P

packed bed A vessel that is filled with a solid *packing material for the purpose of enhancing a chemical reaction or a separation by improving the contact area available for the reaction or separation. The packing material is usually inert and resistant to the process materials and is typically made of ceramic, plastic, glass, or metal. Structured packing consists of corrugated sheets that allow the two phases such as a liquid and a gas to intimately contact one another through complicated channels. Unstructured or random packing consists of small objects that have been designed to provide a high contact area for a minimum volume. *Raschig rings, *Lessing rings, and *Berl saddles are some of the most commonly encountered types of packing material and are loaded into vessels such as distillation columns, adsorption and absorption towers. Catalytic particles also form packed beds to promote chemical reactions and are loaded into vessels or tubes depending on the design. Adsorption materials such as *zeolites are loaded into vessels to form packed beds.

packed bed reactor (PBR) A tubular reactor consisting of one or more tubes within which a solid catalyst is packed to promote a chemical reaction. They are mainly used in heterogeneous gas-phase reactions and operated continuously.

packed column A cylindrical column used to bring about the intimate contact between a rising gas or vapour and a descending liquid typically used for a gas–liquid separation such as stripping. The vessel is packed with small objects that produce a large contact area relative to their size such as *Raschig rings or *Berl saddles, and are used in *distillation columns and adsorption and absorption towers. The liquid descends through the packing through a tortuous route and is in intimate contact with the rising gas or vapour for the purpose of raising the mass transfer area within a limited volume. The amount of packing is determined from calculations involving the number of theoretical stages required determined from vapour–liquid equilibria and the *height equivalent to a theoretical plate (HETP).

packing The small objects that are used in *packed columns and *packed beds. They provide a high surface area per unit volume allowing intimate contact between a rising vapour or gas with a descending liquid. There are many types commonly used, such as saddles and rings, and they are made from plastics, glass, metals, and ceramics that are inert and unreactive to the substances in which they are in contact. They may be arranged in packed columns either in a structured form or randomly, and sit on a support plate designed to take their bulk weight. They are required to allow good passage of liquid and vapour and offer a low pressure drop across the entire packing. The **packing fraction** is the volume taken by the number of particles within a given space or volume.

paddle A type of stirrer used for mixing in vessels to ensure good homogeneity of materials. It consists of flat plates attached to the rotating shaft. The paddle gives *radial flow patterns for which the diameter of the paddle is typically less than half the diameter of the vessel itself.

Pall ring A type of packing material used in a *packed column and consists of a perforated cylinder with a height equal to its diameter. Pall rings are sometimes used in distillation columns to provide an intimate contact between the liquid and vapour. Metal Pall rings have strips that bend inwards, while plastic versions have an internal cross structure.

P&ID *See* PIPING AND INSTRUMENTATION DIAGRAM.

paraffin A former name for the class of saturated hydrocarbons known as *alkanes.

parallel-disc rheometer An instrument used to obtain the rheological properties of fluids. It consists of a fixed flat surface with another rotating surface held at a fixed elevation above, with a sample of the fluid sandwiched between them (see Fig. 33). The rotational speed and distance defines the shear rate. The torque to resist the motion defines the characteristic shear rate. The apparent viscosity is calculated from the ratio of the shear stress to shear rate. The surface can be heated or cooled to determine the rheological properties as a function of temperature.

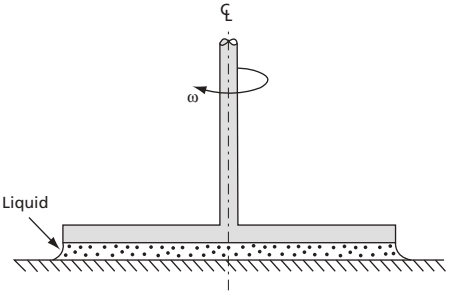

Fig. 33

parallel flow *See* COCURRENT FLOW.

parameter A *variable whose characteristic is not considered and may therefore be taken as being constant.

Parkes process A metallurgical process for the removal of silver from lead using zinc in *liquid–liquid extraction. Zinc is immiscible with lead and its addition to lead containing silver as a contaminant results in silver dissolving in the zinc. The zinc-silver solution is then separated and the zinc removed from the silver by distillation. The process was patented in 1850 by British metallurgist Alexander Parkes (1813–90).

partial condenser A condenser-type heat exchanger used in a distillation process in which only part of the vapour from the top of the distillation column condenses and returns as reflux. The rest of the vapour is used as the top product. A partial condenser is also known as a *dephlegmator. *Compare* TOTAL CONDENSER.

partial derivative The derivative of a function of two or more variables with respect to one of the variables and with the others remaining constant. For example, for the function $z = f(x,y) = x^3y^2 + x^2y + y^3 + x$ then the partial derivative of x with respect to z, is:

$$\frac{\partial z}{\partial x} = 3x^2y^2 + 2xy + 1$$

where y is unchanged; and;

$$\frac{\partial z}{\partial y} = 2x^3 y + x^2 + 3y^2$$

where x is fixed, y is the independent variable, and x is the dependent variable. There are many other examples that use various mathematical rules in their solution such as the chain rule and the quotient rule. They are widely used in chemical engineering, such as in applications involving the movement of fluids or solving energy balances within a space that does not have any defined boundary conditions.

partial fractions A set of simple fractions from which a more complicated fraction can be resolved.

partially miscible liquids Liquids that can dissolve within one another within certain concentration limits to form a single phase, but remain as separate liquids outside those limits. An example is n-butanol and water, in which the liquids separate to a 98 mol per cent water-rich phase and a 56 mol per cent n-butanol-rich phase. Partially miscible liquids are used in the partitioning of a third phase in *liquid–liquid extraction.

partial pressure The pressure exerted by a gas or vapour in a mixture at constant temperature that the gas would exert if it alone occupied the whole volume actually occupied by the mixture. The ratio of partial pressures in a mixture of gases is therefore the same as the ratio of volumes. The partial pressure of a component within a mixture of liquids is the product of the vapour pressure of the pure component and its mole fraction in the liquid phase. The partial pressure, p, of a component, i, of a gas mixture is directly proportional to the total pressure, p, where for an ideal gas:

$$p_i = y_i p$$

where y_i is the mole fraction in the vapour phase.

partial product The mathematical result that is obtained by multiplying a number with one digit of a multiplier.

partial volume The volume occupied by a component in a gas mixture if it alone were present at the total pressure and temperature of the mixture. *See* AMAGAT'S LAW.

particle size distribution The classification of particles in a mixture by size based on their diameter or some other physical characteristic such as weight. The particle size distribution is the broad range of particle sizes in a mixture of particles, expressed as the quantity of the particles whose sizes fall between two measureable characteristics such as the weight percentage of the mixture between two defined diameters. The particle size distribution can also be expressed as a cumulative quantity such as the total weight expressed as a percentage of the mixture above a certain size.

particulate fluidization *See* FLUIDIZATION.

particulates Very small solid bodies often having an irregular shape. They may be a single substance or a mixture of chemical substances often as the product emanating from a process waste stream. They include dirt, dust, smoke, soot, fumes, aerosols, mists, and sprays. They are sufficiently small to be able to penetrate the lower reaches of the lungs.

Dust is classified as particulates that have an aerodynamic diameter of less than 75 micrometres (75 μm), whereas smoke has an aerodynamic diameter of less 15 μm. Inhalable particulates are generally less than 15 μm while respirable dust is less than 5 μm. Cement dust ranges from 1 to 100 μm, while fly ash is approximately 10 μm. Fine particulates have aerodynamic diameters of less than 2.5 μm and abbreviated as $PM_{2.5}$. *See* AIR POLLUTION.

parting A very old process used for separating gold, silver, and platinum from each other by dissolving them in nitric acid. These days, electrochemical processes are used to separate them.

partition coefficient The equilibrium distribution of a substance between two immiscible or *partially miscible liquids. For example, oxalic acid is soluble in both water and diethyl ether, which are themselves immiscible in one another. The partition coefficient is used to determine the effectiveness of a *liquid–liquid extraction process.

Pascal, Blaise (1623–62) A French mathematician, physicist, and thinker on religion and philosophy. With help from his brother-in-law, he arranged an experiment on the Puy de Dome, a mountain in the Auvergne, and was able to show that the height of mercury in a barometer decreases with elevation. He also discovered that liquids transmit pressure in all directions. To show how columns of liquid balance one another, he designed 'Pascal's vases,' which are unusually shaped vessels but the pressure at the bottom of each when filled to the same depth is the same. The unit of pressure is named after him. He suffered ill health throughout most of his life and died at the early age of 39.

pascal (Symbol Pa) The *SI unit of pressure equal to one newton per square metre. It is named after Blaise *Pascal (1623–62). Standard atmospheric pressure is equal to 101 325 Pa.

Pascal's pressure law A law that states that the pressure applied to a fluid is transmitted equally in all directions. It is also known as **Pascal's principle.**

pass The flow of material or energy through a system. In a heat exchanger, the heat transfer medium passes through either the *shell side or *tube side transferring heat. The heat transfer medium can be made to return back through the heat exchanger for further heat exchange. For systems where the medium passes on numerous occasions, the term *multipass is used. *See* PASS PARTITION PLATE.

passive The appearance of being chemically unreactive and is usually the result of the formation of a protective layer that thereby prevents further reaction. For example, aluminium metal reacts with oxygen in air to form a layer of aluminium oxide covering the metal thereby preventing further oxidation to the metal beneath.

pass partition plate A horizontal divider used within the fixed or floating head cover of a shell and tube heat exchanger. It is used to direct the heat transfer fluid from one end of the heat exchanger to the other. Each traverse is called a *pass. The number of passes on the shell side is usually quoted first such as a 2:4 exchanger, which has two *shell side passes and four *tube side passes.

Pasteur, Louis (1822–95) A French chemist and microbiologist who studied the fermentation of wine and introduced the thermal food preservation process of *pasteurization. He later studied diseases and developed vaccines for cholera, anthrax, and rabies. He was director of the Pasteur Institut in Paris from 1888 until his death.

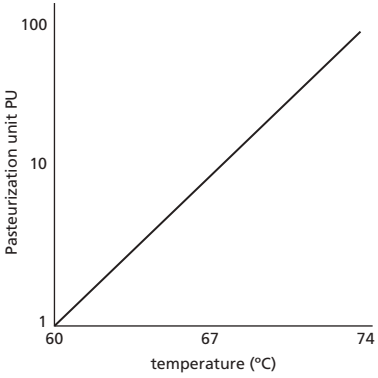

Fig. 34

pasteurization A thermal process used to extend the shelf-life of foods such as fruit juices, beer, milk, and other dairy products by destroying or inactivating harmful and pathogenic microorganisms that might be potentially present. Pasteurization is usually achieved at a specified temperature and time combination. For example, milk can be pasteurized by heating to 72°C and holding the temperature for 15 seconds. There are other temperature-time combinations that will achieve the same effect such as the Holder process, which involves heating between 63°C to 66°C and holding for 30 minutes. The rapid heating and cooling can be achieved using *plate heat exchangers. The process is named after French chemist and biologist Louis *Pasteur (1822–95).

pasteurization unit A sterilizing effect achieved when heating a food product at 60°C for one minute (see Fig. 34). It is used in the pasteurization of foods such as dairy products, beer, and fruit juices in which harmful bacteria can be reduced ten-fold by an increase in temperature of 7°C and is calculated from:

$$PU = t10^{\frac{T-60}{7}}$$

where T is the temperature and t is the holding time. The number of pasteurization units required for a particular product depends on the product, specific type of bacteria, packaging, and expected shelf-life.

patent An official document granted by a government to an inventor of a novel product or process. It assures the legal protection and sole rights to manufacture, use, and sell the product or process within a limited period. A **patentee** is a person, group, or company that has been granted a patent.

pathogen Any harmful disease-causing microorganism or virus. Pathogenic bacteria in foods such as *Clostridium botulinum*, which can produce harmful toxins can be eliminated through processes such as *canning, which involves sterilization by heat.

Pattinson process A process formerly used for the extraction of silver from lead. Developed in 1833 in the UK by H. L. Pattinson, it involved a repeated melting and cooling

process that allowed crystals of lead to form and be skimmed off to yield a silver concentrate. The process was superseded by the *Parkes process and is still used for the recovery of bismuth.

PBR An abbreviation for a ***p**acked **b**ed **r**eactor or *pulsed baffle reactor.

Péclet number A dimensionless number, Pe, used in the study of the thermal transport phenomena of flowing fluids. For the diffusion of heat, it is expressed as the ratio of the molecular to convective heat transfer of a substance:

$$Pe = \frac{vl}{\alpha}$$

where v is the velocity of the substance, l is the distance travelled, and α is the thermal diffusivity. For the diffusion of mass, it is expressed as the ratio of the molecular and mass diffusion of a substance:

$$Pe = \frac{vl}{D}$$

where D is the mass diffusion coefficient. It is named after French physicist Jean Claude Eugène Péclet (1793–1857).

Pekilo process A biochemical process developed in Finland for the production of single-cell protein using a fungal biomass. It uses various forms of carbohydrates as the substrate including spent sulphite liquors from the wood and paper industries as well as waste liquors from the potato and sugar industries.

Peltier effect A thermoelectric cooling effect used in small-scale refrigeration units. It involves a solid-state heat pump that transfers heat from one side of the device to the other through the consumption of electricity. The thermoelectric cooling effect is created between the junction of two different types of conducting materials. The device can also be used for heating. It is named after French physicist Jean Charles Athanase Peltier (1785–1845) who discovered the effect in 1834.

Peng–Robinson (PR) equation of state An equation of state used to predict the behaviour of real gases based on the *van der Waals' equation of state. It describes the variation of molar gas volume and pressure with temperature for many substances in a cubic equation as:

$$p = \frac{RT}{V-b} - \frac{a\alpha(T)}{(V-b)(V+b)}$$

The constants a and b are determined from critical point data. The factor α is related to reduced temperature as:

$$\alpha = \left[1 + (0.37464 + 1.54226\omega - 0.26992\omega^2)(1 - T_r^{0.5})\right]^2$$

where ω is the acentric factor. Developed in 1976, it is also useful for predicting liquid densities and is widely used in the petrochemical industry. It was further modified by Stryjek and Vera in 1986 to improve the accuracy of the model. The **Peng–Robinson-Stryjek-Vera**

(PRSV) equations of state feature an adjustable pure component parameter and a modified polynomial fit for the acentric factor, and can be used for polar substances.

perfect gas A theoretical gas that differs from a real gas that consists of elastic molecules in which the effective volume occupied by the molecules is zero and the gas obeys the *ideal gas law: $pV = nRT$ where p is the pressure, V is the volume occupied by the gas, n is the number of molecules, R is the *universal gas constant, and T is the absolute temperature. It applies to a gas with a low density in which the intermolecular forces between the molecules are neglected. Perfect and ideal gases are often used interchangeably although perfect gases assume a constant specific heat at constant volume.

periodic table The tabular arrangement of all the chemical elements in order of their atomic numbers. The table consists of vertical columns containing groups of elements with similar properties, demonstrating the periodic law. The elements in each group have the same number of electrons in their outer orbitals and therefore share the same valency, thereby accounting for their similar chemical properties. The horizontal rows are periods. The table was originally devised and published by Russian chemist Dmitri Ivanovich Mendeleev (1834–1907) in 1869 and was based on relative atomic masses.

peristaltic pump A positive displacement pump that consists of a flexible tube which contains the process fluid to be transported. The tube is compressed and squeezed between rollers on a rotating wheel thereby moving the fluid along the tubing (see Fig. 35). The roller pressure traps portions of the fluid and carries them forward as discrete volumes. The flow is, however, not pulsation-free. The rate of flow is adjusted by changes in the rotational speed of the wheel. By maintaining the fluid in the sealed tube such that it has no contact with the moving parts of the pump, it is therefore often used in medical applications for fluids such as blood, and for metering applications.

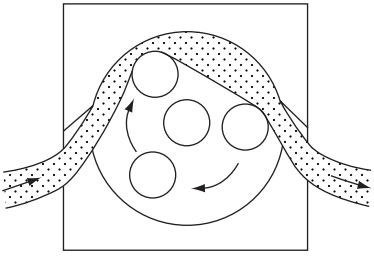

Fig. 35

permanent gas A gas that was once thought to be impossible to liquefy, such as oxygen and nitrogen. It is now considered to be a gas that is not able to be liquefied by pressure alone at normal room temperature. That is, the gas has a *critical temperature below normal room temperature.

permeability The ability of a gas or liquid to flow through a *semi-permeable membrane per unit driving force per unit membrane thickness. It is also known as the **permeability coefficient** and is experimentally determined for a particular separation. The permeability is dependent on the type of permeate, temperature, membrane pore size, flow area, and thickness. For gas separation, the driving force is the pressure difference across the

membrane. For the permeability of oxygen, the barrer is a non-SI unit in which one barrer is equal to 3.348×10^{-19} kmol m m^{-2} s^{-1} Pa^{-1}. It is named after Richard Barrer (1910–96).

permeate The liquid, gas, or vapour that passes through a *semi-permeable membrane in a separation process. *Hollow fibre membranes can be used to separate selectively gases such as nitrogen from oxygen in air in which the smaller nitrogen molecules diffuse through the pores of the membrane as the permeate. In membrane modules used to separate activated sludge, water molecules pass through the membrane as permeate. The material remaining is called the *retentate.

permit to work A formal written and documented procedure that authorizes certain people to carry out specific work within a specified time frame. It is used to control certain types of work that are potentially hazardous and forms an essential part of safe systems of work for many maintenance activities and allows work to begin only after safe procedures have been defined. It provides a clear record that all foreseeable hazards have been considered. Where the proposed work is assessed as having a high risk, strict controls are required detailing the work and how it will be done. It may require a declaration from those involved in a shift handover of the procedures or extensions to the work that is required to be done. Before process equipment or machinery is returned to service, it may also require a declaration from the permit originator that it is ready for normal operational use.

Perry, Robert H. (1924–78) The second editor of *Perry's Chemical Engineers' Handbook*, which was first edited by his father, John H. Perry and published in 1934. He served as chairman of the Department of Chemical Engineering at the University of Oklahoma and was programme director for graduate research at the National Science Research Foundation. He also taught at the University of Rochester and University of Delaware and was advisor to the United Nations and other international organizations.

persistent organic pollutant (POP) A toxic substance that is harmful to the environment, due to being resistant to biodegradation. POPs enter into the food chain causing health issues and concerns. The *Stockholm Convention was a major international conference convened in 2001 to address POPs and identify the twelve substances of greatest concern, including DDT, dioxin, and polychlorinated biphenyls. Other substances have subsequently been added to the list.

personal protective equipment (PPE) Specialist equipment worn or held by a person to reduce or minimize the exposure or contact with injurious workplace hazards. The equipment is used as a barrier to reduce the risk of injury. PPE includes equipment such as safety footwear, hard hats, ear protection, high-visibility waistcoats, goggles, life jackets, respirators, and safety harnesses. In the UK, the principal legislation governing these is the Personal Protective Equipment at Work Regulations 2002 based on the European Council (EC) Directive 89/656/EEC, which requires similar basic laws throughout the European Union on the use of PPE in the workplace.

- Official website of the UK Health and Safety Executive.

