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ASSESSMENT OF THE METEOROLOGICAL DATA AND ATMOSPHERIC DISPERSION ESTIMATES IN THE RANGER I URANIUM MINING ENVIRONMENTAL IMPACT STATEMENT

by

G.H. CLARK

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ABSTRACT

Wind records from Jabiru, Northern Territory, Australia have been re-analysed to give atmospheric dispersion estimates of sulphur dioxide and radioactive contaminants associated with a proposed uranium mining and milling operation. Revisions in the plume rise equations have led to lower annual average sulphur dioxide air concentrations than those presented in the Ranger 1 Uranium Mining Environmental Impact Statement (RUMEIS). Likewise, the short term peak air concentrations of sulphur dioxide were all within the United States Environment Protection Agency (USEPA) air quality standards. Even though the radon gas inventory was revised upwards, predicted concentrations were only slightly higher than those in the RUMEIS. An attempt was made at a first estimate of the uranium dust source term caused by wind suspension from stockpiled ore and waste rock. In a preliminary analysis using a 'surface depletion' model, it was estimated that uranium dust air concentrations would be decreased by about an order of magnitude when dry deposition was

included in the atmospheric dispersion model. Integrating over all sources, radionuclides and meteorological conditions, the annual radiation dose to members of the public in the Regional Centre is estimated to be a maximum of 5 per cent of the recommended annual limits.

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AIR POLLUTION; CONTAMINATION; DUSTS; EARTH ATMOSPHERE; METEOROLOGY; MILLING; MINING; PLUMES; RADIATION DOSES; RADON; STABILITY; SULFUR OXIDES; URANIUM

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1. INTRODUCTION

This report was prepared as an independent and objective study of the meteorological data, atmospheric dispersion models and the estimates of ground level pollutant concentrations presented in the Ranger 1 Uranium Mining Environmental Impact Statement (RUMEIS) [Ranger Uranium Mines Pty Ltd 1975]. In some cases, this has involved further analysis of the basic meteorological records to describe the prevailing atmospheric dispersion climatology. A part of the report is also devoted to summarising the difficulties in defining and applying the atmospheric dispersion models. An attempt is then made to give an idea of variability in the subsequent predictions for the ground level air concentrations downwind of the uranium mining operation.

2. THE PREPARATION OF AN ENVIRONMENTAL IMPACT STATEMENT - BACKGROUND TO THE ON-SITE METEOROLOGICAL PROGRAM

To discuss the impact of a proposed new development, it is necessary to determine the basic environmental conditions with an active on-site experimental and surveillance program. It is usually necessary to conduct the study over an extended period in order that a statistical description of the environmental parameters can be established. This is particularly true when discussing the climatology of a region in relation to atmospheric dispersion estimates. The United States Atomic Energy Commission has published a safety guide in which is prescribed a minimum meteorological measurement program for nuclear power plants [USAEC 1972]. A more complete description of the methodology is included here because it is considered to be important for environmental impact assessment in general.

To develop a climatology of meteorological parameters, the guide states that it is essential to collect data for a minimum of twelve consecutive months. Two full annual cycles would be desirable as a guard against atypical seasonal influences. It also recommends that a tower or mast be instrumented on at least two levels, the lowest being at 10 metres and the upper at the height of the gas emission (plant vent and/or stack height) or at least 30 metres above the lower sensors. Ramsdell [1975] has suggested that a 100 metre tower be instrumented at 10, 40 and 100 metres.

All levels on the tower should have a set of sensors suitable for measuring the wind speed to an accuracy of $\pm$ 0.2 m s^{-1}, the wind direction to ± 5°, the temperature to ± 0.5°C and temperature difference to ± 0.1°C. If it is necessary to monitor conditions associated with the visible plume formation from cooling towers or thermal discharges, the dew point temperature needs to be measured to an accuracy of ± 0.5°C. Because of the quantity of data collected, it is suggested that digital magnetic tape recording could be used as a basis for analysis, with the digital output being supplemented by strip chart recorders. This would probably help achieve 90 per cent data recovery.

To make atmospheric dispersion measurements, the guide also recommends that the wind, temperature and humidity data be averaged over a period of at least 15 minutes, once every hour. The mean wind speed and direction, standard deviation of horizontal wind direction (σ_θ) and vertical temperature gradient ($\frac{\Delta T}{\Delta z}$) can then be calculated. Monthly or seasonal, and annual joint frequency distributions of wind speed and direction by atmospheric stability classes can then be compiled. When fogging or icing could be a problem, similar frequency distributions leading to these meteorological conditions should be summarised.

In the USA, there is increased concern among several large meteorological consultant organisations about the quality of meteorological data currently being recorded. Their concern was echoed by Ramsdell [1975] in a discussion of the quality assurance program in which he dealt with selection, installation and testing of instrumentation and systems, the processing and storage of original data records and copies, and analysis and presentation of data. The instrument system and all components should be calibrated and documented at installation and regular intervals thereafter. In this way, the data accuracy and quality can be maintained at a very high level [USAEC 1972].

The USAEC [1972] guide also makes recommendations on the number of *in situ* locations at which meteorological measurements are necessary. This depends largely on the complexity of the terrain in the vicinity of the site. For example, in hilly terrain with valley features, or in the marine environment close to a coastline, there is likely to be considerable spatial inhomogeneity in the wind and temperature fields. Even in more gentle downward sloping plains there is growing evidence that the single station climatology of winds is unrepresentative of airflow patterns through the whole region [Wendell & Sandusky 1974; Start & Wendell 1974]. This means that the number of measuring points should be increased through the region. Occasionally it may also be necessary to conduct special atmospheric tracer studies to gain a more quantitative understanding of the prevailing atmospheric transport and dispersion conditions.

3. CLASSIFICATION OF THE ATMOSPHERIC STABILITY AND DISPERSION CATEGORIES

For routine application, the bivariate-normal diffusion-model (Equation 1) is the one used most frequently [Slade 1968; Pasquill 1974]. (For definitions of nomenclature used in this report refer to Section 19.)

$$\chi/Q = \frac{1}{2\pi\bar{u}\sigma_y\sigma_z}\left\{\exp -\tfrac{1}{2}\left(\frac{z-h}{\sigma_z}\right)^2 + \right.$$

$$\left. + \exp -\tfrac{1}{2}\left(\frac{z+h}{\sigma_z}\right)^2\right\} \exp\left(-\tfrac{1}{2}\frac{y^2}{\sigma_y^2}\right) . \tag{1}$$

In the case of ground level concentration (z=0), Equation (1) can be re-written as:

$$\chi/Q = \frac{1}{\pi\bar{u}\sigma_y\sigma_z} \exp\left[-\tfrac{1}{2}\left(\frac{y^2}{\sigma_y^2} + \frac{h^2}{\sigma_z^2}\right)\right] . \tag{2}$$

One of the most important problems facing the atmospheric dispersion meteorologist today is how to develop a universally applicable model for describing both the horizontal and vertical diffusion parameters as a function of downwind distance, x. For a detailed summary of atmospheric dispersion models, the reader is referred to Slade [1968] and Guthrie [1974]. In the following discussion, the latest approaches to improving the Pasquill [1961] model will be outlined.

Atmospheric stability has been defined in terms of the vertical lapse rate of potential temperature $\partial\Theta/\partial z$ where

$$\Theta = T_{Eo} + \Gamma z \tag{3}$$

such that

$$\frac{\partial\Theta}{\partial z} \begin{cases} < 0 & \text{unstable atmospheric stability} \\ = 0 & \text{neutral atmospheric stability} \\ > 0 & \text{stable atmospheric stability.} \end{cases}$$

The Pasquill [1961] and Gifford [1961] schemes were developed to relate the variation of horizontal and vertical diffusion parameters to downwind distance as a function of atmospheric stability. Many of the dispersion data were acquired from reasonably homogeneous sites (Porton Down, England; O'Neill, Nebraska; Idaho Falls, Idaho). Over the years, these dispersion curves have been used either as a basis for comparison with new data or applied directly to predictive estimates of diffusion over a range of non-homogeneous sites.

Pasquill [1961] defined six stability categories (Figures 1 and 2) according to the prevailing wind speed and solar heating conditions (Table 1). Here are shown stability ranges from the least stable category A through the near neutral category D to the most stable category F. As can be seen, no predictions are possible when there is a light wind and strong radiational cooling at night. Beattie [1963] has proposed that a category G for greater stability (also designated F1 by Charash [1972]) completes the table. The original table has been similarly revised by Luna & Church [1972] and Charash [1972] to give a more complete description of the atmospheric diffusion categories (Table 2). Luna & Church [1972] also give a detailed procedure for defining the correct Pasquill category based on Turner [1970].

A second set of criteria defining the Pasquill stability categories, produced by the USAEC [1972], is given in Table 3. To discuss these criteria, it is best to consider separately the horizontal standard deviation and the vertical temperature gradient ranges. Several studies [US Weather Bureau 1953; Markee 1963] have verified that the standard deviation of horizontal wind direction measured over 30 minutes can be related to the maximum and minimum fluctuations in the wind direction by $\sigma_\theta = (\theta_{max} - \theta_{min})/6$. There are several problems with this approach. During unstable conditions, it is generally necessary to ignore the greatest swings of the wind vane whereas, under stable conditions, a similar situation arises owing to the low frequency meandering of the wind direction. It is important to keep in mind that the total observed horizontal spread of the plume is a combination of the variance within the real plume and the variance of the centreline of the real plume (meandering component). Ramsdell [1971] found that diffusion within the real tracer plume accounted for only 10-20 per cent of the total dispersion. This indicates that the small values of σ_θ under moderate to extreme stability conditions should be increased to account for the substantial contribution by the meandering component, especially over a time period of 15 minutes to one hour.

It is obvious that the horizontal dispersion of pollutants should have some direct relationship to the horizontal wind turbulence. However, the relationship of vertical diffusion to σ_θ measurements is not so clear. This may be partly the reason for introducing the vertical temperature gradient criteria for defining the Pasquill stability categories. However, there are still many problems with the temperature gradient approach. For instance, although the vertical diffusion may be expected to be influenced by changes in atmospheric stability, it is difficult to relate the horizontal diffusion directly to the vertical gradient of temperature.

Prendergast & Crawford [1974] have presented the results of many statistical manipulations of data collected from a 335 metre tower at the Savannah River Laboratories, South Carolina, USA. They showed that the definition of the prevailing Pasquill stability category can vary markedly, depending on the height of the σ_θ observations and the layer depth at which the temperature gradients are measured. Nickola, Clark & Ludwick [1975] and Vogt & Geiss [1974] have similarly shown that the different criteria can lead to the prediction of diffusion parameters ranging over several orders of magnitude, under the same atmospheric conditions.

Not only have the σ_θ measurements been used to define the Pasquill stability category, but they have also been incorporated directly into a diffusion parameter formulation (Equation 4) [Slade 1968; Singer, Frizzola & Smith 1966].

$$\begin{aligned} \sigma_y &= \alpha\sigma_\theta x^B, \\ \sigma_z &= \alpha\sigma_\phi x^C. \end{aligned} \tag{4}$$

To use these formulae requires sensitive anemometry, in both the vertical and horizontal directions, with magnetic tape digitisation and computer analysis. Therefore, it is not a practical approach for the current Northern Territory data, but it may be useful for future studies.

Briggs [1974] has summarised the atmospheric dispersion data collected by a number of different laboratories. He presents analytical expressions (Table 4) for the variations of the diffusion parameters with downwind distance as a function of atmospheric stability based on the vertical temperature gradient categories. Briggs gives greatest weight to the curves for σ_z < 100 m [Pasquill 1961], 100 m $\leqslant \sigma_z \leqslant$ 2 to 300 m [Smith 1968], and σ_z > 300 m [Montgomery *et al.* 1972]. These dispersion curves still apply to homogeneous terrain.

The diffusion parameters have also been defined in several other schemes based on the turbulent nature of the horizontal wind traces. Singer & Smith [1953] subjectively classified all the wind direction traces according to the degree of turbulence and also by the prevailing atmospheric stability. This was known as the Brookhaven gustiness classification scheme (Figure 3). More recently, Clark & Bendun [1974] have extended this scheme to account for the frequent low turbulence wind traces observed by Slade [1969]; these trace types are shown in Figure 4.

Subsequent to the development of the Brookhaven scheme, Singer & Smith [1966] conducted atmospheric dispersion experiments during which the diffusion parameters were related to the gustiness types measured at an elevation of 108 metres (see Figures 5 and 6, curves B1, B2, C and D). The Brookhaven curves were then semi-objectively extended, according to the degree of turbulence and knowledge of the atmospheric stability, to account for the six extra categories of Clark & Bendun [1974]. Analytical expressions for variations of the diffusion parameters with downwind distance (Table 5) were used in the 'Turbulence' method for subsequent atmospheric dispersion predictions.

In a similar semi-objective approach, Clark & Bendun [1974] defined the atmospheric stability categories by relating the wind direction turbulence traces to the Pasquill stability categories (Table 6). This relationship relied on a knowledge of the wind speed, general weather criteria [Pasquill 1961], temperature gradient measurements in the lower atmosphere and the time of day. Once the climatology of Pasquill stability categories has been determined, the Pasquill method could be used for atmospheric diffusion predictions.

4. TOPOGRAPHICAL, SURFACE ROUGHNESS AND BUILDING WAKE INFLUENCES AND THE PASQUILL DISPERSION SCHEME

As was shown in Section 3, there are many problems in defining the prevailing Pasquill stability category; however, there are other limitations to this scheme. The Pasquill scheme was developed for a homogeneous terrain and no attempt was made to include the effects of surface roughness on dispersion. In this section, a review is made of some experiments using atmospheric tracer releases over a complex terrain in which the measured diffusion parameters were directly compared with the Pasquill curves. Several new methods which include surface effects are also discussed.

Several tracer experiments have been conducted in areas with complex terrain. Vogt & Geiss [1974] found that the downwind distance to the position of maximum concentration was reduced by a factor of 2 to 5 over the flat terrain predictions, depending on the stability category. Start, Dickson & Wendell [1975] also showed that diffusion measurements in a steep canyon indicated a marked variability from the Pasquill predictions, especially under more stable conditions. Under lapse conditions there was little difference; with neutral conditions, dilution increased by a factor of 5 but, under stable type F conditions, the dispersion was a factor of 15 times greater than that predicted. The reasons suggested included enhanced mechanical mixing due to turbulence generated near the mountain tops, drainage flows from the side valleys and wake effects in the lee of topographic variations within the valley.

Several other approaches have attempted to include the effect of surface roughness on atmospheric dispersion. Golder [1972] has included both wind shear (a function of roughness close to the surface) and stability in a new definition of the Pasquill categories. For diffusion near the surface, he used the surface roughness length z_o, and the Monin-Obukhov stability length (Equation 5) in his model (Figure 7).

$$L = \frac{-\Theta\ u_*^3}{kg\ \overline{w'\Theta'}} \tag{5}$$

Application of Golder's method for describing the prevailing atmospheric dispersion conditions would require very sensitive instrumentation to measure the sensible heat flux. Such instrumentation is unsuited to long-term operations and may not describe the important low wind speed, high stability conditions very well, because of lack of instrumental response.

From a climatological viewpoint, a more practical scheme has been suggested by Smith [1972]. He has revised the Pasquill scheme by redefining the stability parameter over a continuous range. Using an empirical relationship to determine the vertical sensible heat flux into the lower atmosphere, and knowing the mean wind speed, the stability parameter can be defined as in Figure 8. A knowledge of the surface roughness length is also used to modify the vertical diffusion parameter as a function of the downwind distance. It should be emphasised that the Smith [1972] scheme only describes the vertical diffusion parameter.

At larger travel distances, it is important to allow for the limitation on σ_z imposed by the depth of the mixing layer. Nomograms are available to describe the influence of the height of the mixing layer on ground level concentrations [Turner 1970].

In the Northern Territory, except for the Mt. Brockman massif and Arnhem Land plateau region to the south of the mining plant, the general topography is undulating. However, there are a number of surface roughness elements in the form of vegetation and trees which could significantly influence both the dispersion and deposition of pollutants released into the lower atmosphere. Garratt [1975] has tabulated the heights of different vegetation elements against the measured roughness lengths and found that generally $\frac{z_o}{h_v}$ ranges between 0.02 and 0.13 (Table 7). At Koorin, near Daly Waters in the Northern Territory, Garratt (personal communication) measured roughness lengths of 85 cm for trees with an average separation of 5-10 metres and heights in the range 8-10 metres. These results will be important for later computations in models of atmospheric dispersion, dry deposition and resuspension.

