UNIVERSITY OF DAIYLA

COLLEGE OF ENGINEERING

CHEMICAL ENGINEERING DEPARTMENT

CHEMICAL ENGINEERING EQUIPMENT DESIGN

For
Third and Fourth Years Chemical Engineering Students
Part -2-

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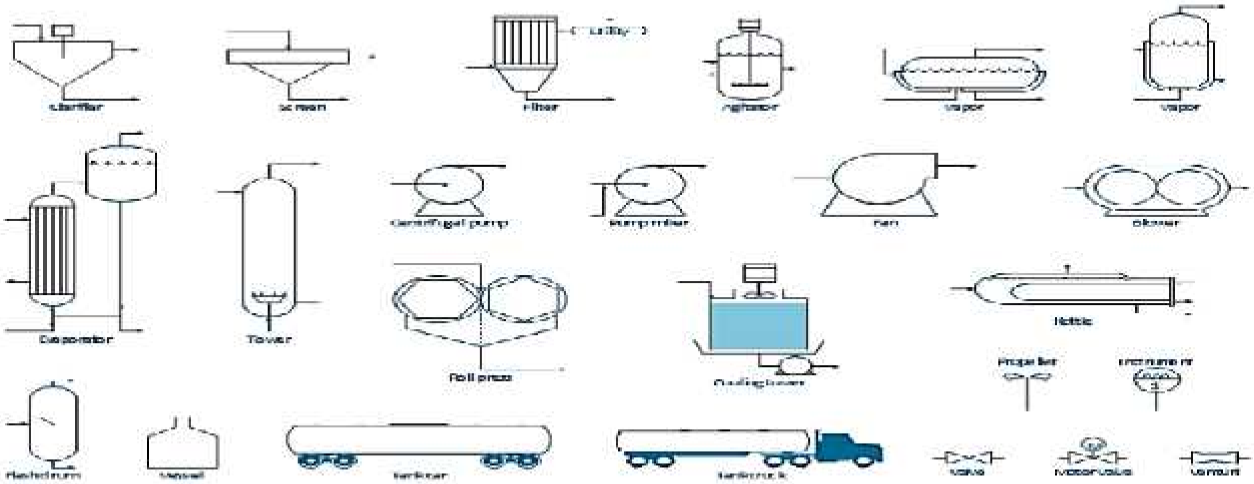

CONTENTS

CHAPTER SIX

SAFETY & LOSS PREVENTION

INTRODUCTION

Any organisation has a legal and moral obligation to safeguard the health and welfare of its employees and the general public. Safety is also good business; the good management practices needed to ensure safe operation will also ensure efficient operation.

The term “loss prevention” is an insurance term, the loss being the financial loss caused by an accident. This loss will not only be the cost of replacing damaged plant and third party claims, but also the loss of earnings from lost production and lost sales opportunity.

All manufacturing processes are to some extent hazardous, but in chemical processes there are additional, special, hazards associated with the chemicals used and the process conditions. The designer must be aware of these hazards, and ensure, through the application of sound engineering practice, that the risks are reduced to acceptable levels.

In this book only the particular hazards associated with chemical and allied processes will be considered. The more general, normal, hazards present in all manufacturing process such as, the dangers from rotating machinery, falls, falling objects, use of machine tools, and of electrocution will not be considered. General industrial safety and hygiene are covered in several books, King and Hirst (1998), Ashafi (2003) and Ridley (2003).

Safety and loss prevention in process design can be considered under the following broad headings:

1. Identification and assessment of the hazards.
2. Control of the hazards: for example, by containment of flammable and toxic materials.
3. Control of the process. Prevention of hazardous deviations in process variables (pressure, temperature, flow), by provision of automatic control systems, interlocks, alarms, trips; together with good operating practices and management.
4. Limitation of the loss. The damage and injury caused if an incident occurs: pressure relief, plant layout, provision of fire-fighting equipment.

INTRINSIC AND EXTRINSIC SAFETY

Processes can be divided into those that are intrinsically safe, and those for which the safety has to be engineered in. An intrinsically safe process is one in which safe operation is inherent in the nature of the process; a process which causes no danger, or negligible danger, under all foreseeable circumstances (all possible deviations from the design operating conditions). The term inherently safe is often preferred to intrinsically safe, to avoid confusion with the narrower use of the term intrinsically safe as applied to electrical equipment (see Section 9.3.4).

Clearly, the designer should always select a process that is inherently safe whenever it is practical, and economic, to do so. However, most chemical manufacturing processes are, to a greater or lesser extent, inherently unsafe, and dangerous situations can develop if the process conditions deviate from the design values.

The safe operation of such processes depends on the design and provision of engineered safety devices, and on good operating practices, to prevent a dangerous situation developing, and to minimise the consequences of any incident that arises from the failure of these safeguards.

The term “engineered safety” covers the provision in the design of control systems, alarms, trips, pressure-relief devices, automatic shut-down systems, duplication of key equipment services; and fire-fighting equipment, sprinkler systems and blast walls, to contain any fire or explosion.

The design of inherently safe process plant is discussed by Kletz in a booklet published by the Institution of Chemical Engineers, Kletz (1984) and Keltz and Cheaper (1998). He makes the telling point that what you do not have cannot leak out: so cannot catch fire, explode or poison anyone. Which is a plea to keep the inventory of dangerous material to the absolute minimum required for the operation of the process.

THE HAZARDS

In this section the special hazards of chemicals are reviewed (toxicity, flammability and corrosivity); together with the other hazards of chemical plant operation.

1) Toxicity

Most of the materials used in the manufacture of chemicals are poisonous, to some extent. The potential hazard will depend on the inherent toxicity of the material and the frequency and duration of any exposure. It is usual to distinguish between the short-term effects (acute) and the long-term effects (chronic). A highly toxic material that causes immediate injury, such as phosgene or chlorine, would be classified as a safety hazard. Whereas a material whose effect was only apparent after long exposure at low concentrations, for instance, carcinogenic materials, such as vinyl chloride, would be classified as industrial health and hygiene hazards. The permissible limits and the precautions to be taken to ensure the limits are met will be very different for these two classes of toxic materials. Industrial hygiene is as much a matter of good operating practice and control as of good design.

The inherent toxicity of a material is measured by tests on animals. It is usually expressed as the lethal dose at which 50 per cent of the test animals are killed, the LD50 (lethal dose fifty) value. The dose is expressed as the quantity in milligrams of the toxic substance per kilogram of body weight of the test animal.

Some values for tests on rats are given in Table 9.1. Estimates of the LD50 for man are based on tests on animals. The LD50 measures the acute effects; it gives only a crude indication of the possible chronic effects.

Table 9.1. Some LD_{50} values

Compound	mg/kg
Potassium cyanide	10
Tetraethyl lead	35
Lead	100
DDT	150
Aspirin	1500
Table salt	3000

Source: Lowrance (1976).