PERT *See* PROGRAMME EVALUATION AND REVIEW TECHNIQUE.

pervaporation A membrane separation process used to separate volatile substances from dilute solutions in which the membrane provides a selective barrier. Being independent of vapour–liquid equilibria, pervaporation operates by permeation of a substance

through the membrane followed by its evaporation into the vapour phase. The separation is based on a difference in transport rates of individual components in the liquid *retentate and vapour *permeate on either side of the membrane. The upstream side of the membrane is typically at ambient pressure and the downstream side is under vacuum to allow the evaporation of the selective component after permeation through the membrane. The driving force for the separation is the difference in the partial pressures of the components on either side of the membrane.Pervaporation is used by many industries for purification and separation and is popular due to its simplicity, low energy consumption, and low temperature and pressure operation. It is effective for separating diluting solutions containing small amounts of a component to be removed. Hydrophilic membranes are used for dehydration of alcohols containing small amounts of water, while hydrophobic membranes are used for the removal of organic substances from aqueous solutions. It is a less aggressive separation process than distillation and is therefore used for the separation of ethanol from yeast fermentations, removal of water from esterification reactions, organic solvents from industrial wastewater, and for separating hydrophobic flavour compounds from aqueous solutions.

petrochemicals Organic chemicals produced from petroleum or natural gas.

petroleum (motor gasoline) A liquid mixture of light hydrocarbons used as a fuel in internal combustion engines. It is distilled from crude oil between 35°C and 215°C and can include oxygenates to reduce the amount of carbon monoxide formed during combustion, as well as octane enhancers. It can also be mixed with anhydrous ethanol such as bioethanol. The word 'petroleum' is derived from the Latin *petra* meaning 'rock or stone' and *oleum* meaning 'oil.'

petroleum coke A black solid residue used as a feedstock in coke ovens used in the steel industry for heating and chemical production. Obtained by the process of *cracking and carbonizing petroleum-derived feedstocks, tars, and pitches, it has a high carbon content of up to 95 per cent and a low ash content. However, it has a high sulphur content, which can result in environmental issues.

petroleum ether A mixture of volatile alkanes comprising mainly pentane and hexane. It has a boiling point of between 30°C and 70°C. It is widely used as a solvent and in the extraction of edible oils. It is also an anaesthetic.

petroleum feedstock Chemicals derived from petroleum and natural gas such as naphtha that are used as the raw materials to produce other chemicals, plastics, and synthetic rubbers.

petroleum refinery *See* OIL REFINERY.

petroleum reservoir A naturally occurring subsurface pool of hydrocarbons trapped within rock formations in the Earth's crust. The hydrocarbons may exist as crude oil or natural gas, and are the result of the high pressure and temperature decomposition of aquatic organisms that lived millions of years ago. Petroleum reservoirs are broadly classified as being oil or gas reservoirs and quantified in terms of the composition of the hydrocarbon mixture, their initial temperature and pressure, and surface production temperature and pressure. *See* WELL.

PFD 1. An abbreviation for ***p**rocess **f**low **d**iagram. **2.** An abbreviation for **p**robability of **f**ailure on **d**emand, which is the likelihood that a process, system, or item of process plant will fail to operate in the required and expected manner on demand. *See* PROBABILITY.

PFR *See* PLUG FLOW REACTOR.

pH A measure of the acidity or alkalinity of a liquid based on the negative logarithm of the hydrogen ion concentration:

$$pH = \log_{10} \frac{1}{[H^+]}$$

The scale ranges from 1.0 (highly acidic) to 14.0 (highly alkaline) with neutral solutions such as deionized water with a pH of 7.0. The scale was developed in 1909 by Danish chemist Søren Peder Lauritz Sørensen (1868–1939).

phase A state of matter being either solid, liquid, or gas. *Single-phase flow is the flow of a substance or mixtures of substances of the same phase. *Multiphase flow involves a substance or a mixture of substance of different phases. A refrigerant in the evaporator in a *refrigeration cycle is an example of multiphase flow involving a liquid and a vapour.

phase diagram A diagram representing the relationship of solid, liquid, and gaseous phases over a range of temperatures and pressures (see Fig. 36 for a typical example). Phase diagrams for pure substances of pressure and temperature show the existence of triple and critical points. Phase diagrams for binary mixtures showing liquid and gaseous phases at constant temperature illustrate the variation of pressure, and where *tie lines join the two phases in equilibrium. Phase diagrams for binary mixtures such as metals with temperature show the existence of eutectic points. The *liquidus is the line or curve between liquid and liquid/solid at equilibrium, and the *solidus is the line or curve between solid and liquid/solid at equilibrium.

phase rule *See* GIBBS' PHASE RULE.

phase separation The separation of two or more distinct phases. An example is the separation of immiscible liquids such as oil and water, which settle to form two distinct layers where the oil, being of a lower density, floats on the water. The oil and water can then be readily separated using overflow weirs. Phase separation is used to separate crude oil, natural gas, water, and sand in separators on offshore oil platforms.

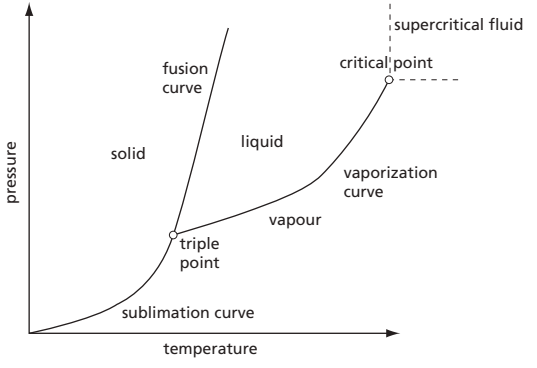

Fig. 36 Phase diagram

phase transition The change from one phase of a substance into another such as a solid to a liquid, a liquid to a gas, etc. The boiling of water to steam is a phase transition, as is the freezing of water to ice.

Phillips process 1. A liquid-phase catalytic process used for polymerizing linear olefins (alkenes) such as ethylene into linear thermoplastic polymers such as high density polyethylene. It uses a Phillips catalyst, which is based on a chromium (VI) oxide on silica. *Compare* ZIEGLER-NATTA CATALYST. **2.** A fractional crystallization process used for freeze-concentrating beer and fruit juices. **3.** A two-stage process used for the dehydrogenation of butane to form butadiene.

photochemistry The study of chemical reactions that are initiated or accelerated by exposure to visible light, ultraviolet radiation, or infrared radiation. The basic laws of photochemistry state that light must be absorbed by a compound for a chemical reaction to take place, known as the first or Grotthus–Draper law. The second or Stark–Einstein law states that for each photon of light absorbed by a chemical system, one molecule is activated for the subsequent reaction. It was derived by Albert *Einstein during his development of the quantum theory of light. The Bunsen–Roscoe law of reciprocity states that a photochemical effect is directly proportional to the total energy dose, irrespective of the time required to deliver the dose.

photolytic reaction A chemical reaction that is the result of exposure to visible light or ultraviolet radiation. The reactions often involve free radicals. Photolysis is an important reaction in the photosynthesis of plants, in which energy from sunlight is absorbed by chlorophyll to produce gaseous oxygen, electrons, and hydrogen ions.

physical chemistry A branch of chemistry that is concerned with the effects of chemical structure on the physical properties of substances.

physical explosion An explosion that does not involve any form of combustion or chemical reaction. The most common is the rupture and bursting of a vessel of which a *boiling liquid expanding vapour explosion (BLEVE) is an example, as is the rupture of a gas cylinder with the rapid release of energy.

pi (Symbol π) A transcendental number with a value of 3.141 592 . . . It is the ratio of the circumference of a circle to its diameter.

pickling The removal of scale such as oxides from substances by immersion in a liquid containing sulphuric acid or hydrochloric acid. It is usually used between hot- and cold-rolling in the processing of sheet steel.

PID control The modes of control used to control processes or part of a process. The three basic modes of control are *proportional control, *integral control, and *derivative control. Derivative control is always used in combination with proportional control or both proportional and integral control. Integral control is generally used in combination with proportional or with both proportional and derivative control. PID control is also known as **three-term control**.

Pidgeon process A process used for the production of magnesium developed by Canadian scientist Lloyd Montgomery Pidgeon (1903–99) in 1941. It involves the high temperature reaction of silicon and magnesia to form silica and magnesium:

$$Si + 2MgO \leftrightarrow SiO_2 + 2Mg$$

The magnesium vapour produced is removed by distillation and recovered as magnesium crystals.

piezometer An instrument used to determine the static pressure of a liquid such as in a pipe. It consists of a vertical tube in which the vertical elevation of the liquid is a measure of the pressure. **Piezoelectric pressure sensors** are used to measure the pressure and convert it to an electrical signal. There are various types commonly used including pneumatic, strain gauges, and vibrating wire sensors. The data is then captured on a data logger.

pig A device used to clean or clear away the inside of a pipeline, particularly those used offshore carrying natural gas and crude oil which are prone to the build-up of deposits such as waxes and hydrates. Pigs are made of rubber or polyurethane and the basic design consists of two plates held apart by a short rod. They can also incorporate various sensing and recording equipment. They are launched into the pipeline and move under the effect of an applied pressure; they emit a squealing sound as their blades scrape along the pipeline and are recovered from a receiving trap, which are loops in the pipeline that can be isolated by shut-off valves. **Smart pigs** or intelligent pigs are inspection devices used to measure the condition of the pipe including metal loss, restrictions, and pipe deformation.

pig iron Another name for cast iron.

pilot-operated safety relief valve (POSRV) An automatic valve system that relieves pressure in a vessel or pipeline by the remote command from a pilot. *See* SAFETY VALVE.

pilot plant A small-scale process unit based on laboratory-scale research or findings. It is used to evaluate the feasibility and potential for full-scale process design and operation. A **pilot scale experiment** is a small-scale preliminary study used to check the feasibility or to improve the design of a process or piece of research. They are often carried out before committing to large-scale process construction and operation in order to avoid wasting time and money. They can also be used to determine the optimum conditions required in a full-scale process or to gain a valuable insight into a process under carefully controlled conditions.

pinch analysis A technique for minimizing energy usage in a process. It is based on calculating the minimum energy consumption by optimizing the heat recovery, energy supply, and process operating conditions. It uses process data represented as energy flows, or streams, as a function of heat load against temperature. These data are combined for all the hot and cold streams in the process to give two composite curves—the hot streams releasing heat and the cold streams requiring heat. The point of closest approach between the hot and cold composite curves is called the **pinch point** and corresponds to the point where the design is most constrained. Using this point, the energy targets can be achieved using heat exchange to recover heat between the hot and cold streams in two separate systems, with one for temperatures above the pinch temperature and one for temperatures below pinch temperatures. First developed by chemical engineer Bodo Linnhoff in 1977 at the University of Leeds, it is also known as *process integration, heat integration, and **pinch technology**.

pinch point 1. Used in multistage separation calculations, it represents the point of no further enrichment between stages. On the *McCabe–Thiele diagram, the point is located where the operating line touches the equilibrium curve. **2.** The point in a *pinch analysis that corresponds to the point where the hot and cold streams in an integrated process are most constrained (see Fig. 37).

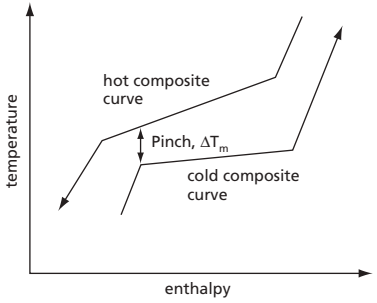

Fig. 37

pipe An enclosed conduit used to transport fluids. These are circular in cross section and available in widely varying sizes, wall thicknesses, and materials. Pipes are specified in terms of their diameter and wall thickness. The wall thickness is indicated by the *schedule number. Pipes are commonly made from metals and alloys, glass, and various plastics. Low-carbon steel pipes are most commonly used in process plants. PVC pipes are typically used for water and gas lines. Lengths of pipes are joined together by *flanges, welding, or screw fittings.

pipe chase An enclosed space used to conceal pipes. Electrical wires and cables may also run through the pipe chase.

pipeline A long section of large-bore pipe used to transport fluids. Natural gas and crude oil from offshore reservoirs are transported over long distances across the seabed up to platforms for separation and treatment, and then transported sub-sea through pipelines for onshore processing. Pipelines are the principal means of transporting hydrocarbon feedstocks such as ethylene over long distances through buried pipelines between petrochemical refineries. Natural gas is transported in similar pipelines over long distances for distribution. Process water including seawater is also transported in great quantities. Pumps and compressors are used to transport such fluids in large volumes at the required pressure. Single-phase flow is easier to transport and meter than multiphase fluid flow. In wet gas lines, large volumes of liquid are required to be routinely swept out using a *pig. *Methane clathrate, waxes, and other deposits can also complicate flow.

pipestill *See* FRACTIONAL DISTILLATION.

pipetrack The organized routing of pipework above ground to transport raw materials, products, and utilities such as water and steam to and from process equipment. The pipetrack is supported on structures such as trestles and gantries with sufficient overhead clearance. Being overhead, leaks are easy to detect and are harmlessly dispersed into the atmosphere. *Compare* TRENCHED PIPING.

pipework A collective term used for all the piping in a process plant irrespective of its purpose and size. A **pipe run** is the route taken by a length of pipe in a process.

piping and instrumentation diagram (P&ID) A schematic representation of the interconnecting pipelines and control systems for a process or part of a process (see Fig. 38 for an example). Using a standard set of symbols for process equipment and controllers, it

includes the layout of branches, reducers, valves, equipment, instrumentation, and control interlocks. They also include process equipment names and numbers; process piping including sizes and identification; valves and their identification; flow directions, instrumentation, and designations; vents, drains, samplings lines, and flush lines. P&IDs are used to operate the process system as well as being used in plant maintenance and process modifications. At the design stage, they are useful in carrying out safety and operations investigations such as *HAZOP.

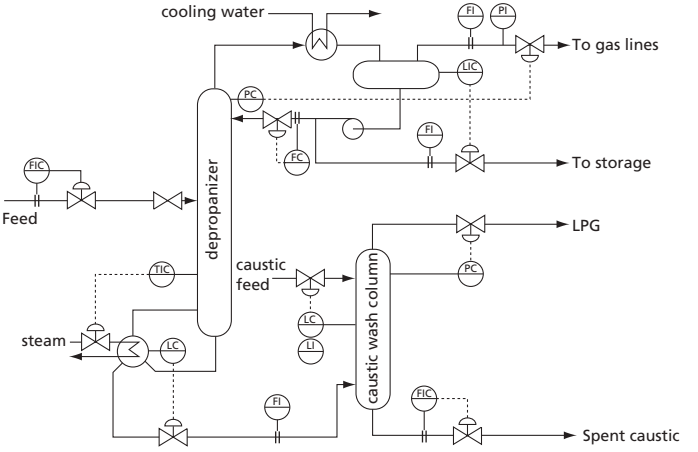

Fig. 38 Piping and instrumentation diagram

p

piston A movable device used in a cylindrical chamber to transmit a force either onto a fluid in the chamber, such as in a reciprocating pump, or by the expansion of a fluid in the chamber, such as in an internal combustion engine (see Fig. 39). The piston is attached to a connecting rod and crank to transmit or provide power. A **piston pump** is a type of self-priming positive displacement pump used to transfer and meter fluids using a piston that sweeps into a chamber containing the fluid and displaces it. Check valves are used to ensure that the flow is in the correct direction. The rate of flow is dependent on the frequency of the stroke of the piston and the swept volume. They are capable of generating very high

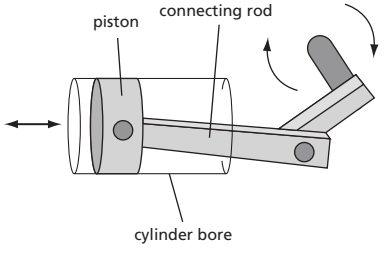

Fig. 39

pressures of up to 500 bar, and therefore have a pressure relief valve installed on the delivery side. The sealing of the piston and the check valves are the weak points and they are usually only used for clean fluids of low viscosity, due to the need for quick action by the check valves and the possibility of scoring of the piston.

pitch 1. The distance between the centre-line of tubes used to carry fluids for heat transfer in a shell-and-tube heat exchanger. Square and triangular pitches are commonly used (see Fig. 40). **2.** A generic term used for a flammable semi-solid tar-like substance produced naturally or by the distillation of heavy or long-chained hydrocarbons. It is also known as bitumen or asphalt and used to surface roads.

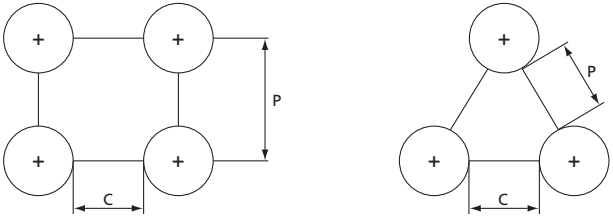

Fig. 40

Pitot tube An instrument used to measure the velocity of a flowing fluid by measuring the difference between the impact pressure and static pressure in the fluid. The device normally consists of two concentric tubes arranged in parallel; one with a face directed towards the flow to measure the impact pressure, the other face perpendicular to the flow to measure the static pressure. By taking a number of readings at various points in the cross section of a pipe or duct, known as a **Pitot traverse**, the overall rate of flow can be determined. As with all flow measurement devices, Pitot tubes should ideally be located away from disturbances such as bends. The device was devised by Italian-born French engineer Henri de Pitot (1695–1771).