In terms of surface roughness influences, mention should be made of the effect of urban areas on atmospheric dispersion. Bowne [1973] and McElroy [1969] have revised the Pasquill curves on the basis of experiments conducted in the urban environment. In a preliminary approach, Briggs [1974] has suggested some new analytical expressions for urban atmospheric dispersion (Table 8). These remain to be tested against the increasing volume of quantitative dispersion data being collected in the urban environment.

Again, from the viewpoint of the Northern Territory development, it is conceivable that advection of an elevated plume over the proposed Regional Centre under stable conditions could be dispersed to ground level. However, this probably would not be due to a change of stability from the urban 'heat island' effect, but rather to a change in the nature of the surface roughness generating increased atmospheric turbulence. Such an effect would occur when there was at least a small wind speed to interact with the roughness elements.

Buildings or other obstructions frequently disturb the transport of atmospheric contaminants released from elevated sources. A wake region of low wind speed flow forms downwind of the obstacle and exerts some influence on diffusion in that region. Wake effects usually only extend to downwind distances of the order of 30 times the building height [Gifford 1976], beyond which ambient atmospheric diffusion processes dominate. Under low wind speed and stable atmospheric stability conditions, plumes diffusing in the wake region have been observed to meander in a horizontal direction [Halitsky & Woodward 1974]. As yet, no diffusion models have been formulated to account for this. Wind tunnel studies by Meroney & Yang [1971] have indicated that wake diffusion, in stronger winds and near neutral stability conditions, is only weakly dependent on atmospheric stability and that ground level axial concentrations are higher than those predicted by the Pasquill-Gifford diffusion curves. If the effective source height is greater than about three times the building height, then wake effects should not influence the downwind atmospheric dispersion predictions [Slade 1968].

5. DIFFUSION PARAMETER CLASSIFICATION SCHEMES: SUMMARY AND RECOMMENDATIONS

Under ideal conditions (*e.g.* flat plain, stationary meteorological and emission variables), the best attainable accuracy for atmospheric dispersion estimates using the Gaussian model is ± 15%. This accuracy worsens for 'moderately rough terrain' (± 30%), confined river valleys (± 50%) and in building wakes (by a factor of two) for peak short-term (one hour) concentrations [Mahoney & Spengler 1975]. Apart from measurement errors in the basic meteorological variables (wind speed, direction, temperature gradient, *etc.*), methods used to define the prevailing stability categories, and thus the diffusion parameters, should be treated with caution. The former Division of Licensing and Regulation, USAEC (now the Nuclear Regulatory Commission (NRC)) has adopted both the vertical temperature gradient and standard deviation of horizontal wind direction to define the Pasquill stability category. Because reliable measurements of these variables were not available from the Jabiru site, alternative methods had to be formulated. The 'Pasquill' and 'Turbulence' methods, developed using semi-objective methods of interpretation of the wind direction traces, will give alternative atmospheric dispersion predictions. Without further experimental studies, it is not possible to determine the relative or intrinsic accuracy of each of these methods.

For future studies, it is recommended that both $\partial\Theta/\partial z$ and σ_θ measurements be used to define the prevailing dispersion climatology. Sensitive instruments unsuited to long-term exposure are necessary to measure σ_θ. A more practical approach might involve a short-term study to measure and relate σ_θ to the wind direction turbulence categories [Clark & Bendun 1974]. In the climatological study it would then only be necessary to classify wind direction traces from less sensitive instruments operating on a routine basis.

If the terrain around the site is not homogeneous, corrections will be necessary for variations of the surface roughness along the downwind trajectory of the aerosol plume. In this case it is recommended that the Smith [1972] scheme be used for defining σ_z as a function of stability parameter, surface roughness and height of the mixing layer. Once more, it should be emphasised that research and operational experience has not indicated the relative or intrinsic accuracy of these different diffusion parameter classification schemes.

6. PLUME RISE FORMULAE

In preparing supporting data for the RUMEIS [Ranger Uranium Mining Pty Ltd 1975], the Holland plume rise equation was used to calculate the effective height of release of the sulphur dioxide. The Holland formula predicted a daytime plume rise of 3 metres, increasing to 8 metres under cooler nocturnal conditions. Compared with the current calculations, these are very conservative estimates.

Over the past few years there has been a proliferation of plume rise formulae describing the discharge of effluents from chimney stacks. Most formulae incorporate some measure of the plume turbulence in the form of the discharge velocity, and also the effect of the vertical temperature gradient. In several cases, plume rise formulae have also been developed for different atmospheric stability conditions, *e.g.* neutral, calm and stable atmospheres, *etc.* There have been several excellent summary reports written on plume rise formulae [Briggs 1969; Guthrie 1975]. The recommendations of Briggs [1969] for near ground level stack releases were chosen for the current calculations. The formulae are summarised in Equation (6).

Unstable and neutral stratification

$$\Delta h = 1.6\, F^{1/3} \bar{u}^{-1}\, x^{2/3} \quad \text{(m)} \tag{6}$$

where $$F = \frac{g}{T_{Po}}\, w_o R_o^{\,2}\, [T_{Po} - T_{Eo}]$$

Stable stratification

$x \leqslant x_s$ - use Equation (6)

$$x > x_s \qquad \Delta h = 2.9 \left(\frac{F}{\bar{u}S}\right)^{\frac{1}{3}}$$

where $x_s = \dfrac{2.4\,\bar{u}}{S^{\frac{1}{2}}}$

$$S = \frac{g}{T_{Eo}} \left(\frac{\partial\theta}{\partial z}\right) = \text{stability parameter.}$$

It is important to note that, under all atmospheric stabilities (stable for $x \leqslant x_s$), the plume continues to rise with downwind distance according to the '$\frac{2}{3}$ power law'. With light winds ($\bar{u}$ = 0.9 m s^{-1}) and an unstable to neutral atmosphere, values of Δh to 1700 metres have been predicted at a downwind distance near 10 km. The effective stack height is then given by $h = h_s + \Delta h$.

7. ANNUAL AVERAGE AIR CONCENTRATIONS

To obtain the long-term or annual average air concentrations, the atmospheric dispersion formula (1) is crosswind integrated (in the y direction) and then multiplied by the frequency of occurrence of the winds in a particular wind direction sector. This leads to the formula [Turner 1970]:

$$\frac{\chi(x,\theta)}{Q} = \sum_s \sum_m \frac{f(\theta,s,m)}{\sqrt{2\pi}\sigma_{zs}\bar{u}_m \left(\frac{2\pi x}{8}\right)} \left\{\exp\left[\frac{-(h-z)^2}{2\sigma_{zs}^{\ 2}}\right] + \exp\left[\frac{-(h+z)^2}{2\sigma_{zs}^{\ 2}}\right]\right\}.$$

In this case, the wind directions have been subdivided into eight sectors each of 45 degrees of azimuth. To obtain this formula, the winds were assumed to be randomly distributed within each of these sectors.

8. DUSTS AND RADIONUCLIDES

The sources of dust and radionuclides in the uranium mining operation have been identified in the RUMEIS as follows:

- The mining operation - drilling, blasting, loading and traffic movement.
- The primary, secondary and tertiary crushers.
- The rod mill feed.
- The yellowcake calciner and packaging plant.

In the above categories, no account has been taken of the movement of dust, both at the source and from its transported location, by the process of wind resuspension and subsequent deposition. In Sections 9-12 a review is made of the current literature pertaining to wet and dry deposition and resuspension. There was insufficient information to give qualitative estimates of wet deposition and resuspension for the Jabiru site. However, a preliminary attempt will be made to study the effect of dry deposition and wind suspension of uranium dust in Section 14. If sufficient information on the source parameters is then available, a quantitative estimation will be made of the relative influence of these mechanisms.

9. DRY DEPOSITION

Dry deposition of particulate aerosols is a complex mechanism of atmospheric cleansing which is not well understood, either theoretically or from an experimental viewpoint. Dry deposition is a function of a number of different variables and length scales, for example, the chemical nature and particle size distributions of the aerosols, height of release, meteorological conditions, and details of the canopy. In a review paper, Slinn [1975a] has discussed the rate limiting stages of a five-layer model for dry deposition. This model comprises the aloft layer above 1 km, the boundary layer between 50 m and 1 km, the canopy layer between 1 mm and 50 m, the deposition layer between 1 μm and 1 mm, and the edacious or edaphic layer < 1 μm (Figure 9). Sehmel & Hodgson [1975] have considered a more simplified three-layer model which nevertheless incorporates the basic approach of Slinn.

Particle removal from the atmosphere by dry deposition has been described by the dry deposition velocity, v_d, which is defined by:

$$v_d = \frac{N}{\chi} \quad . \tag{8}$$

In the past, deposition velocities have been determined for particular field situations, but the data have never been systematically organised as a function of particle size distribution, surface roughness, turbulence in the surface layer and atmospheric stability. Attempts are now being made to give both empirical and theoretical descriptions of the dry deposition velocities as a function of these variables.

Slinn [1975a] has used a model of turbulence proposed by Jaukowski [described by Goncharov 1964] for deposition from the deposition layer (Figure 10) to give the following expression

$$v_d = v_t + (10 \frac{cm}{s}) \left[\frac{\dot{m}''}{(1 \text{ g cm}^{-3} \text{ s}^{-1})}\right] + \frac{u_*^2}{\beta \bar{u}} \left[10^{-\frac{3}{St}} + \frac{\beta}{\gamma} Sc^{-0.6}\right] . \tag{9}$$

A separate expression was developed for deposition within the canopy layer which relied on the canopy filtration efficiency and the surface collection efficiency among other variables.

Sehmel & Hodgson [1975] also give nomograms relating the dry deposition velocity to the surface roughness length, friction velocity, particle size and density, and atmospheric stability (Figure 11). These curves were developed by non-dimensional correlation techniques using data from wind tunnel studies.

$$\frac{u_*}{v_d} \ell n \left(\frac{1}{1-v_t/v_d}\right) = \exp \{ -23.667 + 5.555 \, \ell n \frac{d}{z_o} - 0.07681 \left(\ell n \frac{d}{z_o}\right)^2 + 0.9722 \, \ell n \frac{u_*}{v_t} + 0.03799 \left(\ell n \frac{u_*}{v_t}\right)^2 - 2.254 \, \ell n \frac{D}{u \, z_o} - 3.724 \, \ell n \frac{\rho_p u_* d^2}{18 \, \nu \, z_o} \} \quad , \tag{10}$$

Smith [1972] has outlined a method for estimating the roughness lengths for a variety of terrains, but it is usually more accurate to make *in situ* measurements of the wind speed profile. Likewise, for measuring the friction velocity under a range of atmospheric stability and wind speed conditions, *in situ* data are most desirable.

As stated previously, the models for the deposition velocity presented above were developed from theoretical and empirical wind tunnel relationships. It is important to see how these models relate to atmospheric measurements taken under a variety of conditions. In practice, it is extremely difficult to make dry deposition velocity measurements in the real atmosphere. During an experiment with two tracers (ZnS - median diameter 5 μm; rhodamine B - median diameter 0.8 μm), Nickola & Lee [1975] found that the deposition velocity over snow was about 0.1 cm s^{-1}. Under different atmospheric stability regimes and over the same snow free terrain (z_o = 3 cm), the deposition velocities were measured to be about an order of magnitude higher.

Not only are particulate aerosols like dust affected by deposition processes, but the gaseous aerosols like sulphur dioxide are similarly deposited. In fact, there appears to be a greater body of experimental data for the gases to support the theoretical models. For instance, Garland [1976] used the flux gradient method to estimate an average v_d of 0.8 cm s^{-1} over grassland areas and < 2 cm s^{-1} in a forest. Heinemann & Vogt [1976] estimated a deposition velocity of 1.2 cm s^{-1} for ^{131}I on a grass surface and tried to develop an empirical relationship between

v_d, u_*, the relative humidity, vegetation and biological quality factors. In the air mass downwind of St. Louis, Missouri, USA, Young *et al.* [1976] measured a deposition velocity for bromine of 0.7 cm s^{-1}.

In summary, it appears necessary to account for many surface, meteorological and aerosol variables when attempting to estimate the dry deposition velocity. Assuming these data are available, how then are the values of v_d used in the dispersion models for depleting the plume as it travels downwind?

In the past, it has been the general practice to use the 'source depletion' model [Slade 1968]. In this case, the source strength is reduced as a function of downwind distance. This approach assumes an instantaneous redistribution of the effect of deposition through the entire plume. Thus the air concentration $\chi(x,y,z,h)$ is given by:

$$\chi(x,y,z,h) = Q(x)\ D(x,y,z,h)\ . \tag{11}$$

From conservation of mass considerations:

$$Q(x) = Q_o\ [\ -\int_o^x v_d\ \bar{D}\ (\xi,z_d,h)\ d\xi\ ]\ . \tag{12}$$

Horst [1976] has suggested that a more accurate description of the deposition processes acting on a Gaussian plume may be given by his 'surface depletion' model. In this case, the deposition flux to the surface is represented as a material sink; this effectively means it is a negative source for downwind diffusion from the point of deposition.

For the 'surface depletion' model, the crosswind integrated air concentration $\bar{\chi}(x,z)$ is given by:

$$\bar{\chi}(x,z) = Q_o\bar{D}(x,z,h) - \int_o^x v_d\ \bar{\chi}\ (\xi,z_d)\ \bar{D}\ (x-\xi,z,o)d\xi\ . \tag{13}$$

For the case of moderately strong deposition and a stable atmosphere, it has been shown that the commonly used source depletion model is in error by factors of three or four [Horst 1976] for some parameters at a downwind distance of 10 km. The 'surface depletion' model will therefore be used in the subsequent calculations.

10. WET DEPOSITION

Precipitation scavenging of aerosols from the lower atmosphere is another efficient, if sometimes transient, cleansing mechanism. In the Northern Territory, precipitation scavenging applies only to rain, whereas in colder climatic regions, snow scavenging could be an equally important mechanism. Rain scavenging can be separated, according to the origin of pollutants, into below-cloud and in-cloud processes. In-cloud scavenging predictions have given greatest problems [Engelmann 1970], but experimentally, below-cloud regions are better documented. In general, the stack plume of ground level emissions will originate at below cloud-base level, in close proximity to ground level.

In trying to predict below-cloud scavenging, the current models are usually simple variations of

$$\chi = \chi_o \, e^{-\Lambda t} \quad . \tag{14}$$

11. PARTICULATE RAIN-OUT

As with dry deposition, rain scavenging depends on the particle size distribution of the aerosols as well as the raindrop size distribution and collection efficiency. It is also important to know the rainfall rate which is related to the drop size distribution by the following expression:

$$J_o = \int_o^\infty da \; n(a) \; \frac{4}{3} \pi a^3 \; v_t(a) \quad . \tag{15}$$

The wash-out coefficient can be approximated by:

$$\Lambda(a) = C_1 \varepsilon J_o \; E(a, R_m)/R_m \quad . \tag{16}$$

Mason [1971] has used the following expression for steady rains:

$$R_m = 0.35 \text{ mm } (J_o/1 \text{ mm h}^{-1})^{\frac{1}{4}} \quad .$$

However, there may be different relationships for R_m depending on whether the precipitation is orographic, convective, frontal or pre-frontal in origin.

Slinn & Hales [1970] also state that diffusiophoresis is the important rain-out mechanism for particles with radii < 3 μm, *i.e.* effects of humidity or water vapour gradients are important for the particle collection efficiency. By contrast, Engelmann [1968] suggests that rain scavenging is unlikely to be important for the sub-micron particulates, although the effect of electrical charges of the raindrops and aerosols has not been fully investigated. An estimate of the ratio of total wet deposition (TWD) to total dry deposition (TDD) during a rainstorm has been made by Slinn [1974]. With some approximations, he finds that:

$$\frac{TWD}{TDD} = \frac{3}{4} k_1 \frac{J_o}{R_m} \frac{\bar{u} \, H}{u^{*2}} \quad . \tag{17}$$

This relationship suggests that wet deposition would be about ten times more important than dry deposition during a rainstorm. Although Slinn [1974] produced experimental evidence which suggested that dry deposition may in fact be as important, the simplifying assumptions used by him may have caused this discrepancy.

At present there is a continuing program studying all aspects of rain-out of particulate aerosols, sponsored by the US Energy Research and Development Agency (ERDA). However, at this stage it is not known whether sufficient experimental information has been accumulated to allow for accurate estimates of the effect of wet deposition.

