NON-DUST ATMOSPHERIC EMISSIONS FROM MINING PROCESSES

Contents

Case Studies

The Sustainable Minerals partnership is seeking case studies which demonstrate how best environmental practice can be applied in diverse environments across Australia, while allowing operational flexibility for specific sites. Case studies should present:

- Basic principals, guidance and advice;
- Case studies from leading Australian companies; and
- Useful references and checklists.

Introduction

Best practice environmental management is an evolving discipline. As new problems emerge and new solutions are developed, or better solutions are devised for existing problems, it is important that best practice be flexible in devising solutions that match site-specific requirements. Although there are underpinning principles, best practice is more an approach and an attitude than a fixed set of practices or a particular technology.

For example, in Australia in 1972 best practice for controlling motor vehicle emissions was to recirculate crankcase gases into the carburettor inlet and to reduce evaporative losses from the fuel system. In 1986 best practice involved these measures and the use of unleaded fuel and catalytic converters in exhaust systems, computer controlled fuel injection and ignition systems, more aerodynamic shapes for vehicles, more efficient radial tyres, the use of lightweight material, more efficient engine cooling systems etc. Today best practice means using hybrid engines and a host of other devices to improve efficiency and reduce harmful emissions and tomorrow it will possibly mean using fuel cells and electric motors.

What is best practice technology today is unlikely to be best practice tomorrow, but the underlying principles of pursuing energy efficiency, minimising waste production

and capturing, treating and recycling residual waste streams and finding productive uses for waste[1] streams are durable principles that underpin best practice environmental management.

Thus a booklet on best practice is on firmer grounds discussing the underlying principles, approaches and attitudes than discussing particular technologies, but it also needs to deal with concrete problems so that readers can implement practical measures for today and so that theoretical concepts can be illustrated by examples. This booklet will use case studies to provide concrete illustrations of best practice. We are seeking new case studies and, if your operation wishes to showcase elements of best practice in managing atmospheric emissions, please contact us.

There is a further stage to best practice, which in the case of the motor vehicle example, would involve exploring the need for motor vehicles at all or reviewing the structure of cities to reduce the need to travel by car etc. Although this booklet acknowledges these important general principles, its main focus is on more practical matters.

Mining and minerals processing have been an important part of the Australian economy since European settlement. In 2000-2001, the value of Australia's mineral and petroleum exports was $A 55.5 billion, amounting to 47% of merchandised exports. Direct contributions to Gross Domestic Product have been about 9% for the past decade. For some pollutants such as sulphur dioxide the minerals processing industry is the largest source of emissions and although many of these emissions occur in remote areas the application of best practice controls in the minerals processing industries is an important part of Australia's air quality management.

In each stage of mining, from exploration to ore recovery to downstream processing, there is the potential for air quality impacts. However, in the exploration and ore recovery stages the principal concerns are in controlling dust and in maintaining safe air quality in underground mines. These issues are dealt with in other booklets - see for example Dust Control Environment Australia (1998).

The focus of this booklet is on impacts associated with non-dust emissions arising from processing minerals. Because of the wide range of processing methods, the potential impacts cover a very broad range and it is useful to examine these and attempt to develop a generic description of the processes that are used. Minerals are dispersed throughout the Earth's crust and most minerals processing involves concentrating the minerals and processing them so that a pure or near pure element can be extracted.

The first step is to find concentrated forms of the mineral where natural processes have done part of the work involved in concentrating the desired material. The next stage usually involves crushing and grinding of the ore to provide a large surface area so the ore can be further processed to yet more concentrated forms containing the mineral, and allow the valuable component to be separated from the waste.

The final stages involve many different processes including extraction by leaching (chemically dissolving material from concentrate), by roasting to drive off chemically bound combustible material such as sulphur, by chemical reduction as is the case with

iron-ore, or by electrolytic reduction such as used in the production of aluminium. Each of these processing steps brings a potential air pollution problem. Examples are emissions of radioactive gases and particles in the processing of uranium ore and mineral sands, release of odorous gases during the concentration of ores using sodium ethyl xanthate, release of acid gases when sulphide ores are roasted to remove the unwanted sulphur from the concentrate, release of hydrogen sulphide and other acid gases when bricks are heated in kilns, or when aluminium is reduced.

The industries considered in this booklet are all found in Australia. They include industries producing aluminium, lead, zinc, copper, iron, uranium, mineral sands, superphosphate and brick and clay products. However, more importantly they present solutions to the management of pollution that are relevant for other industries. For example acid plants are used to control emissions of sulphur dioxide for many processes, not simply those for which the examples are developed.

What is clean air?

The major constituents

The earth's atmosphere has evolved over geological time to its present composition, which, excluding water vapour, comprises a mixture of gases; approximately 78% nitrogen, 21% oxygen and 1% argon. The concentration of water vapour is highly variable but can reach up to 3%. This booklet is mainly concerned about gases present at concentrations much less than 1%.

The importance of trace constituents

With the exception of water vapour, the current proportions of gases are maintained by equilibrium processes which include biogenic and anthropogenic activity as well as geological processes which in many cases are intimately connected with biogenic processes. Scientists estimate that the current level of oxygen in the atmosphere was reached approximately 400 million years ago (Cloud, 1983). As the input and removal rates of the constituent gases change so too does the point at which equilibrium is established. Carbon dioxide is perhaps the most obvious example where this is occurring. Since the industrial revolution, the rate of input of carbon dioxide to the atmosphere has increased. If the input rate were to stabilise at its new higher level a new equilibrium would be established where concentrations would be higher than in the past and at the point where the removal rate matched the rate of input. The same principle applies for all the constituents of the atmosphere.

These gases are transparent to visible light. At sea-level light scattering from particle-free air would allow a theoretical visual range of approximately 320 km (Stern et al., 1984), which is well beyond the distance to horizon for most ground-based observers. Trace contamination can reduce visibility significantly. Small particles will scatter light and reduce visibility. The United States Environmental Protection Agency (US EPA, 1979) estimates that a density of 1 $\mu g/m^3$ of particulate matter in the size range effective for scattering visible light (0.1 to 1 μm) along a sight line will reduce visual range by 30% from 320 km to 224 km and 10 $\mu g/m^3$ will reduce visual range to between 30 and 40 km.

Other pollutants such as nitrogen dioxide absorb light in the visible part of the spectrum particularly at the blue end. In urban areas this can lead to red, brown and yellow haze due to emissions from multiple sources. In other cases discrete plumes containing nitrogen dioxide will appear as brown streaks in the sky. Because of the cumulative effect of light scattering and absorption over long path-lengths, visual effects will often be apparent even when ground-based measurements of pollution indicate quite low levels.

Although this booklet is not about climate change it is interesting to note that the composition of the atmosphere is also important in determining the equilibrium temperature that is established on the planet. Small changes in the minor constituents can give rise to small but significant changes in the equilibrium temperature. One estimate (Seinfeld and Pandis, 1998) is that a doubling of the carbon dioxide concentrations from the pre-industrial revolution level of 0.028% could lead to an increase in average global temperature of 1.5 to 4.5 °C.

Not only do small changes in the composition of the atmosphere have significant effects on visibility and climate, but small changes in the concentrations of other trace gases can have implications for health and the viability of life. For example the World Health Organisation (WHO Fact Sheet No 187, 2000) guideline value for 15-minute exposure to carbon monoxide is $100mg/m^3$ (87 ppm) and the 10-minute exposure guideline for sulphur dioxide is $0.5mg/m^3$ (0.175 ppm). These exposure levels are acceptable, but concentrations at ten times these levels are not.

Thus clean air is best defined by quantifying the trace levels of harmful polluting gases rather than focussing on the major constituents.

From the environmental point of view, the most important property of the atmosphere is that it sustains life and the existing living elements in the environment are adapted to the present composition. Changes, even minute changes, from the present natural composition may have significant consequences. This booklet focuses on managing these minor constituents and keeping their concentrations at the lowest practical levels.

Cleaning the atmosphere

The previous section noted that the composition of most of the constituents of the atmosphere is the result of an equilibrium established between inputs to and losses from the atmosphere. It is instructive to briefly review some of the major processes that remove pollutants from the atmosphere. These cover a wide variety of chemical and physical processes which vary in importance depending on conditions, such as temperature, humidity, intensity of sunlight and the presence of other reactive substances. Atmospheric chemists have developed a substantial body of knowledge that explains many of the processes, but it is reasonable to say that this knowledge is still being developed.

Most pollutants are harmful because they are chemically reactive. They may also be soluble in water. These properties are the main mechanisms for their removal, both in natural and industrial processes, from the atmosphere. The first stage in the processing of pollutant gases in the atmosphere is often the oxidation of the pollutant. For

example, nitrogen oxides may be converted to nitrates and sulphur oxides to sulphates. In some cases this oxidation occurs in reaction with other trace gases that may have been generated by biogenic or anthropogenic processes such as ammonia, in which case the product will be fine particles of ammonium nitrate or ammonium sulphate.

The process of droplet formation in clouds often occurs on a nitrate or sulphate particle. This then becomes part of the droplet and is removed as the droplet falls to the ground. This process is referred to as rainout. Liquid water either in the form of cloud water or raindrops also provides a medium for soluble gases such as nitrogen oxides, sulphur oxides and other gases to dissolve. These gases are thereby removed from the atmosphere.

One of the most important chemical species that assists in the oxidation process is the highly reactive OH- radical. This is a trace constituent of the atmosphere formed via a number of process one of which is by the interaction of short-wave length light (<319 nm) and natural or anthropogenic ozone and water. The OH^- radical does not react with the main constituents of the atmosphere, but will rapidly oxidise other substances. Seinfeld (1998) estimates that the global average concentration of OH^- is 2×10^5 to 10^6 molecules/cm^3. Concentrations vary seasonally and diurnally. Estimated concentrations are:

- Daytime (summer) 5-10 x 10^6 molecules/cm^3
- Daytime (winter) 1-5 x 10^6 molecules/cm^3
- Nighttime < 2 x 10^5 molecules/cm^3.

The OH^- radical is very reactive and operates on almost all pollutants as an atmospheric scavenger oxidising and assisting in the removal of air pollutants.

Reactive gases are also removed from the atmosphere when they are brought into contact with surfaces, such as vegetation, soils, rocks, the surface of lakes and the ocean. This process is referred to as dry deposition.