P/I transducer *See* TRANSDUCER.

pitting A type of corrosion of a metal surface resulting in cavities. It is also one of the damaging effects of long-term *cavitation in centrifugal pumps that occurs on the surface of impellers.

pK$_a$ value A measure of the strength of an acid expressed as the negative base-10 logarithm of the acid dissociation constant, K$_a$:

$$pK_a = \log_{10} \frac{1}{[K_a]}$$

The dissociation constant can be calculated from the dissociation reaction. For example, for the reaction $HB_{aq} \leftrightarrow H^+_{aq} + B^-_{aq}$::

$$K_a = \frac{[H^+][B^-]}{[HB]}$$

The pK value is often used to compare the strengths of different acids.

plait point A point on a triangular diagram used to represent ternary liquid systems where two conjugate phases are mutually soluble and where there is no *tie line. *See* TRIANGULAR DIAGRAM.

plant Major equipment and machinery used in industrial processes. A *process plant is the entire industrial process or factory in which raw materials are converted to products through chemical, physical, or biochemical transformation.

plant layout study An analysis of the different possible physical configurations for an industrial *process plant. Due to the complexity of modern plants and manufacturing facilities that involve complex operations, the study typically involves the physical space and proximity of vessels and equipment, materials handling, piping and auxiliary equipment, utilities and services, communications systems, emergency systems, structural and architectural considerations, and general site work.

plasma 1. A state of matter resulting from the ionization of gases in which the number of positive and negative ions is approximately the same. In a *thermonuclear reactor, a very high temperature is maintained by retaining the plasma away from the walls using strong electromagnetic fields. It was first identified in 1879 and the nature of the matter was then identified by British scientist Sir Joseph John Thomson (1856–1940) in 1897. Irving *Langmuir first used the term plasma in 1928. **2.** The colourless part of blood in which corpuscles are suspended.

plasmid A small extra-chromosomal piece of DNA that is independent of the main chromosomes in the nucleus of a living cell. The DNA can be modified to contain the genetic code for drug resistance and can be transmitted between bacteria and yeast of the same or different species. They are used in *genetic engineering. *See* RECOMBINANT DNA TECHNOLOGY.

plastic A high molecular weight polymer that can be shaped at some stage in its manufacture by the application of heat and pressure to give a product that is stable at normal temperature. A thermoplastic is a substance that can be softened by the application of heat so that it can be shaped and moulded indefinitely. A thermosetting plastic is not able to be softened by reheating due to a chemical change such as the formation of cross-links between chains of the polymerized molecules. PVC (polyvinyl chloride) is a thermoplastic that is often used for piping systems and is stronger and more rigid than most other thermoplastic materials.

plasticity The ability of a body to retain a deformation in shape when a particular loading has been applied and then withdrawn. Fluids that exhibit plasticity require an applied shear stress to exceed the *yield stress before flow can occur. The greater the yield stress, the greater the plasticity.

plate A flat perforated horizontal sheet of metal used in distillation and absorption columns designed to provide an intimate contact between a rising vapour or gas and a liquid to allow vapour–liquid equilibrium to be achieved. The plate lies across the entire cross section of the column and has perforations or small openings that allow the vapour or gas to pass yet allow the liquid to remain on the plate. A variety of designs of plates are commonly used and include sieve plates, *valve trays, and bubble caps. A *distillation column may typically have many plates. *See* PASS PARTITION PLATE.

plate and fin heat exchanger A compact type of heat exchanger with a particularly high heat-transfer area that consists of cross flow channels between parallel plates in which the

parting sheets form the primary heat-transfer surfaces and corrugated fins between the parting sheets. The corrugations are sealed to provide an enclosed and pressure-retaining unit.

plate and frame filter press An apparatus used for the batch separation of solid particles from a liquid slurry. It consists of cloths stretched across a metal plate with a rippled surface and sealed in a metal frame. A number of plates, cloths, and frames are firmly sandwiched together to ensure no leakage from the sides. The liquid slurry to be separated is pumped into each compartment formed by the frames through channels onto one side of the cloth. The cloth allows the liquid to pass through while retaining the solids or **filtrate,** which builds up as a cake. This corresponds to a build-up of pressure and a slow reduction in the rate of flow. The filtration process is halted once a sizable cake has built up. The plate and frames are then decoupled and the cake manually removed from the cloths. The cleaned cloths are then reused.

plate efficiency The measure of the performance of plate used in an *absorption tower or *distillation column. The plate is usually perforated to allow vapour or gas to rise up and make contact with liquid. Ideally, a vapour–liquid equilibrium is reached. However, this is not always the case. Due to these contact inefficiencies, more plates are required to achieve a desired separation. The plate efficiency is usually expressed as a percentage of the ideal or theoretical separation. *See* MURPHREE PLATE EFFICIENCY.

plate heat exchanger A compact and versatile type of heat exchanger consisting of rows of compacted and sealed corrugated metal plates between which liquid flows, transferring heat through the surface of the plates (see Fig. 41). The hot and cold liquids are

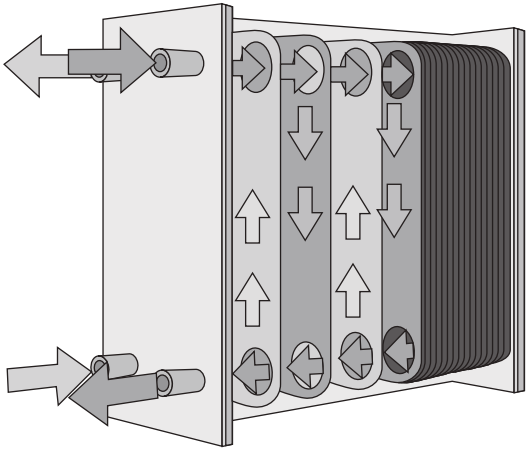

Fig. 41

channelled between alternating plates. The corrugation effect causes turbulence of the heat-transfer liquids thereby enhancing heat transfer. The size and area of the plate heat exchanger can be increased or decreased by adding or removing plates.

platforming process A catalytic reforming process used to convert straight-chain aliphatic hydrocarbons into aromatic hydrocarbons and hydrogen using a platinum catalyst.

The name is derived from **plat**inum-re**forming**. While platinum was the first catalyst to be developed for catalytic reforming, other catalysts and related processes have subsequently been developed over the past 60 years. Continuous catalytic regeneration or *CCR platforming is a widely used continuous version of the process.

platner process A process developed in the nineteenth century to extract gold from ore by a chlorination reaction. The gold chloride is then extracted using water and reduced by ferrous sulphate to gold metal:

$$AuCl_3 + 3FeSO_4 \rightarrow Au + Fe_2(SO_4)_3 + FeCl_3$$

PLC An abbreviation for **p**rogrammable **l**ogic **c**ontroller. It is a fast-acting computer-based monitoring and control system used to control complex processes in which the control actions are based on process data. It uses a computer to continuously monitor the various input signals and logically manipulate the necessary outputs to maintain control.

plenum A large gas chamber usually connected to ducts and maintained under either positive or negative pressure. It is used in air conditioning.

plug flow An intermittent two-phase gas–liquid flow regime found in vertical pipes or tubes often referred to as *slug flow characterized by bullet-shaped bubbles, which tend in size towards the diameter of the pipe. In the continuous liquid phase, the higher-velocity gas bubbles coalesce to form rising plugs or slugs. A **Taylor bubble** is the liquid film around the plug that may move downwards at low velocity. The liquid between Taylor bubbles often contains a dispersion of smaller bubbles.

plug flow reactor (PFR) A type of idealized tubular reactor that features no radial or axial mixing. All the components that flow through the reactor therefore possess the same residence time. A PFR may consist of either one long reactor or many short reactors as a tube bundle. The reactants flow through the length of the reactor during which the chemical reaction rate changes. They are usually used for gas-phase reactions requiring high temperatures. Used for both exothermic and endothermic reactions, heat transfer is effective through the tube walls.

plume The continuous release of a gas as a cloud. In contrast, a puff is the instantaneous release of a gas cloud.

plunger pump A type of reciprocating pump that uses a plunger instead of a piston within a cylinder to displace a liquid. They are used as metering pumps and for liquids that may be abrasive since the plunger moves into the cylinder and is clear of the walls. Check valves on the suction and delivery side of the pump ensure that the flow is in the correct direction.

PM An abbreviation for **p**articulate **m**atter. Often presented with a subscript, for example PM_{10}, which refers to particulates that have an aerodynamic diameter of less than 10 micrometres (10 μm). These pose respiratory health concerns as they can be inhaled and can penetrate the lower reaches of the lungs, and therefore accumulate within the respiratory system. $PM_{2.5}$ are particulates of less than 2.5 micrometers and are referred to as fine particles, which can present severe respiratory problems leading to respiratory, pulmonary, and cardiovascular diseases. *See* PARTICULATES.

pneumatic control valve A valve used to control the flow of process material through a pipe by controlling the flow area through the valve by way of an applied air pressure signal.

The operation of a control valve involves an air supply that positions its movable part (i.e. plug, ball, or vane) relative to the stationary seat of the valve. A valve actuator accurately locates the valve plug in a position determined by the pneumatic control signal and operates to move the valve to either fully open or fully closed positions. The actuators may be either piston or diaphragm types. Air-to-open valves require air to open and therefore automatically close in the event of fail closure. They are therefore used on fuel lines to furnaces. Air-to-close valves fail to open on a loss of air pressure and are used on air lines into fuel burners. In general, fail-to-open and fail-to-close valves operate when the supplied air pressure drops below a minimum value.

pneumatic conveying The transportation of granular free-flowing solids that are suspended in a fast-moving flow of air or gas. The particles move freely and can be readily transported to and from hoppers and silos through pipes and ducts. Pneumatic conveyors are typically used for the transportation of grains and catalyst particles.

pneumatic mixing A type of mixing that involves sparging gas into a liquid to cause turbulence. Often used for biological reactions in bioreactors, bubbles of gas (usually oxygen or filtered air) rise in the liquid generating turbulence. Bubble size and number is dependent on the type of sparger and can influence the rate of mass transfer.

pneumatics The study and production of devices that rely on air pressure for their operation.

pneumercator An instrument used to determine the depth and volume of liquid in a vessel, tank, or reservoir. It consists of a vertical leg down which a compressed gas is gently discharged in the form of bubbles. The pressure of the applied gas is measured from which the hydrostatic depth is determined. Using two such legs, it is possible to determine the density of the liquid, and in the case of immiscible liquids forming two layers, the location of the interface.

pneumoconiosis An occupational disease of the lungs caused by the inhalation of mineral and organic dust particles. Depending on the type of dust, the disease can also be called black lung arising from coal dust, asbestosis from asbestos fibres, siderosis from iron dust, silicosis from silica, and silicosiderosis from a combination of silica and iron dusts.

poise (Symbol P) A c.g.s. unit used for the viscosity of fluids. It is the tangential force expressed in dynes per square centimetre that is required to maintain the difference in velocity of two parallel plates that sandwich the fluid by a distance of one centimetre at a velocity of one centimetre per second. The centipoise (cP) is more commonly used in which one cP is equal to 10^{-3} Pa s.

Poiseuille, Jean Louis Marie (1797–1869) A French physician and physiologist noted for his work on fluids. He had a major interest in the flow of blood through the body. Using narrow glass capillaries, he made detailed studies of flow. He experimentally derived a formula and published his work in 1840, crediting the work of German engineer Gotthilf Hagen who also independently derived the formula.

Poiseuille's equation A relationship used to determine the rate of flow of a fluid with laminar flow through a horizontal cylindrical tube or pipe. Named after French physician and physiologist Jean Louis Marie *Poiseuille(1797–1869), it is given by

$$Q = \frac{\pi}{8\mu}\frac{\Delta p}{L}R^4$$

where μ is the viscosity of the fluid, $\Delta p/L$ is the pressure drop along the tube, and R is the internal radius of the tube.

poison 1. A chemical substance that results in the reduction in effectiveness of a catalyst as the result of it being contaminated by a reactant, a product of the reaction, or some other extraneous material. The poison accumulates on the surface of the catalyst, reducing the effectiveness by reducing active sites for the reaction to occur. **2.** Another name for a *toxic substance.

Poisson's ratio The ratio of the lateral strain to the longitudinal strain in a material held under tension. When a sample of material is stretched (or squeezed), there is a contraction (or extension) in the direction perpendicular to the applied load. Poisson's ratio is the ratio between these two quantities. The value lies between –1.0 and 0.5. It was introduced by French mathematician and physicist Siméon-Denis Poisson (1781–1840).

polarimeter An instrument that measures the polarization of any form of *electromagnetic radiation.

polishing The process of removing the traces of contaminants from a liquid to produce a very clear product, such as in polishing filtration used for beer, or polishing *ion exchange.

pollutant A chemical substance that when released into the environment gives rise to harmful and damaging effects on living organisms. The substance can be either a toxic substance that is harmful to the environment by being resistant to biodegradation such as pesticides, or can already be present in the environment but is added in excessive amounts such as nitrogen into the soil that accumulates in lakes and rivers. *See* PERSISTENT ORGANIC POLLUTANT.

pollution A substance whose uncontrolled release can cause damage to human and animal life, plants, trees and other vegetation, and the environment in general. Airborne pollutants may be in the form of gases, mists, vapours, clouds, dust, smoke, soot, and fumes. Waterborne pollutants may contaminate land and water courses such as rivers. Non-biodegradable pollutants include heavy metals, certain pesticides, many types of plastics, and chlorinated hydrocarbons. Biodegradable pollutants such as certain plastics and sewage can be broken down by microorganisms over a period of time and rendered harmless. Airborne and waterborne radioactive pollutants have a lasting effect on the environment and can enter the food chain. *See* AIR POLLUTION; WATER POLLUTION.

polymerization A process that involves the chemical reaction of simple molecules called *monomers to combine to form longer and more complex molecules called **polymers**. These are large macromolecules made up of many repeating units derived from a small simple number of simple molecules. The polymers are formed into sheets, chains, or three-dimensional structures, and held together by covalent bonds. Functional groups are attracted to each other by intermolecular forces (*van der Waals' forces) and in some cases ionic and hydrogen bonds. There are many types of polymer that exist naturally such as proteins, rubber, and polysaccharides. Many others are produced synthetically such as polyethylene and polypropylene. Synthetic polymers have many applications such as textiles, plastics, rubber, coatings, and adhesives. The feedstock for most polymers is ethylene and is essential in the production of vinyl chloride and styrene, which are used for plastics. Propylene and butadiene are also used in high quantities and are by-products from the manufacture of ethylene. Addition polymers have identical monomer subunits linked

to form a polymer that has the same empirical formula as the monomer. Condensation polymers have monomers joined during a condensation reaction with the elimination of water during the reaction, to form a polymer with a different empirical formula to that of the monomer. Copolymers are composed of two or more different types of monomers. Naturally forming polymers include polysaccharides and proteins. Synthesized polymers include polyvinyl chloride and polyester.

polytropic gas A gas that can be represented by $pV^n = k$ to describe its compression and expansion. The special cases are $n = 1$ (isothermal); $n = k$ (isentropic); $n = 0$ (pressure constant); $n = \infty$ (volume constant).

Ponchon–Savarit A rigorous graphical method used in the analysis of the separation of two heterogeneous liquids by distillation. It is used to determine the number of stages required to bring about a required separation and is based on a stage-wise approach using enthalpy and composition of each theoretical tray or equilibrium stage. The graphical technique is based on the vapour–liquid equilibrium data for the more volatile component in the feed. The method was developed by M. Ponchon and P. Savarit independently between 1921 and 1922.

pool boiling A type of liquid boiling that occurs on a submerged surface. The surface in a stagnant pool of liquid is heated to a temperature above that of the boiling point of the liquid. The boiling that occurs produces vapour whose motion relative to the surrounding liquid is due to the buoyancy effects of the vapour with the bulk of the liquid being at rest.

pool fire The combustion of flammable liquid that is evaporating from the base of the fire. The liquid, such as a pool of vaporizing hydrocarbon fuel, has no or little initial momentum. Well-ventilated open fires are fuel-controlled whereas fires within enclosures may become ventilation-controlled. Pool fires represent a significant element of risk associated with major accidents on offshore oil and gas installations that may have large liquid hydrocarbon inventories.

POP *See* PERSISTENT ORGANIC POLLUTANT.

porosity The proportion of the volume of a porous body that is not occupied by the body itself. It is usually given as a fraction, percentage, or decimal. The porosity of a *packed bed is the ratio of the volume of voids to the total volume of the bed. The value is dependent on the shape and size distribution of the particles, the ratio of the particle size to bed diameter, and the method used for filling the bed. It is usually determined by measuring how much water is used to fill the voids compared with the total volume of the bed. *Compare* VOIDAGE.

port An access point to a process vessel and used for instrument probes and transfer lines, etc.

positive displacement pump A classification of pump type in which fluids are transported by its displacement from one place to another for flow through pipelines, conduits, ducts, and channels. Examples include *reciprocating pumps, which involve the displacement of a fluid from a chamber by a piston or plunger, and *rotary pumps, which involve rotating gears or lobes with the fluid being transported between the teeth. There are many variations such as the *diaphragm pump, which involves a diaphragm flexed to and fro, and the *Mono pump, which involves a rotating helical worm.

POSRV *See* PILOT-OPERATED SAFETY RELIEF VALVE.

potential energy The capacity of a body to do work due to its elevation above a reference point. It is the product of weight and height.

pot still Used for batch distillation, it consists of a boiler with a condenser attached.

pound A unit of mass in *f.p.s. engineering units. One pound (lb_m) is equal to 0.453 592 kilograms.

poundal A unit of force in the f.p.s. system of units and equal to the force needed to accelerate a unit of mass of one *pound by one foot per second.

Pourbaix diagram A diagram used to illustrate the pH dependence of the oxidation-reduction behaviour for compounds of a given element (see Fig. 42).

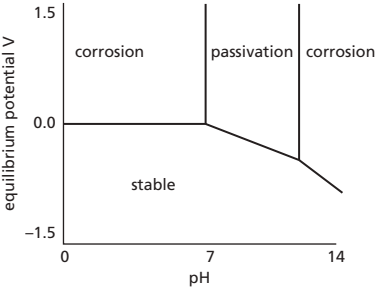

Fig. 42

pour point A rough indicator of the relative paraffinicity and aromaticity of a crude oil. Given as a temperature in degrees, either Fahrenheit or Celsius, a low pour point indicates a low paraffin content and a greater content of aromatics.

powder A mass of fine, dry, particulate matter. Powders are obtained through the process of pulverizing, milling, crushing, and grinding of ores and spray drying. *Compare* DUST.

power The work done or energy transferred per unit time. In SI units, it is measured in watts (that is, joules per second).

power consumption The amount of energy per unit time used by a process or process equipment.

powerforming A catalytic reforming process used to produce aromatics. It uses a platinum catalyst and reforming straight-chain hydrocarbons in the C_6 to C_8 range from *naphtha or gasoline fractions into compounds containing benzene rings. *See* BTX.

power generation The generation of electricity such as from the combustion of natural gas and coal, or nuclear reaction that raises steam to drive turbines linked to generators to produce electricity. Gas turbines are used to generate electricity directly by the combustion of fuel gas in the turbine. The electricity is used as a utility to support process plant operations or sold to the national network.

power input The work or energy per unit time that is applied to a process or item of equipment such as to a pump, an agitator, or stirrer. It is measured using a wattmeter.

power number A dimensionless number, P_o, used to represent the power required in mixing or agitation, and is also used in centrifugal pump design and sizing. It is also known as the *Newton number and given by:

$$P_O = \frac{P}{D^3 N^5 \rho}$$

where P is the power to the shaft, D is the impeller diameter, N is the rotational speed, and ρ is the density of the liquid.

PPE *See* PERSONAL PROTECTIVE EQUIPMENT.

ppm An abbreviation for **p**arts **p**er **m**illion. That is, the number of parts of something per million parts in total. It is often used as a measure of the level of impurities in solids, liquids, and gases.

Prandtl, Ludwig (1875–1953) A German pioneer of aerodynamics; after gaining his PhD at the University of Munich, he was appointed professor of mechanics at the University of Hanover, and was professor of applied mechanics from 1904 to 1953 at the University of Göttingen. He taught and carried out research in fluid mechanics and made a significant contribution to the understanding of boundary-layer theory, which led to the understanding of skin friction and drag on aircraft wings.

Prandtl number A dimensionless number, Pr, representing the ratio of the momentum of diffusivity to thermal diffusivity in fluid convection:

$$\mathrm{Pr} = \frac{c_p \mu}{k} = \frac{Pe}{\mathrm{Re}}$$

where c_p is the specific heat, μ is the viscosity, and k is the thermal conduction, Pe is the *Péclet number, and Re is the *Reynolds number. It is named after German scientist Ludwig *Prandtl (1875–1953).