12. RESUSPENSION AND TRANSLOCATION OF SURFACE PARTICULATES

When dust and other aerosols are diffused and subsequently deposited on the underlying surface, they then become available for translocation downwind by mechanisms of resuspension into the lower atmosphere. Slinn [1975b] has indicated schematically that resuspension is due to a very complex interaction of many variables (Figure 12). For instance, the disturbing mechanism can be by wind, rain, machines, people and animals. The properties of the surface on which the contaminants are located also play an important role, *e.g.* bare or rough soil, vegetation covered, a rough city environment, *etc.* However in the case of the Northern Territory, several of these complexities can be eliminated.

In the Northern Territory, the main mechanisms of disturbance are likely to be by wind movement and machine activity, although the latter would probably be a localised effect. The wind turbulence levels, direction and vertical gradients of speed and diffusivity are probably the most important parameters to be considered. However, another important factor is the surface roughness effect. In the vicinity and downwind of the mining area, there is a medium areal density of trees which could cause some marked variations of both wind speed and direction within the canopy (see data analysis, Section 14.3).

To date, there have been very few experiments conducted to determine the particle resuspension rates as a function of the surface roughness, wind turbulence, and particle size distributions. Sehmel [1975a] found that the airborne concentration of respirable dust particles (1.1 - 3.6 μm) increased to about the third power of wind speed for speeds above 4 m s^{-1} over a near flat terrain. Anspaugh *et al.* [1976], working on aged surface deposits at the Nevada test site, discovered that the air concentrations of resuspended plutonium varied with u_*^2.

However, this does not appear to be a universal relationship because results from a site in Texas suggest that resuspension is proportional to $u_*^{6.09}$. Working both in the wind tunnel and over real vegetation features, Sehmel [1975b] showed that there was a general decrease in the resuspension rate with increasing surface roughness. However, when he studied the resuspension of DDT spray from within a forest canopy (z_o = 100 cm), there was an increase in the resuspension rate, possibly due to the internal movement of the canopy.

Another factor which may be of importance during the dry season in the Northern Territory is the presence of strong thermal activity and dust devils or willy-willies. Sinclair [1976] has calculated that over 7×10^3 tonnes of desert dust and sand in the particle size range 1-250 μm may be transported downwind in the Nevada desert during the summer season. This could be quite a significant mechanism of resuspension but it depends on the intensity, frequency, time and place of occurrence of these transient phenomena.

In reality, both deposition and resuspension mechanisms act simultaneously on aerosols. Horst [1975] has simplified this situation by estimating the air concentrations of resuspended pollutants which were previously deposited on the underlying surface over an extended period of time. He found that the sum of the air concentrations due to dry deposition and resuspension was less than the concentrations from the original source when neither of these processes were present. Although subsequent downwind redeposition of the resuspended particulates was not included, it is thought that this effect would be small. His overall conclusion was that a conservative estimate of the air concentrations could be obtained by ignoring both deposition and resuspension [Horst 1975]. This conclusion was qualified by reference to the simplifying assumptions in the model, *e.g.* resuspension factor independent of wind speed, no accounting of movement of pollutants downwind by successive steps of resuspension and redeposition, *etc.*

13. SUMMARY OF DRY AND WET DEPOSITION AND RESUSPENSION PROCESSES

Dry and wet deposition as mechanisms for cleansing the atmosphere of suspended aerosols, and resuspension as a means by which the deposited materials can be moved downwind have been surveyed to give a more complete picture of the total air pollution problem. It is obvious that knowledge of all the factors involved in these mechanisms is still incomplete. In the next section, preliminary attempts will be made to give a feeling for their relative importance. However, there will still be some uncertainties due to the models being used and the lack of information on the source parameters, *e.g.* dust particle size distributions from the various blasting and crushing processes.

14. RE-ANALYSIS AND DISCUSSION OF THE JABIRU METEOROLOGICAL DATA

14.1 Methods of Analysis of the Dispersion Climatology

Wind records from Woefle anemometers on the Jabiru airstrip (10 m height) and at the 15 m and top levels of the 30 m tower at the plant site have been re-analysed by wind direction, speed and direction turbulence trace type. As discussed in Sections 3 and 5, the mean annual near-ground concentrations of air pollutants in the region have been determined from the frequency of occurrence of the wind direction turbulence classes (Turbulence method) and the Pasquill stability categories (Pasquill method). The two alternative predictions were then compared with those tabulated in the RUMEIS [Ranger Uranium Mines Pty Ltd 1975] and its supporting documents.

14.2 Instrument Calibration, Meteorological Data Recovery and Quality

Before meteorological data can be used to make predictions of downwind air concentrations of pollutants, it is important to know the reliability and accuracy of the instrumentation used in the field study. There was no mention made in either the RUMEIS, the supplements or the supporting documents of calibration procedures (either *in situ* or in a standards laboratory) for any of the meteorological instrumentation used in the Jabiru climatological study. As was stated in the Introduction, regular instrument calibration is required by the USAEC [1972] in meteorological programs associated with the preparation of environmental impact statements. This procedure then confirms that the data quality is maintained at a high standard. In the case of the Jabiru climatological data, there could be some deficiency in the area of data quality.

With this in mind, it is now necessary to proceed with the available data and determine whether they conform with the other requirements for environmental impact assessment. The Jabiru meteorological tower wind data were collected during a two-year period from May 1973 to May 1975. The performance of the instrumentation left much to be desired and did not approach the recommended 90 per cent recovery of good data (USAEC [1972] and Table 9 of this report). In general, better data were collected during the dry season (the exception being the 15 metre level on the meteorological tower) when the instrumentation was more accessible. Overall, the airstrip wind recorder performed best with 80 per cent data recovery, followed by the 30 metre anemometer with 70 per cent and the 15 metre level with 57 per cent.

The other aspect of data collection which caused some concern was the retrieval and cataloguing of the charts. In some cases, the chart on-off times together with any instrument failures were not recorded during the operations. Such charts required time consuming cross-correlation of wind record times with those from other instruments before any usable data could be extracted. In many cases, chart cataloguing was so poor that instrument performance was severely affected.

14.3 <u>A Comparison of Wind Statistics from the Jabiru Area</u>

Wind speed, direction and a direction turbulence classification were extracted as hourly averages on a continuing 24-hour basis for the full two years. The wind speed and direction statistics were summarised using a Bailley-type wind rose (Figure 13).

In Figure 14, wind roses from the three instruments have been separated according to the dry and wet seasons and also summarised over all times and seasons. There are several points to note:

- During the wet season (December to March inclusive) the low level winds from the west and north-west directions predominate. At an altitude of 30 metres above ground level there is a more uniform distribution by direction during the wet season.
- Winds prevail from the east and south-east during the dry season. The effect of the vegetation canopy on winds recorded by the 15 metre anemometer is seen in the relatively low wind speeds. The 10 metre anemometer on the Jabiru airstrip has an unimpeded exposure to winds from all directions. Consequently, it measures a similar distribution of wind speeds to that at 30 metres on the meteorological tower.
- Considering all seasons, stations and observation times, winds from the east and south-east predominate, with most speeds in the range 2 to 8 m s^{-1}.

The 30 metre wind data were used in subsequent analyses because they were unimpeded by local vegetation influences and were considered most appropriate to the atmospheric releases of gases and dusts from the elevated sources at Jabiru. For the purposes of subsequent dispersion and dry deposition analyses, the arithmetic mean wind speeds were calculated for each of the wind speed categories from the 30 metre data (Table 10).

It is interesting to compare the wind direction distributions from re-analysis of the data with those used in the RUMEIS (Table 11). It is apparent that winds from the east were weighted more heavily in the RUMEIS than in the re-analysis. As was discussed previously, in the re-analysed data, the winds prevail from the east and south-east. There is also a secondary peak in the distribution from the south-west.

The 30 metre wind data were also subdivided into night (6 p.m. to 6 a.m.) and day (6 a.m. to 6 p.m.) as shown in Figure 15. Although there was a slight shift to the lower wind speeds at night, more than 85 per cent were higher than 2 m s^{-1}, the majority being in the range 2 to 4 m s^{-1}. Again, the prevailing wind directions were from the east and south-east at night. This indicates the possible influence of the Mt. Brockman escarpment as an area for the formation of nocturnal drainage winds. The observations of some nocturnal air movements through the region could be important for the dispersion of radon gas from the open pit. If long periods of calm had been predicted, then the open pit might have acted as a well for the stagnating radon gas.

The relationship of the atmospheric turbulence and dispersion categories to the wind speeds has been further investigated. By combining all wind directions and times, the ten wind direction turbulence categories were related to the prevailing wind speeds for the 30 metre tower data (Table 12). The restricted turbulence categories (types 5 to 10) accounted for 53 per cent of all cases, the more dispersive type 7 category being predominant. As a whole, categories 2, 3 and 7 made up 54 per cent of all cases and were associated with the stronger more dispersive winds (see Appendix A for a more detailed tabulation of the winds by direction, speed, stability or turbulence category, and time of day).

As suggested by Clark & Bendun [1974], the turbulence categories were subdivided into the Pasquill stability (diffusion) categories (Table 8). The Pasquill categories were then related to the prevailing wind speeds (Table 13). As expected, the neutral to unstable categories (types A to D) were associated with stronger wind speeds. Only 5 per cent of winds were observed in the near calm category (0 to 1 m s^{-1}), with the majority of these falling into the more stable (F and F1) diffusion regimes. This table emphasises the low probability of stagnation conditions with near calm winds occurring in the Jabiru area.

The wind statistics generated by the re-analysis of the Jabiru data can now be compared to those prepared for the RUMEIS (see Table 3 of the RUMEIS [1975] backup document, supplement 1 to item XV). The representative winds given in the RUMEIS appear to be slightly overestimated compared to those in Table 3. In particular, the average wind speed of 2 m s^{-1} for class F1 is probably overestimated by 0.5 to 1 m s^{-1}. Elsewhere in Table 3, some very conservative assumptions have been made. These are summarised in Table 14.

Before the estimation of air concentrations in the RUMEIS [1975], it was assumed that 50 per cent of all cases were associated with the most stable dispersion categories (F and F1). This contrasts markedly with the 14 per cent frequency of occurrence in the re-analysed data. Further, the most unstable category (type A) was observed on more than 23 per cent of all occasions, whereas it was not considered in the RUMEIS. The full repercussions of the shift to more unstable, and therefore more dispersive, conditions in the re-analysed data will only be realised when comparing the current air concentration predictions with those in the RUMEIS.

14.4 Application of the Jabiru Climatology to Predictions of Downwind Aerosol Concentrations

Now that the prevailing atmospheric dispersion and wind climatologies have been established for the Jabiru site, it is important to apply these statistics to the source inventories of the various aerosols in order to make predictions of the annual average air concentrations. For ease of comprehension, the three different sources, sulphur dioxide and radon gases, and uranium dust, will be treated individually. Some of the problems discussed in the Introduction could not be fully investigated owing to the lack of information and time. These will be summarised at the end of this report.

14.5 Sulphur Dioxide Air Concentration Predictions

The rise of the sulphur dioxide gases above the chimney stack has been estimated from the plume rise formulae outlined in Equation (6). For these estimates, a 'stable' atmospheric stratification was considered to apply for Pasquill categories E, F and F1 and for wind direction turbulence categories 5 to 10 inclusive.

The following source inventory for the sulphur dioxide was taken from the supporting document [Strom 1975] to the RUMEIS:

w_o = 12 (m s^{-1})
R_o = 0.8 (m)
T_{Po} = 345 (K)
g = 9.8 (m s^{-2})
h_s = 40 (m)

Using the USAEC [1972] safety guide and a knowledge of the prevailing meteorology at Jabiru, the following ambient temperatures and potential temperature gradients (Equation (3)) were used as a function of the Pasquill stability and wind direction turbulence categories:

Pasquill stability category	A	B	C	D	E	F	F1
T_{Eo} (K)	305.2	304.2	303.7	301.2	298.2	296.7	295.2
$\frac{\partial\Theta}{\partial z}$ (K/100 m)	-1.0	-0.8	-0.6	0.0	1.5	3.7	6.0

Wind direction turbulence category	1	2	3	4	5	6	7	8	9	10
T_{Eo} (K)	305.2	303.2	304.2	301.2	295.2	296.7	298.2	297.2	297.2	295.2
$\frac{\partial\Theta}{\partial z}$ (K/100 m)	-1.0	-0.5	-0.8	0.0	6.0	4.0	1.5	3.0	2.5	6.0

The USAEC [1972] did not specify the accuracy of their categorised $\partial\Theta/\partial z$ measurements. However, Gifford [1976] reports that the average potential temperature gradient associated with the most stable Brookhaven gustiness class D [Singer & Smith 1953] was 2.62 ± 3.1 (K/100 m). At the lowest wind speeds (0.9 m s^{-1}), variations in $\partial\Theta/\partial z$ of this magnitude would cause errors of about ± 50 per cent in the predicted concentrations at 10 km, whereas these errors would decrease to about ± 20 per cent at higher wind speeds. The errors in air concentrations at any particular receptor location due to $\partial\Theta/\partial z$ depend on the relative downwind position of the concentration maximum and the frequency of occurrence of the wind speed and 'stable' stability categories in that direction.

The 'surface depletion' model for dry deposition of sulphur dioxide was not used in the current analyses. The air concentrations of sulphur dioxide were calculated at 1 metre and not at ground level. This method was used because if it was necessary to extract any ground deposition statistics, the deposition velocities (usually measured at 1 metre) could be used. It is important to remember the definition of dry deposition velocity (see Introduction). The calculation of air concentrations at 1 metre will once again lead to a degree of conservatism in the results.

As was previously stated, two different methods were used to compute the air concentrations of sulphur dioxide. The first uses the Pasquill diffusion curves (Table 4) which have a non-linear variation on log-log graph paper (Figure 2). In Figure 16, the downwind variations of sulphur dioxide air concentrations are plotted by wind direction as a function of distance downwind. The concentrations are annual, 24 hour (combining day and night) averages. All the curves have a peak in the range 200 to 300 metres downwind where the plume initially disperses to ground level from its elevated source. The change in the rate of decrease of the curves at larger distances is probably also related to plume rise from the chimney. Because the plume continues to rise with downwind distance under all stability regimes, this could lead to a secondary maximum at much larger distances (*e.g.* near 10 km).

It appears that the non-linearity in the Pasquill curves could damp out or compensate for this secondary maximum. By contrast, the linear diffusion parameter curves (Figure 17) associated with the wind direction turbulence categories lead to a pronounced maximum near 7 km downwind. Of course, the relative position and magnitude of the maximum and all air concentrations in each wind direction are a function of the frequency of occurrence of wind speeds and stability categories in that particular direction. Thus, the predominating east and south-east wind directions cause higher downwind air concentrations. (The release rate of sulphur dioxide used in these calculations was 25 g s^{-1} and is assumed independent of the plant size.)

The sulphur dioxide annual average air concentrations on the Special Mining Lease (SML) boundary have been summarised in Table 15. With the prevailing east and south-east winds, the highest concentrations occur to the west and north-west of the plant site. The maximum concentration is 1.76 $\mu g\ m^{-3}$ on the north-west boundary. To the north the annual average concentrations fall to 0.15 $\mu g\ m^{-3}$. Because the Regional Centre is to be sited west-north-west (in the direction of the prevailing winds), two sets of figures were computed for both the west and north-west directions (Table 16). Again, the sulphur dioxide concentrations are less than 1 $\mu g\ m^{-3}$.

Concentrations on the Mudginberri Pastoral Lease were calculated at two locations, the closest boundary (3.5 km from the plant) and the homestead (10 km downwind). In this case, it is also important to consider two directions because Mudginberri is approximately north-north-west from the plant site. Because the winds prevail to the north-west sector, with only 4 per cent to the north, the northerly concentrations are decreased by nearly an order of magnitude. In both cases, the highest concentration is only 1.3 $\mu g\ m^{-3}$ on the north-west boundary using the Pasquill method of calculation.

A further important point emerges from the data in Tables 15 and 16. The alternative predictions using the Pasquill stability and wind direction turbulence criteria give some idea of the inaccuracies in the atmospheric dispersion models. In the case of sulphur dioxide, the Pasquill predictions were higher than those of the wind direction turbulence by a factor between 1.5 and 2. The variations for radon gas and uranium dust will be discussed later (Section 14.9).

