview of networks and communications
- New section on hydraulics and pneumatics
- New section on overview of motion controller applications
- New section on motor controls and logic functions
- New section on chemical processes and equipment
- New section on applications of basic fluid mechanics in piping systems
- New section on pumping applications
- New "Putting It All Together" section on how real plants are built

Tips on How to Use This Study Guide

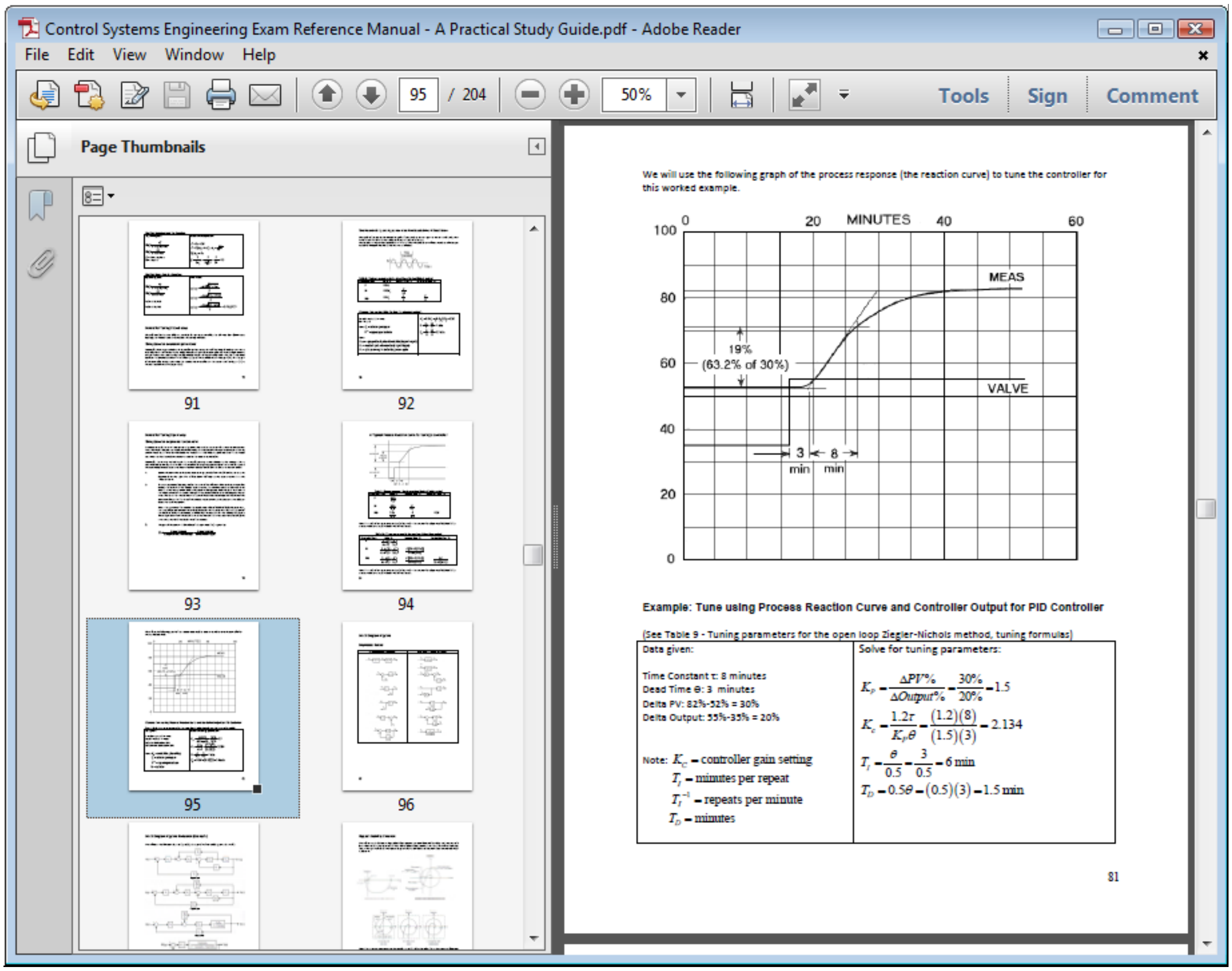
To make the most of this study guide, it may be of interest to use the features built into Adobe Reader. The image below shows where to click, for the display of Page Thumbnails and Bookmarks in this guide. The Bookmarks are a dynamic Table of Contents. See the following images below for illustrations of how thumbnails and bookmarks work. (There is a formula sheet for the exam in the attachments)



Using Page Thumbnails to Navigate

The Page Thumbnail shows a preview of the pages in this guide. Just click on any thumbnail image to instantly jump to the page in the preview.

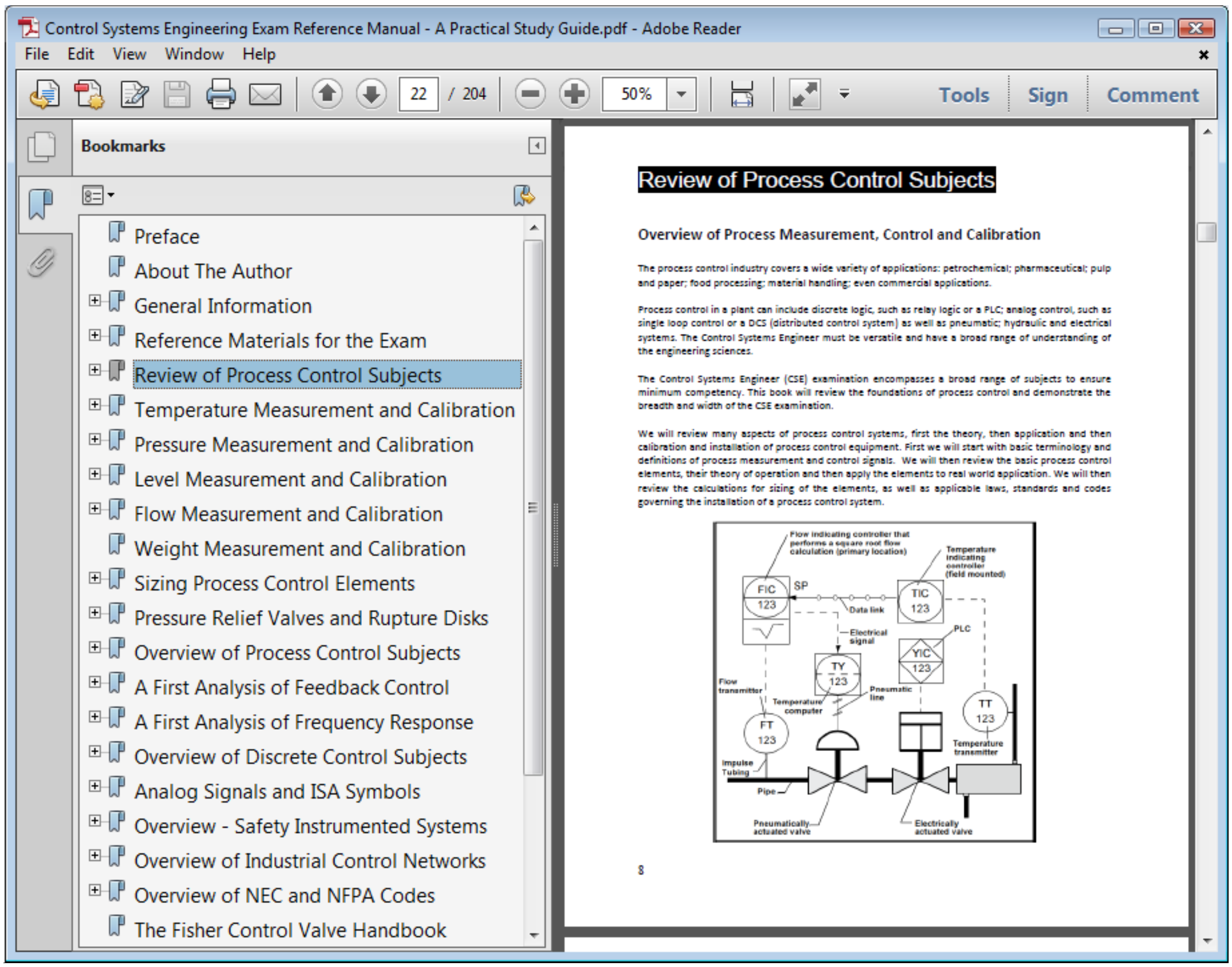
The default viewing mode in Adobe Reader is one column. If you want to view two columns at the same time as shown below, move your mouse over the divider between the thumbnails and the viewing page and drag the column splitter till you show as many columns as you would like to view at once. I recommend viewing only two columns.



Using Bookmarks to Navigate

The Bookmarks in this guide are the same as the Table of Contents collapsed. Quickly navigate to the subject of interest and click on the "+" to expand the contents of the subject matter under the subject heading. Click on the "-" to collapse the subject topics.

The default viewing mode in Adobe Reader shows wrap around text in the bookmark column. If you would like to read your bookmarks as shown below, move your mouse over the divider between the bookmarks and the viewing page and drag the column splitter till you show as much text width as you desire to view.

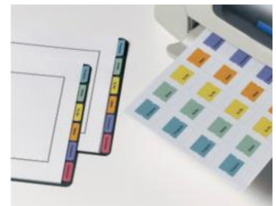


Important File Attachments - Open by clicking on the paper clip!

The instructions are on the next page.
Files attached to this PDF file:

- Formula Sheet.pdf
- Avery Tabs ready to print for this third edition manual for quick reference in the CSE examination

Avery® Printable Self-Adhesive Tabs 16281, 96 Tabs, 1-1/4" x 1"
http://www.avery.com/



See the section in this book "Preparing this Guide for the Exam" for recommended pages to tab for quick reference in the NCEES CSE/PE Examination.

