The ups and downs of chimney plumes

Fortunately, a parcel of material issuing from a chimney tends to disperse rather than hanging together. In this way, pollutants can become so diluted in the atmosphere that they become essentially harmless.

Industrial chimneys should be designed to be high enough so that the emerging plume, spreading out in a cone, disperses sufficiently by the time it contacts the ground. The phenomenon of dispersal is a complex one, depending on a number of meteorological factors such as wind speed, turbulence, inversion-layer height, and so on. Physical properties of the plume itself, in particular its buoyancy (related to its temperature), affect the dispersal also.

And so the question of what is the appropriate height for a particular chimney is not easily answered. We want to specify that the concentration of a pollutant (such as sulfur dioxide) should not exceed a certain concentration at given points from the chimney. We need a good model of plume dispersal to be able to predict the necessary chimney height.

Scientists overseas have used a number of models that seem to work out relatively well in practice. But there is good reason to believe these models do not always work very well in Australia. Indeed, last year the Queensland Electricity Generating Board (QEGB) sought help from CSIRO because it felt apprehensive in applying conventional techniques to the problem of estimating pollutant dispersal from its power stations.

The Board was planning a new 700-MW power station at Callide in central Queensland. This Callide 'B' station, to cost about $500 million, would be situated about a kilometre from the existing 120-MW Callide 'A'.

It was well known that the plume from Callide 'A' behaved very differently from the ideal of an expanding cone: on some days it would loop downwards and 'ground' only 150 m from the 75-m-high

The Callide A power station.

chimney. Luckily, the station is situated in a rural valley, far from human settlement.

But the carryings-on of Callide 'A' are disturbing. Similar behaviour couldn't be tolerated in the new power station, six times larger, and certainly not in power stations planned to be built near populous areas, such as at Gladstone.

The problem is that, at low latitudes, and particularly in winter in northern Australia, atmospheric conditions are dominated by low wind speeds and high solar input through clear skies. Convective turbulence becomes very strong, leading to correspondingly large updraughts and, more troublesomely, downdraughts.

Updraughts make this country one of the best for gliding enthusiasts, but the downdraughts, much less frequently encountered at higher latitudes, are responsible for early grounding of smoke plumes. In northern Australia, smoke plumes are frequently seen to loop up and down as they encounter updraughts and downdraughts. How then can this peculiar behaviour be predicted, and how high must a chimney be? Two CSIRO Divisions were able to bring their expertise to bear on the problem.

Dr Chris Coulman and his colleagues at the Division of Cloud Physics agreed to fly CSIRO's instrumented Fokker F-27 aircraft over the Callide area to study the structure of convective turbulence.

Mr David Williams of the Division of Process Technology had been involved in a similar problem at Mt Isa for a number of years. The empirical model he had developed with Dr John Carras to fit the behaviour of plumes from the Mt Isa stacks should work for Callide as well.

The arrangement was for Dr Coulman

Updraughts and downdraughts were measured from the Fokker F-27. One updraught registered at 7 metres per second.

and his team to make measurements of convective turbulence in the Callide area to determine whether some sites were better, or worse, than others for chimney placement. Mr Williams and his team would make both airborne and ground-based measurements of the dispersion from the existing chimneys at Callide in order to see whether their model could be applied to the situation, and, if so, to refine it with additional observations.

Up in the air

Dr Coulman took to the air on 7 days during July last year, a period when convective turbulence should be at its worst. Indeed, the aircraft's ride was very bumpy, and at times it struck updraughts measured at 7 m per second. Downdraughts, generally weaker than updraughts, reached a maximum 5 m per second.

The Fokker, with its instruments measuring convective velocities and surface temperature, criss-crossed an area 15 km by 10 km at various altitudes.

Terrain certainly had an influence on convective turbulence. Callide lies in a valley, with hills on three sides. Winds created turbulence over the hills, and also gave rise to waves if they were blowing from an easterly direction. This turbulence was in addition to the convective kind, which the researchers found fluctuated a lot, seemingly at random. Flying

How high must a chimney be?

over the same track, they found that strong updraughts or downdraughts recorded at a particular point on one occasion would quite likely have disappeared from that point on a successive fly-over.

However, they did find that updraughts tended to predominate on warm, north-facing hillsides, while over Lake Callide the cool water resulted in downdraughts.

Nevertheless, apart from the lake, no area had updraughts or downdraughts strong enough or persistent enough to recommend or rule out (respectively) the siting of a chimney there.

