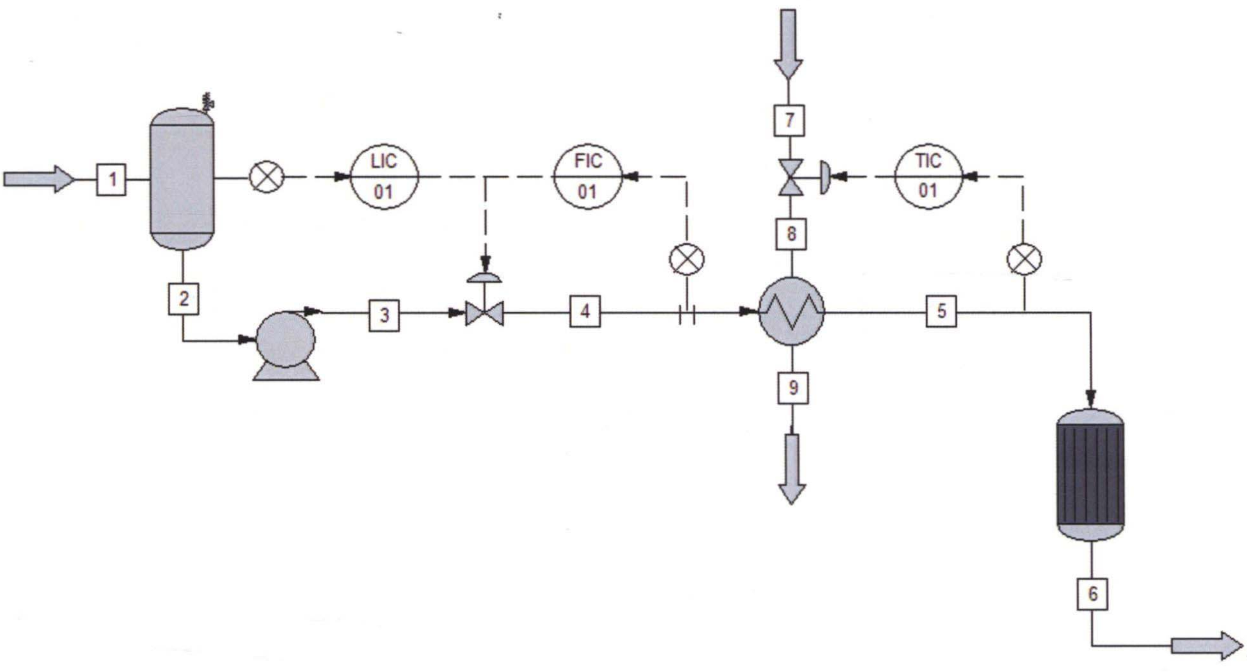
PROCESS MEASUREMENT & CONTROL

IN PRACTICE

Design, Specification and Implementation



Edited by

John E. Edwards

Process Simulation Engineer, P & I Design Ltd

First Edition, November 2013

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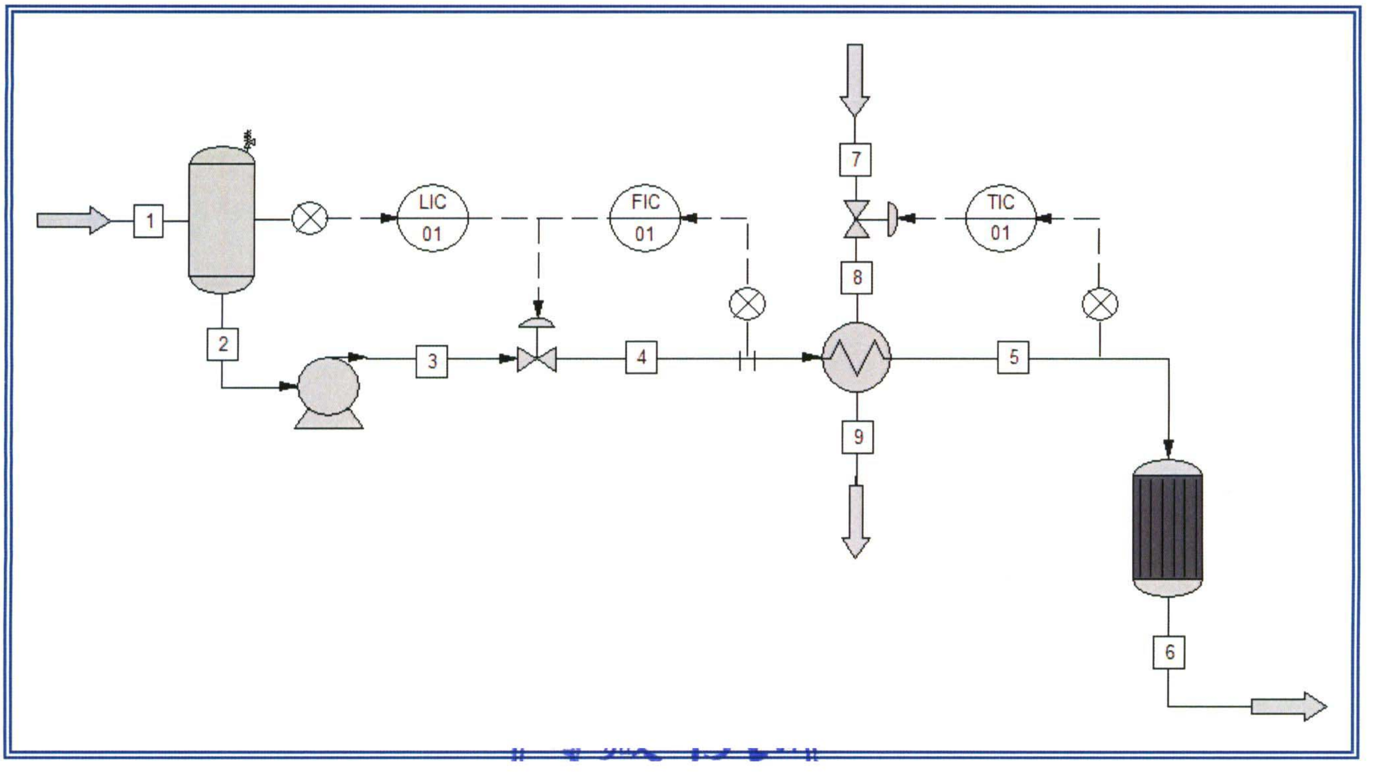