Observations which may help in understanding the longer range transport of sulphur dioxide have recently become available from a joint Commonwealth Scientific & Industrial Research Organisation, Division of Atmospheric Physics, and Commonwealth Bureau of Meteorology (CSIRO/CBM) field experiment in the Northern Territory [Brook 1975]. Atmospheric boundary layer measurements near Daly Waters have indicated that a semi-permanent inversion (stable) surface exists at an altitude of approximately 1.5 km. This could place an important limit on the vertical diffusion of the sulphur dioxide plume at larger distances downwind.

Another observation could assist knowledge of the night-time atmospheric dispersion conditions. It was common in the joint CSIRO/CBM experiment to detect a low level nocturnal wind jet with wind speeds of 20-30 $m\ s^{-1}$ near 600 metres altitude. Thus the wind speed shear between the surface and plume height could significantly aid downwind transport of the sulphur dioxide. To date, the mean wind speeds measured at 30 metres altitude have been applied to all the atmospheric dispersion calculations. For sulphur dioxide, which has the added advantage of buoyant plume rise, the 30 metre winds would probably be too low. In the case of the radon gas and uranium dust which are released closer to the surface, the 30 metre wind data are probably quite appropriate.

14.6 Peak Concentrations and the Single Source Emitter

Most ambient air quality standards have limits which were established to regulate the atmosphere in industrial areas, where there was a multiplicity of sulphur dioxide sources and the population would be subject to relatively long exposures from a diffuse atmosphere of sulphur dioxide. However, in the case of the Ranger I operations, the acid plant is the sole emitter and the main population centre will be located 9 km to the west-north-west. To cover this type of situation, the US Department of Health, Education and Welfare [USDHEW 1967] have stated that:

> 'In areas affected primarily by large single sources, the SO_2 concentrations are usually below the detectable level, but concentrations of considerable magnitude occur briefly from time to time. In such areas, the taste and odour of SO_2 are of prime concern and control measures designed to alleviate these unpleasant sensations should also prevent more serious health hazards.'

These limits would be 0.5 to 0.7 volumes of sulphur dioxide per 10^6 volumes of air (ppm vv) for odour and 0.3 to 1.0 ppm vv for taste. 0.3 ppm vv would correspond to about 900 $\mu g\ m^{-3}$ [USDHEW 1967].

Winds which would carry gases in the direction of the Regional Centre occur on 25 per cent of all occasions during the year. About 1 per cent of all winds fall into the most stable Pasquill G [Charash F1] stability category. With a release rate of 25 $g\ s^{-1}$, a mean wind speed of 0.9 $m\ s^{-1}$ and a plume rise of 18.8 m (using Equation (6)), the maximum (axial) air concentration of sulphur dioxide at 1 m altitude in the Regional Centre is 36 $\mu g\ m^{-3}$.

To calculate the maximum concentration under fumigation conditions, a formula has been taken from Turner [1970]:

$$\chi_F\ (x,o,o,h) = \frac{Q}{\sqrt{2\pi}\ \bar{u}\ \sigma_{yF}\ h_i}\ , \qquad (18)$$

Both σ_y and σ_z are taken as the diffusion parameters appropriate to the most stable layer which existed before the onset of fumigation. With elimination of the inversion to the effective plume height also assumed as the worst possible case, the ground level concentration is estimated to be 793 $\mu g\ m^{-3}$. This is below the limits set by the USDHEW [1967] for unpleasant sensations from a single source emitter of sulphur dioxide.

At this stage, it is appropriate to discuss the relationship between the 10-20 minute average which has been calculated here, and the peak, short-term concentrations which might be experienced in reality. Ramsdell [1972] has related the long- and short-term averaging times to the peak-to-mean concentrations measured during an atmospheric tracer experiment. He showed that the peak concentrations should be corrected by factors up to values of 4.6. For a three minute air concentration measured on the plume axis, the concentrations calculated above should only be increased by a factor of 1.4.

Turner [1970] has also tabulated the ratios of calculated concentrations to a three minute concentration based on the variation of dispersion coefficients with sampling time [Nonhebel 1960]:

Sampling Time	Ratio of Calculated Concentration to 3 minute Concentration
3 min	1.00
15 min	0.82
1 h	0.61
3 h	0.51
24 h	0.36

Applying these corrections to the 15 minute concentrations estimated above, the 1 metre/3 minute air concentration under stable F1 conditions would be 44 $\mu g\ m^{-3}$ and the ground level fumigation air concentration of sulphur dioxide would be 967 $\mu g\ m^{-3}$; this is just within the threshold for sensitive palates. The frequency of these peak concentrations under fumigation conditions would be very low.

14.7 Radon Gas Atmospheric Dispersion Estimates

The source inventory used for the radon gas incorporates the latest revisions of Cook [1975] and is listed in Table 17. The average release height of the dumps and stockpiles was taken as 25 metres. The tailings dam source height was taken as the height of the retention dam wall, *i.e.* 30 metres. This assumes that there is no transfer of radon gas through the wall but only over the top. The source inventory shows that most release rates have been increased quite significantly compared to those of Strom [1975].

It is important to consider the physical state of the sources in relation to the atmospheric dispersion codes which have been used in the analyses. Except for the releases from the treatment plant, which could be regarded as point sources, all other sources are area sources with finite horizontal dimensions. The differences between predictions from the area and point source diffusion codes only become insignificant at downwind distances greater than several times the horizontal dimension of the area source.

For the current calculations, all radon gas sources are considered to be point sources concentrated in the open pit area. These assumptions could cause some of the predicted concentrations on the SML boundary to be slightly underestimated. Those at the Regional Centre and on the Mudginberri Pastoral Lease should be as accurate as the current diffusion code will predict. All sources were combined to give the predicted contour patterns of air concentration with the different plant capacities (Figures 18 & 19). The data used in plotting the concentration isopleths have been summarised in Table 18.

The source inventory (Table 17) indicates that the major releases of radon gas are from the ground level mining and pit walls; these sources also dominate the downwind decrease of the air concentrations. This contrasts with the predictions from the elevated sulphur dioxide source which produced peaks in concentration at several downwind distances.

The radon gas air concentrations on the SML boundary (calculated at 1 metre above the ground) have been summarised in Table 15. The maximum air concentrations around the boundary were extracted and compared with the predictions prepared for the RUMEIS (Table 19). There is reasonable agreement between the predictions, with the re-analysed set of figures being generally higher. This trend agrees with the increased radon gas release rates. The predictions for radon gas air concentrations at two locations on the Mudginberri Pastoral Lease are also presented in Table 16.

14.8 Uranium Dust Air Concentration Predictions

The release rates for uranium ore and yellowcake estimated for in the RUMEIS are not explicitly divided into day and night releases, although the RUMEIS contains information enabling day and night release rates to be separately derived. The contrast between effects of deposition using the surface depletion model (Horst [1976] and Equation (13)] of this report) and the non-deposition calculations requires a derivation (Table 20) which was, in places, inconsistent with the RUMEIS. The more conservative non-deposition atmospheric diffusion code was applied to a corrected set of release rates (Table 21 and Cook [1975]) for the majority of estimates in the present report.

When comparing the source inventories with those prepared for the RUMEIS, it should be noted that the waste dumps were originally assumed to make no contribution to the amount of uranium dust in the air. In the Introduction, mention was made of resuspension as a mechanism by which the wind, and other disturbing influences, can move dust particles to downwind locations. In the current context, it is the mechanism of suspension from the waste dump surface which will initially make the dust airborne. Resuspension will apply once the dust has been deposited on the ground at some downwind location.

A number of assumptions were necessary in the definition of the suspension source terms. The RUMEIS shows that the waste dump will eventually be the dominating rock pile, rather than the ore and lateritic stockpiles. As a first attempt to define the suspension situation, the waste dump was considered to be the sole source. Although the lateritic stockpile has a higher grade of uranium (0.3 per cent U_3O_8) than the waste dump (0.01 per cent U_3O_8), at the final stage of the No.1 orebody it will contain only 0.08 per cent of the volume in the waste dump. The assumption of the single source term, and the assumptions which follow, highlight the overall uncertainty in the uranium dust source inventories.

At the final stage of the No.1 orebody, the waste dump will contain 60×10^6 tonnes of ore with a 0.01 per cent grade of U_3O_8. If the dump is assumed to be trapezoidal with rectangular top (750×250 m^2) and bottom (1100×470 m^2) surfaces, the height of the dump containing this amount of ore (with a specific gravity of 1.65 g cm^{-3}) will be 107 metres. The total surface area of such a dump will be 6.192×10^5 m^2. At this stage, it is necessary to make an important assumption about the depth of the surface layer of respirable dust particles (radii $\leqslant 2.5$ μm) which are available for suspension. For this calculation, it has been decided that the available layer will contain 200 of the largest particles stacked vertically to give an overall depth of 1 mm. The annual average suspension source terms are then calculated as a function of the mean wind speed (Table 22) using the resuspension rates given by Sehmel & Lloyd [1975].

In the case of the large dust particles, it was thought that dry deposition could result in significant depletion of the plume, with a consequent lowering of air concentration predictions. Sehmel & Hodgson [1975] have used wind tunnel and field experiment data to develop an empirical relationship (Equation (10)) between the dry deposition velocities and other surface features such as the roughness length (z_o) and friction velocity (u_*). The dry deposition velocities were calculated as a function of the mean wind speeds (Table 23) assuming a dust particle diameter of 5 μm and a particle density of 2.65 g cm^{-3} in evaluating the terminal settling velocity, and a logarithmic mean wind speed profile in evaluating u_*. Garratt [1975] measured a value of z_o = 84 cm in the Daly Waters experiment conducted over similar vegetation and terrain.

For the subsequent calculations of uranium dust air concentrations, the height of release from the waste dump pile was taken to be 100 metres. Reference is again made to the source inventories and the relative magnitudes of the various operations. Because most winds are less than 8 m s^{-1} (*i.e.* < $\bar{u}$ = 5.1 m s^{-1}), the waste dump source term will usually be less than 638 pCi s^{-1}. This is comparable to the release rate from the open pit in the daytime, but much smaller than the source terms in the treatment plant area.

Another point to be noted relates to the release from the open pit. It has been stated by Strom [1975] that most of the open pit release comes from the blasting of ore before completion of the daytime activities. Truck movements in the pit were assumed to contribute 5 per cent of the airborne dust over a 12 hour period whereas blasting released 95 per cent as an instantaneous 'puff'. Because the puff would probably rise above ground level, the contribution to downwind exposures is likely to be lower. However, this may be compensated by the much higher source release rate in the instantaneous puff, compared to that over a twelve hour period. Presumably, the decision to blast could be delayed to a certain extent until a more favourable wind was prevailing. In the current calculations, we have used a continuous release rate of uranium dust from the open pit during daytime operations. Once more, the uncertainties in the uranium dust source term are apparent.

Using source inventory No.1, the effects of dry deposition are shown in Figure 20 and Table 24. The most important point to emerge is that the dry deposition air concentrations are lower by more than an order of magnitude. The deposition process also leads to a maximum air concentration between 10 and 100 metres downwind in all directions except north. Even though the dominating sources are between 14 and 26 metres above ground level, there is only a slight change in the rate of decrease of air concentrations with downwind distance for the non-deposition case. This probably results from the combined effect of different source heights and strengths with the frequency of the wind speed and atmospheric stability conditions.

Source inventory No.2 was used to calculate the correct uranium dust air concentrations with the non-deposition atmospheric diffusion code. Isopleths of concentration have been contoured by wind direction and downwind distance for the 3000 and 6000 tonnes per year plants (Figures 21 & 22). The downwind distances at which the contoured isopleths occur have also been tabulated by wind direction and method of computation (Pasquill or wind direction turbulence); the data are given in Table 25. Once again, the contours are asymmetrically oriented, with maximum concentrations in the west and north-west sectors.

All point sources for the uranium dust were again assumed to be concentrated in the treatment plant area. The air concentrations at 1 metre were then estimated along the SML boundary (Table 15). As with the radon gas, the turbulence method yields higher uranium dust estimates than that of Pasquill. The maximum concentration on the north-east boundary for the 3000 tonnes per year plant is 6.5×10^{-3} pCi m^{-3}; the north-east boundary is higher than the north-west because it is 1500 metres closer to the source and there is a secondary peak of winds to this sector. For the 6000 tonnes per year plant, the maximum air concentration of 1.18×10^{-2} pCi m^{-3} occurs both on the north-east and north-west boundaries. At the Regional Centre, the maximum air concentration from all sources of uranium dust was 1.48×10^{-3} pCi m^{-3} for the 3000 tonnes per year plant and 2.65×10^{-3} pCi m^{-3} for the 6000 tonnes per year plant (Table 16). Similar estimates have been made for the Mudginberri Pastoral Lease.

14.9 Estimation of Annual Doses to Individuals at the Regional Centre

In a separate calculation, using the yellowcake source alone, the maximum uranium dust concentration (in the north-west direction) at the Regional Centre was estimated to be 1.05×10^{-3} pCi m^{-3} for the 3000 tonnes per year plant and 1.87×10^{-3} pCi m^{-3} for the 6000 tonnes per year plant (using the turbulence method) (see Appendix A for separate ore and yellowcake contributions to other receptors in the area). The dose per unit exposure relationships for the various radioactive elements (see Table 2 of the RUMEIS backup document, supplement 1 to item XV) were then applied to the maximum concentrations from all sources, and also the yellowcake process alone, to give the maximum dose to individuals at the Regional Centre (Table 26). The predicted annual doses were lower than those given in RUMEIS. They are only a small fraction of the dose limits set by the National Health and Medical Research Council (NHMRC [1967] and Table 27 of this report); the maximum dose to the bone of a child only represents about 4.9 per cent of the annual dose limit.

It should be emphasised again that these figures are very conservative and apply only to the non-deposition case for the dispersion of uranium dust in the atmosphere. As was discussed previously, when dry deposition is included, the predicted estimates of air concentrations for the dust will be lowered by about an order of magnitude. However, with uncertainties in the source terms and the use of empirical models (unverified in all atmospheric situations) for the dry deposition velocity the situation of uranium dust dispersion should be fully investigated during the surveillance program.

15. SUMMARY AND CONCLUSIONS

The current re-analysis of meteorological data from the Jabiru site has mainly concentrated on the wind records and atmospheric dispersion estimates. In a test case, dry deposition models were applied to the uranium dust dispersion. The empirical relationship by which the dry deposition velocity was calculated is largely untested in the real atmosphere, having been developed mainly in laboratory wind tunnel experiments.

There has been insufficient time to consider the questions of particulate and gaseous rain-out, acid misting and acid rain downwind of the sulphuric acid plant. Judging from the estimated annual average sulphur dioxide air concentrations, it is thought that the increased soil acidification probably will be insignificant. Most of the deleterious effects of acid rain which have been investigated result from a large number of sulphur dioxide emissions in an industrial area, not from a single source such as that which will be operating at the Jabiru site. In general, the effects of rain-out will be to decrease the air concentrations of all particulate and gaseous aerosols, even though this may be a transient atmospheric cleansing mechanism.

In the time allowed, it was also not practical to consider the complex problem of translocation of the uranium dust from its deposited location by means of resuspension. This subject requires further study especially from the viewpoint of the nature and quantities of dust deposited and then resuspended. The source terms for uranium dust in general require a more comprehensive examination.

The recovery of consistent, high quality climatological wind data from the Jabiru area was not good. The best anemometer only operated with an 80 per cent efficiency and the worst recovered 57 per cent of good data. There was no evidence of any calibration procedures for the anemometers and therefore the accuracy of the data is in doubt.

During the wet season, winds prevailed from the west and north-west at lower levels but, overall, east and south-east winds predominated. There was a very low frequency of occurrence of near calm conditions with minimal dispersive capacity. By subdividing the wind direction turbulence categories into Pasquill stability categories, it was shown that the most stable (F and F1) conditions occurred on 14 per cent of all occasions.

Dry deposition was not included as a plume depletion mechanism for the sulphur dioxide and radon gas calculations. Using the plume rise formulae recommended by Briggs [1969], the annual average air concentration for sulphur dioxide at 1 metre was estimated to be a maximum of 1.65 $\mu g\ m^{-3}$ on the north-west SML boundary. However, it is probably the peak short-term concentration which is the most important for the single source emitter. Under the most stable (F1) conditions, the peak concentration (10-20 minute average) was 36 $\mu g\ m^{-3}$. With fumigation capped by an elevated inversion, the maximum ground level concentration, over the same period was estimated to be 793 $\mu g\ m^{-3}$.