Although siting near the lake appears to be unwise, further study is needed to see whether anywhere else ought to be ruled out for other meteorological reasons. In particular, study of wind-induced waves in the air is warranted, to ensure that wave 'troughs' from prevailing winds don't correspond with the site of a chimney.

Mr Williams and his team also carried out a series of flights during September of last year. Their aircraft, a Beechcraft Twin Bonanza, is fitted out with sensitive detecting instruments that can measure very small amounts of plume material.

By flying across the plume, they measured its width at various distances downwind of the chimney. These measurements, combined with ground-based time-lapse photography (yet to be undertaken), will be used to determine whether the dispersion characteristics at Callide are the same as those previously measured at Mt Isa.

Over Lake Callide the cool water resulted in downdraughts.

To Mt Isa

The copper and lead smelters at Mt Isa have been the subject of discussion in *Ecos* before. (See *Ecos* 3 and 19.) The smelters emit a combined output of about 1500 tonnes of sulfur dioxide per day, along with both dust and sulfuric acid mist. A constant monitoring of the air quality at Mt Isa is maintained by Mt Isa Mines Ltd, and if the plume starts descending over the township the smelters are closed down — an expensive undertaking. The company has therefore gone to great lengths to minimize this occurrence.

At 270 m, the stack of the lead smelter is the highest in the Southern Hemi-

Mr Williams measuring the dispersal of the plume from inside the Beechcraft Twin Bonanza.

sphere. It used to be much lower (74 m), too low to prevent frequent shutdowns. The 153-m-high stack of the copper smelter emits two-thirds of the sulfur dioxide, and now it is the main reason for shutdowns. Doubling the height of this chimney has been proposed. Would that be worth while? This is where the studies of Mr Williams and his colleagues become particularly apt.

During January–March of 1978 and 1979, Mr Williams' team used time-lapse photography to study the behaviour of the plumes. They used two cameras — one located almost due north of the stacks, the other due east, and both about 6 km away — which together allowed them to record the plume's behaviour irrespective of the wind direction.

Every 10 seconds an exposure was made, and this continued for a total of 40 days.

Since the plume from the copper-smelter stack is normally the only one visible, most data were obtained on that stack. However, with the assistance of Mt Isa Mines Ltd, the plume from the 270-m stack was made visible for short periods by pumping fly-ash into it. Puffs of fly-ash could then be seen.

The behaviour of the plume from the lower stack reflected the high convective turbulence at Mt Isa. It looped up and down according to whether it was entrained in an updraught or a downdraught, just like the plume at Callide.

From the film frames, the scientists measured the vertical dimensions of the plume. They characterized this measurement against the two main determining variables: wind speed and time of day (effectively, this latter quantity is a measure of the vertical temperature gradient, and hence turbulence, since the air heats up progressively during the day). Airborne and ground-based measurements, the latter in an instrumented four-wheel-drive vehicle, were also carried out to determine the amount of horizontal spread of the plume.

From all these data, the scientists' major finding was that the plume, while it might snake about and appear to behave quite erratically, was always contained within an envelope of fairly constant shape. This behaviour is shown in the diagram, and the envelope can be regarded as the 'average' plume.

The average concentration of any pollutant is derived by taking its concentration in the actual plume and calculating its dilution when it spreads to fill the envelope. For example, at a wind speed of 2 m per second and a distance of 300 m from the stack, the peak concentration at the ground could be 30 times the long-term average. Peak readings occur when the actual plume touches the ground.

Dr Carras of the CSIRO team found a fairly simple empirical relation between peak and average concentrations, allowing a fairly accurate description (and prediction) of plume behaviour. Both the Mt Isa stack plumes displayed the same relation, suggesting that other plumes elsewhere can be described similarly.

The new model has shown itself to be much better than existing overseas models, as none of the latter are adequate to describe the highly convective conditions experienced at Mt Isa. They are prone to underestimate the strongest concentration of pollutants on the ground, sometimes by factors of 15 or even 25. Similarly, they tend to put the location of that concentration at too remote a point from the stack — under some conditions, 23 times too distant. In other words, under strongly convective conditions, stacks as tall as 270 m can still produce large ground-level concentrations at small distances from the stack.