There is no generally accepted definition of what can be considered toxic and non-toxic. A system of classification is given in the Classification, Packaging and Labelling of Dangerous Substances, Regulations, 1984 (United Kingdom), which is based on European Union (EU) guidelines; for example:

LD_{50}, absorbed orally in rats, mg/kg	
≤25	very toxic
25 to 200	toxic
200 to 2000	harmful

These definitions apply only to the short-term (acute) effects. In fixing permissible limits on concentration for the long-term exposure of workers to toxic materials, the exposure time must be considered together with the inherent toxicity of the material. The "Threshold Limit Value" (TLV) is a commonly used guide for controlling the long-term exposure of workers to contaminated air. The TLV is defined as the concentration to which it is believed the average worker could be exposed to, day by day, for 8 hours a day, 5 days a week, without suffering harm. It is expressed in ppm for vapours and gases, and in mg/m^3) (or $grains/ft^3$) for dusts and liquid mists. A comprehensive source of data on the toxicity of industrial materials is Sax's handbook, Lewis (2004); which also gives guidance on the interpretation and use of the data. Recommended TLV values are published in bulletins by the United States Occupational Safety and Health Administration. Since 1980 the United Kingdom Health and Safety Executive (HSE) has published values for the Occupational Exposure Limits (OEL), for both long and short term exposure, in place of TLV values.

Fuller details of the methods used for toxicity testing, the interpretation of the result and their use in setting standards for industrial hygiene are given in the more specialised texts on the subject; see Carson and Mumford (1988) and Lees (1996).

Control of substances hazardous to health

In the United Kingdom the use of substances likely to be harmful to employees is covered by regulations issued by the Health and Safety Executive (HSE), under the Health and Safety at Work Act, 1974 (HSAWA). The principal set of regulations in force is the Control of Substances Hazardous to Health regulations, 2002; known under the acronym: the COSHH regulations. The COSHH regulations apply to any hazardous substance in use in any place of work.

The employer is required to carry out an assessment to evaluate the risk to health, and establish what precautions are needed to protect employees. A written record of the assessment would be kept, and details made available to employees.

A thorough explanation of the regulations is not within the scope of this book, as they will apply more to plant operation and maintenance than to process design. The HSE has published a series of booklets giving details of the regulations and their application (see www.hse.gov.uk/pubns). A comprehensive guide to the COSHH regulations has also been published by the Royal Society of Chemistry, Simpson and Simpson (1991).

The designer will be concerned more with the preventative aspects of the use of hazardous substances. Points to consider are:

1. Substitution: of the processing route with one using less hazardous material. Or, substitution of toxic process materials with non-toxic, or less toxic materials.
2. Containment: sound design of equipment and piping, to avoid leaks. For example, specifying welded joints in preference to gasketed flanged joints (liable to leak).
3. Ventilation: use open structures, or provide adequate ventilation systems.
4. Disposal: provision of effective vent stacks to disperse material vented from pressure relief devices; or use vent scrubbers.
5. Emergency equipment: escape routes, rescue equipment, respirators, safety showers, eye baths.

In addition, good plant operating practice would include:

1. Written instruction in the use of the hazardous substances and the risks involved.
2. Adequate training of personnel.
3. Provision of protective clothing.
4. Good housekeeping and personal hygiene.
5. Monitoring of the environment to check exposure levels. Consider the installation of permanent instruments fitted with alarms.
6. Regular medical check-ups on employees, to check for the chronic effects of toxic materials.

2) Flammability

The term “flammable” is now more commonly used in the technical literature than “inflammable” to describe materials that will burn, and will be used in this book. The hazard caused by a flammable material depends on a number of factors:

1. The flash-point of the material.
2. The autoignition temperature of the material.
3. The flammability limits of the material.
4. The energy released in combustion.

Flash-point

The flash-point is a measure of the ease of ignition of the liquid. It is the lowest temperature at which the material will ignite from an open flame. The flash-point is a function of the vapour pressure and the flammability limits of the material. It is measured in standard apparatus, following standard procedures (BS 2000). Both open- and closed-cup apparatus is used. Closed-cup flash-points are lower than open cup, and the type of apparatus used should be stated clearly when reporting measurements. Flash-points are given in Sax’s handbook, Lewis (2004). The flash-points of many volatile materials are below normal ambient temperature; for example, ether -45 °C, petrol (gasoline) -43 °C (open cup).

Autoignition temperature

The autoignition temperature of a substance is the temperature at which it will ignite spontaneously in air, without any external source of ignition. It is an indication of the maximum temperature to which a material can be heated in air; for example, in drying operations.

Flammability limits

The flammability limits of a material are the lowest and highest concentrations in air, at normal pressure and temperature, at which a flame will propagate through the mixture. They show the range of concentration over which the material will burn in air, if ignited. Flammability limits are characteristic of the particular material, and differ widely for different materials. For example, hydrogen has a lower limit of 4.1 and an upper limit of 74.2 per cent by volume, whereas for petrol (gasoline) the range is only from 1.3 to 7.0 per cent.

The Flammability limits for a number of materials are given in Table 9.2.

The limits for a wider range of materials are given in Sax’s handbook, Lewis (2004).

A flammable mixture may exist in the space above the liquid surface in a storage tank. The vapour space above highly flammable liquids is usually purged with inert gas (nitrogen) or floating-head tanks are used. In a floating-head tank a “piston” floats on top of the liquid, eliminating the vapour space.

Flame traps

Flame arresters are fitted in the vent lines of equipment that contains flammable material to prevent the propagation of flame through the vents. Various types of proprietary flame arresters are used. In general, they work on the principle of providing a heat sink, usually expanded metal grids or plates, to dissipate the heat of the flame. Flame arrestors and their applications are discussed by Rogowski (1980), Howard (1992) and Mendoza et al. (1988).

Traps should also be installed in plant ditches to prevent the spread of flame. These are normally liquid U-legs, which block the spread of flammable liquid along ditches.

Fire precautions

Recommendations on the fire precautions to be taken in the design of chemical plant are given in the British Standard, BS 5908.

Table 9.2. Flammability ranges

Material	Lower limit	Upper limit
Hydrogen	4.1	74.2
Ammonia	15.0	28.0
Hydrocyanic acid	5.6	40.0
Hydrogen sulphide	4.3	45.0
Carbon disulphide	1.3	44.0
Carbon monoxide	12.5	74.2
Methane	5.3	14.0
Ethane	3.0	12.5
Propane	2.3	9.5
Butane	1.9	8.5
Isobutane	1.8	8.4
Ethylene	3.1	32.0
Propylene	2.4	10.3
n-Butene	1.6	9.3
Isobutene	1.8	9.7
Butadiene	2.0	11.5
Benzene	1.4	7.1
Toluene	1.4	6.7
Cyclohexane	1.3	8.0
Methanol	7.3	36.0
Ethanol	4.3	19.0
Isopropanol	2.2	12.0
Formaldehyde	7.0	73.0
Acetaldehyde	4.1	57.0
Actone	3.0	12.8
Methylethyl ketone	1.8	10.0
Dimethylamine (DEA)	2.8	184
Trimethylamine (TEA)	2.0	11.6
Petrol (gasoline)	1.3	7.0
Paraffin (kerosene)	0.7	5.6
Gas oil (diesel)	6.0	13.5

Volume percentage in air at ambient conditions

3) Explosions

An explosion is the sudden, catastrophic, release of energy, causing a pressure wave (blast wave). An explosion can occur without fire, such as the failure through over-pressure of a steam boiler or an air receiver.