In summary, pollutants in the atmosphere are removed by a variety of chemical and physical processes. The global average concentrations of pollutants depend on the equilibrium level that is established between the generation and removal mechanisms. Best practice management is generally focussed on minimising the emissions of pollutants, so that local ground-level concentrations are at the lowest possible level and make the smallest contribution to the global average.
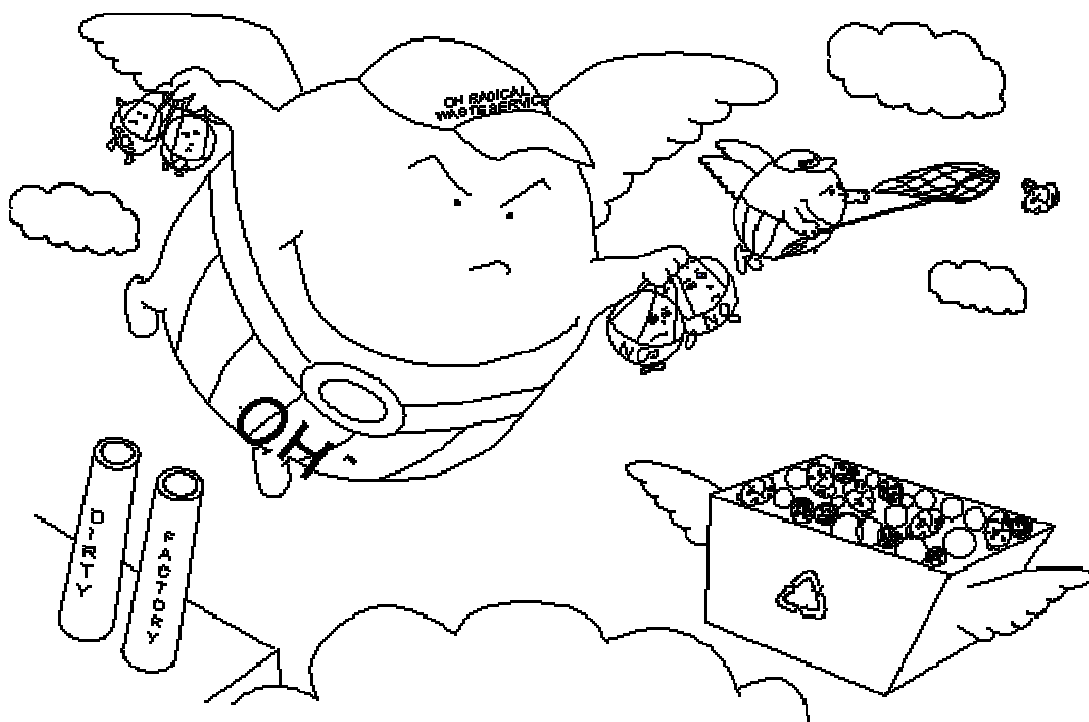
OH⁻ radicals going about their business

The rate of removal depends on the type of pollutant and its local environment. The atmospheric lifetimes of selected pollutants are summarised in Table 1. These should be considered as indicative, rather than precise values. Natural mechanisms for removal of pollutants from the atmosphere cannot be relied upon to maintain a rate of removal which is satisfactory for human and environmental health.

Seinfeld and Pandis (1998) (from which the data in Table 1 were selected) provide a more complete discussion on this topic. The importance of the OH⁻ radical can be seen from the data in the table.

Table 1. Lifetimes and removal mechanisms for selected pollutants		
Pollutant	**Removal mechanism**	**Approximate lifetime**
Criteria Pollutants		
Sulphur dioxide	OH⁻	1 week
Sulphur dioxide	Dry deposition	1 day
Nitrogen oxides	OH⁻	1 to 10 days
Carbon monoxide	OH⁻	1 to 4 months
Selected common hydrocarbons		
n-butane	OH⁻	5.7 days
Methane	OH⁻	10 years
Propene	OH⁻	6.6 days
Benzene	OH⁻	12 days
Toluene	OH⁻	2.4 days

Formaldehyde	OH⁻	1.5 days
Acetaldehyde	OH⁻	11 hours
Acetone	OH⁻	66 days

The most common pollutants

The nature of pollutants

The processing of minerals results in the generation of many different substances, which if present in sufficient concentrations in particular conditions become pollutants. It is important to note that the vast range of activities associated generate an equally broad range of pollutants. This booklet deals with the so-called criteria pollutants sulphur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO) and to a lesser extent with other emissions referred to as air toxics and odour. (Particulate matter is dealt with in the Sustainable Minerals Dust Control booklet). It is useful to briefly discuss the properties of these substances as background material for the following chapters. Much of the information in this section has been taken from WHO publications.

Sulphur dioxide

Sulphur dioxide is perhaps one of the best-known industrial pollutants and is responsible for acid rain. It is a common pollutant from smelting operations and is also a common emission from natural sources such as volcanoes. It is a colourless gas, high concentrations of which can give rise to severe effects in the form of bronchoconstriction and chemical bronchitis and tracheitis as seen in animal experiments and occupational exposures when concentrations exceed 10,000 µg/m³. Concentrations in the range 2,600 to 2,700 µg/m³ give rise to bronchospasm in asthmatics (WHO, 1986). At concentrations of 10,000 µg/m³ sulphur dioxide has a pungent irritating odour and an odour threshold of several thousand mg/m3.

In view of the medical evidence the WHO recommend a ten minute ambient air quality guideline of 350 µg/m³. This level would be expected to protect an exercising asthmatic with a protection factor of two. The protection factor is introduced by WHO to take account of the fact that there may be asthmatics that are more sensitive than those who have participated in the laboratory studies on which the guidelines were developed.

Nitrogen dioxide

There are many species of nitrogen oxides (NO_x) but the form of most interest from the point of view of human health is nitrogen dioxide (NO_2) which forms nitrous or nitric acid in contact with water, for example, when breathed. Nitrogen dioxide is soluble in water. It has a red brown colour and is a strong oxidant. It is formed naturally by bacterial and volcanic action and by lightning. These sources greatly outweigh the quantities generated by anthropogenic activities. However human exposure is caused largely by anthropogenic emissions including, in the case of

mining operations, the combustion of fossil fuels, internal combustion engines and from blasting. In most anthropogenic emissions the primary form of the emission is nitric oxide which accounts for between 5 to 10 percent of the emissions of nitrogen oxides from motor vehicles and from coal burning. Nitric oxide is considerably less toxic to humans than nitrogen dioxide, but depending on conditions, in particular the presence of oxidizing agents such as ozone which is commonly found in urban air, oxidation from NO to NO_2 takes place in a matter of minutes. For example WHO cite a figure of 50% conversion of NO to NO_2 in one minute in the presence of 0.1 ppm ozone.

It should be noted that although nitrogen oxides are formed when nitrogen in a fuel is burnt, it is not necessary for nitrogen to be present in the fuel. At sufficiently high temperatures nitrogen and oxygen in the air will combine to form NO and NO_2. Recent controlled human exposure studies present mixed and conflicting results (WHO, 1987). However there is evidence that at NO_2 levels of 3,760 $\mu g/m^3$ there are clear substantial changes in pulmonary function in normal individuals. Asthmatics appear to be more sensitive.

After evaluating the effects on human health, the WHO recommends 1-hour and 24-hour guidelines of 400 $\mu g/m^3$ and 150 $\mu g/m^3$ respectively.

Carbon monoxide

Carbon monoxide (CO) is a colourless, odourless, tasteless gas which is slightly less dense than air. The affinity of haemoglobin is 200 times greater for carbon monoxide than for oxygen, CO therefore displaces oxygen in humans and interferes with human metabolism. It is arguably one of the most common and widely distributed air pollutants. It is produced as a result of the incomplete combustion of carbon containing materials and is therefore in part a product of poor combustion in mining processes such as blasting. It is also produced by some industrial processes and by biological processes. For human beings exposed to a given concentration of CO, an equilibrium of carboxy haemoglobin is established in which the rate of uptake and rate of metabolism is at equilibrium. In humans this process is well understood and is modelled by the so-called Coburn model. This model has been used by WHO to derive guideline concentrations for various averaging times as follows.

- 15 minutes - 100 mg/m^3
- 30 minutes - 60 mg/m^3
- 1-hour - 30 mg/m^3
- 8-hours - 10 mg/m^3

Hydrogen fluoride

Hydrogen fluoride (HF) is an acid gas with a density approximately 69% of that of dry air. It is formed whenever minerals which contain fluorine are heated to high temperatures and fluorine is released. Fluorine reacts with hydrogen from water vapour and forms hydrogen fluoride. Typical sources of hydrogen fluoride include aluminium smelting and power station combustion. Hydrogen fluoride is generally not considered to be a pollutant harmful to human health at the concentrations typically found in the ambient air however it can be highly toxic to certain types of

plants, in particular, grapes and the uptake of hydrogen fluoride in pastures can have adverse effects on grazing animals. It can also have harmful effects on structures such as the particular glass windscreens of vehicles. The WHO publications do not deal with the health effects of hydrogen fluoride but in Australia various States have set ambient air quality criteria largely for the protection of sensitive vegetation and animals grazing on vegetation where the uptake of hydrogen fluoride can be significant.

Hydrogen chloride

Hydrogen chloride (HCl) is an acid gas produced in a number of industrial processes including brick and clay manufacture. Again, WHO publications do not deal with HCl as an air pollutant however individual Australian States have set limits in the ambient air to protect against adverse effects on human health and nuisance effects resulting from odour.

Air toxics

Air toxics refer to a range of substances including a whole range of hydrocarbons, for example, benzene, polyaromatic hydrocarbons and also metals such as cadmium, lead, mercury, nickel, and so on. The National Pollutant Inventory Substance List shows some important[2] air toxic compounds and ambient air quality criteria, which can be used to assess the potential adverse effects that might arise from exposures to these materials.

Odours

Odours are caused by a large range of substances including some of those noted above for example, sulphur dioxide and hydrogen chloride. They can arise as a result of exposure to pure substances or mixtures of materials. Human beings show a large range of sensitivity to odours and this sensitivity changes with both age and circumstances such as the state of health, pregnancy, etc.