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Most printers have an option to "skip blank pages" in the printer setup dialog box. If your printer does not support this option, then just ***do not*** print the one blank page that immediately follows this book's cover page.

All other pages are preformatted for printing this book.

Table of Contents

Preface

Most state licensing boards in the United States recognize the Control System Engineering (CSE) and offer the NCEES exam in this branch of engineering. There are, however, three states that do not offer the CSE exam—Alaska, Hawaii, and Rhode Island. If you live in one of these states, you may choose to pursue licensing in another discipline (such as electrical, mechanical, or chemical engineering). Or you can try to arrange to take the CSE exam in a neighboring state.

The Control Systems Engineering (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 process control and basic control systems. Experience in engineering or designing process control systems is almost a necessity to pass this exam.

Study of this reference manual should adequately prepare the experienced engineer or designer to take the CSE exam. However, passing the exam depends on an individual applicant's demonstrated ability and cannot be guaranteed.

I have included a list of recommended books and material. The recommended books contain information, invaluable to passing the exam. Even if you could take as many books as you want into the exam site, it is better not to overwhelm yourself—too much information can become distracting. Remember you will be under pressure to beat the clock. Study your reference books and tab the tables and information you need. This will ensure you do not waste time.

Study of the *Fisher Control Valve Handbook* or another equivalent book is strongly recommended, to obtain the full benefits of this study review guide. The *Fisher Control Valve Handbook* can be obtained free or for minimal cost from your local Fisher Valve representative. The book is also available from Brown's Technical Book Shop http://www.browntechnical.org. Address: 1517 San Jacinto, Houston, Texas, 77002. The book can be downloaded in PDF format from the Emerson-Fisher web site as well.

About the Author

Bryon Lewis, CSE / PE, CMfgE, CET, CCST
Professional Engineer (PE)
Certified Manufacturing Engineer (CMfgE)
Certified Journeyman Electronics Technician in Industrial electronics (CET)
Certified Control System Technician Level III (CCST)
Certified Profibus Network Engineer
State of Texas Master Electrician

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Bryon Lewis is a licensed in Control Systems Engineering (CSE). He is also a Senior Member of ISA. Mr. 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. His design experience is in electrical and lighting systems design; pharmaceutical and petrochemical plant design and installation, instrumentation and electrical systems design for compressor stations and food manufacturing plants and maintenance.

Visit the site: http://www.integrated.cc for free study aid materials and utilities, as well as online training.
If there are any questions, please contact Bryon Lewis at his email address.

People who have contributed to the previous editions of this manual

Chad Findlay, PE

Chad graciously reviewed this manual for errors and made numerous suggestions to improve its content. Chad Findlay is a Lead Controls Engineer for General Electric Company where he has worked for 7 years. He develops gas turbine control systems applied to simple and combined cycle power plants. Chad holds a Masters degree in Mechanical Engineering from the University of California, Davis.

Daniel Masso, PE

Daniel also contributed to the review of this manual for errors and made suggestions to improve its content.

Daniel Masso has worked as a DCS engineer for Westinghouse and Emerson Electric for 20 years in sales, project and field/start-up engineering capacities in system, control logic and graphic design and programming capacities. He earned a B.Ch.E from Cleveland State University and continued on a M.S. Ch.E at Case Western Reserve University and is employed by Emerson Process Management Power and Water Solutions.

Neil Frihart, PE

I would like to thank Neil for his encouragement in writing this manual and his friendship and help over the years. We met while I was employed by Advance Control and Technical Services in 1996 in Tulsa.

Neil Frihart is a Senior Controls Engineer for John Zink and was the Director of Business Development for Power & Control Engineering Solutions. He was employed a as a Senior Controls Engineer for Callidus Technologies (Honeywell) and was also Manager of Systems Engineering at Power Flame, Inc. He earned a BSEE from Kansas State University and MBA from Pittsburg State University.

Susan Colwell

I would like to thank Susan for her patience and help in the publication of this manual. She was extremely helpful in the publication of the first edition. Susan Colwell is the Publishing Director for ISA, International Society of Automation.

Susan holds a BA from Franklin Pierce University.

Richard Tunstall

I would like to thank Richard for giving me the opportunity to design the first draft of the Lee College process pilot plant under the advisement of the DuPont training department in Deer Park, Texas and the opportunity to study real processes and their associated control systems in 1994. Richard has been a faculty member of the Instrumentation Technology Program at Lee College - Baytown, Texas for since 1991.

Richard has earned the following:
B.S.Ed from Baylor University
Don Thompson Award - 2010 from ISA (International Society of Automation)
Lee College Outstanding Faculty with over Ten Years of Experience – 2012

Reference Materials for the Exam

Recommended books and materials to take to the exam

The list of recommended books and materials for testing will be necessary to help you pass the CSE examination. Use a book you are comfortable with. 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 examination.

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

- NCEES APPROVED CALCULATOR (Have a spare with new batteries installed). I recommend the TI-36X Solar (any light). Practice with the calculator you will be using. (See http://www.ncees.org for a current list of approved calculators.)
- ISA-5.1-1984 (R1992) - 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
- Fisher Control Valve Handbook / Valve Sizing Book (most data in this study guide)
- A Safety Relief Valve Book (could be useful)

Books for additional study

- The CSE Study Guide from ISA, (I highly recommend purchasing this 4 hour review exam)
- Instrumentation for Process Measurement and Control
  (3rd Ed.), CRC Press LLC, Norman A. Anderson (FOXBORO)
- Basic and Advanced Regulatory Control: Systems Design and Application
  (2^{nd} Ed.), ISA – Dr. Harold Wade
- Fisher Control Valve Handbook
- Masoneilan Control Valve Sizing Handbook
- Crosby® Pressure Relief Valve Engineering Handbook
- Pentair Pressure Relief Valve Engineering Handbook
- Alfa Laval Pump Handbook

National Council of Examiners for Engineering and Surveying

NCEES
advancing licensure for engineers and surveyors

Non-profit organization

The National Council of Examiners for Engineering and Surveying is a national non-profit organization composed of engineering and land surveying licensing boards representing all U.S. states and territories.

Founded: 1920

NCEES on Wikipedia

NCEES on LinkedIn

Click on any link above to visit the site

Courses for additional study

ISA Control Systems Engineer (CSE) PE Review

- **ISA (International Society of Automation)** offers an instructor-led Control Systems Engineer (CSE) PE exam review course at different locations across the nation.

  The ISA Control Systems Engineer (CSE) information page:
  http://www.isa.org/isa-certification/cse-licensure-preparation

  Setting the Standard for Automatio

  This course is typically taught by Gerald Wilbanks, P.E. He is a registered professional engineer in four states, a member of NSPE, and ASQ, and an International Former President (1995) of the International Society of Automation (ISA). Gerald is a graduate of Mississippi State University with a B.S. in electrical engineering and was recognized as the Engineer of the Year in 1991 by the Engineering Council of Birmingham.

  Gerald Wilbanks, P.E.

  He is a Distinguished Engineering Fellow of MSU and is a Life Fellow member of ISA. He has served as an instructor in many courses, seminars, and other educational sessions for ISA and in his own business.

  See the ISA web site http://www.isa.org for more books and training materials on advanced and basic subjects. ISA offers webinars with instructor-led training in many aspects and topics of process control and networking, as well as the popular topic of networking security. They offer several online study courses specializing in instrumentation and process control for people needing an introduction to the fundamentals of instrumentation. As an ISA member, many of the training videos and ISA / ANSI standards are free.

Industrial Network Training

- **Siemens Automation**

  Free Training
  PROFINET and PROFIBUS one-day seminars PI North America and the PROFI Interface Centers throughout North America. Webinars are also available on-demand.

  Certified Courses
  PROFItech certification courses are available to allow attendees to gain the designation "Certified Network Engineer."

  On-Demand Training
  Developer, installers, and other courses are available for both PROFINET and PROFIBUS technology and training is also available for AS-I networks.

- **Fieldbus Center**

  The Fieldbus Center at Lee College, Baytown, Texas offers instructor-led training in the study and certification of FOUNDATION Fieldbus and other process control systems. The training center uses industrial standard equipment and instruments, utilizing the Emerson Delta V DCS (distributed Control System) for programming and as a host system.

  The Fieldbus Center at Lee College was the first national FOUNDATION Fieldbus training center, established by Chuck Carter with a grant from the National Science Foundation. It is supporting most manufacturers in the instrumentation industry.

Control Systems Engineer (CSE) Supplement Course

- **Integrated Systems** offers online study courses in Controls Systems Engineering (CSE) as a supplement to the ISA (CSE) PE REVIEW course. It includes study materials and streaming videos of instructor-led training. These courses use a live small scale online process plant to demonstrate real world applications of calculations and the tuning and response of real process systems. The online plant is live and interactive at scheduled times during your studies. The plant includes a small MCC and multiple Automation PLCs utilizing typical plant control systems, instrumentation and I/O as seen every day in a large plant or manufacturing environments.

  Topics include PLC programming, process equipment sizing, instrumentation calculations and calibration procedures, industrial networking configuration and troubleshooting, motor controls, electrical installations and codes, instrumentation and electrical safety grounding, applications of fluid mechanics for process control and measurement. The student has three months to complete their studies and the courses are led by the author of this exam reference manual.

  Visit http://learncontrolsystems.com or http://www.integrated.cc for more information on training and to run the process plant online for free.

Online Process Plant @ Learn Control Systems.com

Integrated Systems uses the plant shown to teach process and manufacturing control systems to engineers and technicians in the Learn Control Systems courses. It is used to demonstrate in depth training on various applications of industrial instrumentation and industrial networking, including multivariable control systems.

The plant is accessible through a standard web browser and uses live video feed of high definition web cameras, with a wide view and a zoomed close up view of the instrumentation readings.

All variables are set and read over the internet in real time via a web browser. The full course work will be in an HMI format, just like you would use in a real process plant. Desktop remote sessions can be scheduled for personal programming of the PLCs.