When discussing the explosion of a flammable mixture it is necessary to distinguish between detonation and deflagration. If a mixture detonates the reaction zone propagates at supersonic velocity (approximately 300 m/s) and the principal heating mechanism in the mixture is shock compression. In a deflagration the combustion process is the same as in the normal burning of a gas mixture; the combustion zone propagates at subsonic velocity, and the pressure build-up is slow. Whether detonation or deflagration occurs in a gas-air mixture depends on a number of factors; including the concentration of the mixture and the source of ignition. Unless confined or ignited by a high-intensity source (a detonator) most materials will not detonate. However, the pressure wave (blast wave) caused by a deflagration can still cause considerable damage.

Certain materials, for example, acetylene, can decompose explosively in the absence of oxygen; such materials are particularly hazardous.

Confined vapour cloud explosion (CVCE)

A relatively small amount of flammable material, a few kilograms, can lead to an explosion when released into the confined space of a building.

Unconfined vapour cloud explosions (UCVCE)

This type of explosion results from the release of a considerable quantity of flammable gas, or vapour, into the atmosphere, and its subsequent ignition. Such an explosion can cause extensive damage, such as occurred at Flixborough, HMSO (1975). Unconfined vapour explosions are discussed by Munday (1976) and Gugan (1979).

Boiling liquid expanding vapour explosions (BLEVE)

Boiling liquid expanding vapour explosions occur when there is a sudden release of vapour, containing liquid droplets, due to the failure of a storage vessel exposed to fire. A serious incident involving the failure of a LPG (Liquified Petroleum Gas) storage sphere occurred at Feyzin, France, in 1966, when the tank was heated by an external fire fuelled by a leak from the tank; see Lees (1996) and Marshall (1987).

Dust explosions

Finely divided combustible solids, if intimately mixed with air, can explode. Several disastrous explosions have occurred in grain silos.

Dust explosions usually occur in two stages: a primary explosion which disturbs deposited dust; followed by the second, severe, explosion of the dust thrown into the atmosphere. Any finely divided combustible solid is a potential explosion hazard. Particular care must be taken in the design of dryers, conveyors, cyclones, and storage hoppers for polymers and other combustible products or intermediates. The extensive literature on the hazard and control of dust explosions should be consulted before designing powder handling systems: Field (1982), Cross and Farrer (1982), Barton (2001), and Eckhoff (2003).

4) Sources of ignition

Though precautions are normally taken to eliminate sources of ignition on chemical plants, it is best to work on the principle that a leak of flammable material will ultimately find an ignition source.

Electrical equipment

The sparking of electrical equipment, such as motors, is a major potential source of ignition, and flame proof equipment is normally specified. Electrically operated instruments, controllers and computer systems are also potential sources of ignition of flammable mixtures.

The use of electrical equipment in hazardous areas is covered by British Standards BS 5345 and BS 5501. The code of practice, BS 5345, Part 1, defines hazardous areas as those where explosive gas-air mixtures are present, or may be expected to be present, in quantities such as to require special precautions for the construction and use of electrical apparatus. Non-hazardous areas are those where explosive gas-air mixtures are not expected to be present.

Three classifications are defined for hazardous areas:

Zone 0: explosive gas-air mixtures are present continuously or present for long periods.
Specify: intrinsically safe equipment.

Zone 1: explosive gas-air mixtures likely to occur in normal operation.
Specify: intrinsically safe equipment, or flame-proof enclosures: enclosures with pressurizing and purging.

Zone 3: explosive gas-air mixtures not likely to occur during normal operation, but could occur for short periods.
Specify: intrinsically safe equipment, or total enclosure, or non-sparking apparatus.

Consult the standards for the full specification before selecting equipment for use in the designated zones.

The design and specification of intrinsically safe control equipment and systems is discussed by MacMillan (1998) and Cooper and Jones (1993).

Static electricity

The movement of any non-conducting material, powder, liquid or gas, can generate static electricity, producing sparks. Precautions must be taken to ensure that all piping is properly earthed (grounded) and that electrical continuity is maintained around flanges. Escaping steam, or other vapours and gases, can generate a static charge. Gases escaping from a ruptured vessel can self-ignite from a static spark. For a review of the dangers of static electricity in the process industries, see the article by Napier and Russell (1974); and the books by Pratt (1999) and Britton (1999). A code of practice for the control of static electricity is given in BS 5938 (1991).

Process flames

Open flames from process furnaces and incinerators are obvious sources of ignition and must be sited well away from plant containing flammable materials.

Miscellaneous sources

It is the usual practice on plants handling flammable materials to control the entry on to the site of obvious sources of ignition; such as matches, cigarette lighters and battery-operated equipment. The use of portable electrical equipment, welding, spark-producing tools and the movement of petrol-driven vehicles would also be subject to strict control.

Exhaust gases from diesel engines are also a potential source of ignition.

5) Ionising radiation

The radiation emitted by radioactive materials is harmful to living matter. Small quantities of radioactive isotopes are used in the process industry for various purposes; for example, in level and density-measuring instruments, and for the non-destructive testing of equipment.

The use of radioactive isotopes in industry is covered by government legislation, see hse.gov.uk/pubns.

A discussion of the particular hazards that arise in the chemical processing of nuclear fuels is outside the scope of this book.

6) Pressure

Over-pressure, a pressure exceeding the system design pressure, is one of the most serious hazards in chemical plant operation. Failure of a vessel, or the associated piping, can precipitate a sequence of events that culminate in a disaster.

Pressure vessels are invariably fitted with some form of pressure-relief device, set at the design pressure, so that (in theory) potential over-pressure is relieved in a controlled manner.

Three basically different types of relief device are commonly used:

Directly actuated valves: weight or spring-loaded valves that open at a predetermined pressure, and which normally close after the pressure has been relieved. The system pressure provides the motive power to operate the valve.

Indirectly actuated valves: pneumatically or electrically operated valves, which are activated by pressure-sensing instruments.

Bursting discs: thin discs of material that are designed and manufactured to fail at a predetermined pressure, giving a full bore opening for flow.

Relief valves are normally used to regulate minor excursions of pressure; and bursting discs as safety devices to relieve major over-pressure. Bursting discs are often used in conjunction with relief valves to protect the valve from corrosive process fluids during normal operation. The design and selection of relief valves is discussed by Morley (1989a,b), and is also covered by the pressure vessel standards, see Chapter 13. Bursting discs are discussed by Mathews (1984), Askquith and Lavery (1990) and Murphy (1993). In the United Kingdom the use of bursting discs is covered by BS 2915. The discs are manufactured in a variety of materials for use in corrosive conditions; such as, impervious carbon, gold and silver; and suitable discs can be found for use with all process fluids.

Bursting discs and relief valves are proprietary items and the vendors should be consulted when selecting suitable types and sizes.

The factors to be considered in the design of relief systems are set out in a comprehensive paper by Parkinson (1979) and by Moore (1984); and in a book published by the Institution of Chemical Engineers, Parry (1992).

Vent piping

When designing relief venting systems it is important to ensure that flammable or toxic gases are vented to a safe location. This will normally mean venting at a sufficient height to ensure that the gases are dispersed without creating a hazard. For highly toxic materials it may be necessary to provide a scrubber to absorb and "kill" the material; for instance, the provision of caustic scrubbers for chlorine and hydrochloric acid gases. If flammable materials have to be vented at frequent intervals; as, for example, in some refinery operations, flare stacks are used.