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Preface

This book is based on the practical experience gained, over thirty five years, by the process, instrumentation and control engineers at P & I Design Ltd. This experience is based on design and implementation, involving a wide range of projects, in the process and control fields. This includes batch and continuous process plant, terminal storage facilities, safety systems, materials handling and secure data processing facilities installed in safe and hazardous areas. The projects required the selection and application of a wide range of instrumentation and control techniques based on standalone and centralised supervisory control systems using state of the art technologies.

The book is intended as a refresher of the basic principles for the practicing engineer and reviews the latest techniques, practices and legislation in the industry. The engineering fundamentals section has been included to provide a concise and clear introduction to the relevant applied maths, basic electrical and fluid flow principles.

Reference is made to many classic texts, industry standards and manufacturers' data. Information has been mined from individual project reports, technical papers and contributions by specialists working in the instrumentation and control field.

Section 5 - Emergency Relief, Section 8 - Process Control, and Section 9 - Process Simulation have been adapted and developed from a previous book by J.E.Edwards, "Chemical Engineering in Practice".

Each topic is in the form of a condensed refresher and provides useful practical information and data. Each section is numbered uniquely for contents and references, with the appendices and nomenclature being section specific. The references are not a comprehensive list and apologies for unintended omissions.

Any originality may be in the presentation format and as such some would consider this to be a Handbook or Workbook. Many modern text books do not adopt this approach which is not very helpful to the engineer challenged with providing solutions in a timely manner.

Process simulations in Section 9 are carried out using CHEMCAD™ software by Chemstations of Houston. Applications are presented from real situations whether it is design, testing or operations.

The Editor

http://uk.linkedin.com/pub/john-edwards/1b/374/924
John E.Edwards is the Process Simulation Specialist at P&I Design Ltd based in Teesside, UK.
In 1978 he formed P&I Design Ltd to provide a service in the Process and Instrumentation fields. He has over fifty years experience gained whilst working in the process, instrumentation and control system fields.

Acknowledgements

The following personnel at P & I Design Ltd have contributed:

M.Morgan for applying his expertise in reviewing Section 3 on Liquid and Gas Hazardous Areas
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http://uk.linkedin.com/pub/mike-edwards/53/6b9/1b3