The ground level open pit source dominated the radon gas calculations. Radon gas air concentrations using the re-analysed meteorological data were a little higher than those in the RUMEIS because of a revision in the source inventory. By including the effects of deposition in the uranium dust calculations, the air concentrations were predicted to be lower by about an order of magnitude. However, all the major results presented were from the non-deposition atmospheric diffusion code. The predicted annual radiation doses to members of the public in the Regional Centre were all lower than those presented in the RUMEIS. This was in accord with the re-analysed atmospheric stability data which showed a tendency to the less stable, more dispersive conditions.

Uncertainties exist with all these results because of both the source inventories and atmospheric dispersion codes used in the calculations. The Pasquill and wind direction turbulence dispersion curves gave two alternative sets of predictions which were in reasonable agreement. Even then, the diffusion parameters did not account for the increased dispersive effects of surface roughness, topography and vegetation elements. Also, because dry deposition was not included in the majority of the calculations presented here, it is thought that the results are still quite conservative.

16. SOME SUGGESTIONS FOR AN ENVIRONMENTAL SURVEILLANCE PROGRAM - METEOROLOGICAL ASPECTS

To improve the quality of all meteorological data, calibration procedures should be formalised. It is suggested that all instruments should be calibrated in a standards laboratory facility (such as the CSIRO Division of Atmospheric Physics in Victoria) both before and after the climatological study at the site. Regular *in situ* instrument checks should be conducted thereafter. Documentation of all charts should be completed on a twice-weekly, if not daily basis. This would also improve the collection of good quality data.

In the past, the maximum height of the wind and temperature measurements was 30 metres above ground level. To study the influence of the vertical shear of wind speed and direction, on the dispersion of sulphur dioxide especially, it is suggested that a short-term experiment be undertaken to measure these parameters to heights of approximately 1000 metres. The dispersive influence of the low level nocturnal wind jet and wind variations through the Ekman boundary layer over the Jabiru site could then be fully assessed.

To date, the long-term atmospheric stability data have been obtained from the fixed installation of two thermographs on the meteorological tower (2 m and 27 m above the ground). Measurements of vertical gradients in the lowest 30 metres of the atmosphere usually overestimate the stable profile and underestimate the unstable atmospheric stability. Preliminary balloon soundings did, in fact, indicate an overestimation of the inversion strengths by the thermograph method; however, no corrections were then applied to the thermograph data. Therefore, it is suggested that further temperature profiling experiments be undertaken so that the tower data can be calibrated to conditions prevailing higher in the atmosphere. The tower measured temperature gradients would then be applied to the USAEC [1972] guidelines to define the prevailing Pasquill stability categories.

For atmospheric dispersion predictions, the main importance of temperature gradient measurements is in the definition of the Pasquill stability categories (using a criterion suggested by the USAEC [1972]) and also in the buoyant plume rise calculations. Even though the plume rise calculations used the latest available model, there are still uncertainties in the results. As well as the temperature profiling studies, it is also suggested that an *in situ* measurement be made of the sulphur dioxide air concentrations, both for peak and 10-20 minute average.

With prevailing winds from the east and south-east sectors, most of the aerosols will be transported away from the Mount Brockman escarpment and Arnhem Land plateau over the reasonably homogeneous, undulating plains to the west. Even under these uniform terrain conditions, it is important to investigate the horizontal inhomogeneity in the wind fields. It is suggested that anemometers be placed at least 10 metres above the ground on well exposed sites at several strategic locations in the region, *e.g.* the Regional Centre and Mudginberri homestead. The measurements will be very important to the predictions of aerosol concentrations from near ground level releases. In particular, translocation of re-suspended uranium dust may be described more accurately.

The relative importance of dry deposition and resuspension mechanisms has not been fully investigated in the current re-examination of the Jabiru meteorological data, nor in the RUMEIS. It appears important to measure the particle size spectrum of uranium dust at several down-wind distances to determine the effect of dispersion and deposition to the surface. It is also suggested that in a short-term experiment, the surface roughness length (z_o) and turbulence generated by the surface (*e.g.* surface friction velocity, u_*) be measured near the Jabiru site. These are important parameters which were used in the empirical equation to determine the dry deposition velocity. It is suggested that a laboratory with considerable expertise in the subjects of dry deposition and resuspension be consulted on these matters for the Jabiru situation. One such laboratory might be the Atmospheric Sciences Department, Battelle Pacific NW Laboratories, (BNWL), Richland, Washington State, USA.

In summary, the current meteorological surveillance program should be improved and extended. It is also important that the source inventories used in the RUMEIS and the current re-analysis be confirmed by *in situ* measurements.

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19. NOMENCLATURE

a	Aerosol radius	mm
B	Empirical constant which sometimes varies with atmospheric stability	-
C	Empirical constant which sometimes varies with atmospheric stability	-
c_1	A constant $\sim \frac{1}{2}$	-
d	Particle diameter	cm
D	Particle diffusivity	$cm^2\ s^{-1}$
$D(x,y,z,h)$	Bivariate Gaussian diffusion function $\left(= \frac{\chi(x,y,z,h)}{Q}\right.$ see Equation (1))	$s\ m^{-3}$
$\bar{D}(x,z,h)$	Crosswind averaged bivariate Gaussian diffusion function	$s\ m^{-2}$
$E(a,R_m)$	Collection efficiency	-
$E_w(a)$	Raindrop collection efficiency $= k_1 E_d(a)$	-
$E_d(a)$	Correction factor accounting for the difference in collection efficiency between particulates and gases	-
$f(\theta,s,m)$	Wind probability density function	-
g	Gravitational acceleration constant	$m\ s^{-2}$
h	Effective chimney source height	m
H	Atmospheric mixing layer depth	m
h_i	Depth of mixing layer during worst case atmospheric fumigation conditions = $h+2\sigma_{zG(F1)}$	m
h_s	Chimney stack height	m
h_v	Height of vegetation elements	m
Δh	Plume rise	m
J_o	Rainfall rate	$mm\ h^{-1}$
k	Van Karman's constant (~ 0.4)	-
k_1	Constant (~ 0.2)	-
L	Monin-Obukhov stability length	m
m	Wind speed class	-
$\dot{m}''$	Water vapour flux to the surface	$g\ cm^{-2}\ s^{-1}$
Γ	Dry adiabatic lapse rate of temperature $= \frac{1K}{100\ m}$	$K\ m^{-1}$
ε	Retention efficiency, for atmospheric aerosol particles $\simeq 1$	-
θ	Horizontal wind direction	o

Θ	Potential temperature	K
$\Lambda(a)$	Washout coefficient	s^{-1}
ν	Kinematic viscosity of air	$cm^2\ s^{-1}$
ρ_p	Particle density	$g\ cm^{-3}$
σ_y	Lateral or crosswind diffusion coefficient	m
σ_{yF}	Effective lateral diffusion coefficient under atmospheric fumigation conditions $= \sigma_{yG(Fl)} + \frac{h}{8}$	m
$\sigma_{yG(Fl)}$	Lateral diffusion coefficient under Pasquill G(Fl) stability conditions	m
σ_z	Vertical diffusion coefficient	m
$\sigma_{zG(Fl)}$	Vertical diffusion coefficient under Pasquill G(Fl) stability conditions	m
σ_{zs}	Vertical diffusion parameter, a function of s	m
σ_θ	Standard deviation of horizontal wind direction	o
σ_ϕ	Standard deviation of vertical wind direction	o
τ	Particle relaxation time	s
$\chi(x,y,z,h)$	Air concentration at some reference level (units depend on source type, *e.g.* sulphur dioxide = g, uranium dust = pCi)	units m^{-3}
χ_o	Initial air concentration	units m^{-3}
$\frac{\Delta T}{\Delta z}$	Vertical temperature gradient	K m^{-1}
$\frac{\partial \Theta}{\partial z}$	Vertical gradient of potential temperature	K m^{-1}
$\overline{w'\Theta'}$	Time averaged vertical sensible heat flux	mW cm^{-2}
n(a)	Raindrop probability density function	-
N	Deposition flux	$g\ m^{-2}\ s^{-1}$
Q	Source strength (see χ for explanation of units)	units s^{-1}
Q_o	Undepleted source strength at x = o	units s^{-1}
R_m	Mean raindrop radius	mm
R_o	Chimney stack radius	m
s	Atmospheric stability class	-
S	Stability parameter	-
Sc	Schmidt number $(= \frac{\nu}{D})$	-
St	Stokes number for a turbulent fluid $(= \frac{\tau u_*^2}{\nu})$	-

t	Downwind diffusion time	s
T_{Eo}	Ambient temperature	K
T_{Po}	Temperature of plume gases at the chimney stack top	K
$\bar{u}$	Mean wind speed (at source height in diffusion formulae)	m s^{-1}
u_*	Surface friction velocity	cm s^{-1}
v_d	Dry deposition velocity	cm s^{-1}
v_t	Gravitational settling speed	cm s^{-1}
w	Vertical velocity	m s^{-1}
w_o	Gas effluent velocity at chimney stack top	m s^{-1}
x	Downwind distance	m
y	Lateral displacement from the plume centreline	m
z	Height	m
z_d	Air concentration reference level	m
z_o	Surface roughness length	cm
α	Empirical constant which sometimes varies with atmospheric stability	
β	Numerical factor of the order of 1	-
γ	Numerical factor of the order of 1	-

TABLE 1

GENERAL WEATHER CRITERIA USED TO DEFINE THE PASQUILL STABILITY CATEGORIES [PASQUILL 1961]

Surface wind speed (at 10 m), (m s^{-1})	Day			Night	
	Incoming solar radiation			Thinly overcast or ≥4/8 Low cloud	≤3/8 cloud
	Strong	Moderate	Slight		
< 2	A	A-B	B		
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
> 6	C	D	D	D	D

The neutral class, D, should be assumed for overcast conditions during day or night.

TABLE 2

EXTENDED GENERAL WEATHER CRITERIA USED TO DEFINE THE PASQUILL STABILITY CATEGORIES [CHARASH 1972]

Surface wind speed (m s^{-1})	By day (Incoming solar radiation)			By night (Outgoing terrestrial radiation)		
	Strong	Moderate	Slight	Slight	Moderate	Strong
< 2	A	A-B	B	F-F_1	F-F_1	F_1
2-3	A-B	B	C	E	F	F_1
3-5	B	B-C	C	D	E	F_1
5-6	C	C-D	D	D	D	D
> 6	C	D	D	D	D	D

TABLE 3

USAEC [1972] CRITERIA FOR DEFINING THE PASQUILL STABILITY CATEGORIES

Stability classification	Pasquill categories	σ_θ* (deg.)	Temperature change with height (°C/100 m)
Extremely unstable	A	25.0	< -1.9
Moderately unstable	B	20.0	-1.9 to -1.7
Slightly unstable	C	15.0	-1.7 to -1.5
Neutral	D	10.0	-1.5 to -0.5
Slightly stable	E	5.0	-0.5 to 1.5
Moderately stable	F	2.5	1.5 to 4.0
Extremely stable	G	1.7	> 4.0

* *standard deviation of horizontal wind direction fluctuation taken over a period of 15 minutes to 1 hour.*

TABLE 4

ANALYTICAL EXPRESSIONS FOR THE DIFFUSION PARAMETERS AS A FUNCTION OF DOWNWIND DISTANCE (x) AND PASQUILL STABILITY CATEGORIES - OVER HOMOGENEOUS TERRAIN [BRIGGS 1974]

Pasquill stability category	Diffusion parameter	
	σ_y	σ_z
A	$0.22x(1 + 10^{-4}x)^{-\frac{1}{2}}$	$0.20x$
B	$0.16x(1 + 10^{-4}x)^{-\frac{1}{2}}$	$0.12x$
C	$0.11x(1 + 10^{-4}x)^{-\frac{1}{2}}$	$0.08x(1 + 2\cdot10^{-4}x)^{-\frac{1}{2}}$
D	$0.08x(1 + 10^{-4}x)^{-\frac{1}{2}}$	$0.06x(1 + 1.5\cdot10^{-3}x)^{-\frac{1}{2}}$
E	$0.06x(1 + 10^{-4}x)^{-\frac{1}{2}}$	$0.03x(1 + 3\cdot10^{-4}x)^{-1}$
F	$0.04x(1 + 10^{-4}x)^{-\frac{1}{2}}$	$0.02x(1 + 3\cdot10^{-4}x)^{-1}$
G(F1)*	$0.02x(1 + 10^{-4}x)^{-\frac{1}{2}}$	$0.008x(1 + 3\cdot10^{-4}x)^{-1}$

* *G(F1) added by comparing Charash [1972] and Briggs [1974] curves and formulae*

TABLE 5

ANALYTICAL EXPRESSIONS FOR THE DIFFUSION PARAMETERS AS A FUNCTION OF DOWNWIND DISTANCE (x) AND WIND DIRECTION TURBULENCE CATEGORY OVER HOMOGENEOUS TERRAIN

Turbulence category	σ_y	σ_z
1	$0.37x^{0.96}$	$0.48x^{0.96}$
2	$0.36x^{0.86}$	$0.33x^{0.86}$
3	$0.40x^{0.91}$	$0.41x^{0.91}$
4	$0.32x^{0.78}$	$0.22x^{0.78}$
5	$0.31x^{0.71}$	$0.05x^{0.71}$
6	$0.32x^{0.73}$	$0.076x^{0.73}$
7	$0.33x^{0.73}$	$0.10x^{0.74}$
8	$0.34x^{0.735}$	$0.081x^{0.735}$
9	$0.35x^{0.74}$	$0.091x^{0.735}$
10	$0.35x^{0.70}$	$0.056x^{0.70}$

TABLE 6

A TABLE RELATING THE WIND SPEED, DIRECTION TURBULENCE TRACE TYPES AND THE PASQUILL-TYPE STABILITY CATEGORIES [CLARK & BENDUN 1974]

Turbulent trace type	Wind speed ($m\ s^{-1}$)									
	0 < 1		1 < 2		2 < 4		4 < 8		> 8	
	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day
1	75 D 25 E	100 A	75 D 25 E	100 A	80 D 20 E	90 A 10 B	5 C 85 D 10 E	80 A 20 B	10 C 90 D	70 A 30 B
2	60 B 30 C 10 D	50 B 40 C 10 D	45 B 35 C 20 D	40 B 45 C 15 D	25 B 40 C 35 D	30 B 35 C 35 D	15 B 40 C 45 D	20 B 30 C 50 D	15 B 30 C 55 D	5 B 30 C 65 D
3	30 B 60 C 10 D	100 A 0 B 0 C	25 B 65 C 10 D	90 A 10 B 0 C	20 B 60 C 20 D	85 A 10 B 5 C	15 B 50 C 35 D	75 A 15 B 10 C	10 B 40 C 50 D	60 A 20 B 20 C
4	10 B 60 C 30 D	20 B 70 C 10 D	10 B 50 C 40 D	15 B 75 C 10 D	5 B 45 C 50 D	10 B 65 C 25 D	5 B 35 C 60 D	8 B 55 C 37 D	2 B 33 C 65 D	5 B 35 C 60 D
5	0 F 100 F1	0 E 100 F	5 F 95 F1	10 E 90 F	10 F 90 F1	20 E 80 F	20 F 80 F1	30 E 70 F	30 F 70 F1	40 E 60 F
6	5 D 5 E 90 F	20 C 40 D 40 E	10 D 10 E 80 F	15 C 50 D 35 E	10 D 20 E 70 F	15 C 55 D 30 E	20 D 30 E 50 F	10 C 65 D 25 E	35 D 40 E 25 F	10 C 75 D 15 E
7	10 C 10 D 80 E	20 B 60 C 20 D	10 C 20 D 70 E	20 B 55 C 25 D	10 C 35 D 55 E	15 B 50 C 35 D	5 C 50 D 45 E	15 B 45 C 40 D	5 C 55 D 40 E	10 B 40 C 50 D
8	10 C 20 D 70 E	20 B 50 C 30 D	10 C 25 D 65 E	20 B 50 C 30 D	10 C 35 D 55 E	15 B 55 C 30 D	5 C 50 D 45 E	10 B 50 C 40 D	5 C 60 D 35 E	10 B 40 C 50 D
9	10 C 20 D 70 E	20 B 50 C 30 D	10 C 25 D 65 E	20 B 50 C 30 D	10 C 35 D 55 E	15 B 55 C 30 D	5 C 50 D 45 E	10 B 50 C 40 D	5 C 60 D 35 E	10 B 40 C 50 D
10	0 F 100 F1	0 D 10 E 90 F	0 F 100 F1	0 D 15 E 85 F	5 F 95 F1	5 D 35 E 60 F	5 F 95 F1	15 D 50 E 35 F	20 F 80 F1	20 D 55 E 25 F

Frequency measured in per cent.