The rate at which material can be vented will be determined by the design of the complete venting system: the relief device and the associated piping. The maximum venting rate will be limited by the critical (sonic) velocity, whatever the pressure drop (see Volume 1, Chapter 4). The design of venting systems to give adequate protection against over-pressure is a complex and difficult subject, particularly if two-phase flow is likely to occur. For complete protection the venting system must be capable of venting at the same rate as the vapour is being generated. For reactors, the maximum rate of vapour generation resulting from a loss of control can usually be estimated. Vessels must also be protected against over-pressure caused by external fires. In these circumstances the maximum rate of vapour generation will depend on the rate of heating. Standard formulae are available for the estimation of the maximum rates of heat input and relief rates, see ROSPA (1971) and NFPA (1987a,b).

For some vessels, particularly where complex vent piping systems are needed, it may be impractical for the size of the vent to give complete protection against the worst possible situation.

For a comprehensive discussion of the problem of vent system design, and the design methods available, see the papers by Duxbury (1976, 1979).

The design of relief systems has been studied by the Design Institute for Emergency Relief Systems (DIERS), established by the American Institute of Chemical Engineers; Fisher (1985). DIERS has published recommended design methods; see Poole (1985) and AIChemE (1992a,b). Computer programs based on the work by DIERS are also available.

Under-pressure (vacuum)

Unless designed to withstand external pressure (see Chapter 13) a vessel must be protected against the hazard of under-pressure, as well as over-pressure. Under-pressure will normally mean vacuum on the inside with atmospheric pressure on the outside. It requires only a slight drop in pressure below atmospheric pressure to collapse a storage tank. Though the pressure differential may be small, the force on the tank roof will be considerable. For example, if the pressure in a 10-m diameter tank falls to 10 millibars below the external pressure, the total load on the tank roof will be around 80,000 N (8 tonne). It is not an uncommon occurrence for a storage tank to be sucked in (collapsed) by the suction pulled by the discharge pump, due to the tank vents having become blocked. Where practical, vacuum breakers (valves that open to atmosphere when the internal pressure drops below atmospheric) should be fitted.

7) Temperature deviations

Excessively high temperature, over and above that for which the equipment was designed, can cause structural failure and initiate a disaster. High temperatures can arise from loss of control of reactors and heaters; and, externally, from open fires. In the design of processes where high temperatures are a hazard, protection against high temperatures is provided by:

1. Provision of high-temperature alarms and interlocks to shut down reactor feeds, or heating systems, if the temperature exceeds critical limits.
2. Provision of emergency cooling systems for reactors, where heat continues to be generated after shut-down; for instance, in some polymerisation systems.
3. Structural design of equipment to withstand the worst possible temperature excursion.
4. The selection of intrinsically safe heating systems for hazardous materials.

Steam, and other vapour heating systems, are intrinsically safe; as the temperature cannot exceed the saturation temperature at the supply pressure. Other heating systems rely on control of the heating rate to limit the maximum process temperature. Electrical heating systems can be particularly hazardous.

Fire protection

To protect against structural failure, water-deluge systems are usually installed to keep vessels and structural steelwork cool in a fire.

The lower section of structural steel columns are also often lagged with concrete or other suitable materials.

8) Noise

Excessive noise is a hazard to health and safety. Long exposure to high noise levels can cause permanent damage to hearing. At lower levels, noise is a distraction and causes fatigue.

The unit of sound measurement is the decibel, defined by the expression:

$$\text{Sound level} = 20\ \log_{10}\left[\frac{\text{RMS sound pressure (Pa)}}{2 \times 10^{-5}}\right], \text{dB} \qquad (9.1)$$

The subjective effect of sound depends on frequency as well as intensity.

Industrial sound meters include a filter network to give the meter a response that corresponds roughly to that of the human ear. This is termed the "A" weighting network and the readings are reported as dB(A).

Permanent damage to hearing can be caused at sound levels above about 90 dB(A), and it is normal practice to provide ear protection in areas where the level is above 80 dB(A).

Excessive plant noise can lead to complaints from neighbouring factories and local residents. Due attention should be given to noise levels when specifying, and when laying out, equipment that is likely to be excessively noisy; such as, compressors, fans, burners and steam relief valves.

Several books are available on the general subject of industrial noise control, Bias and Hansen (2003), and on noise control in the process industries, Cheremisnoff (1996), ASME (1993).

Basic preventative and protective measures

The basic safety and fire protective measures that should be included in all chemical process designs are listed below. This list is based on that given in the Dow Guide, with some minor amendments.

1. Adequate, and secure, water supplies for fire fighting.
2. Correct structural design of vessels, piping, steel work.
3. Pressure-relief devices.
4. Corrosion-resistant materials, and/or adequate corrosion allowances.
5. Segregation of reactive materials.
6. Earthing of electrical equipment.
7. Safe location of auxiliary electrical equipment, transformers, switch gear.
8. Provision of back-up utility supplies and services.
9. Compliance with national codes and standards.
10. Fail-safe instrumentation.
11. Provision for access of emergency vehicles and the evacuation of personnel.
12. Adequate drainage for spills and fire-fighting water.
13. Insulation of hot surfaces.
14. No glass equipment used for flammable or hazardous materials, unless no suitable alternative is available.

15. Adequate separation of hazardous equipment.
16. Protection of pipe racks and cable trays from fire.
17. Provision of block valves on lines to main processing areas.
18. Protection of fired equipment (heaters, furnaces) against accidental explosion and fire.
19. Safe design and location of control rooms.

Note: the design and location of control rooms, particularly as regards protection against an unconfined vapour explosion, is covered in a publication of the Chemical Industries Association, CIA (1979a).

CHAPTER ELEVEN

GENERAL SITE CONSIDERATIONS

INTRODUCTION

In the discussion of process and equipment design given in the previous chapters no reference was made to the plant site. A suitable site must be found for a new project, and the site and equipment layout planned. Provision must be made for the ancillary buildings and services needed for plant operation; and for the environmentally acceptable disposal of effluent. These subjects are discussed briefly in this chapter.

PLANT LOCATION AND SITE SELECTION

The location of the plant can have a crucial effect on the profitability of a project, and the scope for future expansion. Many factors must be considered when selecting a suitable site, and only a brief review of the principal factors will be given in this section. Site selection for chemical process plants is discussed in more detail by Merims (1966) and Mecklenburgh (1985); see also AIChemE (2003). The principal factors to consider are:

1. Location, with respect to the marketing area.
2. Raw material supply.
3. Transport facilities.
4. Availability of labour.
5. Availability of utilities: water, fuel, power.
6. Availability of suitable land.
7. Environmental impact, and effluent disposal.
8. Local community considerations.
9. Climate.
10. Political and strategic considerations.

Marketing area

For materials that are produced in bulk quantities; such as cement, mineral acids, and fertilisers, where the cost of the product per tonne is relatively low and the cost of transport a significant fraction of the sales price, the plant should be located close to the primary market. This consideration will be less important for low volume production, high-priced products; such as pharmaceuticals.

In an international market, there may be an advantage to be gained by locating the plant within an area with preferential tariff agreements; such as the European Community (EC).

Raw materials

The availability and price of suitable raw materials will often determine the site location. Plants producing bulk chemicals are best located close to the source of the major raw material; where this is also close to the marketing area.

Transport

The transport of materials and products to and from the plant will be an overriding consideration in site selection.