This subjective component to odours makes dealing with and managing odours in a regulatory sense, extremely difficult. Typically odour level is determined in a laboratory by sampling the gas containing the odour and presenting successive samples of the gas diluted with increasing volumes of pure odour free air to a panel of individuals referred to as an odour panel. An odour threshold is determined as the point where the odour becomes undetectable. The odour level for a sample of gas is typically defined as the number of dilutions at which 50% of the odour panel are unable to detect the odour. Thus, odour is quantified in terms of odour units and the odour unit of a sample is the number of dilutions required to reach a point where 50% of the panel cannot detect the odour. There are a number of subtle definitions of odour level and, on occasions, the odour level will be defined in terms of an odour detection level or an odour recognition level. The odour detection level is the point where 50% of the panel are unable to detect the presence of an odour whereas the odour recognition level is the point where 50% of the panel are unable to recognise the odour.

Typically, Australian regulatory agencies define an acceptable level of odour as a value between 2 and 7 odour units depending on circumstances. In practice, 2 odour units is unlikely to give rise to a noticeable odour in the normal environment although it is of course easily measured in laboratory conditions in the absence of interfering background odours.

The Australian regulatory environment

The federal system of government that operates in Australia means that the regulatory environment is different for each state and territory (which will hereafter be referred to as jurisdictions). In recent years agreements made between the Commonwealth Government and the States and Territories have resulted in harmonisation of many of the key aspects of the regulatory environment. In particular the standards for ambient air quality, at least for the criteria pollutants (CO, SO_2, O_3, PM_{10} and Pb), are now broadly consistent with the air quality standards contained within the National Environment Protection Measures (NEPM). Rather than provide a detailed discussion on the way that each jurisdiction manages air quality, this section will focus on the national goals and the general principals that are common to each jurisdiction.

Most legislation and standards apply to either ambient (surrounding or diffuse) levels of a pollutant or point-source emissions. This distinction, which may apply to levels in aquatic or gaseous media, should be clear in any emissions strategy.

In the past it was possible to capture the essential features of a jurisdiction's air quality requirements for a facility by reference to the relevant clean air act and its regulations which would invariably specify various concentration limits for particular pollutants and type of plant. These emissions limits referred to concentrations measured within the stack before the emission was released to the atmosphere. While emission limits are still retained in the regulations applied by most jurisdictions, they are often no longer the determining factor in the design of a plant and its air pollution controls.

Further it is increasingly common for consent authorities, other than the environmental regulatory agency, to impose additional air quality objectives on a plant. For example these objectives might specify that a certain ambient concentration of SO_2 averaged over ten minutes should not be exceeded more than a certain number of times in year. In practice it has always been difficult to prosecute a licensed emission source on the basis of exceeding an ambient air quality limit because it is so difficult to determine the contribution that emission made to the ambient air. Thus stack emission limits (either specified as concentrations (g/m^3) or a loads (g/s)) remain a fundamental part of air quality regulation.

Side Panel 1: References for air quality regulations for Australian States and Territories

Australian Capital Territory
"Environment Protection Act 1997"

New South Wales
"Approved Methods and Guidance: For the Modelling and Assessment of Air Pollutants in NSW"
"Technical Notes: Assessment and Management of Odour from Stationary Sources of in NSW"
"Action for Air – The NSW Government's 25-Year Air Quality Management Plan"

Northern Territory
"Environmental Assessment Act 1994"
"Waste Management and Pollution Control Act and Regs 2002"
"National Environment Protection Council (Northern Territory) Act 1999"
"Environmental Offences and Penalties Act 1997"
"Ozone Protection Act 1996"

Queensland
"Environmental Protection (Air) Policy 1997"

South Australia
"Air Quality Impact Assessment" EPA Technical Bulletin TB No. 26 February 2002. Includes approaches for all classes of pollutants including odour.

Tasmania
"Environment Protection Policy (Air Quality) and Regulatory Impact Statement"

Victoria
"State Environment Protection Policy (Ambient Air Quality)"
"State Environment Protection Policy (Air Quality Management)"

Western Australia
"Odour Methodology Guideline"

To obtain a more complete understanding of the regulations that apply in each jurisdiction the reader is referred to the publications listed in Side Panel 1.

Emissions limits

Historically, emission limits were set to ensure that each industry and process technology was operated in an appropriate and efficient manner. For example, the concentration of sulphur oxides in an acid plant was limited to 7.2 g/Nm^3 or the concentration of particulate matter (PM) in a boiler manufactured after a nominated date was less than 250 mg/Nm^3. The concentration limits would be used with a simple dispersion calculation which would take account of the size of the plant to design a stack that would ensure that reasonable ground-level concentrations were achieved. The concentration limits were set at levels that were practically achievable for the technologies that were available at the time.

More recently it is has become common for emission limits to be set in a different form and at effectively lower levels. This has been done by negotiation between project proponents and the regulatory agency. The negotiation will often use computer-based dispersion models to verify, within the limits of accuracy of the

model, that the emissions will achieve compliance with a particular concentration goal in the ambient air. This goal will usually be set taking into account the existing background pollution level.

The concentration of an emission in the ambient air depends on the mass emission rate of the pollutant, that is, the number of grams per second emitted and not simply the concentration. This means that licence limits will often also specify the volume and concentration of the emission per unit time. Thus the concentration of the pollutant in the stack and the volume of the emission are set to a level that is predicted by dispersion modelling to result in compliance with a specified ambient air quality limit.

Ambient standards

Ambient air quality standards in Australia are set nationally as part of the National Environment Protection Measures (NEPMs) and by individual jurisdictions harmonising their ambient goals with the national standards. Individual jurisdictions may specify goals for additional pollutants not covered by the Air NEPM standards, or may specify more stringent goals than apply in the NEPM. However, since jurisdictions are required to report exceedances of the Air NEPMs, they cannot set ambient air quality goals that are less stringent than the Air NEPMs.

Table 2. Australian Air NEPMs (Ambient Air Quality Standards)			
Pollutant	Averaging period	Maximum concentration	Goal within 10 years (maximum allowable exceedences)
Carbon monoxide	8 hours	9.0 ppm	1 day a year
Nitrogen dioxide	1 hour 1 year	0.12 ppm 0.03 ppm	1 day a year 1 day a year
Photochemical oxidants (as ozone)	1 hour 4 hours	0.10 ppm 0.08 ppm	1 day a year 1 day a year
Sulphur dioxide	1 hour 1 day 1 year	0.20 ppm 0.08 ppm 0.02 ppm	1 day a year 1 day a year none
Lead	1 year	0.05 $\mu g/m^3$	None
Particles are PM_{10}	1 day	50 $\mu g/m^3$	5 days a year

Substances not covered by standards

The pollutants listed in Table 2 are known as the criteria pollutants. They are the most common air pollutants. The standards in the table are all based on the protection of human health. However there are many other substances that have the potential to affect air quality and indeed other ways in which the criteria pollutants can affect the environment. For example particulate matter can affect visibility and, depending on the sizes of the particles and the way in which they are distributed along a line of sight, can do so at concentrations lower than the 50 $\mu g/m^3$ set in the table. For this reason jurisdictions often set additional standards.

Data on appropriate ambient air quality limits for other substances can be obtained from the Victorian EPA SEPP (Air quality Management) (Victorian EPA, 2000) and a very comprehensive list of nearly 2000 air toxics and appropriate short-term exposure standards is provided by the Texas Air Control Board. These are referred to as Effects Screening Levels (ESLs) and are available in the form of a downloadable Excel.

Control technologies

This section deals with the capture and treatment of pollutants however before these are considered the first approach in attempting to deal with any air pollution problem is to ascertain whether or not generation of the pollutant is an essential part of the industrial process being undertaken. That is, the first question that needs to be asked is "can the waste generation be minimised or eliminated, or can the waste be converted to a useful product?" This can be done by selecting alternative processes, by choosing appropriate fuels, or using different feed stocks. For example, sulphur dioxide emissions can be eliminated by using a fuel which is largely free of sulphur, such as natural gas rather than oil or coal. Once it has been ascertained that generating the emission cannot be avoided, then the pollutant has to be captured and treated. Even at this stage it may still be possible to produce a useful outcome. For example sulphur dioxide can be converted to sulphuric acid which in turn can be used as major feedstock for fertiliser manufacture.

In some cases capturing the pollutant is a trivial exercise. For mineral processing that takes place in an enclosed chamber, it is straightforward to capture and duct the air pollutants to the treatment device. However, in many cases pollutants escape or are not completely contained during all phases of a process. These are referred to as fugitive emissions. They can occur for example when material is added or removed from the processing chamber, such as a blast furnace. A brief review of hood design is provided here to deal with this issue.

Capturing pollution

An important part of pollution control is capturing the pollutant so that it can be treated and the residual emissions disposed in away that allows it to disperse effectively. If the process can be totally enclosed then the problem of capture is greatly simplified, but often this is not possible and a local ventilation system needs to be employed. Goodfellow (1992) provides a detailed discussion of the factors that need to be considered in designing capture hoods (Table 3).

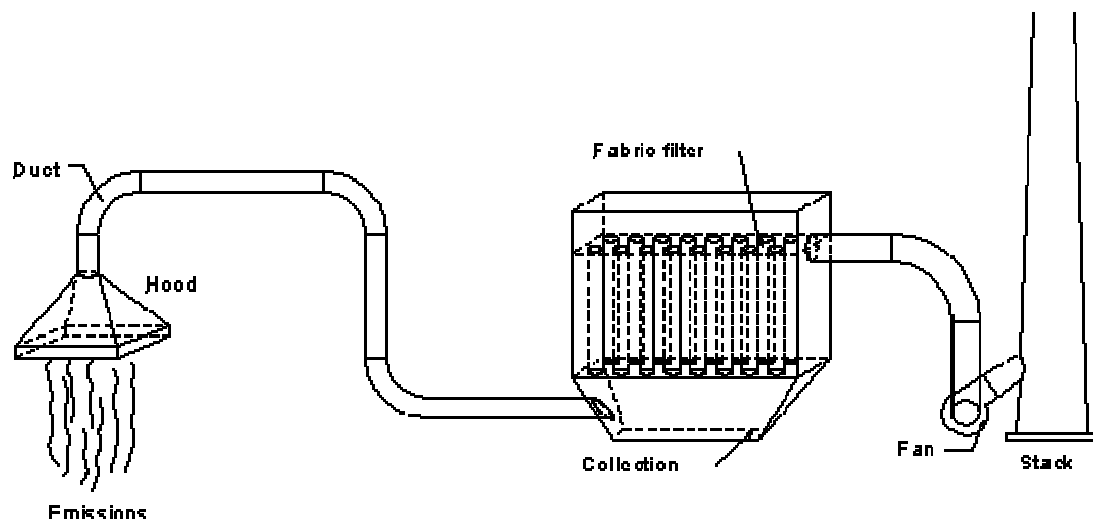Figure 1 illustrates a typical arrangement. Recommended hood and duct velocities suggested by Goodfellow (1992).