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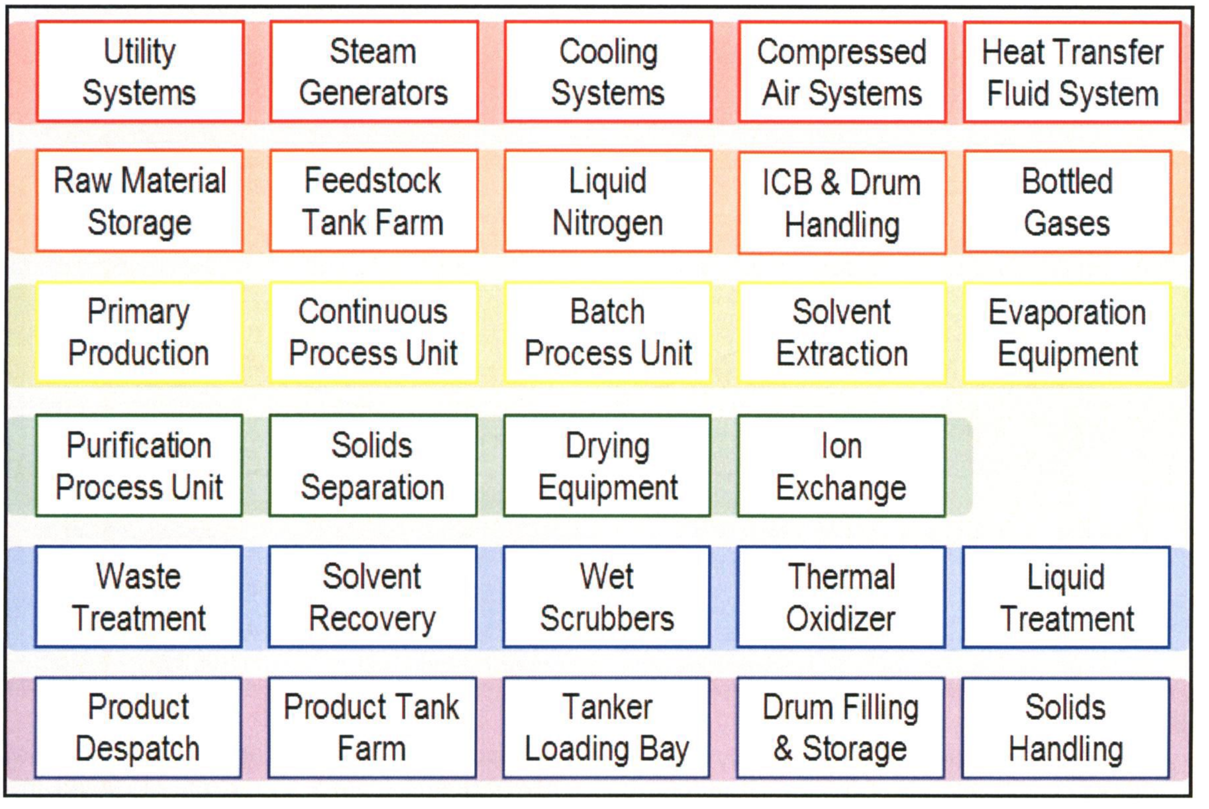
Contents

Section 1

Introduction

The process industry covers a broad spectrum of activities that involve the handling and treatment of gases, liquids and solids over a wide range of physical and processing conditions. The scope of this variety is shown in the following chart.



Electrical, instrument and control engineers, working in this environment, are required to provide safe, practical and timely solutions to design and operational problems frequently without having the opportunity to study the topic in great depth. This book is an attempt to provide a comprehensive review of the fundamentals, definitions and engineering principles for implementation of projects encountered in normal practice and the subsequent maintenance.

The design process should be focused on identifying potential problems and errors at the earliest stage possible in the project life cycle. Many techniques have been developed to achieve this, namely Hazard Identification (HAZID), Hazard and Operability (HAZOP), Layer of Protection Analysis (LOPA) and process simulation.

Processes can be batch, semi-continuous or continuous with the selection depending on many factors. Batch processes are used in the manufacture of a wide variety of fine and speciality chemicals and are inherently transient in nature and as such can present unique control problems.

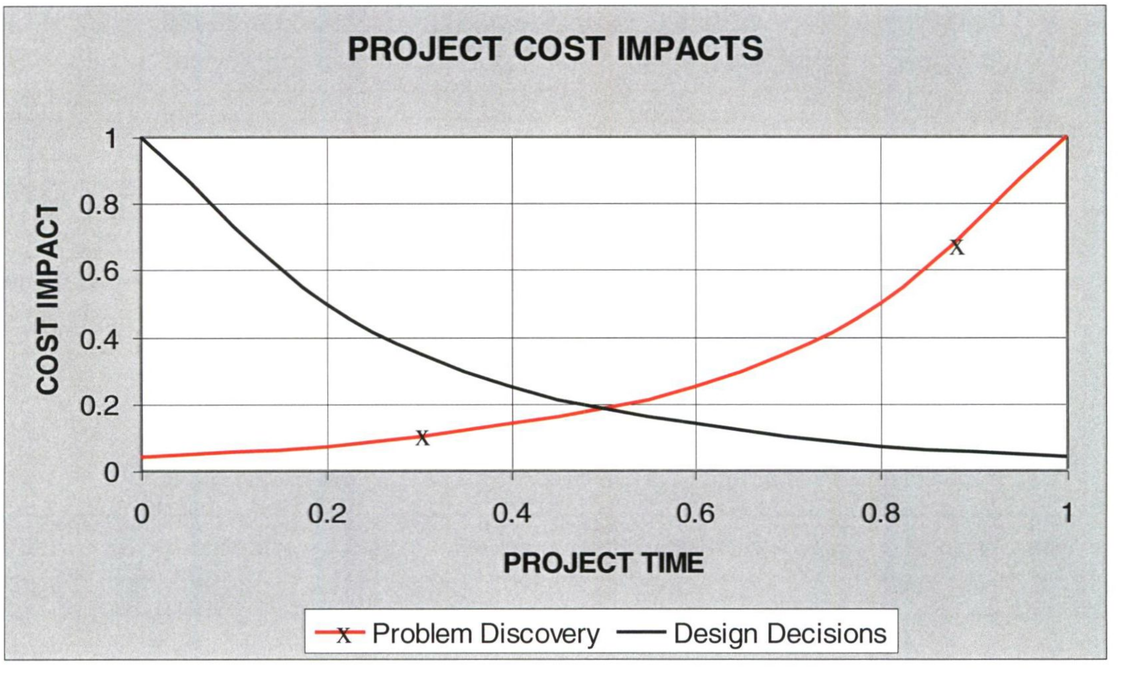
Continuous processes are used in many industries being more prevalent in the oil and gas and petrochemicals industries. Control of continuous processes in steady state does not present any special difficulties, but during start up and process upset conditions special advanced control techniques are relied on.