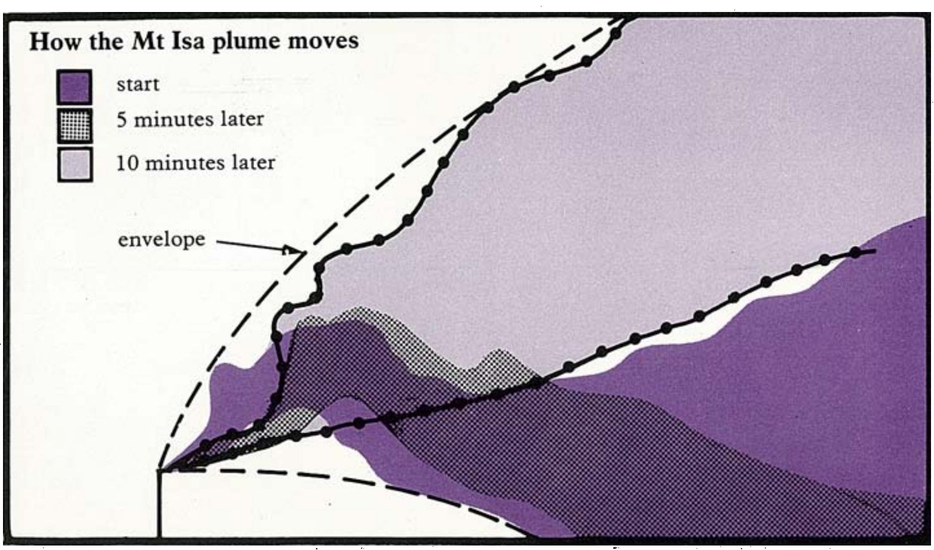
The CSIRO model can accommodate this observation, and the scientists are hopeful it will work just as well in describing the Callide situation. Its use should provide predictions of the frequency of plume grounding for a given stack height.

Mr Williams and Dr Carras intend to take extra ground-based measurements at Callide in the near future. These data should permit the model to be refined further.

In a collaborative project organized by the State Pollution Control Commission, Mr Williams and Dr Carras have also investigated the dispersion of the Liddell power station plume in the Hunter Valley of New South Wales. They found that their model gave a better description of the ground-level concentration of pollutants than the 'standard' overseas models.

During July of last year they also carried out a program of measurements on the plume from the Western Mining nickel smelter at Kalgoorlie, W.A., and the analysis of those data is still in progress. If their results from Kalgoorlie and Callide turn out to be similar to the Mt Isa and Hunter Valley data, then their model could be applied to chimneys sited throughout most of Australia.

Andrew Bell



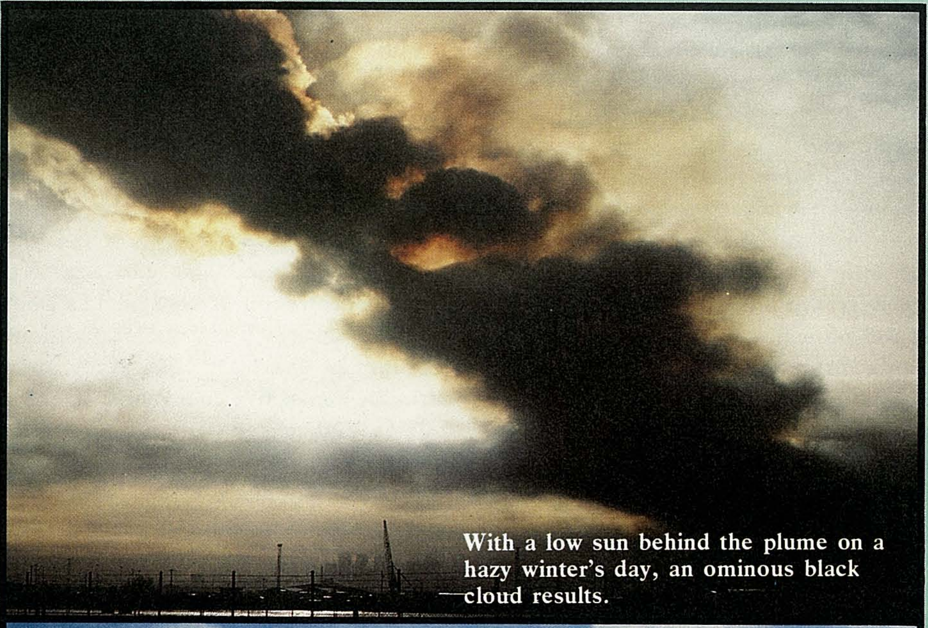
Although the Mt Isa plume loops up and down, for given wind speed and temperature it always stays within a definite envelope.

More about the topic

'A Survey of Convective Structure in the Atmosphere Near Callide Power Station.' C. E. Coulman. (CSIRO Division of Cloud Physics: Epping 1981.)