If practicable, a site should be selected that is close to at least two major forms of transport: road, rail, waterway (canal or river), or a sea port. Road transport is being increasingly used, and is suitable for local distribution from a central warehouse. Rail transport will be cheaper for the long-distance transport of bulk chemicals.

Air transport is convenient and efficient for the movement of personnel and essential equipment and supplies, and the proximity of the site to a major airport should be considered.

Availability of labour

Labour will be needed for construction of the plant and its operation. Skilled construction workers will usually be brought in from outside the site area, but there should be an adequate pool of unskilled labour available locally; and labour suitable for training to operate the plant. Skilled tradesmen will be needed for plant maintenance. Local trade union customs and restrictive practices will have to be considered when assessing the availability and suitability of the local labour for recruitment and training.

Utilities (services)

Chemical processes invariably require large quantities of water for cooling and general process use, and the plant must be located near a source of water of suitable quality. Process water may be drawn from a river, from wells, or purchased from a local authority.

At some sites, the cooling water required can be taken from a river or lake, or from the sea; at other locations cooling towers will be needed.

Electrical power will be needed at all sites. Electrochemical processes that require large quantities of power; for example, aluminium smelters, need to be located close to a cheap source of power.

A competitively priced fuel must be available on site for steam and power generation.

Environmental impact, and effluent disposal

All industrial processes produce waste products, and full consideration must be given to the difficulties and cost of their disposal. The disposal of toxic and harmful effluents will be covered by local regulations, and the appropriate authorities must be consulted during the initial site survey to determine the standards that must be met.

An environmental impact assessment should be made for each new project, or major modification or addition to an existing process, see Section 14.6.5.

Local community considerations

The proposed plant must fit in with and be acceptable to the local community. Full consideration must be given to the safe location of the plant so that it does not impose a significant additional risk to the community.

On a new site, the local community must be able to provide adequate facilities for the plant personnel: schools, banks, housing, and recreational and cultural facilities.

Land (site considerations)

Sufficient suitable land must be available for the proposed plant and for future expansion. The land should ideally be flat, well drained and have suitable load-bearing characteristics. A full site evaluation should be made to determine the need for piling or other special foundations.

Climate

Adverse climatic conditions at a site will increase costs. Abnormally low temperatures will require the provision of additional insulation and special heating for equipment and pipe runs. Stronger structures will be needed at locations subject to high winds (cyclone/hurricane areas) or earthquakes.

Political and strategic considerations

Capital grants, tax concessions, and other inducements are often given by governments to direct new investment to preferred locations; such as areas of high unemployment. The availability of such grants can be the overriding consideration in site selection.

SITE LAYOUT

The process units and ancillary buildings should be laid out to give the most economical flow of materials and personnel around the site. Hazardous processes must be located at a safe distance from other buildings. Consideration must also be given to the future expansion of the site. The ancillary buildings and services required on a site, in addition to the main processing units (buildings), will include:

1. Storages for raw materials and products: tank farms and warehouses.
2. Maintenance workshops.
3. Stores, for maintenance and operating supplies.
4. Laboratories for process control.
5. Fire stations and other emergency services.
6. Utilities: steam boilers, compressed air, power generation, refrigeration, transformer stations.
7. Effluent disposal plant.
8. Offices for general administration.
9. Canteens and other amenity buildings, such as medical centres.
10. Car parks.

When roughing out the preliminary site layout, the process units will normally be sited first and arranged to give a smooth flow of materials through the various processing steps, from raw material to final product storage. Process units are normally spaced at least 30 m apart; greater spacing may be needed for hazardous processes.

The location of the principal ancillary buildings should then be decided. They should be arranged so as to minimise the time spent by personnel in travelling between buildings. Administration offices and laboratories, in which a relatively large number of people will be working, should be located well away from potentially hazardous processes. Control rooms will normally be located adjacent to the processing units, but with potentially hazardous processes may have to be sited at a safer distance.

The siting of the main process units will determine the layout of the plant roads, pipe alleys and drains. Access roads will be needed to each building for construction, and for operation and maintenance.

Utility buildings should be sited to give the most economical run of pipes to and from the process units.

Cooling towers should be sited so that under the prevailing wind the plume of condensate spray drifts away from the plant area and adjacent properties.

The main storage areas should be placed between the loading and unloading facilities and the process units they serve. Storage tanks containing hazardous materials should be sited at least 70 m (200 ft) from the site boundary.

A typical plot plan is shown in Figure 14.1.

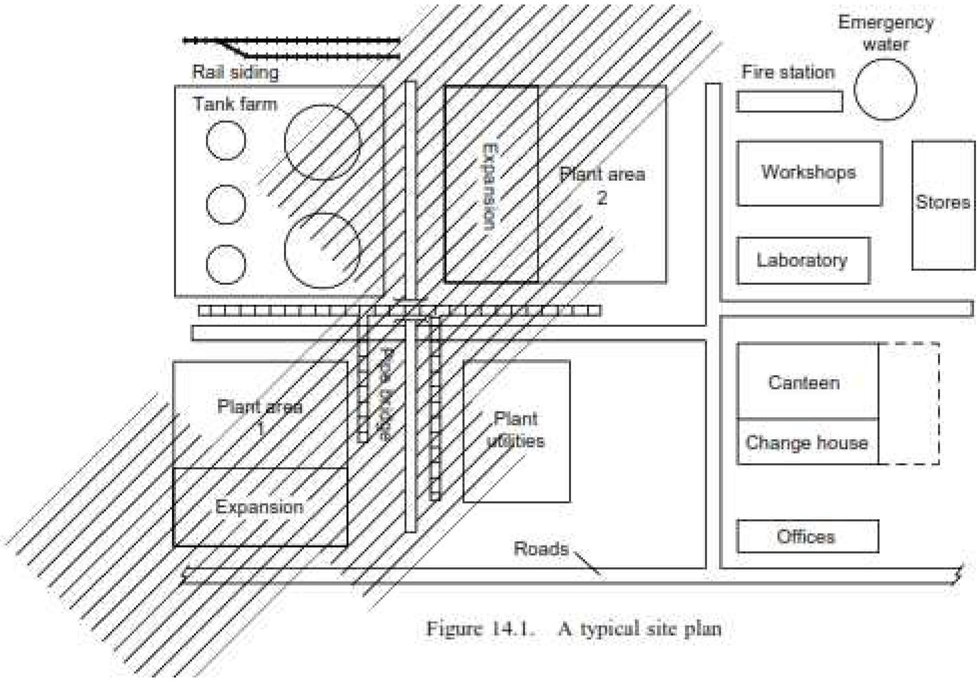

Figure 14.1. A typical site plan

A comprehensive discussion of site layout is given by Mecklenburgh (1985); see also House (1969), Kaess (1970) and Meissner and Shelton (1992).

PLANT LAYOUT

The economic construction and efficient operation of a process unit will depend on how well the plant and equipment specified on the process flow-sheet is laid out.

A detailed account of plant layout techniques cannot be given in this short section. A fuller discussion can be found in the book edited by Mecklenburgh (1985) and in articles by Kern (1977, 1978), Meissner and Shelton (1992), Brandt et al. (1992), and Russo and Tortorella (1992).

The principal factors to be considered are:

1. Economic considerations: construction and operating costs.
2. The process requirements.
3. Convenience of operation.
4. Convenience of maintenance.
5. Safety.
6. Future expansion.