To achieve consistent quality and to operate the process optimally, maximising productivity and minimising raw material and energy costs requires effective control of the key process parameters. This requires process control and data monitoring systems that matches the process to which they are being applied.

A successful outcome does not necessarily require an in depth mathematical study of the control system and its interaction with the process, which is how courses on instrumentation and control are frequently presented. Very often having a good understanding for the process behaviour and the application of common sense can provide satisfactory results.

Steady state and dynamic process simulation proves the capability to achieve stable and reproducible operating conditions with acceptable product purity, yield and cycle times to satisfy the commercial requirements and the safety and environmental issues for the regulatory authorities.

The project cost impact curves show the benefits of stress testing the designs using these techniques to avoid the increased costs of correction, even if economically possible, later in the project life cycle.



It is worth noting that many serious accidents on process plant have been as a result of failures in plant management systems and procedures and not due to failures in design. However the design and commissioning teams have the responsibility to ensure that adequate documentation and procedures are handed over to operations personnel, which should include a clear understanding of accident risks and the safety critical equipment and systems designed to control them. Maintaining a corporate memory is a serious challenge to all managements which can only be achieved by adequate systems, auditing procedures and continual training.

Section 2

Engineering Fundamentals

Contents

References

Maths and Units

1. T.S.Usherwood and C.J.A.Trimble, "Practical Mathematics", MacMillan, Part 1, 1920.

Fluid Flow

1. Crane Co., "Flow of Fluids through Valves, Fittings, and Pipes", Publication 410, 1988.
2. R.M.Olson, "Essentials of Engineering Fluid Mechanics", Intertext Books, London, 1968.

Process

1. F.G.Shinskey, Process Control Systems, McGraw Hill, 1st Edition, 1967
2. R.M.Felder and R.W.Rousseau, "Elementary Principles of Chemical Processes", Wiley, 2nd Edition, 1986.

2.1 Maths and Units [1]

A basic understanding of practical mathematics is frequently sufficient for an engineer working in a general design or operating process plant environment. Note, we are not considering academic study, specialist areas or research and development.

Fractions and Indices (Powers)

Two numbers, such that their product is unity, are called reciprocal numbers; for example **4** and ¼. A powerful concept is to use letters in place of numbers to represent a specific parameter or variable. So we can state that **a/b** is the reciprocal of **b/a** which in our example gives **a=4** and **b=1**.

If **m** is a positive whole number and **a** is any number, where **m** is the index(power) of **a,** the short and convenient way of writing **a x a x a....** where there are **m** number of **a**'s is $\mathbf{a^m}$.

The following rule $\mathbf{a^m \times a^n = a^{m+n}}$ always applies and it can be shown that:

For **m = 0,** we have $\mathbf{a^0 \times a^m = a^{0+n} = a^n}$ making $\mathbf{a^0 = 1}$, note this means $\mathbf{10^0 = 1}$
For **m = 1** and **n = -1,** we have $\mathbf{a^1 \times a^{-1} = a^0 = 1}$ making $\mathbf{a^{-1} = 1/a}$, note this means $\mathbf{10^{-1} = 1/10}$

The following can be proved using the above procedure:

$\mathbf{a^{-2} = 1/a^2}$, $\mathbf{a^{1/2} = \sqrt{a}}$, the square root of **a**

Note that $\mathbf{(a^m)^n = a^{mn}}$ always applies and it can be shown that $\mathbf{x^{p/q} = \sqrt[q]{x^p}}$

$\mathbf{a^{2/3} = \sqrt[3]{a^2}}$ is the cubed root of $\mathbf{a^2}$

Number Convention SI Units – Prefixes

From the above we can deduce that fractions such as $1/10 = 10^{-1}$, $1/100 = 10^{-2}$ and so on. Numbers in the form 10^7 cannot be conveniently represented in computer programs, so the scientific notation is used where the 10^7 is now E07. Note E is not related to the mathematical constant e or the exponential function. The following conventions avoid errors in allocating the correct number of 0's.

