NCEES
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PE | Control Systems

Reference Handbook

Version 1.1

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INTRODUCTION

About the Handbook

The Principles and Practice of Engineering (PE) Control Systems exam is computer-based, and NCEES will supply all the resource material you can use during the exam. Reviewing the *PE Control Systems Reference Handbook* before exam day will help you become familiar with the charts, formulas, tables, and other reference information provided. You will not be allowed to bring your personal copy of the *PE Control Systems Reference Handbook* into the exam room. Instead, the computer-based exam will include a PDF version of the handbook for your use. No printed copies of the handbook will be allowed in the exam room.

The PDF version of the *PE Control Systems Reference Handbook* that you use on exam day will be very similar to this one. However, pages not needed to solve exam questions—such as the cover and introductory material—may not be included in the exam version. In addition, the NCEES will periodically revise and update the handbook, and each PE Control Systems exam will be administered using the updated version.

The *PE Control Systems Reference Handbook* does not contain all the information required to answer every question on the exam. Theories, conversions, formulas, and definitions that examinees are expected to know have not been included. The handbook is intended solely for use on the PE Control Systems exam.

Other Supplied Exam Material

In addition to the *PE Control Systems Reference Handbook*, the exam will include codes and standards for your use. A list of the material that will be included in your exam is shown on the exam specifications. Any additional material required for the solution of a particular exam question will be included in the question itself. You will not be allowed to bring personal copies of any material into the exam room.

Updates on Exam Content and Procedures

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Errata

To report errata in this book, log in to your MyNCEES account and send a message. Examinees are not penalized for any errors in the handbook that affect an exam question.

Contributors

The *PE Control Systems Reference Handbook* was developed by members of the International Society of Automation (ISA) to support the NCEES PE Control Systems exam.

CONTENTS

1 SYMBOLS AND DEFINITIONS

1.1 Variables List for Equations

Variable		Description
A	=	cross-sectional area of the pipe
d	=	orifice bore
d_{oc}	=	orifice bore corrected for thermal expansion
D	=	pipe inner diameter
D_{pc}	=	pipe inner diameter corrected for thermal expansion
F_a	=	thermal expansion coefficient
G	=	specific gravity
G_b	=	specific gravity at base temperature
G_{sg}	=	gas specific gravity
h_w	=	differential pressure at upper range value
N	=	sizing flow units
p_f	=	pressure flowing
Q	=	flow rate
q_{gpm}	=	flow-rate volumetric (gpm)
Q_M	=	flow rate, maximum
R_e	=	Reynolds number
T_f	=	temperature flowing
URV	=	upper range value
V	=	velocity, fluid
Z	=	compressibility factor
ΔP	=	differential pressure
ΔP_1	=	differential pressure, condition 1
ΔP_2	=	differential pressure, condition 2
α_{fe}	=	thermal expansion coefficient for flow element material
α_p	=	thermal expansion coefficient for pipe material
β	=	beta ratio
μ	=	viscosity, centipoises

1.2 Area of a Circle

$$A = \pi r^2$$

$$A = \left(\frac{\pi}{4}\right) D^2$$

where

A	=	area
r	=	radius
D	=	diameter

1.3 Ohm's Law

$$V = IR$$

1.4 Power

$$P = I^2 R$$

$$P = \frac{V^2}{R}$$

$$P = I\,V$$

where

V	=	voltage (volts, V)
I	=	current (amperes, A)
R	=	resistance (ohms, Ω)
P	=	power (watts, W)

1.5 Common Conversion Factors

1 ft	=	0.3048 m
1 in	=	25.4 mm
1 gal	=	0.13368 ft^3
1 gal	=	231 in^3
1 gal	=	128 fl oz
1 gal	=	0.00379 m^3
42 gal	=	1 bbl
1 psi	=	2.31 ft of water
1 psi	=	27.7 in of water
1 psi	=	0.0689 bar
1 psi	=	6.89 kPa
1 in. of mercury	=	13.6 in of water

1 in. of mercury	=	0.49 psi
1 in. of water	=	0.036 psi
1 ft. of water	=	0.433 psi
1 ft^3	=	7.48 gal
1 ft^3	=	0.0283 m^3
14.7 psia	=	0 psig
1 lb	=	16 oz

1.6 Standard Pressure and Temperature (STP)

14.69 psia @ 60°F

1.7 Specific Gravity

specific gravity (G) of water @ 60°F	=	1
specific gravity (G) of air	=	1
molecular weight of air	=	29
molecular weight of water	=	18.02
gas specific gravity	=	molecular weight of gas divided by 29
density of water	=	62.4 lb/ft^3
density of air	=	0.07649 lb/ft^3
specific gravity of liquid	=	liquid density divided by 62.4
specific gravity of gas	=	gas density divided by 0.07649

1.8 Temperature Conversion

Fahrenheit: $°F = (1.8 \times °C) + 32$

Celsius: $°C = \frac{°F - 32}{1.8}$

Rankine: °R = °F + 460

Kelvin: K = °C + 273

1.9 Ideal Gas Constant (R)

This table is based on data from The NIST Reference on Constants, Units, and Uncertainty website, https://physics.nist.gov/cgi-bin/cuu/Value?r.

Values of *R*	Units
SI Units	
8.31446261815324	$J·K^{-1}·mol^{-1}$
8.31446261815324	$m^3·Pa·K^{-1}·mol^{-1}$
8.31446261815324	$kg·m^2·K^{-1}·mol^{-1}s^{-2}$
$8.31446261815324×10^3$	$L·Pa·K^{-1}·mol^{-1}$
$8.31446261815324×10^{-2}$	$L·bar·K^{-1}·mol^{-1}$
U.S. Customary Units	
0.730240507295273	$atm·ft^3·lb\ mol^{-1}°R^{-1}$
10.731557089016	$psi·ft^3·lb\ mol^{-1}°R^{-1}$
1.985875279009	$Btu·lb\ mol^{-1}°R^{-1}$
Other Common Units	
297.049031214	in. $H_2O·ft^3·lb\ mol^{-1}°R^{-1}$
554.984319180	$Torr·ft^3·lb\ mol^{-1}°R^{-1}$
0.082057366080960	$L·atm·K^{-1}·mol^{-1}$
62.363598221529	$L·Torr·K^{-1}·mol^{-1}$
$1.98720425864083…×10^{-3}$	$kcal·K^{-1}·mol^{-1}$
$8.20573660809596...×10^{-5}$	$m^3·atm·K^{-1}·mol^{-1}$
$8.31446261815324×10^7$	$erg·K^{-1}·mol^{-1}$
379.3	Scf/lb-mole

1.10 Ideal Gas Relationships–PVT

1.10.1 Boyle's Law

$$P_1V_1 = P_2V_2$$

1.10.2 Charles' Law

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

1.10.3 Gay-Lussac's Law

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

where

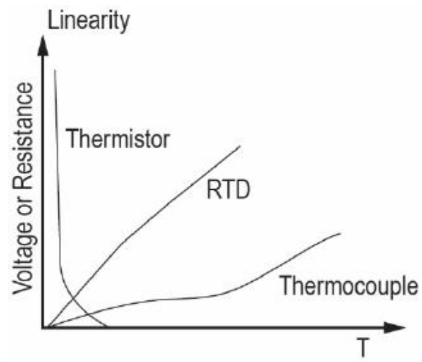
P = pressure

V = volume

T = temperature

2 MEASUREMENT

2.1 Temperature Elements



Temperature Sensor Comparison

Comparison of Contact Temperature Sensors

Relative Advantages of Contact Temperature Sensors			
Quality	**T/Cs**	**RTDs**	**Thermistors**
Temp Range	–400 to 4200°F	–200 to 1475°F	–176 to 392°F
Accuracy	< RTD	> T/C	> T/C & RTD
Ruggedness	Highly Rugged	Sensitive to Shock	NOT Rugged
Linearity	Highly NON-Linear	Somewhat NON-Linear	Highly NON-Linear
Drift	Subject to Drift	< T/C	< T/C
Cold Junction	Required	None	None
Compensation Response	Fast	Relatively Slow	Faster than RTD
Cost	Low, except for noble metals	> T/C	Low

Source: *Control Systems Engineer Technical Reference Handbook* by Chuck Cornell.
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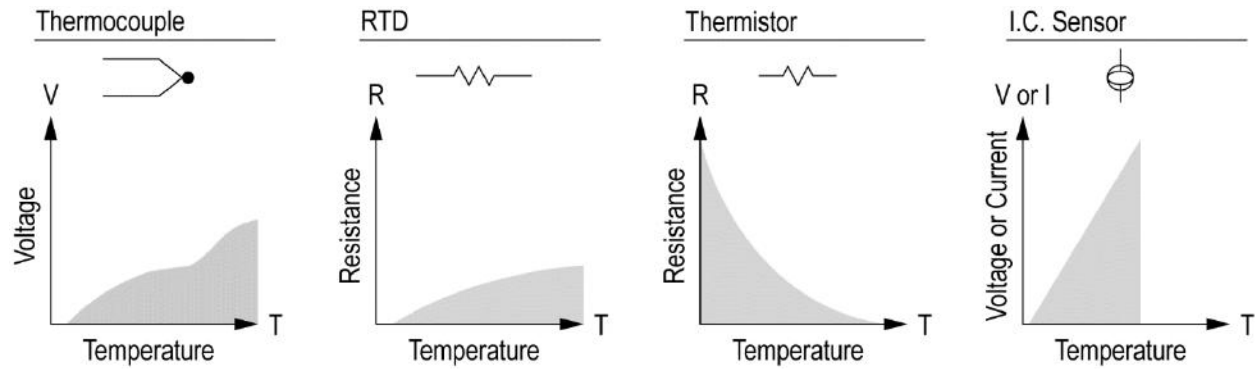

Advantages

▪ Self-powered ▪ Simple ▪ Rugged ▪ Inexpensive ▪ Wide variety of physical forms ▪ Wide temperature range	▪ Most stable ▪ Most accurate ▪ More linear than thermocouple	▪ High output ▪ Fast ▪ Two-wire ohm measurement	▪ Most linear ▪ Highest output ▪ Inexpensive

Disadvantages

▪ Nonlinear ▪ Low voltage ▪ Reference required ▪ Least stable ▪ Least sensitive	▪ Expensive ▪ Slow ▪ Current source required ▪ Small resistance change ▪ Four-wire measurement	▪ Nonlinear ▪ Limited temperature range ▪ Fragile ▪ Current source required ▪ Self-heating	▪ T <250°C ▪ Power supply required ▪ Slow ▪ Self-heating ▪ Limited configurations

Temperature Sensor Calibration Selection Guide

Calibration Type	Conductors Positive	Conductors Negative	Temperature Range °C	Limits of Error Standard	Limits of Error Special	Extension Wire Jacket Color	Color Coding
J	Iron (Magnetic)	Constantan (Non-magnetic)	0°C to 750°C	±2.2°C or ±0.75%	±1.1°C or ±0.4%	Black	White + Red –
K	Chromel (Non-magnetic)	Alumel (Magnetic)	–200°C to 0°C	±2.2°C or ±2%	- -	Yellow	Yellow + Red –
			0°C to 1250°C	±2.2°C or ±0.75%	±1.1°C or ±0.4%		
T	Copper (Non-magnetic)	Constantan (Non-magnetic)	–200°C to 0°C	±1°C or ±1.5%	- -	Blue	Blue + Red –
			0°C to 350°C	±1°C or ±0.75%	±0.5°C or ±0.4%		
E	Chromel (Non-magnetic)	Constantan (Non-magnetic)	–200°C to 0°C	±1.7°C or ±1%	- -	Purple	Purple + Red –
			0°C to 900°C	±1.7°C or ±0.5%	±1°C or ±0.4%		
N	Nicrosil (Non-magnetic)	Nisil (Non-magnetic)	0°C to 1260°C	±3/4%	±3/8%	Orange	Orange + Red –
R	Platinum 13% Rhodium (Non-magnetic)	Pure Platinum (Non-magnetic)	0°C to 1450°C	±1.5°C or ±0.25%	N/A N/A	Green	Black + Red –
S	Platinum 10% Rhodium (Non-magnetic)	Pure Platinum (Non-magnetic)	0°C to 1450°C	±1.5°C or ±0.25%	N/A N/A	Green	Black + Red –
B	Platinum 30% Rhodium (Non-magnetic)	Platinum 6% Rhodium (Non-magnetic)	870°C to 1700°C	±0.5%	N/A N/A	Gray	Black + Red –

Calibration Notes

J- Iron Constantan - Reducing atmosphere recommended. Iron oxidizes rapidly at elevated temperatures. A larger gage size will extend the life of the iron wire.

T- Copper Constantan - Can be used in oxidizing or reducing atmospheres. Rust and corrosion resistant. Best for sub-zero temperatures.

K- Chromel Alumel - Oxidizing atmosphere recommended. Most commonly used base metal thermocouple. Cycling at high temperatures can cause calibration drift. Not recommended in sulfur environments.

E- Chromel Constantan - Oxidizing atmosphere recommended. Highest emf output of thermocouples commonly used. Good corrosion resistance.

S, R- Use in oxidizing or inert atmospheres. Not recommended for reducing atmospheres. Granular precipitation from metal protection tubes can cause failure or calibration drift.

N- Use in oxidizing, reducing and inert atmospheres. Not recommended in sulfur environments. Improved resistance to drift and better stability over K and E at elevated temperatures.

Source: *Technical Reference Manual* by Smart Sensors, Inc. Reproduced with permission from SOR, Inc.

2.2 Flow Elements

Flow Element Comparison

Sensor	Rangeability	Accuracy	Advantages	Disadvantages	Cost
Annubar	3:1	±0.5% to ±1.5% of full scale	• Low permanent pressure loss • Cost when used in large line sizes		• Smaller line sizes, $$ • Larger line sizes, $
Coriolis	100:1	±0.05% to ±0.15% of reading	• Excellent rangeability and accuracy	• Not available in larger line sizes	$$$$$
Elbow	3:1	±5% to ±10% of full scale	• Low permanent pressure loss	• Accuracy	$
Flow nozzle	5:1	±2% of full scale	• Resistant to plugging with slurries • Medium permanent pressure loss	• Limited to smaller line sizes	$$
Magnetic	40:1	±0.5% of reading	• Excellent for slurries and corrosive liquids • Good rangeability and accuracy • Bidirectional	• Fluid must be conductive • Can be sensitive to velocity	$$
Orifice plate	5:1	±2% of full scale	• Useful in a wide variety of applications	• Can plug when used with slurries • High permanent pressure loss	$
Pitot tube	3:1	±0.5% to ±5.0% of full scale	• Low permanent pressure loss • Cost when used in large line sizes	• Prone to plugging in some services	• Smaller line sizes, $ • Larger line sizes, $
Positive displacement	10:1 or better	±1% of reading	• Good rangeability and accuracy • Good in high viscosity services		$$
Turbine meter	20:1	±0.25% of reading	• Good rangeability and accuracy	• Mechanical components are subject to wear • Lower accuracy at start-up and shutdown	$$$
Ultrasonic	100:1	±2% of full scale	• Excellent rangeability and accuracy	• Susceptible to ultrasonic interference from inline devices • Needs adequate space and piping configuration to work properly	$$$$
Venturi	5:1	±1% of full scale	• Low permanent pressure loss • Resistant to plugging with slurries		$$$
Vortex meter	10:1	±1% of reading	• Good rangeability and accuracy	• Flow not measurable at all below meter low end cutoff	• Smaller line sizes, $ • Larger line sizes, $$$

2.3 Analytical Sensor Technologies

2.3.1 Chemical Analytical Methods

Analyzer Selection Chart, Part 1

Analyzer Selection Chemical Name	**Analytical Method(s)**	Electroconductivity, electrochemical, polarographic, or fuel cell	Infrared (IR)	Selective ion or acid analyzer	Colorimeter, autoanalyzer or autotitrator	Electrolytic hygrometer	Capacitance	Polarographic	UV and visible photometers	Refractometers	Thermal conductivity	Phototape	Zirconium oxide	Mass spectrometer	Chromatography	Paramagnetic	Flame ionization	Diffusion elements	Amperometric (galvanic)	Catalytic combustion	Atomic absorption
Acetaldehyde									■												
Acetic anhydride									■												
Acetone									■	■											
Acidity					■																
Acids in water										■											
Acrylonitrile									■												
Air humidity						■	■														
Alcohol in water										■											
Acyl chloride		■																			
Aldehydes									■												
Alkalinity					■																
Aluminum					■																
Amines, ppm																	■				
Ammonia		■	■	■	■						■										
Ammonia, ppb																	■				
Ammonium ions				■																	
Ammonium sulfate										■											
Aniline									■												
Argon						■					■										
Aromatics in vapors or in water									■												
Benzene moisture content							■														
Benzene in ethanol or cyclohexane										■											
Benzene in raffinate or in ethyl alcohol									■												
Benzotriazole in water, ppm									■												
Boron					■					■											
Brine concentration										■											
Bromide ions				■																	
Bromine									■												
Butane			■			■	■														
Butadiene									■	■											
Butadiene in butanes and butylenes									■												
Butadiene in styrene										■											
Cadmium ions				■																	
Caffeine									■												
Calcium ions				■																	
Carbon bisulfide									■												
Carbon disulfide		■																			
Carbon dioxide in carbonated beverages			■																		
Carbon dioxide in gases		■	■		■															■	
Carbon dioxide moisture content						■															
Carbon monoxide in gases		■	■																		
Carbon monoxide moisture content						■															
Carbon tetrachloride in air		■																			
Carbon tetrachloride, ppm							■										■				
Catsup and tomato paste										■											
Caustic concentration			■							■											
Chloride				■	■																
Chlorine		■							■		■	■									
Chlorine in air											■										

Analyzer Selection Chart, Part 2

Analyzer Selection Chemical Name	**Analytical Method(s)**	Electroconductivity, electrochemical, polarographic, or fuel cell	Infrared (IR)	Selective ion or acid analyzer	Colorimeter, autoanalyzer or autotitrator	Electrolytic hygrometer	Capacitance	Polarographic	UV and visible photometers	Refractometers	Thermal conductivity	Phototape	Zirconium oxide	Mass spectrometer	Chromatography	Paramagnetic	Flame ionization	Diffusion elements	Amperometric (galvanic)	Catalytic combustion	Atomic absorption
Chlorine in ethylene dichloride									■												
Chlorine, ppm, in off-gas or phosgene									■												
Chlorine, ppm																	■				
Chlorine residual					■			■											■		
Chloride				■	■																
Chlorobenzene		■																			
Chloroform		■																			
Chromium in water (hexavalent or total)					■																
Citrus juice										■											
COD (chemical oxygen demand)					■																
Color					■																
Combustibles																	■	■		■	
Copper in water				■	■																
Cyanide in water				■	■																
Cyclohexane					■					■											
Cyclohexane in h-hexane and methyl cyclopentane										■											
Diolefin vapors									■												
Divalent ions				■																	
Divinyl acetylenes in acrylonitrile									■												
Ethane			■																		
Ethane moisture content						■															
Ethanol									■												
Ethanol in benzene or in water										■											
Ethyl bromide		■																			
Ethyl chloride		■																			
Ethyl chloride moisture content						■															
Ethylene in %			■																		
Ethylene in C1-C6, H2, CO2															■						
Ethylene bromide, ppm																	■				
Ethylene chloride, ppm																	■				
Ethylene glycol										■											
Ethylene oxide			■								■										
Ethylene oxide in methane, ethane, propane														■							
Fluoride in water				■	■																
Fluorine, ppm																	■				
Freon											■										
Freon moisture content						■															
Furfural									■												
Glycerine and salts in water										■											
Green liquor or white liquor										■											
Hardness (total) in water					■																
Helium in oxygen, nitrogen											■										
Helium moisture content						■															
Hazardous gases																		■			
Hexane			■																		
Hexane moisture content							■														
Hexavalent chromium					■																
Hydrazine in water					■																
Hydrazine, ppb																	■				

Analyzer Selection Chart, Part 3

Analyzer Selection Chemical Name	**Analytical Method(s)**	Electroconductivity, electrochemical, polarographic, or fuel cell	Infrared (IR)	Selective ion or acid analyzer	Colorimeter, autoanalyzer or autotitrator	Electrolytic hygrometer	Capacitance	Polarographic	UV and visible photometers	Refractometers	Thermal conductivity	Phototape	Zirconium oxide	Mass spectrometer	Chromatography	Paramagnetic	Flame ionization	Diffusion elements	Amperometric (galvanic)	Catalytic combustion	Atomic absorption
Hydrocarbon in H2S, CO2, air														■							
Hydrocarbon vapors in ambient air																	■	■		■	
Hydrogen in chlorine									■												
Hydrogen in nitrogen, oxygen, inert gases											■										
Hydrogen chloride		■			■																
Hydrogen chloride, ppb																	■				
Hydrogen cyanide		■																			
Hydrogen fluoride		■																			
Hydrogen fluoride, ppm																	■				
Hydrogen impurities (in O2, N2, CO, H20)														■							
Hydrogen sulfide in air		■							■			■						■			
Hydrogen sulfide in hydrocarbon liquids					■																
Hydrogen sulfide in natural gas or in stack gas		■							■									■			
Iodide ions				■																	
Iron (total) in water					■																
Isobutane in n-butane (liquid)										■											
Isobutane in C3, nC4, iC5															■						
Isoprene in solvents									■												
Jams and jellies										■											
Kerosene moisture content							■														
Ketones									■												
Lead ions				■																	
Mercury in air					■				■												■
Mercury in water					■										■						■
Methane			■								■										
Methane moisture content																					
Methanol						■			■												
Methanol in water										■											
Methyl bromide		■																			
Methyl chloride		■																			
Methylene chloride		■	■																		
Naphtha							■														
Natural gas moisture content						■	■														
Neon moisture content						■															
Nickel carbonyl, ppb							■										■				
Nitrate and nitrite					■																
Nitric acid in water										■											
Nitric oxide in air		■																			
Nitrobenzene									■												
Nitrogen											■										
Nitrogen (ammonia, Kjeldahl, total, nitrite, nitrate, organic)					■																
Nitrogen in argon														■							
Nitrogen dioxide, ppm																	■				
Nitrous fumes		■																			
Nitrous oxide			■																		
Nitrogen moisture content						■															
Nitrogen peroxide									■												
Octane rating of gasoline										■											
Oil in liquid freon			■																		
Oil in wax										■											
Ortho- and meta-xylene in para-xylene										■											

Analyzer Selection Chart, Part 4

Analyzer Selection Chemical Name	Analytical Method(s)	Electroconductivity, electrochemical, polarographic, or fuel cell	Infrared (IR)	Selective ion or acid analyzer	Colorimeter, autoanalyzer or autotitrator	Electrolytic hygrometer	Capacitance	Polarographic	UV and visible photometers	Refractometers	Thermal conductivity	Phototape	Zirconium oxide	Mass spectrometer	Chromatography	Paramagnetic	Flame ionization	Diffusion elements	Amperometric (galvanic)	Catalytic combustion	Atomic absorption
Ortho-phosphate					■																
Oxygen					■			■			■		■								
Oxygen in argon, hydrogen											■										
Oxygen in ethylene, argon														■							
Oxygen in stack gases													■			■					
Oxygen in water		■																			
Oxygen moisture content						■															
Ozone in air									■												
Phenol in water					■				■												
Phosgene									■												
Phosgene in air		■							■			■									
Phosgene, ppm																	■				
Phosphoric acid concentration										■											
Phosphorous (total or 0-phosphate) in water					■																
Polymer										■											
Potassium dichromate									■												
Potassium ions				■																	
Propane			■																		
Propane moisture content						■	■														
Propylene dichloride		■																			
Propylene glycol in water										■											
Propylene moisture content							■														
Proteins									■												
Pyridine									■												
Residual chlorine					■			■											■		
Silicates in water and in seawater					■																
Sodium carbonate in water			■																		
Sodium chloride in water										■											
Sodium hydroxide in water			■																		
Sodium ions				■																	
Starch concentration										■											
Steam in air			■																		
Styrene in ethyl benzene										■											
Sucrose in water					■																
Sugars in water, syrups										■											
Sulfate and sulfite					■																
Sulfur dioxide		■	■		■				■		■										
Sulfur dioxide moisture content						■															
Sulfur dioxide in stack gas			■						■												
Sulfur dioxide, ppm																	■				
Sulfuric acid				■																	
Sulfuric acid in water										■											
Tetrachioroethylene, ppm																	■				
Tetraethyl lead, ppb																	■				
Tetranitromethane in air			■																		
Toluene in hydrocarbons									■												
Toxic gases																		■			
Trans-unsaturation of vegetable oils, detergents			■																		
Trichloroethylene		■																			
Trichloroethylene, ppm																	■				
Vinyl acetate in polymer vapor			■																		
Vinyl chloride		■																			
Water hardness				■																	
Water in liquid SO2			■																		
Water in organic liquids			■																		
Water in methylene chloride liquid			■																		
Water vapor in air			■																		
Wax in oil										■											
White liquor										■											
Wine										■											
Xylenes in hydrocarbon									■												
Xylenes in isomers										■											

2.3.2 Gas Detection—Flammable and Toxic

Gas Detector Comparison

Technology	Gas Type Detected	Output	Works in Inert Atmosphere	Resistant to Poison	Detects Hydrogen	Performance in O_2 Enriched Atmospheres	Performance in 100% Humidity	Performs in All Temperatures	Response Time	Maintenance Requirement
Catalytic bead	Combustible gas	% LEL	No (Requires presence of oxygen)	Susceptible to poisons like lead- and sulfur-containing compounds, silicone vapors, and phosphates	Yes	Yes	Yes	Yes	<20 s	High
Metal oxide semiconductor	Combustible gas Toxic gas	PPM	No (Requires presence of oxygen)	Susceptible to poisons like Halide compounds, silicone vapors, caustic and acid liquids, and concentrated vapors	No	No	No	No (Can be compromised below 10°C and above 40°C)	<60 s	High
Point infrared-short path	Combustible gas	% LEL	Yes	Yes	No	Yes	Yes	Yes	<6.5 s	Low
Open-path infrared	Combustible gas	% LEL per meter	Yes	Yes	No	Yes	Yes	Yes	<3-5 s	Low
Photoacoustic infrared	Combustible gas Toxic gas	% LEL % by volume PPM PPB	Yes	Yes	No	Yes	Yes	No	<7 s	Low
Electrochemical toxic gases	Toxic gas	PPM readings for toxic gases	No (Requires presence of oxygen)	Yes	Yes	No	Yes	No (Can be unstable in very low or very high temperatures)	<30 s	High

Technology	Gas Type Detected	Output	Works in Inert Atmosphere	Resistant to Poison	Detects Hydrogen	Performance in O_2 Enriched Atmospheres	Performance in 100% Humidity	Performs in All Temperatures	Response Time	Maintenance Requirement
Electrochemical oxygen	Oxygen deficiency/ enrichment	Percent volume readings for oxygen	No (Requires presence of oxygen)	Yes	Yes	No	Yes	No (Can be unstable in very low or very high temperatures)	<30 s	High
Thermal conductivity	Combustible gas Toxic gas	PPM up to 100% by volume	No (Requires presence of oxygen)	No (Does not work with gases with thermal conductivities close to that of air, NH_3, CO, NO, O_2, N_2)	Yes	Yes	Yes	Yes		High
Paper tape	Toxic gas	PPM PPB	No (Requires presence of oxygen)	Yes	No	No	No	No (Can be compromised below 10°C and above 40°C)	<10-30 s	High
Photoionization	Toxic (organic compounds)	PPM sub-ppm	Yes	Yes	No	Yes	No	Yes	<5 s	High

2.3.3 Flame Detection

Fire Detector Comparison

Flame Detector Selection Guide				
Detector Type	**Description**	**Advantages**	**Limitations**	**Typical Usage**
UV	UV detector for indoor applications, detects organic and inorganic flames	Fast response speed	- Do not use in dusty or airborne oil droplets - Susceptible to false detection from welding, non-destructive x-ray testing, lightning, and direct/reflected sunlight	Clean burning hydrocarbon gas in indoor or select outdoor locations
UV/IR	Dual UV/IR for detection of organic and inorganic flames for indoor and outdoor applications	- Fast response - Combined UV/IR technology reduces false detection - Wide field of detection	- Cannot detect fire through dense smoky fires - Strong non-fire UV sources can produce false detection - UV/IR combinations can produce false detection	Clean burning hydrocarbon gas in indoor or select outdoor locations
IR	Single IR detector for hydrocarbon fires	- Strong false signal rejection - Long range detection - Detects fire through dense smoke	- Certain heat/gas combination can cause false detection - Cannot be used in sight of flare radiation - Good layout coverage reduces false detection	Hydrocarbon gas and/or liquids, indoor or outdoor locations
Multi Spectrum IR	- Multi spectrum or triple IR (IR3) offers two to three times the detection distance of single IR or UV/IR detectors - Designed for hydrocarbon fire detection - Special detector designed for invisible hydrogen fires	- Virtually immune to false alarms - Fire response in the presence of modulated infrared black body radiation with some brands - Long detection range (60 meters to some fires)	- Typical response time is longer when compared to single frequency detectors - Burning metals, ammonia, hydrogen, and sulphur do not emit significant amounts of IR in the detector's sensitivity range - The detector should be used with caution when the presence of hot objects and the potential for ice build up on the detector are likely	Hydrocarbon fires (liquids, gases, and solids)
Visual - CCTV	Video analytics' algorithms for smoke detection monitor the image for movement of light patterns relative to a stable background. If the movement is consistent with known smoke movement patterns.	- Provides means to confirm fire and assess severity - Technology exists to mask normal other flame source, such as flares, allowing applications normally not achieved with other flame technology	- Not suitable for invisible flame, such as hydrogen or alcohol fires - Detection distance - Sensitivity - Speed of response - Reliability	Hydrocarbon gas and/or liquids, indoor or outdoor locations
UV/IR/Invisible	UV/IR and visible for indoor or outdoor hydrocarbon, hydrogen, silane, inorganic 120° cone of vision	- UV/IR detection with video smoke detection system, visually detects the presence of flame or smoke at its source and reflected fire light - Enables remote personnel to confirm fire and assess severity	- Visual cannot detect invisible flames - UV/IR susceptible to their limitations	- Hydrocarbon fires (liquids, gases, and solids) - UV/IV can be tuned to hydrogen invisible flames

*Maximum detection range based on a one square foot (0.1 square meter) gasoline/heptane pan fire

References:
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https://www.det-tronics.com/content/documents/Best-practices-tipsheet-global-AR-1000-1.4.pdf
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http://www.microtech.co.th/pdf/flame-detector.pdf
https://www.fike.com/products/fike-video-analytics/

2.3.4 Smoke Detection

Smoke Detector Comparison

Fire Risk Examples								
Fire Risk	**Example Fires**	**Ionization Detection**	**Optical (Scatter) Detection**	**CO Detection**	**Heat Detection**	**Flame Detection**	**Typical Multi-sensor Detection, Example: Optical Heat**	**Typical Multi-sensor Detection, Example: Optical Heat-CO**
Smoldering white smoke	Electrical fire	2	5	1	1	1	5	5
	Smoldering wood	3	5	4	1	1	5	5
Smoldering dark smoke	Smoldering furnishings	2	4	5	1	1	4	5
Smoldering changing to flame	Wastepaper bin fire	4	4	2	2	3	4	4
Flaming – clean burn	Burning solvents	1	1	1	3	5	3	4
Flaming – dirty	Burning oils	2	3	2	3	5	4	4
Fire risk detection key: very good = 5; good = 4; moderate = 3; poor = 2; very poor =1								

2.4 Differential Pressure Flow Measurement Calculations

2.4.1 General Flow Equation

$$Q = AV$$

2.4.2 General Flow-Pressure Drop Relationship

$$Q \sim \sqrt{\Delta P}$$

$$\frac{Q_1}{Q_2} = \sqrt{\frac{\Delta P_1}{\Delta P_2}}$$

2.4.3 Beta Ratio

$$\beta = \frac{d}{D}$$

where

d = orifice bore diameter

D = pipe inner diameter

2.4.4 Discharge Coefficient, General

$$C = \frac{True\ Flow\ Rate}{Theoretical\ Flow\ Rate}$$

2.4.5 Discharge Coefficient Factors

The velocity of the approach factor, E, is:

$$E = \frac{1}{\sqrt{1-\beta^4}}$$

where the beta ratio is:

$$\beta = \frac{d}{D}$$

where

d = orifice bore diameter

D = pipe inner diameter

The discharge coefficient is:

$$K = EC$$

$$q_{gpm} = Flow\ Rate$$

2.4.6 Differential Flow Element Sizing Equations and Factors

All differential flow element sizing calculations in this section are from the *Flow Measurement Engineering Handbook,* third edition, by Richard Miller.

List of Symbols

Symbol	Meaning	U.S. units	SI units†
a	constant in specific-heat equation	Btu/(lb_m•mol•°R)	J*/(kg•mol•K)
a	constant in gas viscosity equation		
A	area	ft^2	m^2
A_L	constant in liquid viscosity equation		
b	constant in equation for specific heat at constant pressure		
b	constant in general form of discharge-coefficient equation		
B_L	constant in liquid-viscosity equation		
c	constant in liquid-density equation	$(°F)^{-1}$	$(°C)^{-1}$
C_p	specific heat at constant pressure	Btu/(lb_m•mol•°R)	J*/(kg•mol•K)
$(C_p)_i$	specific heat at constant pressure for ideal gas	Btu/(lb_m•mol•°R)	J*/(kg•mol•K)
$C_{p,mix}$	specific heat at constant pressure of a gas mixture	Btu/(lb_m•mol•°R)	J*/(kg•mol•K)
$(C_p)_p$	specific heat at constant pressure of a perfect gas	Btu/(lb_m•mol•°R)	J*/(kg•mol•K)
C_p/C_v	ratio of specific heats of a real gas		
$(C_p/C_v)_i$	ratio of specific heats of an ideal gas		
$(C_p/C_v)_p$	ratio of specific heats of a perfect gas		
C_v	specific heat of a gas at constant volume	Btu/(lb_m•mol•°R)	J*/(kg•mol•K)
C	discharge coefficient, true flow rate divided by theoretical flow rate		
C_∞	discharge coefficient at infinite Reynolds number		

†Except for dimensionless or defined SI unit symbols, as in T_K, symbols that apply to SI units are shown in the text with a superscript asterisk, as in F_n^*.

List of Symbols (cont'd)

Symbol	Meaning	U.S. units	SI units†
C_{DH}	discharge coefficient for a drain (vent) hole through a primary element		
C_N	discharge coefficient at normal flowing conditions		
C_{mp}	mean molecular heat of a pure gas	$(°F)^{-1}$	$(°C)^{-1}$
$C_{mp,mix}$	mean molecular heat at constant pressure of a gas mixture	$(°F)^{-1}$	$(°C)^{-1}$
d	bore of differential producer at flowing conditions $d = F_{ad}d_{meas}$	in.	mm
d_f	bore of differential producer at flowing conditions corrected for both temperature and pressure, $d = F_{ad}\, F_{\Delta P}\, d_{meas}$	in.	mm
d_h	pressure-tap-hole diameter	in.	mm
d_{meas}	bore of a differential producer measured at a reference temperature, usually 68°F (20°C)	in.	mm
d_w	diameter of a thermal well or other protrusion into a pipe	in.	mm
d_{DH}	diameter of a drain or vent hole	in.	mm
d_M	differential producers bore at flowing conditions		m
D	internal pipe diameter at flowing conditions = F_{aDmeas}	in.	mm
D_f	pipe diameter at flowing pressure and temperature	in.	m
D_F	bore of differential producer at flowing conditions $D_F = F_{aDmeas}$	ft	
D_{meas}	pipe diameter (or upstream venturi inlet diameter) *measured* at a reference temperature, usually 68°F (20°C)	in.	mm
D_M	bore of differential producer at flowing conditions $D^*_M = F^*_{aD} D^*_{M,meas}$		m
E	velocity-of-approach factor, $1/\sqrt{1-\beta^4}$		

†Except for dimensionless or defined SI unit symbols, as in T_K, symbols that apply to SI units are shown in the text with a superscript asterisk, as in F^*_n.

List of Symbols (cont'd)

Symbol	Meaning	U.S. units	SI units†
F	function used in Newton's solution		
F'	derivative of function in Newton's solution of a zero root equation		
F_a	thermal-expansion-factor correction for differential producers	in./(in.•°F)	mm/(mm•°C)
F_{ad}	thermal expansion factor for the bore of the primary element		
F_{aD}	thermal expansion factor for the pipe diameter		
F_k	correction for real gas in an isentropic expansion		
F_g	specific-gravity factor in gas-factor equation, $\sqrt{1/G}$		
F_{Gr}	specific-gravity factor in gas-factor equation, $\sqrt{1/G_r}$		
F_p	correction for liquid compressibility, ρ_f/ρ_F		
F_{pv}	supercompressibility factor, $Z_b\Big/\sqrt{Z_f}$		
F_K	flow-coefficient Reynolds-number correction, K/K_{ref}		
F_Y	gas-expansion-factor correction, Y/Y_N		
F_{Dp}	Flowing pressure correction factor for pipe diameter		
F_{DH}	drain-hole (vent-hole) correction factor		
F_{pb}	pressure base correction factor gas factor equation, $14.73/p_b$		
F_{PB}	pressure base correction in gas factor equation, $14.69595/p_b$		
F_{RF}	recovery factor for dynamic pressure		

†Except for dimensionless or defined SI unit symbols, as in T_K, symbols that apply to SI units are shown in the text with a superscript asterisk, as in F_n^*.

List of Symbols (cont'd)

Symbol	Meaning	U.S. units	SI units†
F_{tb}	temperature base correction factor in gas-factor equation, $T_b/519.67$ or $T_{Kb}/288.7056$		
F_{TB}	base-temperature correction factor in gas-factor equation, Tb/518.67 or $T_{Kb}/288.15$		
F_{tf}	temperature correction factor in gas-factor equation, $\sqrt{519.67 / T_{f1}}$ or $\sqrt{288.7056 / T_{K1}}$		
F_{TF}	flowing-temperature correction factor in gas-factor equation, $\sqrt{518.67 / T_f}$ or $\sqrt{288.15 / T_K}$		
F_{TP}	factor correcting static pressure to total pressure		
$F_{WV,dry}$	factor converting wet-gas volume to dry-gas volume		
$F_{WVM,dry}$	factor converting wet-gas mass to dry-gas volume		
$F_{\Delta p}$	orifice plate correction for applied differential		
$F_{\gamma p}$	correction for pressure to specific heat at constant pressure		
$F_{\gamma R}$	real-gas correction factor to ratio of specific heats		
$F_{\mu p}$	viscosity pressure-correction factor for an oil or gas		
g_c	dimensional conversion constant, 32.17405 lb_m•ft/(lb_f•s^2) or 1 kg•m/(N•s^2)	lb_m•ft/(lb_f•s^2)	kg•m/(N•s^2)
g_{calib}	local gravity at which a device is calibrated	ft/s^2	m/s^2

†Except for dimensionless or defined SI unit symbols, as in T_K, symbols that apply to SI units are shown in the text with a superscript asterisk, as in F_n^*.

List of Symbols (cont'd)

Symbol	Meaning	U.S. units	SI units†
g_t	local gravitational constant	ft/s^2	m/s^2
g_0	standard acceleration due to gravity, 32.17405 ft/s^2 or 9.806650 m/s^2	ft/s^2	m/s^2
G	gas (vapor) specific gravity $M_{w,gas}/M_{w,air}$		
G_b	liquid base specific gravity, $\rho_b/(\rho_w)60,g_0$		
G'_b	liquid base specific gravity at a hydrometer temperature other than 60°F (15.6°C)		
G_f	flowing specific gravity of a liquid, $\rho_f/(\rho_w)_{60,g0}$		
G_{wv}	specific gravity of water vapor, 0.6220		
G_{dry}	specific gravity of dry gas in a gas-water vapor mixture		
G_{mix}	specific gravity of a gas mixture, $M_{w,mix}/M_{w,air}$		
G_{wgt}	specific gravity of a gas mixed with water vapor		
G_F	flowing liquid specific gravity uncorrected for pressure $\rho_F/(\rho w)_{60,g0}$		
G_R	real specific gravity of a gas, ρ_{gas}/ρ_{air}		
h_w	differential pressure in inches of water at 68°F, 14.696 psia, and g_0 =32.17405 ft/s^2		
$h_{w,60°}$	differential pressure in inches of water at 68°F, 14.696 psia, and g_0 =32.17405 ft/s^2		
$(h_w)_g$	differential produced by gas phase in two-phase (or two-component) flow	in.	
$(h_w)_{ss}$	steady-state differential pressure in pulsating flow	in.	
$(h_w)_{ind}$	indicated differential pressure, uncorrected for fluid head in lead lines	in.	

†Except for dimensionless or defined SI unit symbols, as in T_K, symbols that apply to SI units are shown in the text with a superscript asterisk, as in F_n^*.

List of Symbols (cont'd)

Symbol	Meaning	U.S. units	SI units†
$(h_w)_N$	differential pressure at normal operating flow rate	in.	
$(h_w)_{URV}$	upper-range value of differential pressure corresponding to upper-range flow rate	in.	
H_L	pressure loss in feet of flowing fluid	ft	
k	isentropic exponent for a real gas		
k_i	ideal-gas isentropic exponent $(C_p/C_v)_i$		
k_p	perfect-gas isentropic exponent $(C_p/C_v)_p$		
K	flow coefficient, $C/\sqrt{1-\beta^4} = EC$		
K_∞	flow coefficient at infinite Reynolds number		
K_{ref}	flow coefficient at reference Reynolds number		
K_N	flow coefficient at normal operating Reynolds number		
l_2	downstream tap length at a reference temperature	in.	m
l_{1f}	upstream tap length corrected for flowing temperatures	in.	m
l_{2f}	downstream tap length corrected for flowing temperatures	in.	m
L	development length for velocity profile	ft	m
L_s	length of straight pipe following a step between two pipes	ft	m
L_1	dimensionless ratio l_{1f}/D_f for upstream tap location		
L_2	dimensionless ratio l_{2f}/D_f for downstream tap location		
m	mass	lb_m	kg
m	exponent in specific-heat equation		

†Except for dimensionless or defined SI unit symbols, as in T_K, symbols that apply to SI units are shown in the text with a superscript asterisk, as in F_n^*.