Figure 1. Typical local ventilation system

Table 3. Design parameters for local ventilation systems

System	Hood velocity	Duct velocity
Capturing vapour	10.2 m/s	12.7 m/s
Capturing fume	10.2 - 20.4 m/s	10.2 - 20.4 m/s

The best practice principles to be followed in the design are:

- Capture the contaminant at source if possible
- Provide adequate but not excessive capture velocity
- Use a flow design that minimises pressure losses
- Ensure that fans are able to provide the correct flow for all operating modes

Local ventilation systems are much more desirable than general ventilation systems. They can provide a much greater level of contaminant control, the volume of air that must be exhausted is much lower, the contaminant concentrations are much higher making it more economical to apply treatment systems and the performance is not affected by cross drafts or changing ambient winds.

Treating pollutants

Once the pollutant has been captured there are four principal control technologies which are traditionally considered for gaseous pollutants. They are:

- Absorption
- Adsorption
- Condensation
- Incineration

There are a number of criteria that can be used when selecting the type of technology appropriate for removing or treating a particular type of pollutant. Usually a common-sense evaluation of the chemical properties of the pollutant will identify which is the

appropriate treatment process. For example, sulphur dioxide can clearly not be treated by incineration and treatment by incineration is limited to those substances which are combustible or can be chemically broken down at high temperatures. Typical examples of such substances are the different types of hydrocarbons. These are generated for example during the use of hydrocarbons as solvents or in coating operations.

The remainder of this section will discuss the general principles associated with each of the four classes of treatment identified above.

Absorption

A critical component of absorption treatment systems is that the pollutant gas or mixture of gases must be brought into close contact with a liquid or solid into which the gases are to be absorbed. This is done by passing the gas stream through a packed column. Figure 2 represents schematically how this is typically done. A vessel containing plastic or some inert packing material over which the absorption liquid is trickled ensures that the incoming gas stream passes through the packed column and has plenty of opportunity to be absorbed by the fluid.
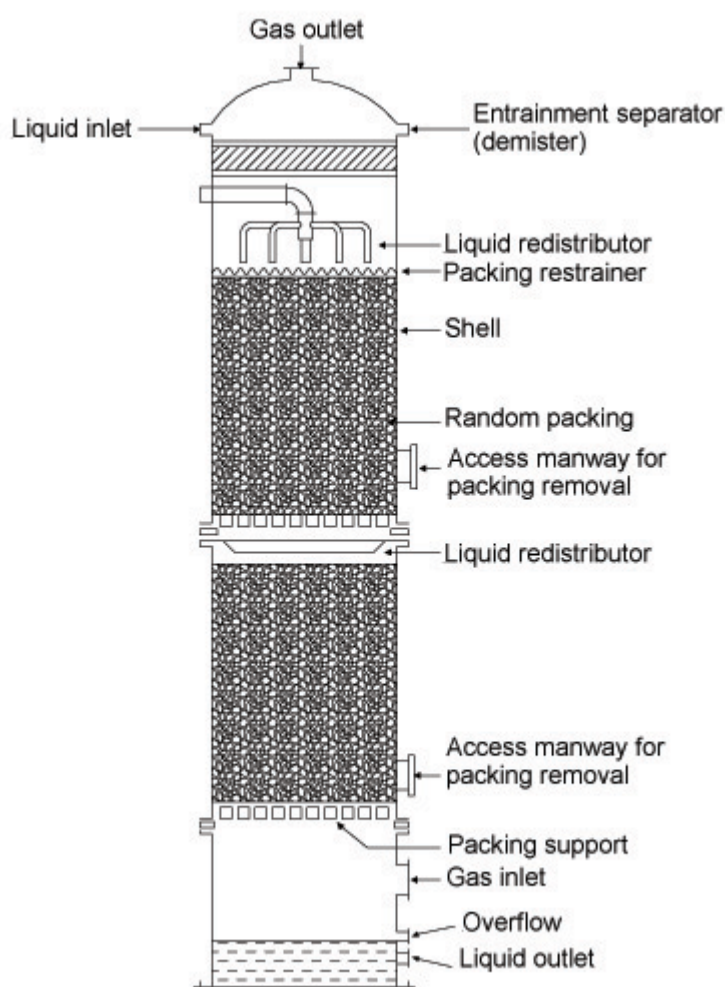
Figure 2. Schematic drawing of packed tower

The rate at which the soluble constituents of the gas are taken into the liquid phase is determined by diffusion at the gas/liquid interface. Molecules which are brought into contact with the solvent are removed however those molecules which remain within the gas part of the system cannot be removed until they come into contact with the solvent. Thus, the rate at which removal takes place depends on the diffusion coefficient of the polluting gas and the distance over which it has to diffuse. Hence the system needs to allow the gas to be in as close contact as is feasible with the solvent.

As the solvent becomes increasingly loaded with the gas that needs to be removed, so the diffusion out of the solvent back into the polluting gas stream becomes greater and with a saturated solvent the removal process becomes ineffective. Therefore the solvent needs to be continually recharged or replenished.

The factors that need to be considered in this type of air cleaning system are as follows.

- The type of solvent to be used
- The mass and energy considerations
- The size of the column
- The column height and the number of plates
- The pressure drop that will occur through the column

Other factors that need to be considered include how the spent solvent is either recharged or disposed of, the toxicity and volatility of the solvent, the cost of the solvent, its viscosity, its chemical stability and its freezing point.

Intimate contact between the pollutant gas to be removed and the solvent can be achieved using other technologies including spray systems which allow the pollutant gas to fall through a fine mist or droplets of the solvent. In this way a large surface area is available for absorption or alternatively a venturi-type scrubber can be employed whereby the gas stream is forced through a narrow orifice with the solvent at high pressure and high velocity.

The efficiency of such systems would typically range between 60 and 99.99% depending on the design of the scrubbing system, in particular its size and the solubility of the pollutant gas in the solvent. These types of systems are very attractive for scrubbing various soluble gases such as hydrogen chloride and ammonia which are extremely soluble in water.

Adsorption

The same principles that apply in absorption are at play in adsorption. The molecules or ions which comprise a solid experience unbalanced electrostatic forces at the surface. The forces on molecules or ions deep within material are generally in balance with forces provided by other neighbouring atoms, molecules or ions. However at the surface there is an imbalance and this allows surfaces to collect pollutant gases. The forces that cause gases or vapours to be adsorbed onto solid surfaces consist of two types - van der Waals and chemical or activated adsorption. Adsorption occurs when the attractive forces between molecules of the vapour and the solid are greater than

those between the existing gas molecules. This allows the gas to condense on the solid even though its pressure may be lower than the vapour pressure at the prevailing temperature. In this type of adsorption, the gas or vapour essentially wets the solid but does not chemically bond with it. It may penetrate into the crevices and cracks in the solid and the adsorption capability of the solid depends to a large extent on the surface area and the complexity of the surfaces of the solid. The adsorption can occur if the temperature is raised, thus the process is largely reversible.

The second type of adsorption, activated adsorption, is caused by a chemical interaction between the solid and adsorbed substance. Often a significant amount of heat is liberated when this type of adsorption occurs. Usually, substances adsorbed in this process are not easily released. There are a number of widely used adsorbents, the most common of these are activated carbon, activated alumina, silica gel and dehydrated zeolites which are alumina silicates.

Activated carbon is formed by charring carbon containing materials such as nutshells and coal which are heated in the absence of air and are then heated with steam to produce an extremely adsorbent carbon material which is widely used for solvent recovery and removing odours and purifying gases.

Activated alumina is formed from the special heat treatment of native aluminas. Silica gel consists of sodium silicate neutralised with a dilute mineral acid. This is then washed to remove salts produced during the neutralisation reaction. It is then dried and roasted. It is usually available in a granular form although beads are also marketed.

The properties of activated carbon, activated alumina and silicate gel are summarised in Table 4. Usually these materials are expensive and need to be regenerated and reused.

Table 4. Properties of commonly used adsorbent materials

	Activated carbon	Activated alumina	Silica gel
Bulk density	350 - 545 kg/m^3	Granules 610 - 930 kg/m^3 Pellets 870 - 931 kg/m^3	710 - 740 kg/m^3
Heat capacity			
Pore volume	0.56 - 1.20 cm^3/g	0.29 - 0.37 cm^3/g	0.37 cm3/g
Surface area	600 - 1600 m^2/g	210 - 360 m^2/g	750 m^3/g
Average pore diameter	15 to 25 x 10^{-10} m	18 to 48 x 10^{-10} m	22 x 10^{-10} m
Regeneration temperature	100 - 140 °C	200 - 250 °C	120 - 250 °C
Maximum allowable temperature	150 °C	Stable to 500 °C	Stable to 400 °C

Incineration

Incineration systems rely on the fact that almost any organic compounds can be destroyed at high temperatures provided that there is an adequate residence time. In particular, hydrocarbons are readily oxidised to carbon dioxide and water vapour during this type of process. Incineration results in the emission of the products of combustion of the incinerator fuel as well as the products of combustion of the material being treated, thus the output of an incinerator may contain materials which are, in themselves, air pollutants. The basic requirement for an incinerator is that the material being treated needs to reach a sufficiently high temperature, for a sufficiently long period of time in a condition in which it is turbulently mixed so that the entire quantity of material is treated effectively. The higher the temperature, the faster the oxidation process will take place.