Factors [Note 1]		Prefix	Symbol
10^{-12}	E-12	pico	p
10^{-9}	E-09	nano	n
10^{-6}	E-06	micro	µ
$10-^{3}$	E-03	milli	m
10^{-2}	E-02	centi	c
10^{-1}	E-01	deci	d
10^{1}	E01	deca	da
10^{2}	E02	hecto	h
10^{3}	E03	kilo	k
10^{6}	E06	mega	M [Note 2]
10^{9}	E09	giga	G
10^{12}	E12	tera	T

Note 1 Tip for setting power, make equal to number 0's so $0.00001 = 10^{-5}$ and $100000 = 10^5$
Note 2 Caution refinery industry sometimes uses MM to signify 10^6

Unit converters are now available from many sources so are not shown here. A typical example for energy is shown. The unit to be converted from is multiplied by the factor shown in column with the desired unit.

from \ to	Btu	joule	kWh	therm
Btu	1	1.055E03	0.2931E-03	10E-06
joule	0.948E-03	1	0.2778E-06	9.48E-09
kWh	3.412E03	3.6E06	1	34.12E-03
therm	100E03	105.5E06	29.31	1

1000 Btu = 10^3 Btu = 1E03 Btu = 1.055E06 joule = 0.2931 kWh = 10E-03 therm

Formulae

The concept of using letters in place of numbers provides a powerful technique to define specific relationships and to perform units conversion. This approach allows the development, in many fields, of formulae to provide a statement in general terms of a whole series of particular facts or physical relationships.

Velocity, acceleration and distance

Let **t** represent time in seconds(s)
The reciprocal of time is called frequency **f** so **f = 1/t** with units of 1/s or in the index form s^{-1}.
If a stirrer in a vessel rotates once in half a second it will rotate 2 times per second or 2/s or $2s^{-1}$.
There are 60 s/minute(m) and 60 m/hour(h).
t /60 represents time in minutes obtained from units equation (s x m/60s), note the s cancels out.
t/3600 represents time in hours obtained from units equation (s x h/3600s)

Consider an object uniformly increasing its speed (ft/s) from **u** to **v** in **t** seconds.
(v-u)/t represents the change in speed over **t** seconds the acceleration **a** (ft/s x 1/s) giving units ft/s^2

This leads to the formula	**a=(v-u)/t**	ft/s^2 or $ft\text{-}s^{-2}$.
The distance travelled in time t is given by	**s= ut+ t(v-u)/2**	ft, number group unit is ft
Substituting for **(v-u) = at** gives	$s = ut + \frac{1}{2}at^2$	ft, number group unit is ft

Temperature Conversion

To convert from °F to °C we have:	**°F = 9/5 °C + 32**
A temperature of -10°C is equivalent to	**°F = 1.8 x -10 + 32 = 14**

Pressure Conversion

Absolute pressure p_a is the pressure above a total vacuum and gauge pressure p_g is the pressure above or below atmospheric pressure p_{atm} giving:

$$p_a = p_g + p_{atm} \text{ for } p_g > p_{atm} \qquad p_a = p_g - p_{atm} \text{ for } p_g < p_{atm}$$

At atmospheric pressure p_{atm}(kg/m^2), the absolute pressure p_a(kg/m^2) at the bottom of a column of liquid with a density ρ(kg/m^3) and height **H**(m) is:

$$p_a = H\rho + p_{atm}$$, check units RHS = kg/m^3 x m = kg/m^2 =LHS

Conversion of p_a from kg/m^2 to bar.
We know 1 kg/cm^2 = 0.98065 bar and 1 cm^2 = 0.0001 m^2 so $1/10^{-4} = 10^4$ kg/m^2 = 0.98065 bar
1.0197 x 10^4 kg/m^2 = 1 bar leading to p = Hρ / (1.0197 x 10^4) bar.

p_{atm} = 1.01325 bar, so a p_g of 5 barg is equivalent to p_a of 6.01325 bar and a vacuum p_g of 0.5 barg is equivalent to p_a of 0.51325 bar.