List of Symbols (cont'd)

Symbol	Meaning	U.S. units	SI units†
m_i	mass of liquid	lb_m	kg
M	M factor in Reynolds-number correction factor F_{RD} with flow coefficient C		
M_K	M factor in Reynolds-number correction factor F_{RD} with flow coefficient K		
M_w	molecular weight	$lb_m/(lb_m•mol)$	kg/(kg•mol)
$M_{w,air}$	molecular weight of air, 29.96247	$lb_m/(lb_m•mol)$	kg/(kg•mol)
$M_{w,gas}$	molecular weight of a gas	$lb_m/(lb_m•mol)$	kg/(kg•mol)
$M_{w,mix}$	molecular weight of a gas mixture	$lb_m/(lb_m•mol)$	kg/(kg•mol)
MV	measured variable; pressure, temperature, flow rate, etc.		
$(MV)_{LRV}$	lower-range value of measured variable		
$(MV)_{URV}$	upper-range value of measured variable		
n	exponent in gas viscosity equation		
n	exponent in specific-heat equation		
N_{vG}	N factor for flowing volume with specific-gravity determination, liquids		
N_{vp}	N factor for flowing volume with density determination, liquids and gases(vapors)		
N_{vhp}	N factor for flowing volume in gas-factor equation		
N_{vpT}	N factor for flowing volume in pvT equation		
N_{MG}	N factor for mass flow with a specific-gravity determination, liquids		
N_{Mp}	N factor for mass flow with a density determination, liquids and gases (vapors)		
N_{Mhp}	N factor for mass flow, gas-factor equation		

†Except for dimensionless or defined SI unit symbols, as in T_K, symbols that apply to SI units are shown in the text with a superscript asterisk, as in F_n^*.

List of Symbols (cont'd)

Symbol	Meaning	U.S. units	SI units†
N_{MpT}	N factor for mass flow pvT equations		
N_{VG}	N factor for base volume with specific-gravity determination; liquids at 60°F (15.6°C) and 14.696 psia (101.325 kPa)		
$N_{V\rho}$	N factor for base volume with density determination, liquids and gases (vapors)		
N_{Vhp}	N factor for standard (ISO 5024) gas base volume, gas-factor equation; p_b = 14.69595 psia (p^*_b = 101.325 kPa), T_b = 518.67°R (T_{Kb} = 288.15 K)		
$(N_{Vhp})_b$	N factor for nonstandard base volume at selected base pressure and temperature, gas-factor equation		
N_{VpT}	N factor for standard (ISO 5024) gas base volume, pvT equation; p_b = 14.69595 psia (p^*_b = 101.325 kPa), T_b = 518.67°R (T_{Kb} = 288.15 K)		
$(N_{VpT})_b$	N factor for nonstandard base volume at selected base pressure and temperature, pvT equation		
p_b	base absolute pressure for gas volume	lb_f/in^2	kPa
p_c	critical absolute pressure of a substance	lb_f/in^2	kPa
$p_{c,atm}$	critical pressure, in atmospheres		
p_{ca}	pseudocritical absolute pressure, Hall-Yarborough equation of state	lb_f/in^2	kPa
p_d	pressure of dry gas in a wet gas mixture	lb_f/in^2	kPa
p_f	absolute pressure at flowing conditions	lb_f/in^2	kPa
p_{f1}	upstream-tap absolute pressure at flowing conditions	lb_f/in^2	kPa
$p_{f1'}$	upstream pressure before upstream pressure tap	lb_f/in^2	kPa
p_{f2}	downstream-tap absolute pressure at flowing conditions	lb_f/in^2	kPa
$p_{f2'}$	downstream pressure after pressure recovery	lb_f/in^2	kPa

†Except for dimensionless or defined SI unit symbols, as in T_K, symbols that apply to SI units are shown in the text with a superscript asterisk, as in F^*_n.

List of Symbols (cont'd)

Symbol	Meaning	U.S. units	SI units†
p_{f3}	fully recovered downstream pressure	lb_f/in^2	kPa
$(p_f)_{des}$	absolute pressure at design flowing conditions	lb_f/in^2	kPa
p_v	vapor pressure	lb_f/in^2	kPa
p_{wv}	absolute pressure of water vapor in gas-water vapor	lb_f/in^2	kPa
p_{sat}	saturation pressure corresponding to flowing temperature	lb_f/in^2	kPa
p_{rsat}	reduced saturation pressure, p_{sat}/p_c		
p_B	barometric pressure	lb_f/in^2	kPa
p_G	gauge pressure, $p_f - p_B$	lb_f/in^2	kPa
$(\Delta p^*)_t$	permanent pressure loss		kPa
$(\Delta p^*)_N$	differential pressure at normal operating conditions		kPa
$(\Delta p^*)_{URV}$	upper-range value of differential pressure corresponding to upper-range flow rate		kPa
P_f	absolute pressure at flowing conditions	lb_f/ft^2	Pa
$P_{f,Pa}$	flowing pressure in Pascals		Pa
P_{f1}	upstream-tap absolute pressure at flowing conditions	lb_f/ft^2	Pa
P_{f2}	downstream-tap absolute pressure at flowing conditions	lb_f/ft^2	Pa
$P_{f1'}$	upstream-tap absolute pressure at lead-line evaluation H_{LL}	lb_f/ft^2	Pa
$P_{f2'}$	downstream-tap absolute pressure at lead-line evaluation H_{LL}	lb_f/ft^2	Pa
$P_{sat,Pa}$	saturation pressure corresponding to flowing temperature in Pascals		Pa
P_{vap}	vapor pressure	lb_f/ft^2	Pa
P_B	barometric pressure	lb_f/ft^2	Pa
P_D	dynamic pressure, $\rho_f V_p^2 / 2g_c$ or $\rho_f^* V_p^{*2} / 2$	lb_f/ft^2	Pa

†Except for dimensionless or defined SI unit symbols, as in T_K, symbols that apply to SI units are shown in the text with a superscript asterisk, as in F_n^*.

List of Symbols (cont'd)

Symbol	Meaning	U.S. units	SI units†
P_G	gauge pressure, $P_f - P_B$	lb_f/ft^2	Pa
P_T	total (stagnation) pressure, $P_f + P_D$	lb_f/ft^2	Pa
ΔP	differential pressure, $P_{f1} - P_{f2}$	lb_f/ft^2	Pa
q_M	mass flow rate: subscript M may be PPH, KPD, KPS, etc.		
q_M^*	mass flow rate: subscript M may be PPH, KPD, KPS, etc.		
q_{KPS}^*, q_{KPM}^*, q_{KPH}^*, q_{KPD}^*	liquid, gas (vapor) mass flow rate		kg/s, kg/min kg/h, kg/24h
q_{PPS}, q_{PPM}, q_{PPH}, q_{PPD}	liquid, gas (vapor) mass flow rate	lb_m/s, lb_m/min lb_m/h, $lb_m/24h$	
q_v	volumetric flow rate calculated at standard (gas) or base (liquid) temperature and pressure		
q_v^*	volumetric flow rate calculated at standard (gas) or base (liquid) temperature and pressure		
$(q_v)_b$	gas (vapor) volumetric flow rate calculated at selected base pressure and temperature		
q_{BPS}, q_{BPM}, q_{BPH}, q_{BPD}	liquid volumetric flow rate at $T_F = 60°F$ and $p_b = 14.696$ psia	bbl/s, bbl/min, bbl/h, bbl/24h	
q_{CFS}, q_{CFM}, q_{CFH}, q_{CFD}	liquid volumetric flow rate at $T_F = 60°F$ and $p_b = 14.696$ psia	ft^3/s, ft^3/min, ft^3/h, $ft^3/24h$	
q_{GPS}, q_{GPM}, q_{GPH}, q_{GPD}	liquid volumetric flow rate at $T_F = 60°F$ and $p_b = 14.696$ psia	gal/s, gal/min gal/h, gal/24h	
q_{LPH}^*, q_{LPM}^*, q_{LPH}^*, q_{LPD}^*	liquid volumetric flow rate at $T_{°C} = 15.6°C$ and $p_b^* = 101.3$ kPa		L/s, L/min L/h, L/24h
q_{CFS}, q_{CFM}, q_{CFH}, q_{CFD}	standard gas (vapor) volumetric flow rate at ISO-5024 base; $T_b = 518.67°R$ and $p_b = 14.69595$ psia	ft^3/s, ft^3/min, ft^3/h, $ft^3/24h$	
$\left.\begin{matrix}(q_{SCFS})_b, \\ (q_{SCFM})_b, \\ (q_{SCFH})_b, \\ (q_{SCFD})_b\end{matrix}\right\}$	standard gas (vapor) volumetric flow rate at selected base temperature and pressure	$\left\{\begin{matrix}ft^3/s, \\ ft^3/min, \\ ft^3/h, \\ ft^3/24h\end{matrix}\right.$	

†Except for dimensionless or defined SI unit symbols, as in T_K, symbols that apply to SI units are shown in the text with a superscript asterisk, as in F_n^*.

List of Symbols (cont'd)

Symbol	Meaning	U.S. units	SI units†
q^*_{SCMS}, q^*_{SCMM}, q^*_{SCMH}, q^*_{SCMD}	standard gas (vapor) volumetric flow rate at ISO-5024 base; T_{Kb} = 288.15 K and p^*_b = 101.325 kPa		m^3/s, m^3/min m^3/h, $m^3/24h$
$\left(q^*_{SCMS}\right)_b$, $\left(q^*_{SCMM}\right)_b$, $\left(q^*_{SCMH}\right)_b$, $\left(q^*_{SCMD}\right)_b$	standard gas (vapor) volumetric flow rate at selected base temperature and pressure		m^3/s, m^3/min, m^3/h, $m^3/24h$
q^*_{SLPS}, q^*_{SLPM}, q^*_{SLPH}, q^*_{SLPD}	standard gas (vapor) volumetric flow rate at ISO-5024 base; T_{Kb} = 288.15 K and p^*_b = 101.325 kPa		L/s, L/min L/h, L/24h
$\left(q^*_{SLPS}\right)_b$, $\left(q^*_{SLPM}\right)_b$, $\left(q^*_{SLPH}\right)_b$, $\left(q^*_{SLPD}\right)_b$	standard gas (vapor) volumetric flow rate at selected base temperature and pressure		L/s, L/min, L/h, L/24h
Q	total mass or volume units		
Q_v	total flow in volume units at flowing conditions; subscript v may be gal, ft^3, m^3, etc.		
Q_{acf}	gas (vapor) total volume at flowing conditions	ft^3	
Q^*_{acm}	gas (vapor) total volume at flowing conditions		m^3
Q_{bbl}	liquid total volume at flowing conditions	bbl	
Q_{cf}	liquid total volume at flowing conditions	ft^3	
Q^*_{cm}	liquid total volume at flowing conditions		m^3
Q_{gal}	total volume at flowing conditions	gal	
Q^*_l	total volume at flowing conditions		L
Q_M	total flow in mass units; subscript may be lb_m, kg, g, etc.		

†Except for dimensionless or defined SI unit symbols, as in T_K, symbols that apply to SI units are shown in the text with a superscript asterisk, as in F^*_n.

List of Symbols (cont'd)

Symbol	Meaning	U.S. units	SI units†
Q^*_{kg}	total mass		kg
Q_{lbm}	total mass	lb_m	
Q_V	total volume at standard (gas) or base (liquid) temperature and pressure	ft^3	m^3
$(Q_V)_b$	gas (vapor) total volume at selected pressure and temperature	ft^3	m^3
Q_{BBL}	liquid total volume at T_F = 60°F and p_b = 14.696 psia	bbl	
Q_{GAL}	liquid total volume at T_F = 60°F and p_b = 14.696 psia	gal	
Q^*_L	liquid total volume at $T_{°C}$ = 15.6°C and p^*_b = 14.696 kPa		L
Q_{SCF}	gas (vapor) total volume at ISO-5024 base: T_b =518.67°R and p_b = 14.69595 psia	ft^3	
$(Q_{SCF})_b$	gas (vapor) total volume at selected base temperature and pressure	ft^3	
Q^*_{SL}	gas (vapor) total volume at ISO-5024 base: T_{KB} = 288.15 K and p^*_b = 101.325 kPa		L
$\left(Q^*_{SL}\right)_b$	gas (vapor) total volume at selected base temperature and pressure		L
Q_{SCM}	gas (vapor) total volume at ISO-5024 base: T_{KB} = 288.15 K and p^*_b = 101.325 kPa		m^3
$\left(Q^*_{SCM}\right)_b$	gas (vapor) total volume at selected base temperature and pressure		m^3
$(Q_{SCF})_{wet}$	total volume of wet gas at standard conditions	ft^3	
$\left(Q^*_{SCM}\right)_{wet}$	total volume of wet gas at standard conditions		m^3
$(Q_{lbm})_{TC}$	total mass of two-component gas mixture	lb_m	

†Except for dimensionless or defined SI unit symbols, as in T_K, symbols that apply to SI units are shown in the text with a superscript asterisk, as in F^*_n.

List of Symbols (cont'd)

Symbol	Meaning	U.S. units	SI units†
$(Q_{lbm})_s$	total mass of dry gas in a two-component mixture	lb_m	
r	radius to a point	in	mm
r_b	elbow radius at centerline	in	mm
r_p	pipe radius	in	mm
R_s	universal gas constant for BWR state equation		atm dm^3/(mol K)
R_d	bore Reynolds number at flowing conditions using corrected pipe diameter, $d = F_{ad}d_{meas}$		
R_0	universal gas constant, 10.73151 psia•ft^3/(lb_m•mol•°R) or 8.31441 J*/(g•mol•K)		
R_{0g}	universal gas constant, in energy units 1.985862662 Btu/(lb_m•mol•°R) or 8314.41 J/(kg•mol•K)		
R_D	pipe Reynolds number at flowing conditions using corrected pipe diameter, $D = F_{aD}$Dmeas		
R_{Df}	pipe Reynolds number using corrected pipe diameter, D_f		
RH	relative humidity, p_{wv}/p_{sat}		
S_M	sizing factor for differential producer, a constant		
SH	specific humidity, ρ_{wv}/ρ_{dry}		
t	time	s	s
t_{min}	minimum orifice plate thickness to prevent yielding	in.	m
t_p	pipe wall thickness	in.	m
T_b	base absolute temperature for a gas volume	°R	
T_c	critical temperature of a substance	°R	K
$T_{d,ref}$	reference temperature for bore measurements	°R	K

†Except for dimensionless or defined SI unit symbols, as in T_K, symbols that apply to SI units are shown in the text with a superscript asterisk, as in F_n^*.

List of Symbols (cont'd)

Symbol	Meaning	U.S. units	SI units†
T_f	flowing absolute temperature, $T_F + 459.67$	°R	
T_{f1}	flowing absolute temperature measured at upstream tap	°R	
$T_{f1'}$	upstream temperature measured in a pipe	°R	K
T_{f2}	flowing absolute temperature measured at downstream tap	°R	
$T_{f2'}$	downstream temperature measured in a pipe	°R	K
T_{fi}	indicated flowing absolute temperature	°R	
T_{ij}	binary mixtures reduced temperature, AGA-8 equation		
T_F	reduced temperature of a gas (vapor), T_f/T_c		
$(T_f)_{des}$	flowing absolute temperature at design conditions	°R	
T_{pr}	pseudocritical reduced temperature at a mixture of gases, T_f/T_{pc}		
T	reciprocal of reduced temperature, $1/T_{pr}$	°R	K
T_B	boiling point, absolute temperature	°R	K
$T_{°C}$	temperature in degrees Celsius		°C
$T_{D,ref}$	reference temperature for a pipe measurement	°R	K
T_F	flowing temperature in degrees Fahrenheit	°F	
ΔT_F	difference in temperature, $T_F - 60$	°F	
T_K	flowing absolute temperature, Kelvin scale		K
T_{K1}	absolute temperature measured at upstream tap		K
T_{K2}	absolute temperature measured at downstream tap		K

†Except for dimensionless or defined SI unit symbols, as in T_K, symbols that apply to SI units are shown in the text with a superscript asterisk, as in F_n^*.

List of Symbols (cont'd)

Symbol	Meaning	U.S. units	SI units†
T_{Kb}	base absolute temperature for a gas volume		K
T_{Kc}	critical temperature, in kelvins		K
$T_{°R}$	absolute temperature in degrees Rankine	°R	
T_{WB}	wet-bulb temperature	°F	°C
u	internal energy	Btu/lb_m	J*/kg
v	specific volume, 1/ρ	ft^3/lb_m	m^3/kg
v_f	flowing specific volume	ft^3/lb_m	m^3/kg
v_{mol}	molar volume	$ft^3/(lb_m•mol)$	$m^3/(kg•mol)$
v_{wv}	specific volume of water vapor	ft^3/lb_m	m^3/kg
V_p	point velocity along pipe radius	ft/s	m/s
V_{free}	free-stream velocity, no confining walls	ft/s	m/s
V_{mol}	molar volume		dm^3/mol, m3/mol
$\overline{V}_{sonic}$	sonic velocity at throat of a critical nozzle	ft/s	m/s
V_{SO}	velocity of sound in a liquid	ft/s	m/s
V	volume	ft^3	m^3
Δ**V**	change in volume with pressure	ft^3	m^3
$\mathbf{V}_0$	liquid volume at zero pressure	ft^3	m^3
$\mathbf{V}_l$	liquid volume	ft^3	m^3
$\mathbf{V}_m$	volume of a standard mass	ft^3	m^3
$\mathbf{V}_{dry}$	volume of dry gas in a wet (water) gas mixture	ft^3	m^3
$\mathbf{V}_{wet}$	volume of wet (water) gas in a wet gas mixture	ft^3	m^3
W	energy	W	W
W	weight force	lb_f	N
W	work	Btu/lb_m	J*/kg

†Except for dimensionless or defined SI unit symbols, as in T_K, symbols that apply to SI units are shown in the text with a superscript asterisk, as in F_n^*.

List of Symbols (cont'd)

Symbol	Meaning	U.S. units	SI units†
x	mole fraction in gas (vapor) phase		
x_m	mass fraction, mass of component ÷ mass of total mixture		
x_1	pressure ratio based on upstream tap pressure, $\Delta p/p_{f1}$		
x_2	pressure ratio based on downstream tap pressure, $\Delta p/p_{f2}$		
X	sensitivity coefficient of a measured variable		
X_{var}	sensitivity coefficient, where subscript var (variable) is denoted as G_b, G_f, Z, etc.		
$\mathbf{X}$	mixture quality, mass of gas phase ÷ mass of total mixture		
y	elevation above sea level	ft	
y	mole fraction in liquid phase		
Y	gas expansion factor		
Y_1	gas expansion factor based on upstream pressure		
$Y_{1.0.66}$	gas expansion factor at pressure ratio of 0.66		
$Y_{1.0.77}$	gas expansion factor at pressure ratio of 0.77, for pipe taps		
Y_2	gas expansion factor based on downstream pressure		
Y_N	gas expansion factor at normal flowing conditions, usually designs conditions		
Y_{CR}	critical flow function		
Z	gas (vapor) compressibility factor		
Z_b	gas (vapor) compressibility factor at base temperature and pressure		
Z_c	gas (vapor) compressibility factor at critical point		
Z_f	gas (vapor) compressibility factor at flowing conditions		

†Except for dimensionless or defined SI unit symbols, as in T_K, symbols that apply to SI units are shown in the text with a superscript asterisk, as in F_n^*.

List of Symbols (cont'd)			
Symbol	**Meaning**	**U.S. units**	**SI units†**
Z_{f1}	gas (vapor) compressibility factor at flowing conditions, upstream		
Z_{f2}	gas (vapor) compressibility factor at flowing conditions, downstream		
Z_{pc}	gas (vapor) pseudocritical compressibility factor for a mixture		
Z_{wv}	water-vapor compressibility factor in a wet gas		
Z_{air}	compressibility factor for air		
Z_{dry}	compressibility factor for dry components in a wet gas		
Z_{wet}	compressibility factor of a wet gas		
Z_L	liquid compressibility factor		
α_{ann}	thermal expansion factor for an annubar	in./(in.°F)	mm/(mm °C)
α_{HO}	thermal-expansion coefficient for meter housing	in./(in.°F)	mm/(mm °C)
α_P	thermal-expansion coefficient for pipe material	in./(in.°F)	mm/(mm °C)
α_{PE}	thermal-expansion coefficient for primary-element material	in./(in.°F)	mm/(mm °C)
β	beta ratio, d/D		
β_f	differential producer's beta ratio d_f/D_f at flowing conditions		
γ_f	specific weight of a fluid, liquid, or a gas (vapor), $(g_t/g_c)\rho_f$	lb_f/ft^3	N/m^3
μ_{app}	apparent viscosity, S/S, absolute viscosity units	lb_m/(ft•s)	cP‡
$(\mu)_a$	absolute viscosity at atmospheric pressure	lb_m/(ft•s)	cP‡
$(\mu)_p$	absolute viscosity corrected for pressure	lb_m/(ft•s)	cP‡

†Except for dimensionless or defined SI unit symbols, as in T_K, symbols that apply to SI units are shown in the text with a superscript asterisk, as in F_n^*.

‡The poise (P) and the stokes (St) are cgs metric units, not SI metric; 1 P = 0.1 Pa•s; 1 St = 0.0001 m^2/s.

List of Symbols (cont'd)

Symbol	Meaning	U.S. units	SI units†
μ_{cP}	absolute viscosity in centipoises		cP‡
μ°_{cP}	viscosity of a gas at low pressure		cP
$\mu_{cP,app}$	apparent absolute viscosity of a two-phase mixture		cP
$\mu_{cP,l}$	viscosity of saturated liquid		cP
$\mu_{cP,mix}$	absolute viscosity of a mixture in centipoises		cP‡
$(\mu_f)_e$	absolute English-system viscosity, force units	lb_f•s/ft^2	
$(\mu_m)_e$	absolute English-system viscosity, mass units	lb_m(ft•s)	
μ_P	absolute viscosity in poises		P‡
μ_p	Poisson's ratio for pipe material	in./in.	m/m
μ_{PE}	Poisson's ratio for primary element material	in./in.	m/m
$\mu_{Pa•s}$	absolute viscosity in Pascal seconds		Pa•s
γ_e	kinematic viscosity in English units	ft^2/s	
γ_{cSt}	kinematic viscosity in centistokes		dSt‡
γ_{St}	kinematic viscosity in stokes		St‡
ρ_b	density at base conditions: liquids, 60°F (15.6°C) and 14.7 psia (101.3 kPa); gases, 59°F (15°C) and 14.69595 psia (101.325 kPa); or at other selected base values	lb_m/ft^3	kg/m^3
ρ_{air}	air density at time of calibration	lb_m/ft^3	kg/m^3
$\rho_{air,c}$	air density for calibrating a weigh tank	lb_m/ft^3	kg/m^3
ρ_f	density at flowing conditions	lb_m/ft^3	kg/m^3
ρ_{f1}	upstream density at flowing conditions	lb_m/ft^3	kg/m^3
ρ_{f2}	downstream density at flowing conditions	lb_m/ft^3	kg/m^3

†Except for dimensionless or defined SI unit symbols, as in T_K, symbols that apply to SI units are shown in the text with a superscript asterisk, as in F_n^*.

‡The poise (P) and the stokes (St) are cgs metric units, not SI metric; 1 P = 0.1 Pa•s; 1 St = 0.0001 m^2/s.

List of Symbols (cont'd)

Symbol	Meaning	U.S. units	SI units†
$(\rho_f)_{des}$	density at design conditions	lb_m/ft^3	kg/m^3
ρ_{g1}	upstream density of gas in two-component or two-phase flow	lb_m/ft^3	kg/m^3
ρ_l	density of liquid in a two-component or two-phase flow	lb_m/ft^3	kg/m^3
ρ_{meas}	density of a standard mass	lb_m/ft^3	kg/m^3
ρ_{mol}	molar density	lb_m•mol/ft^3	kg•mol/m^3
ρ_v	density of water vapor at saturation	lb_m/ft^3	kg/m^3
ρ_r	reduced density, ρ/ρ_c		
ρ_{wet}	density of a wet gas	lb_m/ft^3	kg/m^3
ρ_F	density of fluid at flowing conditions, uncorrected for pressure	lb_m/ft^3	kg/m^3
$(\rho_w)_{T.g0}$	density of water at standard gravity (32.174) and any temperature	lb_m/ft^3	kg/m^3
$(\rho_w)_{68.g0}$	density of water at 68°F, standard gravity, and atmospheric pressure: 62.31572 lb_m/ft^3 (998.2019 kg/m^3)	lb_m/ft^3	kg/m^3
$(\rho_w)_{60.g0}$	density of water at 60°F, standard gravity, and atmospheric pressure: 62.36630 lb_m/ft^3 (999.0121 kg/m^3)	lb_m/ft^3	kg/m^3
σ	standard deviation	%	%
σ_y	yield stress of a material	lb_f/in^2	Pa
ϕ	degrees latitude		

†Except for dimensionless or defined SI unit symbols, as in T_K, symbols that apply to SI units are shown in the text with a superscript asterisk, as in F_n^*.

Relationship Between Fundamental Constant and Derived Flow-Rate Unit for Liquid Flow: U.S. Units

Letter Symbol			
Flow Rate	**Conversion Constant**	**Relationship to Fundamental Unit Equation**	**Definition**
q_M	N_{Mp}	$q_{\text{PPS}} = 0.09970190 \dfrac{q_M}{N_{Mp}}$	Mass flow rate with density determination Example: $q_M = q_{\text{PPD}}$ = pounds-mass per day
q_M	N_{MG}	$q_{\text{PPS}} = 0.7873692 \dfrac{q_M}{N_{MG}}$	Mass flow rate with a specific-gravity determination Example: $q_M = q_{\text{PPM}}$ = pounds-mass per minute
q_v	N_{vp}	$q_{\text{PPS}} = 0.09970190[p_f] \dfrac{q_v}{N_{vp}}$	Volumetric flow rate at flowing conditions with a density determination Example: $q_v = q_{\text{cfm}}$ = cubic feet per minute (flowing)
q_v	N_{vG}	$q_{\text{PPS}} = 0.7873692[F_P\ G_F] \dfrac{q_v}{N_{vG}}$	Volumetric flow rate at flowing conditions with a specific-gravity determination Example: $q_v = q_{\text{gpm}}$ = gallons per minute (flowing)
q_V	N_{Vp}	$q_{\text{PPS}} = 0.09970190[p_b] \dfrac{q_V}{N_{Vp}}$	Volumetric flow rate at base conditions (60°F and 14.696 psia) with a density determination Example: $q_V = q_{\text{GPM}}$ = gallons per minute at base conditions
q_V	N_{VG}	$q_{\text{PPS}} = 0.7873692[G_b] \left(\dfrac{q_V}{N_{VG}} \right)$	Volumetric flow rate at base conditions (60°F and 14.69 psia) with a specific-gravity determination Example: $q_V = q_{\text{CFM}}$ = cubic feet per minute at base conditions

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Relationship Between Fundamental Constant and Derived Flow-Rate Unit for Liquid Flow: SI Units

Letter Symbol			
Flow Rate	**Conversion Constant**	**Relationship to Fundamental Unit Equation**	**Definition**
q_M^*	N_{Mp}^*	$q_{KPS}^* = 0.00003512407 \dfrac{q_M^*}{N_{Mp}^*}$	Mass flow rate with density determination Example: q_{KPD} = kilograms per day
q_M^*	N_{MG}^*	$q_{KPS}^* = 0.001110172 \dfrac{q_M^*}{N_{MG}^*}$	Mass flow rate with a specific-gravity determination Example: $q_M^* = q_{KPH}^*$ = kilograms per hour
q_v^*	N_{vp}^*	$q_{KPS}^* = 0.00003512407[p_f^*] \dfrac{q_v^*}{N_{vp}^*}$	Volumetric flow rate at flowing conditions with a density determination Example: $q_v^* = q_{lpm}^*$ = liters per minute (flowing)
q_v^*	N_{vG}^*	$q_{KPS}^* = 0.001110172[F_P G_F] \dfrac{q_v^*}{N_{vG}^*}$	Volumetric flow rate at flowing conditions with a specific-gravity determination Example: $q_v^* = q_{cmm}^*$ = cubic meters per minute (flowing)
q_V^*	N_{Vp}^*	$q_{KPS}^* = 0.00003512407[q_b^*] \dfrac{q_V^*}{N_{Vp}^*}$	Volumetric flow rate at base conditions (15.6°C and 101.325 kPa) with a density determination Example: $q_V^* = q_{LPM}^*$ = liters per minute at base conditions
q_V^*	N_{VG}^*	$q_{KPS}^* = 0.001110172[G_b] \left(\dfrac{q_v^*}{N_{VG}^*} \right)$	Volumetric flow rate at base conditions (15.6°C and 101.325 kPa) with a specific-gravity determination Example: $q_V^* = q_{CMM}^*$ = cubic meters per minute at base conditions

Symbols that apply to SI units are shown with a superscript asterisk, as in $q^*_{M.}$

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Relationship Between Fundamental Constant and Derived Flow-Rate Unit for Gas Flow: U.S. Units

Letter Symbol			
Flow Rate	**Conversion Constant**	**Relationship to Fundamental Unit Equation**	**Definition**
q_M	N_{Mp}	$q_{\text{PPS}} = 0.09970190 \dfrac{q_M}{N_{Mp}}$	Mass flow rate with density determination Example: $q_M = q_{\text{PPD}}$ = pounds-mass per day
q_M	N_{MpT}	$q_{\text{PPS}} = 0.1637908 \dfrac{q_M}{N_{MpT}}$	Mass flow rate using the *pvT* density equation Example: $q_M = q_{\text{PPM}}$ = pounds-mass per minute
q_v	N_{vp}	$q_{\text{PPS}} = 0.09970190[p_{f1}] \dfrac{q_v}{N_{vp}}$	Volumetric flow rate at flowing conditions with an upstream tap measurement Example: $q_v = q_{\text{acfm}}$ = actual cubic feet per minute
q_v	N_{vpT}	$q_{\text{PPS}} = 0.1637908 \left[\dfrac{Gp_{f1}}{Z_{f1}T_{f1}}\right] \dfrac{q_v}{N_{vpT}}$	Volumetric flow rate at flowing conditions using the *pvT* density equation for upstream tap measurements Example: $q_v = q_{\text{acfm}}$ = actual cubic feet per minute
q_V	N_{Vp}	$q_{\text{PPS}} = 0.09970190[p_b] \dfrac{q_V}{N_{Vp}}$	Volumetric flow rate at standard base conditions with a density determination (p_b density at 14.696 and 59°F or other selected base values) Example: $q_V = q_{\text{SCFM}}$ = standard cubic feet per minute
q_V	N_{VpT}	$q_{\text{PPS}} = 0.1637908 \left[\dfrac{G}{Z_b}\right] \dfrac{q_V}{N_{VpT}}$	Volumetric flow rate at standard base conditions (14.69595 psia and 59°F) using the *pvT* density equation (recommended standard base volume) Example: $q_V = q_{\text{SCFH}}$ = standard cubic feet per hour
q_{Vb}	$(N_{VpT})_b$	$q_{\text{PPS}} = 0.1637908 \left[\dfrac{Gp_b}{Z_bT_b}\right] \dfrac{q_{Vb}}{(N_{VpT})_b}$	Volumetric flow rate at a selected base, other than standard, using the *pvT* equation Example: $q_{Vb} = (q_{\text{SCFD}})_{14.4,70}$ = standard cubic feet per day at 14.4 psia and 70°F

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Relationship Between Fundamental Constant and Derived Flow-Rate Unit for Gas Flow: SI Units

Letter Symbol			
Flow Rate	**Conversion Constant**	**Relationship to Fundamental Unit Equation**	**Definition**
q_M^*	N_{Mp}^*	$q_{KPS}^* = 0.00003512407 \dfrac{q_M^*}{N_{Mp}^*}$	Mass flow rate with density determination Example: $q_M^* = q_{KPD}^*$ = kilograms per day
q_M^*	N_{MpT}^*	$q_{KPS}^* = 0.00006555517 \dfrac{q_M^*}{N_{MpT}^*}$	Mass flow rate using the *pvT* density equation Example: $q_M^* = q_{KPM}^*$ = kilograms per minute
q_v^*	N_{vp}^*	$q_{KPS}^* = 0.00003512407[p_{f1}^*] \dfrac{q_v^*}{N_{vp}^*}$	Volumetric flow rate at flowing conditions with an upstream tap density determination Example: $q_v^* = q_{acmm}^*$ = actual cubic meters per minute
q_v^*	N_{vpT}^*	$q_{KPS}^* = 0.000065555517 \left[\dfrac{Gp_{f1}^*}{Z_{f1}T_{K1}}\right] \dfrac{q_v^*}{N_{vpT}^*}$	Volumetric flow rate at flowing conditions using the *pvT* density equation for upstream tap measurements Example: $q_v^* = q_{acmm}^*$ = actual cubic meters per minute
q_V^*	N_{Vp}^*	$q_{KPS}^* = 0.00003512407 \left[p_b^*\right] \dfrac{q_V^*}{N_{Vp}^*}$	Volumetric flow rate at standard or selected base conditions with a density determination Example: $q_V^* = q_{SCMM}^*$ = standard cubic meters per minute
q_V^*	N_{VpT}^*	$q_{KPS}^* = 0.00006555517 \left[\dfrac{G}{Z_b}\right] \dfrac{q_V^*}{N_{VpT}^*}$	Volumetric flow rate at standard base conditions (101.325 kPa and 15°C) using the *pvT* density equation (recommended standard) Example: $q_v^* = q_{SCMH}^*$ = standard cubic meters per hour
q_{Vb}^*	$(N_{VpT}^*)_b$	$q_{KPS}^* = 0.00006555517 \left[\dfrac{Gp_b^*}{Z_bT_{Kb}}\right] \dfrac{q_{Vb}^*}{(N_{VpT}^*)_b}$	Volumetric flow rate at a selected base, other than standard, using the *pvT* equation Example: $q_{vb}^* = (q_{SCMD}^*)_{100,14}$ = standard cubic meters per day at 100 kPa, 14°C

Symbols that apply to SI units are shown with a superscript asterisk, as in q^*_{M}.

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Relationship Between Fundamental Constant and Derived Flow-Rate Unit for *pvT* Gas Flow Equation Rearranged in Factor Form (F_{PB}, F_{TB}, T_{TF}, F_{pv})

Letter Symbol			
Flow Rate	**Conversion Constant**	**Relationship to Fundamental Unit Equation**	**Definition**
U.S. Units			
q_M	N_{Mhp}	$q_{\text{PPS}} = 0.007191927 \dfrac{q_M}{N_{Mhp}}$	Mass flow rate Example: $q_M = q_{\text{PPH}}$ = pounds-mass per hour
q_v	N_{vhp}	$q_{\text{PPS}} = 0.007191927 \left[\dfrac{F_{TF1}^2 F_{pv1}^2 p_{f1}}{F_g^2}\right] \dfrac{q_v}{N_{vhp}}$	Volumetric flow rate at flowing conditions Example: $q_v = q_{acfs}$ = actual cubic feet per second
q_V	N_{Vhp}	$q_{\text{PPS}} = 0.007191927 \left[\dfrac{1}{F_g^2 F_{PB} F_{TB} Z_b}\right] \dfrac{q_{Vb}}{N_{Vhp}}$	Volumetric flow rate at standard base or at selected temperature and pressure base Example: $q_V = q_{\text{SCFD}}$ = standard cubic feet per day at standard base (p_b = 14.69595 psia, T_b = 518.67°R)
SI Units			
q_M^*	N_{Mhp}^*	$q_{KPS}^* = 0.000003861870 \dfrac{q_M^*}{N_{Mhp}^*}$	Mass flow rate Example: $q_M^* = q_{KPM}^*$ = kilograms per minute
q_v^*	N_{vhp}^*	$q_{KPS}^* = 0.000003861870 \left[\dfrac{F_{TF1}^2 F_{pv1}^2 p_{f1}^*}{F_g^2}\right] \dfrac{q_v^*}{N_{vhp}^*}$	Volumetric flow rate at flowing conditions Example: $q_v^* = q_{acmh}^*$ = actual cubic meters per hour
q_V^*	N_{Vbp}^*	$q_{KPS}^* = 0.000003861870 \left[\dfrac{1}{F_g^2 F_{PB}^* F_{TB}^* Z_b}\right] \dfrac{q_{Vb}^*}{N_{Vhp}^*}$	Volumetric flow rate at standard or selected base pressure and temperature Example: $q_v^* = (q_{SCMH}^*)_{102,16}$ = standard cubic meters per hour at 102 kPa and 16°C

Symbols that apply to SI units are shown with a superscript asterisk, as in q^*_M.

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_N_ Factors for Mass Flow in U.S. Units (Note 1)

Time	Pound-mass (lb_m)	Kilogram (kg) (Note 2)	Gram (g) (Note 2)
N_{M_p} Density Equation, *liquid and gas* (vapor)			
s	0.0997019	0.04522402	45.22402
min	5.982114	2.713441	2713.441
h	358.9268	162.8065	162,806.50
24 h	8614.244	3907.36	3,907,356
N_{MG} Specific Gravity Equation, *liquid* (Note 3)			
s	0.7873692	0.3571447	357.1447
min	47.24215	21.42868	21,428.68
h	2834.529	1285.721	1,285.72
24 h	68,028.70	30,857.30	30,857,300
N_{M_pT} *pvT* equation, *gas* (vapor)			
s	0.1637913	0.07429449	74.29449
min	9.827478	4.4576769	4457.669
h	589.6487	267.4602	267,460.20
24 h	14151.57	6419.044	6,419,044
Note 1	The U.S. units are pressure p_f (psia), differential pressure h_w (inches of water at 68 °F, 14.696 psia, and standard gravity, 32.17405 ft/s^2), temperature T_f (°R), dimensions *d* and *D* (in), and density *p* (lb_m/ft^3).		
Note 2	Specific gravity base: water at 60 °F; pressure = 14.69595 psia		
Note 3	For sizing and calculating mass flow in SI units, *but* with measurement in the U.S. units defined above.		

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_N_ Factors for Mass Flow in SI Units (Note 1)

Time	Kilogram (kg)	Gram (g)
$N^*_{M\rho}$ Density Equation, *liquid and gas* (vapor)		
s	0.00003512407	0.03512407
min	.002107444	2.107444
h	0.1264467	126.4467
24 h	3.03472	3,034.720
N^*_{MG} Specific Gravity Equation, *liquid*		
s	0.001110172	1.110172
min	0.06661032	66.61031
h	3.996619	3996.619
24 h	95.91886	95,918.85
N^*_{MpT} *pvT* equation, *gas* (vapor)		
s	0.00006555517	0.06555517
min	0.003933310	3.933310
h	0.2359986	235.9986
24 h	5.663967	5663.967
Note 1	The U.S. units are pressure p^*_f (kPa), differential pressure Δp^* (kPa), temperature T_K (°K), dimensions d^* and D^* (mm), and density p^* (kg/m^3). For differential pressure Δp^* in bars, multiply table values by 10. For pressure p^*_f in bars, multiply by 10. For *both* differential pressure and pressure in bars, multiply by 100. For Reynolds-number calculations (equations from Table 9.21) *do not* change tabular values.	

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N Factors for Volume Flow: U.S. Units†

Time	Cubic foot (ft^3)	Cubic meter (m^3)‡	Liter (L)‡	U.S. gallon (gal)	U.K. liquid (Imp. gal)	Barrel 42 gal	Barrel 50 gal
			N_{vp}, N_{V_p}, Density equation, *liquid and gas* (vapor)				
s	0.09970190	0.002823244	2.823244	0.7458220	0.6210265	0.01775767	0.01491644
min	5.982114	0.1693946	169.3946	44.74932	37.26159	1.065460	0.8949864
h	358.9268	10.16368	10,163.68	2684.959	2235.696	63.92760	53.69919
24 h	8614.244	243.9283	243,928.3	64,439.02	53,656.69	1534.262	1288.780
			$N_{\upsilon G}$, N_{VG}, Specific-gravity equation, *liquid*				
s	0.01262491	0.0003574978	0.3574978	0.09444092	0.07863849	0.002248593	0.001888819
min	0.7574946	0.02144987	21.44987	5.666455	4.718309	0.1349156	0.1133291
h	45.44968	1.286992	1286.992	399.9873	283.0986	8.094936	6.799747
24 h	1090.793	30.88781	30,887.81	8159.696	6794.365	194.2785	163.1939

pvT equation, *gas* (vapor)

	N_{vpT}, $(N_{\upsilon pT})_b$			N_{V_pT} §		
Time	Cubic foot (ft^3)	Cubic meter (m^3)‡	Liter (L)‡	Cubic foot (ft^3)	Cubic meter (m^3)‡	Liter (L)‡
s	0.0606898	0.001718545	1.718545	2.141951	0.06065330	60.65330
min	3.641391	0.1031127	103.1127	128.5171	3.639198	3639.198
h	218.4834	6.186763	6186.763	7711.023	218.3519	218,351.9
24 h	5243.603	148.4823	148,485.3	185,064.6	5240.445	5,240,445

†The U.S. units are pressure p_f (psia), differential pressure h_w (inches of water at 68°F, 14.696 psia, and standard gravity, 32.17405 ft/s^2), temperature T_f (°R), dimensions d and D (in.), and density ρ (lb_m/ft^3).

‡For sizing and calculating volume flow in SI units, *but* with measurements in the U.S. units defined above.