(The free online demo mode has limited access to control functions. It serves as a course preview.)

Examination 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 which 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 ABET/EAC-accredited program and four years of acceptable experience can be licensed if they pass the Fundamentals of Engineering (FE) exam and the Principles and Practice of Engineering (PE) 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 of the exams 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/EIT exam. Some states require a minimum of four year experiences after passing the FE/EIT exam, before allowing a candidate to sit for the PE (principles and practices) exam. Some states will not allow experience incurred before the passing of the FE/EIT exam.

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 three or four months ahead of the exam date.

Requirements and fees vary among state jurisdictions. Sufficient time must be allotted to complete the application process and assemble 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 verifications 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. They will also describe any unique state requirements such as allowed calculator models or limits on the number of reference books taken into the exam site.

Description of Examination

Exam format

The NCEES Principles-and-Practice of Engineering examination (commonly called the PE examination) in Control Systems Engineering (CSE) is an eight-hour examination. The examination is administered in a four hour morning session and a four hour afternoon session.

Each session contains forty (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 of the questions are compulsory; applicants should try to answer all of 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 subject areas of the CSE exam are described by the exam specification and are given in six areas. ISA supports Control Systems Engineer (CSE) licensing and the examination for Professional Engineering. ISA is responsible for the content and questions in the NCEES examination. Refer to the ISA web site (http://www.isa.org) for the latest information concerning the CSE examination.

For a copy of the latest CSE / PE examination format and content, visit NCEES at: (http://www.ncees.org)

The following is an overview of what categories and content might be expected on the examination. The NCEES website will have the latest specifications of what exactly will be the focus of the exam, as the format and specifications change over the years.

I. MEASUREMENT

- Sensor technologies applicable to the desired type of measurement (e.g., flow, pressure, level, temperature, analytical, counters, motion, vision)
- Sensor characteristics (e.g., rangeability, accuracy and precision, temperature effects, response times, reliability, repeatability)
- Material compatibility
- Calculations involved in: pressure drop
- Calculations involved in: flow element sizing
- Calculations involved in: level, differential pressure
- Calculations involved in: unit conversions
- Calculations involved in: velocity
- Calculations involved in: linearization
- Installation details (e.g., process, pneumatic, electrical, location)

II. SIGNALS, TRANSMISSION, AND NETWORKING

- Signals

  - Pneumatic, electronic, optical, hydraulic, digital, analog, buses
  - Transducers (e.g., analog/digital [A/D], digital/analog [D/A], current/pneumatic [I/P] conversion)
  - Intrinsically Safe (IS) barriers
  - Grounding, shielding, segregation, AC coupling
  - Basic signal circuit design (e.g., two-wire, four-wire, isolated outputs, loop powering, buses)
  - Circuit Calculations (voltage, current, impedance)
  - Calculations: unit conversions

- Transmission

  - Different communications systems architecture and protocols (e.g., fiber optics, coaxial cable, wireless, paired conductors, buses, Transmission Control Protocol/Internet Protocol [TCP/IP], OLE Process Control [OPC])
  - Distance considerations versus transmission medium (e.g., data rates, sample rates)

- Networking

  - Networking (e.g., routers, bridges, switches, firewalls, gateways, network loading, error checking, bandwidth, crosstalk, parity)

III. FINAL CONTROL ELEMENTS

- Valves

  - Types (e.g., globe, ball, butterfly)
  - Characteristics (e.g., linear, low noise, equal percentage, shutoff class)
  - Calculation (e.g., sizing, split range, noise, actuator, speed, pressure drop, air/gas consumption)
  - Selection of motive power (e.g., hydraulic, pneumatic, electric)
  - Applications of fluid dynamics (e.g., cavitation, flashing, choked flow, Joule-Thompson effects, two-phase)
  - Material selection based on process characteristics (e.g., erosion, corrosion, plugged, extreme pressure, temperature)
  - Accessories (e.g., limit switches, solenoid valves, positioners, transducers, air regulators, servo amp)
  - Environmental constraints (e.g., fugitive emissions, packing, special sealing)
  - Installation practices (e.g., vertical, horizontal, bypasses, location, troubleshooting)

- Pressure Relieving Devices

  - Pressure Relieving Valve Types (e.g., conventional spring, balanced bellows, pilot operated)
  - Pressure Relieving Valve Characteristics (e.g., modulating, pop action)
  - Pressure Relieving Valve Calculations (e.g., sizing considering inlet pressure drop, back pressure, multiple valves)
  - Pressure Relieving Device Material Selection based on process characteristics
  - Pressure Relieving Valve Installation Practices (e.g., linking valves, sparing the valves, accessibility for testing, car sealing inlet valves, piping installation)

- Rupture discs (e.g., types, characteristics, application, calculations)

- Motor Controls

  - Types (e.g., motor starters, variable speed drives)
  - Applications (e.g., speed control, soft starters, valve actuators)
  - Calculations (e.g., sizing, tuning, location)
  - Accessories (e.g., encoders, positioners, relays, limit switches)
  - Troubleshooting (e.g., root cause failure analysis and correction)

- Other Final Control Elements

  - Solenoid Valves (e.g., types, sizing)
  - On-Off Devices/relays (e.g., types, applications)
  - Self-Regulating Devices (e.g., types, sizing, pressure, temperature, level and flow regulators)

IV. CONTROL SYSTEMS

- Drawings

  - Drawings (e.g., PFD-process flow diagrams, P&IDs–piping and instrumentation drawings, loop diagrams, ladder diagrams, logic drawings, cause and effects drawings, electrical drawings.)

- Theory

  - Basic processes (e.g., compression, combustion, evaporation, distillation, hydraulics, reaction, dehydration, heat exchangers, crystallization, filtration)
  - Process dynamics (e.g., loop response, P-V-T pressure volume temperature relationships, simulations)
  - Basic control (e.g., regulatory control, feedback, feed forward, cascade, ratio, PID, split-range)
  - Discrete control (e.g., relay logic, Boolean algebra)
  - Sequential control (e.g., batch, assembly, conveying, CNC)

- Implementation

  - HMI (e.g., graphics, alarm management, trending, historical data)
  - Configuration and Programming (e.g., PLC, DCS, hybrid systems, SQL, ladder logic, sequential function chart, structured text, function block programming, data base management, specialized controllers)
  - Systems Comparisons and Capabilities (e.g., advantages and disadvantages, of systems architecture, distributed architecture, remote I/O, buses)
  - Installation Requirements (e.g., shielding, constructability, input/output termination, environmental, heat load calculations, power load requirements, purging, lighting)
  - Network Security (e.g., firewalls, routers, switches, protocols)
  - System Testing (e.g., FAT-factory acceptance test, integrated systems test, site acceptance test)
  - Commissioning (e.g., performance tuning, loop checkout)
  - Troubleshooting (e.g., root cause failure analysis, and correction)

V. SAFETY SYSTEMS

- Basic Documentation

    - Basic Documentation (e.g., safety requirements specification, logic diagrams, test procedures, SIL selection report)

- Theory

    - Reliability (e.g., bathtub curve, failure rates)
    - SIL selection (e.g., risk matrix, risk graph, LOPA)

- Implementation

    - Safety Systems Design (e.g., I/O assignments, redundancy, segregation, software design)
    - Safety Integrity Level (SIL) verification calculations
    - Testing (e.g., methods, procedures, documentation)
    - Management of changes (e.g., scope of change, impact of change)

VI. CODES, STANDARDS, REGULATIONS

- American National Standards Institute (ANSI)
- American Petroleum Institute (API)
- American Society of Mechanical Engineers (ASME)
- International Electrotechnical Commission (IEC)
- Institute of Electrical & Electronics Engineers (IEEE)
- International Society of Automation (ISA)
- National Electrical Code (NEC)
- National Electrical Manufacturers Association (NEMA)
- National Fire Protection Association (NFPA)
- Occupational Safety and Health Administration (OSHA)

Exam Scoring

NCEES exams are scored independently. There are no pre-specified percentages of candidates that must pass or fail.

Assisted by a testing consultant, a panel of licensed CSEs uses recognized psychometric procedures to determine a passing score corresponding to the knowledge level needed for minimally-competent practice in the discipline.

The passing score is expressed as the number of questions out of 80 that must be answered correctly. The method used for pass-point determination assures that the passing score is adjusted for variations in the level of exam difficulty and that the standard is consistent from year to year.

Starting in October 2005, candidates have received results expressed either as “Pass” or “Fail”; failing candidates no longer receive a numerical score. Published passing rates are based on first-time takers only, omitting the results for repeat takers.