Most incinerators operate at temperatures above 650°C which is the minimum temperature required for the thermal destruction of most organic compounds. In designing an incinerator there is usually a trade-off between residence time and temperature according to the following equation:

$$t = v/q$$

where,

t is the residence time in seconds v is the volume of the chamber
q is the volumetric flow rate in the combustion conditions.

Figure 3 shows a schematic diagram of a thermal incinerator. In some cases incinerators may include the use of a catalytic element which enhances the destruction of the material being treated. Figure 4 shows a schematic diagram of a catalytic incinerator.
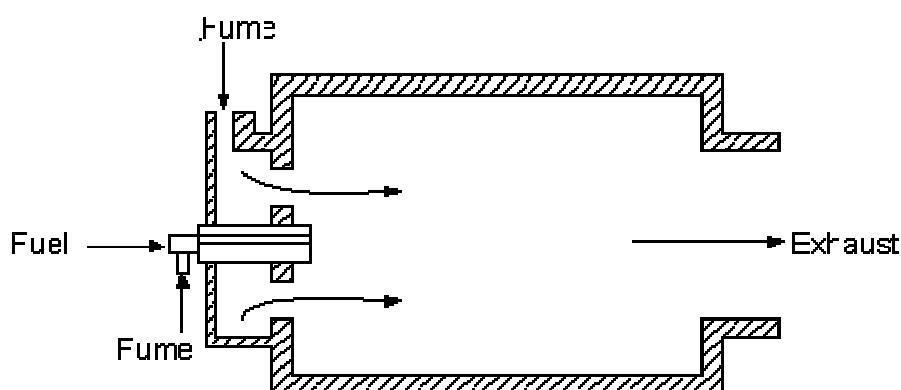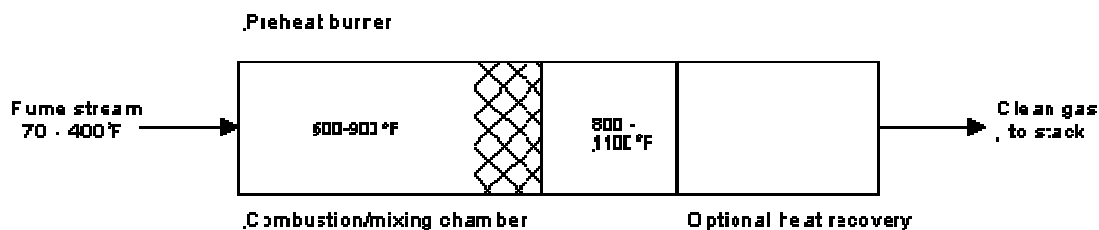

Figure 3. Schematic drawing of thermal incinerator

Figure 4. Schematic drawing of incinerator with catalytic converter

Sulphuric acid plants

Sulphuric acid is a basic feedstock required for a large number of industrial processes. The basic component used in the manufacture of sulphuric acid is sulphur dioxide. This is either created by burning sulphur or very commonly by using "waste" sulphur dioxide from minerals processing operations. This makes it a particularly attractive technology for managing sulphur dioxide because it converts what would otherwise be a potentially harmful waste into a useful product and therefore it is consistent with the best practice principles.

The difficulty with handling sulphur dioxide in this way is that sulphuric acid is cheap and the cost of transport compared with production costs are relatively low which means that markets need to be located close to the sulphuric acid plants. The first stage in manufacturing sulphuric acid is the generation of sulphur dioxide, this is then oxidised to sulphur trioxide and reacted with water to form sulphuric acid. The reaction of sulphur trioxide with water is accomplished by absorbing sulphur trioxide in strong sulphuric acid and then adding the water.

There are two major technologies; the chamber process and the contact process. The contact process is the most widely used approach in Australia. The contact process uses a vanadium based catalyst to oxidise SO_2 to SO_3. Generally in Australia, acid plants attached to minerals processing operations are cold gas plants. The sulphur dioxide gas stream from the smelting or roasting operation is cooled, cleaned and then directed to the contact plant. Frequently the gas cooling system is used to provide energy to a waste heat boiler. Figure 5 shows a flow diagram of a typical single absorption contact sulphuric acid plant.
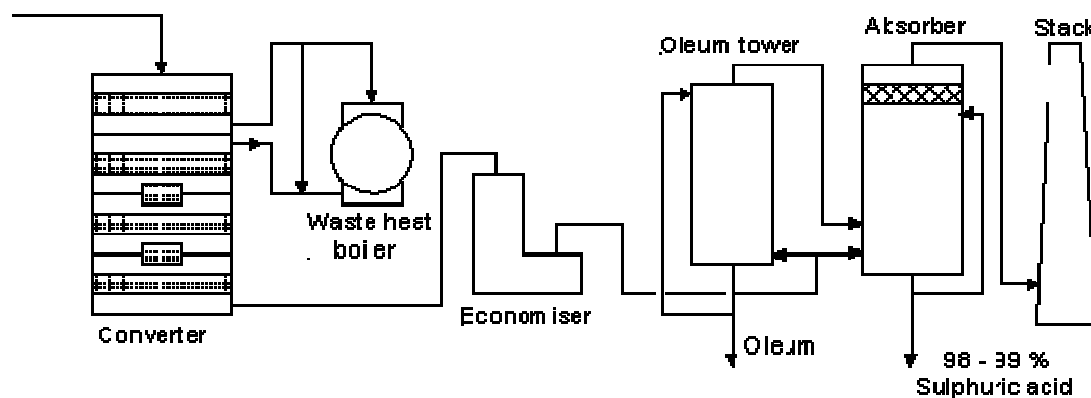

Figure 5. Typical contact sulphuric acid plant

The oxidisation reaction, where sulphur dioxide is converted to sulphur trioxide, is exothermic yielding approximately 41,400 btu/pound (change units). Unlike a combustion reaction, the process is reversible and sulphur dioxide is also formed from decomposition of the sulphur trioxide. Equilibrium is established at a particular temperature when the forward reaction rate is equal to the decomposition reaction rate. To produce additional sulphur trioxide it is necessary to cool the contact plates and a considerable quantity of energy is available from this process which is sufficient to drive a waste heat boiler.

The four factors that affect the effectiveness of the converter are:

- Equilibrium considerations
- The gas strength and temperature
- The minimum temperature required for the catalyst
- The need to keep catalyst mass to a practical size.

These factors mean that a single absorption plant is limited to an efficiency of approximately 98%. While this may seem an impressive capture rate, in many cases it still leaves a significant quantity of sulphur dioxide to be released to the environment. Further, there are start-up and upset operating conditions which can give rise to much higher levels of emission if the catalyst temperatures are not at the operating levels when the gases are introduced.

To achieve a higher conversion rate, a number of plants use a dual absorption (also known as "double absorption" or "double catalyst" or "enter pass absorption plant"). These operate by removing sulphur trioxide from the plant so, although the equilibrium between sulphur dioxide and sulphur trioxide is maintained at the same level, the removal of sulphur trioxide allows the effective conversion efficiency to be increased. Overall conversion efficiencies greater than 99.7% are possible with dual absorption plants.

Single absorption plants can achieve approximately 97.97% conversion efficiency. Dual absorption plants can achieve approximately 99.7% conversion. One factor that needs to be borne in mind when installing an acid plant to reduce sulphur dioxide emissions is that the temperature of an emission from an acid plant is significantly lower than that from untreated roasting or sintering operations. As a result the plume rise from the plant can be lower than without the acid plant and the reduction in ground-level concentrations achieved will not necessarily be in the same ratio as the fraction of captured sulphur dioxide.

In addition, the stack gas leaving an acid plant may contain small amounts of sulphur trioxide and sulphuric acid mist and vapour. The sulphur trioxide reacts rapidly with atmospheric moisture to form sulphuric acid mist adding to the mist which may be directly emitted. These are usually seen as increased opacity in the stack emission and can produce the same environmental hazards as those listed earlier for sulphur dioxide.

There are a number of ways to prevent the emission of mist. One is to maintain the gas temperature at an elevated level to prevent the condensation of the sulphuric acid

and the other is to ensure that moisture levels in the system are kept as low as practical.

In some circumstances it is necessary to reduce sulphur dioxide emissions to even lower levels. In this case tail-gas scrubbing is employed. In some cases scrubbing chemicals are used on a once-through basis and discarded and in other cases regenerative types are used. Three widely used processes are:

- Scrubbing in an absorbing tower with saturated aqueous solution of sodium sulphite and sodium bisulphite.
- Scrubbing in a packed bed counter-current stream with scrubbing solution of sulphuric acid and hydrogen peroxide.
- Scrubbing with ammonia

Typically, sulphur dioxide concentrations in the tail gas from these scrubbing systems is of the order of 200 ppm. In some cases, sulphur trioxide and acid mist must be removed from the tail gas scrubbing plant. This is usually done using packed fibre mist eliminators however these are usually not necessary with a well-operated acid plant.

Using stacks

Once a pollutant emission has been reduced to the minimum practicable level it may still be able to cause environmental harm if released at ground-level. When this is the case, a widely used solution is to ensure that the emission is released in such a way that by the time it reaches ground-level or the point where it first comes into contact with sensitive parts of the environment it is diluted to the point where pollutant concentrations are at safe levels. This section provides a review of the factors that need to be considered when designing a stack.

## Overview of dispersion modelling in designing stacks

The main purpose of a stack is to remove the point of emission from sensitive receptors and to allow the emission to dilute before it reaches sensitive receptors. From this perspective the most important property of a stack is its height. In the past stacks were designed using simple formulae that determined the height of the stack based on the magnitude of the emission. Since the advent of readily available computers in the 1970s these calculations have become integrated into computer programs. These programs take account of nearly all the important factors that determine the ground-level concentrations of emissions from a release. Equations used in this way represent a mathematical model of the physical and in some cases chemical process that the plume will be subjected to once it leaves the stack. The important processes that are simulated by models are:

- Plume rise due to buoyancy and momentum effects
- Transport due to the effects of the wind
- Dispersion due to turbulence
- Enhancement of turbulence due to the effects of obstacles such as buildings and other features

- Chemical transformation which may increase or decrease the concentration of a pollutant

Understanding the way in which these processes work provides us with a framework that will help develop useful ways of dealing with air pollution problems. Many of the things that we will find out are commonsense, but there are subtle issues that if overlooked can lead to embarrassing and expensive problems.