§Standard base volume (ISO 5024): p_b = 14.69595 psia; T_b = 518.67°R

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N Factors for Volume Flow: SI Units†

$N^*_{\upsilon p}, N^*_{Vp}$ Density equation, *liquid and gas* (vapor)			N^*_{vG}, N^*_{VG} Specific-gravity equation, *liquid*		
Time	Cubic meter (m^3)	Liter (L)	Time	Cubic meter (m^3)	Liter (L)
s	0.00003512407	0.03512407	s	0.000001111270	0.001111270
min	0.002107444	2.107444	min	0.00006667619	0.06667619
h	0.1264467	126.4467	h	0.004000571	4.000571
24 h	3.034720	3034.720	24 h	0.09601371	96.01371

$p\upsilon T$ equation, *gas* (vapor)

	N^*_{vpT}, § $(N^*_{Vpt})_b$ ‡		N^*_{VpT} ‡	
Time	Cubic meter (m^3)	Liter (L)	Cubic meter (m^3)	Liter (L)
s	0.00001881927	0.01881927	0.00005351861	0.05351861
min	0.001129156	1.129156	0.003211117	3.211117
h	0.06774938	67.74938	0.1926670	192.6670
24 h	1.625985	1625.985	4.624008	4624.008

†The SI units are pressure p^*_f (kPa), differential pressure Δp^* (kPa), temperature T_K (K), dimensions d^* and D^* (mm), and density ρ^* (kg/m^3). For differential pressure Δp^* in bars, multiply table values by 10. For Reynolds-number calculations (equations from Table 9.21), *do not* change tabular values.

‡For pressure p^*_f in bars, multiply by 10. For *both* differential pressure and pressure in bars, multiply by 100.

§For pressure p^*_f in bars, divide by 10. For *both* differential pressure and pressure in bars, there is no change.

¶Standard base volume (ISO 5024): $p^*_b = 101.325$ kPa; $T_{Kb} = 288.15$ K.

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N Factors for Gas-Factor Equations (F_{PB}, F_{TB}, F_{TF}, F_{pv}): U.S. Units†

N_{Mhp} Mass-flow equation			
Time	Pound-mass (lb_m)	Kilogram (kg)§	Gram (g)§
s	0.007191927	0.003262203	3.262203
min	0.4315156	0.1957322	195.7322
h	25.89094	11.74393	11,743.93
24 h	621.3825	281.8544	281,854.4
N_{vhp} Volume flow at flowing conditions			
Time	Cubic foot (ft^3)	Cubic meter (m^3)§	Liter (L)§
s	1.382170	0.03913871	39.13871
min	82.930213	2.348323	2348.323
h	4975.814	140.8994	140,899.4
24 h	119,419.5	3381.585	3,381.585
N_{Vhp} Volume flow at selected or standard base‡			
Time	Cubic foot (ft^3)	Cubic meter (m^3)§	Liter (L)§
s	0.09405112	0.002663231	2.663231
min	5.643067	0.1597939	159.7939
h	338.5840	9.587633	9587.633
24 h	8126.016	230.1032	230,103.2

†The U.S. units are pressure p_f (psia), differential pressure h_w (inches of water at 68°F, 14.696 psia, and standard gravity, 32.17405 ft/s^2), dimensions d and D (in), and density p (lb_m/ft^3).

‡Standard base volume (ISO 5024, 1976): p_b = 14.69595 psia; T_b = 518.67°R; $F_{PB} = F_{TB} = 1.0$.

§For sizing and calculating flow in SI units, *but* with measurements in the U.S. units defined above.

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N Factors for Gas-Factor Equations

($F^*_{PB}, F^*_{TB}, F^*_{TF}, F^*_{p\upsilon}$): SI Units†

N^*_{Mhp} Mass-flow equation		
Time	Kilogram (kg)	Gram (g)
s	0.000003861870	0.003861870
min	0.0002317122	0.2317122
h	0.01390273	13.90273
24 h	0.3336656	333.6656
N^*_{vhp} Volume flow at flowing conditions‡		
Time	Cubic meter (m^3)	Liter (L)
s	0.0003194568	0.3194568
min	0.01916741	19.16741
h	1.150044	1150.044
24 h	27.60107	27,601.07
N^*_{Vhp} Volume flow at selected or standard base§		
Time	Cubic meter (m^3)	Liter (L)
s	0.000003152793	0.003152793
min	0.0001891676	0.1891676
h	0.01135006	11.35006
24 h	0.2724013	272.4013

†The SI units are pressure p^*_f (kPa), differential pressure Δp^* (kPa), temperature T_K (K), and dimensions d^* and D^* (mm). For differential pressure in bars, multiply table values by 10. For Reynolds-number calculations (equations from Table 9.22) *do not* change tabular values.

‡For pressure in bars, divide by 10. For *both* differential pressure and pressure in bars, there is no change.

§Standard base volume (ISO 5024, 1976): p^*_b = 101.325 kPa; T_{Kb} = 218.15 K (15°C); F^*_{PB} = 1.0. For pressure in bars, multiply by 10. For *both* differential pressure and pressure in bars, multiply by 100.

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2.4.6.1 Reynolds Number

$$R_e = \frac{3160 \times Q \times G}{D \times \mu} \text{ for liquids}$$

where

Q = flow (gpm)

G = specific gravity

D = pipe diameter (in.)

μ = viscosity (cP)

$$R_e = \frac{6316 \times Q}{D \times \mu} \text{ for gases}$$

where

Q = flow (lb/hr)

2.4.6.2 Thermal Expansion Factor

Pipe inner diameter corrected for thermal expansion:

$$D_{pc} = \left[1 + \alpha_p (T_F - 68)\right] D_m$$

Orifice plate bore corrected for thermal expansion:

$$d_{oc} = [1 + \alpha_{fe}(T_F - 68)] d_m$$

Thermal Expansion Factors, α, for Flow Elements

Material	Expansion Coefficients	
	10^{-6} in/in °F	10^{-6} m/m °C
Aluminum, 6061 & 6063	13.00	23.40
Copper (ASTM B112, B124, B133)	9.3	16.7
Hastelloy	8.40	15.00
Inconel	6.40	11.50
Iron, Gray	5.70	10.50
Monel	7.80	14.00
Steel, Carbon	7.00	11.70
Steel, Stainless, 304	9.30	17.00
Steel, Stainless, 316	8.90	16.00
Titanium, Grade 5	5.20	9.36
Titanium, Grade 8	4.80	8.64

2.4.6.3 Discharge Coefficient, C, Based on Primary Device

$C = C_\infty + \frac{b}{R_D^n}$, where values are given as follows.

Equations and Values for C∞, b, and n

Primary Device	Discharge Coefficient C∞ at Infinite Reynolds Number	Reynolds-Number Term	
		Coefficient *b*	Exponent *n*
ISA	$0.9900 - 0.2262\beta^{4.1}$	$(-0.00175\beta^2 + 0.033\beta^{4.15})10^{6.9}$	1.15
Venturi Nozzle (ISA Inlet)	$0.9558 - 0.196\beta^{4.5}$	0	0
Orifice:			
Corner Taps	$0.5959 + 0.312\beta^{2.1} - 0.184\beta^8$	$91.706\beta^{2.5}$	0.75
Flange Taps (*D* in inches)			0.75
$D \ge 2.3$	$0.595 + 0.0312\beta^{2.1} - 0.184\beta^8 + 0.09\frac{\beta^4}{D(1-\beta^4)} - 0.337\frac{\beta^3}{D}$	$91.706\beta^{2.5}$	0.75
$2 \le D \le 2.3^d$	$0.595 + 0.312\beta^{2.1} - 0.184\beta^8 + 0.039\frac{\beta^4}{1-\beta^4} - 0.337\frac{\beta^3}{D}$	$91.706\beta^{2.5}$	0.75
Flange Taps (D* in millimeters)			
$D* \ge 58.4$	$0.595 + 0.0312\beta^{2.1} - 0.184\beta^8 + 2.286\frac{\beta^4}{D^*(1-\beta^4)} - 0.856\frac{\beta^3}{D^*}$	$91.706\beta^{2.5}$	0.75
$50.8 \le D* \le 58.4$	$0.595 + 0.0312\beta^{2.1} - 0.184\beta^8 + 0.039\frac{\beta^4}{1-\beta^4} - 0.856\frac{\beta^3}{D^*}$	$91.706\beta^{2.5}$	0.75
D and *D*/2 taps	$0.595 + 0.0312\beta^{2.1} - 0.184\beta^8 + 0.039\frac{\beta^4}{1-\beta^4} - 0.01584\beta^3$	$91.706\beta^{2.5}$	0.75
$2\frac{1}{2}D$ and 8*D* taps	$0.595 + 0.461\beta^{2.1} + 0.48\beta^8 + 0.039\frac{\beta^4}{1-\beta^4}$	$91.706\beta^{2.5}$	0.75

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Reynolds Number Related to Derived Flow Rate in U.S. Units†

	Liquid	Gas (vapor)
	Mass flow rate	
Density	$R_D = \left[2266.970 \frac{1}{\mu_{cP} D N_{M\rho}}\right] q_M$ (a)	$R_D = \left[2266.970 \frac{1}{\mu_{cP} D N_{M\rho}}\right] q_M$ (g)
Specific gravity	$R_D = \left[17{,}902.78 \frac{1}{\mu_{cP} D N_{MG}}\right] q_m$ (b)	
*p**V*T equation		$R_D = \left[3724.200 \frac{1}{\mu_{cP} D N_{MpT}}\right] q_M$ (h)
	Volumetric flow rate at flowing conditions	
Density	$R_D = \left[2266.970 \frac{\rho_f}{\mu_{cP} D N_{\nu\rho}}\right] q_v$ (c)	$R_D = \left[2266.970 \frac{\rho_{f1}}{\mu_{cP} D N_{\nu\rho}}\right] q_v$ (i)
Specific gravity	$R_D = \left[17{,}902.78 \frac{F_p G_F}{\mu_{cP} D N_{vG}}\right] q_v$ (d)	
*p**V*T equation		$R_D = \left[3724.200 \frac{G p_{f1}}{Z_{f1} T_{f1}} \frac{1}{\mu_{cP} D N_{vpT}}\right] q_v$ (j)
	Volumetric flow rate at base conditions	
Density	$R_D = \left[2266.970 \frac{\rho_b}{\mu_{cP} D N_{V\rho}}\right] q_V$ (e)	$R_D = \left[2266.970 \rho_b \frac{1}{\mu_{cP} D N_{V\rho}}\right] q_V$ (k)
Specific gravity	$R_D = \left[17{,}902.78 \frac{G_b}{\mu_{cP} D N_{VG}}\right] q_V$ (f)	
*p**V*T equation		
Standard base		$R_D = \left[3724.200 \frac{G}{Z_b} \frac{1}{\mu_{cP} D N_{vpT}}\right] q_V$ (l)
Selected base		$R_D = \left[3724.200 \frac{G p_b}{Z_b T_b} \frac{1}{\mu_{cP} D (N_{vpT})_b}\right] q_{vb}$ (m)

† D in these equations is at flowing conditions: $D = F_{eD} D_{meas} = [1 + \alpha_p(T_F - 68)] D_{meas}$ [Eq. (9.50)].

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Reynolds Number Related to Derived Flow Rate in SI units†

	Liquid		Gas (vapor)	
Mass flow rate				
Density	$R_D = \left[44.72136 \frac{1}{\mu_{cP} D^* {N^*}_{M\rho}}\right] q_M^*$	(a)	$R_D = \left[44.72136 \frac{1}{\mu_{cP} D^* {N^*}_{M\rho}}\right] q_M^*$	(g)
Specific Gravity	$R_D = \left[1413.515 \frac{1}{\mu_{cP} D^* N^*}\right] q_M^*$	(b)		
*p*VT equation			$R_D = \left[83.46744 \frac{1}{\mu_{cP} D^* {N^*}_{MpT}}\right] q_M^*$	(h)
Volumetric flow rate at flowing conditions				
Density	$R_D = \left[44.72136 \frac{\rho_f^*}{\mu_{cP} D^* {N^*}_{v\rho}}\right] q_v^*$	(c)	$R_D = \left[44.72136 \frac{\rho_{f1}^*}{\mu_{cP} D^* {N^*}_{v\rho}}\right] q_v^*$	(i)
Specific Gravity	$R_D = \left[1413.515 \frac{F_p G_F}{\mu_{cP} D^* {N^*}_{vG}}\right] q_v^*$	(d)		
*p*VT equation			$R_D = \left[83.46744 \frac{G p_{f1}^*}{Z_{f1} T_{f1}} \frac{1}{\mu_{cP} D^* {N^*}_{vpT}}\right] q_v^*$	(j)
Volumetric flow rate at base conditions				
Density	$R_D = \left[44.72136 \frac{\rho_b^*}{\mu_{cP} D^* {N^*}_{v\rho}}\right] q_V^*$	(e)	$R_D = \left[44.72136 \rho_b^* \frac{1}{\mu_{cP} D^* {N^*}_{V\rho}}\right] q_V^*$	(k)
Specific Gravity	$R_D = \left[1413.515 \frac{G_b}{\mu_{cP} D^* {N^*}_{VG}}\right] q_V^*$	(f)		
*p*VT equation				
Standard base			$R_D = \left[83.46744 \frac{G}{Z_b} \frac{1}{\mu_{cP} D^* {N^*}_{VpT}}\right] q_V^*$	(l)
Selected base			$R_D = \left[83.46744 \frac{G p_b^*}{Z_b T_b} \frac{1}{\mu_{cP} D^* (N_{VpT}^*)_b}\right] q_{Vb}^*$	(m)
† D and D* in these equations is at flowing conditions: $D^* = F_{aD}^* D_{\text{meas}}^* = [1 + \alpha_P^* (T_{\circ C} - 20)] D_{\text{meas}}^* \left[\text{Eq.} (9.53)\right]$.				

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Reynolds Number Related to Derived Flow-Rate Unit for Gas-Factor Equation: U.S. and SI Units†

pVT equation	U.S. units		SI units	
Mass flow rate	$R_D = \left[163.5262 \dfrac{1}{\mu_{cP} D N_{Mhp}} \right] q_M$	(a)	$R_D = \left[4.917086 \dfrac{1}{\mu_{cP} D^* N^*_{Mhp}} \right] q^*_M$	(d)
Volumetric flow rate at flowing conditions	$R_D = \left[163.5263 \dfrac{F^2_{TF1} F^2_{pv1} p_{f1}}{Z^2_b \mu_{cP} D N_{vhp}} \right] q_v$	(b)	$R_D = \left[4.917086 \dfrac{F^{*2}_{TF1} F^2_{pv1} p^{*2}_{f1}}{Z^2_b \mu_{cP} D^* N_{vhp}} \right] q^*_v$	(e)
Volumetric flow rate at standard or selected base conditions	$R_D = \left[163.5262 \dfrac{1}{F^2_g F_{PB} F_{TB} Z_b \mu_{cP} D N_{Vhp}} \right] q_{Vb}$	(c)	$R_D = \left[4.917086 \dfrac{1}{F^2_g F^*_{PB} F^*_{TB} Z_b \mu_{cP} D^* N_{*Vph}} \right] q^*_{Vb}$	(f)

†D and D* in these equations is at flowing conditions:
$D = F_{aD} D_{\text{meas}} = \left[1 + \alpha_P (T_F - 68)\right] D_{\text{meas}} \left[Eq. (9.50)\right]$; $D^* = F^*_{aD} D^*_{\text{meas}} = \left[1 + \alpha^*_P (T_{\circ C} - 68)\right] D^*_{\text{meas}} \left[\text{Eq.} (9.52)\right]$.

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Sizing Factor (S_M) Equations for U.S. Flow Units†

	Liquid	Gas (vapor)
Mass flow rate		
Density	$S_M = \frac{q_M}{N_{M\rho} F_a D^2 \sqrt{F_p \rho_F h_w}}$ (a)	$S_M = \frac{q_M}{N_{M\rho} F_a D^2 \sqrt{\rho_{f1} h_w}}$ (g)
Specific Gravity	$S_M = \frac{q_M}{N_{MG} F_a D^2 \sqrt{F_p G_F h_w}}$ (b)	
*pV*T equation		$S_M = \frac{\sqrt{Z_{f1} T_{f1}}\, q_M}{N_{MpT} F_a D^2 \sqrt{\mathrm{G}\, h_w p_{f1}}}$ (h)
Volumetric flow rate at flowing conditions		
Density	$S_M = \frac{\sqrt{F_p \rho_F}\, q_v}{N_{v\rho} F_a D^2 \sqrt{h_w}}$ (c)	$S_M = \frac{\sqrt{\rho_{f1}} q_v}{N_{v\rho} F_a D^2 \sqrt{h_w}}$ (i)
Specific Gravity	$S_M = \frac{\sqrt{F_p G_F}\, q_v}{N_{vG} F_a D^2 \sqrt{h_w}}$ (d)	
*pV*T equation		$S_M = \frac{\sqrt{G \rho_{f1}}\, q_v}{N_{v\rho} F_a D^2 \sqrt{Z_{f1} T_{f1} h_w}}$ (j)
Volumetric flow rate at base conditions		
Density	$S_m = \frac{\rho_b q_V}{N_{V\rho} F_a D^2 \sqrt{F_p \rho_F h_w}}$ (e)	$S_m = \frac{\rho_b q_V}{N_{V\rho} F_a D^2 \sqrt{\rho_{f1} h_w}}$ (k)
Specific Gravity	$S_m = \frac{G_b q_V}{N_{VG} F_a D^2 \sqrt{F_p G_F h_w}}$ (f)	
*pV*T equation		
Standard base		$S_M = \frac{\sqrt{Z_{f1} T_{f1} G}\; q_V}{N_{VpT} F_a Z_b D^2 \sqrt{h_w p_{f1}}}$ (l)
Selected base		$S_M = \frac{\sqrt{Z_{f1} T_{f1} G}\; p_b q_{Vb}}{(N_{VpT})_b F_a Z_b T_b D^2 \sqrt{h_w p_{f1}}}$ (m)

† Gas (vapor) equations are written for upstream pressure tap. For downstream pressure tap, change subscript 1 to subscript 2, in ρ_{f2}, p_{f2}, Z_{f2}, etc. D in these equations is at flowing conditions: $D = F_{aD} D_{meas} = [1 + \alpha_P (T_F - 68)] D_{meas}$ [Eq. (9.50)].

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Sizing Factor (S_M) Equations for SI Flow Units†

	Liquid		Gas (vapor)	
Mass flow rate				
Density	$S_M = \dfrac{q_M^*}{F_a^* N_{M\rho}^* D^{*2}\sqrt{F_p \rho_f^* \Delta p^*}}$	(a)	$S_M = \dfrac{q_M^*}{F_a^* N_{M\rho}^* D^{*2}\sqrt{\rho_{f1}^* \Delta p^*}}$	(g)
Specific Gravity	$S_M = \dfrac{q_M^*}{N_{MG}^* F_a^* D^{*2}\sqrt{F_p G_F^* \Delta p^*}}$	(b)		
*p**V*T equation			$S_M = \dfrac{\sqrt{Z_{f1} T_{K1}}\, q_M^*}{F_a^* N_{MpT}^* D^{*2}\sqrt{G \Delta p^* p_{f1}^*}}$	(h)
Volumetric flow rate at flowing conditions				
Density	$S_M = \dfrac{\sqrt{F_p \rho_F^*}\, q_v^*}{F_a^* N_{vp}^* D^{*2}\sqrt{\Delta p^*}}$	(c)	$S_M = \dfrac{\sqrt{\rho_{f1}^*}\, q_v^*}{F_a^* N_{vp}^* D^{*2}\sqrt{\Delta p^*}}$	(i)
Specific Gravity	$S_M = \dfrac{\sqrt{F_p G_F^*}\, q_v^*}{F_a^* N_{vG}^* D^{*2}\sqrt{\Delta p^*}}$	(d)		
*p**V*T equation			$S_M = \dfrac{\sqrt{G p_{f1}^*}\, q_v^*}{N_{vpT}^* F_a^* D^{*2}\sqrt{Z_{f1} T_{K1} \Delta p^*}}$	(j)
Volumetric flow rate at base conditions				
Density	$S_M = \dfrac{\rho_b^* q_V^*}{F_a^* N_{V\rho}^* D^{*2}\sqrt{F_p \rho_F^* \Delta p^*}}$	(e)	$S_M = \dfrac{\rho_b^* q_V^*}{F_a^* N_{V\rho}^* D^{*2}\sqrt{\rho_{f1}^* \Delta p^*}}$	(k)
Specific Gravity	$S_M = \dfrac{G_b q_V^*}{F_a^* N_{VG}^* D^{*2}\sqrt{F_p G_F \Delta p^*}}$	(f)		
*p**V*T equation				
Standard base			$S_M = \dfrac{\sqrt{Z_{f1} T_{K1} G}\, q_v^*}{F_a^* N_{VpT}^* Z_b D^{*2}\sqrt{\Delta p^* p_{f1}^*}}$	(l)
Selected base			$S_M = \dfrac{\sqrt{Z_{f1} T_{K1} G}\, p_b^* q_{Vb}^*}{F_a^* (N_{VpT}^*)_b\, Z_b T_{Kb} D^{*2}\sqrt{\Delta p^* p_{f1}^*}}$	(m)

† Gas (vapor) equations are written for upstream pressure tap. For downstream pressure tap, change subscript 1 to subscript 2, in ρ_{f2}, p_{f2}, Z_{f2}, etc. D in these equations is at flowing conditions:
$D^* = F_{aD}^* D_{meas}^* = \left[1 + \alpha_P^* \left(T_{°C} - 20\right)\right] D_{meas}^* \left[\text{Eq.}(9.52)\right]$.

Source: *Flow Measurement Engineering Handbook* by Richard W. Miller. Table 9.24, p. 9.46. Reproduced with permission from McGraw-Hill.

β_0 Approximate Sizing Equations

Type	Equations
Venturi	
Machined inlet	$\beta_0 = \left[1 + \left(\frac{0.995}{S_M}\right)^2\right]^{-1/4}$
Orifice	
Corner, Flange, D-and D/2 taps	
R_D < 200,000	$\beta_0 = \left[1 + \left(\frac{0.6}{S_M} + 0.06\right)^2\right]^{-1/4}$
R_D > 200,000	$\beta_0 = \left[1 + \left(\frac{0.6}{S_M}\right)^2\right]^{-1/4}$
2 1/2*D* and 8*D* tapes	$\beta_0 = \left[1 + \left(\frac{0.61}{S_M} + 0.55\right)^2\right]^{-1/4}$

Source: *Flow Measurement Engineering Handbook* by Richard W. Miller. Table 9.28, p. 9.51.
Reproduced with permission from McGraw-Hill.

2.4.7 Level

2.4.7.1 Level Measurement Comparison—Continuous Level

	Accuracy	Cost***	Limitations
Pressure	±0.1 to 0.5% of full scale***	$$	Only extended diaphragm seals or repeaters can eliminate plugging. Purging and sealing legs are also used. Accuracy will be affected by process specific gravity changes
Capacitance	±2% of full scale	$	Interference between conductive layers and detection of foam is a problem. Does not yield an exact level.
Ultrasonic	±1–2% of full scale (0.1% in some units with temperature compensation)	$$	Strong industrial noise or vibration at the unit's operating frequency will affect performance. In some designs dusts tend to give false readings. Coating may affect performance since deposit buildup on the probe will attenuate the signal.
Guided wave radar	±1/4 in.	$$$ without chamber $$$$ with chamber	Interference from coating, agitator blade, spray, or excessive turbulence. For interface level: A minimum of 4 in. of the upper-level liquid is required. The difference between the upper-layer and the lower-layer liquid must be greater than 10. The dielectric constant of the liquid must be greater than 2.
Non-contacting radar	±0.1 in.	$$	Interference from coating, agitator blade, spray, or excessive turbulence.
Nuclear	Varies based on design	$$$$$	Requires NRC license
Laser	±0.8 in.	$$	Limited to cloudy liquids or bright solids in tanks with transparent vapor spaces
Displacer	±1/4 in., or 0.25% full scale	$$	May be affected by coating, buildup, or dirt that can cling to the displacer. Works on Archimedes' principle
Magnetostrictive	±1 in.	$$–$$$	Generally it is not recommended to be used in places with strong electromagnetic radiation such as power plants. Works on buoyancy principle
Magnetic level indicator (in chamber)	±1 in.	$$	Requires recalibration if the liquid density changes. Works on buoyancy principle
Servo (in stilling well)	±1/8 in.	$$$–$$$$	High level of maintenance and cleaning to ensure the tank contents do not penetrate the system instruments.

Level Measurement Comparison—Continuous Level (cont'd)

	Aeration	Agitation	Ambient temperature changes	Corrosion	Density changes	Dielectric changes	Dust	Emulsion	Foam	High process temp limits	High vessel pressure limits	Interface	Internal obstructions	Low process temperatures (<0°F, <–40)	Low vessel pressures (vacuum)	Noise (EMI, motors)	Product coating	Slurries	Solids	Vapors	Viscous, sticky product
Pressure	M	G	M	M	M	G	G	G	G	G	G	M-P	G	G	M	G	P	M	P	G	M
Capacitance	G	M	G	G	G	P	G	G	M	G	G	M-P	M	G	G	G	P	G	M	M	M
Ultrasonic	M	P	M	G	G	G	P	G	P	P	P	M	M	G	P	M	M	G	M	M	G
Guided wave radar	G	P	G	M	G	G*	G	M**	G	G	G	G	M	G	G	G	M	M	G	G	M
Non-contacting radar	M	G	G	G	G	G	M	G	M	M	M	P	M	G	G	G	G	G	G	G	G
Nuclear	M	G	G	G	M	G	G	G	G	G	G	G	M	G	G	G	M	G	G	G	G
Laser	M	M	G	G	G	G	P	G	P	G	G	P	M	G	G	M	M	G	G	M	G
Displacer	G	G	M	M	M	G	P	G	G	G	G	M	G	M	G	G	P	P	P	G	P
Magnetostrictive	M	M	G	M	M	G	G	M**	G	P	P	M	G	G	G	G	P	M	P	G	P
Magnetic level indicator (in chamber)	G	G	G	M	M	G	P	M**	G	G	M	M	G	M	G	G	P	M	P	G	P
Servo (in stilling well)	M	M	G	M	P	G	P	M**	M	M	M	G	G	G	G	G	P	P	P	G	P

Rating of each technology based on its capability of handling each challenge.

G = Good: This condition has little or no impact on performance of this technology.
M = Moderate: This technology can handle this condition, but performance could be affected or special installation is needed.
P = Poor: This technology does not handle this condition well or does not apply.
* A changing dielectric value will impact interface measurement accuracy
** Overall level OK, interface level moderate
*** Instrument only—does not include flanges or bridles

Source: Adapted from *The Engineer's Guide to Level Measurement for Power and Steam Generation*, 2013 edition.

2.4.7.2 Level Measurement Comparison—Point Level Detection

	Accuracy	**Cost***	**Limitations**
Capacitance	± 1/8 in.	$$–$$$	Interference between conductive layers and detection of foam is a problem.
Nuclear	± 1/4 in.	$$$–$$$$	Requires license
Float switch	1% full span	$–$$$	Moving parts limit most designs to clean service. Only preset density floats can follow interference.
Vibrating fork	0.2 in.	$–$$	Excessive material buildup can prevent operation.

*Instrument only—does not include flanges or bridles

Level Measurement Comparison—Point Level Detection (cont'd)

	Aeration	Agitation	Ambient temperature changes	Corrosion	Density changes	Dielectric changes	Dust	Emulsion	Foam	High process temp limits	High vessel pressure limits	Internal obstructions	Low process temp limits	Low vessel pressure limits	Noise (EMI, motors)	Product coating	Slurries	Solids	Vapors	Viscous, sticky product
Capacitance	G	M	G	G	G	P	G	G	M	G	G	M	G	G	G	P	G	M	M	M
Nuclear	M	G	G	G	M	G	G	G	G	G	G	M	G	G	G	M	G	G	M	G
Float switch	G	G	G	M	M	G	G	G	G	G	G	G	G	G	M	M	M	P	G	M
Vibrating fork	G	G	G	M	G	G	G	G	M	G	G	G	G	G	M	M	M	P	G	M

Rating of each technology based on its capability of handling each challenge.

G = Good: This condition has little or no impact on performance of this technology.

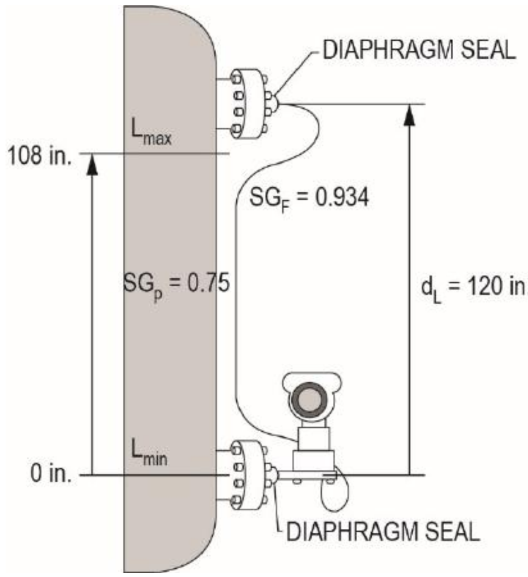
M = Moderate: This technology can handle this condition, but performance could be affected or special installation is needed.

P = Poor: This technology does not handle this condition well or does not apply.

Source: Adapted from *The Engineer's Guide to Level Measurement for Power and Steam Generation*, 2013 edition. Copyright © 2013 Rosemount, Inc. All rights reserved. Permission pending.

2.4.7.3 DP Level Transmitter Application

The figures in this section are from the *Rosemount™ DP Level Transmitters and 1199 Diaphragm Seal Systems* reference manual, 00809-0100-4002, Rev EA, May 2020.



Liquid Level in Closed Tank—Tuned-System Assembly

Source: Reproduced with permission from Emerson Automation Solutions, Rosemount Measurement Division, and adapted for exam use

d_H = vertical distance from transmitter to high-pressure seal

d_L = vertical distance from transmitter to low-pressure seal

L_{max} = maximum level of process above high-pressure seal and typically 20-mA lower range value

L_{min} = minimum level of process above high-pressure seal and typically 4-mA lower range value

SG_F = specific gravity of fill fluid

SG_P = specific gravity of process fluid

Tank span = $L_{max} \times SG_P - L_{min} \times SG_P$

= (108 in. × 0.75) = 81 in. H_2O

4 mA = $L_{min} \times SG_P - (d_L \times SG_F)$

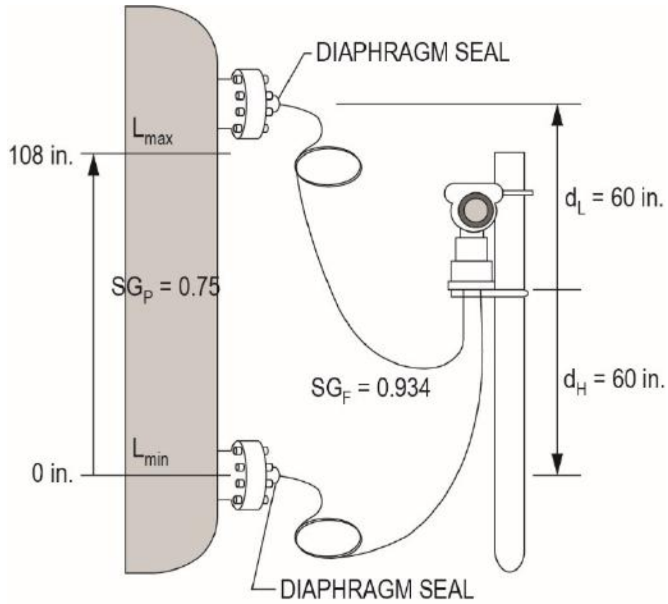
= (0 in. × 0.75) – (120 in. × 0.934) = –112.08 in. H_2O

20 mA = $L_{max} \times SG_P - (d_L \times SG_F)$

= (108 in. × 0.75) – (120 in. × 0.934) = –31.08 in. H_2O

Span = 81 in. H_2O (–112.08 to –31.08 in. H_2O)

Note: Silicone 200 has a specific gravity of 0.934.



Liquid Level in Closed Tank—Balanced System with Transmitter Between Seals

Source: Reproduced with permission from Emerson Automation Solutions, Rosemount Measurement Division, and adapted for exam use

d_H = vertical distance from transmitter to high-pressure seal

d_L = vertical distance from transmitter to low-pressure seal

L_{max} = maximum level of process above high-pressure seal and typically 20-mA lower range value

L_{min} = minimum level of process above high-pressure seal and typically 4-mA lower range value

SG_F = specific gravity of fill fluid

SG_P = specific gravity of process fluid

Tank span $= L_{max} \times SG$

$= (108 \text{ in.} \times 0.75) = 81 \text{ in. } H_2O$

4 mA $= L_{min} \times SG_P - (d_L \times SG_F) + (d_H \times SG_F)$

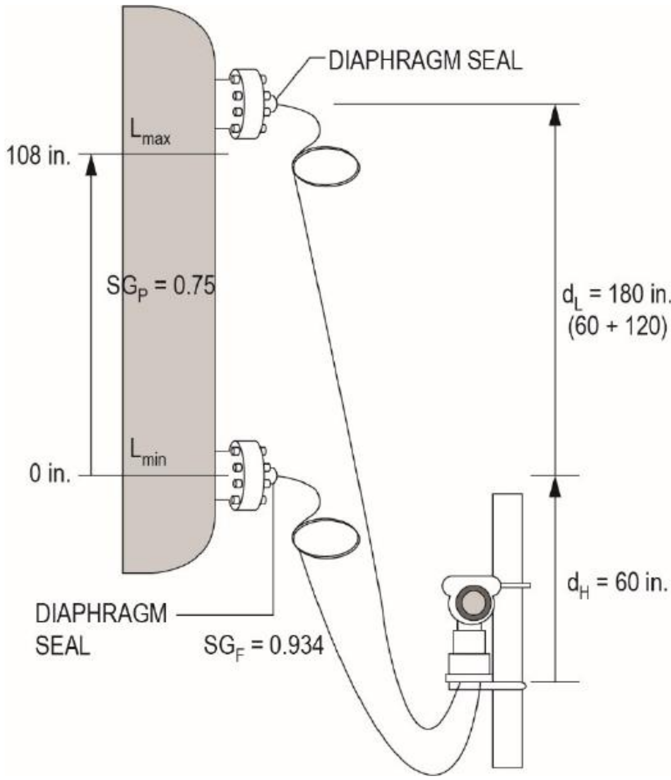
$= (0 \text{ in.} \times 0.75) - (60 \text{ in.} \times 0.934) + (-60 \text{ in.} \times 0.934) = -112.08 \text{ in. } H_2O$

20 mA $= L_{max} \times SG_P - (d_L \times SG_F) + (d_H \times SG_F)$

$= (108 \text{ in.} \times 0.75) - (60 \text{ in.} \times 0.934) + (-60 \text{ in.} \times 0.934) = -31.08 \text{ in. } H_2O$

Span $= 81 \text{ in. } H_2O$ (-112.08 to -31.08 in. H_2O)

Note: Silicone 200 has a specific gravity of 0.934.



Liquid Level in Closed Tank—Balanced System with Transmitter Below Seals

Source: Reproduced with permission from Emerson Automation Solutions, Rosemount Measurement Division, and adapted for exam use

d_H = vertical distance from transmitter to high-pressure seal

d_L = vertical distance from transmitter to low-pressure seal

L_{max} = maximum level of process above high-pressure seal and typically 20-mA lower range value

L_{min} = minimum level of process above high-pressure seal and typically 4-mA lower range value

SG_F = specific gravity of fill fluid

SG_P = specific gravity of process fluid

Tank span $= L_{max} \times SG$

$= (108 \text{ in.} \times 0.75) = 81 \text{ in. } H_2O$

4 mA $= L_{min} \times SG_P - (d_L \times SG_F) + (d_H \times SG_F)$

$= (0 \text{ in.} \times 0.75) - (180 \text{ in.} \times 0.934) + (60 \text{ in.} \times 0.934) = -112.08 \text{ in. } H_2O$

20 mA $= L_{max} \times SG_P - (d_L \times SG_F) + (d_H \times SG_F)$

$= (108 \text{ in.} \times 0.75) - (180 \text{ in.} \times 0.934) + (60 \text{ in.} \times 0.934) = -31.08 \text{ in. } H_2O$

Span $= 81 \text{ in. } H_2O$ (-112.08 to -31.08 in. H_2O)

Note: Silicone 200 has a specific gravity of 0.934.

Note: The transmitter location in a closed tank does not effect the 4-mA and 20-mA set points as shown in the three examples above of liquid levels in closed tanks.

2.4.8 Pressure

2.4.8.1 Generalized Equation

$$P = \frac{F}{A}$$

where

P = pressure in psi

F = force

A = area

2.4.8.2 Ideal Gas Law (Compressible)

Volumetric

$$PV = RTZ$$

$$\frac{P_1 V_1}{T_1 Z_1} = \frac{P_2 V_2}{T_2 Z_2}$$

where

R = gas constant (value = 1544 divided by molecular weight)

P = pressure (psia)

V = volume (cubic feet)

T = temperature (degrees Rankine)

Z = compressibility (dimensionless)

Density

$$\rho = \frac{P}{RTZ}$$

where

R = gas constant (value = 10.73 divided by molecular weight)

P = pressure (psia)

V = volume (cubic feet)

T = temperature (degrees Rankine)

Z = compressibility (dimensionless)

3 CONTROL SYSTEMS

3.1 Analog Control

3.1.1 Proportional-Integral-Derivative (PID) Control Definitions

- **Process Gain** – The change in the process variable divided by the change in controller output.

  $$K_p = \frac{\Delta PV}{\Delta CO}$$

  where

  PV = process variable

  CO = controller output

- **Integral Time** – The time integration of a measured process error. Added to the control signal to stabilize the process.

  $$I_n = I_{n-1} + P_n$$

- **Derivative Time** – The time derivative of a measured process error. Added to the control signal to stabilize the process.

  $$D_n = P_n - P_{n-1}$$

3.1.2 Proportional (P) Only

Controller output is a function of the gain setting of the unit. The output contribution resulting from an input change will be:

$$m = K_C e + Bias$$

where

m = output of controller after input change

K_C = controller gain setting (reciprocal of proportional band)

e = error or difference between set point and measurement

$Bias$ = the value of the output prior to the error

3.1.3 Proportional Plus Integral (PI) Control

Controller output is based on the function of proportional action with an integral or reset factor to drive the loop back to the set point.

$$m = K_C \left[e + \frac{1}{T_i} \int edt \right] + Bias$$

where

m = output of controller after input change

K_C = controller gain setting (reciprocal of proportional band)

e = error or difference between set point and measurement

$Bias$ = the value of the output prior to the error

T_i = reset time in minutes per repeat

3.1.4 Proportional plus Integral plus Derivative (PID) Control

Controller output is based on the function of proportional action with an integral or reset factor to drive the loop back to set point and a derivative contribution based on the rate of change of the error.

$$m = K_C\left[e + \frac{1}{T_i}\int edt + T_d\frac{de}{dt}\right] + Bias$$

where

m = output of controller after input change

K_C = controller gain setting (reciprocal of proportional band)

e = error or difference between the set point and measurement

$Bias$ = the value of the output prior to the error

T_i = reset time in minutes per repeat

T_D = derivative time in minutes

3.1.5 Cascade

Cascade control is a function where the output of one feedback controller sets the set point on a second feedback controller.

3.1.6 Feedforward

Feedforward control is when a final control element (valve or the set point of another controller) is manipulated by a measurement of the process disturbance rather than by the output of a feedback controller.

3.1.7 Open-Loop Tuning

The object of tuning a control loop is to obtain an acceptable response to a set-point change. The desired result is minimal overshoot or a one-quarter decay ratio. Two of the most common methods are the Ziegler-Nichols open-loop method and the Ziegler-Nichols closed-loop method.

Open-Loop Tuning Parameters

	P	PI	PID
K_C	$\frac{\tau}{K_P T_d}$	$\frac{0.9\ \tau}{K_P T_d}$	$\frac{1.2\ \tau}{K_P T_d}$
T_i	—	3.33 T_d	2.0 T_d
T_D	—	—	0.5 T_d

where

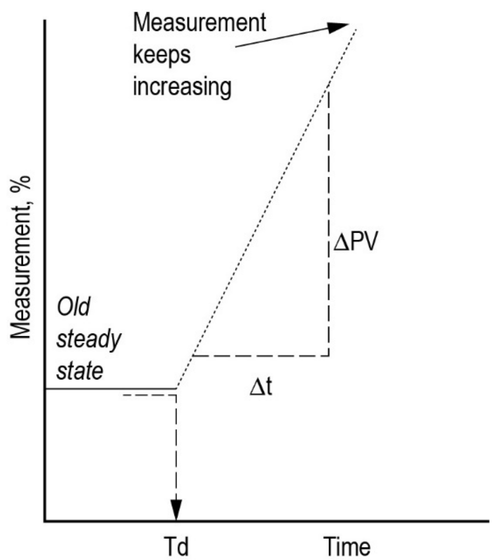
K_C = controller gain setting (reciprocal of proportional band)
T_i = reset time in minutes per repeat
T_D = derivative time in minutes

K_P = process gain from the step change in the system; reaction rate (RR) may be used as shown in the table above

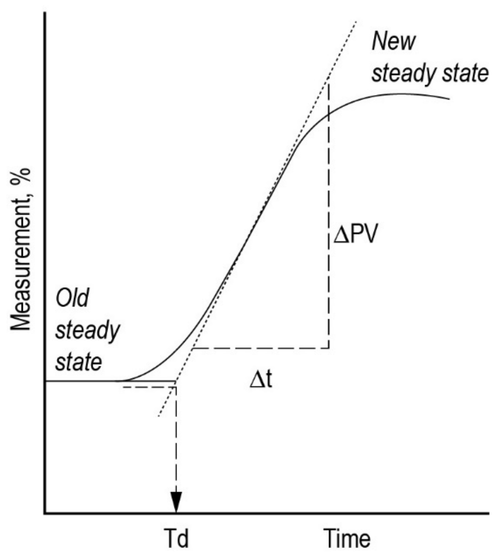
τ = time constant (tau) for the step change (time for the process variable to reach 63.2% of the new value)

T_d = dead time for the step change

Open-loop response



Closed-loop response



<u>Process Analysis</u>

Response rate per change in controller output

$$\text{RR} = \frac{\Delta\text{PV}/\Delta\text{t}}{\Delta\text{MV}} = \frac{\%/\text{time}}{\%} = \frac{1}{\text{time}}$$

Process dead time = Td = time

<u>Zieglar-Nicols Optimum PID</u>

P only

PB = 100 × RR × Td

PI

PB = 111.1 × RR × Td

I = 3.33 × Td

PID

PB = 83.3 × RR × Td

I = 2 × Td

D = 0.5 × Td

Ziegler-Nichols Open-Loop and Closed-Loop Methods

3.1.8 Closed-Loop Tuning

Closed-Loop Tuning Parameters

	P	PI	PID
K_{CU}	$0.5\ K_{CU}$	$0.45\ K_{CU}$	$0.6\ K_{CU}$
T_i	—	$0.83\ P_U$	$0.5\ P_U$
T_D	—	—	$0.125\ P_U$

where

K_C = controller gain setting (reciprocal of proportional band)

T_i = reset time in minutes per repeat

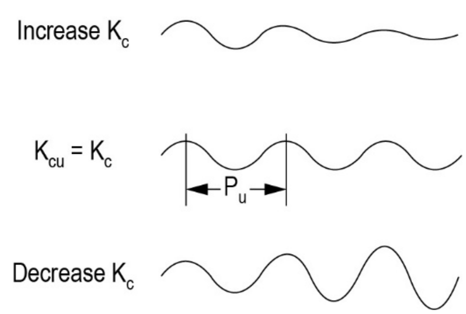
T_D = derivative time in minutes

K_{CU} = ultimate gain from oscillating loop response

P_U = ultimate period from oscillating loop response

With the loop in automatic, slowly increase the controller gain until sustained oscillations are obtained. The figure below indicates the need to increase the gain more to sustain oscillations or decrease the gain when the oscillations become erratic.