Notes

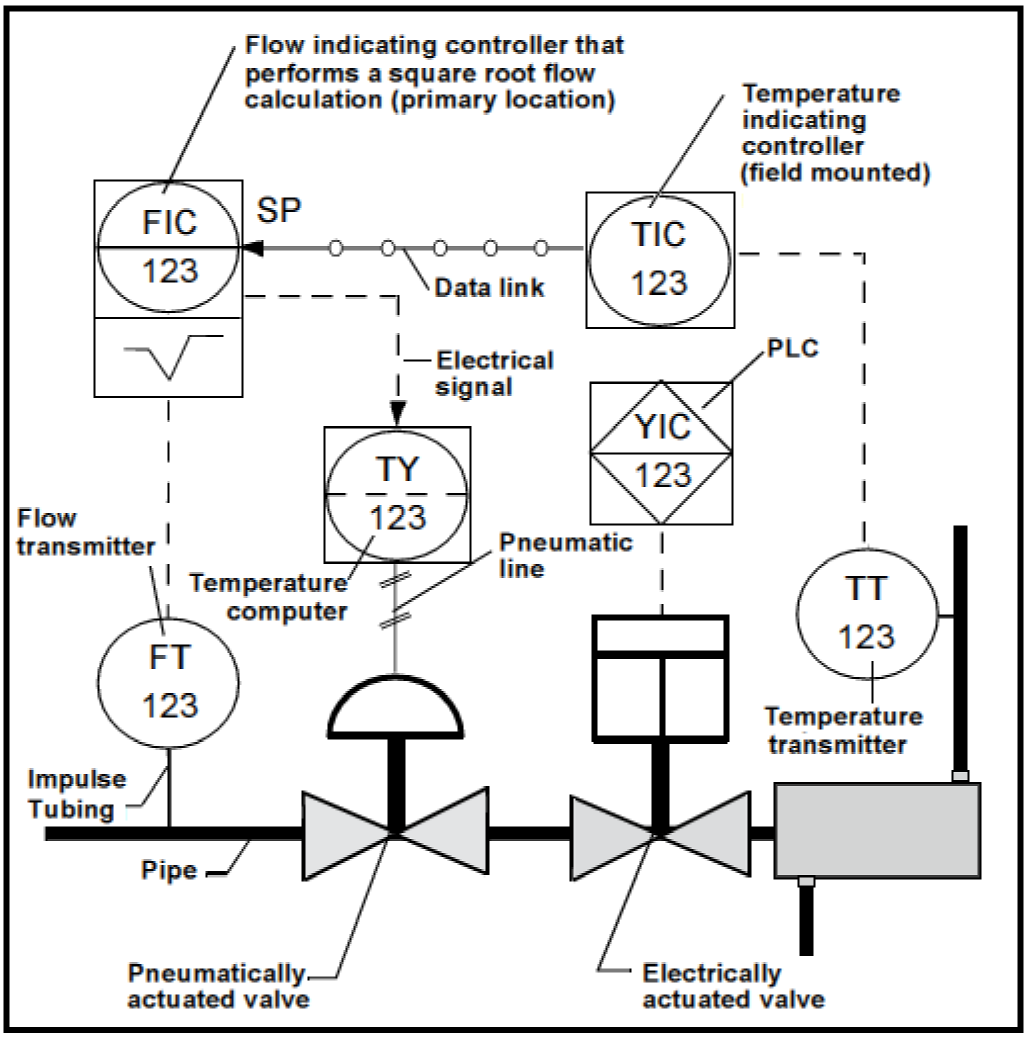
Review of Process Control Subjects

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; even commercial applications. Experience designing process control systems is almost a necessity to pass the Control Systems Engineer PE examination.

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

The Control Systems Engineer (CSE) examination 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 examination. We will then review the basic process control elements, their theory of operation and then apply the elements to real-world application. We will then review the calculations for sizing of 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; Suppressed Zero.

Definition of the Range of an instrument

Range: 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 1 and 2.

NOTE 4: For multi-range devices, this definition applies to the particular range that the device is set to measure.

Range-limit, lower: LRV (Lower Range Value) The lowest value of the measured variable that a device is adjusted to measure.

Range-limit, upper: URV (Upper Range Value) 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 1 and 2. Range-limit, upper: URV (Upper Range Value) The highest value of the measured variable that a device is adjusted to measure.

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 1 and 2, Span: The algebraic difference between the upper and lower range-values.

NOTE 1: For example:
Range: 0 to 150°F, Span 150°F
Range: –10 to 180°F, Span 190°F
Range: 50 to 100°C, Span 50°C

NOTE 2: The following compound terms are used with suitable modifications to the units: measured variable range, measured signal range, etc.

NOTE 3: For multi-range devices, this definition applies to the particular range that the device is set to measure. See Tables 1 and 2.

Range-limit, lower: LRV (Lower Range Value) The lowest value of the measured variable that a device is adjusted to measure.

Range-limit, upper: URV (Upper Range Value) The highest value of the measured variable that a device is adjusted to measure.

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NOTE 5: 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 1 and 2.

Definition of the Span of an instrument

Span: The algebraic difference between the upper and lower range-values.

NOTE 1: For example:
Range: 0 to 150°F, Span 150°F
Range: –10 to 180°F, Span 190°F
Range: 50 to 100°C, Span 50°C

NOTE 2: The following compound terms are used with suitable modifications to the units: measured variable range, measured signal range, etc.

NOTE 3: For multi-range devices, this definition applies to the particular range that the device is set to measure. See Tables 1 and 2.

Definition of the use of zero in instrumentation

Live-Zero

The lower range value (LRV) is said to be set to zero, as a reference point, whether it is at zero or not. This LRV can be 0%; -40°F; 4mA; 1V or 3 PSI. All LRVs are an example of the ZERO (Live Zero), in process control signals or elements.

Elevated-Zero

The lower range-value of the range is below the value of zero. The LRV of the range must be raised to Live Zero, for the instrument to function properly. The output signal of the measured value will always be 0 to 100%. If the LRV of the range is too low, the instrument may not be able to reach 100% output***.***

NOTE: For example: input signal = (-100 in H_2O to 25 in H_2O)
output signal = (4mA to 20mA)

The output signal may only reach 12mA for 25 in H_2O (100%) input, due to limitation in the electronics or pneumatics. Therefore the Elevate jumper must be set in the transmitter or an elevation kit must be installed in a pneumatic transmitter. See Table 1.

Suppressed-Zero

The lower range-value of the span is above the value of zero. The LRV of the range must be lowered to Live Zero, for the instrument to function properly. The output signal of the measured value will always be 0 to 100%. If the LRV of the range is too high, the instrument may not be able to reach 0% output.

NOTE: For example: input signal = (50 in H_2O to 200 in H_2O)
output signal = (4mA to 20mA)

The output signal may only reach 6mA for 50 in H2O (0%) input, due to limitation in the electronics or pneumatics. Therefore the Suppress jumper must be set in the transmitter or a suppression kit must be installed in a pneumatic transmitter. See Table 1.

Illustrations of range and span terminology

Table 1 – Examples of range and span terminology

TYPICAL RANGES	NAME	RANGE	LOWER RANGE VALUE	UPPER RANGE VALUE	SPAN	SUPPLEMENTARY DATA
0 +100	—	0 to 100	0	+100	100	—
20 +100	SUPPRESSED ZERO RANGE	20 to +100	20	+100	80	SUPPRESSION RATIO = 0.25
-25 +100	ELEVATED ZERO RANGE	–25 to +100	–25	+100	125	—
–100 0	ELEVATED ZERO RANGE	–100 to 0	-100	0	100	—
–100 –20	ELEVATED ZERO RANGE	–100 to –20	-100	-20	80	—

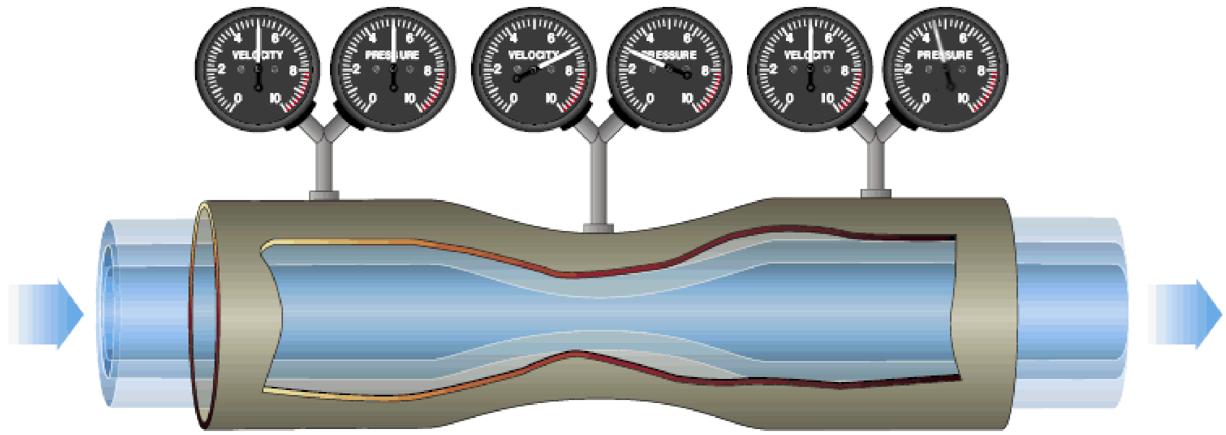
Illustrations of measured variable, measured signal, range and span

Table 2 – Examples of measured variable, measured signal, range and span

TYPICAL RANGES	TYPE OF RANGE	RANGE	LOWER RANGE VALUE	UPPER RANGE VALUE	SPAN
THERMOCOUPLE 0 2000°F TYPE K T/C	MEASURED VARIABLE	0 to 2000°F	0°F	2000°F	2000°F
– 0.68 + 44.91 mV	MEASURED SIGNAL	–0.68 to +44.91 mV	–0.68 mV	+44.91 mV	45.59 mV
FLOWMETER 0 10,000 lb/h	MEASURED VARIABLE	0 to 10 000 lb/h	0 lb/h	10,000 lb/h	10,000 lb/h
0 100 in H2O	MEASURED SIGNAL	0 to 100 in H_2O	0 in H_2O	100 in H_2O	100 in H_2O
0 10 x1000=lb/h	SCALE AND/OR CHART	0 to 10,000 lb/h	0 lb/h	10,000 lb/h	10,000 lb/h
4 20 mA	MEASURED SIGNAL	4 to 20 mA	4 mA	20 mA	16 mA
1 5 Volts	MEASURED SIGNAL	1 to 5V	1V	5V	4V

Relationship of pressure and flow

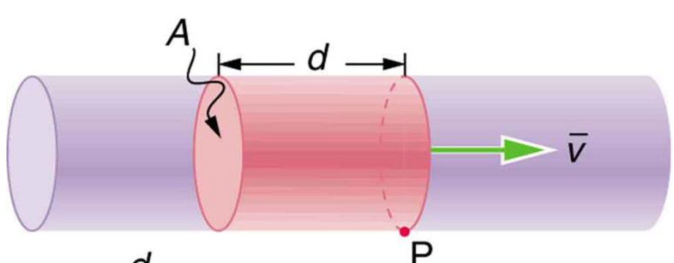
In a pipe, the static pressure distributed across the pipe is even during no flow. You have the same pressure at both ends of the pipe because the total energy in the system is at equilibrium. As the fluid flows, it is accelerated through the pipe. There is a pressure drop across the pipe. The static 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 pressures 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. It can be seen 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, due to the fact that work is being done on the pipe. The pump head energy is used up doing work on the pipe.