Power to pump liquids

The following example demonstrates the rigorous application of unit conversions and the use of a formula to calculate the power to pump a liquid. The theoretical power to pump **Q**(litres/min) of liquid, with density ρ(kg/m^3), against a differential head **h**(m) or Δ**p**(bar) is given by:

$$P = Qh\rho/(6116\times10^3) = Q\Delta p/600 \text{ kW}$$

Density of water ρ_{H2O}= 1 gm/cm^3,
We need to convert to kg/m^3 we know 1000 gm = 1 kg and 1 cm^3 = 10^{-6} m^3
ρ_{H2O} = 1 x 1/1000 x $1/10^{-6}$ =1000 kg/m^3, check units RHS =gm/cm^3 x kg/gm x cm^3/m^3 = kg/m^3 = LHS

Power to pump 1000 litres/min of water 50 metres equals 1000x50x1000/(6116x10^3) = 8.167 kW

The overall efficiency η_o, a fraction in range 0 – 1, is derived from the drive efficiency η_d the transmission efficiency η_t and the pumping efficiency η_p from $\eta_o = \eta_{d+} \times \eta_t \times \eta_p$.

The volumetric efficiency η_v = actual pump flow Q_{act} / theoretical pump flow Q_t

Dimensionless Numbers

In the study of fluids, dimensionless numbers are used to predict behaviour. The Reynolds Number (Re), the most well-known, gives a prediction of the fluid flowing state (laminar, transitional or turbulent) which then guides the selection of the appropriate pressure drop correlation.

For a fluid of density **ρ**(lb/ft^3) and viscosity **μ**(lb/ft-s) flowing in a circular pipe of inside diameter **d**(ft) with a velocity **v**(ft/s) we have:

$$\mathbf{Re = vd\rho/\mu}$$

The unit equation ft/s x ft x lb/ft^3 x ft-s/lb shows that Re is dimensionless

Organic Chemistry

Organic chemistry classifies aliphatic (straight chain) hydrocarbon compounds into homologous series using an algebraic system:

Paraffins are defined by $\mathbf{C_nH_{2n+2}}$, first member methane (n=1), giving the formula $\mathbf{CH_4}$, followed by Ethane(n=2) $\mathbf{C_2H_6}$, propane(n=3) $\mathbf{C_3H_8}$, n butane(n=4) $\mathbf{C_4H_{10}}$
Olefines are defined by $\mathbf{C_nH_{2n}}$, first member ethylene (n=2), giving $\mathbf{C_2H_4}$, then propylene $\mathbf{C_3H_6}$
Acetylenes are defined by $\mathbf{C_nH_{2n-1}}$, first member acetylene (n=2), giving $\mathbf{C_2H_2}$

The above examples demonstrate how simple concepts can allow the development of inter related phenomena. Applying these concepts enable unit conversions to be made accurately and many engineering relationships to be derived and handled.

Areas, Volumes and Angles

To calculate areas of curved surfaces and volumes we use π which is defined as the ratio of the circumference C of a circle divided by the diameter D = 2r and has a constant value 22/7 or 3.1429.

$\mathbf{\pi = C/D}$	dimensionless	$\mathbf{C = \pi D}$	with units of L

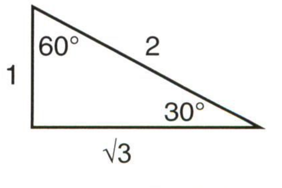
The radian is the unit of circular measure, defined as the angle between two radii which form an arc of length equal to the radius C_{arc} = r and has a value of ~57.27°; note that the angle subtended by a chord of length r is 60°.

The number of radians in 180° = 3.14136 = π radians.

The following relationships can be derived:

Area of a circle	$\mathbf{A = (\pi/4)\ D^2}$	with units of L^2
Note relationship $\mathbf{A/D^2 = \pi/4}$ a constant for all circles!		
Volume of a cylinder height H	$\mathbf{V = (\pi/4)\ D^2H}$	with units of L^3
Area of curved surface of cylinder	$\mathbf{A = \pi DH}$	with units of L^2
Volume of a sphere	$\mathbf{V = (3\pi/4)r^3 = \pi D^3/14}$	with units of L^3
Area of curved surface of sphere	$\mathbf{A = 4\pi r^2 = \pi D^2}$	with units of L^2

The triangle with dimensions shown can be used to determine trigonometrical values.



sinθ = opposite/hypotenuse	sin30 = 1/2 = 0.5	sin60 = √3/2 = 0.866
tanθ = opposite/adjacent	tan30 = 1/√3 = 0.577	tan60 = √3/1 = 1.732
cosθ = adjjacent/hypoteneuse	cos30 = √3/2 = 0.866	cos60 = 1/2 = 0.5

Note from Pythagoras equation the hypotenuse has been calculated from $\sqrt{(1^2+\sqrt{3}^2)} = \sqrt{(1 + 3)} = 2$

Percentages

The principles involved in applying percentages are quite basic but a failure to apply the simple relationships rigorously will easily lead to errors as demonstrated below.

A number **y** divided by 100 is referred to as **y** per cent. **y**% of a number **n** is **y / 100** x **n**
25% of 200 is given by 25/100 x 200 = 50.