The ultimate gain should be recorded as $K_{CU,}$ and the ultimate period should be recorded as P_U.



Effects of Increasing and Decreasing Controller Gain

3.1.8.1 Cohen-Coon Tuning Rule

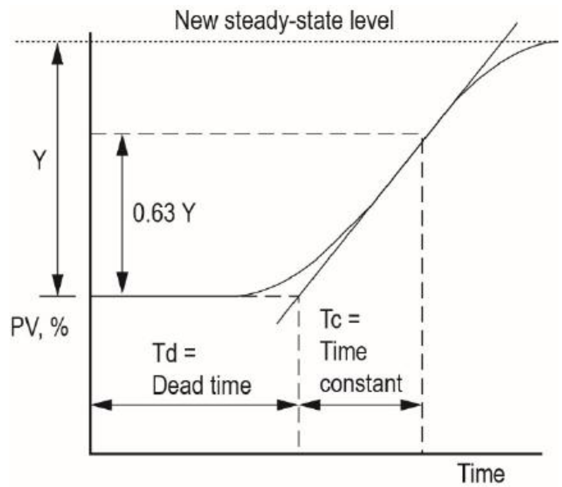
The Cohen-Coon tuning rule provides another method for estimating PID controller settings. This rule is applicable only for systems that are inherently self-regulating or those that will settle out at a new process variable in response to a step change in the output to the final control element. This change is made with the controller in manual or with an open-loop check.

Three parameters must be recorded to use the equations for the controller modes. These are:

Dead time – T_d or θ

Time constant – T_C or τ

Open-loop gain – k (% change in the process variable / % change in the output to the valve)



Process Response to Step Change and Response Factors

These values may then be used in the appropriate equations shown below to determine the starting point for the controller settings. Use the equations for the configuration of the specific controller and the modes to be employed.

Tuning Constants Formulas

$\frac{ke^{-\theta s}}{\tau s+1}$	K	T_i	T_d
P	$\frac{1}{k}\left(\frac{\tau}{\theta}+0.35\right)$		
PI	$\frac{0.9}{k}\left(\frac{\tau}{\theta}+0.92\right)$	$\frac{3.3\tau+0.3\theta}{\tau+2.2\theta}\theta$	
PD	$\frac{1.24}{k}\left(\frac{\tau}{\theta}+0.13\right)$		$\frac{0.27\tau-0.09\theta}{\tau+0.13\theta}\theta$
PID	$\frac{1.35}{k}\left(\frac{\tau}{\theta}+0.18\right)$	$\frac{2.5\tau+0.5\theta}{\tau+0.61\theta}\theta$	$\frac{0.37\tau}{\tau+0.19\theta}\theta$

3.1.8.2 Ziegler-Nichols Tuning

Tuning Parameters for the Ziegler-Nichols Closed-Loop Method

Controller Type	Gain, K_c	Integral Time, T_I	Derivative Time, T_D
Proportional (P)	0.5 K_u		
Proportional-Integral (PI)	0.45 K_u	$\frac{T_u}{1.2}$	
Proportional–Integral–Derivative (PID)	0.6 K_u	$\frac{T_u}{2}$	$\frac{T_u}{8}$

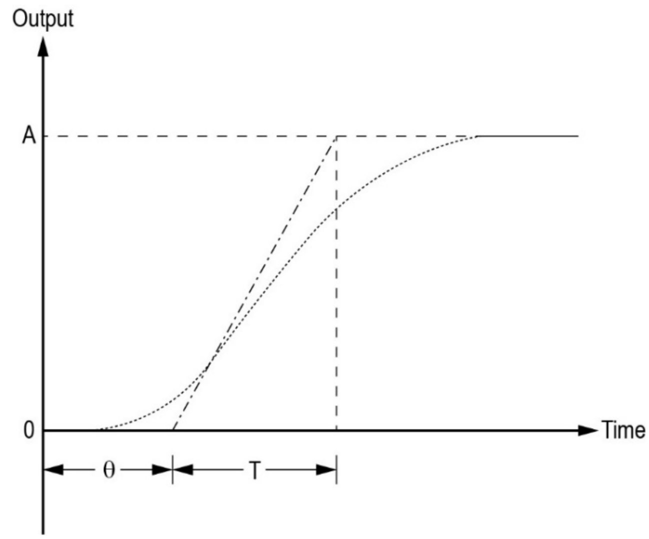
Variable	Description	Units
K_c, K_u	Gain	–
T_u	Time constant	min
T_I	Integral time	min/repeat
T_D	Derivative time	min
T_I = minutes per repeat $1/T_I$ = repeats per minute		

Tuning Parameters for the Ziegler-Nichols Open-Loop Method

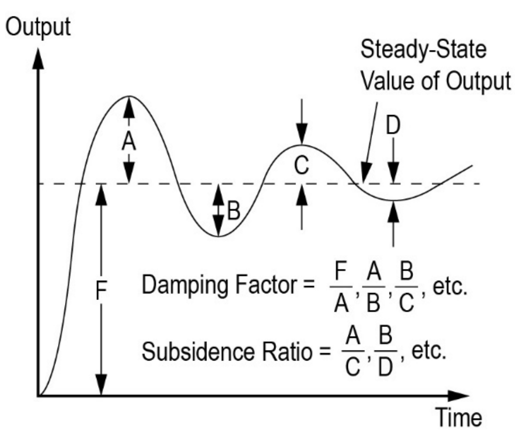
Controller Type	Gain, K_c	Integral Time, T_I	Derivative Time, T_D
Proportional (P)	$\frac{T}{K\theta}$		
Proportional-Integral (PI)	$\frac{0.9T}{K\theta}$	$\frac{\theta}{0.3}$	
Proportional–Integral–Derivative (PID)	$\frac{4T}{3K\theta}$	$\frac{\theta}{0.5}$	0.5θ

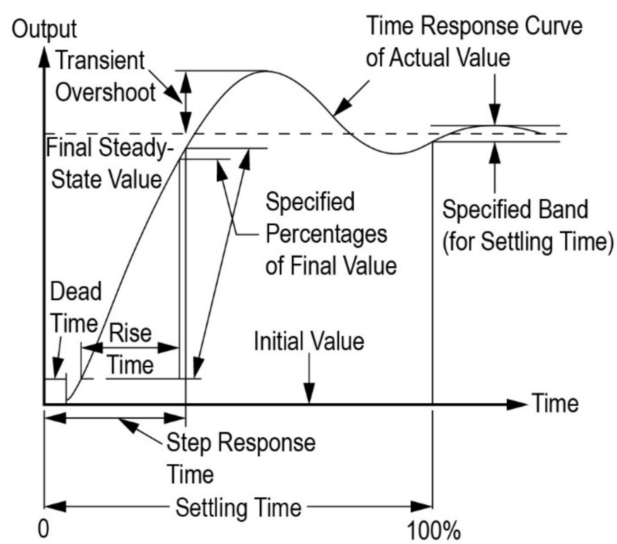
Tuning Parameters for the Ziegler-Nichols Open-Loop Method (continued)

Variable	Description	Units
K_c, K	Gain	–
A	Steady-state value	psi/°F
T	Time constant	min
θ	Dead time	min
T_I	Integral time	min/repeat
T_D	Derivative time	min
K = A/T T_I = minutes per repeat $1/T_I$ = repeats per minute		



3.1.9 Damping





Damping Equations

$A\%OS = 100e^{\frac{-\pi\xi}{\sqrt{1-\xi^2}}}$ $C\%OS = 100e^{\frac{-2\pi\xi}{\sqrt{1-\xi^2}}}$ $\varsigma = \sqrt{\frac{[\mathbf{1n}(\boldsymbol{OS})]^2}{\boldsymbol{\pi}^2+[\mathbf{1n}(\boldsymbol{OS})]^2}}$ H(s) = Zeros / Poles $\tau = T_{SR} - T_d$ $\tau = \frac{\sqrt{1-\xi^2}}{2\pi} P$ $P = \frac{2\pi\tau}{\sqrt{1-\xi^2}}$ $t_p = \frac{\pi}{\omega_n\sqrt{1-\xi^2}}$ $\omega_n = \frac{\pi}{t_p\sqrt{1-\xi^2}}$	(see table below)

Variable	Description	Units
τ	Time constant	s
A%OS	Percent overshoot	%
OS	Overshoot	psi
P	Period	s
T_d	Dead time	s
t_p	Time to peak	s
T_{SR}	Step response time	s
$\boldsymbol{\xi}$	Damping ratio	-
ω_n	Natural frequency of oscillation or undamped resonant frequency	

Find the Damping from the Function

$G(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}$ $G(s) = \frac{25}{s^2 + 5s + 25}$ ξ = damping ratio Damping: 0.5	$s^2 + 5s + 25$ $s^2 + 2\xi\omega_n s + \omega_n^2; \omega_n = \sqrt{25}$ $2\xi\omega_n s = 5s$ $\varsigma = \frac{5}{2\omega_n}; = \frac{5}{2\sqrt{25}} = \frac{5}{10} = 0.5$

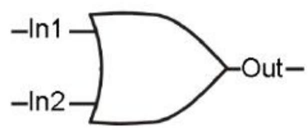
Find the Poles from the Function

$G(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}$ $G(s) = \frac{25}{s^2 + 5s + 25}$ Pole1: –2.5 + j 4.33 Pole2: –2.5 – j 4.33	$p_1; p_2 = \frac{-b \pm \sqrt{b^2 - 4ac}}{2}$ $p_1; p_2 = \frac{-5 \pm \sqrt{25 - 4(25)}}{2}$ $p_1; p_2 = \frac{-5 \pm \sqrt{\lvert 25 - 100\rvert}}{2} = -2.5 \pm j\ 4.33$

3.2 Discrete Control—Boolean Logic Operations

AND Gate

Input 1	Input 2	Output
0	0	0
0	1	0
1	0	0
1	1	1

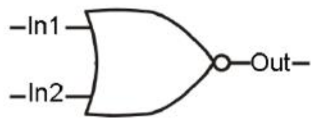


OR Gate

Input 1	Input 2	Output
0	0	0
0	1	1
1	0	1
1	1	1

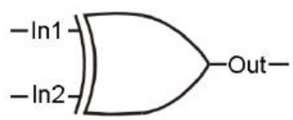
NAND Gate

Input 1	Input 2	Output
0	0	1
0	1	1
1	0	1
1	1	0



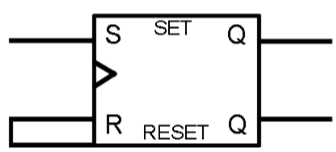
NOR Gate

Input 1	Input 2	Output
0	0	1
0	1	0
1	0	0
1	1	0



XOR Gate

Input 1	Input 2	Output
0	0	0
0	1	1
1	0	1
1	1	0



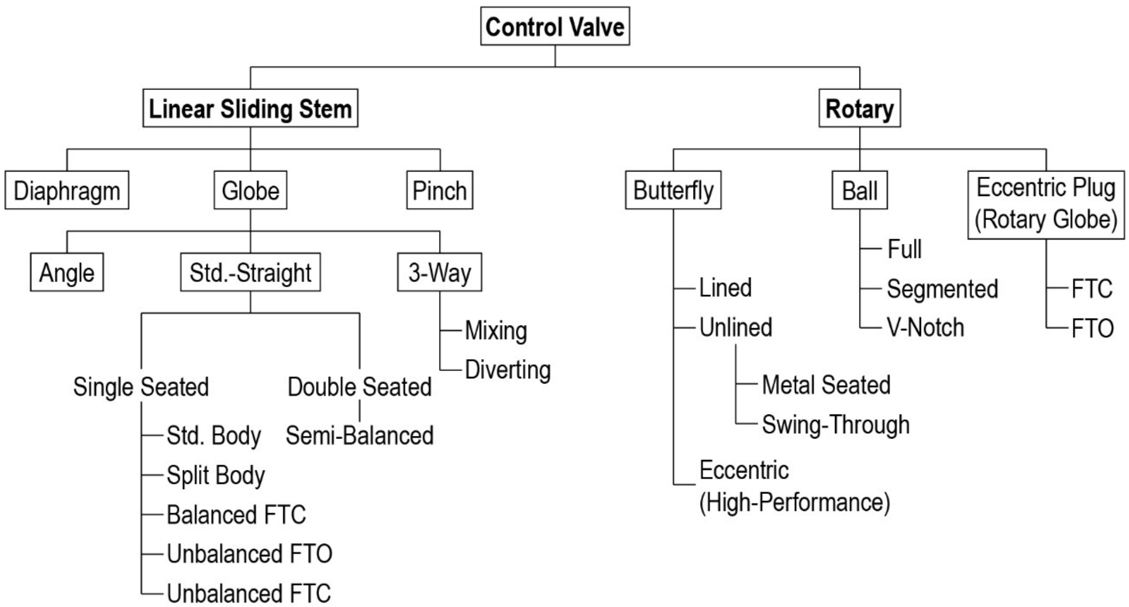
S-R Flip-Flop

Input 1	Input 2	Q	Qnot
0	0	Keep output state	Keep output state
0	1	0	1
1	0	1	0
1	1	Unstable condition	Unstable condition

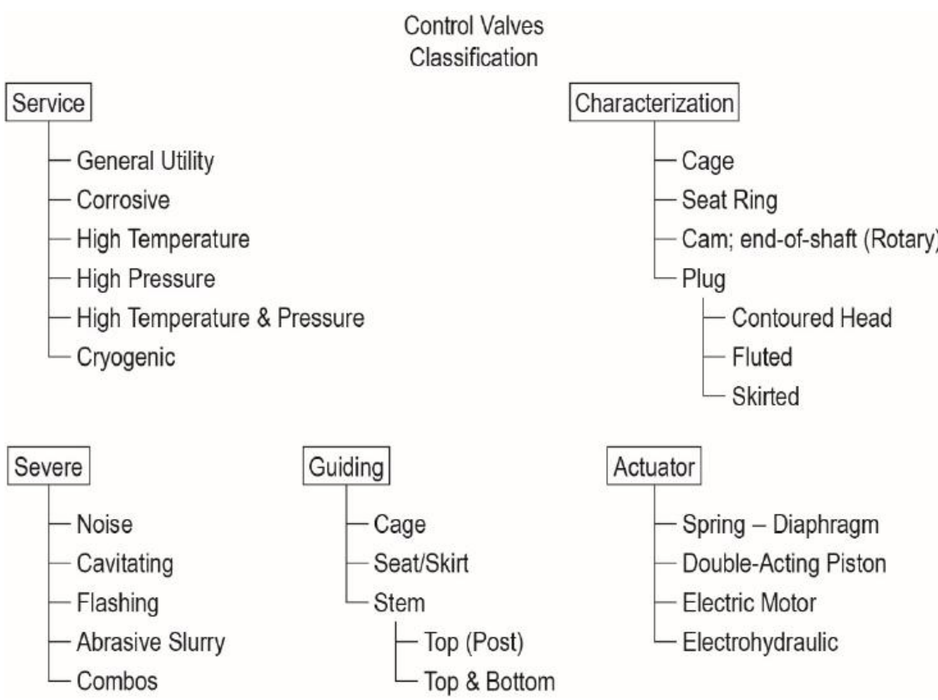
4 FINAL CONTROL ELEMENTS

4.1 Valves

4.1.1 Types

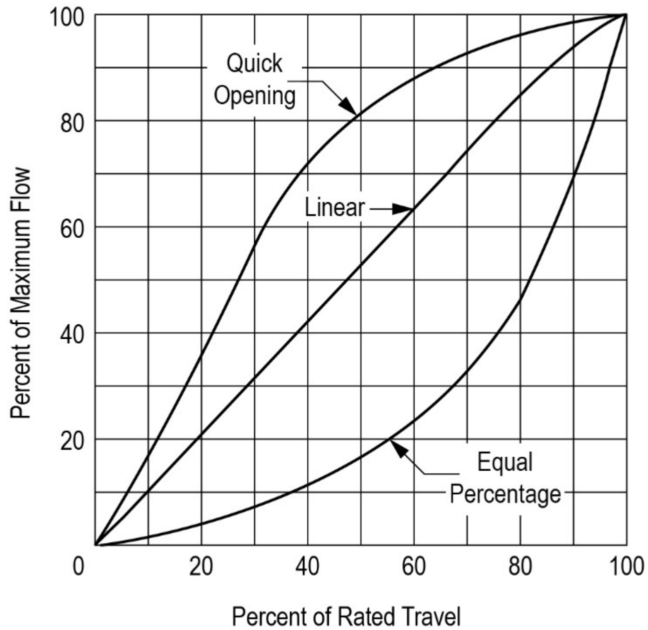


Control On-Off Valve Types



Control Valve Service, Guiding, Trim Characterization, and Actuators

4.1.2 Trim Characteristics



Valve Trim Characteristics Curve

4.1.3 Valve Packing Selection Tables

Packing Selection Guidelines for Sliding-Stem Valves

Packing System	Maximum Pressure and Temperature Limits for 100 PPM Service(1)		Application Guideline for Non-Environmental Service(1)	
	Metric	Imperial	Metric	Imperial
Single PTFE V-Ring	20.7 bar –18 to 93°C	300 psi 0 to 200°F	See Figure 5.15 –46 to 232°C	See Figure 5.15 –50 to 450°F
Double PTFE V-Ring	- - -	- - -	See Figure 5.15 –46 to 232°C	See Figure 5.15 –50 to 450°F
ENVIRO-SEAL PTFE	See Figure 5.14 –46 to 232°C	See Figure 5.14 –50 to 450°F	See Figure 5.15 –46 to 232°C	See Figure 5.15 –50 to 450°F
ENVIRO-SEAL Duplex	51.7 bar –46 to 232°C	750 psi –50 to 450°F	See Figure 5.15 –46 to 232°C	See Figure 5.15 –50 to 450°F
ENVIRO-SEAL H2 Duplex	138 bar –46 to 149°C	2000 psi –50 to 300°F	330 bar –46 to 149°C	4800 psi –50 to 300°F
KALREZ® with Vespel® CR-6100 (K-VSP 500)(3)	24.1 bar 4 to 260°C	350 psig 40 to 500°F	See Figure 5.15 –40 to 260°C	See Figure 5.15 –40 to 500°F
ENVIRO-SEAL Graphite ULF	103 bar –7 to 315°C	1500 psi 20 to 600°F	207 bar –198 to 371°C	3000 psi –325 to 700°F
HIGH-SEAL Graphite ULF	103 bar –7 to 315°C	1500 psi 20 to 600°F	290 bar(4) –198 to 538°C	4200 psi(4) –325 to 1000°F
Graphite Composite / HIGH-SEAL Graphite	- - -	- - -	290 bar(4) –198 to 649°C	4200 psi(4) –325 to 1200°F
Braided Graphite Filament	- - -	- - -	290 bar –198 to 538°C(5)	4200 psi –325 to 1000°F(5)
Graphite ULF	- - -	- - -	290 bar –198 to 538°C	4200 psi –325 to 1000°F

1. *The values shown are only guidelines. These guidelines can be exceeded, but shortened packing life or increased leakage might result. The temperature ratings apply to the actual packing temperature, not to the process temperature.*
2. *See Fisher Catalog 14 for actual friction values.*
3. *The KALREZ pressure/temperature limits referenced in this bulletin are for Fisher valve applications only. DuPont may claim higher limits.*
4. *Except for the 9.5 mm (3/8 inch) stem, 110 bar (1600 psi).*
5. *Except for oxidizing service, –198 to 371°C (–325 to 700°F).*

Packing Selection Guidelines for Sliding-Stem Valves (continued)

Packing System	Seal Performance Index	Service Life Index	Packing Friction[2]
Single PTFE V-Ring	Better	Long	Very low
Double PTFE V-Ring	Better	Long	Low
ENVIRO-SEAL PTFE	Best	Very long	Low
ENVIRO-SEAL Duplex	Best	Very long	Low
ENVIRO-SEAL H2 Duplex	Best	Very long	Medium
KALREZ with Vespel CR-6100 (K-VSP 500)[3]	Best	Long	Low
ENVIRO-SEAL Graphite ULF	Best	Very long	Medium
HIGH-SEAL Graphite ULF	Best	Very long	Medium
Graphite Composite / HIGH-SEAL Graphite	Better	Very long	Very high
Braided Graphite Filament	Good	Moderate	High
Graphite ULF	Better	Very long	Medium

1. *The values shown are only guidelines. These guidelines can be exceeded, but shortened packing life or increased leakage might result. The temperature ratings apply to the actual packing temperature, not to the process temperature.*
2. *See Fisher Catalog 14 for actual friction values.*
3. *The KALREZ pressure/temperature limits referenced in this bulletin are for Fisher valve applications only. DuPont may claim higher limits.*
4. *Except for the 9.5 mm (3/8 inch) stem, 110 bar (1600 psi).*
5. *Except for oxidizing service, –198 to 371°C (–325 to 700°F).*

Source: *The Fisher Control Valve Handbook,* 5 ed. Reproduced with permission from Emerson Automation Solutions.

Packing Selection Guidelines for Rotary Valves

Packing System	Maximum Pressure and Temperature Limits for 100 PPM Service[1]		Application Guideline for Non-Environmental Service[1]	
	Metric	Customary U.S.	Metric	Customary U.S.
Single PTFE V-Ring	- - - - - -	- - - - - -	103 bar –46 to 232°C	1500 psig –50 to 450°F
ENVIRO-SEAL PTFE	103 bar –46 to 232°C	1500 psig –50 to 450°F	207 bar –46 to 232°C	3000 psig –50 to 450°F
Live-Loaded PTFE for V250 Valves	69 bar –29 to 93°C	1000 psig –20 to 200°F	155 bar –46 to 232°C	2250 psig –50 to 450°F
KALREZ with Vespel CR-6100 (K-VSP 500)[3]	24.1 bar 4 to 260°C	350 psig 40 to 500°F	51 bar –40 to 260°C	750 psig –40 to 500°F
ENVIRO-SEAL Graphite	103 bar –7 to 315°C	1500 psig 20 to 600°F	207 bar –198 to 371°C	3000 psig –325 to 700°F
Graphite Ribbon	- - - - - -	- - - - - -	103 bar –198 to 538°C[2]	1500 psig –325 to 1000°F[2]

1. *The values shown are only guidelines. These guidelines can be exceeded, but shortened packing life or increased leakage might result. The temperature ratings apply to the actual packing temperature, not to the process temperature.*
2. *Except for oxidizing service, –198 to 371°C (–325 to 700°F).*
3. *The KALREZ pressure/temperature limits referenced in this bulletin are for Fisher valve applications only. DuPont may claim higher limits.*

Packing Selection Guidelines for Rotary Valves (continued)

Packing System	Seal Performance Index	Service Life Index	Packing Friction
Single PTFE V-Ring	Better	Long	Very low
ENVIRO-SEAL PTFE	Excellent	Very long	Low
Live-Loaded PTFE for V250 Valves	Excellent	Very long	Low
KALREZ with Vespel CR-6100 (K-VSP 500)(3)	Excellent	Long	Very low
ENVIRO-SEAL Graphite	Excellent	Very long	Moderate
Graphite Ribbon	Acceptable	Acceptable	High

1. *The values shown are only guidelines. These guidelines can be exceeded, but shortened packing life or increased leakage might result. The temperature ratings apply to the actual packing temperature, not to the process temperature.*
2. *Except for oxidizing service, –198 to 371°C (–325 to 700°F).*
3. *The KALREZ pressure/temperature limits referenced in this bulletin are for Fisher valve applications only. DuPont may claim higher limits.*

Source: *The Fisher Control Valve Handbook,* 5 ed. Reproduced with permission from Emerson Automation Solutions.

4.1.4 Leakage Class

Maximum Valve Seat Leakage Allowance for Class VI (according to ANSI/FCI 70-21)

Nominal Port Diameter		Bubbles per Minute*	
in	**mm**	**mL per minute**	**Bubbles per minute**
1	25	0.15	1
1-1/2	38	0.30	2
2	51	0.45	3
2-1/2	64	0.60	4
3	76	0.90	6
4	102	1.70	11
6	152	4.00	27
8	203	6.75	45

*Bubbles per minute specified in this table are a suggested alternative based on a properly calibrated measuring device, in this case a 1/4 inch (6.3 mm) O.D. × 0.032 inch (0.8 mm) wall tube submerged in water to a depth of 1/8 to 1/4 inch (3 to 6 mm). The tube end must be cut square and must be smooth with no chamfers or burrs, and the tube axis must be perpendicular to the surface of the water. Other measuring devices may be utilized and the number of bubbles per minute may differ from those listed as long as they correctly indicate the flow in mL per minute.

4.1.5 Control Valve Sizing

4.1.5.1 Liquid Control Valve Sizing

Volumetric Flow

$$C_v = \frac{q}{N_1\sqrt{\frac{\Delta P}{G}}}$$

where

C_v = valve flow coefficient

G = fluid specific gravity

q = volumetric flow

N_1 = use Valve Sizing Equation Constants Table on p. 83

Mass Flow

$$C_v = \frac{w}{N_6\sqrt{\Delta P \rho}}$$

where

C_v = valve flow coefficient

ρ = fluid density

w = mass flow rate

N_6 = use Valve Sizing Equation Constants Table on p. 83

Check for critical flow conditions. Use $\Delta P_{allowable}$ as your differential pressure sizing when it is less than the calculated ΔP:

$$\Delta P_{allowable} = F_L^2(P_{1-F_F P_V})$$

where

F_L = pressure recovery coefficient

P_1 = inlet pressure

P_V = vapor pressure

F_F = liquid critical pressure ratio factor

$$F_F = 0.96 - 0.28\sqrt{\frac{P_V}{P_C}}$$

where

P_C = critical pressure

4.1.5.2 Gas Sizing – Volumetric Flow

When gas specific gravity is known:

$$C_v = \frac{q}{N_7 P_1 Y \sqrt{\frac{x}{G T_1 Z}}}$$

When molecular weight is known:

$$C_v = \frac{q}{N_9 P_1 Y \sqrt{\frac{x}{M T_1 Z}}}$$

where

q = volumetric flow rate

P_1 = inlet pressure

T_1 = inlet temperature

G = gas specific gravity

M = molecular weight

Z = compressibility factor

N_7 = use Valve Sizing Equation Constants Table on p. 83

N_9 = use Valve Sizing Equation Constants Table on p. 83

x = pressure drop ratio

x_r = rated pressure drop ratio factor (dimensionless)

Y = expansion factor

$$x = \frac{\Delta P}{P_1}$$

With expansion factor Y

$$Y = 1 - \frac{x}{3 \frac{k}{1.4} x_T}$$

where

k = specific heat ratio = $\frac{C_p}{C_v}$

C_p = specific heat of gas at constant pressure

C_v = specific heat of gas at constant volume

4.1.5.3 Gas Sizing—Mass Flow

When gas density is known:

$$C_v = \frac{w}{N_6 Y \sqrt{x P_1 \rho_1}}$$

When molecular weight is known:

$$C_v = \frac{w}{N_8 P_1 Y \sqrt{\frac{xM}{T_1 Z}}}$$

where

w = mass flow rate

P_1 = inlet pressure

T_1 = inlet temperature

ρ_1 = inlet density

M = molecular weight

Z = compressibility factor

N_6 = use Valve Sizing Equation Constants Table on p. 83

N_8 = use Valve Sizing Equation Constants Table on p. 83

x = pressure drop ratio

Y = expansion factor

$$x = \frac{\Delta P}{P_1}$$

Check for choked flow conditions. Use x_{choked} when sizing if it is less than the calculated value for x:

$$x_{choked} = \frac{k}{1.4} x_T$$

With expansion factor Y:

$$Y = 1 - \frac{x}{3 \frac{k}{1.4} x_T}$$

where

k = specific heat ratio = $\frac{C_p}{C_v}$

C_p = specific heat of gas at constant pressure

C_v = specific heat of gas at constant volume

Valve Sizing Equation Constants[1]

Constant	Conditions	N	w	q	P[2]	γ	T	d, D
N_1		0.0865	---	m^3/h	kPa	---	---	---
		0.865	---	m^3/h	bar	---	---	---
		1.00	---	gpm	psia	---	---	---
N_2		0.00214	---	---	---	---	---	mm
		890	---	---	---	---	---	inch
N_5		0.00241	---	---	---	---	---	mm
		1000	---	---	---	---	---	inch
N_6		2.73	kg/h	---	kPa	kg/m^3	---	---
		27.3	kg/h	---	bar	kg/m^3	---	---
		63.3	lb/h	---	psia	lb/ft^3	---	---
N_7[3]	Normal Conditions $T_N = 0°C$	3.94	---	m^3/h	kPa	---	deg K	---
		394	---	m^3/h	bar	---	deg K	---
	Standard Conditions $T_s = 15.5°C$	4.17	---	m^3/h	kPa	---	deg K	---
		417	---	m^3/h	bar	---	deg K	---
	Standard Conditions $T_s = 60°F$	1360	---	scfh	psia	---	deg R	---
N_8		0.948	kg/h	---	kPa	---	deg K	---
		94.8	kg/h	---	bar	---	deg K	---
		19.3	lb/h	---	psia	---	deg R	---
N_9[3]	Normal Conditions $T_N = 0°C$	21.2	---	m^3/h	kPa	---	deg K	---
		2120	---	m^3/h	bar	---	deg K	---
	Standard Conditions $T_s = 15.5°C$	22.4	---	m^3/h	kPa	---	deg K	---
		2240	---	m^3/h	bar	---	deg K	---
	Standard Conditions $T_s = 60°F$	7320	---	scfh	psia	---	deg R	---

1. Many of the equations used in the sizing procedures in Section 4.1.5 of this document contain a numerical constant, N, with a numerical subscript. The numerical constants provide a means of using different units in the equations. Values for the constants and the corresponding applicable units are provided here. For example, if the flow rate is given in U.S. gpm and the pressure is in psia, the value of N_1 is 1.00. If the flow rate is in m^3/hr and the pressure is in kPa, the value of N_1 is 0.0865.
2. All pressure values shown are absolute.
3. The pressure base is 1013 kpa (1.013 bar or 14.7 psia).

4.2 Material Selection

4.2.1 Chemical Compatibility for Metals

The following tables are intended to give only a general indication of how various metals will react when in contact with certain process fluids. Recommendations cannot be absolute as concentration, temperature, pressure, and other conditions may affect suitability of a particular metal. Use this table as a guide only.

Ambient Temperature Corrosion Information

LEGEND: A = Normally suitable, B = Minor to moderate effect, C = Unsatisfactory

FLUID \ METAL	Aluminum	Brass	Cast Iron & Steel	416 & 440C	17-4 SST	304 SST	316 SST	Duplex SST	254 SMO	Alloy 20	Alloy 400	Alloy C276	Alloy B2	Alloy 6	Titanium	Zirconium
Acetaldehyde	A	A	C	A	A	A	A	A	A	A	A	A	A	A	A	A
Acetic Acid, Air Free	C	C	C	C	C	C	A	A	A	A	A	A	A	A	A	A
Acetic Acid, Aerated	C	C	C	C	B	B	A	A	A	A	C	A	A	A	A	A
Acetone	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Acetylene	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Alcohols	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Aluminum Sulfate	C	C	C	C	B	A	A	A	A	A	B	A	A	A	A	A
Ammonia	A	C	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Ammonium Chloride	C	C	C	C	C	C	B	A	A	A	B	A	A	B	A	A
Ammonium Hydroxide	A	C	A	A	A	A	A	A	A	A	C	A	A	A	A	B
Ammonium Nitrate	B	C	B	B	A	A	A	A	A	A	C	A	A	A	C	A
Ammonium Phosphate (Mono-Basic)	B	B	C	B	B	A	A	A	A	A	B	A	A	A	A	A
Ammonium Sulfate	C	C	C	C	B	B	A	A	A	A	A	A	A	A	A	A
Ammonium Sulfite	C	C	C	C	A	A	A	A	A	A	C	A	A	A	A	A
Aniline	C	C	C	C	A	A	A	A	A	A	B	A	A	A	A	A
Asphalt	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Beer	A	A	B	B	A	A	A	A	A	A	A	A	A	A	A	A
Benzene (Benzol)	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Benzoic Acid	A	A	C	C	A	A	A	A	A	A	A	A	A	A	A	A
Boric Acid	C	B	C	C	A	A	A	A	A	A	B	A	A	A	A	A
Bromine, Dry	C	C	C	C	B	B	B	A	A	A	A	A	A	A	C	C
Bromine, Wet	C	C	C	C	C	C	C	C	C	C	A	A	A	C	C	C
Butane	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Calcium Chloride	C	C	B	C	C	B	B	A	A	A	A	A	A	A	A	A
Calcium Hypochlorite	C	C	C	C	C	C	C	A	A	A	C	A	B	B	A	A
Carbon Dioxide, Dry	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Carbon Dioxide, Wet	A	B	C	C	A	A	A	A	A	A	A	A	A	A	A	A
Carbon Disulfide	C	C	A	B	B	A	A	A	A	A	B	A	A	A	A	A
Carbonic Acid	A	B	C	C	A	A	A	A	A	A	A	A	A	A	A	A
Carbon Tetrachloride	A	A	B	B	A	A	A	A	A	A	A	A	A	A	A	A
Caustic Potash (see Potassium Hydroxide)																
Caustic Soda (see Sodium Hydroxide)																
Chlorine, Dry	C	C	A	C	B	B	B	A	A	A	A	A	A	A	C	A
Chlorine, Wet	C	C	C	C	C	C	C	C	C	C	B	B	B	C	A	A
Chromic Acid	C	C	C	C	C	C	C	B	A	C	C	A	B	C	A	A
Citric Acid	B	C	C	C	B	B	A	A	A	A	A	A	A	A	A	A
Coke Oven Acid	C	B	A	A	A	A	A	A	A	A	B	A	A	A	A	A
Copper Sulfate	C	C	C	C	C	C	B	A	A	A	C	A	A	C	A	A
Cottonseed Oil	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Creosote	C	C	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Dowtherm	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A

Ambient Temperature Corrosion Information (continued)

LEGEND: A = Normally suitable, B = Minor to moderate effect, C = Unsatisfactory

FLUID \ METAL	Aluminum	Brass	Cast Iron & Steel	416 & 440C	17-4 SST	304 SST	316 SST	Duplex SST	254 SMO	Alloy 20	Alloy 400	Alloy C276	Alloy B2	Alloy 6	Titanium	Zirconium
Ethane	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Ether	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A
Ethyl Chloride	C	B	C	C	B	B	B	A	A	A	A	A	A	A	A	A
Ethylene	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Ethylene Glycol	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Ferric Chloride	C	C	C	C	C	C	C	C	B	C	C	A	C	C	A	A
Fluorine, Dry	B	B	A	C	B	B	B	A	A	A	A	A	A	A	C	C
Fluorine, Wet	C	C	C	C	C	C	C	C	C	C	B	B	B	C	C	C
Formaldehyde	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A
Formic Acid	B	C	C	C	C	C	B	A	A	A	C	A	B	B	C	A
Freon, Wet	C	C	B	C	B	B	A	A	A	A	A	A	A	A	A	A
Freon, Dry	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A
Furfural	A	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A
Gasoline, Refined	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Glucose	A	A	A	A	A	A	A	C	A	A	A	A	A	A	A	A
Hydrochloric Acid (Aerated)	C	C	C	C	C	C	C	C	C	C	C	B	A	C	C	A
Hydrochloric Acid (Air Free)	C	C	C	C	C	C	C	C	C	C	C	B	A	C	C	A
Hydrofluoric Acid (Aerated)	C	C	C	C	C	C	C	C	C	C	B	B	B	C	C	C
Hydrofluoric Acid (Air Free)	C	C	C	C	C	C	C	C	C	C	A	B	B	C	C	C
Hydrogen	A	A	A	C	B	A	A	A	A	A	A	A	A	A	C	A
Hydrogen Peroxide	A	C	C	C	B	A	A	A	A	A	C	A	C	A	A	A
Hydrogen Sulfide	C	C	C	C	C	A	A	A	A	A	A	A	A	A	A	A
Iodine	C	C	C	C	A	A	A	A	A	A	C	A	A	A	C	B
Magnesium Hydroxide	B	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Mercury	C	C	A	A	A	A	A	A	A	A	B	A	A	A	C	A
Methanol	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Methyl Ethyl Ketone	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Milk	A	A	C	A	A	A	A	A	A	A	A	A	A	A	A	A
Natural Gas	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Nitric Acid	C	C	C	C	A	A	A	A	A	A	C	B	C	C	A	A
Oleic Acid	C	C	C	B	B	B	A	A	A	A	A	A	A	A	A	A
Oxalic Acid	C	C	C	C	B	B	B	A	A	A	B	A	A	B	C	A
Oxygen	C	A	C	C	B	B	B	B	B	B	A	B	B	B	C	C
Petroleum Oils, Refined	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Phosphoric Acid (Aerated)	C	C	C	C	B	A	A	A	A	A	C	A	A	A	C	A
Phosphoric Acid (Air Free)	C	C	C	C	B	B	B	A	A	A	B	A	A	B	C	A
Picric Acid	C	C	C	C	B	B	A	A	A	A	C	A	A	A	A	A
Potash/Potassium Carbonate	C	C	B	B	A	A	A	A	A	A	A	A	A	A	A	A
Potassium Chloride	C	C	B	C	C	B	B	A	A	A	A	A	A	A	A	A
Potassium Hydroxide	C	C	B	B	A	A	A	A	A	A	A	A	A	A	A	A
Propane	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A

Ambient Temperature Corrosion Information (continued)

LEGEND: A = Normally suitable, B = Minor to moderate effect, C = Unsatisfactory

FLUID \ METAL	Aluminum	Brass	Cast Iron & Steel	416 & 440C	17-4 SST	304 SST	316 SST	Duplex SST	254 SMO	Alloy 20	Alloy 400	Alloy C276	Alloy B2	Alloy 6	Titanium	Zirconium
Rosin	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A
Silver Nitrate	C	C	C	C	B	A	A	A	A	A	C	A	A	A	A	A
Soda Ash (see Sodium Carbonate)																
Sodium Acetate	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Sodium Carbonate	C	C	A	B	A	A	A	A	A	A	A	A	A	A	A	A
Sodium Chloride	C	A	C	C	B	B	B	A	A	A	A	A	A	A	A	A
Sodium Chromate	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Sodium Hydroxide	C	C	A	B	B	B	A	A	A	A	A	A	A	A	A	A
Sodium Hypochlorite	C	C	C	C	C	C	C	C	C	C	C	A	B	C	A	A
Sodium Thiosulfate	C	C	C	C	B	B	A	A	A	A	A	A	A	A	A	A
Stannous Chloride	C	C	C	C	C	C	B	A	A	A	C	A	A	B	A	A
Steam	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Stearic Acid	C	B	B	B	B	A	A	A	A	A	A	A	A	B	A	A
Sulfate Liquor (Black)	C	C	A	C	C	B	A	A	A	A	A	A	A	A	A	A
Sulfur	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Sulfur Dioxide, Dry	C	C	C	C	C	C	B	A	A	A	C	A	A	B	A	A
Sulfur Trioxide, Dry	C	C	C	C	C	C	B	A	A	A	B	A	A	B	A	A
Sulfuric Acid (Aerated)	C	C	C	C	C	C	C	A	A	A	C	A	C	B	C	A
Sulfuric Acid (Air Free)	C	C	C	C	C	C	C	A	A	A	B	A	A	B	C	A
Sulfurous Acid	C	C	C	C	C	B	B	A	A	A	C	A	A	B	A	A
Tar	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Trichloroethylene	B	B	B	B	B	B	A	A	A	A	A	A	A	A	A	A
Turpentine	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A
Vinegar	B	B	C	C	A	A	A	A	A	A	A	A	A	A	A	A
Water, Boiler Feed, Amine Treated	A	A	A	A	A	A	A	A	A	A	A	A	A	C	A	A
Water, Distilled	A	A	C	C	A	A	A	A	A	A	A	A	A	A	A	A
Water, Sea	C	A	C	C	C	C	B	A	A	A	A	A	A	A	A	A
Whisky and Wines	A	A	C	C	A	A	A	A	A	A	A	A	A	A	A	A
Zinc Chloride	C	C	C	C	C	C	C	B	B	B	A	A	A	B	A	A
Zinc Sulfate	C	C	C	C	A	A	A	A	A	A	A	A	A	A	A	A

4.2.2 Chemical Compatibility for Elastomers

The following table rates and compares the compatibility of elastomer materials with specific fluids. Chemical compatibility tends to decrease with increases in service temperature so a material may not be suitable over the entire range of its capability. Full details of pressure, temperature, chemical considerations, and mode of operation must be considered in selection. These recommendations are to be used as a general guide only.