The ∆P measurement across the flow element acts just a little bit different. Flow is measured in the units of ∆P or DP (differential pressure). There is a pressure drop across the orifice element and there will be more 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. This is because more work is being done on the element as the velocity increases. But remember the pressure on the downstream side the flow element drops as the velocity increases. How does the pressure for the flow measurement increase? It doesn't, it is an increase in ∆P or DP (differential pressure), not in the static pressure.

We are measuring the ∆P differential pressure 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 by 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.

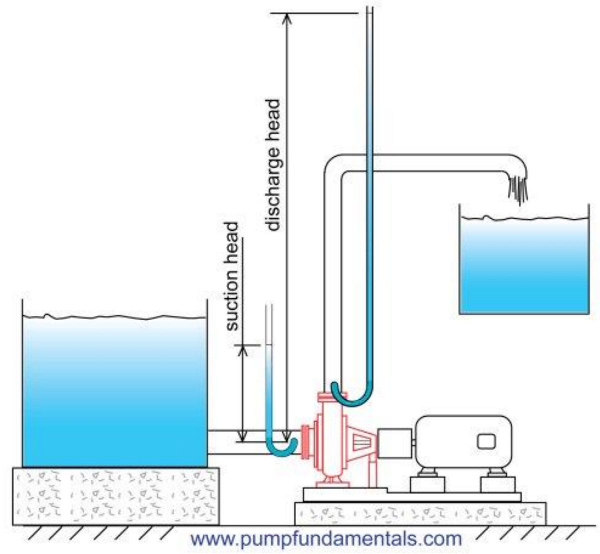


$$\bar{v} = \frac{d}{t}$$

$$Q = \frac{V}{t} = \frac{Ad}{t} = A\bar{v}$$

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 measure in PSI. The water is constantly "falling" down the pipe toward the other end of the pipe and the pump has to 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.

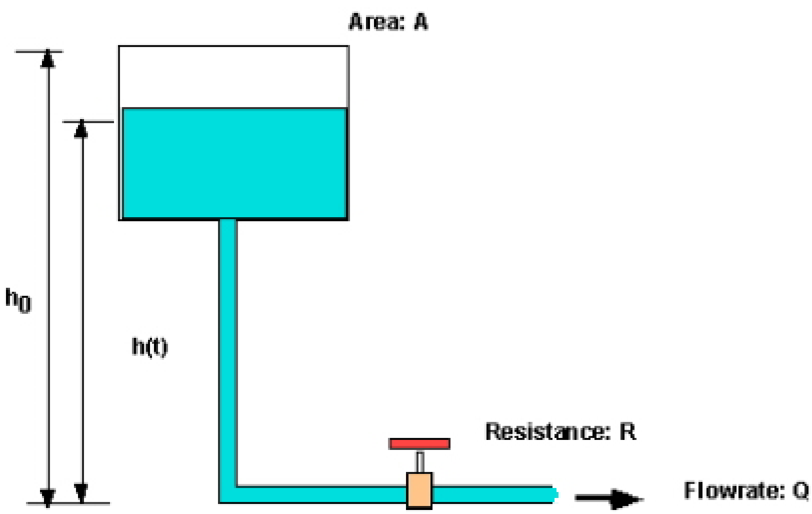
The kinetic energy is used to overcome the resistance of the pipe and the work done on the pipe as the fluid flows to the other end. If there is energy left over in the fluid, it is again transformed back into to potential energy at the other end of the pipe, as an available pressure at the end of the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



Note: The image at the right shows the pump has to 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).

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 and 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 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. Remember mass in has to equal mass out.

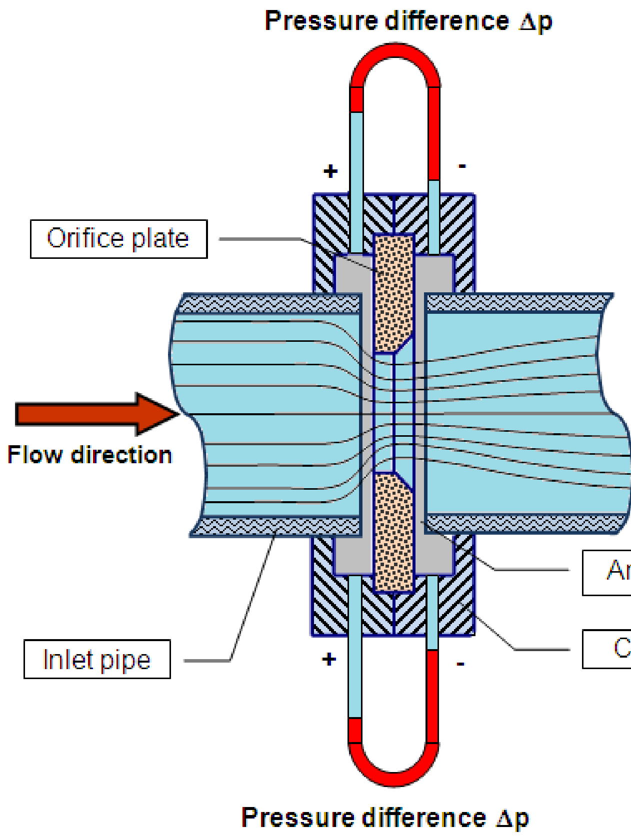


Energy is lost doing work on the orifice plate and the pressure drops on the exit side of the orifice. This can be seen in the profile of the vena contracta of the fluid flowing and the ΔP (differential pressure) across the orifice element. As the fluid exits the small opening into the much larger area 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, due to the fact that 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 ΔP (differential pressure) across the orifice. Note that as the pressure drops in the pipe due to increased velocity, the ΔP 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 into 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 ΔP (differential pressure) 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 as the fluid flow approaches a stop, the two water columns are almost even in height. The pressure differential, ΔP, 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 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.

Since we know the fluid's specific gravity (S.G.), we can now calculate the fluid's height as if it were a column of water. Remember (F=m*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.

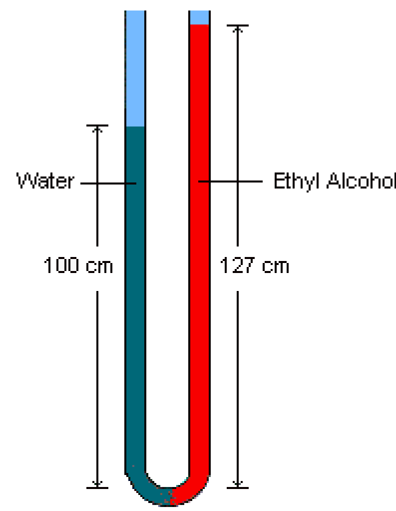
Stack 231 cubic inches of water on top of each other, to form a tall column of water, with a base of one (1) square inch. The column of water will be 231 inches tall. Divide the height of the column of water, 231 inches, by the weight of one (1) gallon of water, 8.324 pounds at 60°F. The result will be 27.691 or 27.7 inches of water column per pound of water, over a one square inch of area. Therefore 27.7 inches H_2O, of head pressure, equals one (1) PSI.

Therefore the column of water can be measured in pounds per square inch (psi), not just "HEAD PRESSURE" as a height of inches of water in the measurement meter. Just by knowing the height of the column we can determine the pressure it can excerpt and the inferred amount work it can do. A column of fluid with a lesser weight or density compared to water has specific gravity less than one (1).

Specific gravity is the ratio of the density or weight of a fluid compared to the density or weight of water. The more dense the fluid is the more mass it has, therefore the more force it excerpt due to the acceleration of gravity (F=m*a). So a fluid with a specific gravity less than one (1) cannot excerpt as much force as water because it has less mass. Therefore, a column of fluid with a specific gravity less than 1 excerpts less pressure on a measurement meter, compared to the pressure excerpted by a column of water. This is why we divide the pressure head by the specific gravity to give it a "gain" of force equal to that excerpted by water, the industrial standard of measurement.

From the previous demonstration, it can be seen that a column of fluid with a specific gravity less than one (1), needs to be taller than a column of water, to excerpt the same pressure on the measurement meter. If we had a fluid such as solvent, it may have a S.G. of (0.7874). We use the industrial standard of water to calibrate the meter. So to measure the height of the column of solvent in the standard of calibration with water, the column of solvent needs to be taller than a column of water to excerpt the same force on a weight scale. It would seem that the taller column of solvent would be falling faster than the velocity we need to measure and it is. It has less mass; therefore, it needs to be accelerated faster than the column of water to develop more force on impact. This force at impact will be the same force generated by the column of water falling from a lower height and the pressure on the measurement element will be the same. It can be seen we have an equivalent force and an equivalent pressure on the meter, for the two different height columns of fluid.

In level measurement, the column of water used to calibrate the meter will less than the column of solvent being measured. The water must fall from a lower height to excerpt the same pressure as the taller column of solvent. So if we have a s.g. of 0.7874 for the solvent, the column of water will be 0.7874 times the height of the solvent column or 78.74% of the intended height measurement. This will produce a 78.74" column of water (100" H_2O * 0.7874 s.g. = 78.74" H_2O). The solvent column will be 100" tall but will appear to be only 78.74" of water to the measurement meter. Zero to 100% output will equal 0 to 100" of solvent.



The height of solvent needed to produce a pressure equal to that of 100 cm of water is shown to the right. The solvent column height is taller than the column of water, 100 cm / (S.G. = 0.7874). So the column of solvent equals 100 cm / 0.7874 = 127 cm. It can be seen that both columns produce the exact same pressure at the bottom of the "U" tube.