Value Added Tax

Consider an item selling at a gross price $\mathbf{P_G}$ that includes tax $\mathbf{P_T}$ being **y**% of price before tax of $\mathbf{P_N}$
We can derive the following $\mathbf{P_G = P_N + P_T = P_N + P_N(y/100) = P_N(1 + y/100)}$
By manipulation we can show that
Given $\mathbf{P_G}$ and **y** we can find $\mathbf{P_N = P_G / (1 + y/100)}$ and $\mathbf{P_T = P_N - P_G}$
Given $\mathbf{P_G}$ and $\mathbf{P_T}$ we can find $\mathbf{P_N = P_G - P_T}$ $\mathbf{y = 100(P_G / P_N - 1)}$

Consider an item selling at £200 ($\mathbf{P_G}$) with VAT at 20% (**y**).
Applying $\mathbf{P_N = P_G / (1 + y/100)}$ gives a net price of £200/(1 + 0.2) = £166.66 with a tax of £33.33.
Consider same item but this time tax is £15 ($\mathbf{P_T}$)
Net price is £200 - £30 =£170 gives VAT (**y**) applying $\mathbf{y = 100(P_G / P_N - 1)}$ 100(200/170 -1) = 17.64%

Instrument Scaling

Electronic transmission in instrumentation uses an elevated zero signal of 4 mA dc with a span of 16 mA dc giving a full scale signal of 20 mA dc.

A temperature transmitter calibrated 50 to 250°C is reading 75°C giving 100x75/(250-50) = 37.5% of the calibrated range. The transmitted signal will be (20 – 4)x37.5/100 + 4 = 10 mA.

A flow transmitter with an orifice plate primary element calibrated 0 to 100 in.wc for 0 to 25000 kg/h is reading 12500 kg/h on a recorder fitted with square root scaled paper the orifice plate differentials and measurement signal are determined as follows:
At maximum flow W_{Max}, orifice differential is 100 in.wc(h_{Max}), with transmitted signal 20 mA and at measured flow W orifice differential is h.
The following relationship applies:
$W/W_{Max} = \sqrt{(h/h_{Max})}$ which leads to $h = h_{Max} (W/W_{Max})^2$ giving $h = 0.25\ h_{Max}$ = 25 in.wc giving a transmitted signal = 0.25 x 16 + 4 = 8 mA

Accuracy

Measurement accuracy is the closeness a reading approaches its true value and is quoted in the literature as % value, % span or % full scale reading. Specification % value gives the highest accuracy of the other two, with % full scale reading giving the lowest accuracy.

Consider a resistance element fitted with an integral 4-20 mA transmitter measuring temperature over a calibrated range of -50 to 250°C. The mean element accuracy over the range is ±0.8°C of true value, the transmitter accuracy is ±0.25% span and the indicator accuracy ±0.1% span.
If the reading is 200°C the element accuracy is 100x0.8/200 = ±0.4% reading.
Transmitter accuracy, ±0.25% span = (250+50)x0.25/100 = ±0.75°C = ±0.375% reading.
Read out instrument accuracy, ±0.1% span = ±0.3°C or ±0.15% reading
The accuracy of devices in series is obtained from the square root of the sum of the squares.
Reading accuracy = $\sqrt{(0.004^2 + 0.00375^2 + 0.0015^2)}$ = 0.0057 or 0.57% giving 200°C ±1.14°C.

If the element accuracy was quoted as 0.1% of span the reading accuracy would become:
$\sqrt{(0.001^2 + 0.0025^2 + 0.0015^2)}$ = ±0.308% of span namely ±0.925°C.

Linear Expansion

The linear expansion of a metal length L_{Ref} from a reference temperature of 68°F to a temperature t°F is determined from $L_t = L_{Ref}(1 + \alpha(t - 68))$.
For an orifice plate we are considering the change in area which is determined from
$A_t = A_{Ref}(1 + 2\alpha(t - 68))$ giving correction factor $F_a = A_t / A_{Ref} = (1 + 2\alpha(t - 68))$
An ANSI304 stainless steel plate has an expansion coefficient of 9.6E-06 in/in °F so for a flowing temperature of 250°F the orifice expansion correction factor F_a = (1 + 1.92E-05 x 182) = 1.0035

Probability

This review is included by the kind permission of Colin Howard and is applicable to Section 4.

Safety Integrity Level (SIL) Capability Assessment
Cautionary note for Probability of Failure on Demand (pfd_{avg}) Calculations

The outcome of a pfd_{avg} calculation is a probability that the protection will fail when there is a demand on the system and is a dimensionless number. It is calculated from information that has frequency (equipment dangerous failures) and time periods (for proof testing) as the basis, with a wide choice of different measurement units for each item. Using a consistent set of units is key to successful pfd_{avg} calculations. If an inappropriate combination of units is used in the calculation then the resultant pfd_{avg} will be incorrect. Care should be taken at the outset to ensure that the data and actual calculations normally use either hours or years as the basis of the units, but not a mixture. If data in a combination of units is supplied then appropriate conversion factors must be applied.