Elastomer Ratings for Compatibility with Fluids

LEGEND: A+ = Best Possible Selection, A = Generally Compatible, B = Marginally Compatible, C = Not Recommended, — = NO DATA

FLUID \ ELASTOMER	ACM, ANM Poly-acrylic	AU, EU Poly-urethane	CO, ECO Epichlorohydrin	CR Chloroprene Neoprene[1]	EPM, EPDM Ethylene Propylene	FKM Fluoro-elastomer Viton[1]	FFKM Perfluoro-elastomer	IIR Butyl	VMQ Silicone	NBR Nitrile BUNA N	NR Natural Rubber	TFE/P Terafluoroethyelene-propylene copolymer
Acetic Acid (30%)	C	C	C	C	A+	C	A+	A	A	B	B	C
Acetone	C	C	C	C	A	C	A	A	C	C	C	C
Air, Ambient	A	A	—	A	A	A	A	A	A	A	B	A
Air, Hot (200°F, 93°C)	B	B	—	C	A	A	A	C	A	A	B	A
Air, Hot (400°F, 204°C)	C	C	—	C	C	A	A	C	A	C	C	A
Alcohol, Ethyl	C	C	—	A	A	C	A	A	A	A	A	A
Alcohol, Methyl	C	C	B	A+	A	C	A	A	A	A	A	A
Ammonia, Anhydrous, Liquid	C	C	—	A+	A	C	A	A	B	B	C	A
Ammonia, Gas (Hot)	C	C	—	B	B	C	A	B	A	C	C	A+
Beer (Beverage)	C	C	A	A	A	A	A	A	A	A	A	A
Benzene	C	C	C	C	C	A	A	C	C	C	C	C
Black Liquor	C	C	—	B	B	A+	A	C	C	B	B	A
Blast Furnace Gas	C	C	—	C	C	A+	A	C	A	C	C	A
Brine (Calcium Chloride)	A	A	A	A	A	A	A	A	A	A	A	A
Butadiene Gas	C	C	C	C	C	A+	A	C	C	C	C	—
Butane Gas	A	C	A	A	C	A	A	C	C	A+	C	B
Butane, Liquid	A	C	A	B	C	A	A	C	C	A	C	C
Carbon Tetrachloride	C	C	B	C	C	A+	A	C	C	C	C	C
Chlorine, Dry	C	C	B	C	C	A+	A	C	C	C	C	C
Chlorine, Wet	C	C	B	C	C	A+	A	C	C	C	C	B
Coke Oven Gas	C	C	—	C	C	A+	A	C	B	C	C	A
Dowtherm A[2]	C	C	C	C	C	A+	A	C	C	C	C	B
Ethyl Acetate	C	C	C	C	B	C	A	B	B	C	C	C
Ethylene Glycol	C	B	A	A	A+	A	A	A	A	A	A	A
Freon 11[1]	A	C	—	C	C	B+	B	C	C	B	C	C
Freon 12[1]	B	A	A	A+	B	B	B	B	C	A	B	C
Freon 22[1]	B	C	A	A+	A	C	A	A	C	C	A	C
Freon 114[1]	—	A	A	A	A	A	B	A	C	A	A	C
Freon Replacements[1] (See Suva)[1]												
Gasoline	C	B	A	C	C	A	A	C	C	A+	C	C
Hydrogen Gas	B	A	—	A	A	A	A	A	C	A	B	A
Hydrogen Sulfide (Dry)	C	B	B	A	A+	C	A	A	C	A	A	A
Hydrogen Sulfide (Wet)	C	C	B	A	A+	C	A	A	C	C	C	A
Jet Fuel (JP–4)	B	B	A	C	C	A	A	C	C	A	C	B
Methylene Chloride	C	C	—	C	C	B+	A+	C	C	C	C	B
Milk	C	C	—	A	A	A	A	A	A	A+	A	A
Naphthalene	—	B	—	C	C	A+	A	C	C	C	C	B
Natural Gas	B	B	A	A	C	A	A	C	C	A+	B	A
Natural Gas + H2S (Sour Gas)	C	B	A	A+	C	C	A	C	C	B	C	A
Natural Gas, Sour + Ammonia	C	C	—	B+	C	C	A	C	C	B	C	A+
Nitric Acid (10%)	C	C	C	C	B	A+	A	A	C	C	C	A
Nitric Acid (50–100%)	C	C	C	C	C	A+	A	A	C	C	C	B
Nitric Acid Vapor	C	C	C	B	B	A	A	B	C	C	C	A
Nitrogen	A	A	A	A	A	A	A	A	A	A	A	A
Oil (Fuel)	B	C	A	B	C	A	A	C	C	A+	C	A
Ozone	B	A	A	B	A	A	A	B	A	C	C	A
Paper Stock	—	C	—	B	B	A	A	B	C	B	C	—
Propane	A	B	A	A	C	A	A	C	C	A+	C	A
Sea Water	C	B	—	B	A	A	A	A	A	A	B	A
Sea Water + Sulfuric Acid	C	B	—	B	B	A	A	B	C	C	C	A
Soap Solutions	C	C	A	A	A	A	A	A	A	A	B	A

Elastomer Ratings for Compatibility with Fluids (continued)

LEGEND: A+ = Best Possible Selection, A = Generally Compatible, B = Marginally Compatible, C = Not Recommended, — = NO DATA

FLUID \ ELASTOMER	ACM, ANM Poly-acrylic	AU, EU Poly-urethane	CO, ECO Epichlorohydrin	CR Chloroprene Neoprene[1]	EPM, EPDM Ethylene Propylene	FKM Fluoro-elastomer Viton[1]	FFKM Perfluoro-elastomer	IIR Butyl	VMQ Silicone	NBR Nitrile BUNA N	NR Natural Rubber	TFE/P Terafluoroethylene-propylene copolymer
Steam	C	C	C	C	B+	C	A	B	C	C	C	A+
Sulfur Dioxide (Dry)	C	—	—	C	A+	—	—	B	B	C	B	—
Sulfur Dioxide (Wet)	C	B	—	B	A+	C	A	A	B	C	C	B
Sulfuric Acid (to 50%)	B	C	B	C	B	A+	A	C	C	C	C	A
Sulfuric Acid (50–100%)	C	C	C	C	C	A+	A	C	C	C	C	A
Suva HCFC-123[1]	—	C	—	A+	A+	B	—	A+	B	C	C	—
Suva HFC134a[1]	—	—	—	B	A	C	—	B	B	A+	B	—
Water (Ambient)	C	C	B	A	A	A	A	A	A	A	A	A
Water (200°F, 93°C)	C	C	B	C	A+	B	A	B	A	C	A	—
Water (300°F, 149°C)	C	C	—	C	B+	C	A	B	C	C	C	—
Water (De-ionized)	C	A	—	A	A	A	A	A	A	A	A	A
Water, White	C	B	—	B	A	A	A	A	B	B	B	—

[1]Registered trademark of DuPont Performance Elastomers
[2]Trademark of Dow Chemical Co.

4.3 Pressure Relieving Devices

4.3.1 Orifice Sizing Calculations for Pressure Relieving Valves

4.3.1.1 Conventional Relief Valve—Orifice Calculations for Vapors or Gases

$$A = \frac{W}{CK_cK_dP}\sqrt{\frac{T}{M}}$$

$$A = \frac{V\sqrt{GT}}{1.175\ CK_cK_dP}$$

Steam

$$A = \frac{W}{51.5\ K_cK_dK_nP}$$

Liquids

$$A = \frac{Q}{38\ K_cK_d}\sqrt{\frac{G}{\Delta P}}$$

4.3.1.2 Bellows Relief Valve—Orifice Calculations for Vapors or Gases

$$A = \frac{W}{CK_bK_cK_dP}\sqrt{\frac{T}{M}}$$

$$A = \frac{V\sqrt{GT}}{1.175\ CK_bK_cK_dP}$$

Steam

$$A = \frac{W}{51.5\ K_bK_cK_dK_nP}$$

Liquids

$$A = \frac{Q}{38\ K_cK_dK_w}\sqrt{\frac{G}{\Delta P}}$$

where

A = required orifice area (in.^{2})

W = required flow capacity (lb/hr)

V = required flow capacity (scfm)

Q = required flow capacity (gpm)

G = specific gravity

M	=	molecular weight
P	=	set pressure in pounds per square inch absolute + overpressure; minimum overpressure is 3 psi
ΔP	=	set pressure + overpressure-inlet loss-backpressure (psig)
T	=	inlet temperature absolute
C	=	gas or vapor flow constant based on the ratio of specific heats (K)
K	=	ratio of specific heats, Cp/Cv. If this ratio is unknown, the value k = 1.0, C = 315 will result in a safe valve size.
K_b	=	vapor or gas flow factor for variable back pressures
K_c	=	combination correction factor for installation with a rupture disk upstream of relief valve: 1.0 if a rupture disk is not installed; 0.9 when a rupture disk is installed in combination with a relief valve and the combination does not have a certified value
K_d	=	coefficient of discharge: air, steam, vapor, and gas = 0.858; liquid = 0.652
K_n	=	Napier steam correction factor: 1.0 if P < 1500 psia
K_w	=	Liquid flow factor for variable and constant backpressures

4.3.2 Advantages and Limitations of Valve Types

Weighted-Pallet Type	
Advantages	**Limitations**
Low initial cost Very low set pressures available Simple	Set pressure not readily adjustable Long simmer and poor tightness High overpressure required for full lift Cryogenic fluids can freeze seat close Set pressure limited to 1 or 2 psi (69 mbar or 138 mbar)
Conventional Metal-Seated Type	
Advantages	**Limitations**
Low initial cost Wide chemical compatibility High-temperature compatibility Standardized flanged center-to-face dimensions Accepted for ASME Sections I and VIII	Seat leakage Simmer and blowdown adjustment interactive Vulnerable to inlet pressure losses Opening pressure changes with superimposed back pressure In-situ testing can be inaccurate Built-up back pressure limitations
Balanced Bellows Metal-Seated Type	
Advantages	**Limitations**
Wide chemical compatibility High-temperature compatibility Standardized flanged center-to-face dimensions Protected guiding surfaces and spring No change in opening pressure at any superimposed back pressure Withstand higher built-up back pressures	Seat leakage Simmer and blowdown adjustment interactive Vulnerable to inlet pressure losses In-situ testing can be inaccurate Bellows can limit amount of superimposed back pressure High initial cost High maintenance costs
Conventional Soft-Seated Type	
Advantages	**Limitations**
Low initial cost Standardized flanged center-to-face dimensions Good seat tightness before relieving and after reseating Low maintenance costs	Simmer and blowdown adjustment interactive Vulnerable to inlet pressure losses Opening pressure changes with superimposed back pressure Built-up back pressure limitations High process fluid temperatures Chemical compatibility
Balanced Bellows Soft-Seated Type	
Advantages	**Limitations**
Standardized flanged center-to-face dimensions Protected guiding surfaces and spring No change in opening pressure at any superimposed back pressure Withstand higher built-up back pressures Good seat tightness before relieving and after reseating	Simmer and blowdown adjustment interactive Vulnerable to inlet pressure losses Bellows can limit amount of superimposed back pressure High initial cost High maintenance costs High process fluid temperatures Chemical compatibility
Balanced Piston Soft-Seated Type	
Advantages	**Limitations**
No change in opening pressure at any superimposed back pressure Withstand higher built-up back pressures Good seat tightness before relieving and after reseating Low initial cost Low maintenance cost	Simmer and blowdown adjustment interactive Vulnerable to inlet pressure losses High process fluid temperatures Chemical compatibility

Pilot-Operated Soft-Seated Type	
Advantages	**Limitations**
Standardized flanged center-to-face dimensions No change in opening pressure at any superimposed back pressure Withstand higher built-up back pressures Good seat tightness before relieving and after reseating Higher set pressures available Maximum capacity per inlet valve connection Smaller and lighter valves in higher pressure classes and sizes In-line maintenance of main valve Pop or modulating action Remote pressure sensing Accurate in-situ testing Full lift at zero overpressure available Operational pressure can be within 98% of set pressure	High initial cost High process fluid temperatures Chemical compatibility Polymer or viscous fluids Complexity

Source: *Adapted from Pressure Relief Valve Engineering Handbook*, Anderson Greenwood, Crosby and Varec Products, Technical Publication No. TP-V300. Copyright © 2012 Emerson.

4.3.3 Pressure Relieving Valve Chemical Sizing Data

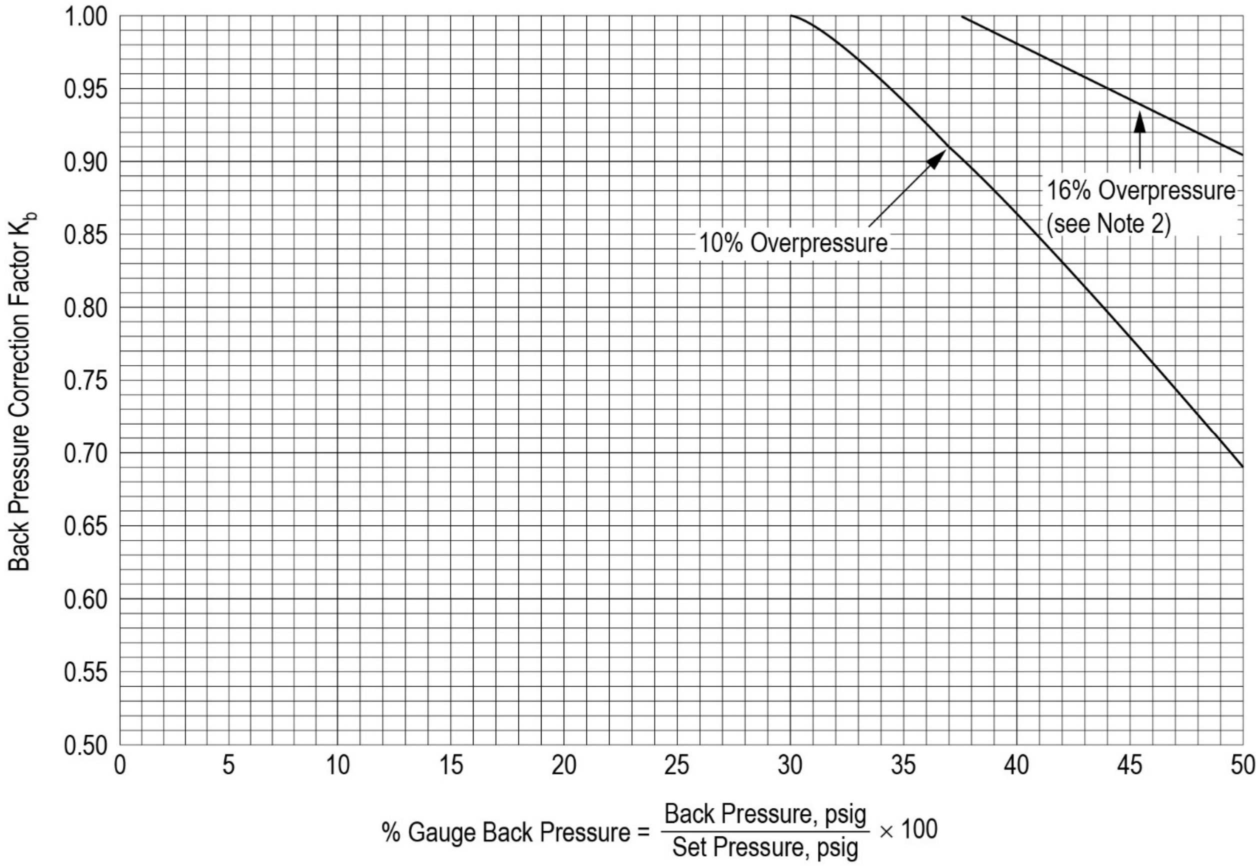
The data in this table is for use in the PE Control Systems exam only and is not intended for any other purpose or use. Curtiss-Wright makes no claims to the accuracy or content of the reference data provided.

Fluid Data

Fluid	Formula	Molecular Weight	Specific Gravity		k (C_p/C_v)	C (Constant)
			Liquid	Gas		
Acetic Acid	$HC_2H_3O_2$	60.05	1.049	2.073	1.15	332
Acetone	C_3H_6O	58.08	0.791	—	—	—
Acetylene	C_2H_2	26.04	0.62	0.899	1.26	343
Air	—	28.97	0.86	1	1.4	356
Ammonia	NH_3	17.03	0.817	0.588	1.33	350
Argon	A	39.94	1.65	1.388	1.67	378
Benzene	C_6H_6	78.11	0.879	2.696	1.12	329
Butane/n-Butane	C_4H_{10}	58.12	0.579	2.006	1.094	326
Carbon Dioxide	CO_2	44.01	1.101	1.519	1.3	347
Carbon Disulfide	CS_2	76.13	1.263	2.628	1.21	338
Carbon Monoxide	CO	28	0.814	0.966	1.4	356
Chlorine	Cl_2	70.9	1.58	2.45	1.36	353
Cyclohexane	C_6H_{12}	84.16	0.779	2.905	1.09	326
Dowtherm A	—	165	1.064	—	—	—
Dowtherm J	—	134	0.931	—	—	—
Ethane	C_2H_6	30.07	0.546	1.04	1.22	339
Ethyl Alcohol (Ethanol)	C_2H_6O	46.07	0.789	1.59	1.13	330
Ethyl Chloride	C_2H_5Cl	64.52	0.903	2.227	1.19	336
Ethylene (Ethene)	C_2H_4	28.05	0.566	0.968	1.26	343
Freon 12	CCl_2F_2	120.9	1.35	4.17	1.14	331
Helium	He	4	—	0.138	1.66	377
Hexane	C_6H_{14}	86.17	0.659	2.974	1.06	322
Hydrochloric Acid	HCl	36.5	1.64	—	—	—
Hydrofluoric Acid	HF	20.01	0.92	—	—	—
Hydrogen	H_2	2.016	0.0709	0.069	1.14	357
Hydrogen Sulfide	H_2S	34.07	0.79	1.176	1.32	349
Kerosene	C_9H_2O	128.3	0.815	—	—	—
Methane	CH_4	16.04	0.415	0.554	1.31	348
Methyl Alcohol	CH_4O	32.04	0.792	1.111	1.2	337
Methyl Chloride	CH_3Cl	50.49	0.952	1.743	1.2	337
Natural Gas (typical)	—	19	0.45	0.656	1.27	344
Nitric Acid	HNO_3	63.02	1.502	—	—	—
Nitrogen	N_2	28	1.026	0.967	1.4	356
Nitrous Oxide	N_2O	44	1.226	1.519	1.3	347
Oxygen	O_2	32	1.426	1.104	1.4	356
Pentane	C_5H_{12}	72.15	0.631	2.49	1.07	323
Propane	C_3H_8	44.09	0.585	1.522	1.13	330
Styrene	C_8H_8	104.14	0.906	3.6	1.07	323
Sulfur Dioxide	SO_2	64.06	1.434	2.21	1.29	346
Sulfuric Acid	H_2SO_4	98.08	1.83	—	—	—
Therminol D-12	—	162	0.76	—	—	—
Therminol VP-1	—	166	1.061	—	—	—
Toluene	C_7H_8	92.1	0.87	3.18	1.1	327
Water	H_2O	18.02	1	0.622	1.31	348

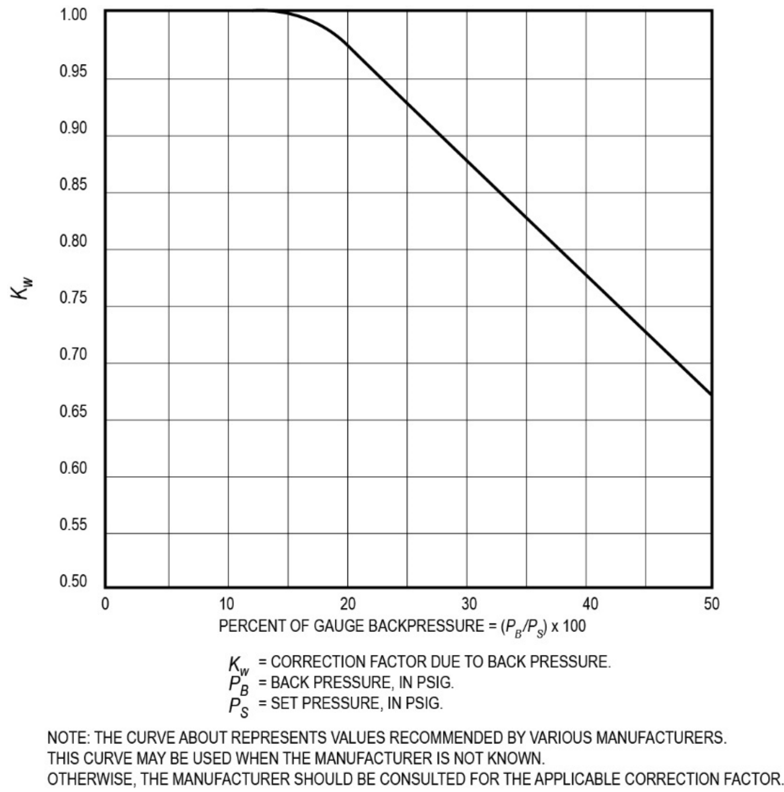
Source: Series 2600 Farris Engineering Pressure Relief Valves brochure, 2015. Reproduced with permission from Curtiss-Wright.

4.4 Back Pressure Sizing



Back Pressure Correction Factor (K_b) for Balanced, Spring-Loaded Relief Valves in Vapor or Gas Service

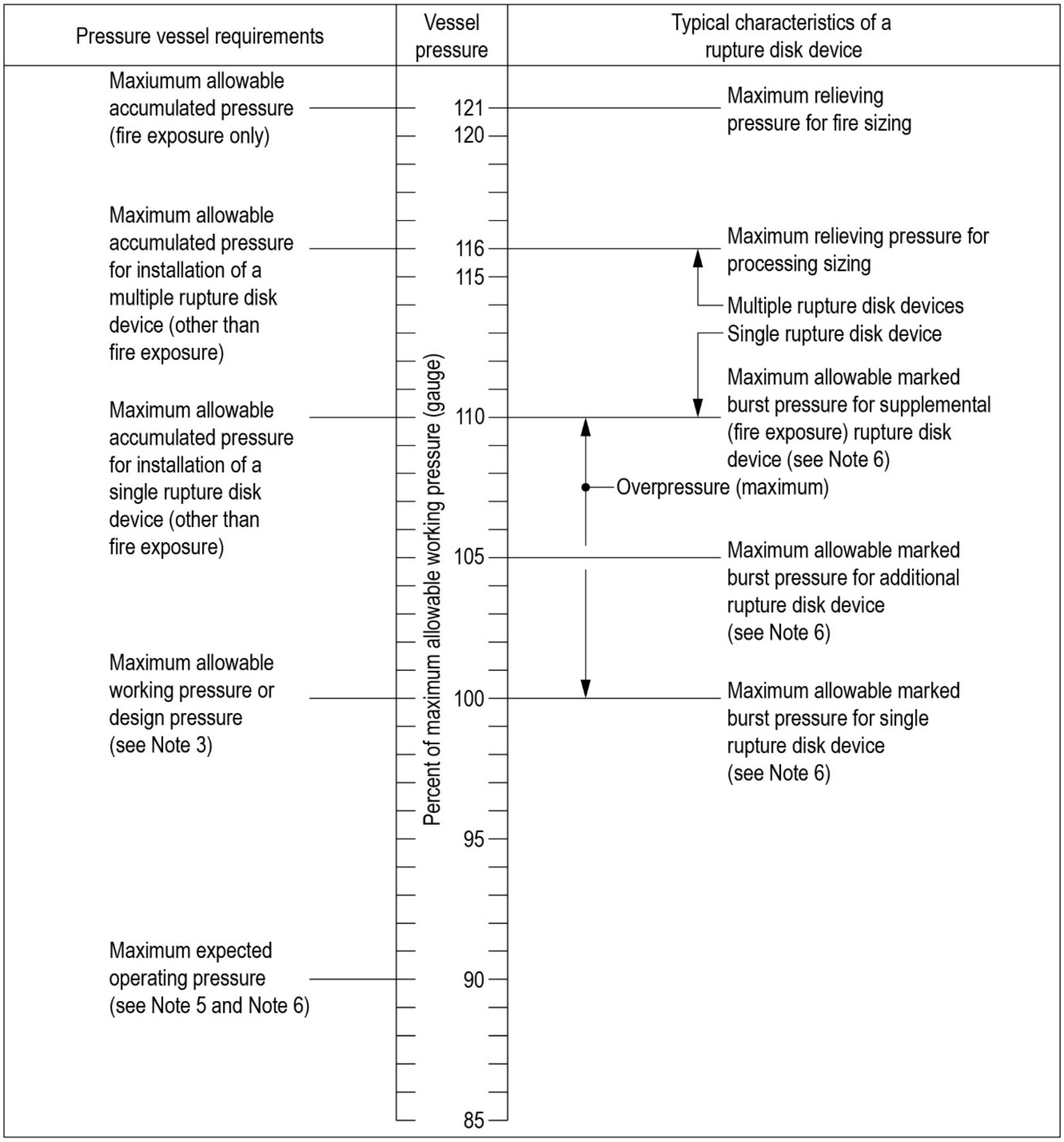
Source: *API Std 520, Sizing, Selection, and Installation of Pressure-relieving Devices*, 10 ed., Figure 31. Reproduced courtesy of the American Petroleum Institute.



Capacity Correction Factor (K_w) Due to Back Pressure on Balanced, Spring-Loaded, Pressure-Relief Valves in Liquid Service

Source: *API Std 520, Sizing, Selection, and Installation of Pressure-relieving Devices*, 10 ed., Figure 32.
Reproduced courtesy of the American Petroleum Institute.

4.4.1 Rupture Disks



NOTE 1 This figure conforms with the requirements of Section VIII of the ASME *Boiler and Pressure Vessel Code* for MAWPs greater than 30 psig.

NOTE 2 The pressure conditions shown are for rupture disk devices installed on a pressure vessel.

NOTE 3 The margin between the maximum allowable working pressure and the operating pressure must be considered in the selection of a rupture disk.

NOTE 4 The allowable burst-pressure tolerance will be in accordance with the applicable code.

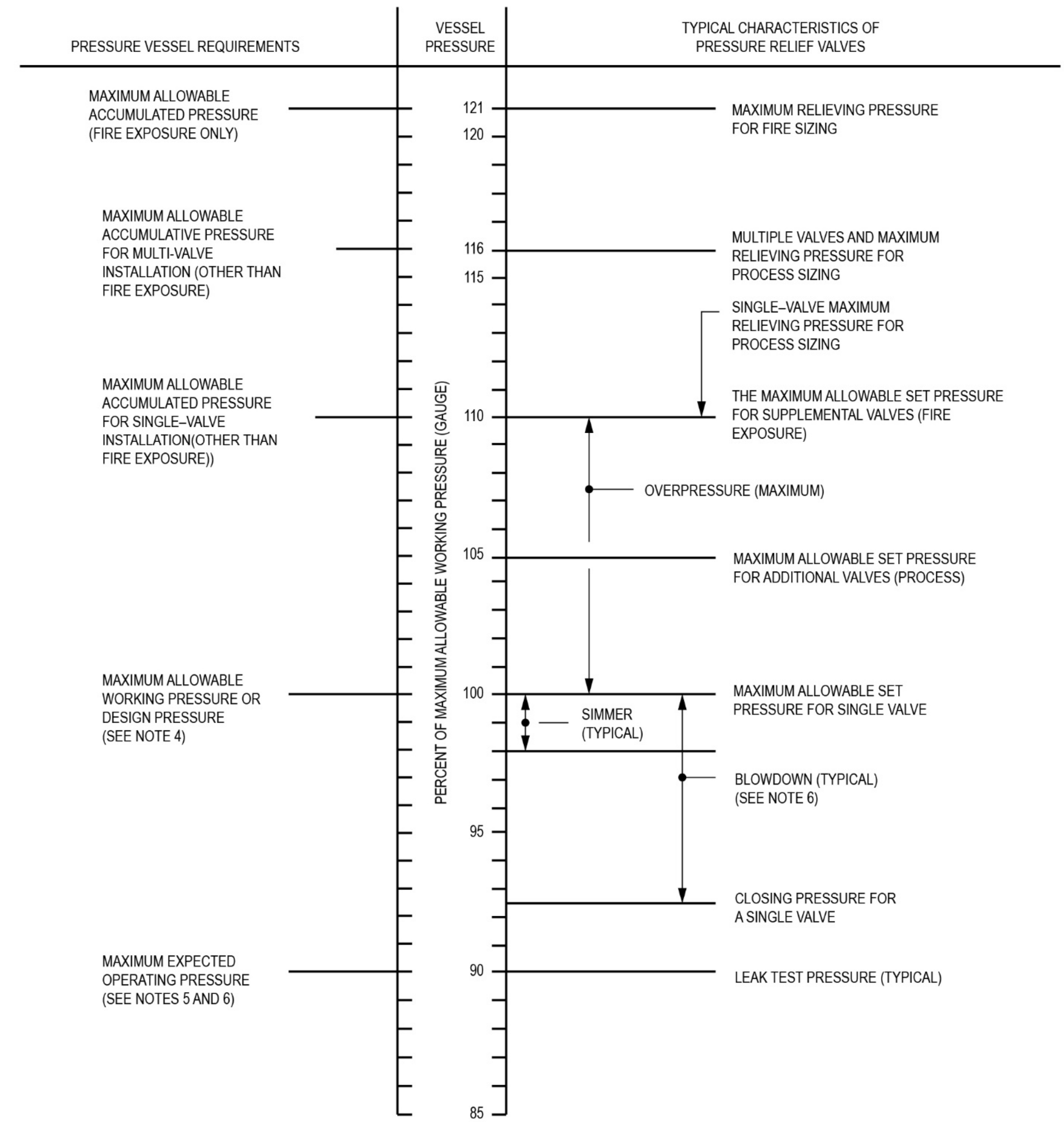
NOTE 5 The operating pressure may be higher or lower than 90% depending on the rupture disk design.

NOTE 6 The marked burst pressure of the rupture disk may be any pressure at or below the maximum allowable marked burst pressure.

Pressure Level Relationships for Rupture Disk Devices

Source: *API Std 520, Sizing, Selection, and Installation of Pressure-relieving Devices*, 10th edition, Figure 19. Reproduced courtesy of the American Petroleum Institute.

4.4.2 Pressure Relief Valves



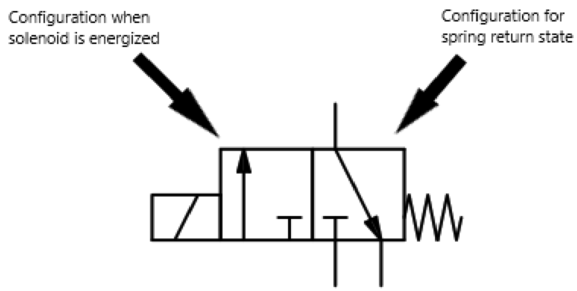
NOTES:

1. THIS FIGURE CONFORMS WITH THE REQUIREMENTS OF SECTION VIII OF THE ASME BOILER AND PRESSURE VESSEL CODE FOR MAWPS GREATER THAN 30 PSIG.
2. THE PRESSURE CONDITIONS SHOWN ARE FOR PRESSURE RELIEF VALVE INSTALLED A PRESSURE VESSEL.
3. ALLOWABLE SET-PRESSURE TOLERANCES WILL BE IN ACCORDANCE WITH THE APPLICABLE CODES.
4. THE MAXIMUM ALLOWABLE WORKING PRESSURE IS EQUAL TO OR GREATER THAN THE DESIGN PRESSURE FOR COINCIDENT DESIGN TEMPERATURE.
5. THE OPERATING PRESSURE MAYBE HIGHER OR LOWER THAN 90%.
6. SECTION VIII, DIVISION 1, APPENDIX M OF THE ASME CODE SHOULD BE REFERRED TO FOR GUIDANCE ON BLOWDOWN AND PRESSURE DIFFERENTIALS.

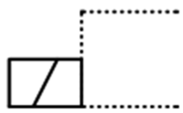
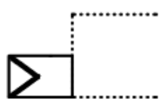
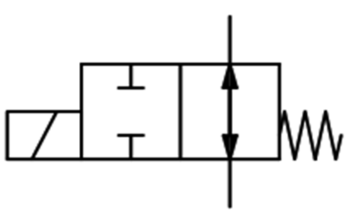
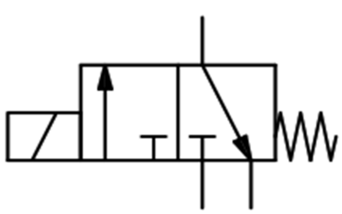
Pressure Level Relationships for Pressure Relief Devices

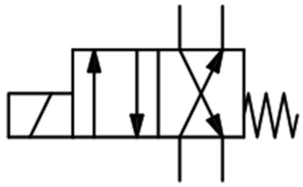
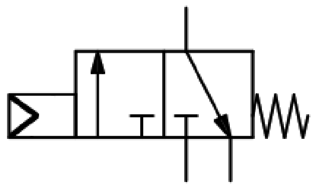
Source: *API Std 520, Sizing, Selection, and Installation of Pressure-relieving Devices*, 8th edition.

4.5 Pneumatic Schematics



Pneumatic Schematics

Symbol	Description
	Solenoid operator
	Spring return
	Pneumatic operator
	Two-port, two-position, solenoid-operated valve with a spring return
	Three-port, two-position, solenoid-operated valve with a spring return

Symbol	Description
	Four-port, two-position, solenoid-operated valve with a spring return
	Three-port, two-position, pneumatically operated valve with a spring return

4.6 Vibration Analysis

The following is from *Control Systems Engineer Technical Reference Handbook* by Chuck Cornell.

The two most important criteria of vibration to monitor are amplitude and frequency.

Amplitude or *displacemen*t is the magnitude of the equipment vibration. The larger the amplitude (i.e., the larger the displacement), the greater the movement or stress that is experienced by the equipment.

- Velocity amplitude is the rate of change of the displacement (i.e., how fast something is vibrating back and forth). The velocity amplitude is the criteria that provides the best indication of the condition of the equipment being monitored. The unit associated with velocity amplitude is inches per second (in/sec).
- A velocity vibration transducer (velomitor) measures how fast the displacement is moving.
- An acceleration transducer (accelerometer) measures how fast the velocity is changing.
- Vibration transducers are typically mounted near the bearings of the equipment. The closer the transducer is mounted to the centerline of a bearing, the less likely the transducer will pick up distorted signals.

5 SIGNALS, TRANSMISSION, AND NETWORKING

5.1 Classified Electrical Area Purging Systems

Purging Systems Descriptions and Requirements

Type Z Purge **Reduces Enclosure from Division 2 to Nonhazardous**	**Type Y Purge** **Reduces Enclosure from Division 1 to Division 2**	**Type X Purge** **Reduces Enclosure from Division 1 to Nonhazardous**
1. Label stating four volumes of purge gas needed before power 2. Pressure of 0.1 inch water 3. Enclosure temperature < 80% of ignition temperature of gas 4. Purge failure alarm or indicator (no automatic power-off necessary) 5. Warning nameplate 6. 1/4-inch tempered glass window	1. Label stating four volumes of purge gas needed before power 2. Pressure of 0.1 inch water 3. Fused based on enclosure thickness to ensure enclosure temperature < 80% of ignition temperature of gas 4. Purge failure alarm or indicator (no automatic power-off necessary) 5. Warning nameplate 6. 1/4-inch tempered glass window 7. Equipment mounted within enclosure must meet Division 2 (hermetically sealed switches, relays, and contacts)	1. Timer to allow four volumes of purge gas 2. Pressure of 0.1 inch water 3. Fused based on enclosure thickness to ensure enclosure temperature < 80% of ignition temperature of gas 4. Power disconnect on purge loss (pressure or flow actuated) 5. Warning nameplate 6. 1/4-inch tempered glass window 7. Automatic power disconnect switch on door

Source: Data obtained from *The Art of Intrinsic Safety*, Figure 3-4, page 7, by Ronan Systems (originally published under Ronan Engineering Co.). Used with permission from Ronan Systems.

5.2 Network Model

OSI and IEC 61158 Network Layers

OSI layer	Function	IEC 61158 layer
7 Application	Translates demands placed on the communications stack into a form understood by the lower layers and vice versa	Application (IEC 61158-5-*tt*, IEC 61158-6-*tt*)
6 Presentation	Converts data to/from standardized network formats	↑
5 Session	Creates and manages dialogue among lower layers	↑
4 Transport	Provides transparent reliable data transfer (end-to-end transfer across a network which may include multiple links)	↓ or ↑
3 Network	Performs message routing	↓ or ↑
2 Data-link	Controls access to the communication medium. Performs error detection (point-to-point transfer on a link)	Data-link (IEC 61158-3-*tt*, IEC 61158-4-*tt*)
1 Physical	Encodes/decodes signals for transmission/reception in a form appropriate to the communications medium. Specifies communication media characteristics	Physical (IEC 61158-2)
Note 1. -***tt*** is a placeholder for the part numbers representing types. Note 2. ↓ and ↑ indicate that the functionality of this layer, when present, is included in the fieldbus layer that is nearest in the direction of the arrow. Thus, it is possible that the network and transport functionality are included in either the data-link or application layers, and it is possible that the session and presentation functionality are included in the application layer but not in the data-link layer.		

5.3 Fieldbus Network Configuration Rules

The following information is Section 13.3.3 "Work configuration rules," from IEC 61158-2:2014.

An MAU that claims conformance to Clause 13 shall meet the requirements of Clause 13 when used in a network that complies with these rules.

Rule 1: One fieldbus shall be capable of communication between two and 32 devices, all operating at the same bit rate, both for a powered and a non-powered bus and in a hazardous area using distributed barriers.

Note 1: The use of a single barrier in the safe area may limit the number of devices in the hazardous area.

Note 2: This rule does not preclude the use of more than the specified number of devices in an installed system. The numbers of devices were calculated on the assumption that a bus-powered device draws 100 mW.

Rule 2: A fully loaded (maximum number of connected devices), current-mode fieldbus segment shall have a total cable length, between any two devices, of up to 750 m.

Note 3: 750 m maximum cable length is the requirement for conformance to Clause 13 but this does not preclude the use of longer lengths in an installed system.

Rule 3: The total number of waveform regenerations by repeaters and active couplers between any two devices is repeater implementation dependent.

Note 4: Prior editions of this standard limited this total number to four.

Rule 4: The maximum propagation delay between any two devices shall not exceed 40 T_{bit}.

For efficiency of the network, that part of the turn-around time of any device on the network caused by a PhE between the end of a received frame and the beginning of the transmitted frame containing an associated immediate response should not exceed 5 bit times, no more than 2 bit times of which should be due to the MAU.

Note 5: As it is not mandatory to expose the DLL – PhL interface or the MDS – MAU interface, that part of the turn-around time of a fieldbus device caused by the PhL or the MAU is not specified and thus not available for conformance testing.

Rule 5: The fieldbus shall be capable of continued operation while a device is being connected or disconnected. Data errors induced during connection or disconnection shall be detected.

Rule 6: Failure of any communication element or spur (including a short circuit or open circuit, but excluding jabber) shall not interfere with transactions between other communication elements for more than 1 ms.

Rule 7: The network shall not be polarity sensitive with or without power injected on the line.

Rule 8: The degradation of the electrical characteristics of the signal, between any two devices, due to attenuation, attenuation distortion and mismatching shall be limited to the values indicated below.

a) Signal attenuation: The signal attenuation due to each device shall not exceed 0,2 dB. The configuration of the bus (trunk and spur lengths, number of devices, IS barriers, galvanic isolators, and possible matching devices) shall be such that the attenuation between any two devices at the frequency corresponding to the bit rate shall not exceed 16 dB.

b) Attenuation distortion: The configuration of the bus (trunk and spur lengths and number of devices) shall be such that between any two devices:

   [Attenuation (1,25 f_r) – Attenuation (0,25 f_r)] $\leq$ 6 dB

   Attenuation (1,25 f_r) $\geq$ Attenuation (0,25 f_r)

   where f_r is the frequency corresponding to the bit rate. Attenuation shall be monotonic for all frequencies from 0,25 f_r to 1,25 f_r (250 kHz to 1,25 MHz).

c) Mismatching distortion: Mismatching (due to spurs or any other effect, including one open circuit spur of maximum length) on the bus shall be such that, at any point along the trunk, in the frequency band 0,25 f_r to 1,25 f_r (250 kHz to 1,25 MHz):

   $$|Z - Zfr| / |Z + Zfr| \leq 0{,}2$$

   where

   Z_o is the characteristic impedance of the trunk cable;

   Z is the parallel combination of Z_o and the load impedance at the coupler.

Note 6: This rule minimizes restrictions on trunk and spur length, number of devices etc. by specifying only the transmission limitations imposed by combinations of these factors. It is possible to use different combinations depending on the needs of the application.

Rule 9: The following rules shall apply to systems implemented with redundant media:

a) each channel (cable) shall comply with the network configuration rules;

b) there shall not be a non-redundant segment between two redundant segments;

c) repeaters shall also be redundant;

d) if the system is configured (by Systems management) to transmit on more than one channel simultaneously then the propagation time difference between any two devices on any two channels shall not exceed five bit times;

e) channel numbers shall be maintained throughout the fieldbus, that is, channels 1,2,3… from Systems management shall always connect to physical channels 1,2,3…

5.4 Serial Communication Protocols

Protocol Comparisons

Name	**Sync /Async**	**Type**	**Duplex**	**Max devices**	**Max speed (kbps)**	**Max distance (kbpft)**	**Pin count (1)**
RS-232	async	peer	full	2	20(2)	30(3)	2(4)
RS-422	async	multi-drop	half	10(5)	10,000	4,000	1(6)
RS-485	async	multi-point	half	32(5)	10,000	4,000	2
I^{2}C	sync	multi-master	half	-7	3,400	<>	2
SPI	sync	multi-master	full	-7	>1,000	<>	3+1(8)
Microwire	sync	master/slave	full	-7	>625	<>	3+1(8)
1-Wire	async	master/slave	half	-7	16	1,000	1s
Notes							
-1	Not including ground.						
-2	Faster speeds available but not specified.						
-3	Dependent on capacitance of the wiring.						
-4	Software handshaking. Hardware handshaking requires additional pins.						
-5	Device count given in unit loads (UL). More devices are possible if fractional-UL received.						
-6	Unidirectional communication only. Additional pins needed for each bidirectional communication.						
-7	Limitation based on bus capacitance and bit rate.						
-8	Additional pins needed for every slave if slave count is more than one.						