The basic equation used in most regulatory models is the Gaussian dispersion equation. It is illustrated in Side Panel 2, which shows the essential features of the core equation used in the Gaussian computer-based dispersion model. We shall spend a little time briefly reviewing how this equation works.
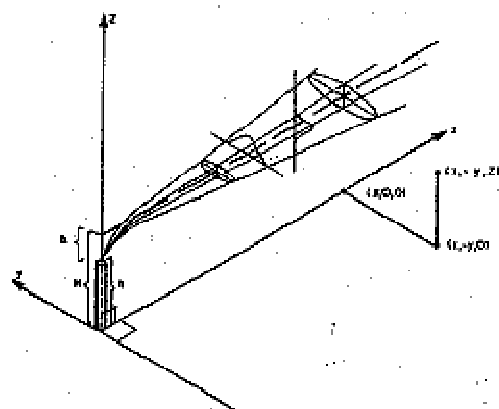
Dispersing plume for Equation 1.

$$\chi = Q \frac{Q}{2\pi\, \sigma_y \sigma_z u} \exp\left[-\frac{y^2}{2\sigma_y^2}\right]\left\{\exp\left[-\frac{(H-z)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(H+z)^2}{2\sigma_z^2}\right]\right\}$$

where,

χ = air pollutant concentration (g/m^3)

Q = emission rate (g/s)

u = wind speed at stack tip (m/s)

σ_y = the standard deviation of concentration in the horizontal (m)

σ_z = the standard deviation of concentration in the vertical (m)

H = the effective height of the plume centreline (m).

Side Panel 2. Dispersing Plume

The effects of meteorology

The most important and most obvious meteorological effect is that the wind blows the emissions in a particular direction. In the upwind direction the pollutant concentration will essentially be zero and to the side the concentration will decrease as we move laterally away from the plume centreline either to the side or up and down. The rate at which the concentration decreases with distance from the plume centreline is calculated in the Gaussian model by assuming that the concentration profile along a line perpendicular to and through the plume centreline can be described by Gaussian functions. The parameters that determine the rate at which the plume concentration decreases with crosswind distance are sy and sz. These are called the horizontal and vertical plume-spread parameters respectively. The larger the values for the plume-spread parameters, the broader and more slowly will the plume concentration change with cross-wind distance. In practice the plume-spread parameters are determined by field studies and empirical equations that best fit the field data. They are functions of downwind distance x and vary for different meteorological conditions.

Standard dispersion conditions

To assist in modelling and describing the rate at which plumes disperse many dispersion models make use of the Pasquill-Gifford scheme in which the dispersive capacity of the atmosphere is classified into six (sometimes seven) stability categories A to F (or G in the case where seven categories are employed). For each category there is an equation, or set of equations, that allow sy and sz to be calculated as functions of downwind distance. The estimates of sy and sz relate to the dimensions of the plume averaged over a specified time. In the original experiments that determined sy and sz the time was not precisely defined, but was in the range 3 to 10 minutes. The most widely used regulatory models interpret the curves as applying to 1-hour averages.

The plume-spread parameters are closely related to the intensity of turbulence that the plume experiences; the greater the turbulence more rapidly will the plume disperse. The main factors that control the level of turbulence are the wind speed and the aerodynamic roughness of the ground and the intensity of convective activity which is usually driven by solar radiation.

The stability category that the atmosphere is in at any particular time can be determined in a number of ways:

- observations of wind speed, cloud cover and the solar elevation
- direct measurements of turbulence[3] (preferable both in the horizontal and vertical)
- measurements of wind speed and temperature gradient.

Side Panel 3 shows one of the most widely used schemes for assigning stability category.

Side Panel 3

Pasquill stability categories using observations of cloud cover and wind speed

Insolation				Night	
Hourly average wind speed(at 10 m)m/s	Strong	Moderate	Slight	Thinly overcast or > 4/8low cloud	< 3/8 cloud
<2	A	A - B	B	G	G
2 - 3	A - B	B	C	E	F
3 - 5	B	B - C	D	D	E
5 - 6	C	C - D	D	D	D
>6	C	D	D	D	D

1. Strong insolation corresponds to sunny midday in midsummer in England; slight insolation to similar conditions in midwinter
2. Night refers to the period from one hour before sunset to one hour after sunrise
3. The neutral category D should also be used, regardless of wind speed, for overcast conditions during the day or night and for any sky condition during the hour preceding, or following night as defined above.

Source: from Pasquill (1961)

Plume-rise and stack-tip downwash

When an emission leaves a stack it will continue to rise because of the momentum and buoyancy it has at the time of its release. This plume-rise increases the effective height of the stack and is therefore an important component in stack design. To properly account for dispersion, computer-based models need to take account of the effects of momentum and buoyancy-rise.

It is also necessary to consider the fact that when the wind blows past a stack a low pressure region develops in the lee of the stack. This can draw the emission downward. The phenomenon is referred to as stack-tip downwash. It can be effectively eliminated by maintaining the efflux velocity (v_e) from the stack at greater than 1.5 times the wind speed (u). Figure 6 illustrates the effects of stack-tip downwash for two v_e/u ratios.
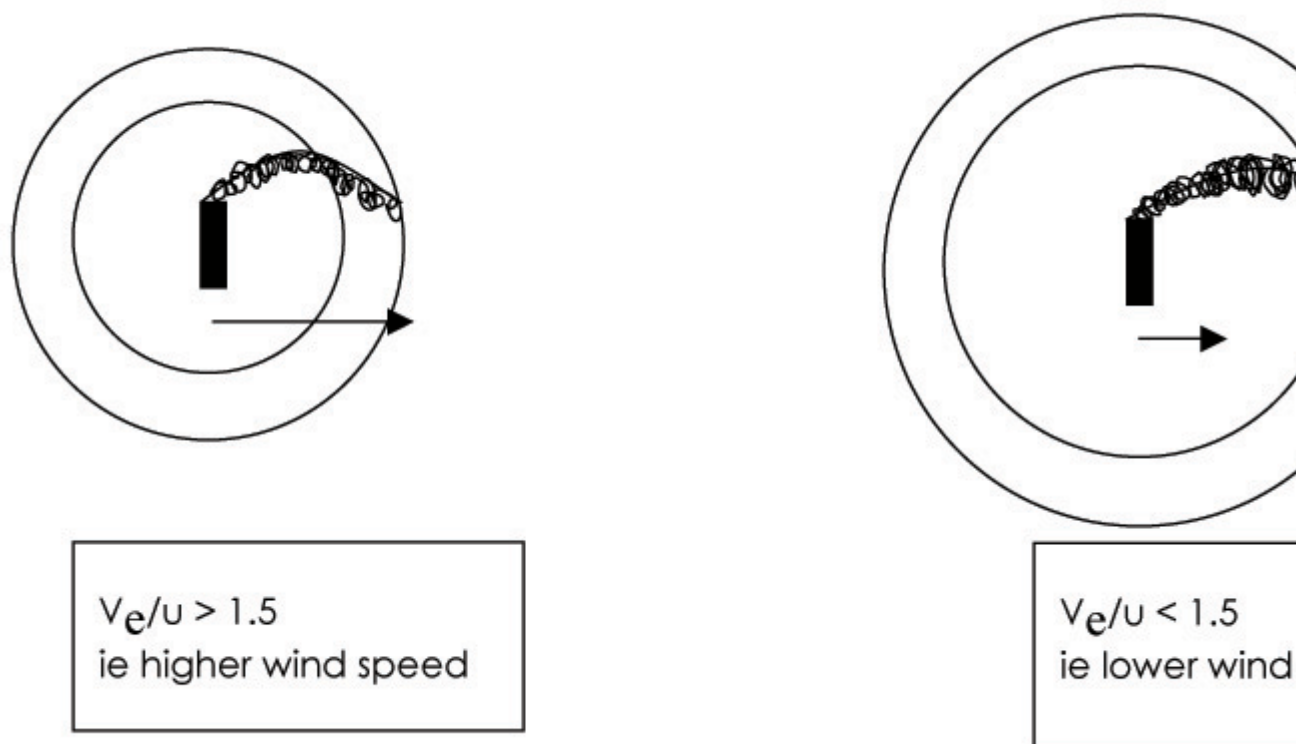
Figure 6. Stack-tip downwash

Best practice requires that efflux velocities be at least 1.5 times the maximum wind speeds expected in an area. In practice this means that exit velocities should be greater than 15 to 20 m/s. Of course if the emissions have been reduced to a negligible level then downwash may not be a problem and this rule can be relaxed.

A number of studies provide a theoretical framework that allows momentum and buoyancy plume rises to be estimated. The most widely used plume rise equations are those developed by Briggs (1975). In this section we will explore the physical processes that are significant in determining plume rise without going into any mathematical detail.

The effects of momentum are lost rapidly as the plume mixes with the ambient air. Nevertheless, the effects of momentum can be extremely important because it allows the plume to rapidly penetrate through the turbulent flow that is associated with wind blowing over buildings. It is important that plumes are not trapped in these areas of enhanced turbulence. It they are they may be entrained into the recirculation zones that apply around buildings (see next section). For this reason regulatory agencies will often specify minimum exit velocities of the order of 15 m/s and minimum stack heights of the order of 4 m above the top of buildings. These rules of thumb are designed to ensure that in most circumstances the plume escapes the intense turbulence that surrounds factory buildings.

Buoyancy plume rise occurs because the plume initially finds itself in an environment where it is warmer than the surrounding air. Negative buoyancy can also occur if the plume is cooler, or more precisely denser, than the surrounding air. The plume can be

thought of as a warm bubble of air sitting in a cooler ambient environment. In most cases the pollutant concentrations, even in quite concentrated plumes, will be relatively low so that the density of the bubble can be considered proportional to its absolute temperature. (In some cases this is not true and the density of the plume material needs to be considered as well as the temperature). The warm bubble will experience an upward buoyancy force which will move the plume material upwards. As it rises two things will happen: it will entrain ambient air and it will expand as the pressure decreases with increasing height. Both of these processes will lead the plume to cool and to approach the temperature of the surrounding air.