Prandtl's one-seventh power law A relationship used to determine the velocity distribution for turbulent flow in pipes carrying fluids given as:

$$v = v_m \left(\frac{y}{r_o} \right)^{\frac{1}{7}}$$

where v is the local velocity, at a distance y from the wall of a pipe of radius r_o, and v_m is the maximum velocity at the centre line of the pipe. It was formulated by German scientist Ludwig Prandtl (1875–1953).

precipitation The formation of a suspension of solid particles, known as a **precipitate,** as the result of a chemical reaction or a physical change such as through the reduction in the solubility of the dissolved material in the solvent. Solid materials can be formed in a solution by the addition of compound, which causes a reaction in the solution that converts the material to be separated into an insoluble state. The solid material can then be separated by centrifugation or filtration. Liquid materials can also be precipitated as a condensate from a gas. Precipitation is used to separate metals from aqueous solutions, and also be used to

separate impurities and contaminants from biochemical processes. A precipitator is a vessel used to carry out the process of precipitation.

precision A measure of the exactness of a measured quantity. Used in statistics, the precision may be increased by increasing the sample size. On a calculator, it is the number of significant figures to which a reading is taken: the greater the number of significant figures, the greater the precision. *Compare* ACCURACY.

pressing A mechanical process used to extract liquid from a liquid slurry or liquid-bearing solid, and involves applying a controlled pressure in order to free the liquid and retain the solid material. Juice is extracted from grapes as a first stage in making wine by pressing. Likewise, pressing is used to extract oil from nuts and seeds.

pressure The force applied over a given area. Instrument gauges used to measure the pressure of fluids are either expressed as *absolute pressure, which is measured above a vacuum, and *gauge pressure, which is the pressure measured above atmospheric pressure, which is variable. The SI units are N m^{-2} or pascals. Some gauges are calibrated in the Imperial units of psi (pounds force per square inch). Gauges used to measure a vacuum are expressed in *torr.

pressure drop The decrease in pressure between two points in a system caused by frictional losses of a moving fluid in a pipe or duct, or by some other resistance such as across a filter, packed bed, or catalyst, or due to the effects of hydrostatic head such as across the liquid on the tray of a *distillation column.

pressure drop multiplier (Symbol φ^2) A parameter used in two-phase gas–liquid frictional pressure drop calculations where the overall pressure drop along a length of pipe is due to contributions from the flowing gas and liquid. That is:

$$\frac{dp_f}{dz} = \varphi_g^2 \left(\frac{dp_g}{dz} \right)_g = \varphi_L^2 \left(\frac{dp_L}{dz} \right)_L$$

where φ_g^2 and φ_L^2 are the pressure drop multipliers for the liquid and gas phases in which the parameter X^2 is defined as:

$$X^2 = \frac{\left(\frac{dp_L}{dz} \right)_L}{\left(\frac{dp_g}{dz} \right)_g} = \frac{\varphi_g^2}{\varphi_L^2}$$

Correlations have been developed to determine relationships for the multipliers for combinations of laminar and turbulent gas and liquid phases.

pressure gauge An instrument used to determine the pressure of a fluid. There are various types commonly used, such as *manometers that consist of a column of liquid whose vertical elevation is dependent on the applied pressure; the expanding element type such as the *Bourdon gauge; and the electrical transducer type that use strain gauges.

pressure head The equivalent height of a column of liquid that can produce a given applied pressure:

$$h = \frac{p}{\rho g}$$

where p is the pressure, ρ the density, and g the gravitational acceleration. A barometer is used to measure atmospheric pressure from the elevation of a fluid such as mercury in a sealed vertical glass tube. The pressure head of standard atmospheric pressure corresponds to 760 mm Hg.

pressure relief valve (PRV) A valve used on a process vessel or pipe designed to operate as a safety device and activate to discharge the pressurized gas or liquid whenever it has reached a set point pressure. The valve will automatically close again once the pressure has fallen below the set point. In comparison, a **pressure safety valve** (PSV) has a level that can be manually activated in the event of an emergency.

pressure-swing adsorption (PSA) A process used to selectively adsorb one or more components in a gas mixture under pressure onto a porous solid surface and then to release them again under reduced pressure. It is used in the separation of gases from mixtures such as the absorption of nitrogen from air onto a *zeolite. The air leaving the process is therefore richer in oxygen. The zeolite is regenerated by reducing the pressure. Other commonly used absorbents include activated carbon, silica gel, and alumina.

pressure-temperature diagram A phase diagram representing thermodynamic data for a multicomponent mixture illustrating the existence of liquid and gas phases, and the coexistent liquid and gas phases (see Fig. 43). They are typically used to classify oil hydrocarbon systems and describe the phase behaviour found in oil and gas reservoirs.

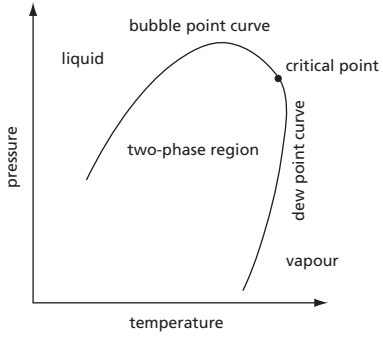

Fig. 43

pressure vessel A closed container designed to hold gases or liquids at a pressure greater than ambient pressure. Pressure vessels are used in a wide variety of applications including compressed air receivers, distillation columns, autoclaves, and as storage vessels for liquefied gases such as propane, butane, chlorine, ammonia, and LPG. Pressure vessels are broadly divided into simple vessels and those that have more complex features. Simple vessels have a cylindrical body with dished ends and no supports or sections; they are classified based on the product of pressure and volume: Class I: 3,000 to 10,000 bar litres; Class II: 200 to 3,000 bar litres; Class III 50 to 200 bar litres. More complex pressure and higher-pressure vessels follow accepted international design codes such as the Pressure Equipment Directive legislation and EN13444 design code in the European Union, the ASME Boiler and Pressure Code Section VIII in the US, and BS PD5500 in the UK.

pressure-volume diagram A diagram used to illustrate the variation of volume and pressure for a substance (see Fig. 44). Spanning a wide range of volumes and pressures, isotherms (lines of constant temperature) are used to illustrate features such as liquid phase, gas phase, and critical point. Developed in the eighteenth century and once known as indicator diagrams, they were used to analyse the behaviour and efficiency of steam engines.

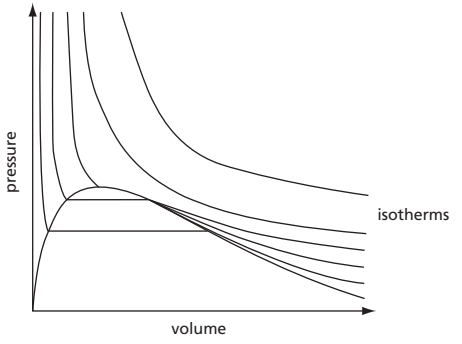

Fig. 44

preventative maintenance The scheduled inspection and testing of process equipment and machinery inspection aimed at avoiding premature and costly failure. It involves cleaning, minor component replacement, and lubrication as a means of extending the life of the equipment. It is intended to prevent emergency and unscheduled repairs and downtime by detecting problems before they arise. *See* MAINTENANCE.

prevention The act of not allowing something to happen. *See* LOSS PREVENTION.

prilling A process used to make solid pellets from a molten material or solution. The liquid is poured under gravity into an upward flow of air. It is used in the manufacture of fertilizers such as ammonium nitrate.

primary heating The use of heat to maintain heavy grades of oil in storage tanks at a controlled viscosity so that it can be pumped. The heating is achieved using steam or hot-water coils in the tank, or by electric heating elements. The minimum temperature required depends on the grade of oil. **Secondary heating** is the temperature required for the oil to be efficiently atomized.

prime mover Any machine or device used to transfer energy, power, or motion to another device. Examples include water and steam turbines used to turn a generator for producing electricity, or an electrical motor to drive a *compressor.

priming 1. The filling of a centrifugal-type pump with the process liquid to be pumped by displacing residual air or vapour. It is carried out manually or, in some cases, remotely by activated control valves. Centrifugal pumps are not self-priming. **2.** The entrainment of boiler water in steam produced in a boiler. It may be caused by excessively high water levels or foaming caused by excessive salts in the water.

probability The statistical likelihood of an event or a sequence of events occurring during a defined interval of time, or the chances of a success or failure of an event. It is used in *quality control, *risk assessment, and also to determine the reliability of process equipment and operations (*see* FMEA). The probability of something happening or not happening is expressed as a dimensionless number ranging from 0 and 1. For example, if there are m possible outcomes and n ways an event can occur, then there is a probability of n/m chances of an occurrence. If the probability of success of a pump operating is S, then the probability of pump failure is F = 1–S. For example, if a process operates with three pumps, A, B, and C, each with equal chances of success in operating, then the possible combination of success and failure for the pumps is:

Pump

A	B	C	Probability
S	S	S	S^3
S	S	F	S^2F
S	F	S	S^2F
S	F	F	SF^2
F	S	S	S^2F
F	F	S	SF^2
F	S	F	SF^2
F	F	F	F^3

The sum of the probabilities is:

$$S^3 + 3S^2F + 3SF^2 + F^3 = (S+F)^3$$

If there is an equal chance of each pump functioning being 1 in 10, say, then the probability of at least one pump being functional is:

$$S^3 + 3S^2F + 3SF^2 = 0.9^3 + 3\times 0.9^2 \times 0.1 + 3\times 0.9\times 0.1^2 = 0.999$$

whereas the chance of at least two pumps being functional is:

$$S^3 + 3S^2F = 0.9^3 + 3\times 0.9^2 \times 0.1 = 0.972.$$

The **probability of failure on demand** is therefore the likelihood that a process, system, or item of process plant will fail to operate in the required and expected manner on demand.

problem-solving A set of mental techniques used to solve complex problems. There are many techniques commonly used including: brainstorming, which is used to present solutions and developed to reach an optimum; root cause analysis, which aims to eliminate the problem; *trial and error, which involves systematically testing possible solutions; and lateral thinking, which seeks solutions either indirectly or creatively.

process 1. Refers to the changes from one equilibrium state, or steady state, to another that take place within a *system. For example, in a heating process, heat is transferred to the system from the surroundings. **2.** A term used in process control to describe the collective functions performed in and by the process in which the process variables such as temperature, pressure, flow, and level are controlled. **3.** A shorthand for *chemical process, which is a collective description of the way that useful chemical products are manufactured from raw materials through chemical, physical, or biochemical means.

process control The adjustment of process variables such as pressure, flow rate, level, and temperature in a process plant at an intended or desired value. Processes are designed to operate safely and in a designed and intended manner to achieve product quality, energy efficiency, and waste minimization according to *flowsheet conditions. However, all processes are dynamic and subject to disturbances such that they tend to deviate from the designed conditions. They therefore need to be controlled and returned back to the desired conditions of operation.

Processes may be controlled automatically or manually. Manual operation involves process operators who make adjustments to temperatures, pressures, flow, and levels. Automatic control is used to control complex processes, or for remote and hazardous processes, or where a high level of product quality is required. Computers are routinely used to operate and control processes.

A control system consists of several components including the process itself, a controller, and a valve. A good understanding is required to control the process. However, this may not always be possible since many processes are multivariable or non-linear in behaviour, or not well understood such as in the case of biological processes.

*Feedback control and *feedforward control are two forms of automatic process control. The former involves comparing a controlled signal with the desired value of a process variable and automatically making adjustments to minimize the difference. Feedforward control involves controlling a process in which the disturbance is detected before it enters the system. The controller calculates the required counteracting disturbance. Process disturbances are measured and compensated for without waiting for a change in the controlled variable to indicate that a disturbance has occurred. It is useful where the final controlled variable cannot be measured.

process costing A way of determining the cost of production in a process in which all the costs are obtained and the average unit costs of production then determined. The main product, coproducts, and by-products are each separately distinguished.

process design The design of industrial processes that use physical, chemical, or biochemical transformations for the production of useful products. It is used for the design of new processes, plant modifications, and revamps. It starts with conceptual and feasibility studies, and includes detailed material and energy balances, the production of *block flow diagrams (BFDs), *process flow diagrams (PFDs), *engineering line diagrams (ELDs), and *piping and instrumentation diagrams (P&IDs). It also includes the production of reports and documents for plant construction, commissioning, start-up, operation, and shutdown. The reports and documents are used by vendors, regulatory bodies, operators, and other engineering disciplines.

process dynamics The behaviour of a system or process with time. All processes are inherently unstable and dynamic as their properties vary with time. It is therefore necessary to control the system or process to disturbances, and to restore the controlled variable back to its design or desirable value. This is done by using mathematical rate equations to describe the process such as material, energy, and momentum equations. Dynamic analysis

is then used to determine how the associated process variables change with time and how their behaviour changes in response to disturbances.

process economics An evaluation of a process in terms of all the costs that are involved. It considers the cost of raw materials and how they are processed, as well as the costs associated with waste processing such as recycling or disposal. It also includes the optimization of a process to best utilize materials and energy. The fixed costs of a process are not dependent on the rate of production whereas the variable costs are and must be met by the revenue generated by sales. Taxes are deducted to leave the net profit.

process engineering A branch of engineering that encompasses petrochemical, mineral processing, advanced material, food, pharmaceutical, and biotechnological industries. It focuses on the design, operation, control, and optimization of chemical, physical, and biological processes. It is also known as **process systems engineering**, which is a specialist area of research in US, Europe, Japan, Korea, and China.

process flow diagram (PFD) A schematic representation of a process or part of a process that converts raw materials to products through the various unit operations. It typically uses a symbolic representation for the major items of equipment such as storage vessels, reactors, and separators, process piping to and from the equipment, as well as by-pass and recirculation lines, and the principal flow routes. Key temperatures and pressures corresponding to normal operation are included, as well as equipment ratings, minimum and maximum operational values. Material flows and compositions are included. It may also include important aspects of control and pumping, as well as any interaction with other process equipment or flows. The design duties or sizes of all the major equipment are also featured, which can collectively provide a comprehensive representation of the process. It is also known as a **system flow diagram**. *Compare* FLOWSHEET; ENGINEERING LINE DIAGRAM.

process integration 1. A holistic approach used in process design that considers the process as a whole with the interactions between unit operations in comparison with the optimization of unit operations separately and independently. It is also known as *process synthesis. **2.** A technique used to minimize the energy consumption and heat recovery in a process. It is also known as **process heat integration** and *pinch analysis.

process intensification An approach to engineering design, manufacture, and operation of processes that aims to substantially improve process performance through energy efficiency, cost-effectiveness, reduction in waste, improvement in purification steps, reduction of equipment size, increase in safety, and operational simplicity. It involves a wide range of innovative mixing, reactor, and separation technologies that can result in dramatic improvements in process performance. Involving an integrative approach that considers overall process objectives rather than the separate performance of individual unit operations, process intensification can enable a process to achieve its maximal performance leading to the development of cheaper, smaller, cleaner, safer, and sustainable technologies.

process plant A collective name for an industrial facility used to convert raw materials into useful products. It includes all the process equipment such as mixers, reactors, and separation units, all the associated pipework and pumps, heat exchangers, and utilities such as steam and cooling water. It is often used interchangeably with *chemical plant, although process plants may not always involve chemical transformation or the production of chemicals as in the case of power stations.

process reaction-curve method A widely used empirical procedure used to tune and control a process using *PID control with optimum controller settings. Developed by J. G. Ziegler (1898–1973) and N. B. Nichols (1903–79) in 1942, it is based on using results from open-loop tests. The settings from the tuned controller result in an underdamped transient response with a *decay ratio of one-quarter.

process safety A comprehensive management system that focuses on the management and control of potential major hazards that arise from process operations. It aims at reducing risk to a level that is as low as is reasonably practicable by the prevention of fires, explosions, and accidental or unintended chemical releases that can cause harm to human life and to the environment. It includes the prevention of leaks, spills, equipment failure, over- and under-pressurization, over-temperatures, corrosion, and metal fatigue. It covers a range of tools and techniques required to ensure safe operation of plant and machinery to ensure the safety of personnel, the environment, and others, through detailed design and engineering of facilities, maintenance of equipment, use of effective alarms and control points, procedures, and training. It also includes risk assessments, *layers of protection analysis, and use of *permit to work authorizations.

process simulation The use of computers to model and predict the operational and thermodynamic behaviour of a process. Sophisticated commercial software packages are used to simulate and model batch, continuous, steady-state, and dynamic processes. They require combined material and energy balances, the properties of the materials being processed, and sometimes combine the use of experimental data with mathematical descriptions of the process being simulated. Most software packages feature optimization capabilities involving the use of complex cost models and detailed process equipment size models.

process synthesis The conceptual design of a process that identifies the best process *flowsheet structure, such as the conversion of raw materials into a product. This requires the consideration of many alternative designs. Due to the complexity of most processes, the flowsheet is divided into smaller parts and each considered in turn, then choices and decisions made. Various techniques are used to arrive at the best flowsheet such as those based on total cost, which needs to be minimized, the use of graphical methods, the use of *heuristics, and various other forms of minimization such as the use of *process integration.

process upset A sudden, gradual, or unintended change in the operational behaviour of a process. It may be due to process equipment failure or malfunction, operator intervention, a surge or fall in pressure, flow, level, concentration, etc.

process validation The documented evidence that a procedure, process, or change has been fully evaluated before its implementation that it, which can provide a high degree of assurance of meeting pre-determined specifications and quality. First used by the Food and Drugs Administration in the US in the 1970s to improve the quality of pharmaceuticals, it is widely used in many industries and, in particular, the pharmaceutical and allied medical industries. It is used alongside other regulatory requirements such as Good Manufacturing Practice. Before the validation process begins, it is necessary to ensure that the system is properly qualified, which includes a design, installation, operational, performance, and component qualification. These define the function, operation, and specification of the equipment, process and product.

process variable A dynamic feature of a process or system that is required to be controlled to ensure that it operates according to design requirements and does not deviate so

as to be unsafe or result in undesirable consequences. The commonly measured process variables include temperature, pressure, flow, level, and concentration.

process waste *See* WASTE.

producer gas A mixture of carbon monoxide and nitrogen used in a *gasification process and formed by the partial combustion of coal, coke, or anthracite in a blast of air. The exothermic reaction produces carbon monoxide:

$$2C + O_2 \rightarrow 2CO$$

Nitrogen in the air remains unchanged in the process. Adding steam to the gasification process results in a gas mixture also containing hydrogen. Producer gas is used as a *fuel gas in furnaces and the generation of power in gas turbines. A **producer process** is a generic name for processes that convert solid fuels into gaseous fuels.

product A chemical substance formed as the output from a process or unit operation that has undergone chemical, physical, or biological change.

production platform An offshore structure that features all the necessary equipment to maintain an oil or gas field in production. It has facilities for temporarily storing the output of several wells.

production separator A horizontal cylindrical vessel used on offshore platforms for the separation of gas and water from several crude oil wells. The oil enters the separator in which the reduction of pressure causes the release of dissolved gases that are removed from the top of the vessel. The water and oil separate by virtue of being immiscible and having different densities. The oil and condensate is separated from the water by overflowing a weir.

product recovery The extraction and purification of valuable chemicals, including biochemicals such as therapeutic proteins produced in biochemical reactions. It is also used for the recovery and recycling of waste materials.

programme evaluation and review technique (PERT) A project planning technique used to help plan and manage complex projects. In its simplest form, it is known as *critical path analysis or network analysis. It is marketed as computer software under various trade names and has five identifiable, sequential steps. These involve identifying and listing all the individual activities, establishing the dependencies for the activities, creating a network of how they fit together, completing the critical path analysis that introduces a timescale to the project, and finally, producing a Gantt chart giving a visual representation of progress.

project management An activity concerned with the overall planning and coordination of a project from its conception to its completion. It is aimed at meeting the defined requirements and ensuring completion on time, within budget, and to defined quality standards.

project network techniques A group of management tools aimed at planning, analysing, and managing projects. They consider the logical interrelationships of all the project activities and are concerned with time, resources, costs, and other influencing factors such as uncertainty. They have three identifiable phases of planning, scheduling, and control.

*Critical path analysis and *programme evaluation and review techniques are examples of project network techniques.

proof 1. A rigorously defined, logical, and complete demonstration of the correctness of a statement, formula, law, or *theorem. It involves a set of basic assumptions known as axioms or premises that are used to derive and lead to a conclusion to show that the statement, formula, law, or theorem has been proved. **2.** A former measure of the amount of alcohol in *whisky defined as the most dilute spirit that would ignite gunpowder: 100 per cent proof corresponds to 57.15 per cent ABV (alcohol by volume).

propellant 1. A chemical substance used as a fuel that burns in a controlled manner and is used to propel projectiles such as rockets. **2.** A volatile substance that is used to produce a spray in an aerosol can. It can be liquefied by pressure and dissolved into the working substance. On release of pressure, the liquefied propellant vaporizes producing the spray. Chlorofluorocarbons (CFCs) were once widely used but have been discontinued due to their harmful effects on the ozone in the atmosphere; they have now been largely replaced by hydrocarbons such as pentane or mixtures of hydrocarbons.

propeller An agitation device that consists of blades attached to a rotating shaft giving axial flow. They are used for the agitation of low-viscosity liquids. **Propeller fans** or *blowers have two or more propeller blades on a shaft contained in a cylindrical casing and used for transporting gases.

property diagram A graphical representation of the thermodynamic properties of a fluid. Any two properties can be plotted and from the *two-property rule, the other state properties can be determined once two have been fixed. The most commonly encountered property diagrams are the *pressure-volume diagram, the *temperature-entropy diagram, the pressure-enthalpy diagram, and the entropy-enthalpy diagram.

proportional (Symbol $\propto$) A mathematical relationship between two quantities that vary in a constant ratio. For example, the viscosity of a *Newtonian fluid is the ratio of the shear stress to shear rate over all values, $\tau \propto \gamma$. That is, the shear stress, τ, is directly proportional to the shear rate, γ. The **proportionality constant** is the constant that links the two quantities. In this case, it is the viscosity, μ. If the quantities are inversely proportional, then the product is a constant. For example, *Boyle's law states that the volume of a fixed mass of gas is inversely proportional to its pressure at constant temperature.

proportional band Used in the control of a process, the controller output is proportional to the error or a change in a *process variable. The proportional band is the fractional or percentage change in input that is required to produce a 100 per cent change in controller output. The proportional band is therefore a value of 100 divided by the gain of the process. For example, a 100 per cent controller output may be a signal that fully opens a valve, while a 0 per cent controller output fully closes it.

proportional control A mode of feedback control of a process in which the output from the controller is proportional to the error in the signal. This is the difference between desired (set point) and measured values. *See* PID.

prototype An experimental version of a machine or process, in which the initial design can be tested and improved based on testing.

proximate analysis A type of compositional analysis of fuels in terms of moisture content, volatile matter, ash, and fixed carbon content. *Compare* ULTIMATE ANALYSIS.