TABLE 7

SURFACE ROUGHNESS PARAMETERS AS A FUNCTION OF SURFACE TYPE [GARRATT 1976]

Surface type	Source of data	h (m)	d (m)	z_o (cm)	z_o/h	Comments
1) Very sparse grass	Clarke *et al.* [1971]	0.02-0.03	zero	0.12	0.048	
2) Fields	"	~ 0.10	?	0.6	0.06	
3) Cotton bush	"	0.40	?	2.0	0.05	
4) Grassland	Moore [1975]	0.25	~ h	1.0	0.04	Dense grass
5) Grass	Deacon [1953]	0.015 0.45 0.65		0.2 1.7 3.7	0.13 0.04 0.06	Low wind speed cases omitted due to to Reynolds' number effect
6) Wheat crop	Garratt (unpublished)	0.25 0.40 1.00 1.10	~ .8h ~ .9h	0.5 1.5 5.0 7.0	0.02 0.038 0.05 0.064	These data follow the growth of a single wheat crop through the season; thus the physical characteristics would change considerably: from sparse distribution of elements at start of season to a dense cover of main (stem) and secondary (leaves, ears) elements at end of season
7) Corn field	Kung [1961]	0.8	~ h	6.4	0.08	Results for the orange orchard, fir forest and Idaho forest omitted due to suspect data.
8) Brush field	"	1.3	~ h	15.7	0.12	
9) Bean crop	Thom [1971]	1.18	0.88	7.4	0.065	
10) Vineyard	Hicks [1973]	0.90-1.40	?	(i) 3.0	0.026	(i) Wind blowing parallel to rows
				(ii) 10.0	0.087	(ii) Wind blowing normal to rows. Each row was some 1 m width, and a separation of ~ 5m between rows
11) Pine forest	Hicks *et al.* [1975]	12.4	9.8	32	0.026	
		13.3	11.9	54	0.041	
12) Scattered trees and scrub	Garratt (unpublished)	8-10	~ 5	(i) 45	0.05	(i) Trees (scattered) with average separation ~ 10-20 m
		8-10	~ 5	(ii) 85	0.09	(ii) Trees with average separation ~ 5-10 m

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TABLE 8

ANALYTICAL EXPRESSIONS FOR THE DIFFUSION PARAMETERS AS A FUNCTION OF DOWNWIND DISTANCE (x) AND PASQUILL STABILITY CATEGORIES - IN AN URBAN ENVIRONMENT [BRIGGS 1974]

Pasquill stability category	Diffusion parameter	
	σ_y	σ_z
A-B	$0.32x(1 + 4\cdot10^{-4}x)^{-\frac{1}{2}}$	$0.24x(1 + 10^{-3}x)^{-\frac{1}{2}}$
C	$0.22x(1 + 4\cdot10^{-4}x)^{-\frac{1}{2}}$	$0.20x$
D	$0.16x(1 + 4\cdot10^{-4}x)^{-\frac{1}{2}}$	$0.14x(1 + 3\cdot10^{-4}x)^{-\frac{1}{2}}$
E-F	$0.11x(1 + 4\cdot10^{-4}x)^{-\frac{1}{2}}$	$0.08x(1 + 1.5\cdot10^{-3}x)^{-\frac{1}{2}}$

TABLE 9

WIND INSTRUMENTS PERFORMANCE - per cent DATA RECOVERY

Season		Jabiru airstrip 10 m	Meteorological tower 15 m	Meteorological tower 30 m
Wet	Good	69.8	67.8	50.5
	Bad	30.2	32.2	49.5
Dry	Good	85.5	51.3	80.1
	Bad	14.5	48.7	19.9
All	Good	80.3	56.8	70.3
	Bad	19.7	43.2	29.7

Wet season = Dec., Jan., Feb., Mar.
Dry season = All other months.

Bad = no data available + bad data.

TABLE 10

MEAN WIND SPEED ($\bar{u}$) AS A FUNCTION OF WIND SPEED CLASS FOR THE 30 metre WIND DATA

Wind speed class (m s^{-1})	$\bar{u}$ (m s^{-1})
0-1	0.9
1-2	1.6
2-4	3.0
4-8	5.1
> 8	9.3

TABLE 11

A COMPARISON BETWEEN WIND DIRECTION FREQUENCIES USED IN THE ENVIRONMENTAL IMPACT STATEMENT AND THOSE FROM THE RE-ANALYSIS

Data source	N	NE	E	SE	S	SW	W	NW
Table XV 5.1 (supporting document)* [Strom 1975]	13	8	29	18	6	7	9	10
Reanalysis** Jabiru airstrip	10.7	8.4	25.2	26.0	5.0	7.1	6.6	11.0
30 metre meteorological tower	8.7	8.1	24.0	26.0	4.2	13.5	6.6	8.9

* data from June 1971 to March 1973 from the Jabiru airstrip.

** data from May 1973 to May 1975.

TABLE 12

FREQUENCY OF OCCURRENCE(%) OF WIND DIRECTION TURBULENCE CATEGORIES VERSUS WIND SPEED- ALL TIMES AND DIRECTIONS COMBINED FOR THE 30 metre TOWER DATA

WIND SPEED (m s^{-1})

Turbulence	0-1	1-2	2-4	4-8	>8	Total
1	0.15	2.52	4.94	0.47	0.00	8.08
2	0.01	0.28	6.87	8.20	0.06	15.43
3	0.05	1.12	11.31	7.79	0.02	20.29
4	0.00	0.03	0.63	2.25	0.06	2.97
5	0.85	2.60	1.93	0.05	0.00	5.44
6	0.18	2.31	5.05	0.37	0.00	7.90
7	0.08	2.81	13.06	2.59	0.00	18.55
8	1.33	5.52	1.87	0.01	0.00	8.73
9	0.17	3.63	4.31	0.11	0.00	8.21
10	2.23	2.07	0.11	0.00	0.00	4.41
TOTAL	5.05	22.90	50.08	21.84	0.14	12309.

The total number of hourly observations is recorded in the lower right hand corner of the table.

TABLE 13

FREQUENCY OF OCCURRENCE(%) OF PASQUILL STABILITY CATEGORIES VERSUS WIND SPEED - ALL TIMES AND DIRECTIONS COMBINED FOR THE 30 metre TOWER DATA

WIND SPEED (m s^{-1})

Pasquill	0-1	1-2	2-4	4-8	>8	Total
A	0.20	3.50	13.64	6.12	0.01	23.47
B	0.17	1.02	4.44	3.01	0.01	8.65
C	0.52	3.02	8.03	4.78	0.04	16.40
D	0.43	3.52	10.36	6.46	0.08	20.84
E	0.62	5.78	8.79	1.27	0.00	16.46
F	0.97	2.41	3.34	0.15	0.00	6.87
F1	2.15	3.65	1.50	0.03	0.00	7.32
Total	5.05	22.91	50.09	21.82	0.14	12306.

The total number of hourly observations is recorded in the lower right hand corner of the table.

TABLE 14

FREQUENCY OF OCCURRENCE(%) OF PASQUILL STABILITY CATEGORIES VERSUS WIND DIRECTION

Pasquill stability category		Wind direction								
		N	NE	E	SE	S	SW	W	NW	Total
A	1	1.92	2.93	6.89	4.32	1.27	2.34	2.02	1.78	23.47
	2									0
B	1	0.83	0.70	2.31	2.21	0.32	1.05	0.47	0.76	8.65
	2	4.17		12.5	12.5			4.17	4.17	37.51
C	1	1.54	1.04	3.87	4.72	0.57	2.37	0.80	1.49	16.40
	2	4.17						4.17	4.17	12.51
D	1	1.77	1.22	4.67	6.55	0.61	3.18	0.96	1.89	20.84
	2									0
E	1	1.36	1.26	3.49	4.49	0.55	2.39	1.13	1.77	16.46
	2									0
F	1	0.41	0.32	1.67	1.99	0.30	1.04	0.53	0.60	6.87
	2	3.13	3.13	3.13	3.13	3.13	3.13	3.13	3.13	25.04
F1	1	0.85	0.59	1.13	1.70	0.57	1.14	0.70	0.63	7.32
	2			12.5	12.5					25.0

1 = Re-analysis statistics: 30th April 1973 to 1st May 1975.
2 = Statistics from Table 3 in the Back-up Document Supplement 1, Item XV [Strom 1975] June 1971 to March 1973.

TABLE 15

AIR CONCENTRATIONS (AT 1 metre ALTITUDE) ON THE SML BOUNDARY; ANNUAL AVERAGES

ASSUMING ALL SOURCES LOCATED AT THE PLANT SITE, UNLESS OTHERWISE STATED

Source information	Computational Method	Direction from plant site N	NE	E	SE	S	SW	W	NW	
SO_2 (g m^{-3}) 3000 or 6000 tonne y^{-1}	Pasquill	2.6×10^{-7}	1.08×10^{-6}	4.9×10^{-7}	6.3×10^{-7}	5.2×10^{-7}	3.0×10^{-7}	1.4×10^{-6}	1.65×10^{-6}	
	Turbulence	1.5×10^{-7}	5.0×10^{-7}	3.3×10^{-7}	3.1×10^{-7}	2.7×10^{-7}	3.0×10^{-7}	8.3×10^{-7}	8.3×10^{-7}	
Uranium dust (pCi m^{-3}) 3000 tonne y^{-1} Pasquill method	no deposition	2.1×10^{-3}	5.2×10^{-3}	3.9×10^{-3}	3.4×10^{-3}	2.2×10^{-3}	8.2×10^{-4}	4.3×10^{-3}	4.9×10^{-3}	Source inventory No.1
	with deposition	1.9×10^{-4}	5.5×10^{-4}	4.1×10^{-4}	3.1×10^{-4}	1.5×10^{-4}	4.8×10^{-5}	3.6×10^{-4}	3.9×10^{-4}	
Uranium dust (pCi m^{-3}) (no deposition) 3000 tonne y^{-1}	Pasquill	1.84×10^{-3}	4.55×10^{-3}	3.4×10^{-3}	2.95×10^{-3}	1.93×10^{-3}	7.4×10^{-4}	3.75×10^{-3}	4.38×10^{-3}	
	Turbulence	2.75×10^{-3}	6.5×10^{-3}	4.85×10^{-3}	4.34×10^{-3}	2.73×10^{-3}	9.8×10^{-4}	5.7×10^{-3}	6.3×10^{-3}	Source inventory No.2
Uranium dust (pCi m^{-3}) (no deposition) 6000 tonne y^{-1}	Pasquill	3.27×10^{-3}	8.3×10^{-3}	6.2×10^{-3}	5.3×10^{-3}	3.48×10^{-3}	1.33×10^{-3}	6.6×10^{-3}	7.7×10^{-3}	
	Turbulence	4.9×10^{-3}	1.18×10^{-2}	8.4×10^{-3}	7.7×10^{-3}	4.8×10^{-3}	1.78×10^{-3}	1.02×10^{-2}	1.18×10^{-2}	
Radon gas* (µCi m^{-3}) 3000 tonne y^{-1}	Pasquill	1.95×10^{-5}	4.9×10^{-5}	4.77×10^{-5}	5.35×10^{-5}	3.9×10^{-5}	1.85×10^{-5}	6.55×10^{-5}	4.75×10^{-5}	
	Turbulence	2.75×10^{-5}	7.05×10^{-5}	6.8×10^{-5}	7.9×10^{-5}	5.25×10^{-5}	2.72×10^{-5}	9.8×10^{-5}	6.8×10^{-5}	
Radon gas* (µCi m^{-3}) 6000 tonne y^{-1}	Pasquill	2.34×10^{-5}	6.08×10^{-5}	5.8×10^{-5}	6.4×10^{-5}	4.68×10^{-5}	2.26×10^{-5}	8.3×10^{-5}	5.8×10^{-5}	
	Turbulence	3.6×10^{-5}	8.95×10^{-5}	8.8×10^{-5}	1.03×10^{-4}	6.68×10^{-5}	3.35×10^{-5}	1.28×10^{-4}	8.7×10^{-5}	

* *Because the open pit source dominates, all point sources for the radon gas are assumed located at the open pit and SML Boundary concentrations are calculated accordingly.*

TABLE 16

AIR CONCENTRATIONS (AT 1 metre ALTITUDE) AT CENTRES OUTSIDE THE SML BOUNDARY; ANNUAL AVERAGES ASSUMING ALL SOURCES LOCATED AT THE PLANT SITE

Source information	Computational method	Location						
		Regional centre		Mudginberri Pastoral Lease				
				Homestead		Closest boundary		
		West	North-west	North-west	North	North-west	North	
Sulphur dioxide ($g\ m^{-3}$) 3000 or 6000 tonne y^{-1}	Pasquill	6.12×10^{-7}	7.51×10^{-7}	6.76×10^{-7}	9.8×10^{-8}	1.28×10^{-6}	1.97×10^{-7}	
	Turbulence	8.3×10^{-7}	9.72×10^{-7}	9.2×10^{-7}	1.6×10^{-7}	1.01×10^{-6}	1.1×10^{-7}	
Uranium dust ($pCi\ m^{-3}$) Pasquill method 3000 tonne y^{-1}	no deposition	1.08×10^{-3}	1.41×10^{-3}	1.24×10^{-3}	3.46×10^{-4}	2.99×10^{-3}	1.24×10^{-3}	Source inventory No.1
	with deposition	4.42×10^{-5}	5.25×10^{-5}	4.21×10^{-5}	8.29×10^{-6}	1.76×10^{-4}	7.3×10^{-5}	
Uranium dust ($pCi\ m^{-3}$) (no deposition) 3000 tonne y^{-1}	Pasquill	9.69×10^{-4}	1.26×10^{-3}	1.10×10^{-3}	3.08×10^{-4}	2.67×10^{-3}	1.11×10^{-3}	Source inventory No.2
	Turbulence	1.20×10^{-3}	1.48×10^{-3}	1.25×10^{-3}	3.52×10^{-4}	3.73×10^{-3}	1.6×10^{-3}	
Uranium dust ($pCi\ m^{-3}$) (no deposition) 6000 tonne y^{-1}	Pasquill	1.75×10^{-3}	2.28×10^{-3}	2.00×10^{-3}	5.56×10^{-4}	4.81×10^{-3}	1.9×10^{-3}	
	Turbulence	2.14×10^{-3}	2.65×10^{-3}	2.23×10^{-3}	6.25×10^{-4}	6.66×10^{-3}	2.88×10^{-3}	
Radon gas ($\mu Ci\ m^{-3}$) 3000 tonne y^{-1}	Pasquill	1.49×10^{-5}	1.91×10^{-5}	1.67×10^{-5}	4.71×10^{-6}	3.25×10^{-5}	1.35×10^{-5}	
	Turbulence	1.89×10^{-5}	2.30×10^{-5}	1.93×10^{-5}	5.52×10^{-6}	4.38×10^{-5}	1.90×10^{-5}	
Radon gas ($\mu Ci\ m^{-3}$) 6000 tonne y^{-1}	Pasquill	1.84×10^{-5}	2.34×10^{-5}	2.04×10^{-5}	5.84×10^{-6}	4.00×10^{-5}	1.64×10^{-5}	
	Turbulence	2.43×10^{-5}	2.92×10^{-5}	2.45×10^{-5}	7.15×10^{-6}	5.58×10^{-5}	2.52×10^{-5}	
Distance from plant site (open pit for radon*)		9 km		10 km		5 km * 6 km	3.5 km 4.4 km	

TABLE 17

RADON GAS SOURCE INVENTORY

Source	Release height (m)	Time	Source strength (μ Ci s^{-1})	Plant size (tonne y^{-1})
Mining and Pit Walls	0	Day Night	113.4 60.2	3000
		Day Night	166.6 60.2	6000
Dumps and stockpiles	25	Day Night	30.1 30.1	3000
		Day Night	30.1 30.1	6000
Crushing plant	25.9	Day Night	53.2 0	3000
		Day Night	106.4 0	6000
Milling plant	13.7	Day Night	19.7 19.7	3000
		Day Night	39.4 39.4	6000
Tailings Dam	30	Day Night	45.1 45.1	3000
		Day Night	45.1 45.1	6000