It is interesting to examine what would happen to the bubble of air if there were no entrainment of cooler ambient air. As the bubble rises it will expand and the expansion will cause it to cool however dry ambient air will also cool as the pressure decreases and the height increases. In a dry well-mixed atmosphere, the temperature will decrease at approximately 9.8 °C per thousand metres. This is exactly the same rate at which a dry plume will cool due to adiabatic expansion. Therefore theoretically the buoyancy plume rise could continue indefinitely however the entrainment of cooler ambient air will ensure that this is never the case.

Further, there is always an inversion present in the atmosphere. It may be at the tropopause, but more often it will be at much lower altitudes, from a few hundred to a few thousand metres. At night it may extend from the ground upward. These inversions will ultimately halt the rise of even the most buoyant of plumes.

Ground based inversions occur at night when the sky is clear and the winds are moderate to light. As the ground cools by radiating to outer space it chills the air in the immediate surface layer. This cooling effect is transmitted through a depth determined by the effectiveness of turbulence in bringing the warm air from aloft to the ground where is can lose heat. Thus for a given loss of radiation overnight the atmosphere will develop either a strong, but shallow inversion, or a weak deeper inversion. In the presence of an inversion as the plume rises it will cool adiabatically at the rate of 9.8 °C per thousand metres, but the air will increase in temperature and the plume will eventually find itself at a point where its temperature is equal to the ambient temperature. At this height all buoyancy forces will be reduced to 0 °C. The point at which this happens is the plume stabilisation height.

The following bullet points summarise the more important issues raised in the forgoing discussion:

- The higher the exit velocity, the greater momentum plume rise
- The stronger the horizontal wind, the more rapidly will the plume be bent over and both momentum and buoyancy effects reduced
- The hotter the plume and the greater its volume, the higher will be the buoyancy plume rise
- The stronger the inversion, the lower will be the plume stabilisation height

Dispersion during transitional periods

In the morning the atmosphere undergoes a transition as solar heating of the ground causes it to change from its stable nocturnal state to a convectively mixed atmosphere.

This will occur on most days. Very high[4] short-term (ten minute to one or so hours) ground-level concentrations can occur under these conditions. The conventional Gaussian model does simulate these conditions and they need to be dealt with as special calculations. The approach set out by Turner (1994) is often used. This is generally considered a conservative approach. It is based on the following equation,

$$\chi_F = \frac{Q}{\sqrt{2\pi}\, u\, \sigma_{yF}\, h_i}\, \exp\left[-0.5\left(\frac{y}{\sigma_{yF}}\right)^2\right]$$

χ_F = concentration under fumigation conditions,
Q = mass emission rate of pollutant (g/s),
u = wind speed at plume height (m/s),
y = cross wind distance (takes as 0 m),
σ_{yF} = modified plume - spread parameter , and
h_i = plume height (m).

The first step in using the above equation is to determine the height above ground-level at which the plume is residing. A common and conservative approach to doing this is to estimate plume rise under stable dispersion conditions.

Using this approach it is possible to develop a conservative estimate of ground-level concentrations likely to occur under inversion break-up conditions.

Effects of buildings and obstacles

Buildings and other obstacles including the stacks themselves distort the air flow and create turbulence. This additional turbulence is superimposed on the existing turbulence in the incoming wind. The extent of the additional turbulence is generally confined to a height no greater than about 2.5 times the height of the obstacle and extends no further than approximately ten times the obstacle height downwind. However within this region the distribution of turbulence and the distortion of the streamlines are extremely complicated. Figure 7 (from Hosker, 1979) summarises the general features of the flow pattern that is developed as an oncoming wind encounters a sharp edged building.
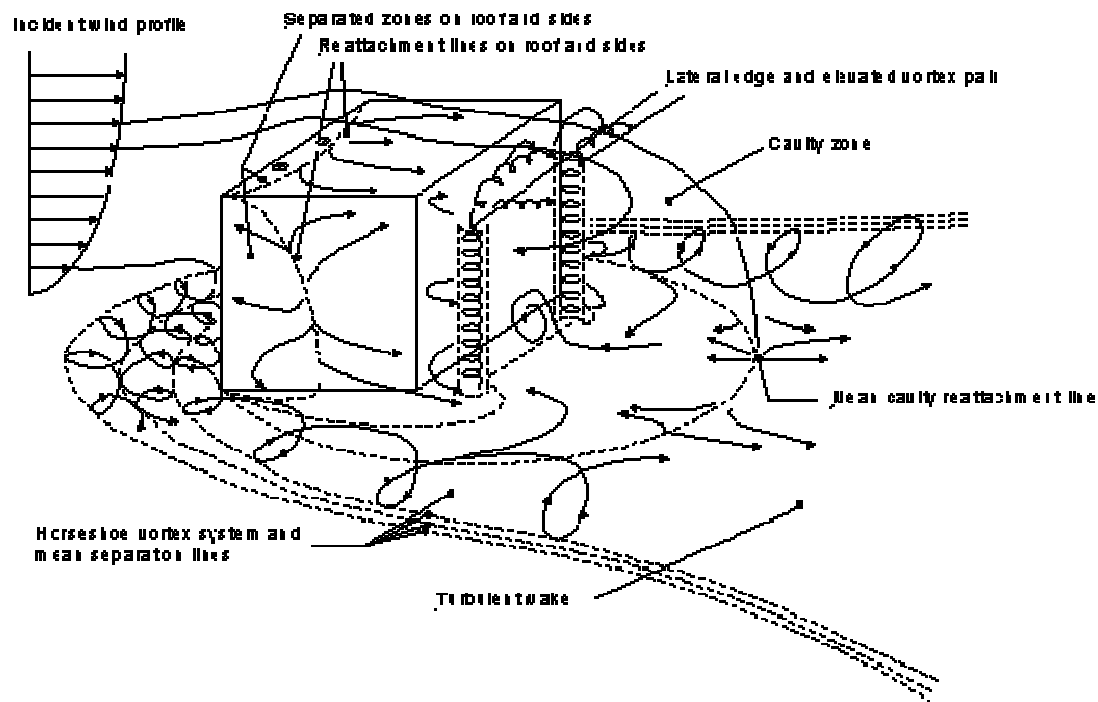
Figure 7. Turbulent flow over a building

On the upstream face of the building there is a stagnation point where the wind speed is effectively zero. This occurs approximately two thirds of the way up the face of the building. At the stagnation point the oncoming wind splits and is either deflected horizontally and goes around the building or is deflected upward and goes over the top of the building. In the lee of the building there is a recirculation zone where the streamlines are deflected downwards and for the lower parts the wind direction is reversed and flows towards the lee-side of the building and then upwards and around in an eddy. This eddy is referred to as the recirculation zone. The recirculation zone typically extends about three times the height of the building downwind. Beyond this zone there is an enhanced region of turbulence which extends to approximately ten times the height of the building downwind. After approximately ten building-heights downwind the turbulence levels begin to approach those of the oncoming airstream.

In any stack design it is important that the emission is able to escape the recirculation zones. Any material which is trapped within the recirculation zones can give rise to very high concentrations locally. An emission that escapes the recirculation zone but is caught in the enhanced region of turbulence downwind of the building, from 3 - 10 building heights downwind, undergoes enhanced dispersion which in some cases can be desirable but in other cases is not.

Stack designers refer to a principal known as "good engineering practice" (GEP), which requires that the height of the stack is set at 2.5 times the height of the nearest influential building. When this is done it is extremely rare for the emission to be trapped in the recirculation zones or significantly influenced by the enhanced turbulence generated by the building.

Most modern Gaussian models are able to take account of these features in a satisfactory way provided the building arrangements are not too complex. If the

building arrangements are complex and screening calculations indicate that significant impacts could occur, the best practice dictates that the problem be assessed using a physical model, that is wind tunnel studies or tank modelling.

Effects of terrain

Terrain effects are those caused by the interaction of the wind and plume with the land. Land forms around industrial sites range from rolling hills to rugged mountains and steep escarpments, hills and cliffs. Plumes interact with these in a complicated way. As the wind carrying a plume blows over a terrain feature the stream lines will respond to the changes in ground. The first question to be answered is will the plume impact on the terrain, will it ride over the obstacle or will it be deflected around the obstacle. What happens depends on the stability of the atmosphere, the height of obstacle and the strength of the wind.

In neutral and unstable conditions (A, B, C and D in the Pasquill-Gifford scheme), the streamlines will be deflected upward and the plume will tend to ride over the obstacle. This will also occur in stable conditions provided the wind speed is sufficiently strong that the oncoming flow has sufficient kinetic energy to overcome potential energy that must be expended to cause the parcels of air to rise up over the hill. That is the kinetic energy must be sufficient to overcome gravitational effects and the effects of negative buoyancy that might arise because of stable atmospheric conditions.

Standard Gaussian plume models will normally take into account the interaction of the plume with the terrain feature by either assuming conservatively that the plume stabilisation height does not change and the plume simply impacts on the terrain feature, or less conservatively but more realistically, that the plume responds to the terrain variations in accordance with fluid dynamic principles. A commonly used approach is referred to as the Egan approach, which is depicted in Figure 8. The approach assumes that the plume will increase in height so that the effective height of the plume is given by either, h +ht or ht + h/2 depending on whether the height of the hill is greater than or less than the stabilisation height of the plume (see Figure 8).
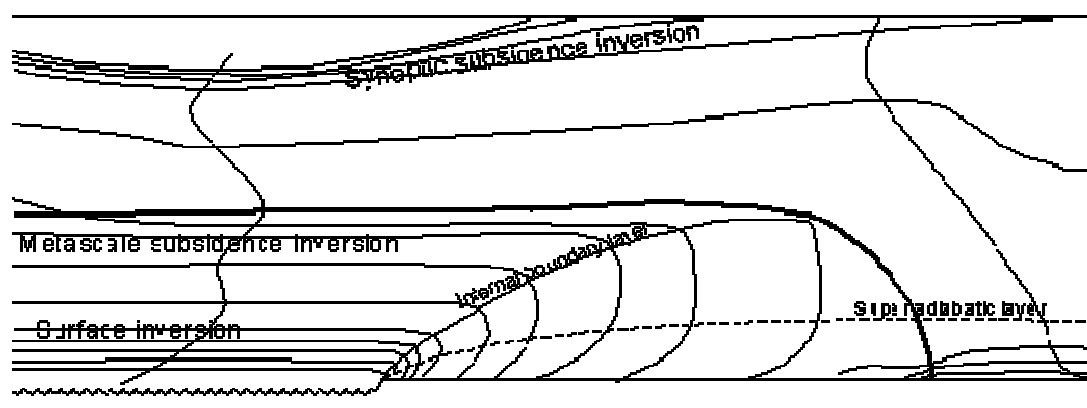

Figure 8. Air flow over terrain

If the ground slopes downwards with a slope greater than about 2% there may also be a downwash effect as illustrated in Figure 8. If the terrain drops very steeply then

there may be a cavity effect produced much in the same way as the cavity behind a building.