PRV *See* PRESSURE RELIEF VALVE.

PSA *See* PRESSURE-SWING ADSORPTION.

PSD An abbreviation for **p**rocess **s**hut**d**own. *See* SHUTDOWN.

PSDS An abbreviation for **p**roduct **s**afety **d**ata **s**heet. *See* MSDS.

pseudocomponent Used in computations and computer simulations of complex processes such as hydrocarbon processes and petroleum refining in which many non-polar molecules may be present in a mixture. Rather than representing the mixture by all the components, it is easier to group them by some useful property thereby reducing the number of components. The properties of these groupings can be represented by an average boiling point, specific gravity, and molecular weight. The converse is referred to as **real components**.

pseudocritical properties Empirical values used for the critical properties in multicomponent chemical systems. They are based on mixing rules of pure components and often have very different properties from their true critical points, and have no real physical significance. For example, the **pseudocritical viscosity** is a viscosity parameter used in an empirical relationship to determine the viscosity of liquids as a function of temperature. Tabulated data are available for hydrocarbons, ethers, ketones, aldehydes, acetates, alcohols, and organic acids.

pseudo-order The order of a chemical reaction that appears to be less than the actual order as the result of the experimental conditions used. It occurs when one reactant is present in excess such that the reaction may appear to be due to the large amount of the reactant present.

pseudoplastic A time-independent *non-Newtonian fluid, which is shear thinning. The apparent viscosity expressing the ratio of shear stress, τ, to shear rate, γ, decreases with increasing shear rate: $\tau = k\gamma^n$ where k is a proportionality constant and n has a value between 0 and 1. Examples include polymer melts, paper pulp, wallpaper paste, printing inks, tomato purée, mustard, rubber solutions, and protein concentrations.

psi An Imperial unit of pressure expressed in pounds force per square inch. Some pressure gauges are given in **psig**, which represents the gauge pressure and is distinguished from **psia** or absolute pressure in pounds per square inch. Standard atmospheric pressure corresponds to a gauge pressure of 14.7 psi.

PSV An abbreviation for **p**ressure **s**afety **v**alve, which is a type of spring-loaded pressure relief valve. It is activated by the static pressure upstream of the valve and characterized by its ability to open rapidly.

psychrometer An instrument used to determine the humidity of air. It comprises both dry and *wet bulb temperature measurements. The difference in the two thermometer readings is used to determine the humidity. A whirling psychrometer is used to provide a consistent reading with greater accuracy and involves swinging the instruments to ensure a high air velocity over the bulbs of the thermometers.

psychrometric chart A graphical representation of the thermodynamic properties of water and air with dry bulb temperature on the y-axis and moisture content on the x-axis

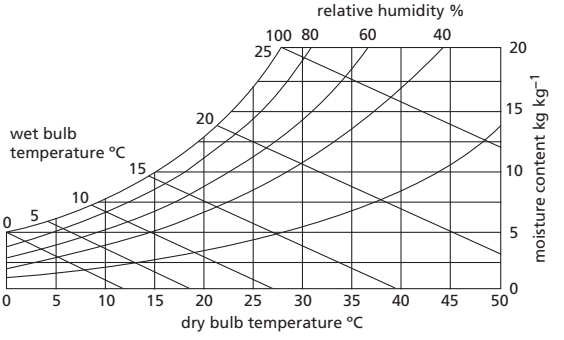

Fig. 45

(see Fig. 45). Other characteristic curves and lines include *wet bulb temperature and *relative humidity (shown here), and *specific volume and enthalpy of humid air (not shown here). The charts are usually presented at atmospheric pressure and are used for the design of air-conditioning systems and water-cooling towers.

psychrometry The study and measurement of the humidity of air.

puddling process A process once used for the production of wrought iron from pig iron. It was based on the partial decarburization of the pig iron in a reverberatory furnace, which is a long, low structure built of fire bricks and fuelled by coal. By ensuring the smoke and flame remained above the iron, the carbon content could be controlled.

pulsed baffle reactor (PBR) A tubular vessel used to carry out a chemical reaction such as polymerization in which the reactants are gently oscillated by either pulsing the feed by way of a reciprocating pump or by bellows of the entire contents on the reactor. The reactor contains either ring-shaped or plate-shaped baffles separated along the length of the reactor that encourage fluid turbulence and mixing, and promote reaction.

pulsed column A column used in *liquid–liquid extraction in which two immiscible liquids enter the column in the same direction. A reciprocating-type pump causes sharp pulsations in the direction of the flow, causing the liquids to disperse in one another, allowing intimate mixing of the liquids, and encouraging mass transfer. The dispersion is encouraged in columns that may contain perforated distribution plates, packing, or horizontal discs to prevent coalescence. Pulsed columns have found many applications, particularly in the nuclear-reprocessing industry for the separation of radioactive waste materials.

pulverizer A device used for grinding solid fuels such as coal as finely as possible with a minimum of power required to achieve a given *particle size distribution. Pulverized fuels are used in power stations for electricity generation and also for boilers for raising steam. The small particle size enables the fuel to be carried into the furnace with a current of air and allows for rapid and controlled combustion. Pulverizers are classified by the speed of operation and include various forms of mill such as the *ball mill.

pump A mechanical device used to transport a fluid from one place or level to another by imparting energy to the fluid. The three broad groupings are reciprocating, rotary, and

centrifugal-type pumps. The most commonly used pump is the centrifugal type, which has a rotating impeller used to increase the velocity of the fluid and where part of the energy is converted to pressure energy. Rotary and reciprocating pumps are *positive displacement pumps in which portions of fluid are moved in the pump between the teeth of gears, and by the action of a piston in a cylinder, respectively. There are many variations of these types and each has a particular application and suitability for a fluid in terms of its properties, required flow rate, and delivery pressure. Pumps that do not conform to these groupings include acid eggs, air-lift pumps, and steam ejectors. All involve the use of energy to transport the fluid.

pump priming Used for the start-up and successful operation of centrifugal pumps in which the casing housing the *impeller is first filled or primed with liquid before operation begins. Since the density of a liquid is many times greater than that of a gas, vapour, or air, the suction pressure is otherwise insufficient to draw in more liquid. Depending on the type of pump, priming can be achieved either manually or by drawing liquid in using a vacuum pump. Valves can be used to prevent drainage and ensure that the pump does not require priming once the pump stops. Alternatively, the pump can be configured in such a way that it always maintains a reservoir of liquid at the suction side.

pump selection chart A diagram supplied by manufacturers of pumps and used to identify a pump for a particular duty (see Fig. 46). The rate of flow is presented on the x-axis and the delivered head or pressure on the y-axis. The performances of a number of pumps are typically presented spanning an acceptable range of efficiencies. Each area corresponds to a name or code, which is a combination of case number, impeller size, and speed.

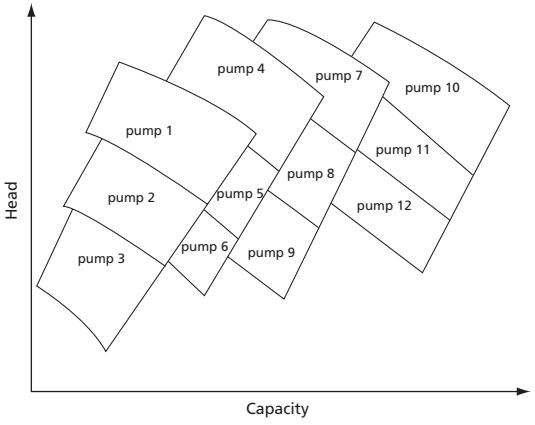

Fig. 46

purex process A process used to recover spent nuclear fuel from nuclear reactors by solvent extraction for recycling and fabrication into new fuels. An abbreviation for **p**lutonium and **u**ranium **r**ecovery by **e**xtraction, it is a hydrometallurgical process that was developed in the late 1940s in which spent nuclear fuel is initially dissolved in refluxing nitric acid. Solvent extraction is then used to extract the uranium and plutonium from the fission product

containing nitric acid solution into a kerosene diluent containing the solvent tri-butyl phosphate (TBP). Final separation of the uranium from the plutonium involves manipulation of the plutonium oxidation state. It superseded the earlier butex process, which used solvent extraction of spent nuclear fuel by solvent extraction from a nitric acid solution using diethylene-glycol dibutyl ether as the solvent. *See* NUCLEAR REPROCESSING.

purge The controlled removal of a small amount of material from a process as a side-stream that prevents an accumulation of undesired materials. It is also known as a *bleed.

purification The process of removing impurities. The **purity** is the extent to which a substance is free from extraneous or contaminating material. A substance is considered to be pure when the level of impurity can no longer be detected. The purity is typically expressed as a percentage of the substance that is free from the extraneous material.

pyro- A prefix meaning fire, burning, heat, etc.

pyrolysis The irreversible chemical decomposition or transformation due to temperature, and without the reaction with oxygen. It is used to produce coke from coal for use in making steel using temperatures of up to 2,000°C. Coke can also be made by pyrolysis using other hydrocarbon substances in petroleum refining.

pyrometer An instrument used to measure high temperatures such as in furnaces. Since the level of thermal radiation varies in processes, there are various types of pyrometers commonly used. These include thermocouple, optical, and radiation types. Optical pyrometers measure the infrared wavelength of heat using a lens whereas a radiation pyrometer measures the radiation wavelength without being near the hot object.

pyrophoricity A material that is capable of auto-ignition upon contact with ambient air. Certain gases, liquids, and solids are capable of auto-ignition such as sodium, potassium, finely divided uranium, and iron sulphide. Pyrophoric materials can often react with water, and therefore are required to be stored and transported under careful conditions.

Pythagoras' theorem A theorem that states that in a right-angled triangle, the square of the hypotenuse is equal to the sum of the squares on the other two sides. It is named after the Greek mathematician and philosopher Pythagoras (*c.*570 BC–*c.*495 BC), who provided a mathematical proof.

Q

q-line A representation of the condition of the feed to a binary distillation process used in the *McCabe–Thiele graphical method (see Fig. 47). The line represents the condition of the feed in which q is the mole fraction of the more volatile component in the feed. The slope of the q-line is $q / (q - 1)$ and can be used to indicate the condition of the feed. Where the feed is a saturated liquid then q = 1 and the slope of the q-line is vertical. If the feed is saturated vapour then q = 0 and the slope of the q-line is horizontal.

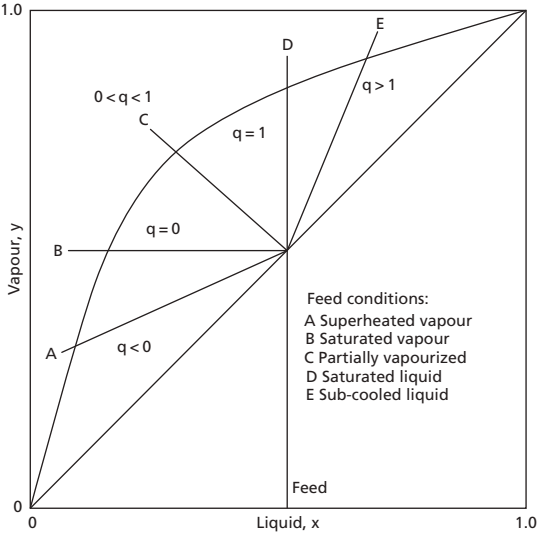

Fig. 47

QSL process A smelting process used to extract lead from ores. It involves feeding pellets of lead sulphide ore concentrate into a bath of molten slag in a rotating cylindrical furnace. By feeding oxygen below the slag on the surface, sulphur dioxide is formed along with heat. The lead oxide is reduced to metal by the addition of powdered coal. The process is named after its inventors P. E. Queneau, R. Schumann, and is now operated by Lurgi GmbH.

quadratic equation A type of polynomial equation in which the highest power of the unknown variable is two, such as x^2. It has the general form:

$$ax^2 + bx + c = 0$$

where a, b, and c are constants. The two roots of the equation can be obtained using the formula:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

quadruple-effect A multiple-effect unit, such as an evaporator, in which there are four stages. *See* MULTIPLE EFFECT.

qualitative analysis The identification of the part or parts present in a sample without consideration to the relative proportions of each.

quality 1. The features and characteristics of a product set against defined standards. The quality of a product such as a material produced in a manufacturing process or a detailed engineering design is measured in terms of a compliance with predetermined standards and specifications such as composition, level of impurities, functionality, etc. Deviation from these standards leads to poor quality. **2.** The percentage of saturation of a vapour. A fully saturated vapour has a quality of 100 per cent while a totally dry vapour has a quality of 0 per cent.

quality assurance (QA) A set of procedures or planned system of activities used to ensure that the quality control programme for a manufactured product from a process or a service is properly implemented. Planned and systematic actions are taken to provide adequate confidence that the product or service satisfies specified requirements. *Compare* QUALITY CONTROL.

quality control (QC) A set of procedures or planned system of activities used to ensure that a manufactured product from a process or a service meets a defined set of standards or criteria. For example, a product may be required to contain a maximum level of impurity, achieve a certain density specification, or have a certain viscosity. The standards may be set by the customer or by a regulatory body, as is the case with pharmaceutical manufacture. Not all the product manufactured is required to be tested but instead representative random samples are taken and tested. Where unacceptable statistical deviations are found, remedial action is required to correct the process in order to achieve the prescribed quality control standards.

quantitative analysis The determination of the amount or proportion of one or more constituents in a sample.

quantity of heat (Symbol Q) The total amount of heat in a body, process, or reaction. The SI unit is joules. The *calorie is also still used, which is the amount of heat required to raise the temperature of one gram of water by 1°C. The definition is not very precise since the specific heat capacity of water varies with temperature. In the *f.p.s. engineering unit system, the *British thermal unit is defined as the heat required to raise the temperature of one pound of water through one degree Fahrenheit. The therm is 10^5 Btu.

quantum mechanics A branch of mechanics that is based on the *quantum theory used for interpreting and understanding the behaviour of elementary particles, atoms, and molecules, which do not obey Newtonian mechanics.

quantum state The state of a system that is characterized by a set of quantum numbers and represented by an eigenfunction. Each state has an energy that has a value, which is precise within the limits imposed by the uncertainty principle but which may be changed by applying a field force.

quantum statistics The statistics concerned with the distribution of the number of identical elementary particles, atoms, ions, or molecules amongst possible quantum states.

quantum theory A theory concerning the behaviour of physical systems first developed by German physicist Max Planck (1858–1947) in 1900. The theory is based on the idea that such systems possess certain properties, such as energy and angular momentum, in discrete amounts or quanta.

quarl The refractory throat surrounding the burner port of a furnace. It is designed to direct air into the flame from the combustion of fuel and the radiation from the hot refractory. It also assists with efficient combustion of the fuel.

quart A British Imperial volumetric unit of measure equal to two pints and is a quarter of the volume of a gallon. It is equal to 1.136 522 litres. The Winchester quart is no longer used and is approximately equal to two quarts (2.25 litres). Some laboratory chemicals are supplied in Winchester quart bottles that have a volume of 2.5 litres.

quarter damping The ratio of successive peaks or troughs of the signal in an underdamped controlled system above or below the final steady-state value equal to 4:1 (see Fig. 48). That is, the peaks are progressively smaller and equal to one quarter of the height or depth of the previous peak or trough. This corresponds to an optimal control of a process. *See* DECAY RATIO.

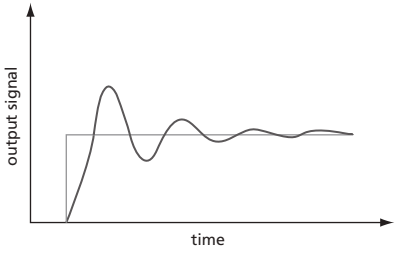

Fig. 48

quasi-steady state A system that is considered to be operating in a steady state although it may actually be an unsteady state process in which a *process variable varies with time. An example is a vessel containing a viscous liquid that discharges through a small orifice. A steady-state material balance is conveniently used to describe the rate of discharge and change in capacity in the vessel although the progressive fall in level is dependent on the characteristics of the orifice. The validity of a quasi-steady-state mathematic model can be assessed by setting the time derivative to zero.

Queeny, John Francis (1859–1933) An American industrialist who founded the Monsanto Company in 1901. It was the first American company to produce saccharine as an

artificial sweetener at a time when the only commercial sources were from German chemical companies. He commercialized many processes including a butter substitute and hydrogenated vegetable fats. In the 1920s he developed a process to manufacture sulphuric acid using a vanadium catalyst as an alternative to the more expensive platinum catalyst that was used at the time. He named his company after his wife, whose maiden name was Olga Mendez Monsanto.

quench column A tall cylindrical vessel used to bring about the rapid cooling of a liquid or gas. Cooled liquid is sprayed down the column and intimately mixed with the hot rising vapour.

Quentin process A process using a solution of magnesium chloride that regenerates ion exchange resin used in the sugar refining industry. It is named after its inventor G. Quentin who developed it in 1957.

quick-acting valve A manually operated valve used to rapidly shut off the flow of a fluid such as fuel to a burner.

quick freezing A process used to rapidly freeze foodstuffs in which the temperature zone of maximum crystallization takes place as quickly as possible. After stabilization, the food is held at a temperature of –18°C or lower. The purpose of the rapid freezing process is to avoid slow ice-crystal growth that results in damage to delicate cell walls causing a loss of mechanical structure and quality of the foodstuff on subsequent thawing. To achieve quick freezing, either liquid nitrogen or liquid carbon dioxide is used as a spray into a chamber containing the food to be quick frozen. *See* FLASH FREEZING.

quiescence A non-dividing state of microbial cells. In batch fermentations, viable yeast cells reach a state of inactivity or dormancy and no longer proceed through the cell cycle once all the limiting substrate has been exhausted.

Quinan, Kenneth Bingham (1878–1948) An American chemical engineer who designed and built explosives factories. With no formal chemical engineering qualifications, he began working for his uncle in an explosives factory in California. He followed his uncle to South Africa when offered the opportunity to build an explosives factory for the De Beers mining company. He built a factory that manufactured glycerine used in explosives just as the First World War was beginning. He was then commissioned to design, construct, and operate munitions and explosives factories in the UK. He received recognition with awards including the Croix de Guerre from the French government. He was the first vice president of the *Institution of Chemical Engineers.

quotient The mathematical result of dividing one quantity by another. For example, 13 divided by 3 gives a quotient of 4 remainder 1.