TABLE 18

DISTANCES AT WHICH RADON GAS AIR CONCENTRATIONS OCCUR AS A FUNCTION OF WIND DIRECTION AND METHOD OF CALCULATION (PASQUILL OR WIND DIRECTION TURBULENCE)

Wind direction \ Air conc'n (μCi m^{-3})	Method	10^{-2}	5×10^{-3}	10^{-3}	5×10^{-4}	10^{-4}	5×10^{-5}	Plant size (tonne y^{-1})
N	Pasquill	79	132	360	550	1530	2440	3000
	Turbulence	93	145	392	612	1830	3050	
	Pasquill	91	150	400	612	1710	2770	6000
	Turbulence	103	164	442	690	2190	3480	
NE	Pasquill	69	113	314	478	1280	2000	3000
	Turbulence	82	128	348	538	1602	2570	
	Pasquill	78	129	346	535	1470	2310	6000
	Turbulence	92	144	394	613	1880	3090	
E	Pasquill	130	200	530	820	2320	3740	3000
	Turbulence	153	226	630	1000	3050	4900	
	Pasquill	148	230	610	958	2730	4140	6000
	Turbulence	172	270	750	1190	3650	5800	
SE	Pasquill	144	223	594	928	2700	4400	3000
	Turbulence	165	252	708	1120	3400	5600	
	Pasquill	163	250	680	1060	3100	5060	6000
	Turbulence	187	292	820	1320	4170	6500	
S	Pasquill	52	95	272	412	1090	1710	3000
	Turbulence	70	116	310	483	1380	2220	
	Pasquill	64	108	306	458	1260	2000	6000
	Turbulence	82	130	352	550	1650	2680	
SW	Pasquill	102	168	426	660	1850	2980	3000
	Turbulence	117	179	488	760	2370	3830	
	Pasquill	111	176	490	740	2110	3450	6000
	Turbulence	133	207	558	893	2770	4400	
W	Pasquill	70	118	322	480	1340	2120	3000
	Turbulence	86	133	365	563	1660	2750	
	Pasquill	80	131	358	542	1520	2450	6000
	Turbulence	92	144	393	616	1980	3250	
NW	Pasquill	82	128	348	532	1480	2360	3000
	Turbulence	96	150	408	537	1910	3120	
	Pasquill	90	143	390	598	1680	2700	6000
	Turbulence	108	170	454	718	2300	3700	

TABLE 19

MAXIMUM PREDICTED ANNUAL AVERAGE AIR CONCENTRATIONS (μCi m^{-3}) OF RADON GAS (AT 1 metre ALTITUDE)

Plant size (tonne y^{-1})	Data source	Direction	SML boundary	Regional centre
3 000	Reanalysis	West	9.8×10^{-5}	2.30×10^{-5}*
	Table 9 Back-up Document Supplement 1 to Item XV [Strom 1975]	West	6.22×10^{-5}	8.0×10^{-6}
6 000	Reanalysis	West	1.28×10^{-4}	2.92×10^{-5}*
	Table 3.10 Back-up Document Supplement 2 to Item XV [Strom 1975]	West	6.2×10^{-5}	1.0×10^{-5}

* *Maximum concentration in north-west direction.*

TABLE 20

URANIUM DUST SOURCE INVENTORY No. 1 - 3000 tonne y^{-1} PLANT

Source	Height of release (m)	Time	Source strength (pCi s^{-1})
Open pit	0*	Day	735
		Night	0
Treatment Plant			
1. as ore crushing	25.9	Day	3367
		Night	0
Rod mill	13.7	Day	3422
		Night	3422
2. as yellowcake	18.3	Day	8350
		Night	8350
Ore and waste dumps due to suspension	100		
$\bar{u}$ ($m\ s^{-1}$)		Day or Night	
0.9			20.2
1.6			24.4
3.0			63.8
5.1			638
9.3			2129

* *for the purposes of the deposition program, the open pit source height was taken as 5 m.*

TABLE 21

URANIUM DUST SOURCE INVENTORY No. 2

Source	Height of release (m)	Time	Source strength (p Ci s^{-1})	Plant size (tonne y^{-1})
Open pit	0	Day	750	3000
		Night	0	
		Day	1206	6000
		Night	0	
Treatment Plant				
1. as ore crushing	25.9	Day	4044	3000
		Night	0	
		Day	4878	6000
		Night	1392	
Rod mill	13.7	Day	2053	3000
		Night	2053	
		Day	3556	6000
		Night	3556	
2. as yellowcake	18.3	Day	8350	3000
		Night	8350	
		Day	14844	6000
		Night	14844	
Ore and waste dumps suspension	100			
$\bar{u}$ (m s^{-1})		Day or Night		3000 or 6000
0.9			20.2	
1.6			24.4	
3.0			63.8	
5.1			638	
9.3			2129	

TABLE 22

URANIUM DUST SUSPENSION SOURCE INVENTORY FOR THE WASTE DUMP

Mean wind speed (m s^{-1})	Resuspension rate (fraction s^{-1})	Source inventory g s^{-1}	Source inventory pCi s^{-1}
0.9	1.9×10^{-10}	6.06×10^{-5}	20.2
1.6	2.3×10^{-10}	7.30×10^{-5}	24.4
3.0	6.0×10^{-10}	1.91×10^{-4}	63.8
5.1	6.0×10^{-9}	1.91×10^{-3}	638
9.3	2×10^{-8}	6.38×10^{-8}	2129

TABLE 23

SURFACE FRICTION VELOCITIES (u_*) AND DRY DEPOSITION VELOCITIES (v_d) AS A FUNCTION OF THE MEAN WIND SPEED (ASSUMED AVERAGE PARTICLE RADIUS = 2.5 μm)

Mean wind speed (m s^{-1})	Friction velocity u_* (cm s^{-1})	Deposition velocity v_d (cm s^{-1})
0.9	9.99	7.1
1.6	17.76	9.9
3.0	33.3	14.2
5.1	56.6	18.9
9.3	103.2	25.9

TABLE 24

DISTANCES AT WHICH URANIUM DUST AIR CONCENTRATIONS (AT 1 metre ALTITUDE) OCCUR AS A FUNCTION OF WIND DIRECTION AND DIFFUSION CODE (WITH OR WITHOUT DEPOSITION INCLUDED) - tonne y^{-1} PLANT

Wind direction \ concentration (pCi m^{-3})	Diffusion code	5 x 10^{-2}	10^{-2}	5 x 10^{-3}	10^{-3}	5 x 10^{-4}
N	with deposition	38 and 95	360	530	1 250	1 790
	without deposition	210	930	1 630	6 300	>10 000
NE	with deposition	28 and 106	340	500	1 180	1 750
	without deposition	192	700	1 350	4 900	8 700
E	with deposition	9 and 230	620	865	1 190	2 730
	without deposition	490	1 700	2 900	9 500	>10 000
SE	with deposition	13 and 235	650	920	2 100	2 950
	without deposition	560	1 980	3 300	>10 000	>10 000
S	with deposition	-	230	360	890	1 300
	without deposition	100	520	970	4 180	7 400
SW	with deposition	30 and 120	450	670	1 550	2 200
	without deposition	300	1 220	2 150	7 800	>10 000
W	with deposition	43 and 66	300	455	1 120	1 590
	without deposition	143	770	1 350	5 300	9 500
NW	with deposition	50 and 57	372	540	1 300	1 850
	without deposition	185	1 000	1 720	6 200	10 500

Predictions using the Pasquill method with source inventory No.1.

TABLE 25

DISTANCES AT WHICH URANIUM DUST AIR CONCENTRATIONS (AT 1 metre ALTITUDE) OCCUR AS A FUNCTION OF WIND DIRECTION, METHOD OF CALCULATION AND PLANT SIZE

Wind direction \ Concentration ($pCi\ m^{-3}$)	Method	10^{-1}	5×10^{-2}	10^{-2}	5×10^{-3}	Plant size (tonne y^{-1})
N	Pasquill	44	180	835	1 450	3000
	Turbulence	77	140	800	1 940	
	Pasquill	140	326	1 340	2 400	6000
	Turbulence	120	200	1 740	3 180	
NE	Pasquill	54	170	740	1 260	3000
	Turbulence	73	132	650	1 700	
	Pasquill	140	300	1 130	2 000	6000
	Turbulence	115	190	1 500	2 800	
E	Pasquill	225	450	1 560	2 600	3000
	Turbulence	175	300	2 080	3 000	
	Pasquill	390	700	2 375	4 000	6000
	Turbulence	255	630	3 280	5 200	
SE	Pasquill	235	490	1 780	3 020	3000
	Turbulence	162	290	2 380	4 000	
	Pasquill	435	800	2 750	4 750	6000
	Turbulence	240	780	3 850	6 000	
S	Pasquill	28	86	385	900	3000
	Turbulence	47	91	290	950	
	Pasquill	65	160	775	1 460	6000
	Turbulence	78	134	620	2 110	
SW	Pasquill	74	250	1 110	1 950	3000
	Turbulence	95	175	1 350	2 650	
	Pasquill	200	450	1 800	3 150	6000
	Turbulence	150	265	2 420	4 200	
W	Pasquill	35	122	700	1 250	3000
	Turbulence	55	115	505	1 700	
	Pasquill	99	230	1 150	2 100	6000
	Turbulence	98	168	1 440	2 880	
NW	Pasquill	40	160	890	1 580	3000
	Turbulence	70	134	960	2 100	
	Pasquill	166	326	1 440	2 500	6000
	Turbulence	115	194	1 900	3 350	

TABLE 26

ESTIMATES OF ANNUAL DOSES TO MEMBERS OF THE PUBLIC AT THE REGIONAL CENTRE

Material contributing radionuclides	For insoluble particulate and radon		For soluble particulate					
	Lung		Kidney	Bone		Whole body	Data source	Plant size (tonne y^{-1})
	Adult	Child	All ages	Adult	Child	All ages		
Ore	2.8	7.84	3.35	17.6	79.2	0.56	1	3000
	6	17	7	36	162	1	2	
	5.1	14.3	6.08	31.98	143.9	1.01	1	6000
	16	45	19	99	446	3	2	
Yellowcake	0.79	2.21	0.063	0.32	1.44	0.018	1	3000
	3	8	0.2	1	5	0.06	2	
	1.4	3.9	0.112	0.56	2.52	0.032	1	6000
	5	13	0.4	2	9	0.1	2	
Radon	34.5	34.5					1	3000
	11	11					2	
	43.8	43.8					1	6000
	15	15					2	

1 = Re-analysis 2 = Environmental Impact Statement

Annual Doses measured in millirem

TABLE 27

COMPARISON OF ESTIMATED ANNUAL DOSE AT THE REGIONAL CENTRE WITH RECOMMENDED ANNUAL DOSE LIMITS

Organ	Member of public	Annual dose limit (millirem) (NHMRC [1967] standard)	Estimated annual dose for airborne effluent (millirem)	Estimated annual dose as a per cent of the dose limit	Plant size (tonne y^{-1})
Lung	child	1 500	44.55	2.97	3000
			62.0	4.13	6000
	adult	1 500	38.09	2.54	3000
			50.3	3.35	6000
Kidney	all ages	1 500	3.41	0.23	3000
			6.19	0.41	6000
Bone	child	3 000	80.64	2.69	3000
			146.42	4.88	6000
	adult	3 000	17.92	0.60	3000
			32.54	1.08	6000
Whole Body	all ages	500	0.58	0.11	3000
			1.04	0.21	6000