7. Modular construction.

Costs

The cost of construction can be minimised by adopting a layout that gives the shortest run of connecting pipe between equipment, and the least amount of structural steel work. However, this will not necessarily be the best arrangement for operation and maintenance.

Process requirements

An example of the need to take into account process considerations is the need to elevate the base of columns to provide the necessary net positive suction head to a pump (see Chapter 5) or the operating head for a thermosyphon reboiler (see Chapter 12).

Operation

Equipment that needs to have frequent operator attention should be located convenient to the control room. Valves, sample points, and instruments should be located at convenient positions and heights. Sufficient working space and headroom must be provided to allow easy access to equipment.

Maintenance

Heat exchangers need to be sited so that the tube bundles can be easily withdrawn for cleaning and tube replacement. Vessels that require frequent replacement of catalyst or packing should be located on the outside of buildings. Equipment that requires dismantling for maintenance, such as compressors and large pumps, should be placed under cover.

Safety

Blast walls may be needed to isolate potentially hazardous equipment, and confine the effects of an explosion.

At least two escape routes for operators must be provided from each level in process buildings.

Plant expansion

Equipment should be located so that it can be conveniently tied in with any future expansion of the process.

Space should be left on pipe alleys for future needs, and service pipes over-sized to allow for future requirements.

Modular construction

In recent years there has been a move to assemble sections of plant at the plant manufacturer's site. These modules will include the equipment, structural steel, piping and instrumentation. The modules are then transported to the plant site, by road or sea.

The advantages of modular construction are:

1. Improved quality control.
2. Reduced construction cost.
3. Less need for skilled labour on site.
4. Less need for skilled personnel on overseas sites.

Some of the disadvantages are:

1. Higher design costs.
2. More structural steel work.
3. More flanged connections.
4. Possible problems with assembly, on site.

A fuller discussion of techniques and applications of modular construction is given by Shelley (1990), Hesler (1990), and Whitaker (1984).

General considerations

Open, structural steelwork, buildings are normally used for process equipment; closed buildings are only used for process operations that require protection from the weather.

The arrangement of the major items of equipment will usually follow the sequence given on the process flow-sheet: with the columns and vessels arranged in rows and the ancillary equipment, such as heat exchangers and pumps, positioned along the outside. A typical preliminary layout is shown in Figure 14.2.

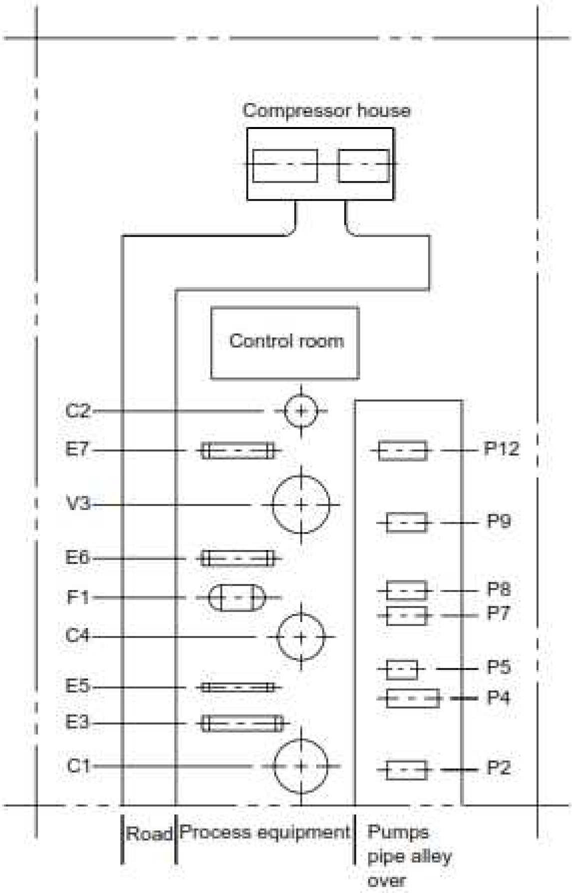

Figure 14.2. A typical plant layout

Techniques used in site and plant layout

Cardboard cut-outs of the equipment outlines can be used to make trial plant layouts. Simple models, made up from rectangular and cylindrical blocks, can be used to study alternative layouts in plan and elevation. Cut-outs and simple block models can also be used for site layout studies. Once the layout of the major pieces of equipment has been decided, the plan and elevation drawings can be made and the design of the structural steel-work and foundations undertaken.

Large-scale models, to a scale of at least 1 : 30, are normally made for major projects. These models are used for piping design and to decide the detailed arrangement of small items of equipment, such as valves, instruments and sample points. Piping isometric diagrams are taken from the finished models. The models are also useful on the construction site, and for operator training. Proprietary kits of parts are available for the construction of plant models.

Computers are being increasingly used for plant layout studies, and computer models are complementing, if not yet replacing, physical models. Several proprietary programs are available for the generation of 3-dimensional models of plant layout and piping. Present systems allow designers to zoom in on a section of plant and view it from various angles. Developments of computer technology will soon enable engineers to virtually walk through the plant. A typical computer generated model is shown in Figure 14.3.

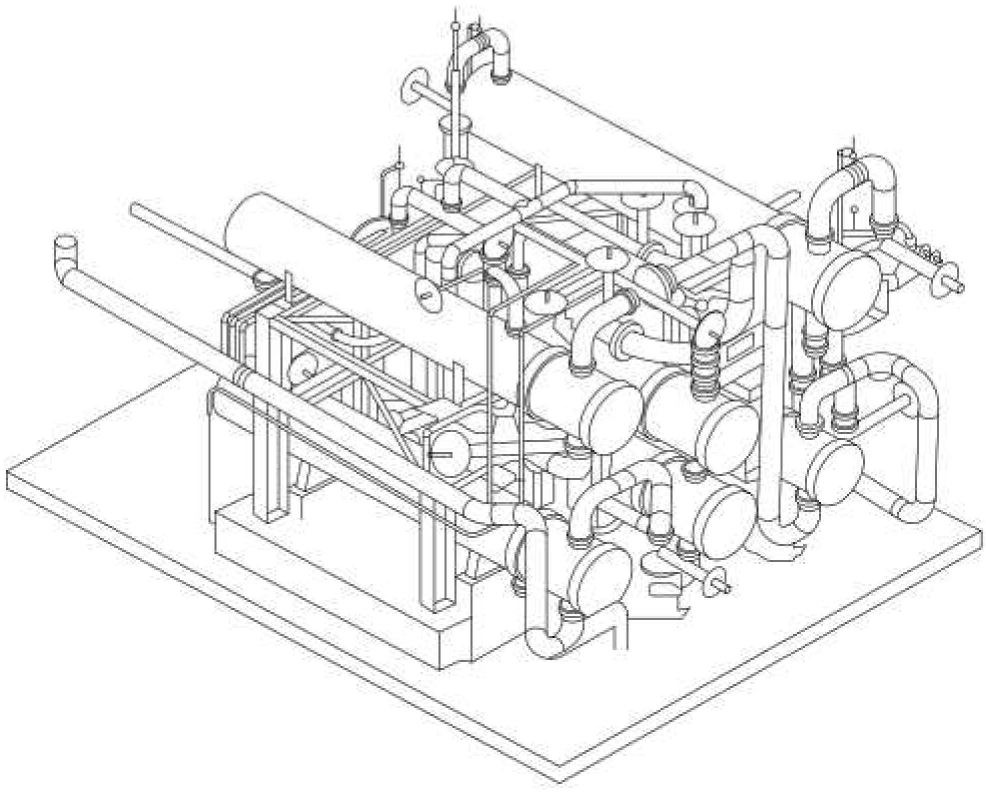

Figure 14.3. Computer generated layout "model" (Courtesy: Babcock Construction Ltd.)