R

rad 1. A unit of radioactivity defined as the absorbed dose of *ionizing radiation when 1 g of material absorbs 0.01 J kg^{-1} of energy. **2.** The symbol for *radian which is the plane angle between two radii of a circle that form an arc on the circumference that is equal in length to the radius.

radial In the direction of the radius. For example, **radial flow** is the flow of fluid in the direction of the radius such as from the effects of a *Rushton turbine type impeller, whereas a propeller provides **axial flow**.

radial-flow fan A mechanical device used to move air or a gas and comprises a power-driven shaft with a **radial impeller** or vanes. The air or gas enters near the axis of rotation and moves the air along the radius using the centrifugal force or rotation.

radial-flow fixed-bed reactor A type of chemical reactor that has a bed of catalyst with very small pressure drop across it. The catalyst is held in a toroidal basket placed in a cylindrical shell. The reaction gases enter either through the centre core or within the annulus and the products leave on the other side of the bed depending on the application. Unlike axial flow reactors, the design is more complicated, involving the flow distribution along the length of the bed, *voidage, catalyst settling, bed expansion, and contraction. It is used in the large-scale synthesis of ammonia, ethylbenzene dehydrogenation, and *catalytic reforming.

radial velocity The speed of a particle or fluid away from a central point.

radian (Symbol rad) The plane angle between two radii of a circle that form an arc on the circumference that is equal in length to the radius.

radiation 1. The transfer of energy by electromagnetic waves through a transmitting medium. The radiation may be absorbed, transmitted, or reflected by a receiving body although only the absorbed radiation is converted to heat. **2.** Emission of particles, especially alpha or beta particles from a radioactive source or neutrons from a nuclear reactor.

radioactive A substance such as an element that exhibits radioactivity.

radioactive decay The process in which unstable atomic nuclei spontaneously lose some of their excess energy by disintegrating into more stable nuclei. This is accompanied by the emission of alpha particles, beta particles, or gamma rays. Several of the heavier radioactive elements decay through a series of unstable radioisotopes before reaching a stable end-product. It is possible, in some cases, to induce artificial radioactivity through bombardment of the nuclei with particles such as neutrons.

radioactive fallout *See* FALLOUT.

radioactive isotope *See* RADIOISOTOPE.

radioactive series A sequence of radioactive nuclides in which each member is formed by the *radioactive decay of the nuclide proceeding it. The series ends with a stable nuclide. For example, in the thorium decay series, each step involves the loss of either an alpha particle or a beta particle, or occasionally both, until eventually a stable isotope of lead is formed.

radioactive waste (nuclear waste) The solid, liquid, or gaseous substances and materials that contain radionuclides that remain after the mining of radioactive ores, the reprocessing of nuclear fuels, the operation of nuclear reactors, the manufacture or decommissioning of nuclear weapons, and the waste from hospitals and research laboratories. The radionuclides may be highly radioactive and have very long half-lives presenting a danger to all living organisms. Their disposal is therefore highly regulated. Radioactive waste is classified as being either high-level, intermediate-level, or low-level waste. High-level waste includes spent nuclear fuel from nuclear power stations and is first required to be cooled for very long periods of time before being disposed of. Intermediate-level waste arises from the reprocessing of nuclear fuels and includes sludges, liquid, and the equipment used in the reprocessing. The waste is solidified, mixed with concrete, and packed into steel drums. It is stored in deep geologically stable mines. Low-level waste arises from materials used in the everyday activities of nuclear reprocessing, hospitals, and research laboratories, and includes liquids and solids. It is packed into steel drums and disposed of in special concrete-lined landfill sites. In the UK, these sites are under the authority of the UK Nuclear Decommissioning Authority that manages the site at Drigg near the UK reprocessing plant at Sellafield in Cumbria.

SEE WEB LINKS

- Official website of the UK Nuclear Decommissioning Authority.

radioactivity A qualitative term used to describe the phenomenon resulting from the spontaneous disintegration of atomic nuclei usually with the emission of penetrating radiation or particles. The phenomenon was first noticed by Henri *Becquerel in 1896 in uranium salts in which rays emitted by these salts were found to affect a photographic plate. Marie and Pierre *Curie detected more intense radioactivity in a new element which they called polonium, and later isolated another radioactive element, which they named radium.

radiobiology A branch of biology concerned with the effects of radioactive substances on living organisms and the use of radioactive substances as *tracers to study the biological processes of living cells.

radiocarbon dating A technique used to determine the age of organic materials such as wood and based on the content of the isotope carbon-14 acquired from the atmosphere when they were formed. The *half-life of the radioisotope is 5,730 years and decays to the isotope nitrogen-14. Measurement of the amount of carbon remaining in the material therefore gives an estimate of its age.

radiochemistry A branch of chemistry concerned with radioactive elements, their compounds, and ionization. It includes the use of radionuclides in chemical reactions. *See* RADIOLYSIS.

radiogenic Produced or resulting from radioactive decay.

radiography A process that produces an image on a sensitive plate or film by X-rays or other ionizing radiation. As well as being used in medicine and surgery, it is used as a *non-destructive testing technique to identify cracks and faults in metal such as welds in vessels and pipes. It is used in the nuclear industry particularly to check the quality of welds. The advantage of this method is that the source of radiation can be very small.

radioisotope (radioactive isotope) An isotope of an element that is radioactive. Every element has at least one isotope, although for many they can only be obtained by bombarding the elements with high-energy particles or in nuclear reactions.

radiology The study and use of X-rays, radioactive materials, and other ionizing radiations for medical purpose especially for the diagnosis and treatment of cancer and associated diseases.

radiolysis The use of ionizing radiation in chemical reactions, it involves the use of alpha particles, electrons, X-rays, and gamma radiations emitted from radioactive materials.

radionuclide A nuclide that is radioactive.

radiosity Used to calculate the thermal radiation heat transfer exchange between surfaces, it is the sum of the emissive power and the portion of the radiation that is reflected by a surface. By conveniently combining the radiation being emitted by and reflected from a surface, it is useful in determining the net thermal energy exchange between multiple surfaces.

radiotherapy The use of ionizing radiation such as X-rays and radioactive isotopes in medical treatment.

raffinate The residual or waste liquid stream leaving a liquid–liquid solvent extraction process after the extraction has taken place with an immiscible liquid to remove solutes from the original liquid. The word is derived from the French *raffiner* meaning to refine. *See* SOLVENT EXTRACTION.

ramp response The behaviour of a system or process to a change resulting from a sudden increase in the rate of change from zero to some finite value. It includes the combined transient and steady-state behaviour.

Ramsay, Sir William (1852–1916) A British scientist noted for the discovery of radon, which at the time was the last of the noble gases to be discovered. He worked under German chemist Robert Bunsen (1811–99) before taking up professorships at Bristol (1880–87) and then London (1887–1912). He worked with *Rayleigh on the gases in air. Together they discovered argon in 1894. He worked with Morris Travers (1872–1961) and discovered neon, krypton, and xenon, discovering radon in 1904. He was awarded the Nobel Prize for Chemistry in 1904.

random error *See* ERROR.

random packing Used in packed columns, it is the arrangement of packing materials such as saddles and rings that have no structured order. The orientation of packing materials that are charged into columns in bulk typically lie randomly on support plates. The packing is used to intimately contact a gas and a liquid to bring about effective mass transfer by providing a high surface area per unit volume.

Raney nickel A porous solid catalyst made from an activated alloy of nickel and aluminium. The nickel is the catalytic metal with the aluminium as the structural support. It was developed by American mechanical engineer Murray Raney (1885–1966) in 1926 for the hydrogenation of vegetable oil and is now used in hydrogenation reactions in various forms of organic synthesis. It is widely used as an industrial catalyst for the conversion of olefins and acetylenes to paraffins, nitriles, and nitro compounds to amines, and benzene to cyclohexane amongst others.

range The extent over which a quantity is measured such as temperature, pressure, and level. It is defined by stating both its lower and upper range values.

Rankine cycle An ideal reversible thermodynamic cycle used in steam power plants (see Fig. 49) that more closely approximates to the cycle of a real steam engine than the *Carnot cycle and converts heat into mechanical work. It involves water being introduced under pressure into a boiler and evaporation taking place, followed by expansion of the vapour without the loss of heat, ending in condensation. The cycle therefore consists of four stages: i) steam passes from the boiler to the cylinder at constant pressure; ii) the steam expands adiabatically to the condenser pressure; iii) heat is given to the condenser at constant temperature; iv) condensation is completed and the condensate is returned to the boiler. In the Rankine cycle, the work done is equivalent to the total heat in the steam at the end of the adiabatic expansion subtracted from the total heat in the steam at the beginning of the expansion. The heat supplied is equal to the sensible heat in the condensed steam subtracted from the total heat.

The Rankine cycle is used to describe the way steam-operated heat engines that are found in thermal power generating plants generate power for which the heat sources are nuclear fission, or the combustion of coal, oil, or gas. It is named after Scottish civil engineer and physicist William John Macquorn Rankine (1820–72).

Rankine scale A thermodynamic temperature scale based on the absolute zero of the Fahrenheit temperature system such that –459.67°F is equal to 0°R. It was proposed by Scottish engineer William Macquorn Rankine (1820–72) in 1859.

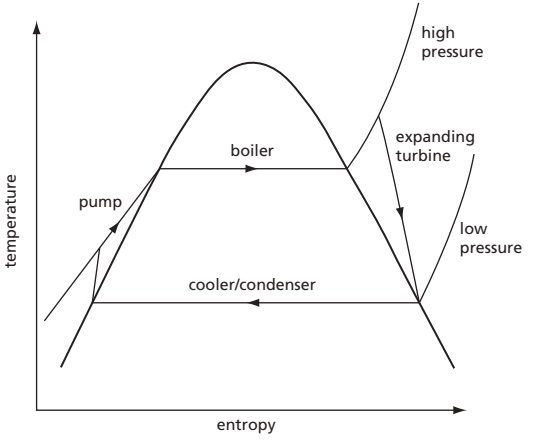

Fig. 49

Raoult, François-Marie (1830–1901) A French chemist who studied the behaviour of solutions and their physical properties. He is best known for his work on solutions, in particular the depression of freezing points and the depression of a solvent's vapour pressure due to a solute that was shown to be proportional to the solute's molecular weight. Both became ways of determining molecular weights of organic substances. *Raoult's law is named after him.

Raoult's law A law that states that the partial pressure exerted by each component in an ideal liquid mixture is the product of the vapour pressure of each component and its mole fraction at the temperature of the liquid expressed as:

$$P_A = x_A p_A$$

where P_A is the partial pressure, x_A is the mole fraction of component A, and p_A is the vapour pressure. Formulated by French chemist François-Marie Raoult (1830–1901) in 1882.

rare earth elements The oxides of a group of elements in the *periodic table known as lanthanoids. Unlike their name would suggest, they are not rare but are widely found. They are extracted for use in electronic equipment such as mobile telephones.

rarefaction A process of making less dense or the state of being less dense. A reduction in the pressure of a fluid therefore reduces its density.

rare gas Another name for a noble gas and includes helium, neon, argon, krypton, xenon, and radon.

Raschig, Friedrich (Fritz) August (1863–1928) A German chemist who, after gaining his PhD in 1884 from the University of Berlin, started working for BASF but began his own chemical company in 1891. He patented many processes, mainly based on phenols. He also made many process improvements such as to distillation. He also developed a small ring, known as a *Raschig ring, that is used in *distillation columns and packed columns to improve extraction and separation performance.

Raschig process 1. A process used for the production of chlorobenzene. It uses a gas-phase catalytic reaction between benzene vapour, hydrogen chloride, and oxygen in the form of air at a temperature of 230°C in the presence of a copper chloride catalyst:

$$2C_6H_6 + 2HCl + O_2 \rightarrow 2H_2O + 2C_6H_5Cl$$

The chlorobenzene produced is then used for the production of phenol:

$$C_6H_5Cl + H_2O \rightarrow C_6H_5OH + HCl$$

The reaction takes place at 430°C in the presence of a silicon catalyst. The process is named after German chemist Fritz *Raschig (1863–1928). The **Hooker–Raschig process** is a variation and uses a different type of catalyst. **2.** A two-step process used for the production of hydrazine using the oxidation of ammonia with sodium hypochlorite in the presence of gelatine:

$$NH_3 + NaOCl \rightarrow NaOH + H_2NCl$$
$$H_2NCl + NH_3 \rightarrow N_2H_4 + HCl$$

The **Olin–Raschig process** is a refinement of the process; developed by the Olin Corporation, it involves mixing a solution of sodium hypochlorite with ammonia at 5°C to form chloramine and sodium hydroxide, and then quickly adding it to anhydrous ammonia under pressure and a temperature of 130°C to produce the hydrazine, water, and sodium chlorine.

Raschig ring A type of packing material used in packed columns and towers (see Fig. 50). It consists of a hollow cylinder whose length is equal to its diameter. Raschig rings are made from various materials such as plastic, glass, and ceramic. Raschig rings made from borosilicate glass are sometimes used in vessels containing nuclear materials such as uranyl nitrate to act as neutron absorbers to prevent the possibility of a *criticality incident. They are named after German chemist Fritz *Raschig (1863–1928).

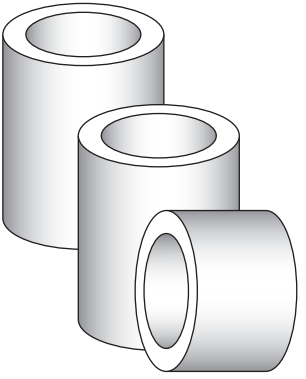

Fig. 50

rate constant A constant associated with chemical reactions and is a measure of the rate at which the reaction takes place. The SI unit is dependent on the order of the reaction and is expressed in terms of one of the reacting species. The *Arrhenius equation is often used to relate the rate constant for the reaction to reaction temperature.

rate-determining step Most chemical reactions involve several stages. If one of these stages is slower than the others then the overall rate of the reaction will be determined by the rate of the slowest stage. In catalytic reactions, for example, the overall process involves diffusion, adsorption, reaction, and desorption. The rate-limiting step is the step that consumes most of the driving force.

rational number The ratio of two integers presented as a quotient or fraction, for example 3/2. They can be both positive and negative. A number that is not rational is irrational.

raw data Data that has not been organized or processed in any way.

raw materials The starting materials used in a process that may be characterized on the basis of their chemical and physical form. For example, crude oil is the starting material in the petroleum industry and is converted into many useful and valuable products. Coal and natural gas are also the starting materials for many other useful products. Inorganic starting materials include metal ores, salt, air, water, and sulphur.

Rayleigh, Lord (1842–1919) A British scientist born as John William Strutt. He studied mathematics at Cambridge and was appointed professor of experimental physics and head of the Cavendish laboratory at Cambridge in 1879. He succeeded to the barony on the death of his father in 1873. He was appointed professor of natural philosophy at the Royal Institution until 1905, was president of the Royal Society between 1905 and 1908, and was awarded the Nobel Prize for Physics in 1904. His contribution to science covered many aspects of physics including optics, vibrating systems, sound, wave theory, colour vision, electrodynamics, electromagnetism, light scattering, flow of liquids, hydrodynamics, density of gases, viscosity, capillarity, elasticity, and photography. He published extensively and contributed to the *Encyclopaedia Britannica*.

Rayleigh equation An equation that relates the quantity to the concentration of the more volatile component in *batch distillation. The equation is formulated from an unsteady-state material balance in which vapour leaving the still is in equilibrium with the liquid. As the vapour is richer in the more volatile component, the composition of the liquid and vapour are not constant:

$$\ln\frac{L_1}{L_2}=\int_{x_2}^{x_1}\frac{dx}{y-x}$$

where L_1 and L_2 are the initial and final number of moles in the still, x_1 and x_2 are the initial and final mole fractions of the more volatile liquid, and y is the mole fraction in the vapour phase. The integral can be integrated graphically or numerically using equilibrium data. It is named after Lord *Rayleigh (1842–1919) who first derived it.

Rayleigh–Jeans law A formula giving the intensity of *black-body radiation at long wavelengths for a body at a particular temperature. It is an approximation to Planck's full formula for the black-body intensity based on quantum concepts.

Rayleigh's dimensional analysis method A method used in *dimensional analysis that expresses a functional relationship for the variables involved in an observable phenomenon. It involves expressing all the independent variables that influence a dependent variable in the form:

$$y=fa^x b^y c^z \ldots z^n$$

where f is a dimensionless constant. Grouping the exponents, x, y, z ...n, in their fundamental units and solving the set of equations simultaneously leads to the formation of dimensionless groups by grouping the variables with each exponent. The number of dimensionless groups formed is equal to the *fundamental units subtracted from the total number of variables. It is named after Lord *Rayleigh (1842–1919).

reaction The transformation of a substance by physical, chemical, or biochemical means into other substances with the release or consumption of energy. Single reactions are rare in practice but instead are generally complex resulting in several products, intermediates, and undesirable products. In parallel reactions, the concentration level of desired product is key to the control of the product distribution. For reactions in series, the mixing of the different compositions is the key to the formation of an intermediate. Series-parallel reactions are seen from the point of view of the constituents. The thermodynamic feasibility of a chemical reaction can be determined from the free energy while the kinetics of the reaction determines the rate at which the reaction takes place, and therefore determines the size of the reactor required to contain the reaction. The choice of reactor, such as *plug

flow reactor or *continuous stirred-tank reactor, is dependent on the heating and cooling requirements of the reaction. Heats of reaction can be determined from heats of combustion and heats of formation of the individual components in the reaction.

reaction rate (Symbol r) The number of moles of a species, i, undergoing chemical change per unit volume of reactor, V, per unit time:

$$r_i = \frac{-1}{V}\frac{dn_i}{dt}$$

It may be expressed in terms of the rate of decrease in concentration of a reactant or the rate of increase in concentration of a product. The rate of reaction may be affected by the concentration of reactants, pressure, temperature, physical form of the reactants, and the presence of catalysts. Convention uses a negative sign to represent the disappearance of reactants and a positive sign to represent product formation.

reactive distillation A distillation process that involves a chemical reaction taking place within the *distillation column. As with conventional distillation, the reactants and the products are separated by virtue of differing boiling points and are therefore dependent on phase equilibria properties as well as hydraulic behaviour. Reactive distillation can also involve the presence of a catalyst and is known as **catalytic distillation**. Reactive distillation is used for esterification and etherification amongst other processes where the reaction takes place in the liquid phase. The benefits of reactive distillation include the elimination of product recovery along with the separation and recycling of unconverted reactants.

reactor A containment within which a controlled chemical, biochemical, or nuclear reaction takes place. There are various forms of chemical reactors whose design and application is dependent on the form of the chemical reaction. They may be large vessels or pipes, operated continuously or as a batch. The design of the reactor used for contacting of the reactants is important in determining the yield of desired product. In general, batch reactors are used where chemical conversion is dependent on reaction time only, whereas tubular reactors are used where chemical conversion is dependent on the position. *Continuous stirred-tank reactors are used where neither time nor position is critical. Batch reactors require a charge of reactants, whereas continuous reactors operate at steady state with a continuous flow of fresh reactants and the removal of products. The reactants and products may be liquid or gaseous. Catalysts may be required within the reactor or the presence of inert materials such as in *fluidized bed reactors. Continuous stirred-tank reactors are commonly used in which liquid reactants are continuously charged to the reactor, which is equipped with an agitator to ensure homogeneity of the reactants. There is a continuous overflow to maintain a constant volume within the reactor. A *plug flow reactor also operates continuously and consists of tubes that may be packed with a catalyst and used for gas- and liquid-phase reactions. They assume idealized plug flow of materials flowing through them and are used for both exothermic and endothermic reactions that require rapid heat transfer from or to the reaction. Fluidized bed reactors involve reactants to be injected under a bed of solid particles such as a catalyst and are effective at promoting heat and mass transfer as well as reaction rates. There are many other types of reactor such as *pulsed baffle reactors and semi-batch reactors, which operate with both continuous and batch feeds and outputs.