The dangerous undetected failure rate for equipment λ_{du} can be quoted in a number of different ways, the most common ones being:-

Failures per hour
Failures per million hours
FIT's – Failures In Time, where the unit of time is 10^9 hours,
Failures per year

The proof test interval T can be quoted in units of:-

Hours,
Weeks,
Months,
Years

Some key conversion factors that are useful in achieving consistent data units are:-

8760 hours = 1 year
10000 (10^4) hours = 1.141 years
100000 (10^5) hours = 11.41 years (as used in BS EN 61508/61511)
1 million (10^6) hours = 114.1 years
10^9 hours = 114100 years
1 hour = 1.1141 x 10^{-4} years
1 week = 168 hours
1 month = 730 hours
3 months =¼ year
6 months = ½ year

A dangerous undetected failure rate λ_{du} quoted as 0.2 / million (10^6) hours is the same as:-

200 FIT's
2 x 10^{-7} / hour
1.752 x 10^{-3} / year (i.e. 0.2 / 114.1 = 2/1.141 x 10^{-3})

Example pfd_{avg} calculations using this data and the different units, for a one year (8760 hour) proof test interval, using the basic 1oo1 calculation equation: $pfd_{avg} = \square_{du} \times T/2$ are:-

Data in years – pfd_{avg} = 1.752 x 10^{-3} x 1 / 2 = 8.76 x 10^{-4}
Data in hours – pfd_{avg} = 2 x 10^{-7} x 8760 / 2 = 8.76 x 10^{-4}
Calculation based on FIT's - pfd_{avg} = 200 x 10^{-9} x 8760 / 2 = 8.76 x 10^{-4}

Alternative example calculations incorporating conversion factors (shown in italics for clarity) in the calculations are:-

λ_{du} in years, T in hours - pfd_{avg} = 1.752 x 10^{-3} x 8760 / (*8760* x 2) = 8.76 x 10^{-4}
λ_{du} in hours, T in years - pfd_{avg} = 2 x 10^{-7} x (1 x *8760*) / 2 = 8.76 x 10^{-4}
λ_{du} per million hours, T in years – pfd_{avg} = 0.2 x 1 / (*114.1* x 2) = 8.76 x 10^{-4}
λ_{du} in FIT's, T in years - pfd_{avg} = 200 x 10^{-9} x (1 x *8760*) / 2 = 8.76 x 10^{-4}

2.2 Electrical

Circuit diagrams prepared using
http://www.physicsbox.com/indexsolveelec2en.html
Ladder Logic Diagrams prepared using Wade Instruments EZ Schematics
http://www.wadeinstruments.com/index.htm

Units

The basic unit of power is the Watt (W) being the rate of work of 1 joule/sec
1 calorie = 4.18 joules and 1 HP = 746 W = 550 ft lb/sec
1 kWh = 10^3 x 3600 = 3.6 x 10^6 or 3.6E06 W-s = joules Ω

A hydro-electric station generates 50 MWh with a turbine efficiency η_T of 85% and a generator efficiency η_G of 95% giving an overall station η_O of 80.7%.
The water head available H is 500 ft. and water density 62.5 lb/ft^3

Energy output = 50E06 x 3.6E06 = 1.8E14 W-sec x 550/746 = 1.327E14 ft-lb/s
Energy input = 1.327E14/0.807 ft-lb/s = 1.645E14

Energy available per ft^3 water = 500 ft x 62.5 lb/ft^3 = 3.12E04 lb/ft^2

Water flow rate = 1.645E14/3.12E04 = 5.274E09 ft^3/s Units equation ft-lb/s x 1/(lb/ft^2) = ft^3/s

Direct Current Circuits

In a direct current(DC) circuit the power P Watts(W) transferred between a source voltage V and a load of resistance R ohms(Ω) is given by:

$$P = V I$$

Where

I current flowing in amperes

Ohms Law states:

$$I = V/R \text{ leading to } P = I^2R$$

When current is taken from a source voltage E the terminal voltage falls due to internal resistance r leading to the following adjustment for voltage V applied to a load R.

$$I = E_1/(r+R) \qquad V = IR = ER/(R+r) \qquad V = E - Ir$$

Kirchoff's Laws apply in a closed circuit which state:

The sum of currents meeting at a point equals zero. $\sum I = 0$

The sum of voltage drops around the circuit is zero $\sum V = 0$

For resistances in series we have:

$$R = R1 + R2 + R3$$

For resistances in parallel we have:

$$1/R = 1/R1 + 1/R2 + 1/R3$$