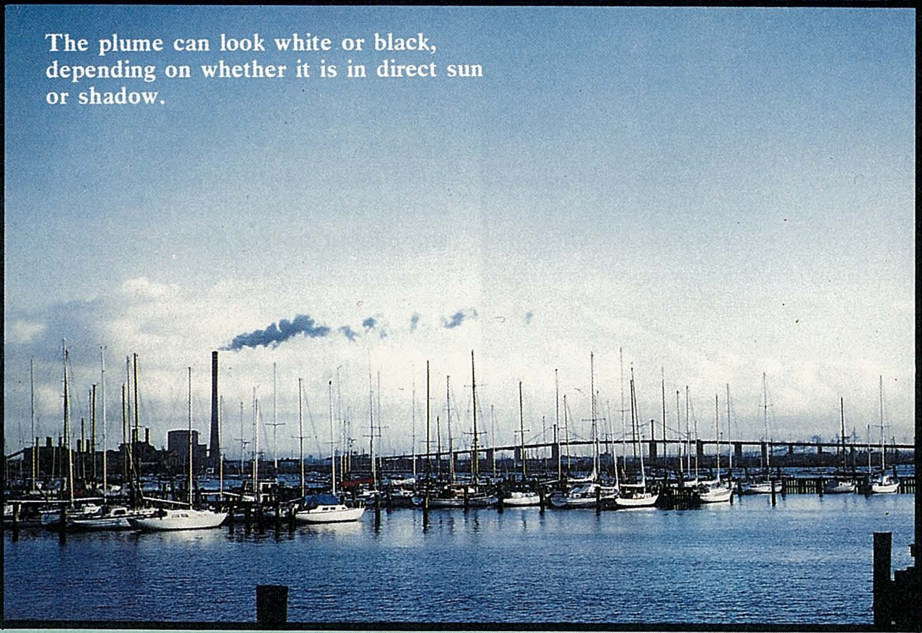
Observations of near-field plume dispersion under extremely convective conditions. J. N. Carras and D. J. Williams. *Proceedings, Seventh International Clean Air Conference, Adelaide, August 1981.*

It looks like smoke, but it's not



With a low sun behind the plume on a hazy winter's day, an ominous black cloud results.

Bifurcating plumes. Dr Spillane is making a separate study of what causes the plume to split in two.



The plume can look white or black, depending on whether it is in direct sun or shadow.

Irregular winds can cause cloud 'puffs'.

When seeing a plume belching from a power station chimney, the observer immediately thinks that the plume is smoke. Perhaps combustion in the boilers is incomplete, or the electrostatic precipitators are not working properly.

Before the indignant observer rings the local environment protection authority with a report of the power utility polluting his environment, he should consider another possibility: the plume could be water droplets.

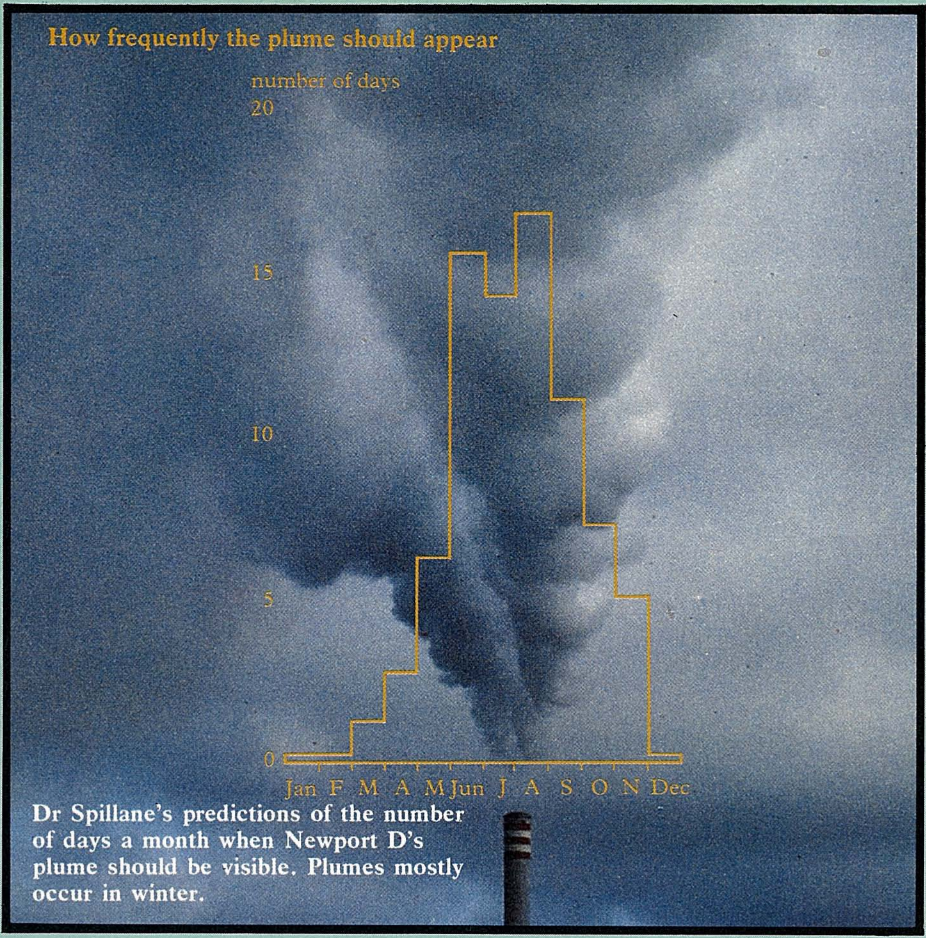
Dr Kevin Spillane of the CSIRO Division of Atmospheric Physics has made a study of plumes issuing from Melbourne's Newport D power station. Even when the station seems to be discharging a filthy black plume that stretches for kilometres, the culprit is only water droplets seen against the light (as with a brooding thunder cloud).