real gas A gas that does not behave as an ideal gas. This is, its behaviour deviates from ideality. The molecules of a real gas are finite in size and an attractive force exists between

them. A number of *equations of state have been established such as the *van der Waals' equation of state that allows for the size of the molecules and the attractive forces. The ideal gas law can also be used to mathematically describe the behaviour of a real gas or gas mixture and includes a *fugacity to represent a pseudo-pressure in place of partial pressure.

real number A number that can be expressed using a decimal point.

real-time control The control of processes in which a computer receives data signals from a process plant and returns control signals within a defined time constraint. The data signals are rapidly processed and can use past trends, experimental data, and databases, as well as permitting operator intervention. The output-controlled signals are used to make adjustments to valve positions, etc. and the controlled process variables displayed on screen in a control room.

reboiler A type of heat exchanger associated with *distillation columns for boiling the liquid from the bottom of the column to totally or partially vaporize it and be returned to the column to drive the separation. Reboilers usually consist of a horizontal cylindrical body containing hairpin tubes for heating with a characteristic vapour dome above the boiling liquid. Vertical *thermo-syphon reboilers are also used. Condensing steam, waste heat, or a hot liquid from the process is usually used as the heating medium. *See* KETTLE REBOILER.

reciprocating pump, compressor A positive displacement device consisting of a piston and cylinder arrangement. The piston is driven by a crankshaft though a connecting rod such that the piston enters and leaves the cylinder expelling and drawing in liquid for transportation in a cyclic fashion. A tight tolerance is required between the piston and cylinder to ensure no leakage. Check valves are used to ensure that the flow is in the desired direction. Multiple cylinders operated out of phase are used to provide a more continuous flow. Variations include the *plunger pump and the *diaphragm pump.

recombinant DNA technology A biotechnological process used to produce many useful and valuable products with medical, healthcare, agricultural, and veterinary applications. It involves taking genes from the cells of a living organism and transferring them to the cells of another organism. The genes transferred contain the genetic code for the expression of a required biochemical product, such as a protein with therapeutic properties, or provide resistance to an antibiotic or other substance. Recombinant human insulin, used for the treatment of diabetes, has virtually replaced insulin derived from pigs and cows, and is produced by bacteria containing human genes. Human growth hormones, hepatitis B vaccine, blood-clotting agents known as Factor VIII, anti-cancer drugs, and vaccines against scours, a toxic diarrhoea in pigs, are all produced by recombinant DNA technology. Crops developed through recombinant DNA technology that are resistance to herbicides, insects, low moisture, and other environmental conditions include rice, maize, canola (oil-seed rape), and cotton. The biotechnology was pioneered by Stanley Cohen from Stanford School of Medicine and Herbert Boyer from the California School of Medicine, San Francisco in 1973.

recrystallization 1. A process used to purify a substance or to obtain more regular crystals of a purified substance by repeated crystallization. **2.** A solid-state process that involves the reformation of the lattice structure of a crystal. It requires a rapid diffusion to the lattice and is carried out at an elevated temperature but below its melting point temperature. The homologous temperature is the absolute temperature as a fraction of

the melting point also in absolute temperature. Recrystallization typically takes place at a homologous temperature of 0.6.

rectification The process of purifying liquids by way of *distillation.

rectification section The part of a *distillation column above the *feed point where the more volatile component in both the liquid and vapour increases. The part of a distillation column below the feed point is known as the *stripping section.

Rectisol process The tradename for an *acid gas removal process. It uses methanol as the solvent to remove hydrogen sulphide and carbon dioxide from gas streams.

recuperator A type of heat exchanger used to heat process fluids using hot waste fluids. The hot and cold fluids pass through separate channels as either single or multipass.

recycle 1. The return of materials or energy to a previous stage in a cyclic process. It is used to increase yields, to enrich a product, to conserve heat, and to improve operations. **2.** The conversion of waste or used products to reusable material as a way of preventing the waste of potentially useful materials, reducing the consumption of fresh *raw materials, reducing energy usage, and reducing pollution. Recycling is the third component of the 'Reduce, Reuse, Recycle' waste hierarchy.

recycle ratio The ratio of recirculated reactant for reprocessing to the same reactant entering the process as fresh feed.

Redlich–Kwong (RK) equation of state A cubic equation of state based on the *van der Waals' equation of state used to describe the behaviour of real gases:

$$p = \frac{RT}{V-b} - \frac{a}{T^{0.5}V(V+b)}$$

The constants a and b are determined from the critical point data of the gas. The compressibility factor at the critical point is equal to one-third. The equation was developed by Austrian chemist Otto Redlich (1896–1978) and Joseph Neng Shun Kwong in 1949. The equation was further developed and modified by Pitzer, Wilson, and Soave to improve the predictability of gas behaviour. *See* SOAVE–REDLICH–KWONG (SRK) EQUATION OF STATE.

redox reaction *See* REDUCTION.

reduced pressure (Symbol p_r) The ratio of the pressure of a component to its critical pressure, p_C:

$$p_r = \frac{p}{p_C}$$

reduced temperature (Symbol T_r) The ratio of the temperature of a component to its critical temperature, T_C:

$$T_r = \frac{T}{T_C}$$

reduction Any chemical reaction in which oxygen is removed from a substance, hydrogen is added, or in which an atom or group of atoms gain electrons. Reduction is accompanied

by oxidation in many reactions. Such combined oxidation and reduction reactions are called **redox reactions**.

redundant Superfluous to requirements such as an item of process plant that is no longer required or in operation. *Compare* MOTHBALLING.

refine To make or become free from impurities. Metals, oils, and sugar are all refined.

refinery A factory for the purification of some crude or unprocessed material such as crude oil and sugar. Petroleum refining processes begin with distillation by boiling the crude oil into separate fractions or *cuts. These cuts are then converted to changing the size and structure of the molecules through *cracking, *reforming, and other conversion processes, followed by various treatment and separation processes to remove undesirable components and improve product quality. Refineries are complex and highly integrated facilities.

refining 1. A process used to purify an impure material but that does not involve chemical change. The refining of metals involves either hydrometallurgical or pyrometallurgical processes. The *cupellation process involves the extraction of silver from lead by melting the lead in a vessel known as a cupel and blowing air over the surface to oxidize the lead and leave pure silver. **2.** The refining of petroleum products involving the conversion of crude oil into usual petroleum products such as naphtha, diesel fuel, kerosene, and LPG. It is carried out in petroleum refineries.

reflectivity The portion of radiant energy falling on a surface that is reflected back. *Compare* ABSORPTIVITY; TRANSMISSIVITY.

reflux The boiling, condensing, and subsequent return to the boiler of a volatile liquid. It is used to enhance the separation of liquids of differing volatilities as in the process of distillation. In a *distillation column used to separate volatile liquids by virtue of their differing boiling points, using more reflux decreases the number of plates required for the separation. Conversely, using less reflux increases the number of plates required. The *reflux ratio is the ratio of *distillate taken from the distillation process to the reflux returned as liquid for further separation. Where no distillate is taken, the process operates on **total reflux**. The *minimum reflux ratio corresponds to an infinite number of trays to bring about a separation. Ideally, the reflux ratio should be optimal for which the combined fixed costs and the cost of operation should be least.

reflux drum A vessel used with *distillation columns to receive condensed reflux liquid from the top of the column to be returned back to the column in order to provide cooling and condensation of the rising vapour. Level control is used to control the amount of condensed liquid that leaves the drum and returns to the column.

reflux ratio Used in the control of the purity of top products from a distillation column, it is the ratio of the molar flow of liquid, L, returned to the top of the column to the amount of top product or distillate, D, removed.

$$R = \frac{L}{D}$$

reforming A process used to rearrange the molecular structure of hydrocarbons to alter their properties by *cracking or by *catalytic conversion. In *petroleum refining, reforming is used to produce hydrocarbons for use in gasoline. *Steam reforming is the conversion of

methane from natural gas into hydrogen. It is used in ammonia production, which is produced from desulphurized and scrubbed natural gas that is mixed with steam and passed over nickel catalyst packed in tubes at a high temperature of around 900°C.

$$CH_4 + H_2O \rightarrow CO + 3H_2$$
$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

As both reactions are endothermic, heat is supplied to the reformer.

refractory A non-metallic material used to line furnaces, kilns, ovens, and some high-temperature reactors, which can maintain its mechanic strength at high temperature. They are made from chemically inert materials such as fire clay, silicon oxide, and aluminium oxide, and are able to withstand very high temperatures without cracking or expansion. Some refractory materials are also required to be resistant to alkaline and acidic environments.

refrigerant A low boiling liquid used as the working fluid in the process of *refrigeration that is capable of phase change at low temperatures. CFCs were once popular due to their excellent thermodynamic properties but have been internationally banned due to their ozone-depleting potential. Modern refrigerants do not contain harmful chlorine. Ammonia is the refrigerant used in absorption refrigeration.

refrigeration The process of cooling or freezing substances such as foods or process liquids and maintaining them at a temperature below that of their surroundings. The most commonly used refrigeration plants use a vapour compression refrigeration cycle. This consists of a compressor, evaporator, expansion valve, and condenser connected in series. Heat is absorbed by a refrigerant causing it to boil. The vapour is then compressed to an elevated pressure, and then condensed to a liquid releasing the absorbed heat. The liquid is then returned to the low-pressure evaporator through a throttle valve for reuse (see Fig. 51). The ideal cycle can be presented on a temperature-entropy diagram or a pressure-volume diagram. Within the refrigeration process, the *coefficient of performance is the ratio of the refrigeration effect to the work input. The *vapour absorption cycle is also used in industrial refrigeration systems and involves a refrigerant such as ammonia. Small-scale refrigeration can be achieved using the *Peltier effect.

refuel A process that receives a supply of fresh fuel such as a coal, coke, hydrocarbon liquid or gas, or nuclear fuel within a nuclear reactor.

regenerate The process of restoring or of being restored to its original chemical or physical state. For example, *ion exchange units consist of a fixed bed of ion exchange resins used to exchange ions within a solution, and are used in water treatment to remove calcium and magnesium ions replacing them with soluble sodium ions. The resins are regenerated for reuse by applying pressure and temperature to return them to their original state.

regenerator A type of heat exchanger in which hot and cold fluids pass alternately through the same chamber. The process is unsteady in which the chamber is first heated and then cooled by the cold fluid.

Regnault, Henri Victor (1810–78) A French scientist who was born in poverty and rose to become an outstanding chemist and physicist. He discovered carbon tetrachloride and measured the chemical composition of the atmosphere around the world. He made a series

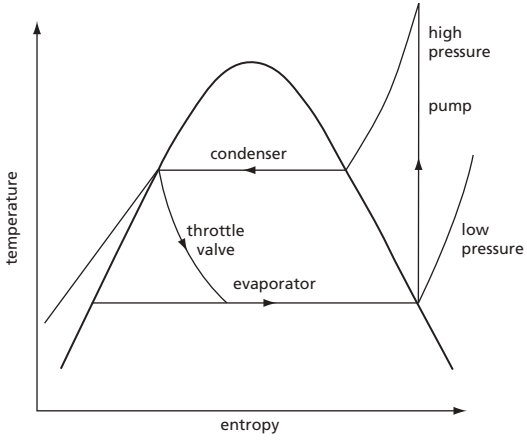

Fig. 51

of measurement of the specific heats of many solids, liquids, and gases, of the expansion of gases, and of vapour pressures. He developed the use of an accurate air thermometer. He also designed an efficient hygrometer for measuring *dew point and invented an apparatus for measuring the coefficient of expansion of mercury.

Regnault's method A method of measuring the density of a gas involving weighing an evacuated glass bulb of known volume and then admitting the gas at a known pressure and temperature. The method is named after French chemist and physicist Henri Victor *Regnault (1810–78).

regression analysis (least squares method) The statistical analysis and measure of the association between a dependent variable (y) and an independent variable (x) that involves calculating the best straight line for a linear equation between x and y as $y = a + bx$ where a and b are constants. While x can be measured accurately, there is a statistical random error associated with y. The least squares method aims to minimize the sum of the square of the difference between all (n) values of y on the line at x:

$$an + b\Sigma x = \Sigma y$$
$$a\Sigma x + b\Sigma x^2 = \Sigma xy$$

The **regression line** is the calculated line of best fit.

regulator 1. A device such as a valve used to control the flow of fluid, pressure, temperature, voltage, etc. in a process. **2.** A person or organization that has responsibility for regulating the activities of an industry such as the release of emissions into the atmosphere. **3.** A gene within the DNA of living organisms responsible for controlling the synthesis of a product from another gene. *See* RECOMBINANT DNA TECHNOLOGY.

Reid vapour pressure The vapour pressure of a fluid measured at 100°F (38°C) in a bomb where the initial liquid volume is about a quarter of the air volume. It is applied to the vapour pressure of hydrocarbons.

reimbursable A form of engineering contract in which the contractor is reimbursed for the time taken to carry out and complete a project. *Compare* TURN-KEY.

rejection coefficient A measure of the amount of a solute in a feed solution fed to a *semi-permeable membrane that does not permeate the membrane in a separation process such as *ultrafiltration:

$$R = 1 - \frac{C_P}{C_R}$$

where R is the solute rejection coefficient, C_p is the concentration of the solute in permeate, and C_R is the concentration of solute in the retentate. For a given membrane with a pore size distribution there is a relationship between the rejection coefficient and the solute molecular weight.

relative atomic mass The mass of an atom relative to one-twelfth the mass of an atom of carbon-12. It is dependent on the number of protons and neutrons in the atoms. The electrons have negligible mass.

relative density The ratio of the density of a substance to a reference substance. A substance with a relative density less than one is less dense than the reference; if greater than one then it is denser than the reference. If the relative density of the substance and reference substance is exactly the same, then the densities are equal; i.e. equal volumes of the two substances have the same mass. The temperature and pressure must be specified for both the sample and the reference. *Compare* SPECIFIC DENSITY.

relative humidity The moisture content of dry air expressed as a percentage. This corresponds to the ratio of the mass of water vapour in a given volume of air at a given temperature and pressure, to the maximum quantity of water vapour that can be held in the air at those conditions.

relative molecular mass (molecular weight) The mass of a molecule relative to one-twelfth of the mass of an atom of carbon-12. It is determined by adding the relative atomic masses of the atoms that comprise the molecule.

relative roughness (Symbol ε) Ratio of the absolute pipe wall roughness to the inside diameter of the pipe in consistent units. Being dimensionless, the magnitude of the surface roughness is relative only to the inside pipe diameter as a form of shape factor. *See* ABSOLUTE ROUGHNESS.

relative volatility (Symbol α) The ratio of the vapour pressure of one liquid component to another in a heterogeneous mixture and is a measure of their separability. For a binary mixture, the relative volatility can be expressed in terms of the mole fraction of the more volatile component in the liquid and vapour phases, x and y, as:

$$\alpha = \frac{y(1-x)}{x(1-y)}$$

The greater the value of the relative volatility, the greater the degree of separation. If $y = x$ then no separation is possible.

release agent A substance that is applied to surfaces to prevent them from sticking together. They are used in many industrial processes such as food, plastics, polymers, and glass. They include waxes, silicones, and glycerides, amongst others. For example, zinc stearate is used to prevent polymerized methyl methacrylate from sticking to steel moulds used in the production of household appliances.

reliability The statistical chance of a system, process, item of equipment, performing its intended purpose or function without failure or within required levels of performance.

relief valve (RV) An automatic type of safety valve that is activated by the static pressure in a liquid-filled vessel. It opens in proportion to increasing pressure. *See* SAFETY VALVE.

renaturation The reconstruction of a denatured protein or nucleic acid to its original conformation and function. The process of renaturation may be aided by reversing the process conditions that causes *denaturation, but in practice may be very slow or may not actually occur at all.

renewable energy Energy derived from sources that do not deplete the Earth's finite and non-renewable mineral resources. Examples include geothermal energy, tidal power, wave power, wind power, solar energy, biomass, biofuels, and hydroelectric power. Many others are currently being investigated due to concerns that fossil fuel reserves are running out, as well as the effects of carbon dioxide emissions from their combustion in terms of climate change. The use of renewable energy is not new. Hydropower uses kinetic energy in water flow to drive a water turbine, which in turn drives an electric generator. The first hydropower plant was open at Niagara Falls in North America in 1899. Tidal power is generated by passing water through a two-way turbine and was first used in the 1900s. Wind turbines generate electricity by using the kinetic energy of the wind to drive a set of turbine blades and thus a generator. There is no atmospheric pollution and no fuel costs. However, there is a visual impact and some noise. Wind turbines were once a common site across Europe for milling grain since the fourteenth century.

repeatability The closeness of agreement of a consecutively measured statistical data sample.

Reppe process A general name for catalytic processes used to produce vinyl compounds from acetylene. They use high pressure in the presence of metal acelylide catalysts. They are named after German chemist Walter Reppe (1892–1969) who developed the safe industrial use of acetylene.

reproducibility The closeness of agreement amongst repeated measurements of data in a statistical sample.

residence time The duration of a substance within a process or item of equipment. The residence time is used to give a measure of chemical reaction or required equipment size.

residence time distribution (RTD) A concept used to characterize the macro-mixing in a continuous flow system such as a reactor. It is expressed as the fraction of a material remaining in the system as a function of time given either as a cumulative distribution or as the derivative of the cumulative curve. The RTD can be determined by adding either a step increase in a tracer substance or an instantaneous pulse of a tracer into the flow system,

and measuring the response at the other end or output. The RTD information is useful to determine the performance of a reactor throughput.

residual moisture The moisture that remains within a substance following a normal drying process to remove the moisture.

residue 1. The material remaining after boiling off the volatile liquid in a mixture containing solids or high boiling-point liquids. **2.** The distillation of all but the heaviest components from liquid materials such as crude oil.

resistance 1. A force, such as friction, that opposes the direction of motion having the effect of slowing a body such as fluid flowing in a pipe. **2.** The ability of the human body to withstand the harmful effects of chemical pollutants, viruses, microorganisms, and physical conditions such as extremes of temperature and pressure.

resistance in parallel A system arranged so that a flow is divided through each part such that the resistance is the same in each part. In electric circuits, resistors are connected such that the current divides between them. For pipes in parallel, the flow of fluid divides into each pipe such that the pressure drop resistance of each pipe is the same:

$$\Delta p_A = \Delta p_B = \Delta p_C = \ldots$$

resistance in series A system arranged in sequence such that the flow through each part is the same. In electric circuits in which the circuit elements are arranged in sequence, the same current flows through each in turn where the total resistance is equal to the sum of the individual resistances. In heat transfer, the temperature drop across a wall comprising several materials is the sum of the temperature drops for each material:

$$\Delta T = \Delta T_A + \Delta T_B + \ldots$$

For pipe flow, the total pressure drop across several pipes linked in series is the sum of the pressure drops for each pipe:

$$\Delta p = \Delta p_A + \Delta p_B + \ldots$$

resistance temperature detector An instrument used to measure temperature through changes in electrical resistance. It consists of an element of fine coiled wire made from copper, nickel, or platinum wrapped around a glass core. The wire has a known change of resistance with temperature. It is noted for its accuracy and reliability across a wide range of temperatures.

resolution 1. The smallest increment of change that can be detected by an instrument or other measurement system. **2.** The process of separating something into its constituent parts.

respiration The process of oxygen exchange in living organisms from the surroundings, releasing energy and carbon dioxide. The **respiration quotient** is the ratio of the production rate of carbon dioxide to the oxygen uptake by a culture of microorganisms within a bioreactor. It is a measure of the performance of the bioreactor in terms of the ability of the culture to use a carbon-limiting substrate and is often correlated with the product yield. It is also used to measure the performance of the human body as the ratio of carbon dioxide liberated from the lungs to the oxygen consumed.