The same thing is happening in the flow meter. The solvent is less dense than water and excerpts less pressure on the meter for the same flow rate as water. 10 gallons a minute of water traveling down a pipe or conveyor weights (10 * 8.33 lb. = 83.3 lbs.). 10 gallons a minute of solvent traveling down a pipe or conveyor weights (10 * 8.33 lb. * 0.7874 s.g. = 65.59 lbs.). The pressure the solvent excerpts on the scale is less for the same volumetric flow rate. Again the flow meter will be calibrated in water with a lower measure of water column applied to the meter to read the desired flow rate of solvent.

Applications of the formulas

Let's do a quick overview of how we use fluid mechanics in process control measurements and then we will discuss how we get the formulas and how fluid mechanics are used in detail in the following sections of this guide to provide safe and accurate control of process plants.

Part One

Let's look at the flow measurement formula for calibration. We have 100 gpm of water flowing in a 3″ schedule 40 pipe (ID=3.068″) with a S.G. of 1 and the orifice diameter is 1.534". The "Beta Ratio" is the pipe inside diameter divided by the orifice hole diameter.

$$Q(gpm) = 5.667SD^2\sqrt{\frac{h}{G_f}}$$

The Beta Ratio = 0.5 (3.068 /1.534 =0.5).

From Table 3: Beta = 0.500, $S = 0.1568$

$$100(gpm) = 5.667\left(0.1568\right)\left(3.068\right)^2\sqrt{\frac{h}{1}}$$

$$\frac{100(gpm)}{5.667\left(0.1568\right)\left(3.068\right)^2} = \sqrt{\frac{h}{1}}$$

$$\left(\frac{100(gpm)}{8.3639}\right)^2 = \left(\sqrt{\frac{h}{1}}\right)^2$$

$$11.9561^2 = \frac{h}{1}$$

$$142.95''\ \mathrm{H_2O} = h$$

Now we will have 100 gpm of solvent flowing in a 3” schedule 40 pipe (ID=3.068”) with a S.G. of 0.7874.

$$Q(gpm) = 5.667SD^2\sqrt{\frac{h}{G_f}}$$

From Table 3: Beta = 0.500, $S = 0.1568$

$$100(gpm) = 5.667\left(0.1568\right)\left(3.068\right)^2\sqrt{\frac{h}{0.7874}}$$

$$\frac{100(gpm)}{5.667\left(0.1568\right)\left(3.068\right)^2} = \sqrt{\frac{h}{0.7874}}$$

$$\left(\frac{100(gpm)}{8.3639}\right)^2 = \left(\sqrt{\frac{h}{0.7874}}\right)^2$$

$$11.9561^2 = \frac{h}{0.7874}$$

$$142.95\left(0.7874\right) = h$$

$$112.56''\ \mathrm{H_2O} = h$$

It can be seen we need less water to calibrate the flow meter in the calibration standard of water, to measure the flow of solvent.

Part two

Let's apply Bernoulli's principal to the pressure drop in pipes:

For a change in the static pressure anywhere in the piping system:

$$p_1 F_1^2 = p_2 F_2^2 \qquad p_2 = \left(\frac{F_1}{F_2}\right)^2 p_1$$

This is practical for a pressure meter to measure the available pressure at a flow rate, but it does not tell the loss of pressure across the piping system or flow element.

We have 100 gpm of water flowing through 100 foot of 2" schedule 40 pipe (ID=2.067") at 60°F (cST=1.22). The pump is producing 100 feet of water or 43.32 psi. When the pump is running at full speed and the pipe is blocked by a valve at the exit end of the pipe, the pressure of 100 feet of head is distributed evenly throughout the pipe.

We crack open the valve until the water is flowing at 100 gpm. Let's calculate the head drop (delta pressure drop) across the pipe.

First find the velocity of the fluid:

$$velocity(ft/\sec) = \frac{gpm * 0.4085}{ID^2(inches)}$$

$$9.56(ft/\sec) = \frac{100 * 0.4085}{2.067^2(inches)}$$

Find the Reynolds number for the pipe:

$$R_e = \frac{3160 * \ flow\ rate(gpm) * Specific\ Gravity}{Pipe\ ID(inches) * Viscosity(cST)}$$ Note: for liquids

$$125{,}310 R_e = \frac{3160 * 100 * 1}{2.067"ID \ * 1.22(cST)}$$

Find the head loss across the pipe using the Darcy-Weisbach equation:

Find the friction factor:

Friction factor for Darcy-Weisbach equation
Note: *e* = 0.00015 for steel pipes

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

$$0.0217 = 0.0055 + 0.0055\left[20{,}000\left(\frac{0.00015 \ *12}{2.067"}\right) + \frac{10^6}{125{,}310}\right]^{\frac{1}{3}}$$

Find the head loss in the piping system:

$$h_L = f\left(\frac{Length(ft) \ * \ 12}{Pipe \ ID(inches)}\right) * \frac{V^2\left(ft/\sec\right)}{64}$$

$$17.99\,feet = 0.0217\left(\frac{100' \ * \ 12}{2.067''}\right) * \frac{9.56^2\left(ft/\sec\right)}{64}$$

There is a head loss (pressure drop) across the pipe of 17.99 feet of water (or 7.8 psi) at 100 gpm. This leaves 82 feet of head (100' – 18' = 82') or 35.52 psi, at the end of the pipe to do work across a control valve or overcome a pressure in a vessel. Note: Usually there is no more than a 10 psi differential of pressure across the control valve.

It is recommended that an additional 10% to 40% increase in pump head be added to the required system pump pressure for normal pumping through the piping system, minus the required head to overcome any vessel pressure (pressurized tank, vessel or column). We only need to add to the pump head that is needed to overcome the friction loss of the pipe and to do the foot-pounds of work to accelerate the fluid through the pipe.

Important Note: You cannot size the pump for just the pressure drop across the piping system due to friction loss and flow rate. The valve will not work. There must be extra pressure head across the of valve or the valve will not function.

The ΔP across the valve for 10% should be:
17.99 psi * 0.10 = 1.799 psi or 4.153 feet of head for the valve sizing calculation.
There will be 1.799 psi across the valve, if there is a 10% increase in the pump head for the piping system.

The ΔP across the valve for 40% should be:
17.99 psi * 0.40 = 7.196 psi or 16.61 feet of head for the valve sizing calculation.
There will be 1.799 psi across the valve, if there is a 40% increase in the pump head for the piping system.

Let's now calculate the head loss at 50 gpm:

$$4.78(ft/\sec) = \frac{50 * 0.4085}{2.067^2(inches)}$$

$$62,655 R_e = \frac{3160 * 50 * 1}{2.067''ID \ * 1.22(cST)}$$

$$0.0217 = 0.0055 + 0.0055\left[20,000\left(\frac{0.00015 \ *12}{2.067''}\right) + \frac{10^6}{62,655}\right]^{\frac{1}{3}}$$

$$4.8\,feet = 0.0232\left(\frac{100' \ * \ 12}{2.067''}\right) * \frac{4.78^2\left(ft/\sec\right)}{64}$$

There is a head loss (pressure drop) across the pipe of 4.8 feet of water (or 2.08 psi) at 50 gpm. This leaves 95.2 feet of head (100'– 4.8 '= 95.2') or 41.24 psi, at the end of the pipe to do work across a control valve or overcome a pressure in a vessel.

Note: The psi drop across the control valve increases as the flow slows down and the valve absorbs the remaining pressure left in the system across the control valve. The difference of the system pressure is the pump head minus the head loss across the piping system and minus any head needed to overcome entry into a pressurized vessel. Just like I*R=E, the valve has more resistance to flow as it closes down, so the pressure drop across the valve increases to maintain the flow rate. So even though the control valve is trying to slow down the flow rate of the fluid, the fluid will try to maintain its flow rate as the valve absorbs the extra pressure in the system. The control valve controls the flow by burning up the extra energy head in the fluid as it flows through the piping system. We will discuss this in much more detail in the section on control valves.

$$1\,gpm = 1\,C_V * \sqrt{1\,\Delta P_{psig}}$$

Visit http://www.integrated.cc/download.htm for more resources to study. A piping system calculator can be downloaded for free from my web site. It is an Excel Spreadsheet to show real-world system results, with generated graphs of response curves of valve characteristics for a given system.

Liquid System Sizer - version 2.7 (Size Pump, Valve, Orifice, Transmitter and Piping System)
http://www.integrated.cc/download_System_Sizer.htm

Summary of fluid mechanics for process control

The DP across the orifice decreases as the velocity of the fluid decreases. It can be seen that the pressure on the exit side of the orifice increases as the fluid's velocity decreases and the pressure drop across the pipe decreases (less work is being done).

The velocity being measured is a "SCALED" velocity. It is scaled by the orifice size; the beta factor "THE SPINK FACTOR; the pipe ID and the s.g. of the fluid. Velocity equals the "square root of (2gH)". The fluid's velocity through the pipe may be much different than the measured differential height of the two water columns that are being measured to obtain the fluid's velocity.

Depending on the orifice size and the beta factor (say 0.3), for a given flow rate, the DP may be 1,000 inches of water column differential across a small orifice opening. The fluid has to do much more work to get through the high resistance of the small opening. The DP could be only 100 inches water column differential for a much larger beta ratio (say 0.7). The larger opening has less resistance and therefore much less work is being done to flow through it.