Dr Spillane has found that Newport's plume can present a remarkable diversity of appearances, as can be appreciated from the photographs reproduced here. Yet the diversity is due virtually entirely to meteorological factors, coupled with the angle of lighting. The composition and state of the stack gases remain fairly constant.

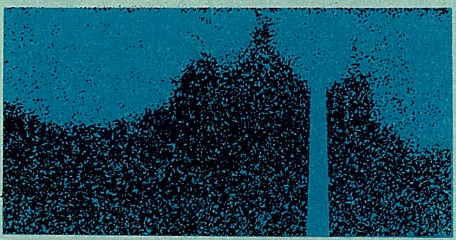
Newport D generates 500 MW by natural-gas firing of a single boiler, and it discharges the furnace gases through a single 183-m-high chimney. The station has no cooling towers; sea-water from Hobson's Bay cools the condensers.

The chimney exhaust contains no particulates (smoke) so there are often no visible external signs of the station's operation — save for cloud droplets condensed in the plume. Slight variations in the temperature and water content of the chimney gases occur, depending on operating conditions. The gas-to-air ratio and flow rate of the exhaust can cause the temperature at the chimney's outlet to vary from 120 to 150°C. The amount of water vapour in the exhaust stays close to 10–11% by weight.

Ironically, the more efficient the operation of the natural-gas boiler, the more frequently will its plume be visible. When maximum energy is being extracted from the gas, the chimney temperature will be at its lowest and water content at its highest. This is just the condition that maximizes the opportunity for the plume to become visible when it interacts with the atmosphere.



Dr Spillane's predictions of the number of days a month when Newport D's plume should be visible. Plumes mostly occur in winter.



The interaction is obviously affected by the temperature and humidity of the air, and also by the strength and steadiness of the wind. Can we predict its outcome? We would like to know whether a plume forms or not and, if it does, how long and wide it will be.

Prior to the opening of Newport D, Dr Spillane and his colleague Mr Clive Elsum developed a mathematical model of the plume-forming process. Using the model, they predicted the frequency of occurrence of visible plumes, and their size. The accompanying bar chart shows the number of days per month when a visible plume should occur. The figures exclude mornings of fog, or times when the cloud base is below the chimney top.

The chart shows that during a cool damp Victorian winter, plumes should be visible on half the number of days. During summer, however, plumes should rarely be seen.

Dr Spillane confirmed the validity of his predictions during a program of observations of Newport D. His model has also proved successful in describing the effects of cooling towers at Yallourn in the Latrobe Valley. Plume formation from proposed power stations could also be predicted.

Although some of the Newport plumes are spectacular, Dr Spillane predicts that those emanating from the huge Loy Yang power station, under construction in the Latrobe Valley, may on occasions be such as to be tourist attractions.

Footnote: a strange phenomenon, a splitting of the plume in two, is sometimes observed at Newport (one of the photographs shows it). This bifurcation, which the model did not predict, forms the subject of another study by Dr Spillane.

'Cloud Effects Expected in Chimney Plumes from Newport D Power Station.' Scientific Report 50/80/23. K. T. Spillane and C. C. Elsum. (State Electricity Commission of Victoria: Melbourne, in press.)