response The behaviour of a process to a disturbance such as a change in flow, temperature, pressure, etc. It is measured using an instrument and the information used by a controller to return the process back to its desired value. A **step response** is the behaviour of the controlled process to adjust from one steady-state condition to another. A **dynamic response** is the behaviour of the controlled process with respect to time. The **response time** is the time for a process or instrument to adjust to a disturbance and return to a new steady-state value. It is expressed as the time required to fall within a specified percentage of the change final steady-state value. This is often taken as 5 per cent or occasionally 3 per cent.

retentate The material (liquid, gas, or vapour) that does not pass through a semi-permeable membrane in a separation process such as *ultrafiltration. In membrane modules used to separate activated sludge, for example, water molecules pass through the membrane as *permeate while the material remaining is the retentate.

retention time The time at which a certain amount of a substance has been removed or eluted from a process or process pipe. In a gas or liquid chromatograph, which is used to separate mixtures of unknown components by injection into a packed column and carried by a solvent or gas to a detector, the time for a substance to appear is measured relative to an internal standard component so that an accurate identification on the components can be made against known standards.

revamp An informal term used for the maintenance, repair, redesign, and return to operation of process plant or an item of process equipment such as a pump.

reverse-acting controller A type of controller used to control a process in which the output signal from the controller decreases with increasing measured (input) value. It has a positive gain. *Compare* DIRECT-ACTING CONTROLLER.

reverse flow plate A type of plate used in distillation columns that consists of a downcomer and a separation or baffle running perpendicular to the downcomer weir across most of the plate, causing liquid entering the plate to flow along one side and around the other.

reverse osmosis A process in which liquid flows through a *semi-permeable membrane used to separate two solutions. The most concentrated solution is a pressure above that of the osmotic pressure. This causes the liquid to flow from the more concentrated solution to the less concentrated solution. A common use of reverse osmosis is water purification from seawater.

reversible A phenomenon or action that can take place in two directions. It is applied to mechanical, thermal, chemical, and biological processes. For example, the *Carnot cycle is a reversible thermodynamic cycle. A **reversible process** is a process in which the *process variables that define the equilibrium thermodynamics can be made to change in such a way that the process can be made to return to its original thermodynamic equilibrium. All natural processes are irreversible. A **reversible reaction** is a chemical or physical phenomenon that can take place in two directions. Strictly, all chemical reactions are reversible. For many chemical reactions, the equilibrium conversion is effectively complete such as the combustion of fuel and therefore considered to be irreversible. For example, the reversible reaction:

$$aA + bB \underset{k_2}{\overset{k_1}{\leftrightarrow}} cC + dD$$

where k_1 and k_2 are the forwards and reverse reaction constants. The rate equation for component A assuming a constant volume reactor is therefore:

$$\frac{dC_A}{dt} = -k_1 C_A^a C_B^b + k_2 C_C^c C_D^d$$

At equilibrium:

$$\frac{dC_A}{dt} = 0$$

such that the equilibrium constant, K, for the reaction is:

$$K = \frac{k_1}{k_2} = \frac{C_C^c C_D^d}{C_A^a C_B^b}$$

Reynolds, Osborne (1842–1912) An English engineer born in Belfast. A graduate of Cambridge, he was appointed as the first professor of engineering at the University of Manchester in 1868, where he remained for 37 years. He studied a wide range of engineering problems and his most notable work was in the field of hydrodynamics. He studied cavitation in hydraulic machines, designed the first multistage centrifugal pump, and patented the use of guide vanes in centrifugal pumps, which are still used today. The *Reynolds number is named after him. He was elected a member of the Royal Society in 1877.

Reynolds number A dimensionless number, Re, expressing the ratio of inertial to viscous forces in a flowing fluid, and can be used to determine the flow regime. For a fluid in a pipe of circular cross section:

$$\mathrm{Re} = \frac{\rho v d}{\mu}$$

where ρ is the density, v is the mean velocity, d is the diameter of a pipe, and μ is the viscosity. Where the value for circular pipes falls below 2,000, the flow is *laminar flow or streamline. For Reynolds numbers above 4,000, the flow is turbulent.

Various forms of Reynolds number are used, such as the flow through an annulus in which case a *mean hydraulic diameter is used, or the flow of fluid in the vicinity of an impeller of diameter, D, and rotational speed, N, given as:

$$\mathrm{Re} = \frac{\rho N D^2}{\mu}$$

It is named after British engineer Osborne *Reynolds (1842–1912).

rheogram A graphical plot of rheological parameters for fluids such as shear stress with shear rate. They are used in the study of the behaviour of fluids.

rheology The study of the deformation and flow of fluids and includes the fundamental parameters of *elasticity, *plasticity, and *viscosity. The state of a fluid is characterized by three principal types of behaviour depending on the nature of flow:

1 Time-independent fluids. Examples include *Newtonian fluids in which the ratio of shear stress to shear rate is a constant, such as water, oils, and honey; *pseudoplastic fluids in which the apparent viscosity decreases with increasing shear rate, such as

polymer melts, paper pulp, wallpaper paste, printing inks, tomato purée, mustard, and rubber solutions; and dilatants in which the apparent viscosity increases with increasing shear rate. These are more rare and include titanium dioxide suspensions, cornflour/sugar suspensions, cement aggregates, starch solutions, and certain honeys.

2 Time-dependent fluids. For these fluids, the relation between shear stress and shear rate depends on the time and flow history of the fluid. They are classified as being either thixotropic or antithixotropic (or rheopectic). For thixotropic fluids, the shear stress decreases with time for a given shear stress. This is due to a structural breakdown of the fluid. If a cyclic experiment is carried out, a hysteresis loop is formed. Examples include greases, printing inks, jelly, paints, and drilling muds. In antithixotropic fluids the shear stress increases with time for a given shear stress. Examples include clay suspensions and gypsum suspensions.

3 Viscoelastic fluids. Fluids that possess the properties of both viscosity and elasticity. Unlike purely viscous fluids where the flow is irreversible, viscoelastic fluids recover part of their deformation. The rheological measurement of these fluids is understandably very difficult. Examples include polymeric solutions, partially hydrolyzed polymer melts such as polyacrylamide, thick soups, crème fraîche, ice cream, and some melted products such as cheese.

rheometer An instrument used to obtain the rheological properties of fluids. It involves a small quantity of the fluid being entrapped between two geometric surfaces with one surface static and the other in motion at constant speed. This defines the shear rate. The torque to resist the motion defines the characteristic shear rate. A limitation with the rotational speed is the need to avoid secondary flow patterns that give false readings. *Parallel-disc, *cone and plate rheometer, and *Couette are all forms of rheometer.

rheometry The study of the flow of fluids and fluid deformation.

rheopexy A non-Newtonian property of certain fluids that shows a time-dependent change in viscosity setting more rapidly when they are stirred or shaken. **Rheopectic fluids** are relatively rare and include gypsum suspensions, Bentonite clay suspensions, certain lubricants, and printing inks. They are also known as *antithixotropic fluids. *Compare* THIXOTROPIC FLUIDS.

Richardson, John Francis (1920–2011) A British chemical engineer best known as a coauthor and editor for a series of six textbooks entitled *Chemical Engineering*, which were first published in 1954. After gaining a BSc and PhD in chemical engineering at Imperial College, London, 'Jack' joined the academic staff there before being appointed as head of the department of chemical engineering at the University of Swansea in 1960 where he remained until his retirement in 1987. He was president of the Institution of Chemical Engineers (1975–76). He was awarded an OBE in 1981 for services to industry based on his various government involvements.

rig An apparatus constructed specifically for obtaining or validating process plant data. It is often a small-scale version or a specific part of a process plant. Offshore structures or platforms for oil and gas recovery are loosely termed as rigs.

rigorous multicomponent distillation methods Computational procedures that enable the rigorous solution of equilibrium-stage multicomponent distillation problems to be effected rapidly to an accuracy depending only on equilibrium and enthalpy data. There are four types of restricting equations in the equilibrium stage model.

1 The equilibrium relation:

$$y_{i,n} = K_{i,n} x_{i,n}$$

2 Componential mass balance for stage *n*:

$$L_{i,n} + V_{i,n} - L_{i,n+1} - V_{i,n+1} - f_{i,n} = 0$$

where $f_{i,n}$ represents the feed or side stream.

3 Energy balance for stage n:

$$L_n h_n + V_n h_n - L_{n+1} h_{n+1} - V_{n-1} h_{n-1} - f_n h_{f,n} - q_n = 0$$

where q_n represents the heat input on stage n.

4 Inherent restrictions on mole fractions:

$$\sum x_{i,n} = 1.0$$
$$\sum y_{i,n} = 1.0$$

These equations are insufficient in number to define a unique operation of a column and fix the concentrations, temperature, pressure, and flow-rate variable in the column. For a column with a single feed, a total condenser, and a partial reboiler, the number of design variables is C+2N+9 for C components with N-1 trays.

riser 1. The vertical tube under a bubble cap plate used in a *distillation column for vapour to rise. **2.** Used in offshore oil and gas processing, it is a vertical pipe rising from the seabed to a production platform carrying oil, gas, or a mixture of the two.

rise time The time taken for the response of a signal in a controlled process to reach its first peak.

rising film evaporator A type of evaporator used to concentrate solutions. It consists of a vertical tube heat exchanger in which the liquid to be evaporated is fed to the bottom of the evaporator and which forms a thin film on the surface. The evaporator is operated under vacuum and the overall flow of the liquid is upward. It is also known as a **climbing film evaporator**.

risk The statistical probability or likelihood of an undesired event occurring within a defined period or in specified circumstances and the severity or impact it could have if it were to happen. It is therefore a measure of the potential for causing human injury, loss of life, economic loss, or environmental impact. The likelihood may be expressed either as a frequency of specified events occurring in a given time, or as a probability of a specified event occurring. Acute risk is where the consequence occurs quickly, such as the effect of an electrical storm. Chronic risk is where the consequence builds up slowly over time although a single dosage may be small.

risk analysis The quantitative analysis of the risk associated with the likelihood of undesirable events occurring. The analysis is based on engineering evaluations and mathematical techniques that combine the statistical probability of occurrence with the consequences.

risk assessment The evaluation of the likelihood of undesired events and the likelihood of harm or damage being caused, together with the judgements made concerning

the significance of the results. A risk assessment considers the elimination, substitution, reduction, and adequate control of risks, through the identification of hazards, impact, and likelihood of events occurring. The decisions are taken based on relative ranking of risk reduction strategies or through the use of targets levels that are required to be met.

risk management A management procedure used to identify, assess, control, and reduce risks. This is through the reduction of the likelihood of an event occurring or the effect of loss due to an event occurring. The risk may be associated with human injury, loss of life, damage to process plant, loss of production, or financial loss. It is proactive and not reactive in its approach and achieved through applying engineering principles.

rivet A pin that fixes together two sheets of material by insertion through a hole in the two sheets. The pin is usually metal and the head is expanded by striking it flat.

roasting A process involving the burning of a finely ground sulphide-containing ore with air to produce sulphur dioxide, and used prior to smelting. The roasting process is also used to remove any chemically bound moisture and the ore is converted to an oxide. A fluidized bed is used for the roasting of pyrite ore.

rock An aggregate of minerals that makes up part of the Earth's surface. Sand, mud, and clay are unconsolidated forms, while granite, limestone, and coal are consolidated forms. It may contain minerals of economic value that require extraction and purification.

roentgen (Symbol r) A unit of measurement for ionizing electromagnetic radiation from X-rays and gamma rays, defined as the charge in air of 2.58×10^{-4} coulombs on all ions of one sign when all the electrons of both signs liberated are completely stopped by a mass of one kilogram of air. It is named after German physicist Wilhelm Konrad Röentgen (1845–1923) who discovered X-rays. A lethal dose to humans corresponds to an exposure of 200 roentgens over a five-hour period. The unit is no longer used.

Romankov number A dimensionless number, Ro. Used in drying, it is the ratio of the dry bulb temperature to the absolute temperature of the product:

$$Ro = \frac{T_{db}}{T_p}$$

root The solution to an algebraic equation involving real or complex numbers.

root locus A method of analysis used in process control to determine the stability of a closed-loop control system.

root-mean-square (RMS) A statistical measure defined as the square root of the mean of the squares of a sample:

$$RMS = \frac{\sqrt{x_1^2 + x_2^2 + x_3^2 + \ldots x_N^2}}{N}$$

Roots blower A type of low-gauge pressure compressor for the transport of large volumes of gas. It consists of two rotating lobe-type rotors that have a small clearance between the rotors and the casing. It is named after its American inventor Francis Roots (1824–89) and his brother Philander (1813–79), who founded the Roots Blower Company.

Rotameter A registered name for a type of *variable area flow meter used to measure the rate of flow of fluids. It consists of a tapered tube and contains a float. The elevation of the float in the tube gives a measure of the rate of flow and is read from a calibrated scale on the tube.

rotary drum filter A type of continuous filter used to remove bulk liquid from a liquid suspension such as a precipitate. The drum operates at reduced pressure and sits semi-submerged in the liquid. As the drum slowly rotates, a filter cake is formed on the drum, lifted from the liquid, and removed using a blade.

rotary kiln A type of furnace used for *roasting various sulphide ores prior to metal extraction. The kiln consists of a slowly rotating cylinder inclined slightly to the horizontal with a refractory lining. Material is fed into the rotating kiln allowing it to cascade down. Hot air from a burner which provides the heat is also fed into the kiln either cocurrently but more usually countercurrently. At the end, the product is collected and any entrained product with the hot gases separated by a cyclone. They are used in the manufacture of cement and pelletizing of iron ore, titanium dioxide, and alumina.

rotary pump A type of positive displacement pump consisting of gears with meshing teeth (see Fig. 52). The rate of flow is determined by the number and size of the spaces between the teeth and their rotational speed. A close tolerance is required between the teeth to prevent leakage, although unlike the reciprocating type pump, check valves are not required. They require liquids with good lubricating properties and are unsuitable for fluids with abrasive properties.

rotary vacuum filter A type of continuous filter used to remove bulk liquid from a suspension of particles such as a precipitate to produce a wet filter cake (see Fig. 53). It consists of a perforated circular plate that slowly rotates. Material is fed onto a point on the plate that

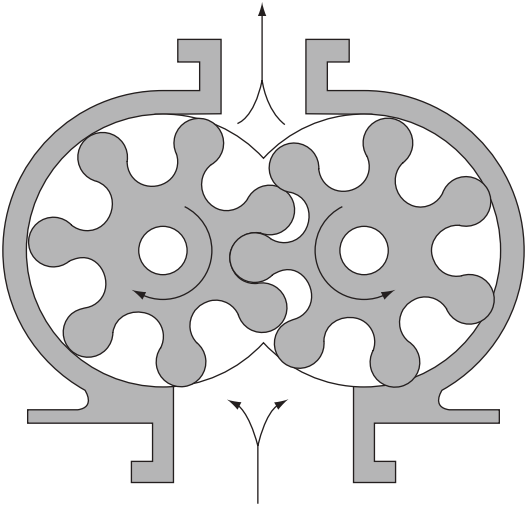

Fig. 52 Gear-type rotary pump

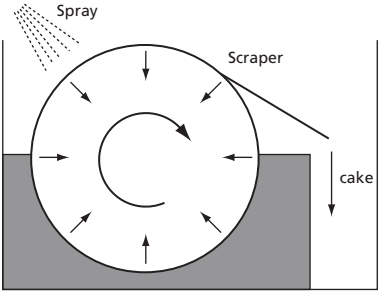

Fig. 53 Rotary drum filter

rotates over a plenum operating at a reduced pressure drawing the liquid through the plate. The remaining filter cake is continuously scraped from the surface.

rotating disc atomizer A device used to atomize a liquid in a gas. It consists of a disc that rotates at a very high speed. Liquid is fed onto the disc where the high-speed shearing effect reduces the liquid to a fine spray. It is typically used in *spray dryers to reduce the liquid containing a heat-labile solid to a fine spray for rapid low-temperature evaporation such as in spray-drying milk.

rotor Rotating part of a pump, turbine, or generator, etc.

Royal Australian Chemical Institute (RACI) The qualifying body in Australia for professional chemists and a learned society promoting the science and practice of chemistry in all its branches.

SEE WEB LINKS

- Official website of the Royal Australian Chemical Institute.

rules of thumb A set of suggested values used by engineers that are considered to be reasonable and based on experience. While based on the application of fundamentals, they do not replace them but instead assist with solving problems. They are typically used to judge the reasonableness of answers, quickly assess assumptions, guide understanding of complex systems and situations, and provide rapid order of magnitude estimates.

runaway reaction A chemical reaction in which control has been lost and it continues to accelerate to a point that either it exhausts its reactants or the vessel containing the reaction over-pressurizes and loses containment. This is often in the form of an explosion with catastrophic consequences. **Thermal runaway** exothermic reactions may occur due to insufficient cooling or loss of cooling, a loss of or excessive mixing, excessive reactant or catalyst, the loss of an inhibitor, or external fire. Where a runaway is likely, pressure relief systems are used. The *Seveso and Bhopal accidents are examples of runaway reactions with disastrous consequences.

rupture disc *See* BURSTING DISC.

Rushton, John Henry (1905–85) An American chemical engineer noted for his work on mixing. He obtained his first degree in chemical engineering from the University of

Pennsylvania in 1926 and worked as an engineer before becoming an academic. He was professor and head of chemical engineering at the University of Virginia. In 1946 he moved to the Illinois Institute of Technology as professor and director of the Department of Chemical Engineering. He joined Purdue University in 1955 and remained there until 1971. He was considered a world expert on design and application of large-scale mixing, mass transfer equipment, and on process design, and was president of *AIChE in 1957.

Rushton turbine A type of impeller used for gas dispersion such as in biochemical reactors and consists of a flat disc with six vertical flat blades mounted on the circumference (see Fig. 54). It therefore provides radial-flow mixing. It is named after American chemical engineer John Henry *Rushton (1905–85), who was noted for his work on mixing. There have been many subsequent modifications and improvements to the basic design.

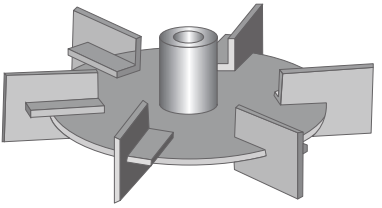

Fig. 54 Rushton impeller

rusting An electrochemical corrosion process involving the oxidation of iron to form a hydrated iron oxide that occurs in the presence of both water and oxygen. It is very damaging to process equipment and support structures. Rust has a characteristic red colour and is permeable to both water and air. Rust prevention involves coatings that can exclude oxygen from the iron surface. Certain paints can provide the necessary seal. *Galvanization is an effective process involving coating the iron with zinc. The use of stainless steels involves an *alloy with chromium that forms a passivation layer of chromium oxide on the surface. *Compare* CORROSION.

Rutherford, Lord Ernest (1871–1937) A New Zealand-born British scientist who became Baron Rutherford of Nelson in 1931. He studied in New Zealand, gaining a double First in physics and mathematics, before going to Cambridge to study under Sir J. J. Thomson in the Cavendish Laboratory. He became professor of physics at the age 27 at McGill University, Canada and studied radioactivity. Working with British chemist Frederick Soddy (1877–1956), he discovered alpha particles, beta particles, and gamma radiation. He moved to Manchester University in 1907 and, working with H. Geiger and E. Marsden, he developed an experiment that led to the discovery of the atomic nucleus in 1911. In 1919 he succeeded in transforming nitrogen into an isotope of oxygen by bombarding it with alpha particles. He was awarded the Nobel Prize for Chemistry in 1908 for his work on radioactivity.

SEE WEB LINKS

- Official website of McGill University and its museum to Rutherford.

rutherford A unit of radioactivity corresponding to 10^6 disintegrations per second. The curie is another unit of radioactivity corresponding to 3.7×10^{10} disintegrations where 37 rutherford = 1 mCi.

RV *See* RELIEF VALVE.