Some of the advantages of computer graphics modelling compared with actual scale models are:

1. The ease of electronic transfer of information. Piping drawings can be generated directly from the layout model. Bills of quantities: materials, valves, instruments, are generated automatically.
2. The computer model can be part of an integrated project information system, covering all aspects of the project from conception to operation.

3. It is easy to detect interference between pipe runs, and pipes and structural steel: occupying same space.
4. A physical model of a major plant construction can occupy several hundred square metres. The computer model is contained on a few discs.
5. The physical model has to be transported to the plant site for use in the plant construction and operator training. A computer model can be instantly available in the design office, the customer's offices, and at the plant site.
6. Expert systems and optimisation programs can be incorporated in the package to assist the designer to find the best practical layout; see Madden et al. (1990).

UTILITIES

The word "Utilities" is now generally used for the ancillary services needed in the operation of any production process. These services will normally be supplied from a central site facility; and will include:

1. Electricity.
2. Steam, for process heating.
3. Cooling water.
4. Water for general use.
5. Demineralised water.
6. Compressed air.
7. Inert-gas supplies.
8. Refrigeration.
9. Effluent disposal facilities.

Electricity

The power required for electrochemical processes; motor drives, lighting, and general use, may be generated on site, but will more usually be purchased from the local supply company (the national grid system in the UK). The economics of power generation on site are discussed by Caudle (1975).

The voltage at which the supply is taken or generated will depend on the demand. For a large site the supply will be taken at a very high voltage, typically 11,000 or 33,000 V. Transformers will be used to step down the supply voltage to the voltages used on the site. In the United Kingdom a three-phase 415-V system is used for general industrial purposes, and 240-V single-phase for lighting and other low-power requirements. If a number of large motors is used, a supply at an intermediate high voltage will also be provided, typically 6000 or 11,000 V.

A detailed account of the factors to be considered when designing electrical distribution systems for chemical process plants, and the equipment used (transformers, switch gear and cables), is given by Silverman (1964).

Steam

The steam for process heating is usually generated in water tube boilers; using the most economical fuel available. The process temperatures required can usually be obtained with low-pressure steam, typically 2.5 bar (25 psig), and steam is distributed at a relatively low mains pressure, typically around 8 bar (100 psig). Higher steam pressures, or proprietary heat-transfer fluids, such as Dowtherm (see Conant and Seifert, 1963), will be needed for high process temperatures. The generation, distribution and utilisation of steam for process heating in the manufacturing industries is discussed in detail by Lyle (1963).

Combined heat and power (co-generation)

The energy costs on a large site can be reduced if the electrical power required is generated on site and the exhaust steam from the turbines used for process heating. The overall thermal efficiency of such systems can be in the range 70 to 80 per cent; compared with the 30 to 40 per cent obtained from a conventional power station, where the heat in the exhaust steam is wasted in the condenser. Whether a combined heat and power system scheme is worth considering for a particular site will depend on the size of the site, the cost of fuel, the balance between the power and heating demands; and particularly on the availability of, and cost of, standby supplies and the price paid for any surplus power electricity generated. The economics of combined heat and power schemes for chemical process plant sites in the United Kingdom is discussed by Grant (1979).

On any site it is always worth while considering driving large compressors or pumps with steam turbines and using the exhaust steam for local process heating.

Cooling water

Natural and forced-draft cooling towers are generally used to provide the cooling water required on a site; unless water can be drawn from a convenient river or lake in sufficient quantity. Sea water, or brackish water, can be used at coastal sites, but if used directly will necessitate the use of more expensive materials of construction for heat exchangers (see Chapter 7).

Water for general use

The water required for general purposes on a site will usually be taken from the local mains supply, unless a cheaper source of suitable quality water is available from a river, lake or well.

Demineralised water

Demineralised water, from which all the minerals have been removed by ion-exchange, is used where pure water is needed for process use, and as boiler feed-water. Mixed and multiple-bed ion-exchange units are used; one resin converting the cations to hydrogen and the other removing the acid radicals. Water with less than 1 part per million of dissolved solids can be produced.

Refrigeration

Refrigeration will be needed for processes that require temperatures below those that can be economically obtained with cooling water. For temperatures down to around 10 °C chilled water can be used. For lower temperatures, down to -30 °C, salt brines (NaCl and $CaCl_2$) are used to distribute the "refrigeration" round the site from a central refrigeration machine. Vapour compression machines are normally used.

Compressed air

Compressed air will be needed for general use, and for the pneumatic controllers that are usually used for chemical process plant control. Air is normally distributed at a mains pressure of 6 bar (100 psig). Rotary and reciprocating single-stage or two-stage compressors are used. Instrument air must be dry and clean (free from oil).

Inert gases

Where large quantities of inert gas are required for the inert blanketing of tanks and for purging (see Chapter 9) this will usually be supplied from a central facility. Nitrogen is normally used, and is manufactured on site in an air liquefaction plant, or purchased as liquid in tankers.

Effluent disposal

Facilities will be required at all sites for the disposal of waste materials without creating a public nuisance; see Section waste management.

ENVIRONMENTAL CONSIDERATIONS

All individuals and companies have a duty of care to their neighbours, and to the environment in general. In the United Kingdom this is embodied in the Common Law. In addition to this moral duty, stringent controls over the environment are being introduced in the United Kingdom, the European Union, the United States, and in other industrialised countries and developing countries.

Vigilance is required in both the design and operation of process plant to ensure that legal standards are met and that no harm is done to the environment.

Consideration must be given to:

1. All emissions to land, air, water.
2. Waste management.
3. Smells.
4. Noise.
5. The visual impact.
6. Any other nuisances.
7. The environmental friendliness of the products.

Waste management

Waste arises mainly as byproducts or unused reactants from the process, or as offspecification product produced through mis-operation. There will also be fugitive emissions from leaking seals and flanges, and inadvertent spills and discharges through mis-operation. In emergency situations, material may be discharged to the atmosphere through vents normally protected by bursting discs and relief values.

The designer must consider all possible sources of pollution and, where practicable, select processes that will eliminate or reduce (minimise) waste generation. The Institution of Chemical Engineers has published a guide to waste minimisation, IChemE (1997).

Unused reactants can be recycled and off-specification product reprocessed. Integrated processes can be selected: the waste from one process becoming the raw material for another. For example, the otherwise waste hydrogen chloride produced in a chlorination process can be used for chlorination using a different reaction; as in the balanced, chlorination-oxyhydrochlorination process for vinyl chloride production. It may be possible to sell waste to another company, for use as raw material in their manufacturing processes. For example, the use of off-specification and recycled plastics in the production of lower grade products, such as the ubiquitous black plastics bucket.