These circumstances represent nightmares for dispersion modellers and in many cases if the emission is significant and the potential impacts are significant, these cases should be treated using wind tunnels or physical models.

Effects of sea-breezes

Whenever the surface over which the wind is blowing changes its character, the flow has to adjust to the new conditions. These adjustments are complicated to take into account in dispersion modelling. A classic example of this is at the land-water interface. This occurs when air, which has travelled for long distances over generally aerodynamically smooth water of a uniform temperature, encounters land that is aerodynamically rough and warmer. This causes the development of an internal boundary layer: a zone of increased turbulence embedded within the atmospheric boundary layer. This zone is referred to either as a thermal internal boundary layer (TIBL) or a mechanical internal boundary layer (MIBL).

The MIBL and the TIBL will increase in height as the air flow penetrates further inland. If the on-shore breeze is a sea breeze, that is the flow is induced by the differential heating between the land and the sea rather than a flow that arises from large scale synoptic pressure conditions, then an additional characteristic will develop and there will be a return flow at higher levels. Figure 9 illustrates the most important features that are involved.
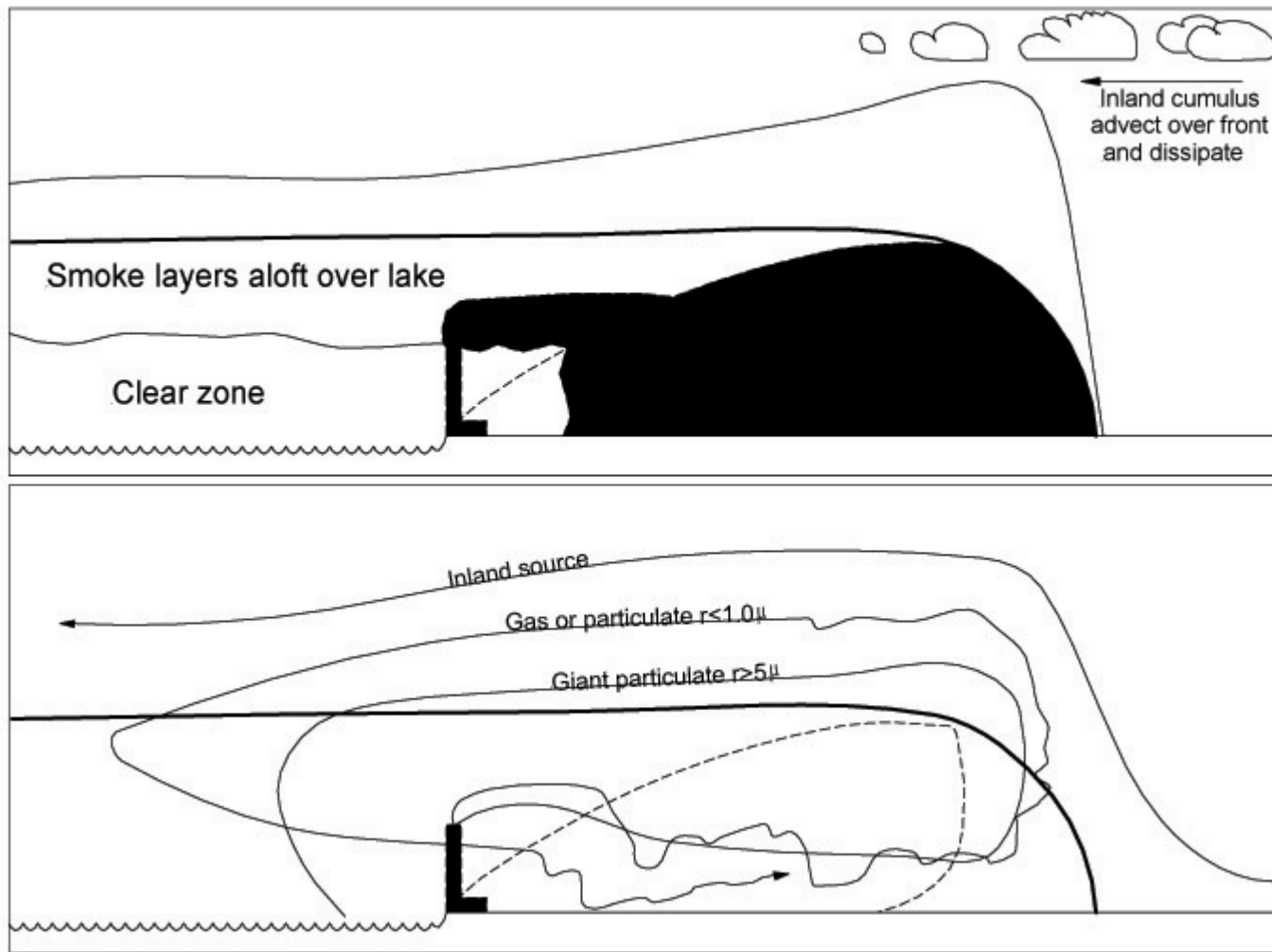
Figure 9. Air flow and turbulence in sea-breeze conditions

Sea-breezes are particularly difficult for the Gaussian dispersion model to handle. Initially the emission from the tall stack can find itself dispersing under relatively low turbulence conditions. Under these conditions the plume-spread occurs gradually both in the horizontal and vertical and concentrations remain high. In the absence of the sea breeze this is not a particular problem because the plume remains well removed from the ground. However at the point where the TIBL or MIBL reach the height of the plume, the plume material will find itself in a region of enhanced turbulence and will be rapidly mixed to the ground. At the point where the plume reaches the ground, high ground-level concentrations can occur. These can be persistently high and repeated regularly as the sea-breeze land-breeze cycle is often a regular feature of coastal environments and because sea breezes are often associated with winds from fixed directions.

The Kwinana Air Modelling Study (KAMS, 1982) in Western Australia studied this phenomena extensively. Individuals who may have to deal with sea breeze effects should refer to this work to gain a proper appreciation of potential effects and the design features that need to be incorporated into stacks which, by necessity, have to be constructed in coastal environments.

Effects of strong convection

In the earlier discussion on turbulence it has been assumed that turbulence results in the dilution of the plume, however this needs to be considered carefully. Dilution of a plume will occur when clean air can penetrate into the plume and the polluted air can be mixed into the clean outside air. This process is of course simply another description of turbulence. Turbulence in the atmosphere exists over a large range of scales from millimetres (below which viscosity forces in the air suppress turbulent movement) to hundreds and thousands of kilometres, where the size of the earth and the depth of the atmosphere constrain the scale at which turbulent motions take place. Plumes also can exist on scales from centimetres to many tens of kilometres in the case urban plumes. However most industrial plumes commence life with the dimensions of the order of a few metres and are so diluted by the time they are kilometres in size, that the range of turbulent eddies which are responsible for diluting the emisson or which are of interest to dispersion modellers are those on these scales a few metres to a kilometre or so.

When a plume is small, eddies which are effective in diluting it are those which are of the same scale or smaller than the plume itself. Larger eddies simply move the plume bodily from one place to another without significantly diluting the material within it. As the plume grows in size, so does the scale of eddies which can effectively cause it to dilute. In some circumstances the eddies in the atmosphere are not conducive to diluting the plume but simply move it from one place to another. This is particularly true in the case of strong convection which can occur in all parts of the Australian mainland particularly in summer and in the tropics in all seasons.

Convective eddies, with scales of the order of a few hundred metres, are often established in daytime conditions. These transport warm air from the ground to the top of the mixed layer and cool air back down to the ground again. The eddies can only dilute the plume when the plume is larger than the scale of the eddies otherwise their effect is to transport the entire plume without significant dilution. In some cases this will be upwards and in other cases downward. Thus they can effectively transport the partly diluted plume to ground-level well before it has had an opportunity to disperse to a safe concentration. Strong convective cells are responsible for extremely high ground concentrations. In these circumstances stacks do not work effectively. For a chimney to work effectively, the scale of the eddies should be smaller than the height of chimney. When this is not the case, considerable care needs to be taken to ensure that ground level concentrations do not reach problem levels and the best practice approach is to treat the emission or to create a dedicated buffer zone that can accept the high concentrations, or to avoid emissions when convective activity is strong. The two latter options are difficult to manage in practice and are not recommended as best practice solutions.

Summary of Best Practice Principles

This booklet has provided a basic overview of the theoretical and practical issues that need to be considered in managing air quality from minerals processing facilities. From the theory and the case studies it is possible to identify best practice approaches

which are currently in place in the Australian minerals processing industry. These are summarised below.

- Step back and look at the big picture.
- Use technologies that do not create wastes.
- Eliminate waste streams by recycling.
- Treat air emissions to reduce them to the lowest limits practicable.
- Discharge residual emissions through appropriately sized stacks.
- Take care when sizing stacks to take proper account of reduced emission temperatures which can arise from gas cleaning technologies such as scrubbers, acid plants etc.
- Recognise the limitations of dispersion models in dealing with complicated terrain, sea breezes, transitional periods which give rise to inversion break-up of fumigation and building wake effects.
- Ensure that stacks are sized to avoid building wake effects.
- Capture fugitive emissions with appropriately sized hooding systems and sufficient air flow to ensure that capture efficiencies are at satisfactory levels.
- Take care when assessing odour effects to ensure that proper account is taken of the fast response time of the nose relative to the predicted averages provided by dispersion models.
- Identify all pollutants carefully and select appropriate technologies for controlling emissions.

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Case Studies

The Sustainable Minerals partnership is seeking case studies which demonstrate how best environmental practice can be applied in diverse environments across Australia, while allowing operational flexibility for specific sites. Case studies should present:

- Basic principals, guidance and advice;
- Case studies from leading Australian companies; and
- Useful references and checklists.

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