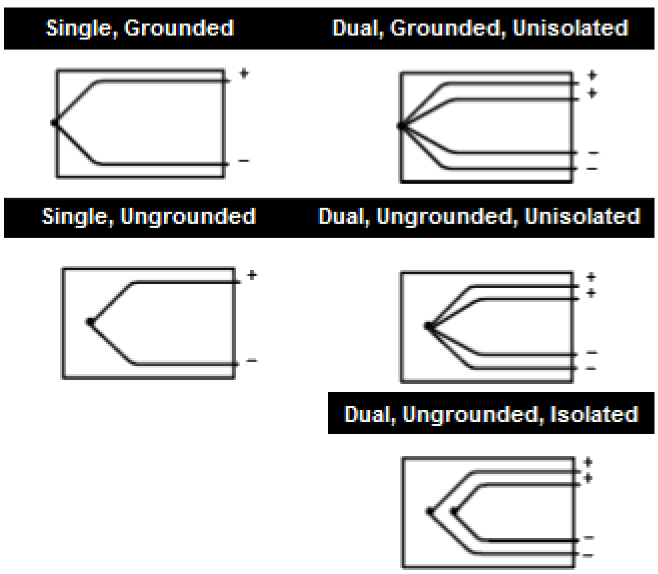
Therefore less potential energy has to change into kinetic and the height of the water column on the exit side of the orifice is much higher than with a beta ratio of (say 0.3). Therefore there is less DP across the orifice for the same flow rate that has been "SCALED" to calculate the volumetric flow rate.

Now we will discuss most process measurement subjects in detail, including the application of the fluid mechanics we just reviewed. These basic principles work for level, flow, orifice sizing, pump sizing, pipe sizing and understanding the basics of process operations.

Notes

Temperature measurement devices and calibration

In the process industry, temperature measurements are typically made with thermocouples, RTDs (Resistance Temperature Detector) and industrial thermometers. Industrial thermometers are typically of the liquid (class I), vapor (class II), and gas (class III) type.

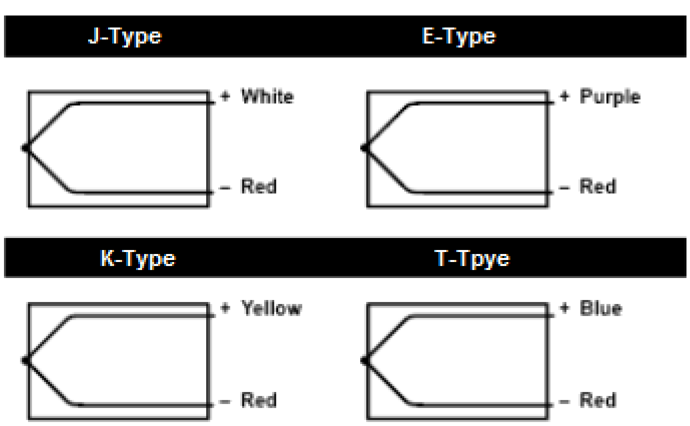


The five major types of thermocouple configurations are shown to the left.

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

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

Thermocouples should be extended with thermocouple extension wire and thermocouple termination blocks, but can be extended with standard copper wire and standard terminal blocks. This is due to the fact that the voltages generated at the extension junctions almost cancel each other out with very little error. One side is positive and the other side is negative.

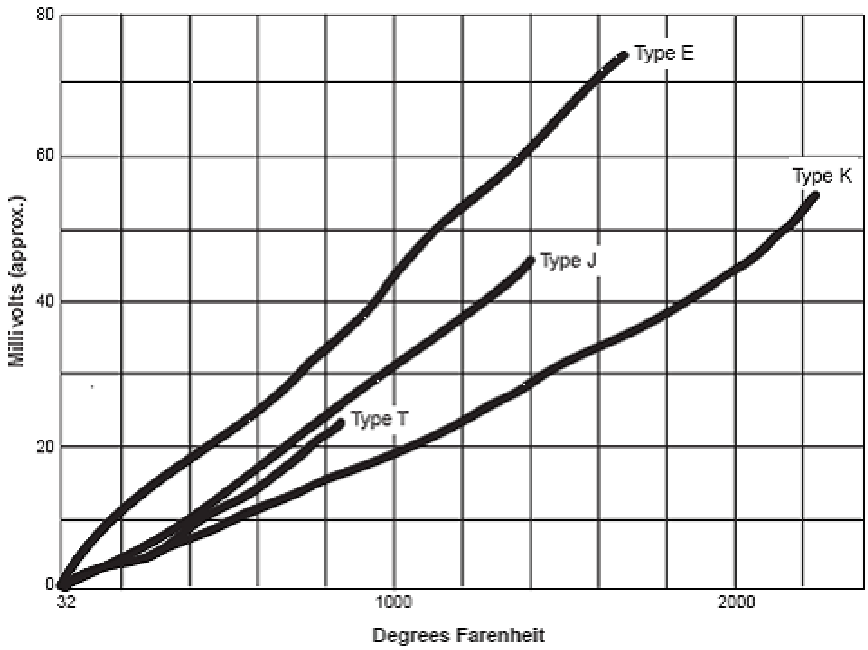


The four major thermocouples used in the process industry are Type J, Type E, Type K, Type T. The red wire is always the negative wire with thermocouples.

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

Thermocouple millivolt tables for the examination can be found in the Table A1 – Thermocouple Table (Type J) through Table A4 – Thermocouple Table (Type T) in the Appendix section of this guide.

Thermocouple Linearity Chart



Thermocouple Makeup Material and Color Code

TC Type	THEMOCOUPLE MATERIAL	RANGE FOR CALIB. DEG F	USEFUL RANGE DEF F	TC 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 250	200 to 2300	Yellow Wire Jacket Yellow (+) Red (-)
R	Platinum 13% Rodium (+) Platinum (-)	0 to 3100	1600 to 2640	Green Wire Jacket Black (+) Red (-)
S	Platinum 10% Rodium (+) 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 + 8ºF = (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°F = 14.479mV
672°F = mV
680°F = 14.713mV

We will have to interpolate the mV value for the desired temperature as follows:

interpolation:

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

Therefore the new mV for 672°F:

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

The mV at 672°F is 14.526 mV

This can be verified in *Table* ***A2 –Thermocouple Table (Type K)*** in the appendix.

RTD (Resistance Temperature Detector)

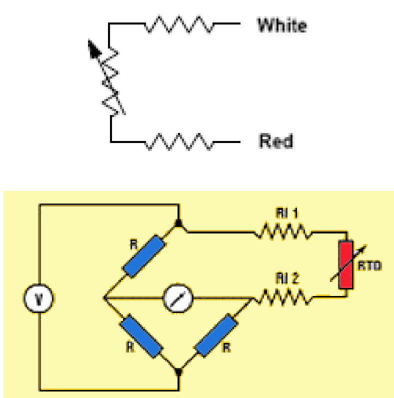
The process control industry also uses RTDs (Resistance Temperature Detectors) for many applications, for example, when precise temperature measurement is needed, such as mass flow measurements or critical temperature measurements of motor bearings.

RTDs typically come in 10 ohm copper and 100 ohm platinum elements. Their resistance is typically very linear over the scale.

Resistance values for the examination can be found in the ***Table A5 - Platinum 100 Ohm RTD Table in ohms***, in the Appendix section of this guide.

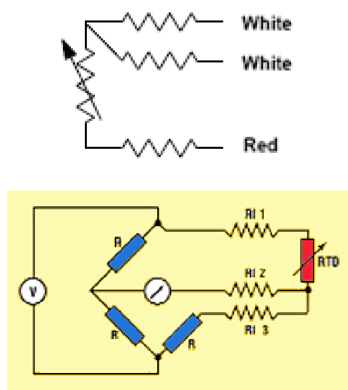
Typical wiring configurations and uses of RTDs

2-wire RTD



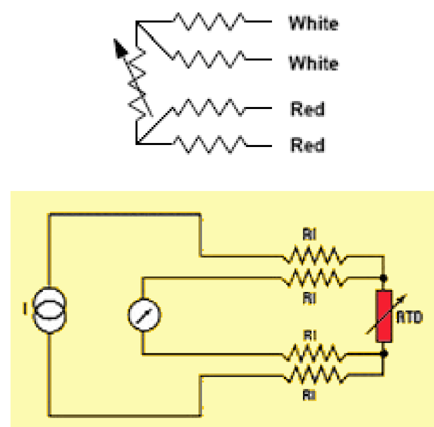
Good for close applications, at the transmitter.

3-wire RTD



Good for further distance applications. Remote from the transmitter.

4-wire RTD



Best application and usually uses 20 mA driving current and a voltage measurement.

RTD worked examples

Sample problem: A RTD is platinum and has a resistance of 100 ohms at a temperature of 32°F and an alpha 0.2178 ohms per °F. What is the resistance of the RTD at a temperature of 240°F?

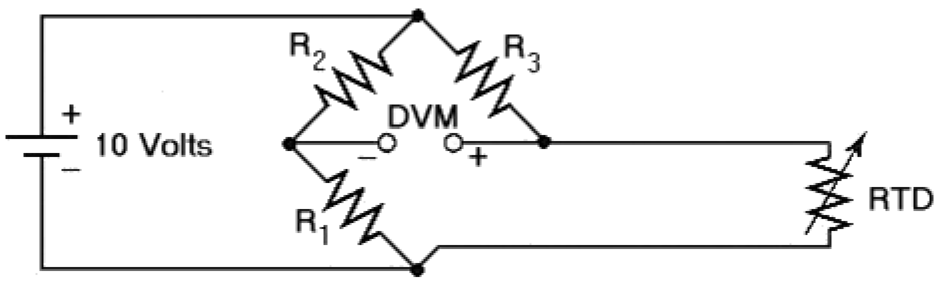
Find the difference in the temperature first. 240°F – 32°F = 208°F

Now find the resistance for the differential temperature:
208°F * 0.2178 ohms/deg F = 45.3 ohms

Now we add the change in resistance to the resistance at 32°F:
100 ohms + 45.3 = 145.3 ohms

Referring to ***Table-A5. Platinum 100 Ohm RTD Table in ohms***, in the appendix. The resistance value for the RTD can be interpolated and found for a given temperature.