Processes and equipment should be designed to reduce the chances of mis-operation; by providing tight control systems, alarms and interlocks. Sample points, process equipment drains, and pumps should be sited so that any leaks flow into the plant effluent collection system, not directly to sewers. Hold-up systems, tanks and ponds, should be provided to retain spills for treatment. Flanged joints should be kept to the minimum needed for the assembly and maintenance of equipment.

When waste is produced, processes must be incorporated in the design for its treatment and safe disposal. The following techniques can be considered:

1. Dilution and dispersion.
2. Discharge to foul water sewer (with the agreement of the appropriate authority).
3. Physical treatments: scrubbing, settling, absorption and adsorption.
4. Chemical treatment: precipitation (for example, of heavy metals), neutralisation.
5. Biological treatment: activated sludge and other processes.
6. Incineration on land, or at sea.
7. Landfill at controlled sites.
8. Sea dumping (now subject to tight international control).

A British Standard has been published to assist with the management of waste systems, BS EN ISO 14401 (1996).

The sources of air pollution and their control are covered in several books: Walk (1997), Heumann (1997), Davies (2000), and Cooper and Ally (2002).

Gaseous wastes

Gaseous effluents which contain toxic or noxious substances will need treatment before discharge into the atmosphere. The practice of relying on dispersion from tall stacks is seldom entirely satisfactory. Witness the problems with acid rain in Scandinavian countries attributed to discharges from power stations in the United Kingdom. Gaseous pollutants can be removed by absorption or adsorption. Finely dispersed solids can be removed by scrubbing, or using electrostatic precipitators; see Chapter 10. Flammable gases can be burnt. The subject of air pollution is covered by Strauss and Mainwarring (1984).

Liquid wastes

The waste liquids from a chemical process, other than aqueous effluent, will usually be flammable and can be disposed of by burning in suitably designed incinerators. Care must be taken to ensure that the temperatures attained in the incinerator are high enough to completely destroy any harmful compounds that may be formed; such as the possible formation of dioxins when burning chlorinated compounds. The gases leaving an incinerator may be scrubbed, and acid gases neutralised. A typical incinerator for burning gaseous or liquid wastes is shown in Chapter 3, Figure 3.16. The design of incinerators for hazardous waste and the problems inherent in the disposal of waste by incineration are discussed by Butcher (1990) and Baker-Counsell (1987).

In the past, small quantities of liquid waste, in drums, has been disposed of by dumping at sea or in land-fill sites. This is not an environmentally acceptable method and is now subject to stringent controls.

Solid wastes

Solid waste can be burnt in suitable incinerators or disposed by burial at licensed land-fill sites. As for liquid wastes, the dumping of toxic solid waste at sea is now not acceptable.

Aqueous wastes

The principal factors which determine the nature of an aqueous industrial effluent and on which strict controls will be placed by the responsible authority are:

1. pH.
2. Suspended solids.
3. Toxicity.
4. Biological oxygen demand.

The pH can be adjusted by the addition of acid or alkali. Lime is frequently used to neutralise acidic effluents.

Suspended solids can be removed by settling, using clarifiers (see Chapter 10). For some effluents it will be possible to reduce the toxicity to acceptable levels by dilution. Other effluents will need chemical treatment.

The oxygen concentration in a water course must be maintained at a level sufficient to support aquatic life. For this reason, the biological oxygen demand of an effluent is of utmost importance. It is measured by a standard test: the BOD5 (five-day biological oxygen demand). This test measures the quantity of oxygen which a given volume of the effluent (when diluted with water containing suitable bacteria, essential inorganic salts, and saturated with oxygen) will absorb in 5 days, at a constant temperature of 20 °C. The results are reported as parts of oxygen absorbed per million parts effluent (ppm). The BOD5 test is a rough measure of the strength of the effluent: the organic matter present. It does not measure the total oxygen demand, as any nitrogen compounds present will not be completely oxidised in 5 days. The Ultimate Oxygen Demand (UOD) can be determined by conducting the test over a longer period, up to 90 days. If the chemical composition of the effluent is known, or can be predicted from the process flow-sheet, the UOD can be estimated by assuming complete oxidation of the carbon present to carbon dioxide, and the nitrogen present to nitrate:

$$UOD = 2.67C + 4.57N$$

where C and N are the concentrations of carbon and nitrogen in ppm.

Activated sludge processes are frequently used to reduce the biological oxygen demand of an aqueous effluent before discharge.

A full discussion of aqueous effluent treatment is given by Eckenfelder et al. (1985); see also Eckenfelder (1999).

Where waste water is discharged into the sewers with the agreement of the local water authorities, a charge will normally be made according to the BOD value, and any treatment required. Where treated effluent is discharged to water courses, with the agreement of the appropriate regulatory authority, the BOD5 limit will typically be set at 20 ppm.

Noise

Noise can cause a serious nuisance in the neighbourhood of a process plant. Care needs to be taken when selecting and specifying equipment such as compressors, air-cooler fans, induced and forced draught fans for furnaces, and other noisy plant. Excessive noise can also be generated when venting through steam and other relief valves, and from flare stacks. Such equipment should be fitted with silencers. Vendors' specifications should be checked to ensure that equipment complies with statutory noise levels; both for the protection of employees (see Chapter 9), as well as for noise pollution considerations. Noisy equipment should, as far as practicable, be sited well away from the site boundary. Earth banks and screens of trees can be used to reduce the noise level perceived outside the site.

Visual impact

The appearance of the plant should be considered at the design stage. Few people object to the fairyland appearance of a process plant illuminated at night, but it is a different scene in daylight. There is little that can be done to change the appearance of a modern style plant, where most of the equipment and piping will be outside and in full view, but some steps can be taken to minimise the visual impact. Large equipment, such as storage tanks, can be painted to blend in with, or even contrast with, the surroundings. Landscaping and screening by belts of trees can also help improve the overall appearance of the site.

Legislation

It is not feasible to review the growing body of legislation covering environmental control in this short chapter.

Stricter legislation and tighter control of discharges into the environment are being introduced in most countries. The specialist texts brought out by publishers catering for management topics, and by the government departments, should be consulted for up-to-date information on environmental legislation.

Legislation and control procedures in the United Kingdom are increasingly being derived from regulations promulgated by the European Union (EU).

Kiely (1996) gives a comprehensive summary of EU and US environmental legislation.

All the legislation embodies the concept of Best Practicable Means (BPM). This requires the designer to use the most appropriate treatment to comply with the regulation, whilst taking into account: local conditions, current technology and cost. The concept of BPM also applies to the installation, maintenance and operation of the plant.

Environmental auditing

An environmental audit is a systematic examination of how a business operation affects the environment. It will include all emissions to air, land, and water; and cover the legal constraints, the effect on community, the landscape, and the ecology. Products will be considered, as well as processes.

When applied at the design stage of a new development it is more correctly called an *environmental impact assessment*.

The aim of the audit or assessment is to:

1. Identify environmental problems associated with manufacturing process and the use of the products, before they become liabilities.
2. To develop standards for good working practices.
3. To provide a basis for company policy.
4. To ensure compliance with environmental legislation.
5. To satisfy requirements of insurers.
6. To be seen to be concerned with environmental questions: important for public relations.
7. To minimise the production of waste: an economic factor.

Environmental auditing is discussed by Grayson (1992). His booklet is a good source of references for commentary on the subject, and to government bulletins.