Source: Embedded, "Serial Protocols Compared," http://www.embedded.com/design/connectivity/ 4023975/Serial-Protocols-Compared. Reproduced with permission from Embedded.

5.5 Fiber-Optic Cables

Multimode Cable Characteristics

- The larger diameter core > 10 µm (typically 50 µm or 62.5 µm) allows the rays of light to travel along several different angles between the core and cladding.
- The larger core size simplifies connections and also allows the use of lower-cost electronics such as light-emitting diodes (LEDs) and vertical-cavity, surface-emitting lasers (VCSELs), which operate at the 850-nm wavelength.
  - LEDs emit incoherent light: light waves that lack a fixed-phase relationship.
  - VCSELs emit coherent light: light waves with a fixed-phase relationship (both spatial and temporal) between points on the electromagnetic wave.
- Due to the modal dispersion in the fiber, multimode fiber has higher pulse spreading rates than single-mode fiber, which limits the multimode fiber's information transmission capacity.
- Multimode fiber is used for shorter distance communication links (typically < 500 m), such as within a building.
- Typical multimode links have data rates of 10 Mbit/s to 10 Gbit/s.
- Multimode fiber is used when higher power must be transmitted.
- Multimode fiber is typically less expensive than single-mode.
- To distinguish multimode cables from single-mode, multimode patch cable jackets are typically orange and single-mode cable jackets are usually yellow.

Single-Mode Cable Characteristics

- The smaller-diameter core, 8 to 10 µm (typically 9 µm), allows only one path for the rays of light to travel through the fiber.
- The light source is typically a single-mode laser.
- Single-mode is typically used for communication links > 200 m.
- Single-mode fibers are most often used in high-precision areas because the allowance of only one propagation mode of the light makes the light easier to focus properly.
- Single-mode fibers are better at retaining the fidelity of each light pulse over long distances than multimode fibers. For these reasons, single-mode fibers can have a higher bandwidth than multimode fibers.
- Single-mode fibers have the broadest bandwidth.

5.6 Copper Cabling

Characteristics of STP/UTP Cables

Cable Type	Data Rate	Common Usage
Category 1	N/A	Voice Grade Analog
Category 2	4 Mbps	Digital Voice
Category 3	10 Mbps	10BaseT
Category 4	16 Mbps	Token Ring
Category 5	100 Mbps*	100BaseT
Category 5e	1000 Mbps	1000BaseT
Category 6	10 Gbps	
Category 6A	10 Gbps	10GBaseT
* Indicates has been successfully used at 1000 Mbps (though Cat 5e is the better choice).		

Category 1, 2 & 4 Cables: These are no longer commonly used. They have been replaced by higher category cables.

Source: Table 4-1 from *Control Systems Engineer Technical Reference Handbook* by Chuck Cornell. Reproduced with permission from ISA.

5.7 Cable Resistivity Table

Electrical Resistance in Copper Wire

AWG Gauge*	Area (*Circular* Mils)	Diameter (mils, *1000th in*)	Electrical Resistance (Ohms/1000 ft)		Weight (lb/1000 ft)
			at 77ºF (25ºC)	at 149ºF (65ºC)	
0000 (4/0)	212000	460	0.0500	0.057	641
000 (3/0)	168000	410	0.0630	0.073	508
00 (2/0)	133000	365	0.0795	0.092	403
0 (1/0)	106000	325	0.100	0.116	319
1	83700	289	0.126	0.146	253
2	66400	258	0.159	0.184	201
3	52600	229	0.201	0.232	159
4	41700	204	0.253	0.292	126
5	33100		0.319		100
6	26300	162	0.403	0.465	79.5
7	20800		0.508		63.0
8	16500	128	0.641	0.739	50.0
9	13100		0.808		39.6
10	10400	102	1.02	1.18	31.4
11	8230		1.28		24.9
12	6530	81	1.62	1.87	19.8
13	5180		2.04		15.7
14	4110	64	2.58	2.97	12.4
15	3260		3.25		9.86
16	2580	51	4.09	4.73	7.82
17	2050		5.16		6.20
18	1620	40	6.51	7.51	4.92
19	1290		8.21		3.90
20	1020	32	10.4	11.9	3.09
21	810		13.1		2.45
22	642	25.3	16.5	19.0	1.94
23	509		20.8		1.54
24	404	20.1	26.2	30.2	1.22
25	320		33.0		0.970
26	254	15.9	41.6	48.0	0.769
27	202		52.5		0.610
28	160	12.6	66.2	76.4	0.484
29	127		83.4		0.384
30	101	10	105	121	0.304
31	79.7		133		0.241
32	63.2	8	167	193	0.191
33	50.1		211		0.152
34	39.8	6.3	266	307	0.120

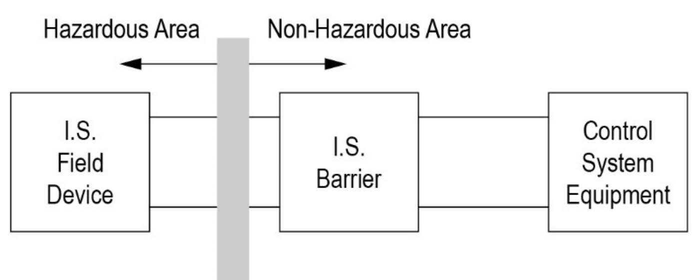
AWG Gauge*	Area *(Circular* Mils*)*	Diameter (mils, *1000th in)*	Electrical Resistance (Ohms/1000 ft)		Weight (lb/1000 ft)
			at 77ºF (25ºC)	at 149ºF (65ºC)	
35	31.6		335		0.095
36	25.0	5	423	488	0.076
37	19.8		533		0.060
38	15.7	4	673	776	0.048
39	12.5		848		0.038
40	9.9	3.1	1070	1230	0.020

* solid strand
- 1 lb = 0.4536 kg
- 1 ft = 0.3048 m

American Wire Gauge (AWG) is a U.S. standard for wire conductor size. The "gauge" is related to the diameter of the wire.

Source: Engineering ToolBox, (2008). Copper Wire - Electrical Resistance vs. Gauge. https://www.engineeringtoolbox.com/ copper-wire-d_1429.html. Accessed December 16, 2021.

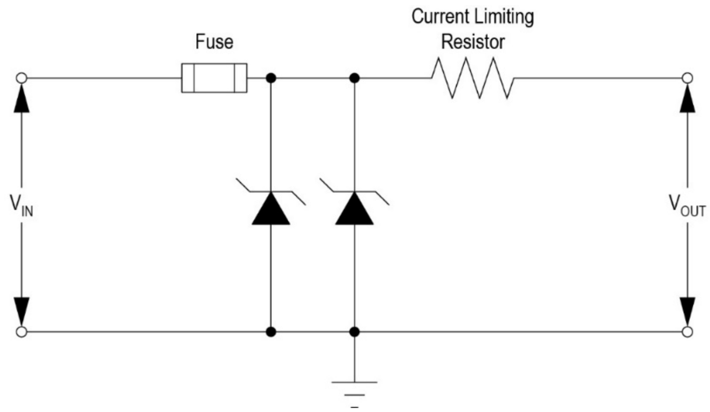
5.8 Intrinsic Safety



General Intrinsic Safety Installation

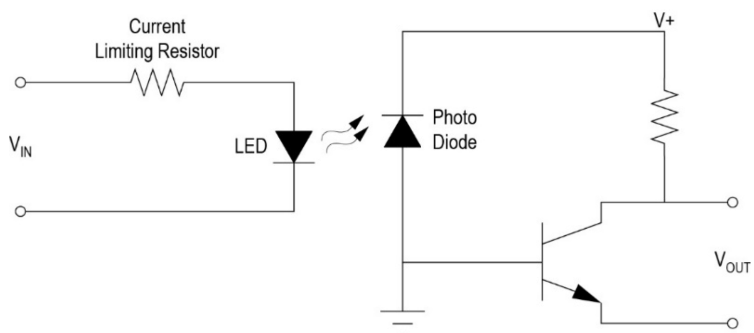
I.S. barriers generally fall into two classifications, active and passive:

Passive: Passive barriers are typically of the Zener diode design. If there should be a short circuit within the wiring or instrumentation in the hazardous area, there will be a corresponding drop in voltage going through the barrier. This short circuit will cause the fuse within the barrier to open and the Zener diode will conduct current to ground, thereby eliminating all possibility of any spark or thermal energy sufficient to ignite a flammable atmospheric condition. (Note the use of ground in the generic schematic shown below).



Passive Barrier

Active: Active barriers are typically of the galvanic isolator design. There is no physical connection between the input and output. A generic schematic of an active barrier is shown below.



Active Barrier

Barrier Types

Source: Figures of barrier types from *Control Systems Engineer Technical Reference Handbook* by Chuck Cornell.
Reproduced with permission from ISA.

5.9 Grounding Transmission Circuits

There are two types of grounding practices in instrumentation: those concerned with personnel safety and those concerned with signal accuracy and dependability. Both types must conform to the National Electric Code (NEC) and the regulations of any local governing bodies.

Electrical interference is any spurious voltage or current from external sources that appears in the signal transmission circuit. When these voltages are excessive, signals are changed or cannot be detected. According to API RP 552, Section 5.1, "Sources of Electrical Interference":

> Unwanted voltages enter an electronic signal transmission system by the following means:
>
> a. Inductive pickup from alternating-current (ac) fields and/or radio-frequency (RF) interference.
> b. Electrostatic or capacitive coupling with other circuits.
> c. Direct coupling with other circuits by means of leakage current paths, ground current loops, or a common return lead for more than one circuit.

Methods for Minimizing Unwanted Voltages in Signal Transmission Circuits

Source of Electrical Interference	Recommended Methods for Minimizing Interference
Electromagnetic coupling	Use twisted pair wires.
	Routing away from strong AC fields.
	Eliminate or reduce the source.
	Install signal wiring in steel conduit or covered trays.
	Shield the power line.
Electrostatic or capacitive coupling	Use grounded signal cable.
	Use a single point signal ground.
	Eliminate resistances common to multiple circuits.
	Use single, shielded, twisted pair copper wire.
	Use multipair, overall shielded cable of shielded twisted pairs.
	Use individually isolated (floating) circuits when using single or multipair unshielded cables.
Direct coupling by leakage paths	Eliminate moisture in cable by using properly insulated wire, terminal strips, and dry air purges.
Direct coupling by ground current loop	Remove multiple grounds, only a single ground should be established.
Direct coupling by common return lead	Use single pairs. Common return leads can introduce additive resistance to circuits.
Separation of instrument and power circuits	Use proper spacing between circuits of different power levels. See Wire Separation Table below.

Source: Section 4, "General Information on Electronic Systems," and Section 5, "Reducing Electrical Interference in Electronic Systems," in API RP 552, *Transmission Systems,* 1 ed.

Wire Separation Table from API RP 552, Section 5.3

Power and signal run in separate steel conduit; signal: individual shielded twisted pairs with overall cable shield (API Type III and VI)[a]

Power Cable(s)	Low Level (millivolts)	mA DC (4–20 or 10–50)
Up to 125 V @20 A	4"	None Required
125 V to 500 V @200 A	12"	6"
Over 500 V	36"	18"

Power and signal run in separate steel conduit; signal: twisted pair (API Type II and V)[b]

Power Cable(s)	Low Level (millivolts)	mA DC (4–20 or 10–50)
Up to 125 V @20 A	8"	4"
125 V to 500 V @200 A	15"	6"
Over 500 V	48"	24"

Power and signal in tray; signal: shielded twisted pair (API III and VI)
OR
Power and signal in tray with metallic barrier; signal: twisted pair (API II and V[c])

Power Cable(s)	Low Level (millivolts)	mA DC (4–20 or 10–50)
Up to 125 V @20 A	30"	15"
125 V to 500 V @200 A	60"	30"
Over 500 V	180"	96"

Power: steel conduit; signal: tray shielded twisted pair (API III and VI)
OR
Power in tray; signal in steel conduit; signal: shielded twisted pair (API III and VI)[d]

Power Cable(s)	Low Level (millivolts)	mA DC (4–20 or 10–50)
Up to 125 V @20 A	30"	15"
125V to 500 V @200 A	30"	15"
Over 500 V	60"	30"

Notes: mA = milliampere, DC = direct current, A = ampere

[a] The above tables are for parallel runs up to 500 feet long; for longer runs increase spacing proportionately to the parallel length.

[b] 120-volt instrument circuits for alarms, solenoids, and similar circuits should be treated as power circuits in the above tables.

[c] Group wiring by type and level: low-level signals farthest from power, next mA DC circuits, next alarms; next 120V alarms; closest are 120V solenoid valves and limit switches.

[d] This information is based partly on data and partly on accepted and proven experience.

Source: Data taken from Table 3 in API RP 552, 1 ed., Section 5.3, "Instruments to be Interconnected." Reproduced courtesy of the American Petroleum Institute.

Types of Wire or Cable for Signal Transmission

Type	Description
I	Untwisted copper wire
II	Single, unshielded twisted-pair copper wire
III	Single, shielded twisted-pair copper wire
IV	Multipair cable of Type II wire
V	Multipair, overall shielded cable of Type II wire
VI	Multipair, overall shielded cable of Type III wire

Note: In the above, replace the word *pair* with *triple* or *triad* for wiring certain items such as some resistance bulb sensors (RTD), or strain gauges, and others like these.

Source: Table 4 in API RP 552, 1 ed., Section 6, "Engineering Factors in Selection of Wire Types for Electronic Systems." Reproduced courtesy of the American Petroleum Institute.

5.10 Pneumatic Signal Transmission

The following information is from Section 21.2.6, "General Information on Pneumatic Systems," API RP 552, *Transmission Systems*, 1st edition.

> The capacity of an instrument air system is based on the total requirements of all connected loads, assuming all instruments operate simultaneously. Where accurate figures are not available, 1.0 standard cubic foot per minute (1.7 cubic meters per hour) shall be used for each consumer of instrument air. At least 100 percent extra capacity shall be provided for miscellaneous instrument purges and leaks in the distribution system. Instrument air is to be used for instruments and instrument purges only.
>
> The use of instrument air for other purposes such as for pneumatically operated tools, air cleaning, or vessel purging can reduce the safety and reliability of the plant system.

Line Sizing Guide for Pipe Headers

Pipe Headers	Number of Users	Nominal Pipe Size (Inches)	Nominal Pipe Size (mm)
Main	80	1 ½	40
	150	2	50
	300	3	75
Branch	4	½	15
	20	¾	20
	25	1	25
	80	1 ½	40

Source: Table 7, in API RP 552, 1 ed., Section 21.2.11, "Distribution Systems." Reproduced courtesy of the American Petroleum Institute.

5.11 Standard References

API Std 520. *Sizing, Selection, and Installation of Pressure-relieving Devices.* 10th ed. Washington, DC: API (American Petroleum Institute), October 2020.

API RP 552. *Transmission Systems*. 1st ed. Washington, DC: API (American Petroleum Institute), October 1994.

IEC 61158-2:2014. *Industrial Communication Networks - Fieldbus Specifications – Part 2: Physical Layer Specification and Service Definition.* Geneva 20 – Switzerland: IEC (International Electrotechnical Commission).

IEC 61158-1:2019. *Industrial Communication Networks Fieldbus Specifications – Part 1: Overview and Guidance for the IEC 61158 and IEC 61784 Series.* Geneva 20 – Switzerland: IEC (International Electrotechnical Commission).

ISA-62443-1-1-2007. *Security for Industrial Automation and Control Systems – Part 1-1: Terminology, Concepts, and Models.* Research Triangle Park, NC: ISA (International Society of Automation).

NEMA 250-2014. *Enclosures for Electrical Equipment (1000 Volts Maximum)*. Rosslyn, VA: NEMA (National Electrical Manufacturers Association).

6 SAFETY INSTRUMENTED SYSTEMS (SIS)

6.1 Safety Integrity Levels (SILs)—Probability of Failure on Demand

6.1.1 Demand Mode

Safety Integrity Requirements: PFD_{avg}

Demand Mode of Operation		
Safety integrity level (SIL)	**PFD_{avg}**	**Required risk reduction**
4	$\geq 10^{-5}$ to $< 10^{-4}$	> 10 000 to ≤ 100 000
3	$\geq 10^{-4}$ to $< 10^{-3}$	> 1 000 to ≤ 10 000
2	$\geq 10^{-3}$ to $< 10^{-2}$	> 100 to ≤ 1 000
1	$\geq 10^{-2}$ to $< 10^{-1}$	> 10 to ≤ 100

Source: ANSI/ISA-61511-1-2018 / IEC 61511-1:2016+AMD1:2017 CSV, *Functional Safety – Safety Instrumented Systems for the Process Industry Sector – Part 1: Framework, Definitions, System, Hardware and Application Programming Requirements* (IEC 61511-1:2016+AMD1:2017). *Reproduced with permission from ISA.*

6.1.2 Continuous Mode

Safety Integrity Requirements: Average Frequency of Dangerous Failures of the Safety Instrumented Function (SIF)

Continuous Mode or Demand Mode of Operation	
Safety integrity level (SIL)	**Average frequency of dangerous failures (failures per hour)**
4	$\geq 10^{-9}$ to $< 10^{-8}$
3	$\geq 10^{-8}$ to $< 10^{-7}$
2	$\geq 10^{-7}$ to $< 10^{-6}$
1	$\geq 10^{-6}$ to $< 10^{-5}$

Source: ANSI/ISA-61511-1-2018 / IEC 61511-1:2016+AMD1:2017 CSV, *Functional Safety – Safety Instrumented Systems for the Process Industry Sector – Part 1: Framework, Definitions, System, Hardware and Application Programming Requirements* (IEC 61511-1:2016+AMD1:2017). Reproduced with permission from ISA.

6.2 Failure Rate

Failure rate = number of failures / total time

Failure rates, however, are normally expressed as *failures per hour.*

Example:

To calculate for a 10-year interval:

Because 1 year = 8,760 hours

a 10-year interval = 87,600 hours

Therefore:

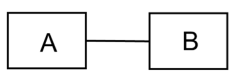
1 failure / 87,600 hours becomes

1.14 E–5 failures/hour

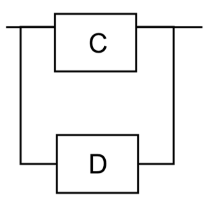
6.3 Reliability Block Diagram (Probability of Failure)

When calculating the probability of a safety instrumented function (SIF) using reliability block diagrams (RBDs), probabilities are added or multiplied depending upon whether the blocks are shown in series or in parallel.

- Add probabilities of items in series.

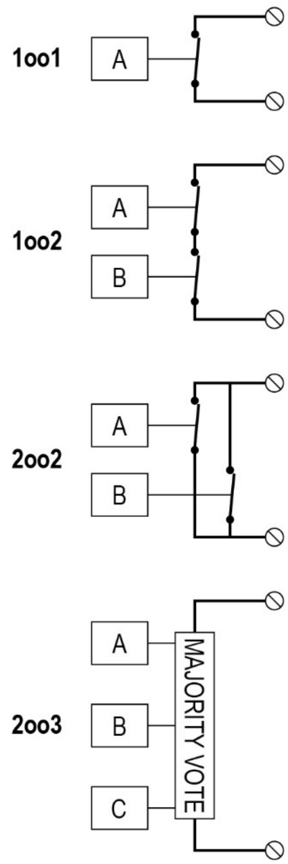


- Multiply probabilities of items in parallel.



Availability calculations are multiplied in series and added in parallel.

6.4 Architectures/Configurations



Probabilities

Configuration	Fail Safe	Fail Danger
1oo1	0.04 (25 years)	0.02 (50 years)
1oo2	0.08 (12.5 years)	0.0004 (2,500 years)
2oo2	0.0016 (625 years)	0.04 (25 years)
2oo3	0.0048 (208 years)	0.0012 (833 years)

Configurations and Examples of Performance

Source: Figure 9-7 from *Safety Instrumented Systems: A Life-Cycle Approach* by Paul Gruhn and Simon Lucchini. Reproduced with Permission from ISA.

Notes:

1. The term "architecture" can apply to any subsystem, for example, sensors, logic solvers, and final elements.
2. The probability figures shown above do not account for common cause, they are merely based on adding or multiplying probabilities of single events.
3. The probabilities for 2oo3 are three times greater than probabilities for certain dual configurations (as there are three times as many dual failure combinations), again, not accounting for common cause failures.
4. 1oo2D (one out of two with diagnostics) is based on the best of both dual probabilities (0.0004 and 0.0001 in the example above), again, not accounting for common cause failures.
5. 1oo2 offers the best safety, at the expense of more nuisance trips. 2oo2 offers the best protection against nuisance trips, but the worst safety protection. 2oo3 (and 1oo2D) offer very good performance in both modes.

6.5 Hardware Fault Tolerance Tables

The HFT requirements below represent the minimum system or, where relevant, the SIS subsystem redundancy. Depending on the application, device failure rate and proof-testing interval, additional redundancy can be required to satisfy the failure measure for the SIL of the SIF according to 11.9.

Minimum HFT for a SIS (or its SIS subsystems) Implementing a Safety Instrumented Function (SIF)

SIL	Minimum required HFT
1 (any mode)	0
2 (low demand mode)	0
2 (high demand or continuous mode)	1
3 (any mode)	1
4 (any mode)	2

Source: Section 11.4.5 of ANSI/ISA-61511-1-2018 / IEC 61511-1:2016+AMD1:2017 CSV. Reproduced with permission from ISA.

6.6 Reliability Modeling

Basic formulas for MTTFsp (mean time to fail spurious)

1oo1 $1 / \lambda_S$

1oo2 $1 / (2 * \lambda_S)$

2oo2 $1 / ((2 * \lambda_S^2 * MTTR) + (\beta * \lambda_S))$

2oo3 $1 / ((6 * \lambda_S^2 * MTTR) + (\beta * \lambda_S))$

where

λ_{DU} = dangerous undetected failure rate

λ_S = safe failure rate

MTTR = mean time to repair

β = beta (common cause) percentage

λ = (1/MTTF)

Basic formulas for PFD (probability of failure on demand)

1oo1 $\lambda_{DU} * TI/2$

1oo2 $[((\lambda_{DU})^2 * (TI)^2) / 3] + [\lambda_{DU} * \beta * TI/2]$

2oo2 $[\lambda_{DU} * TI] + [\lambda_{DU} * \beta * TI/2]$

2oo3 $[(\lambda_{DU})^2 * (TI)^2] + [\lambda_{DU} * \beta * TI/2]$

where

λ_{DU}	=	dangerous undetected failure rate
TI	=	manual test interval (yr)
β	=	beta (common cause) percentage
MTTR	=	mean time to repair
MTTF	=	mean time to failure
MTBF	=	mean time between failures
λ	=	(1/MTTF)
λ_{DU}	=	$(1 - DC)\ \lambda_D$
DC	=	diagnostic coverage
λ_D	=	$\lambda_{DD} + \lambda_{DU}$
λ_D	=	dangerous failures
λ_{DD}	=	dangerous detected failure rate
λ_{SLF}	=	$\lambda_{sensor} + \lambda_{logic\ solver} + \lambda_{final\ element}$

6.7 Standard References

ANSI/ISA-61511-1-2018 / IEC 61511-1:2016+AMD1:2017 CSV. *Functional Safety – Safety Instrumented Systems for the Process Industry Sector – Part 1: Framework, Definitions, System, Hardware and Application Programming Requirements* (IEC 61511-1:2016+AMD1:2017 CSV, IDT). Research Triangle Park, NC: ISA (International Society of Automation).

ISA-TR84.00.02-2015, *Safety Integrity Level (SIL) Verification of Safety Instrumented Functions.* Research Triangle Park, NC: ISA (International Society of Automation).

7 GENERAL INFORMATION

7.1 NEMA 250-2014, Enclosures for Electrical Equipment (1000 Volts Maximum)

Comparison of Specific Applications of Enclosures for Indoor Nonhazardous (Unclassified) Locations

Provides a Degree of Protection against the Following Conditions	Type of Enclosure									
	1	2	4	4X	5	6	6P	12	12K	13
Access to hazardous parts	X	X	X	X	X	X	X	X	X	X
Ingress of solid foreign objects (falling dirt)	X	X	X	X	X	X	X	X	X	X
Ingress of water (dripping and light splashing)	…	X	X	X	X	X	X	X	X	X
Ingress of solid foreign objects (circulating dust, lint, fibers, and flyings**)	…	…	X	X	…	X	X	X	X	X
Ingress of solid foreign objects (settling airborne dust, lint, fibers, and flyings**)	…	…	X	X	X	X	X	X	X	X
Ingress of water (hosedown and splashing water)	…	…	X	X	…	X	X	…	…	…
Oil and coolant seepage	…	…	…	…	…	…	…	X	X	X
Oil or coolant spraying and splashing	…	…	…	…	…	…	…	…	…	X
Corrosive agents	…	…	…	X	…	…	X	…	…	…
Ingress of water (occasional temporary submersion)	…	…	…	…	…	X	X	…	…	…
Ingress of water (occasional prolonged submersion)	…	…	…	…	…	…	X	…	…	…

** These fibers and flyings are not considered Class III type ignitable fibers or combustible flyings. For Class III type ignitable fibers or flyings see the *National Electrical Code*®, Article 500.5(D).

Source: NEMA 250-2014, *Enclosures for Electrical Equipment (1000 Volts Maximum)*, Table 2-1. Reproduced with permission of the National Electrical Manufacturers Association (NEMA).

Comparison of Specific Applications of Enclosures for Indoor and Outdoor Nonhazardous (Unclassified) Locations

Provides a Degree of Protection against the Following Conditions	Type of Enclosure									
	3	**3X**	**3R**	**3RX**	**3S**	**3SX**	**4**	**4X**	**6**	**6P**
Access to hazardous parts	X	X	X	X	X	X	X	X	X	X
Ingress of solid foreign objects (falling dirt)	X	X	X	X	X	X	X	X	X	X
Ingress of water (dripping and light splashing)	X	X	X	X	X	X	X	X	X	X
Ingress of water (rain, snow, and sleet**)	X	X	X	X	X	X	X	X	X	X
Sleet***	…	…	…	…	X	X	…	…	…	…
Ingress of solid foreign objects (windblown dust, lint, fibers, and flyings****)	X	X	…	…	X	X	X	X	X	X
Ingress of water (hosedown and splashing water)	…	…	…	…	…	…	X	X	X	X
Corrosive agents	…	X	…	X	…	X	…	X	…	X
Ingress of water (occasional temporary submersion)	…	…	…	…	…	…	…	…	X	X
Ingress of water (occasional prolonged submersion)	…	…	…	…	…	…	…	…	…	X

** External operating mechanisms are not required to be operable when the enclosure is ice covered.

*** External operating mechanisms are operable when the enclosure is ice covered. See subsection 5.6.

**** These fibers and flyings are not considered Class III type ignitable fibers or combustible flyings. For Class III type ignitable fibers or flyings see the *National Electrical Code*®, Article 500.5(D).

Source: NEMA 250-2014, *Enclosures for Electrical Equipment (1000 Volts Maximum)*, Table 2-2. Reproduced with permission of the National Electrical Manufacturers Association (NEMA).

Comparison of Specific Applications of Enclosures for Indoor Hazardous (Classified) Locations

If the installation is outdoors and/or additional protection is required by tables on pp. 118-119, a combination-type enclosure is required.

Provides a Degree of Protection against Atmospheres Typically Containing (See NFPA 497 & 499 for Complete Listing)	Class	Enclosure Types 7 and 8, Class I Groups**				Enclosure Type 9, Class II Groups			
		A	B	C	D	E	F	G	10
Acetylene	I	X	…	…	…	…	…	…	…
Hydrogen, manufactured gas	I	…	X	…	…	…	…	…	…
Diethyl ether, ethylene, cyclopropane	I	…	…	X	…	…	…	…	…
Gasoline, hexane, butane, naphtha, propane, acetone, toluene, isoprene	I	…	…	…	X	…	…	…	…
Metal dust	II	…	…	…	…	X	…	…	…
Carbon black, coal dust, coke dust	II	…	…	…	…	…	X	…	…
Flour, starch, grain dust	II	…	…	…	…	…	…	X	…
Fibers, flyings*	II	…	…	…	…	…	…	X	…
Methane with or without coal dust	MSHA	…	…	…	…	…	…	…	X

* For Class III type ignitable fibers or combustible flyings see the *National Electrical Code®*, Article 500.

** Due to the characteristics of the gas, vapor, or dust, a product suitable for one Class or Group may not be suitable for another Class or Group unless marked on the product.

Source: NEMA 250-2014, *Enclosures for Electrical Equipment (1000 Volts Maximum)*, Table B-1. Reproduced with permission of the National Electrical Manufacturers Association (NEMA).

Area Classification Definitions

Class	Division	Definition
I	1	A location where an ignitable concentration of flammable gases, vapors, or liquids can exist all of the time or some of the time under normal operating conditions.
I	2	A location where an ignitable concentration of flammable gases, vapors, or liquids are handled, processed, or used but not normally present in concentrations high enough to be ignitable.
II	1	A location where combustible dust may be in suspension in the air under normal conditions in sufficient quantities to produce explosive or ignitable mixtures (emitted into the air continuously, intermittently, or periodically), or where failure or malfunction of equipment might cause a hazardous location to exist and provide an ignition source with the simultaneous failure of electrical equipment, including locations in which combustible dust of an electrically conductive nature may be present.
II	2	A location in which combustible dust will not normally be in suspension nor will normal operations put dust in suspension, but where accumulation of dust may interfere with heat dissipation from electrical equipment or where accumulations near electrical equipment may be ignited.
III	1	A location where fiber and flyings may exist (manufactured, stored, or handled) that have the potential to become flammable or ignitable.
III	2	A location where fiber and flyings may exist (stored or handled) that have the potential to become flammable or ignitable.

7.2 IEC 60529 Ingress Protection Tables for Enclosures

Degrees of Protection Against Solid Foreign Objects Indicated by First Characteristic Numeral

First characteristic numeral	Degree of protection		Test conditions, see
	Brief description	Definition	
0	Non-protected	–	–
1	Protected against solid foreign objects of 50 mm ∅ and greater	The object probe, sphere of 50 mm ∅, shall not fully penetrate [1)]	13.2
2	Protected against solid foreign objects of 12,5 mm ∅ and greater	The object probe, sphere of 12,5 mm ∅, shall not fully penetrate [1)]	13.2
3	Protected against solid foreign objects of 2,5 mm ∅ and greater	The object probe, sphere of 2,5 mm ∅, shall not penetrate at all [1)]	13.2
4	Protected against solid foreign objects of 1,0 mm ∅ and greater	The object probe of 1,0 mm ∅, shall not penetrate at all [1)]	13.2
5	Dust-protected	Ingress of dust is not totally prevented, but dust shall not penetrate in a quantity to interfere with satisfactory operation of the apparatus or to impair safety	13.4 13.5
6	Dust-tight	No ingress of dust	13.4 13.6

[1)] The full diameter of the object probe shall not pass through an opening of the enclosure.

Degrees of Protection against Water Indicated by Second Characteristic Numeral

Second characteristic numeral	Degree of protection		Test conditions, see
	Brief description	Definition	
0	Non-protected	–	–
1	Protected against vertically falling water drops	Vertically falling drops shall have no harmful effects	14.2.1
2	Protected against vertically falling water drops when enclosure tilted up to 15°	Vertically falling drops shall have no harmful effects when the enclosure is tilted at any angle up to 15° on either side of the vertical	14.2.2
3	Protected against spraying water	Water sprayed at an angle up to 60° on either side of the vertical shall have no harmful effects	14.2.3
4	Protected against splashing water	Water splashed against the enclosure from any direction shall have no harmful effects	14.2.4
5	Protected against water jets	Water projected in jets against the enclosure from any direction shall have no harmful effects	14.2.5
6	Protected against powerful water jets	Water projected in powerful jets against the enclosure from any direction shall have no harmful effects	14.2.6
7	Protected against the effects of temporary immersion in water	Ingress of water in quantities causing harmful effects shall not be possible when the enclosure is temporarily immersed in water under standardized conditions of pressure and time	14.2.7
8	Protected against the effects of continuous immersion in water	Ingress of water in quantities causing harmful effects shall not be possible when the enclosure is continuously immersed in water under conditions which shall be agreed between manufacturer and user but which are more severe than for numeral 7	14.2.8
9	Protected against high pressure and temperature water jets	Water projected at high pressure and high temperature against the enclosure from any direction shall not have harmful effects	14.2.9

7.3 Pipe Data

Carbon Steel Pipe Schedules

Pipe Size (in.)	OD (in.)	OD (mm)	Weights and Dimensions of Seamless and Welded Steel Pipe (P.E.)												
			10	20	30	40	STD.	60	80	XS	100	120	140	160	XXS
1/8	**0.405**	**10.3**				0.068 **.024**	0.068 **.024**		0.095 **0.31**	0.095 **0.31**					
1/4	**0.540**	**13.7**				0.088 **0.43**	0.088 **0.43**		0.119 **0.54**	0.119 **0.54**					
3/8	**0.675**	**17.1**				0.091 **0.57**	0.091 **0.57**		0.126 **0.74**	0.126 **0.74**					
1/2	**0.840**	**21.3**				0.109 **0.85**	0.109 **0.85**		0.147 **1.09**	0.147 **1.09**				0.188 **1.31**	0.294 **1.72**
3/4	**1.050**	**26.7**				0.113 **1.13**	0.113 **1.13**		0.154 **1.48**	0.154 **1.48**				0.219 **1.95**	0.308 **2.44**
1	**1.315**	**33.4**				0.133 **1.68**	0.133 **1.68**		0.179 **2.17**	0.179 **2.17**				0.250 **2.85**	0.358 **3.66**
1-1/4	**1.660**	**42.2**				0.140 **2.27**	0.140 **2.27**		0.191 **3.00**	0.191 **3.00**				0.250 **3.77**	0.382 **5.22**
1-1/2	**1.900**	**48.3**				0.145 **2.72**	0.145 **2.72**		0.200 **3.63**	0.200 **3.63**				0.281 **4.86**	0.400 **6.41**
2	**2.375**	**60.3**				0.154 **3.66**	0.154 **3.66**		0.218 **5.03**	0.218 **5.03**				0.344 **7.47**	0.436 **9.04**
2-1/2	**2.875**	**73.0**				0.203 **5.80**	0.203 **5.80**		0.276 **7.67**	0.276 **7.67**				0.375 **10.02**	0.552 **13.71**
3	**3.500**	**88.9**				0.216 **7.58**	0.216 **7.58**		0.300 **10.26**	0.300 **10.26**				0.438 **14.34**	0.600 **18.60**
3-1/2	**4.000**	**101.6**				0.226 **9.12**	0.226 **9.12**		0.318 **12.52**	0.318 **12.52**					0.636 **22.85**
4	**4.500**	**114.3**				0.237 **10.80**	0.237 **10.80**	0.281 **12.67**	0.337 **15.00**	0.337 **15.00**		0.438 **19.02**		0.531 **22.53**	0.674 **27.57**
5	**5.563**	**141.3**				0.258 **14.63**	0.258 **14.63**		0.375 **20.80**	0.375 **20.80**		0.500 **27.06**		0.625 **32.99**	0.750 **38.59**
6	**6.625**	**168.3**				0.280 **18.99**	0.280 **18.99**		0.432 **28.60**	0.432 **28.60**		0.562 **36.43**		0.719 **45.39**	0.864 **53.21**

To convert the inch dimensions of outside diameters and wall thickness to millimeters, multiply the inch dimensions by 25.4.

MEDIUM TYPE = WALL THICKNESS IN INCHES
BOLD TYPE = WEIGHT PER FOOT IN POUNDS

Carbon Steel Pipe Schedules (continued)

Pipe Size (in.)	OD (in.)	OD (mm)	Weights and Dimensions of Seamless and Welded Steel Pipe (P.E.)												
			10	20	30	40	STD.	60	80	XS	100	120	140	160	XXS
8	**8.625**	**219.1**		0.250 **22.38**	0.277 **24.22**	0.322 **28.58**	0.322 **28.58**	0.406 **35.67**	0.500 **43.43**	0.500 **43.43**	0.594 **51.00**	0.719 **60.77**	0.812 **67.82**	0.906 **74.76**	0.875 **72.49**
10	**10.750**	**273.1**		0.250 **28.06**	0.307 **34.27**	0.365 **40.52**	0.365 **40.52**	0.500 **54.79**	0.594 **64.49**	0.500 **54.79**	0.719 **77.10**	0.844 **89.38**	1.000 **104.23**	1.125 **115.75**	1.000 **104.23**
12	**12.750**	**323.9**		0.250 **33.41**	0.330 **43.81**	0.406 **53.57**	0.375 **49.61**	0.562 **73.22**	0.688 **88.71**	0.500 **65.48**	0.844 **107.42**	1.000 **125.61**	1.125 **139.81**	1.312 **160.42**	1.000 **125.61**
14	**14.000**	**355.6**	0.250 **36.75**	0.312 **45.65**	0.375 **54.62**	0.438 **63.50**	0.375 **54.62**	0.594 **85.13**	0.750 **106.23**	0.500 **72.16**	0.938 **130.98**	1.094 **150.93**	1.250 **170.37**	1.406 **189.29**	
16	**16.000**	**406.4**	0.250 **42.09**	0.312 **52.32**	0.375 **62.64**	0.500 **82.85**	0.375 **62.64**	0.656 **107.60**	0.844 **136.74**	0.500 **82.85**	1.031 **164.98**	1.219 **192.61**	1.438 **223.85**	1.594 **245.48**	
18	**18.000**	**457.2**	0.250 **47.44**	0.312 **58.99**	0.438 **82.23**	0.562 **104.76**	0.375 **70.65**	0.750 **138.30**	0.938 **171.08**	0.500 **93.54**	1.156 **208.15**	1.375 **244.37**	1.562 **274.48**	1.781 **308.79**	
20	**20.000**	**508.0**	0.250 **52.78**	0.375 **78.67**	0.500 **104.23**	0.594 **123.23**	0.375 **78.67**	0.812 **166.56**	1.031 **209.06**	0.500 **104.23**	1.281 **256.34**	1.500 **296.65**	1.750 **341.41**	1.969 **379.53**	
24	**24.000**	**609.6**	0.250 **63.47**	0.375 **94.71**	0.562 **140.81**	0.688 **171.45**	0.375 **94.71**	0.969 **238.57**	1.219 **296.86**	0.500 **125.61**	1.531 **367.74**	1.812 **429.79**	2.062 **483.57**	2.344 **542.64**	
26	**26.000**	**660.4**	0.312 **85.68**	0.500 **136.30**			0.375 **102.72**			0.500 **136.30**					
30	**30.000**	**762.0**	0.312 **99.02**	0.500 **157.68**	0.625 **196.26**		0.375 **118.76**			0.500 **157.68**					
36	**36.000**	**914.4**	0.312 **119.03**	0.500 **189.75**	0.625 **236.35**	0.750 **282.62**	0.375 **142.81**			0.500 **189.75**					
42	**42.000**	**1067.0**					0.375 **166.86**			0.500 **221.82**					
48	**48.00**	**1219.0**					0.375 **190.92**			0.500 **253.89**					

To convert the inch dimensions of outside diameters and wall thickness to millimeters, multiply the inch dimensions by 25.4.

MEDIUM TYPE = WALL THICKNESS IN INCHES
BOLD TYPE = WEIGHT PER FOOT IN POUNDS

Source: Chicago Tube & Iron website, *https://www.chicagotube.com/products-2/stainless-pipe-tube-bar/seamless-pipe-a-312/*, accessed December 14, 2021. Reproduced with permission from Chicago Tube & Iron.

Seamless Stainless Pipe

ASTM/ASME SA312
Schedule 40S

Iron Pipe Size (in.)	Diameter (in.)		Wall Thickness (in.)	Weight (lb/ft)	Type 304/304L	Type 316/316L
	OD	ID				
1/8	0.405	0.269	0.068	0.244	X	X
1/4	0.504	0.364	0.088	0.424	X	X
3/8	0.675	0.493	0.091	0.567	X	X
1/2	0.840	0.622	0.109	0.851	X	X
3/4	1.050	0.824	0.113	1.131	X	X
1	1.315	1.049	0.133	1.679	X	X
1-1/4	1.660	1.380	0.140	2.273	X	X
1-1/2	1.900	1.610	0.145	2.718	X	X
2	2.375	2.067	0.154	3.653	X	X
2-1/2	2.875	2.469	0.203	5.793	X	X
3	3.500	3.068	0.216	7.576	X	X
3-1/2	4.000	3.548	0.226	9.109	X	X
4	4.500	4.026	0.237	10.790	X	X
5	5.563	5.047	0.258	14.620	X	X
6	6.625	6.065	0.280	18.970	X	X
8	8.625	7.981	0.322	28.550	X	X
10	10.750	10.020	0.365	40.480	X	X
12	12.750	12.000	0.375	49.560	X	X

Source: Chicago Tube & Iron website, *https://www.chicagotube.com/products-2/stainless-pipe-tube-bar/seamless-pipe-a-312/*, accessed December 17, 2021. Reproduced with permission from Chicago Tube & Iron.

Seamless Stainless Pipe

ASTM/ASME SA312
Schedule 80S

Iron Pipe Size (in.)	Diameter (in.)		Wall Thickness (in.)	Weight (lb/ft)	Type 304/304L	Type 316/316L
	OD	ID				
1/8	0.405	0.215	0.095	0.314	X	X
1/4	0.540	0.302	0.119	0.535	X	X
3/8	0.675	0.423	0.126	0.738	X	X
1/2	0.840	0.546	0.147	1.088	X	X
3/4	1.050	0.742	0.154	1.474	X	X
1	1.315	0.957	0.179	2.172	X	X
1-1/4	1.660	1.278	0.191	2.997	X	X
1-1/2	1.900	1.500	0.200	3.631	X	X
2	2.375	1.939	0.218	5.022	X	X
2-1/2	2.875	2.323	0.276	7.661	X	X
3	3.500	2.900	0.300	10.250	X	X
3-1/2	4.000	3.364	0.318	12.500	X	X
4	4.500	3.826	0.337	14.980	X	X
5	5.563	4.813	0.375	20.780	X	X
6	6.625	5.761	0.432	28.570	X	X
8	8.625	7.625	0.500	43.390	X	X

Source: Chicago Tube & Iron website, *https://www.chicagotube.com/products-2/stainless-pipe-tube-bar/seamless-pipe-a-312/*, accessed December 17, 2021. Reproduced with permission from Chicago Tube & Iron.