Sample problem: In the bridge circuit above, if R1 and R2 are 200 ohms and the RTD is at 60°F. What resistance should R3 measure, to balance the circuit and give the meter a reading of 0 volts? The RTD is platinum and measures 100 ohms at 32°F with an alpha of 0.2178 ohms per °F.



Find the difference in the temperature first. 60°F – 32°F = 28°F

Now find the resistance for the differential temperature:

28°F * 0.2178 ohms/°F = 6.0984 ohms

Now we add the change in resistance to the resistance at 32°F:

100 ohms + 6.0984 = 106.0984 ohms

The resistor R3 needs to be 106 ohms to balance the bridge and give 0 volts at the meter.

Sample problem: In the bridge circuit above, R1 and R2 are 200 ohms. R3 is150 ohms. The excite voltage to the bridge is 10 volts. If the meter is reading 0.4 volts (the positive is on the right side and the negative on the left side) what is the temperature at the RTD?

Find the voltage on the left side of the bridge. This is the voltage we will add to the meter voltage on the right side. We will use the voltage divider theorem to find the voltage across R1.

$$V_{R1} = \frac{R_1}{R_1 + R_2}(10V) = \frac{200}{200+200}(10V) = 5V$$

This means the voltage across the RTD is 5.0V + 0.4V = 5.4 volts.

We will now use the voltage divider theorem to find the resistance of RTD.

$$V_{RTD} = \frac{R_{RTD}}{R_{RTD} + R_{R3}}(10V)\ ;\ 5.4V = \frac{R_{RTD}}{R_{RTD} + 150}(10V)$$

Solving for R_{RTD}:

$$5.4 = \left(\frac{R_{RTD}}{R_{RTD} + 150}\right)10$$

$$\frac{5.4}{10}=\left(\frac{R_{RTD}}{R_{RTD}+150}\right)\frac{10}{10}$$

$$0.54\left(R_{RTD}+150\right)=\left(\frac{R_{RTD}}{R_{RTD}+150}\right)\left(R_{RTD}+150\right)$$

$$0.54(R_{RTD}+150)=R_{RTD}$$

$$0.54R_{RTD}+0.54(150)=R_{RTD}$$

$$0.54R_{RTD}+81=R_{RTD}$$

$$0.54R_{RTD}-0.54R_{RTD}+81=R_{RTD}-0.54R_{RTD}$$

$$81=R_{RTD}-0.54R_{RTD}$$

$$81=(1-0.54)R_{RTD}$$

$$81=(0.46)R_{RTD}$$

$$\frac{81}{0.46}=\frac{(0.46)R_{RTD}}{0.46}$$

$$176.087=R_{RTD}$$

We can prove that the 176.087 ohms for the RTD is correct by plugging the value into the voltage divider formula to find the 5.4 volts at the meter.

$$V_{RTD}=\frac{176.087}{176.087+150}(10V)=5.4V$$

We have the ohms of the RTD, now we can find the temperature.

100 ohms = 32°F,

So subtract the difference in ohms 176.087 – 100 = 76.087 ohms.

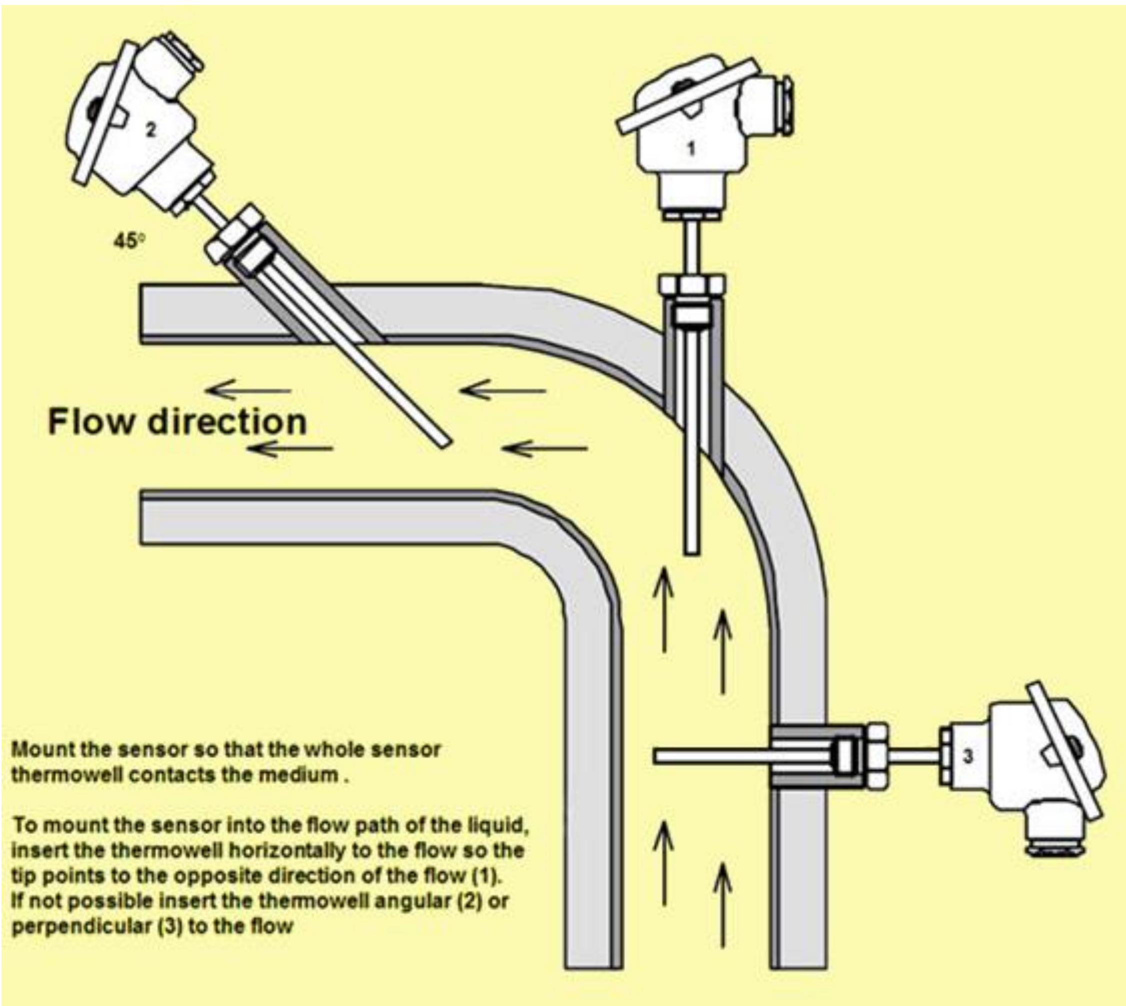
Divide the 76.087 ohms by the alpha 0.2178 ohms per °F.

$$°F = \frac{76.087\ ohms}{\left(\frac{0.2178\ ohms}{\deg F}\right)} = 349.34°F$$

Add the 32°F bias for 100 ohms to the 349.34°F for 76.087 ohms and we get:

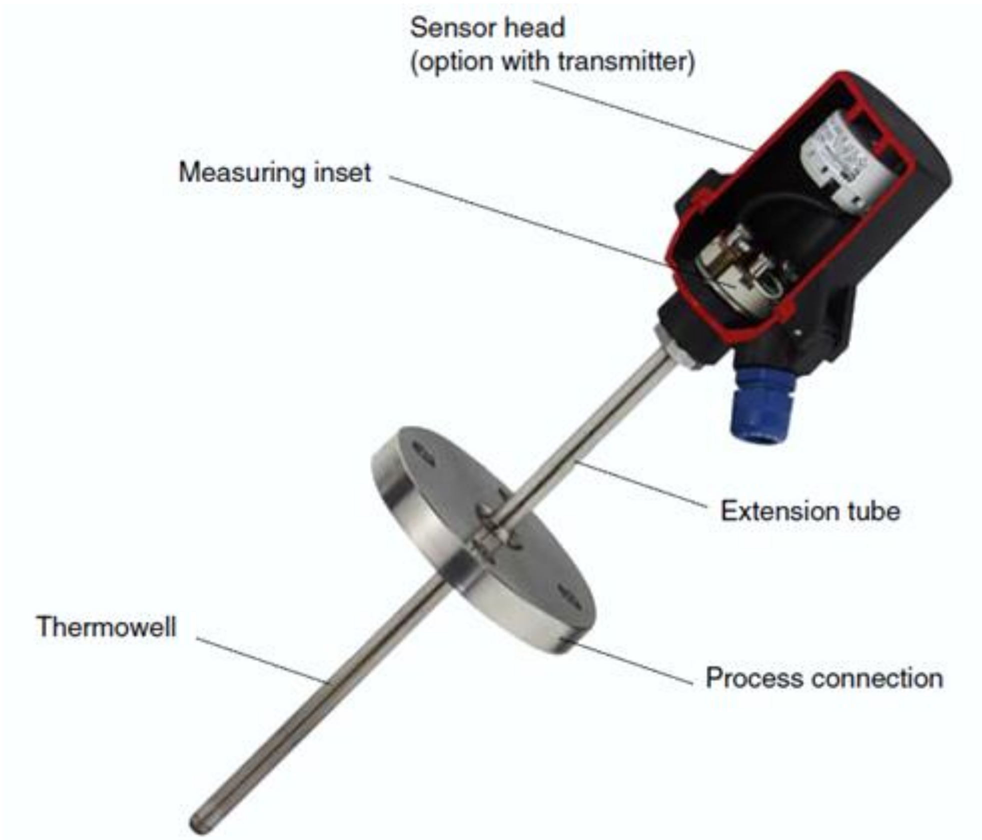
349.34°F + 32.00°F = 381.34°F.

Installing RTDs and Thermocouples into a process stream



Typical RTD and thermocouple applications

A complete assembly with a 4-20mA transmitter in an explosion proof housing



Industrial RTD or Thermocouple with head
A straight thermowell is shown in the middle

Various Industrial Thermometers
Threaded for mounting in tanks and pipes