Seamless Stainless Pipe

ASTM/ASME SA312
Schedule 160

Iron Pipe Size (in.)	Diameter (in.)		Wall Thickness (in.)	Weight (lb/ft)	Type 304/304L	Type 316/316L
	OD	ID				
1/2	.840	.466	.188	1.309	X	X
3/4	1.050	.614	.219	1.944	X	X
1	1.315	.815	.250	2.844	X	X
1-1/4	1.660	1.160	.250	3.765	X	X
1-1/2	1.900	1.338	.281	4.859	X	X
2	2.375	1.689	.344	7.462	X	X
2-1/2	2.875	2.125	.375	10.010	X	X
3	3.500	2.624	.438	14.320	X	X
4	4.500	3.438	.531	22.510	X	X
5	5.563	4.313	.625	32.960	X	X
6	6.625	5.189	.719	45.350	X	X

Source: Chicago Tube & Iron website, *https://www.chicagotube.com/products-2/stainless-pipe-tube-bar/seamless-pipe-a-312/*, accessed December 17, 2021. Reproduced with permission from Chicago Tube & Iron.

Seamless Stainless Pipe

ASTM/ASME SA312
XX HVY

Iron Pipe Size (in.)	Diameter (in.)		Wall Thickness (in.)	Weight (lb/ft)	Type 304/304L	Type 316/316L
	OD	ID				
1/2	.840	.252	.294	1.714	X	X
3/4	1.050	.434	.308	2.441	X	X
1	1.315	.599	.358	3.659	X	X
1-1/2	1.900	1.100	.400	6.408	X	X
2	2.375	1.503	.436	9.029	X	X

Source: Chicago Tube & Iron website, *https://www.chicagotube.com/products-2/stainless-pipe-tube-bar/seamless-pipe-a-312/*, accessed December 17, 2021. Reproduced with permission from Chicago Tube & Iron.

7.4 Steam Tables

The tables in this section are from *ASME Steam Tables, Compact Edition*, published by the American Society of Mechanical Engineers (ASME) and are reproduced with permission from ASME.

Properties of Saturated Water and Steam (Temperature)

Temp. °F	Pressure psia	Volume, ft³/lbm v_L	v_V	Enthalpy, Btu/lbm h_L	h_V	Entropy, Btu/(lbm·°R) s_L	s_V	Temp. °F
32	0.08865	0.016022	3302.0	-0.018	1075.2	0.0000	2.1868	32
35	0.09998	0.016020	2945.5	3.004	1076.5	0.0061	2.1762	35
40	0.12173	0.016020	2443.4	8.032	1078.7	0.0162	2.1590	40
45	0.14757	0.016021	2035.6	13.052	1080.9	0.0262	2.1421	45
50	0.17813	0.016024	1702.9	18.066	1083.1	0.0361	2.1257	50
55	0.21414	0.016029	1430.3	23.074	1085.3	0.0459	2.1097	55
60	0.25639	0.016035	1206.1	28.079	1087.4	0.0555	2.0941	60
65	0.30579	0.016043	1020.8	33.080	1089.6	0.0651	2.0788	65
70	0.36334	0.016052	867.19	38.078	1091.8	0.0746	2.0640	70
75	0.43015	0.016062	739.30	43.074	1094.0	0.0840	2.0495	75
80	0.50744	0.016074	632.44	48.069	1096.1	0.0933	2.0353	80
85	0.59656	0.016086	542.84	53.062	1098.3	0.1025	2.0215	85
90	0.69899	0.016100	467.45	58.054	1100.4	0.1116	2.0080	90
95	0.81636	0.016115	403.79	63.046	1102.6	0.1207	1.9948	95
100	0.95044	0.016131	349.87	68.037	1104.7	0.1296	1.9819	100
105	1.1032	0.016148	304.05	73.028	1106.9	0.1385	1.9693	105
110	1.2766	0.016166	264.99	78.019	1109.0	0.1473	1.9570	110
115	1.4730	0.016185	231.60	83.010	1111.1	0.1560	1.9450	115
120	1.6949	0.016205	202.96	88.002	1113.2	0.1647	1.9333	120
125	1.9449	0.016225	178.34	92.994	1115.3	0.1732	1.9218	125
130	2.2258	0.016247	157.10	97.987	1117.4	0.1817	1.9106	130
135	2.5407	0.016269	138.74	102.98	1119.5	0.1902	1.8996	135
140	2.8929	0.016293	122.82	107.98	1121.6	0.1985	1.8888	140
145	3.2858	0.016317	108.99	112.97	1123.7	0.2068	1.8783	145
150	3.7231	0.016342	96.934	117.97	1125.7	0.2151	1.8680	150
155	4.2089	0.016367	86.405	122.97	1127.8	0.2232	1.8580	155
160	4.7472	0.016394	77.186	127.98	1129.8	0.2313	1.8481	160
165	5.3426	0.016421	69.097	132.98	1131.9	0.2394	1.8384	165
170	5.9998	0.016449	61.982	137.99	1133.9	0.2474	1.8290	170
175	6.7237	0.016478	55.710	143.00	1135.9	0.2553	1.8197	175
180	7.5196	0.016507	50.171	148.01	1137.9	0.2631	1.8106	180
185	8.3930	0.016538	45.267	153.03	1139.9	0.2709	1.8017	185
190	9.3497	0.016569	40.918	158.05	1141.8	0.2787	1.7930	190
195	10.396	0.016601	37.053	163.07	1143.8	0.2864	1.7844	195
200	11.538	0.016633	33.611	168.10	1145.7	0.2940	1.7760	200
205	12.782	0.016667	30.540	173.13	1147.6	0.3016	1.7678	205
210	14.136	0.016701	27.796	178.17	1149.5	0.3092	1.7597	210
215	15.606	0.016736	25.339	183.20	1151.4	0.3167	1.7517	215
220	17.201	0.016771	23.135	188.25	1153.3	0.3241	1.7440	220
225	18.928	0.016808	21.155	193.30	1155.1	0.3315	1.7363	225
230	20.795	0.016845	19.373	198.35	1157.0	0.3388	1.7288	230
235	22.811	0.016883	17.766	203.41	1158.8	0.3461	1.7214	235
240	24.985	0.016921	16.316	208.47	1160.5	0.3534	1.7141	240
245	27.326	0.016961	15.004	213.54	1162.3	0.3606	1.7070	245
250	29.843	0.017001	13.816	218.62	1164.0	0.3678	1.7000	250

Properties of Saturated Water and Steam (Temperature)

Temp. °F	Pressure psia	Volume, ft³/lbm v_L	v_V	Enthalpy, Btu/lbm h_L	h_V	Entropy, Btu/(lbm-°R) s_L	s_V	Temp. °F
255	32.546	0.017042	12.739	223.70	1165.7	0.3749	1.6930	255
260	35.445	0.017084	11.760	228.79	1167.4	0.3820	1.6862	260
265	38.551	0.017127	10.870	233.88	1169.1	0.3890	1.6796	265
270	41.874	0.017170	10.059	238.99	1170.7	0.3960	1.6730	270
275	45.426	0.017214	9.3196	244.10	1172.3	0.4030	1.6665	275
280	49.218	0.017259	8.6442	249.21	1173.9	0.4099	1.6601	280
285	53.261	0.017305	8.0265	254.34	1175.5	0.4168	1.6538	285
290	57.567	0.017352	7.4610	259.47	1177.0	0.4236	1.6476	290
295	62.150	0.017400	6.9425	264.61	1178.5	0.4305	1.6414	295
300	67.021	0.017449	6.4666	269.76	1180.0	0.4372	1.6354	300
305	72.193	0.017498	6.0293	274.91	1181.4	0.4440	1.6294	305
310	77.680	0.017548	5.6270	280.08	1182.8	0.4507	1.6235	310
315	83.496	0.017600	5.2564	285.26	1184.2	0.4574	1.6177	315
320	89.654	0.017652	4.9148	290.44	1185.5	0.4640	1.6120	320
325	96.168	0.017705	4.5994	295.64	1186.8	0.4706	1.6063	325
330	103.05	0.017760	4.3079	300.85	1188.0	0.4772	1.6007	330
335	110.32	0.017815	4.0384	306.07	1189.3	0.4838	1.5952	335
340	118.00	0.017871	3.7888	311.30	1190.5	0.4903	1.5897	340
345	126.08	0.017929	3.5574	316.54	1191.6	0.4968	1.5843	345
350	134.60	0.017987	3.3428	321.79	1192.7	0.5033	1.5789	350
355	143.57	0.018047	3.1435	327.06	1193.8	0.5097	1.5736	355
360	153.00	0.018108	2.9582	332.34	1194.8	0.5162	1.5684	360
365	162.92	0.018170	2.7859	337.63	1195.8	0.5226	1.5632	365
370	173.33	0.018233	2.6254	342.94	1196.7	0.5289	1.5580	370
375	184.25	0.018297	2.4758	348.26	1197.6	0.5353	1.5529	375
380	195.71	0.018363	2.3363	353.59	1198.5	0.5416	1.5478	380
385	207.72	0.018430	2.2061	358.94	1199.3	0.5479	1.5428	385
390	220.29	0.018498	2.0843	364.31	1200.1	0.5542	1.5378	390
395	233.45	0.018568	1.9705	369.70	1200.8	0.5605	1.5329	395
400	247.22	0.018639	1.8640	375.10	1201.5	0.5667	1.5280	400
405	261.61	0.018711	1.7643	380.52	1202.1	0.5729	1.5231	405
410	276.64	0.018785	1.6708	385.95	1202.6	0.5791	1.5182	410
415	292.34	0.018861	1.5830	391.41	1203.2	0.5853	1.5134	415
420	308.71	0.018938	1.5007	396.89	1203.6	0.5915	1.5086	420
425	325.79	0.019016	1.4234	402.38	1204.0	0.5977	1.5038	425
430	343.59	0.019097	1.3507	407.90	1204.4	0.6038	1.4991	430
435	362.13	0.019179	1.2822	413.44	1204.7	0.6100	1.4943	435
440	381.44	0.019263	1.2179	419.01	1204.9	0.6161	1.4896	440
445	401.53	0.019349	1.1572	424.59	1205.1	0.6222	1.4849	445
450	422.42	0.019437	1.1000	430.20	1205.2	0.6283	1.4802	450
455	444.14	0.019527	1.0461	435.84	1205.2	0.6344	1.4755	455
460	466.71	0.019619	0.9952	441.50	1205.2	0.6405	1.4709	460
465	490.15	0.019713	0.9471	447.19	1205.1	0.6466	1.4662	465
470	514.48	0.019810	0.9016	452.91	1204.9	0.6526	1.4615	470
475	539.73	0.019908	0.8586	458.66	1204.7	0.6587	1.4569	475

Properties of Saturated Water and Steam (Temperature)

Temp. °F	Pressure psia	Volume, ft³/lbm v_L	v_V	Enthalpy, Btu/lbm h_L	h_V	Entropy, Btu/(lbm-°R) s_L	s_V	Temp. °F
480	565.92	0.02001	0.8180	464.44	1204.4	0.6648	1.4522	480
485	593.07	0.02011	0.7795	470.25	1204.0	0.6708	1.4475	485
490	621.20	0.02022	0.7430	476.10	1203.5	0.6769	1.4429	490
495	650.35	0.02033	0.7084	481.97	1203.0	0.6829	1.4382	495
500	680.53	0.02044	0.6756	487.89	1202.3	0.6890	1.4335	500
505	711.77	0.02056	0.6445	493.84	1201.6	0.6951	1.4288	505
510	744.09	0.02068	0.6149	499.83	1200.8	0.7011	1.4241	510
515	777.52	0.02080	0.5868	505.86	1199.9	0.7072	1.4193	515
520	812.08	0.02092	0.5601	511.93	1198.9	0.7133	1.4145	520
525	847.81	0.02105	0.5347	518.05	1197.9	0.7194	1.4098	525
530	884.73	0.02118	0.5105	524.21	1196.7	0.7255	1.4049	530
535	922.85	0.02132	0.4875	530.42	1195.4	0.7316	1.4001	535
540	962.23	0.02146	0.4656	536.69	1194.0	0.7377	1.3952	540
545	1002.9	0.02161	0.4446	543.00	1192.5	0.7438	1.3903	545
550	1044.8	0.02176	0.4247	549.37	1190.8	0.7500	1.3853	550
555	1088.1	0.02192	0.4056	555.80	1189.1	0.7562	1.3803	555
560	1132.7	0.02208	0.3875	562.29	1187.2	0.7624	1.3752	560
565	1178.7	0.02225	0.3701	568.85	1185.2	0.7686	1.3701	565
570	1226.2	0.02242	0.3535	575.48	1183.0	0.7749	1.3649	570
575	1275.1	0.02260	0.3376	582.18	1180.7	0.7812	1.3596	575
580	1325.4	0.02279	0.3223	588.95	1178.2	0.7875	1.3543	580
585	1377.3	0.02299	0.3077	595.81	1175.6	0.7939	1.3489	585
590	1430.8	0.02319	0.2938	602.75	1172.8	0.8003	1.3433	590
595	1485.8	0.02341	0.2803	609.79	1169.8	0.8067	1.3377	595
600	1542.5	0.02363	0.2675	616.93	1166.6	0.8133	1.3320	600
605	1600.8	0.02387	0.2551	624.17	1163.2	0.8198	1.3261	605
610	1660.8	0.02411	0.2432	631.53	1159.6	0.8265	1.3202	610
615	1722.6	0.02437	0.2317	639.01	1155.7	0.8332	1.3140	615
620	1786.1	0.02465	0.2207	646.62	1151.6	0.8400	1.3077	620
625	1851.5	0.02494	0.2101	654.38	1147.2	0.8469	1.3012	625
630	1918.8	0.02525	0.1998	662.30	1142.5	0.8539	1.2945	630
635	1988.0	0.02558	0.1899	670.40	1137.4	0.8610	1.2876	635
640	2059.2	0.02593	0.1802	678.69	1132.0	0.8683	1.2804	640
645	2132.4	0.02631	0.1709	687.21	1126.1	0.8757	1.2729	645
650	2207.7	0.02672	0.1618	695.99	1119.7	0.8833	1.2651	650
655	2285.2	0.02717	0.1530	705.06	1112.8	0.8911	1.2569	655
660	2364.8	0.02766	0.1444	714.47	1105.3	0.8991	1.2482	660
665	2446.8	0.02821	0.1359	724.30	1097.2	0.9075	1.2390	665
670	2531.2	0.02883	0.1276	734.63	1088.1	0.9163	1.2292	670
675	2618.0	0.02953	0.1194	745.57	1078.0	0.9255	1.2185	675
680	2707.3	0.03035	0.1112	757.30	1066.6	0.9354	1.2068	680
685	2799.3	0.03133	0.1030	770.10	1053.5	0.9462	1.1937	685
690	2894.2	0.03256	0.09444	784.45	1037.9	0.9582	1.1786	690
695	2991.9	0.03422	0.08531	801.35	1018.3	0.9723	1.1602	695
700	3092.9	0.03683	0.07466	823.64	990.64	0.9910	1.1350	700
705	3197.9	0.04662	0.05338	882.44	913.89	1.0409	1.0679	705
T_c	3200.1	0.0497	0.0497	897.48	897.48	1.0538	1.0538	T_c

T_c = 705.1028 °F

Properties of Saturated Water and Steam (Pressure)

Pressure psia	Temp. °F	Volume, ft³/lbm v_L	v_V	Enthalpy, Btu/lbm h_L	h_V	Entropy, Btu/(lbm-°R) s_L	s_V	Pressure psia
0.1	35.00	0.016020	2945.0	3.009	1076.5	0.0061	2.1762	**0.1**
0.2	53.13	0.016027	1525.9	21.204	1084.4	0.0422	2.1156	**0.2**
0.3	64.45	0.016042	1039.4	32.532	1089.4	0.0641	2.0805	**0.3**
0.5	79.55	0.016073	641.32	47.618	1095.9	0.0925	2.0366	**0.5**
0.7	90.05	0.016100	466.81	58.100	1100.4	0.1117	2.0079	**0.7**
1.0	101.69	0.016137	333.51	69.728	1105.4	0.1326	1.9776	**1.0**
1.5	115.64	0.016187	227.68	83.650	1111.4	0.1571	1.9435	**1.5**
2.0	126.03	0.016230	173.72	94.019	1115.8	0.1750	1.9195	**2.0**
3.0	141.42	0.016299	118.70	109.39	1122.2	0.2009	1.8858	**3.0**
4.0	152.91	0.016356	90.628	120.89	1126.9	0.2198	1.8621	**4.0**
6	170.00	0.016449	61.979	137.99	1133.9	0.2474	1.8290	**6**
8	182.81	0.016524	47.345	150.83	1139.0	0.2675	1.8056	**8**
10	193.16	0.016589	38.423	161.22	1143.1	0.2836	1.7875	**10**
12	201.91	0.016646	32.398	170.02	1146.4	0.2969	1.7728	**12**
14	209.52	0.016697	28.048	177.68	1149.4	0.3084	1.7605	**14**
16	216.27	0.016745	24.755	184.49	1151.9	0.3186	1.7497	**16**
18	222.36	0.016788	22.173	190.63	1154.2	0.3276	1.7403	**18**
20	227.92	0.016829	20.092	196.25	1156.2	0.3358	1.7319	**20**
25	240.03	0.016922	16.306	208.51	1160.5	0.3534	1.7141	**25**
30	250.30	0.017003	13.748	218.93	1164.1	0.3682	1.6995	**30**
35	259.25	0.017078	11.900	228.03	1167.2	0.3809	1.6873	**35**
40	267.22	0.017146	10.500	236.15	1169.8	0.3921	1.6766	**40**
45	274.42	0.017209	9.4023	243.50	1172.2	0.4022	1.6672	**45**
50	280.99	0.017268	8.5171	250.23	1174.2	0.4113	1.6588	**50**
55	287.06	0.017325	7.7878	256.45	1176.1	0.4196	1.6512	**55**
60	292.69	0.017378	7.1762	262.24	1177.8	0.4273	1.6443	**60**
65	297.96	0.017429	6.6557	267.66	1179.4	0.4345	1.6378	**65**
70	302.92	0.017477	6.2071	272.76	1180.8	0.4412	1.6319	**70**
75	307.59	0.017524	5.8164	277.59	1182.1	0.4475	1.6264	**75**
80	312.03	0.017569	5.4730	282.18	1183.3	0.4534	1.6212	**80**
85	316.25	0.017613	5.1686	286.55	1184.5	0.4590	1.6163	**85**
90	320.27	0.017655	4.8969	290.73	1185.6	0.4644	1.6117	**90**
95	324.12	0.017696	4.6528	294.73	1186.6	0.4695	1.6073	**95**
100	327.82	0.017736	4.4324	298.57	1187.5	0.4744	1.6032	**100**
110	334.78	0.017813	4.0496	305.84	1189.2	0.4835	1.5954	**110**
120	341.26	0.017886	3.7286	312.62	1190.7	0.4920	1.5883	**120**
130	347.33	0.017956	3.4554	318.98	1192.1	0.4998	1.5818	**130**
140	353.04	0.018023	3.2199	324.99	1193.4	0.5072	1.5757	**140**
150	358.43	0.018089	3.0148	330.68	1194.5	0.5141	1.5700	**150**
160	363.55	0.018152	2.8345	336.10	1195.5	0.5207	1.5647	**160**
170	368.43	0.018213	2.6746	341.27	1196.5	0.5269	1.5596	**170**
180	373.08	0.018272	2.5320	346.21	1197.3	0.5328	1.5549	**180**
190	377.54	0.018330	2.4038	350.96	1198.1	0.5385	1.5503	**190**
200	381.81	0.018387	2.2880	355.53	1198.8	0.5439	1.5460	**200**
210	385.92	0.018442	2.1829	359.94	1199.5	0.5491	1.5419	**210**

Properties of Saturated Water and Steam (Pressure)

Pressure psia	Temp. °F	Volume, ft³/lbm v_L	v_V	Enthalpy, Btu/lbm h_L	h_V	Entropy, Btu/(lbm-°R) s_L	s_V	Pressure psia
0.1	35.00	0.016020	2945.0	3.009	1076.5	0.0061	2.1762	**0.1**
0.2	53.13	0.016027	1525.9	21.204	1084.4	0.0422	2.1156	**0.2**
0.3	64.45	0.016042	1039.4	32.532	1089.4	0.0641	2.0805	**0.3**
0.5	79.55	0.016073	641.32	47.618	1095.9	0.0925	2.0366	**0.5**
0.7	90.05	0.016100	466.81	58.100	1100.4	0.1117	2.0079	**0.7**
1.0	101.69	0.016137	333.51	69.728	1105.4	0.1326	1.9776	**1.0**
1.5	115.64	0.016187	227.68	83.650	1111.4	0.1571	1.9435	**1.5**
2.0	126.03	0.016230	173.72	94.019	1115.8	0.1750	1.9195	**2.0**
3.0	141.42	0.016299	118.70	109.39	1122.2	0.2009	1.8858	**3.0**
4.0	152.91	0.016356	90.628	120.89	1126.9	0.2198	1.8621	**4.0**
6	170.00	0.016449	61.979	137.99	1133.9	0.2474	1.8290	**6**
8	182.81	0.016524	47.345	150.83	1139.0	0.2675	1.8056	**8**
10	193.16	0.016589	38.423	161.22	1143.1	0.2836	1.7875	**10**
12	201.91	0.016646	32.398	170.02	1146.4	0.2969	1.7728	**12**
14	209.52	0.016697	28.048	177.68	1149.4	0.3084	1.7605	**14**
16	216.27	0.016745	24.755	184.49	1151.9	0.3186	1.7497	**16**
18	222.36	0.016788	22.173	190.63	1154.2	0.3276	1.7403	**18**
20	227.92	0.016829	20.092	196.25	1156.2	0.3358	1.7319	**20**
25	240.03	0.016922	16.306	208.51	1160.5	0.3534	1.7141	**25**
30	250.30	0.017003	13.748	218.93	1164.1	0.3682	1.6995	**30**
35	259.25	0.017078	11.900	228.03	1167.2	0.3809	1.6873	**35**
40	267.22	0.017146	10.500	236.15	1169.8	0.3921	1.6766	**40**
45	274.42	0.017209	9.4023	243.50	1172.2	0.4022	1.6672	**45**
50	280.99	0.017268	8.5171	250.23	1174.2	0.4113	1.6588	**50**
55	287.06	0.017325	7.7878	256.45	1176.1	0.4196	1.6512	**55**
60	292.69	0.017378	7.1762	262.24	1177.8	0.4273	1.6443	**60**
65	297.96	0.017429	6.6557	267.66	1179.4	0.4345	1.6378	**65**
70	302.92	0.017477	6.2071	272.76	1180.8	0.4412	1.6319	**70**
75	307.59	0.017524	5.8164	277.59	1182.1	0.4475	1.6264	**75**
80	312.03	0.017569	5.4730	282.18	1183.3	0.4534	1.6212	**80**
85	316.25	0.017613	5.1686	286.55	1184.5	0.4590	1.6163	**85**
90	320.27	0.017655	4.8969	290.73	1185.6	0.4644	1.6117	**90**
95	324.12	0.017696	4.6528	294.73	1186.6	0.4695	1.6073	**95**
100	327.82	0.017736	4.4324	298.57	1187.5	0.4744	1.6032	**100**
110	334.78	0.017813	4.0496	305.84	1189.2	0.4835	1.5954	**110**
120	341.26	0.017886	3.7286	312.62	1190.7	0.4920	1.5883	**120**
130	347.33	0.017956	3.4554	318.98	1192.1	0.4998	1.5818	**130**
140	353.04	0.018023	3.2199	324.99	1193.4	0.5072	1.5757	**140**
150	358.43	0.018089	3.0148	330.68	1194.5	0.5141	1.5700	**150**
160	363.55	0.018152	2.8345	336.10	1195.5	0.5207	1.5647	**160**
170	368.43	0.018213	2.6746	341.27	1196.5	0.5269	1.5596	**170**
180	373.08	0.018272	2.5320	346.21	1197.3	0.5328	1.5549	**180**
190	377.54	0.018330	2.4038	350.96	1198.1	0.5385	1.5503	**190**
200	381.81	0.018387	2.2880	355.53	1198.8	0.5439	1.5460	**200**
210	385.92	0.018442	2.1829	359.94	1199.5	0.5491	1.5419	**210**

Properties of Saturated Water and Steam (Pressure)

Pressure psia	Temp. °F	Volume, ft³/lbm v_L	v_V	Enthalpy, Btu/lbm h_L	h_V	Entropy, Btu/(lbm-°R) s_L	s_V	Pressure psia
220	389.89	0.018496	2.0870	364.19	1200.1	0.5541	1.5379	**220**
230	393.71	0.018549	1.9992	368.30	1200.6	0.5588	1.5342	**230**
240	397.41	0.018601	1.9184	372.29	1201.1	0.5635	1.5305	**240**
250	400.98	0.018653	1.8439	376.16	1201.6	0.5679	1.5270	**250**
260	404.45	0.018703	1.7749	379.92	1202.0	0.5723	1.5236	**260**
270	407.82	0.018753	1.7108	383.58	1202.4	0.5764	1.5203	**270**
280	411.09	0.018801	1.6512	387.14	1202.8	0.5805	1.5172	**280**
290	414.27	0.018849	1.5955	390.61	1203.1	0.5844	1.5141	**290**
300	417.37	0.018897	1.5434	394.00	1203.4	0.5883	1.5111	**300**
320	423.33	0.018990	1.4487	400.54	1203.9	0.5956	1.5054	**320**
340	429.01	0.019081	1.3647	406.81	1204.3	0.6026	1.5000	**340**
360	434.43	0.019170	1.2898	412.82	1204.6	0.6093	1.4949	**360**
380	439.63	0.019257	1.2224	418.60	1204.9	0.6156	1.4900	**380**
400	444.63	0.019343	1.1616	424.18	1205.0	0.6217	1.4853	**400**
420	449.43	0.019427	1.1064	429.56	1205.1	0.6276	1.4807	**420**
440	454.06	0.019510	1.0560	434.78	1205.2	0.6333	1.4764	**440**
460	458.53	0.019592	1.0098	439.84	1205.2	0.6387	1.4722	**460**
480	462.86	0.019672	0.9673	444.75	1205.1	0.6440	1.4682	**480**
500	467.05	0.019752	0.9282	449.53	1205.0	0.6490	1.4643	**500**
520	471.11	0.019831	0.8919	454.19	1204.9	0.6540	1.4605	**520**
540	475.05	0.019909	0.8582	458.72	1204.7	0.6588	1.4568	**540**
560	478.89	0.019987	0.8268	463.15	1204.4	0.6634	1.4532	**560**
580	482.62	0.02006	0.7976	467.48	1204.2	0.6679	1.4498	**580**
600	486.25	0.02014	0.7702	471.71	1203.9	0.6723	1.4464	**600**
620	489.79	0.02022	0.7445	475.85	1203.5	0.6766	1.4430	**620**
640	493.24	0.02029	0.7203	479.91	1203.2	0.6808	1.4398	**640**
660	496.62	0.02037	0.6976	483.88	1202.8	0.6849	1.4367	**660**
680	499.91	0.02044	0.6761	487.79	1202.4	0.6889	1.4336	**680**
700	503.14	0.02051	0.6559	491.62	1201.9	0.6928	1.4305	**700**
720	506.29	0.02059	0.6367	495.38	1201.4	0.6966	1.4276	**720**
740	509.38	0.02066	0.6185	499.08	1200.9	0.7004	1.4246	**740**
760	512.40	0.02073	0.6012	502.72	1200.4	0.7040	1.4218	**760**
780	515.36	0.02081	0.5848	506.30	1199.9	0.7076	1.4190	**780**
800	518.27	0.02088	0.5692	509.83	1199.3	0.7112	1.4162	**800**
820	521.12	0.02095	0.5543	513.30	1198.7	0.7146	1.4135	**820**
840	523.92	0.02102	0.5401	516.73	1198.1	0.7181	1.4108	**840**
860	526.67	0.02110	0.5265	520.10	1197.5	0.7214	1.4082	**860**
880	529.37	0.02117	0.5135	523.43	1196.8	0.7247	1.4056	**880**
900	532.02	0.02124	0.5011	526.72	1196.2	0.7279	1.4030	**900**
920	534.63	0.02131	0.4892	529.96	1195.5	0.7311	1.4005	**920**
940	537.20	0.02138	0.4777	533.17	1194.8	0.7343	1.3980	**940**
960	539.72	0.02146	0.4667	536.34	1194.1	0.7374	1.3955	**960**
980	542.21	0.02153	0.4562	539.47	1193.3	0.7404	1.3930	**980**
1000	544.65	0.02160	0.4461	542.56	1192.6	0.7434	1.3906	**1000**
1050	550.61	0.02178	0.4223	550.15	1190.6	0.7507	1.3847	**1050**

Properties of Saturated Water and Steam (Pressure)

Pressure psia	Temp. °F	Volume, ft³/lbm v_L	v_V	Enthalpy, Btu/lbm h_L	h_V	Entropy, Btu/(lbm-°R) s_L	s_V	Pressure psia
1100	556.35	0.02196	0.4006	557.55	1188.6	0.7578	1.3789	1100
1150	561.90	0.02214	0.3808	564.77	1186.4	0.7647	1.3733	1150
1200	567.26	0.02233	0.3625	571.84	1184.2	0.7714	1.3677	1200
1250	572.46	0.02251	0.3456	578.76	1181.9	0.7780	1.3623	1250
1300	577.50	0.02270	0.3299	585.55	1179.5	0.7843	1.3570	1300
1350	582.39	0.02288	0.3153	592.21	1177.0	0.7905	1.3517	1350
1400	587.14	0.02307	0.3017	598.77	1174.4	0.7966	1.3465	1400
1450	591.76	0.02327	0.2890	605.23	1171.8	0.8025	1.3414	1450
1500	596.27	0.02346	0.2770	611.59	1169.0	0.8084	1.3363	1500
1550	600.66	0.02366	0.2658	617.87	1166.2	0.8141	1.3312	1550
1600	604.93	0.02386	0.2553	624.07	1163.3	0.8197	1.3262	1600
1650	609.11	0.02407	0.2453	630.21	1160.3	0.8253	1.3212	1650
1700	613.19	0.02428	0.2358	636.28	1157.2	0.8307	1.3163	1700
1750	617.18	0.02449	0.2269	642.30	1154.0	0.8361	1.3113	1750
1800	621.07	0.02471	0.2184	648.27	1150.7	0.8415	1.3063	1800
1850	624.89	0.02493	0.2103	654.20	1147.3	0.8467	1.3014	1850
1900	628.62	0.02516	0.2026	660.09	1143.8	0.8519	1.2964	1900
1950	632.27	0.02539	0.1952	665.96	1140.2	0.8571	1.2914	1950
2000	635.85	0.02563	0.1882	671.80	1136.5	0.8622	1.2864	2000
2050	639.36	0.02588	0.1814	677.62	1132.7	0.8673	1.2814	2050
2100	642.81	0.02614	0.1750	683.44	1128.7	0.8724	1.2763	2100
2150	646.18	0.02640	0.1687	689.26	1124.6	0.8774	1.2711	2150
2200	649.50	0.02668	0.1627	695.09	1120.4	0.8825	1.2659	2200
2250	652.75	0.02696	0.1569	700.93	1116.0	0.8875	1.2606	2250
2300	655.94	0.02726	0.1514	706.80	1111.5	0.8926	1.2553	2300
2350	659.08	0.02757	0.1459	712.71	1106.8	0.8976	1.2498	2350
2400	662.16	0.02789	0.1407	718.67	1101.9	0.9027	1.2443	2400
2450	665.19	0.02823	0.1356	724.69	1096.8	0.9078	1.2387	2450
2500	668.17	0.02859	0.1307	730.78	1091.5	0.9130	1.2329	2500
2550	671.10	0.02897	0.1258	736.97	1086.0	0.9183	1.2269	2550
2600	673.98	0.02938	0.1211	743.27	1080.2	0.9236	1.2208	2600
2650	676.81	0.02981	0.1165	749.71	1074.1	0.9290	1.2144	2650
2700	679.60	0.03028	0.1119	756.32	1067.6	0.9346	1.2078	2700
2750	682.34	0.03078	0.1074	763.13	1060.7	0.9403	1.2009	2750
2800	685.03	0.03134	0.1029	770.20	1053.4	0.9462	1.1936	2800
2850	687.69	0.03195	0.09843	777.59	1045.5	0.9524	1.1859	2850
2900	690.30	0.03264	0.09391	785.39	1036.8	0.9590	1.1776	2900
2950	692.88	0.03344	0.08930	793.75	1027.3	0.9660	1.1686	2950
3000	695.41	0.03438	0.08453	802.90	1016.5	0.9736	1.1585	3000
3050	697.90	0.03554	0.07945	813.22	1003.8	0.9823	1.1469	3050
3100	700.35	0.03708	0.07381	825.57	988.14	0.9926	1.1328	3100
3150	702.75	0.03947	0.06686	842.34	966.17	1.0068	1.1133	3150
3200	705.10	0.04897	0.05052	893.85	901.07	1.0507	1.0569	3200
p_c	705.1028	0.0497	0.0497	897.48	897.48	1.0538	1.0538	p_c

p_c = 3200.11 psia

Superheated Steam

Pressure psia (Sat. T)		Temperature—Degrees Fahrenheit 200	250	300	350	400	450	500	600	700	800	900	1000	1200
1	*v*	392.53	422.42	452.28	482.11	511.93	541.74	571.55	631.15	690.74	750.32	809.91	869.48	988.64
(101.69)	*h*	1150.1	1172.8	1195.7	1218.6	1241.8	1265.1	1288.6	1336.2	1384.6	1433.9	1484.1	1535.1	1640.0
	s	2.0510	2.0842	2.1152	2.1445	2.1723	2.1986	2.2238	2.2710	2.3146	2.3554	2.3937	2.4299	2.4973
5	*v*	78.155	84.220	90.248	96.254	102.25	108.23	114.21	126.15	138.09	150.02	161.94	173.87	197.71
(162.18)	*h*	1148.5	1171.7	1194.8	1218.0	1241.3	1264.7	1288.2	1335.9	1384.4	1433.7	1483.9	1535.0	1640.0
	s	1.8716	1.9055	1.9370	1.9665	1.9944	2.0209	2.0461	2.0934	2.1371	2.1779	2.2162	2.2525	2.3198
10	*v*	38.851	41.942	44.993	48.022	51.036	54.042	57.042	63.030	69.008	74.980	80.949	86.915	98.841
(193.16)	*h*	1146.4	1170.2	1193.8	1217.2	1240.6	1264.1	1287.8	1335.6	1384.2	1433.5	1483.8	1534.9	1639.9
	s	1.7926	1.8275	1.8595	1.8893	1.9174	1.9440	1.9693	2.0167	2.0605	2.1013	2.1397	2.1760	2.2434
15	*v*		27.846	29.906	31.943	33.966	35.979	37.986	41.988	45.981	49.968	53.950	57.931	65.886
(212.99)	*h*		1168.7	1192.7	1216.3	1239.9	1263.6	1287.3	1335.3	1383.9	1433.3	1483.6	1534.7	1639.8
	s		1.7811	1.8137	1.8438	1.8721	1.8989	1.9243	1.9718	2.0156	2.0565	2.0949	2.1312	2.1986
20	*v*		20.796	22.362	23.903	25.430	26.947	28.458	31.467	34.467	37.461	40.451	43.438	49.408
(227.92)	*h*		1167.2	1191.6	1215.5	1239.3	1263.0	1286.9	1334.9	1383.6	1433.1	1483.4	1534.6	1639.7
	s		1.7477	1.7808	1.8113	1.8398	1.8667	1.8922	1.9398	1.9838	2.0247	2.0631	2.0994	2.1669
25	*v*		16.565	17.835	19.079	20.308	21.528	22.741	25.155	27.559	29.957	32.352	34.743	39.521
(240.03)	*h*		1165.6	1190.4	1214.6	1238.6	1262.5	1286.4	1334.6	1383.4	1432.9	1483.3	1534.5	1639.6
	s		1.7213	1.7551	1.7859	1.8146	1.8417	1.8673	1.9150	1.9590	2.0000	2.0384	2.0748	2.1422
30	*v*			14.816	15.863	16.894	17.915	18.930	20.947	22.954	24.955	26.952	28.946	32.930
(250.30)	*h*			1189.3	1213.8	1237.9	1261.9	1286.0	1334.3	1383.1	1432.7	1483.1	1534.3	1639.5
	s			1.7338	1.7650	1.7939	1.8211	1.8468	1.8947	1.9387	1.9797	2.0182	2.0546	2.1221
35	*v*			12.659	13.565	14.455	15.334	16.207	17.941	19.664	21.381	23.095	24.806	28.222
(259.25)	*h*			1188.1	1212.9	1237.2	1261.4	1285.5	1333.9	1382.9	1432.5	1482.9	1534.2	1639.4
	s			1.7156	1.7472	1.7764	1.8037	1.8295	1.8774	1.9216	1.9626	2.0011	2.0375	2.1050
40	*v*			11.041	11.841	12.625	13.398	14.165	15.686	17.197	18.702	20.202	21.700	24.691
(267.22)	*h*			1186.9	1212.0	1236.5	1260.8	1285.0	1333.6	1382.6	1432.3	1482.7	1534.0	1639.3
	s			1.6996	1.7316	1.7610	1.7885	1.8144	1.8625	1.9067	1.9478	1.9863	2.0227	2.0903
45	*v*			9.7814	10.500	11.202	11.893	12.577	13.933	15.278	16.617	17.952	19.285	21.945
(274.42)	*h*			1185.7	1211.1	1235.9	1260.3	1284.6	1333.2	1382.3	1432.1	1482.6	1533.9	1639.2
	s			1.6854	1.7178	1.7474	1.7750	1.8010	1.8493	1.8935	1.9347	1.9733	2.0097	2.0772
50	*v*			8.7735	9.4273	10.063	10.688	11.306	12.530	13.743	14.950	16.153	17.353	19.748
(280.99)	*h*			1184.5	1210.2	1235.1	1259.7	1284.1	1332.9	1382.1	1431.9	1482.4	1533.8	1639.1
	s			1.6724	1.7053	1.7352	1.7629	1.7891	1.8374	1.8818	1.9229	1.9615	1.9980	2.0656
55	*v*			7.9484	8.5492	9.1315	9.7027	10.267	11.382	12.487	13.585	14.680	15.772	17.951
(287.06)	*h*			1183.2	1209.3	1234.4	1259.1	1283.6	1332.6	1381.8	1431.7	1482.2	1533.6	1639.0
	s			1.6606	1.6939	1.7240	1.7520	1.7782	1.8267	1.8711	1.9123	1.9509	1.9874	2.0550
60	*v*			7.2604	7.8173	8.3549	8.8813	9.4004	10.425	11.440	12.448	13.453	14.454	16.453
(292.69)	*h*			1181.9	1208.4	1233.7	1258.6	1283.2	1332.2	1381.5	1431.4	1482.1	1533.5	1638.9
	s			1.6496	1.6834	1.7138	1.7419	1.7682	1.8168	1.8613	1.9026	1.9413	1.9777	2.0454
65	*v*			6.6776	7.1978	7.6978	8.1862	8.6673	9.6160	10.554	11.486	12.414	13.340	15.185
(297.96)	*h*			1180.5	1207.4	1233.0	1258.0	1282.7	1331.9	1381.3	1431.2	1481.9	1533.3	1638.8
	s			1.6394	1.6737	1.7043	1.7326	1.7590	1.8078	1.8523	1.8937	1.9323	1.9688	2.0365
70	*v*				6.6666	7.1344	7.5904	8.0389	8.9223	9.7951	10.662	11.524	12.384	14.099
(302.92)	*h*				1206.5	1232.3	1257.4	1282.2	1331.5	1381.0	1431.0	1481.7	1533.2	1638.7
	s				1.6646	1.6955	1.7239	1.7505	1.7994	1.8440	1.8854	1.9241	1.9606	2.0283

v = specific volume, ft^3/lb_m *h* = enthalpy, Btu/lb_m *s* = entropy, $Btu/(lb_m \cdot °R)$

Superheated Steam (Continued)

Pressure psia (Sat. T)		Temperature—Degrees Fahrenheit 350	400	450	500	550	600	700	800	900	1000	1100	1200	1400
80	*v*	5.8030	6.2186	6.6220	7.0176	7.4081	7.7949	8.5614	9.3216	10.078	10.831	11.583	12.333	13.831
(312.03)	*h*	1204.5	1230.8	1256.2	1281.3	1306.1	1330.8	1380.5	1430.6	1481.4	1532.9	1585.3	1638.5	1747.5
	s	1.6480	1.6795	1.7082	1.7350	1.7602	1.7842	1.8289	1.8704	1.9092	1.9457	1.9804	2.0135	2.0755
90	*v*	5.1307	5.5061	5.8686	6.2232	6.5724	6.9180	7.6019	8.2794	8.9529	9.6237	10.293	10.960	12.292
(320.27)	*h*	1202.5	1229.3	1255.1	1280.3	1305.3	1330.1	1380.0	1430.2	1481.0	1532.6	1585.0	1638.3	1747.4
	s	1.6330	1.6651	1.6943	1.7213	1.7466	1.7707	1.8156	1.8572	1.8960	1.9326	1.9673	2.0004	2.0625
100	*v*	4.5923	4.9358	5.2658	5.5875	5.9039	6.2165	6.8342	7.4456	8.0529	8.6576	9.2602	9.8615	11.061
(327.82)	*h*	1200.4	1227.8	1253.9	1279.3	1304.5	1329.5	1379.4	1429.8	1480.7	1532.3	1584.8	1638.1	1747.2
	s	1.6194	1.6521	1.6816	1.7089	1.7344	1.7586	1.8037	1.8453	1.8842	1.9209	1.9556	1.9887	2.0508
110	*v*	4.1513	4.4689	4.7724	5.0674	5.3568	5.6424	6.2061	6.7634	7.3166	7.8671	8.4156	8.9627	10.054
(334.78)	*h*	1198.3	1226.2	1252.6	1278.3	1303.6	1328.8	1378.9	1429.4	1480.4	1532.1	1584.6	1637.9	1747.1
	s	1.6068	1.6402	1.6701	1.6976	1.7233	1.7476	1.7928	1.8345	1.8735	1.9102	1.9450	1.9781	2.0402
120	*v*	3.7832	4.0796	4.3611	4.6339	4.9009	5.1640	5.6827	6.1949	6.7030	7.2083	7.7117	8.2137	9.2148
(341.26)	*h*	1196.1	1224.6	1251.4	1277.3	1302.8	1328.1	1378.4	1428.9	1480.0	1531.8	1584.3	1637.7	1746.9
	s	1.5950	1.6292	1.6595	1.6872	1.7131	1.7375	1.7829	1.8247	1.8637	1.9005	1.9353	1.9684	2.0306
130	*v*	3.4711	3.7500	4.0130	4.2670	4.5151	4.7592	5.2398	5.7138	6.1838	6.6509	7.1162	7.5800	8.5047
(347.33)	*h*	1193.8	1223.0	1250.2	1276.3	1302.0	1327.3	1377.8	1428.5	1479.7	1531.5	1584.1	1637.5	1746.8
	s	1.5839	1.6189	1.6496	1.6776	1.7037	1.7282	1.7737	1.8156	1.8547	1.8915	1.9263	1.9595	2.0217
140	*v*		3.4673	3.7145	3.9524	4.1843	4.4122	4.8602	5.3015	5.7387	6.1732	6.6057	7.0368	7.8960
(353.04)	*h*		1221.4	1248.9	1275.3	1301.1	1326.6	1377.3	1428.1	1479.3	1531.2	1583.8	1637.3	1746.7
	s		1.6092	1.6404	1.6687	1.6949	1.7195	1.7652	1.8072	1.8464	1.8832	1.9180	1.9512	2.0135
150	*v*		3.2220	3.4557	3.6797	3.8976	4.1115	4.5311	4.9441	5.3530	5.7591	6.1632	6.5660	7.3685
(358.43)	*h*		1219.7	1247.6	1274.3	1300.3	1325.9	1376.8	1427.7	1479.0	1530.9	1583.6	1637.1	1746.5
	s		1.6001	1.6317	1.6602	1.6866	1.7114	1.7573	1.7994	1.8386	1.8754	1.9103	1.9435	2.0058
160	*v*		3.0073	3.2291	3.4411	3.6468	3.8483	4.2432	4.6314	5.0155	5.3968	5.7761	6.1540	6.9069
(363.55)	*h*		1218.0	1246.3	1273.3	1299.5	1325.2	1376.2	1427.2	1478.7	1530.7	1583.4	1636.9	1746.4
	s		1.5914	1.6235	1.6523	1.6789	1.7038	1.7498	1.7920	1.8313	1.8682	1.9031	1.9363	1.9986
170	*v*		2.8176	3.0291	3.2304	3.4253	3.6160	3.9892	4.3555	4.7177	5.0771	5.4345	5.7905	6.4996
(368.43)	*h*		1216.3	1245.0	1272.2	1298.6	1324.5	1375.7	1426.8	1478.3	1530.4	1583.1	1636.7	1746.2
	s		1.5831	1.6157	1.6448	1.6716	1.6966	1.7428	1.7851	1.8244	1.8613	1.8963	1.9296	1.9919
180	*v*		2.6487	2.8512	3.0431	3.2285	3.4095	3.7633	4.1103	4.4530	4.7929	5.1309	5.4674	6.1376
(373.08)	*h*		1214.5	1243.7	1271.2	1297.7	1323.8	1375.1	1426.4	1478.0	1530.1	1582.9	1636.5	1746.1
	s		1.5752	1.6082	1.6377	1.6646	1.6898	1.7361	1.7785	1.8179	1.8549	1.8899	1.9232	1.9855
190	*v*		2.4975	2.6920	2.8755	3.0524	3.2248	3.5613	3.8908	4.2161	4.5387	4.8592	5.1784	5.8137
(377.54)	*h*		1212.7	1242.4	1270.1	1296.9	1323.0	1374.6	1426.0	1477.6	1529.8	1582.7	1636.3	1745.9
	s		1.5676	1.6011	1.6309	1.6580	1.6833	1.7298	1.7723	1.8118	1.8488	1.8838	1.9171	1.9795
200	*v*		2.3612	2.5485	2.7246	2.8938	3.0585	3.3794	3.6933	4.0030	4.3098	4.6147	4.9182	5.5222
(381.81)	*h*		1210.9	1241.0	1269.1	1296.0	1322.3	1374.1	1425.5	1477.3	1529.5	1582.4	1636.1	1745.8
	s		1.5602	1.5943	1.6243	1.6517	1.6771	1.7238	1.7664	1.8059	1.8430	1.8780	1.9114	1.9738
220	*v*		2.1252	2.3006	2.4638	2.6198	2.7712	3.0652	3.3521	3.6348	3.9146	4.1924	4.4688	5.0186
(389.89)	*h*		1207.0	1238.3	1266.9	1294.3	1320.8	1373.0	1424.7	1476.6	1529.0	1581.9	1635.7	1745.5
	s		1.5461	1.5814	1.6121	1.6399	1.6656	1.7126	1.7554	1.7950	1.8322	1.8673	1.9007	1.9631
240	*v*		1.9277	2.0936	2.2462	2.3914	2.5317	2.8034	3.0678	3.3279	3.5852	3.8404	4.0943	4.5990
(397.41)	*h*		1203.0	1235.4	1264.7	1292.5	1319.4	1371.9	1423.8	1475.9	1528.4	1581.5	1635.3	1745.2
	s		1.5327	1.5694	1.6007	1.6289	1.6549	1.7023	1.7453	1.7851	1.8223	1.8575	1.8909	1.9534

v = specific volume, ft^3/lb_m *h* = enthalpy, Btu/lb_m *s* = entropy, $Btu/(lb_m\text{-}°R)$

Superheated Steam (Continued)

Pressure psia (Sat. T)		Temperature—Degrees Fahrenheit 450	500	550	600	700	800	900	1000	1100	1200	1300	1400	1500
260	*v*	1.9182	2.0620	2.1980	2.3290	2.5818	2.8272	3.0683	3.3065	3.5426	3.7774	4.0111	4.2439	4.4763
(404.45)	*h*	1232.5	1262.5	1290.7	1317.9	1370.8	1423.0	1475.2	1527.8	1581.0	1634.9	1689.5	1744.9	1801.1
	s	1.5580	1.5901	1.6188	1.6450	1.6928	1.7359	1.7758	1.8132	1.8484	1.8819	1.9138	1.9445	1.9739
280	*v*	1.7676	1.9039	2.0322	2.1552	2.3919	2.6210	2.8457	3.0676	3.2874	3.5058	3.7231	3.9396	4.1556
(411.09)	*h*	1229.5	1260.2	1288.8	1316.3	1369.7	1422.1	1474.5	1527.2	1580.5	1634.5	1689.1	1744.6	1800.8
	s	1.5473	1.5801	1.6092	1.6358	1.6839	1.7273	1.7673	1.8047	1.8400	1.8735	1.9055	1.9362	1.9656
300	*v*	1.6367	1.7668	1.8883	2.0045	2.2272	2.4423	2.6529	2.8605	3.0662	3.2704	3.4735	3.6758	3.8776
(417.37)	*h*	1226.4	1257.9	1287.0	1314.8	1368.5	1421.2	1473.8	1526.7	1580.0	1634.0	1688.8	1744.3	1800.6
	s	1.5370	1.5706	1.6002	1.6271	1.6756	1.7191	1.7593	1.7968	1.8322	1.8657	1.8978	1.9284	1.9579
320	*v*	1.5219	1.6467	1.7624	1.8726	2.0831	2.2859	2.4841	2.6793	2.8726	3.0644	3.2551	3.4450	3.6344
(423.33)	*h*	1223.3	1255.5	1285.1	1313.3	1367.4	1420.4	1473.1	1526.1	1579.6	1633.6	1688.4	1744.0	1800.3
	s	1.5271	1.5615	1.5916	1.6189	1.6677	1.7115	1.7518	1.7894	1.8248	1.8584	1.8905	1.9212	1.9507
340	*v*	1.4203	1.5405	1.6512	1.7562	1.9560	2.1478	2.3351	2.5195	2.7018	2.8826	3.0624	3.2414	3.4198
(429.01)	*h*	1220.0	1253.1	1283.2	1311.7	1366.3	1419.5	1472.4	1525.5	1579.1	1633.2	1688.1	1743.7	1800.1
	s	1.5175	1.5529	1.5835	1.6111	1.6603	1.7043	1.7447	1.7824	1.8179	1.8516	1.8837	1.9144	1.9439
360	*v*	1.3297	1.4460	1.5523	1.6527	1.8429	2.0252	2.2028	2.3774	2.5500	2.7211	2.8911	3.0604	3.2291
(434.43)	*h*	1216.6	1250.6	1281.3	1310.1	1365.2	1418.6	1471.7	1525.0	1578.6	1632.8	1687.7	1743.4	1799.8
	s	1.5082	1.5446	1.5757	1.6036	1.6533	1.6975	1.7381	1.7758	1.8114	1.8451	1.8772	1.9080	1.9375
380	*v*	1.2483	1.3613	1.4637	1.5600	1.7418	1.9154	2.0843	2.2502	2.4141	2.5765	2.7379	2.8984	3.0584
(439.63)	*h*	1213.1	1248.1	1279.3	1308.5	1364.0	1417.8	1471.0	1524.4	1578.1	1632.4	1687.4	1743.1	1799.5
	s	1.4991	1.5365	1.5683	1.5965	1.6466	1.6910	1.7317	1.7696	1.8052	1.8389	1.8711	1.9019	1.9314
400	*v*	1.1747	1.2850	1.3839	1.4765	1.6507	1.8166	1.9777	2.1358	2.2919	2.4464	2.6000	2.7527	2.9048
(444.63)	*h*	1209.5	1245.6	1277.3	1306.9	1362.9	1416.9	1470.3	1523.8	1577.7	1632.0	1687.0	1742.8	1799.3
	s	1.4901	1.5288	1.5611	1.5897	1.6402	1.6848	1.7257	1.7636	1.7993	1.8331	1.8653	1.8961	1.9257
450	*v*		1.1232	1.2151	1.3001	1.4584	1.6079	1.7526	1.8942	2.0337	2.1718	2.3088	2.4449	2.5805
(456.32)	*h*		1238.9	1272.2	1302.8	1360.0	1414.7	1468.6	1522.4	1576.5	1631.0	1686.2	1742.0	1798.6
	s		1.5103	1.5442	1.5737	1.6253	1.6705	1.7117	1.7499	1.7857	1.8196	1.8519	1.8828	1.9124
500	*v*		0.9930	1.0797	1.1587	1.3044	1.4409	1.5725	1.7009	1.8272	1.9521	2.0758	2.1987	2.3211
(467.05)	*h*		1231.9	1267.0	1298.6	1357.0	1412.4	1466.8	1520.9	1575.3	1630.0	1685.3	1741.3	1798.0
	s		1.4928	1.5284	1.5591	1.6117	1.6576	1.6991	1.7375	1.7735	1.8076	1.8399	1.8708	1.9005
550	*v*		0.8856	0.9685	1.0428	1.1783	1.3043	1.4251	1.5428	1.6583	1.7723	1.8852	1.9973	2.1088
(476.98)	*h*		1224.5	1261.5	1294.3	1354.0	1410.2	1465.0	1519.5	1574.0	1629.0	1684.4	1740.5	1797.3
	s		1.4760	1.5137	1.5454	1.5993	1.6457	1.6876	1.7263	1.7624	1.7966	1.8290	1.8600	1.8898
600	*v*		0.7953	0.8754	0.9460	1.0732	1.1904	1.3023	1.4110	1.5175	1.6225	1.7264	1.8295	1.9320
(486.25)	*h*		1216.5	1255.8	1289.9	1351.0	1407.9	1463.2	1518.0	1572.8	1628.0	1683.6	1739.8	1796.7
	s		1.4597	1.4996	1.5325	1.5877	1.6348	1.6770	1.7159	1.7523	1.7865	1.8190	1.8501	1.8799
650	*v*		0.7178	0.7962	0.8639	0.9841	1.0940	1.1983	1.2994	1.3983	1.4957	1.5920	1.6874	1.7823
(494.94)	*h*		1208.0	1249.9	1285.3	1347.9	1405.6	1461.4	1516.6	1571.6	1626.9	1682.7	1739.0	1796.0
	s		1.4434	1.4861	1.5203	1.5768	1.6246	1.6672	1.7063	1.7428	1.7772	1.8098	1.8410	1.8708
700	*v*			0.7280	0.7933	0.9077	1.0113	1.1092	1.2038	1.2962	1.3871	1.4768	1.5657	1.6540
(503.14)	*h*			1243.7	1280.6	1344.8	1403.3	1459.6	1515.1	1570.4	1625.9	1681.8	1738.3	1795.4
	s			1.4730	1.5087	1.5666	1.6150	1.6580	1.6974	1.7341	1.7686	1.8013	1.8325	1.8624
750	*v*			0.6684	0.7319	0.8414	0.9396	1.0320	1.1209	1.2077	1.2929	1.3770	1.4602	1.5428
(510.90)	*h*			1237.3	1275.8	1341.6	1401.0	1457.8	1513.6	1569.2	1624.9	1681.0	1737.5	1794.7
	s			1.4602	1.4975	1.5569	1.6060	1.6494	1.6890	1.7259	1.7605	1.7933	1.8245	1.8545

v = specific volume, ft^3/lb$_m$ h = enthalpy, Btu/lb$_m$ s = entropy, Btu/(lb$_m$-°R)

Superheated Steam (Continued)

Pressure psia (Sat. T)		Temperature—Degrees Fahrenheit 550	600	650	700	750	800	900	1000	1100	1200	1300	1400	1500
800	*v*	0.6159	0.6780	0.7328	0.7834	0.8311	0.8768	0.9643	1.0484	1.1302	1.2105	1.2896	1.3679	1.4456
(518.27)	*h*	1230.5	1270.8	1306.0	1338.4	1369.0	1398.6	1456.0	1512.1	1568.0	1623.9	1680.1	1736.8	1794.0
	s	1.4476	1.4866	1.5191	1.5476	1.5735	1.5975	1.6413	1.6812	1.7182	1.7529	1.7858	1.8171	1.8471
850	*v*	0.5691	0.6302	0.6834	0.7320	0.7777	0.8214	0.9047	0.9844	1.0619	1.1378	1.2125	1.2864	1.3597
(525.30)	*h*	1223.4	1265.7	1302.0	1335.1	1366.3	1396.2	1454.1	1510.7	1566.7	1622.8	1679.2	1736.0	1793.4
	s	1.4351	1.4761	1.5096	1.5388	1.5651	1.5894	1.6336	1.6737	1.7109	1.7457	1.7787	1.8101	1.8401
900	*v*	0.5269	0.5875	0.6394	0.6864	0.7303	0.7721	0.8516	0.9275	1.0011	1.0731	1.1440	1.2140	1.2834
(532.02)	*h*	1215.8	1260.4	1297.9	1331.8	1363.5	1393.8	1452.3	1509.2	1565.5	1621.8	1678.3	1735.3	1792.7
	s	1.4226	1.4658	1.5004	1.5302	1.5570	1.5816	1.6262	1.6666	1.7040	1.7389	1.7720	1.8035	1.8336
950	*v*	0.4887	0.5491	0.5998	0.6454	0.6878	0.7280	0.8041	0.8766	0.9467	1.0153	1.0827	1.1492	1.2152
(538.46)	*h*	1207.8	1254.9	1293.7	1328.4	1360.6	1391.4	1450.4	1507.7	1564.3	1620.8	1677.4	1734.5	1792.1
	s	1.4100	1.4557	1.4914	1.5220	1.5492	1.5742	1.6192	1.6599	1.6974	1.7325	1.7657	1.7972	1.8273
1000	*v*	0.4538	0.5143	0.5641	0.6085	0.6495	0.6883	0.7614	0.8308	0.8978	0.9632	1.0275	1.0909	1.1537
(544.65)	*h*	1199.1	1249.3	1289.4	1324.9	1357.8	1389.0	1448.5	1506.2	1563.0	1619.7	1676.6	1733.7	1791.4
	s	1.3971	1.4457	1.4827	1.5140	1.5418	1.5670	1.6125	1.6535	1.6911	1.7264	1.7596	1.7912	1.8214
1100	*v*		0.4536	0.5022	0.5446	0.5833	0.6196	0.6875	0.7516	0.8133	0.8733	0.9322	0.9902	1.0476
(556.35)	*h*		1237.2	1280.5	1317.9	1351.9	1384.0	1444.7	1503.2	1560.6	1617.7	1674.8	1732.2	1790.1
	s		1.4259	1.4658	1.4987	1.5275	1.5535	1.5999	1.6414	1.6794	1.7149	1.7483	1.7801	1.8104
1200	*v*		0.4020	0.4501	0.4910	0.5279	0.5622	0.6259	0.6856	0.7428	0.7984	0.8528	0.9063	0.9592
(567.26)	*h*		1224.1	1271.1	1310.5	1345.9	1378.9	1440.9	1500.1	1558.1	1615.6	1673.0	1730.7	1788.8
	s		1.4061	1.4494	1.4842	1.5141	1.5408	1.5882	1.6302	1.6686	1.7043	1.7379	1.7698	1.8002
1300	*v*		0.3574	0.4057	0.4455	0.4809	0.5136	0.5738	0.6298	0.6832	0.7350	0.7856	0.8353	0.8843
(577.50)	*h*		1209.8	1261.3	1302.9	1339.7	1373.7	1437.0	1497.0	1555.6	1613.5	1671.3	1729.2	1787.4
	s		1.3859	1.4334	1.4701	1.5012	1.5288	1.5772	1.6198	1.6585	1.6945	1.7283	1.7604	1.7909
1400	*v*		0.3178	0.3671	0.4063	0.4405	0.4718	0.5290	0.5819	0.6321	0.6806	0.7280	0.7744	0.8202
(587.14)	*h*		1193.7	1250.8	1295.0	1333.4	1368.5	1433.1	1493.9	1553.1	1611.4	1669.5	1727.7	1786.1
	s		1.3649	1.4175	1.4566	1.4890	1.5174	1.5668	1.6100	1.6491	1.6854	1.7194	1.7515	1.7821
1500	*v*		0.2819	0.3331	0.3720	0.4054	0.4356	0.4902	0.5403	0.5878	0.6335	0.6780	0.7217	0.7646
(596.27)	*h*		1175.4	1239.6	1286.8	1326.9	1363.1	1429.1	1490.8	1550.5	1609.3	1667.7	1726.1	1784.8
	s		1.3423	1.4016	1.4433	1.4771	1.5064	1.5569	1.6007	1.6403	1.6768	1.7110	1.7433	1.7740
1600	*v*			0.3029	0.3418	0.3745	0.4037	0.4562	0.5040	0.5490	0.5923	0.6343	0.6755	0.7160
(604.93)	*h*			1227.7	1278.3	1320.2	1357.6	1425.1	1487.7	1548.0	1607.2	1665.9	1724.6	1783.5
	s			1.3855	1.4302	1.4656	1.4959	1.5475	1.5920	1.6319	1.6687	1.7031	1.7355	1.7663
1700	*v*			0.2757	0.3149	0.3471	0.3756	0.4262	0.4719	0.5148	0.5559	0.5958	0.6348	0.6731
(613.19)	*h*			1214.7	1269.3	1313.3	1351.9	1421.0	1484.5	1545.4	1605.0	1664.1	1723.0	1782.1
	s			1.3691	1.4172	1.4544	1.4857	1.5385	1.5836	1.6240	1.6610	1.6956	1.7282	1.7591
1800	*v*			0.2507	0.2908	0.3227	0.3505	0.3994	0.4433	0.4844	0.5236	0.5615	0.5986	0.6349
(621.07)	*h*			1200.6	1259.9	1306.2	1346.2	1416.9	1481.3	1542.8	1602.9	1662.3	1721.5	1780.8
	s			1.3520	1.4043	1.4434	1.4758	1.5299	1.5756	1.6164	1.6537	1.6885	1.7212	1.7522
1900	*v*			0.2277	0.2689	0.3007	0.3280	0.3755	0.4178	0.4572	0.4947	0.5309	0.5662	0.6008
(628.62)	*h*			1185.1	1250.1	1298.8	1340.3	1412.7	1478.1	1540.2	1600.8	1660.5	1720.0	1779.5
	s			1.3340	1.3914	1.4325	1.4662	1.5215	1.5680	1.6091	1.6468	1.6817	1.7146	1.7457
2000	*v*			0.2059	0.2489	0.2807	0.3076	0.3539	0.3948	0.4327	0.4686	0.5033	0.5370	0.5701
(635.85)	*h*			1167.5	1239.7	1291.2	1334.3	1408.5	1474.9	1537.6	1598.6	1658.7	1718.4	1778.1
	s			1.3146	1.3783	1.4218	1.4567	1.5134	1.5606	1.6022	1.6401	1.6752	1.7083	1.7395

v = specific volume, ft^3/lb_m h = enthalpy, Btu/lb_m s = entropy, $Btu/(lb_m\text{-}°R)$

Superheated Steam (Continued)

Pressure psia (Sat. T)		Temperature—Degrees Fahrenheit 650	700	750	800	850	900	950	1000	1100	1200	1300	1400	1500
2200	*v*	0.1635	0.2136	0.2459	0.2723	0.2955	0.3166	0.3363	0.3550	0.3903	0.4236	0.4556	0.4867	0.5171
(649.50)	*h*	1122.0	1217.1	1275.2	1321.8	1362.6	1399.8	1434.8	1468.3	1532.4	1594.3	1655.1	1715.3	1775.5
	s	1.2673	1.3514	1.4006	1.4383	1.4700	1.4980	1.5232	1.5466	1.5891	1.6276	1.6631	1.6964	1.7279
2400	*v*		0.1827	0.2164	0.2426	0.2651	0.2854	0.3042	0.3219	0.3550	0.3861	0.4159	0.4447	0.4729
(662.16)	*h*		1191.0	1258.0	1308.8	1352.0	1390.9	1427.2	1461.6	1527.1	1589.9	1651.4	1712.2	1772.8
	s		1.3226	1.3793	1.4204	1.4541	1.4833	1.5094	1.5335	1.5769	1.6159	1.6519	1.6855	1.7172
2600	*v*		0.1548	0.1909	0.2173	0.2393	0.2589	0.2769	0.2938	0.3251	0.3544	0.3823	0.4092	0.4355
(673.98)	*h*		1160.0	1239.4	1295.0	1341.0	1381.8	1419.4	1454.8	1521.7	1585.6	1647.8	1709.1	1770.1
	s		1.2905	1.3577	1.4027	1.4386	1.4692	1.4963	1.5210	1.5654	1.6050	1.6414	1.6753	1.7073
2800	*v*		0.1280	0.1685	0.1953	0.2171	0.2362	0.2535	0.2697	0.2995	0.3272	0.3535	0.3788	0.4034
(685.03)	*h*		1120.6	1219.0	1280.5	1329.7	1372.5	1411.5	1447.9	1516.3	1581.2	1644.1	1706.0	1767.4
	s		1.2520	1.3353	1.3852	1.4235	1.4555	1.4837	1.5092	1.5545	1.5948	1.6316	1.6658	1.6980
3000	*v*		0.0984	0.1484	0.1760	0.1977	0.2164	0.2332	0.2487	0.2773	0.3037	0.3286	0.3525	0.3757
(695.41)	*h*		1059.8	1196.4	1265.2	1317.9	1362.9	1403.4	1441.0	1510.9	1576.7	1640.4	1702.8	1764.7
	s		1.1959	1.3118	1.3675	1.4086	1.4423	1.4716	1.4978	1.5442	1.5851	1.6223	1.6569	1.6893
3200	*v*			0.1300	0.1589	0.1806	0.1990	0.2154	0.2304	0.2579	0.2830	0.3067	0.3294	0.3514
(705.10)	*h*			1171.0	1248.9	1305.7	1353.0	1395.1	1433.9	1505.4	1572.3	1636.7	1699.7	1762.0
	s			1.2866	1.3497	1.3939	1.4294	1.4598	1.4869	1.5343	1.5759	1.6136	1.6484	1.6810
3400	*v*			0.1129	0.1435	0.1654	0.1836	0.1996	0.2143	0.2407	0.2648	0.2875	0.3091	0.3299
	h			1141.8	1231.6	1292.9	1342.9	1386.7	1426.6	1499.8	1567.8	1633.0	1696.6	1759.3
	s			1.2587	1.3316	1.3793	1.4168	1.4484	1.4763	1.5248	1.5671	1.6052	1.6403	1.6732
3600	*v*			0.0964	0.1296	0.1518	0.1699	0.1856	0.1999	0.2255	0.2487	0.2704	0.2910	0.3109
	h			1107.2	1213.2	1279.7	1332.5	1378.1	1419.3	1494.2	1563.3	1629.2	1693.4	1756.6
	s			1.2269	1.3129	1.3648	1.4043	1.4373	1.4660	1.5157	1.5586	1.5972	1.6327	1.6658
3800	*v*			0.0802	0.1169	0.1396	0.1576	0.1731	0.1870	0.2118	0.2342	0.2551	0.2748	0.2939
	h			1064.4	1193.4	1266.0	1321.9	1369.4	1411.9	1488.5	1558.8	1625.5	1690.3	1753.9
	s			1.1888	1.2936	1.3502	1.3921	1.4264	1.4561	1.5069	1.5505	1.5896	1.6254	1.6587
4000	*v*			0.0637	0.1052	0.1285	0.1465	0.1617	0.1754	0.1996	0.2212	0.2413	0.2603	0.2785
	h			1009.2	1172.1	1251.7	1310.9	1360.5	1404.4	1482.8	1554.2	1621.7	1687.1	1751.2
	s			1.1409	1.2734	1.3355	1.3799	1.4157	1.4463	1.4983	1.5427	1.5822	1.6183	1.6519
4500	*v*			0.0393	0.0796	0.1047	0.1229	0.1378	0.1509	0.1737	0.1938	0.2122	0.2296	0.2462
	h			891.0	1111.1	1213.4	1282.3	1337.5	1385.3	1468.4	1542.7	1612.3	1679.2	1744.5
	s			1.0395	1.2183	1.2980	1.3497	1.3896	1.4229	1.4780	1.5242	1.5650	1.6019	1.6361
5000	*v*			0.0337	0.0594	0.0855	0.1039	0.1186	0.1313	0.1530	0.1719	0.1890	0.2051	0.2204
	h			853.0	1041.9	1171.5	1252.1	1313.7	1365.5	1453.8	1531.2	1602.9	1671.3	1737.7
	s			1.0053	1.1582	1.2593	1.3198	1.3643	1.4005	1.4590	1.5071	1.5491	1.5869	1.6217
5500	*v*			0.0313	0.0463	0.0701	0.0885	0.1030	0.1153	0.1361	0.1540	0.1701	0.1851	0.1993
	h			834.1	980.9	1126.9	1220.4	1289.1	1345.4	1439.0	1519.6	1593.4	1663.4	1731.0
	s			0.9872	1.1060	1.2198	1.2899	1.3396	1.3788	1.4409	1.4910	1.5343	1.5729	1.6084
6000	*v*			0.0298	0.0395	0.0582	0.0759	0.0901	0.1021	0.1221	0.1391	0.1544	0.1684	0.1817
	h			821.7	940.8	1083.1	1187.7	1263.8	1324.8	1424.0	1507.9	1583.9	1655.5	1724.3
	s			0.9747	1.0710	1.1818	1.2604	1.3154	1.3579	1.4237	1.4759	1.5204	1.5599	1.5960
7000	*v*			0.0279	0.0334	0.0438	0.0576	0.0705	0.0817	0.1004	0.1160	0.1298	0.1424	0.1542
	h			805.6	898.4	1013.3	1124.8	1213.1	1283.4	1394.0	1484.6	1565.1	1639.8	1711.0
	s			0.9570	1.0321	1.1215	1.2051	1.2689	1.3179	1.3913	1.4476	1.4948	1.5361	1.5734

v = specific volume, ft^3/lb_m h = enthalpy, Btu/lb_m s = entropy, $Btu/(lb_m\text{-}°R)$

Superheated Steam (Continued)

Pressure psia (Sat. T)		Temperature—Degrees Fahrenheit												
		750	**800**	**850**	**900**	**950**	**1000**	**1050**	**1100**	**1150**	**1200**	**1300**	**1400**	**1500**
8000	*v*	0.0267	0.0306	0.0371	0.0465	0.0571	0.0672	0.0763	0.0844	0.0919	0.0988	0.1115	0.1230	0.1337
	h	795.1	876.0	971.0	1073.2	1165.6	1243.0	1307.9	1364.3	1414.9	1461.5	1546.4	1624.3	1697.9
	s	0.9441	1.0096	1.0836	1.1601	1.2269	1.2808	1.3246	1.3614	1.3933	1.4218	1.4715	1.5146	1.5532
9000	*v*	0.0258	0.0289	0.0335	0.0401	0.0483	0.0568	0.0650	0.0725	0.0794	0.0858	0.0975	0.1081	0.1179
	h	787.5	861.6	945.1	1036.2	1125.7	1205.8	1275.1	1335.6	1389.6	1438.9	1528.1	1609.1	1685.1
	s	0.9338	0.9938	1.0588	1.1270	1.1917	1.2475	1.2942	1.3337	1.3678	1.3980	1.4502	1.4949	1.5348
10000	*v*	0.0251	0.0276	0.0312	0.0362	0.0425	0.0495	0.0566	0.0633	0.0697	0.0756	0.0864	0.0962	0.1053
	h	781.8	851.3	927.6	1010.1	1094.2	1173.6	1245.0	1308.5	1365.4	1417.2	1510.4	1594.3	1672.6
	s	0.9252	0.9815	1.0409	1.1027	1.1634	1.2188	1.2669	1.3083	1.3442	1.3759	1.4304	1.4768	1.5179
11000	*v*	0.0245	0.0267	0.0296	0.0336	0.0385	0.0442	0.0503	0.0563	0.0621	0.0675	0.0776	0.0867	0.0952
	h	777.3	843.6	915.0	991.3	1070.0	1146.8	1218.5	1283.5	1342.6	1396.5	1493.3	1579.9	1660.4
	s	0.9177	0.9714	1.0269	1.0841	1.1409	1.1945	1.2428	1.2852	1.3225	1.3555	1.4121	1.4600	1.5022
12000	*v*	0.0240	0.0260	0.0285	0.0317	0.0357	0.0404	0.0456	0.0509	0.0561	0.0611	0.0704	0.0789	0.0868
	h	773.8	837.5	905.3	977.1	1051.3	1125.1	1195.6	1261.2	1321.6	1377.1	1477.0	1566.1	1648.6
	s	0.9111	0.9627	1.0155	1.0692	1.1228	1.1743	1.2218	1.2646	1.3027	1.3366	1.3951	1.4444	1.4876
13000	*v*	0.0236	0.0253	0.0275	0.0303	0.0336	0.0376	0.0420	0.0467	0.0513	0.0559	0.0645	0.0724	0.0798
	h	771.0	832.7	897.8	966.1	1036.6	1107.5	1176.3	1241.6	1302.6	1359.2	1461.5	1552.9	1637.2
	s	0.9051	0.9551	1.0057	1.0569	1.1079	1.1573	1.2036	1.2462	1.2847	1.3193	1.3792	1.4297	1.4739
14000	*v*	0.0232	0.0248	0.0267	0.0291	0.0320	0.0354	0.0392	0.0433	0.0475	0.0516	0.0596	0.0670	0.0739
	h	768.7	828.8	891.7	957.3	1024.9	1093.1	1160.1	1224.6	1285.7	1342.8	1446.9	1540.3	1626.3
	s	0.8996	0.9483	0.9973	1.0464	1.0952	1.1428	1.1879	1.2299	1.2685	1.3035	1.3644	1.4161	1.4611
15000	*v*	0.0229	0.0243	0.0261	0.0282	0.0308	0.0337	0.0370	0.0406	0.0443	0.0481	0.0554	0.0624	0.0689
	h	766.9	825.6	886.7	950.1	1015.3	1081.2	1146.5	1209.8	1270.6	1327.9	1433.3	1528.4	1615.8
	s	0.8946	0.9422	0.9897	1.0372	1.0843	1.1303	1.1742	1.2155	1.2539	1.2890	1.3506	1.4032	1.4490

7.5 Decimal, Binary, Hexadecimal Conversion Chart

Decimal, Binary, Hexadecimal Conversion Chart

Decimal	Binary	Hex	Decimal	Binary	Hex	Decimal	Binary	Hex	Decimal	Binary	Hex
Bits >	76543210		Bits >	76543210		Bits >	76543210		Bits >	76543210	
0	00000000	00	64	01000000	40	128	10000000	80	192	11000000	C0
1	00000001	01	65	01000001	41	129	10000001	81	193	11000001	C1
2	00000010	02	66	01000010	42	130	10000010	82	194	11000010	C2
3	00000011	03	67	01000011	43	131	10000011	83	195	11000011	C3
4	00000100	04	68	01000100	44	132	10000100	84	196	11000100	C4
5	00000101	05	69	01000101	45	133	10000101	85	197	11000101	C5
6	00000110	06	70	01000110	46	134	10000110	86	198	11000110	C6
7	00000111	07	71	01000111	47	135	10000111	87	199	11000111	C7
8	00001000	08	72	01001000	48	136	10001000	88	200	11001000	C8
9	00001001	09	73	01001001	49	137	10001001	89	201	11001001	C9
10	00001010	0A	74	01001010	4A	138	10001010	8A	202	11001010	CA
11	00001011	0B	75	01001011	4B	139	10001011	8B	203	11001011	CB
12	00001100	0C	76	01001100	4C	140	10001100	8C	204	11001100	CC
13	00001101	0D	77	01001101	4D	141	10001101	8D	205	11001101	CD
14	00001110	0E	78	01001110	4E	142	10001110	8E	206	11001110	CE
15	00001111	0F	79	01001111	4F	143	10001111	8F	207	11001111	CF
16	00010000	10	80	01010000	50	144	10010000	90	208	11010000	D0
17	00010001	11	81	01010001	51	145	10010001	91	209	11010001	D1
18	00010010	12	82	01010010	52	146	10010010	92	210	11010010	D2
19	00010011	13	83	01010011	53	147	10010011	93	211	11010011	D3
20	00010100	14	84	01010100	54	148	10010100	94	212	11010100	D4
21	00010101	15	85	01010101	55	149	10010101	95	213	11010101	D5
22	00010110	16	86	01010110	56	150	10010110	96	214	11010110	D6
23	00010111	17	87	01010111	57	151	10010111	97	215	11010111	D7
24	00011000	18	88	01011000	58	152	10011000	98	216	11011000	D8
25	00011001	19	89	01011001	59	153	10011001	99	217	11011001	D9
26	00011010	1A	90	01011010	5A	154	10011010	9A	218	11011010	DA
27	00011011	1B	91	01011011	5B	155	10011011	9B	219	11011011	DB
28	00011100	1C	92	01011100	5C	156	10011100	9C	220	11011100	DC
29	00011101	1D	93	01011101	5D	157	10011101	9D	221	11011101	DD
30	00011110	1E	94	01011110	5E	158	10011110	9E	222	11011110	DE
31	00011111	1F	95	01011111	5F	159	10011111	9F	223	11011111	DF
32	00100000	20	96	01100000	60	160	10100000	A0	224	11100000	E0
33	00100001	21	97	01100001	61	161	10100001	A1	225	11100001	E1
34	00100010	22	98	01100010	62	162	10100010	A2	226	11100010	E2
35	00100011	23	99	01100011	63	163	10100011	A3	227	11100011	E3
36	00100100	24	100	01100100	64	164	10100100	A4	228	11100100	E4
37	00100101	25	101	01100101	65	165	10100101	A5	229	11100101	E5
38	00100110	26	102	01100110	66	166	10100110	A6	230	11100110	E6
39	00100111	27	103	01100111	67	167	10100111	A7	231	11100111	E7
40	00101000	28	104	01101000	68	168	10101000	A8	232	11101000	E8
41	00101001	29	105	01101001	69	169	10101001	A9	233	11101001	E9
42	00101010	2A	106	01101010	6A	170	10101010	AA	234	11101010	EA
43	00101011	2B	107	01101011	6B	171	10101011	AB	235	11101011	EB
44	00101100	2C	108	01101100	6C	172	10101100	AC	236	11101100	EC
45	00101101	2D	109	01101101	6D	173	10101101	AD	237	11101101	ED
46	00101110	2E	110	01101110	6E	174	10101110	AE	238	11101110	EE
47	00101111	2F	111	01101111	6F	175	10101111	AF	239	11101111	EF
48	00110000	30	112	01110000	70	176	10110000	B0	240	11110000	F0
49	00110001	31	113	01110001	71	177	10110001	B1	241	11110001	F1
50	00110010	32	114	01110010	72	178	10110010	B2	242	11110010	F2
51	00110011	33	115	01110011	73	179	10110011	B3	243	11110011	F3

Decimal	Binary	Hex		Decimal	Binary	Hex		Decimal	Binary	Hex		Decimal	Binary	Hex
Bits >	**76543210**			**Bits >**	**76543210**			**Bits >**	**76543210**			**Bits >**	**76543210**	
52	00110100	34		116	01110100	74		180	10110100	B4		244	11110100	F4
53	00110101	35		117	01110101	75		181	10110101	B5		245	11110101	F5
54	00110110	36		118	01110110	76		182	10110110	B6		246	11110110	F6
55	00110111	37		119	01110111	77		183	10110111	B7		247	11110111	F7
56	00111000	38		120	01111000	78		184	10111000	B8		248	11111000	F8
57	00111001	39		121	01111001	79		185	10111001	B9		249	11111001	F9
58	00111010	3A		122	01111010	7A		186	10111010	BA		250	11111010	FA
59	00111011	3B		123	01111011	7B		187	10111011	BB		251	11111011	FB
60	00111100	3C		124	01111100	7C		188	10111100	BC		252	11111100	FC
61	00111101	3D		125	01111101	7D		189	10111101	BD		253	11111101	FD
62	00111110	3E		126	01111110	7E		190	10111110	BE		254	11111110	FE
63	00111111	3F		127	01111111	7F		191	10111111	BF		255	11111111	FF

7.6 Periodic Table of Elements

Atomic Number
Symbol
Atomic Weight

I	II											III	IV	V	VI	VII	VIII
1 **H** 1.0079																	2 **He** 4.0026
3 **Li** 6.941	4 **Be** 9.0122											5 **B** 10.811	6 **C** 12.011	7 **N** 14.007	8 **O** 15.999	9 **F** 18.998	10 **Ne** 20.179
11 **Na** 22.990	12 **Mg** 24.305											13 **Al** 26.981	14 **Si** 28.086	15 **P** 30.974	16 **S** 32.066	17 **Cl** 35.453	18 **Ar** 39.948
19 **K** 39.098	20 **Ca** 40.078	21 **Sc** 44.956	22 **Ti** 47.88	23 **V** 50.941	24 **Cr** 51.996	25 **Mn** 54.938	26 **Fe** 55.847	27 **Co** 58.933	28 **Ni** 58.69	29 **Cu** 63.546	30 **Zn** 65.39	31 **Ga** 69.723	32 **Ge** 72.61	33 **As** 74.921	34 **Se** 78.96	35 **Br** 79.904	36 **Kr** 83.80
37 **Rb** 85.468	38 **Sr** 87.62	39 **Y** 88.906	40 **Zr** 91.224	41 **Nb** 92.906	42 **Mo** 95.94	43 **Tc** (98)	44 **Ru** 101.07	45 **Rh** 102.91	46 **Pd** 106.42	47 **Ag** 107.87	48 **Cd** 112.41	49 **In** 114.82	50 **Sn** 118.71	51 **Sb** 121.75	52 **Te** 127.60	53 **I** 126.90	54 **Xe** 131.29
55 **Cs** 132.91	56 **Ba** 137.33	57–71	72 **Hf** 178.49	73 **Ta** 180.95	74 **W** 183.85	75 **Re** 186.21	76 **Os** 190.2	77 **Ir** 192.22	78 **Pt** 195.08	79 **Au** 196.97	80 **Hg** 200.59	81 **Tl** 204.38	82 **Pb** 207.2	83 **Bi** 208.98	84 **Po** (209)	85 **At** (210)	86 **Rn** (222)
87 **Fr** (223)	88 **Ra** 226.02	89–103	104 **Rf** (261)	105 **Db** (262)	106 **Sg** (266)	107 **Bh** (264)	108 **Hs** (269)	109 **Mt** (268)	110 **Ds** (269)	111 **Rg** (272)	112 **Cn** (277)	113 **Uut** unknown	114 **Fl** (289)	115 **Uup** unknown	116 **Lv** (298)	117 **Uus** unknown	118 **Uuo** unknown

Lanthanide Series	57 **La** 138.91	58 **Ce** 140.12	59 **Pr** 140.91	60 **Nd** 144.24	61 **Pm** (145)	62 **Sm** 150.36	63 **Eu** 151.96	64 **Gd** 157.25	65 **Tb** 158.92	66 **Dy** 162.50	67 **Ho** 164.93	68 **Er** 167.26	69 **Tm** 168.93	70 **Yb** 173.04	71 **Lu** 174.97
Actinide Series	89 **Ac** 227.03	90 **Th** 232.04	91 **Pa** 231.04	92 **U** 238.03	93 **Np** 237.05	94 **Pu** (244)	95 **Am** (243)	96 **Cm** (247)	97 **Bk** (247)	98 **Cf** (251)	99 **Es** (252)	100 **Fm** (257)	101 **Md** (258)	102 **No** (259)	103 **Lr** (260)

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