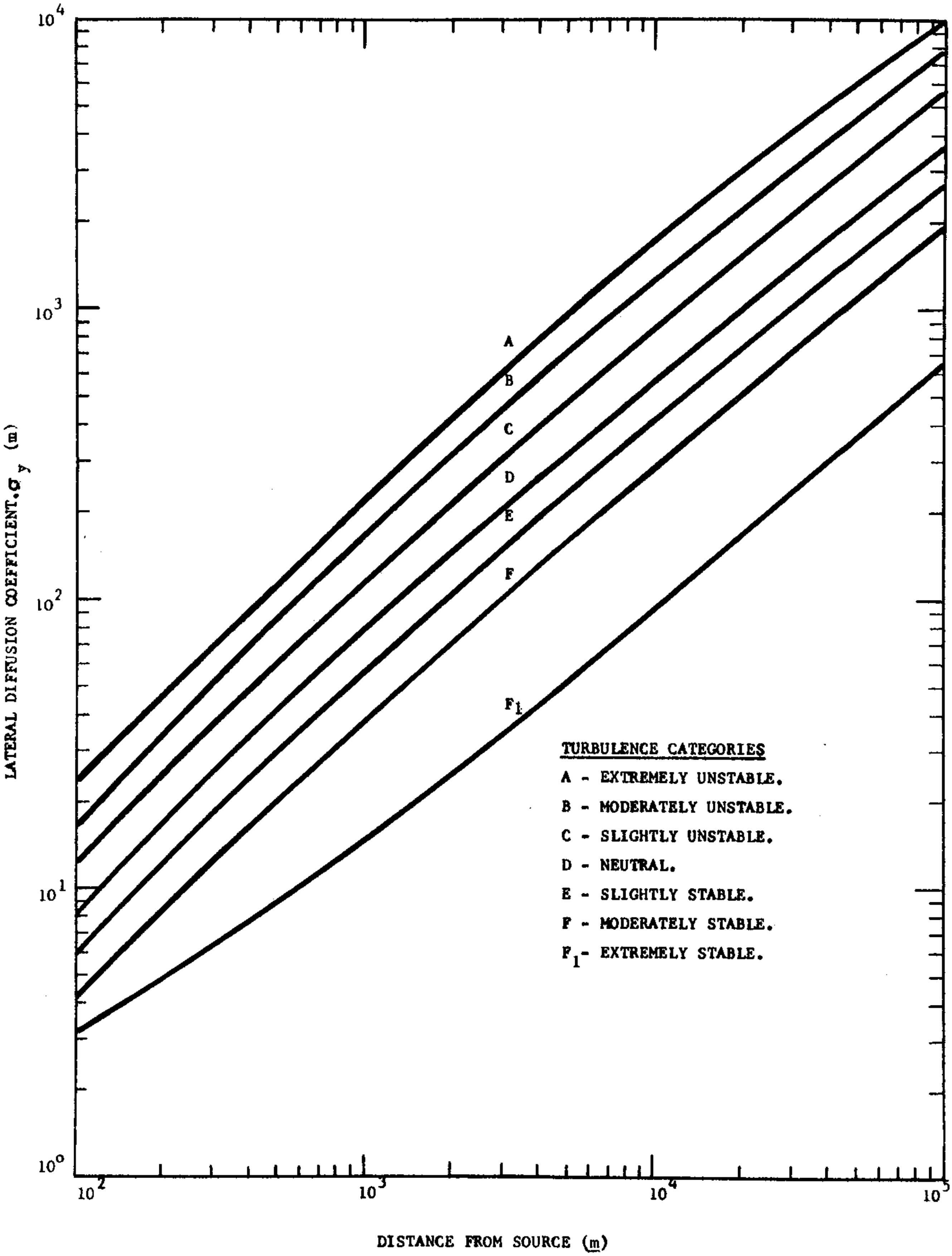


FIGURE 1. LATERAL DIFFUSION, σ_y, AS A FUNCTION OF DOWNWIND DISTANCE FROM THE SOURCE

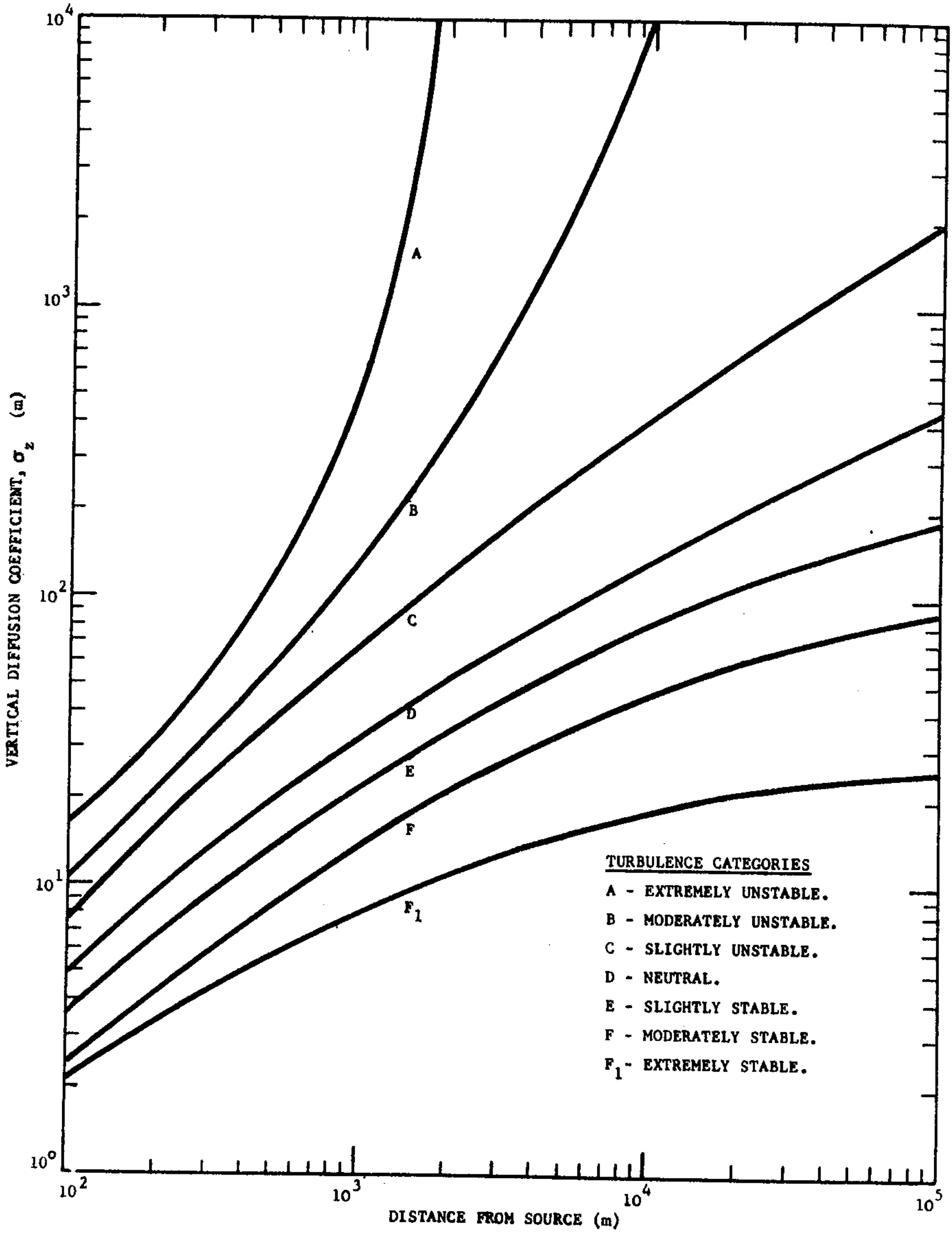


FIGURE 2. VERTICAL DIFFUSION, σ_z, AS A FUNCTION OF DOWNWIND DISTANCE FROM THE SOURCE

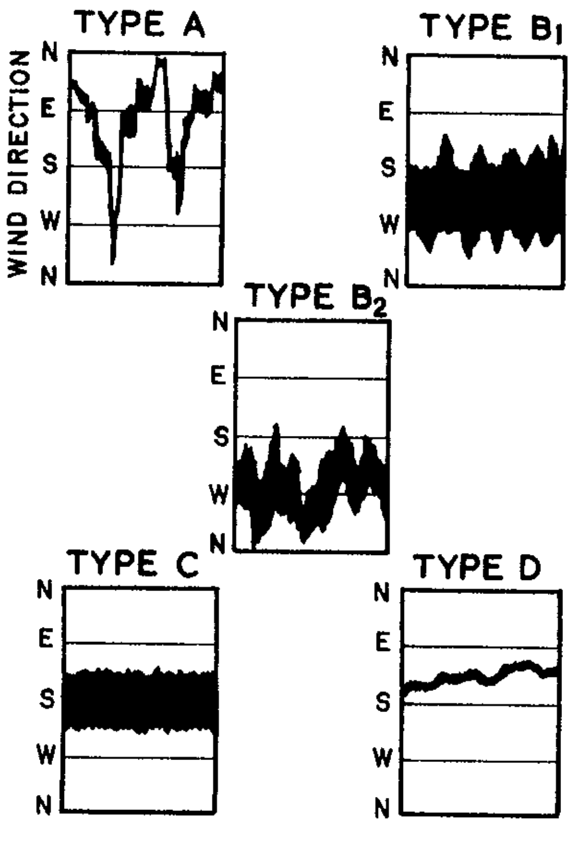


FIGURE 3. THE BROOKHAVEN GUSTINESS CLASSIFICATION SCHEME (After Singer and Smith 1953)

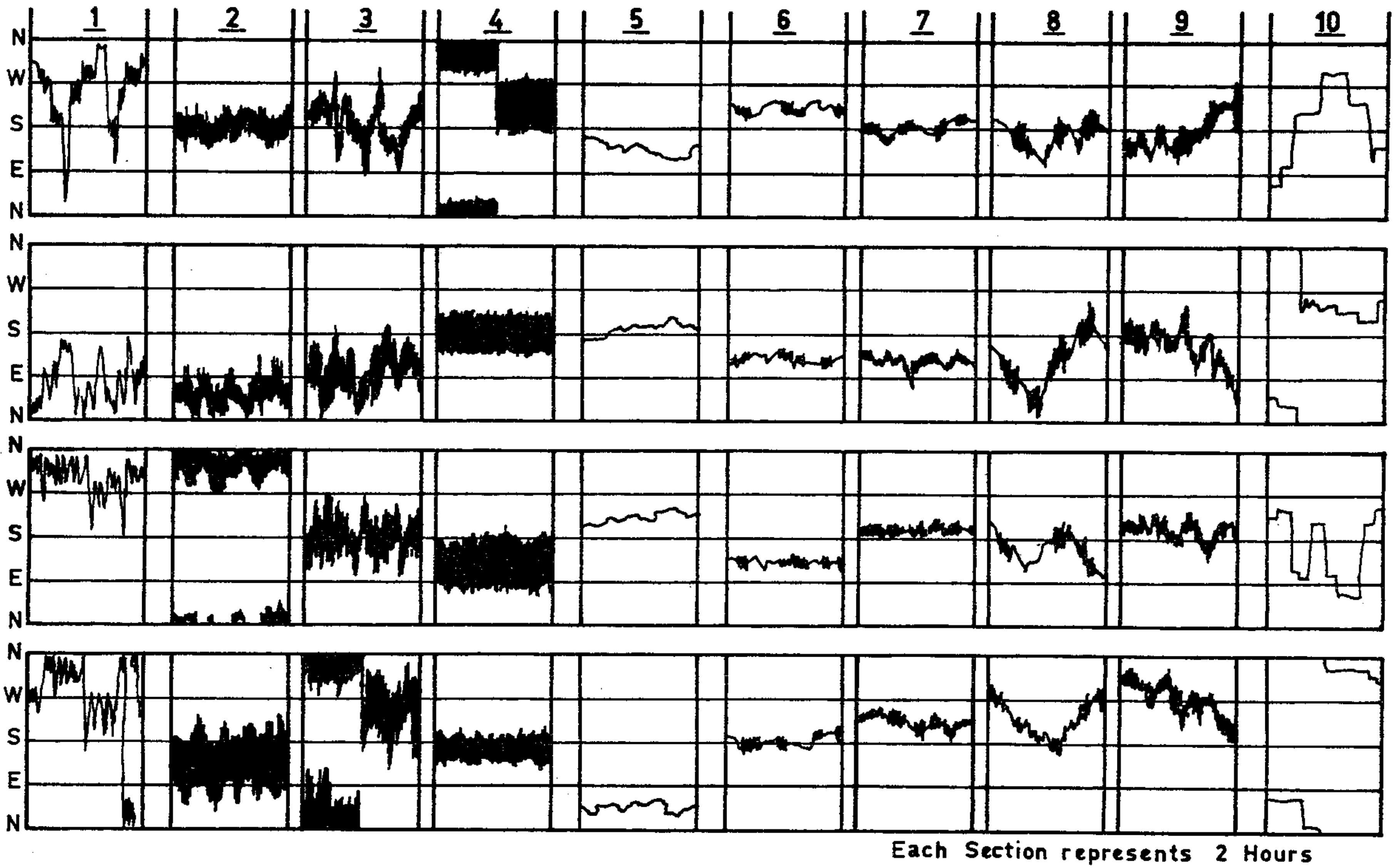


FIGURE 4. WIND DIRECTION TURBULENCE TRACE TYPES (After Clark and Bendun 1974)

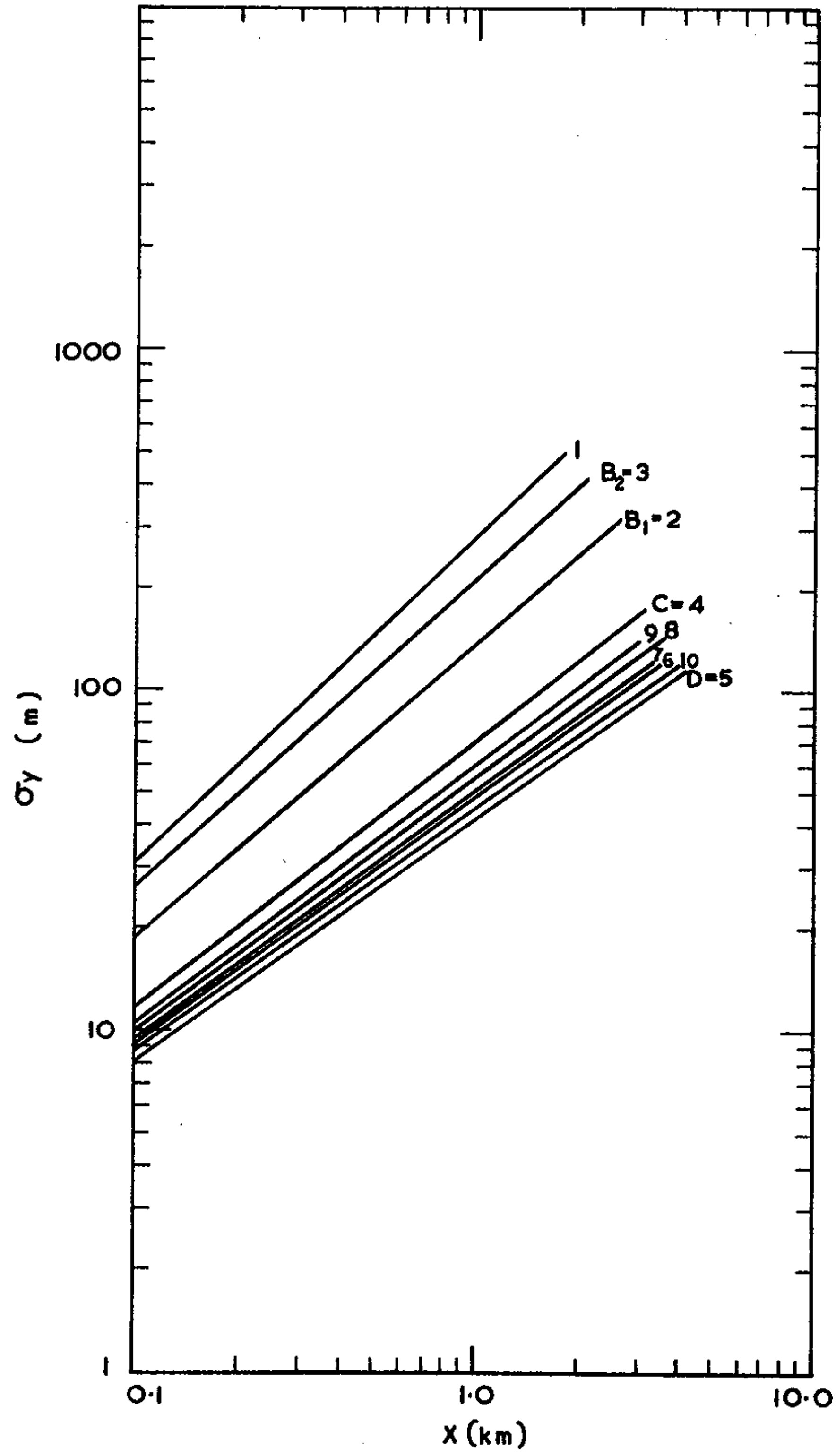


FIGURE 5. LATERAL DIFFUSION PARAMETER (σ_y) AS A FUNCTION OF THE DOWNWIND DISTANCE AND WIND DIRECTION TURBULENCE CATEGORIES (CURVES B1, B2, C AND D (After Singer and Smith 1953))

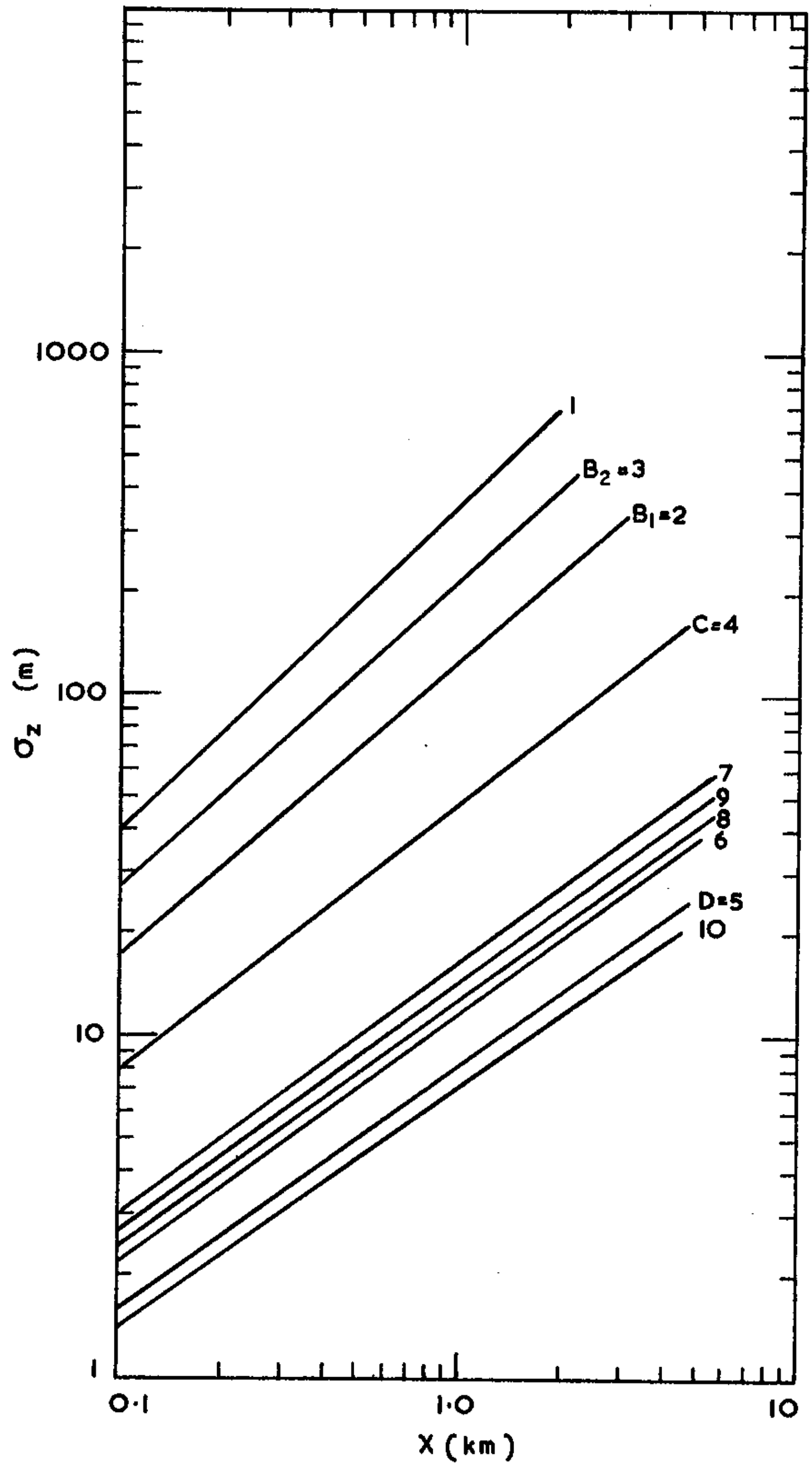


FIGURE 6. VERTICAL DIFFUSION PARAMETER (σ_z) AS A FUNCTION OF THE DOWNWIND DISTANCE AND WIND DIRECTION TURBULENCE CATEGORIES (CURVES B1, B2, C AND D (After Singer and Smith 1953)

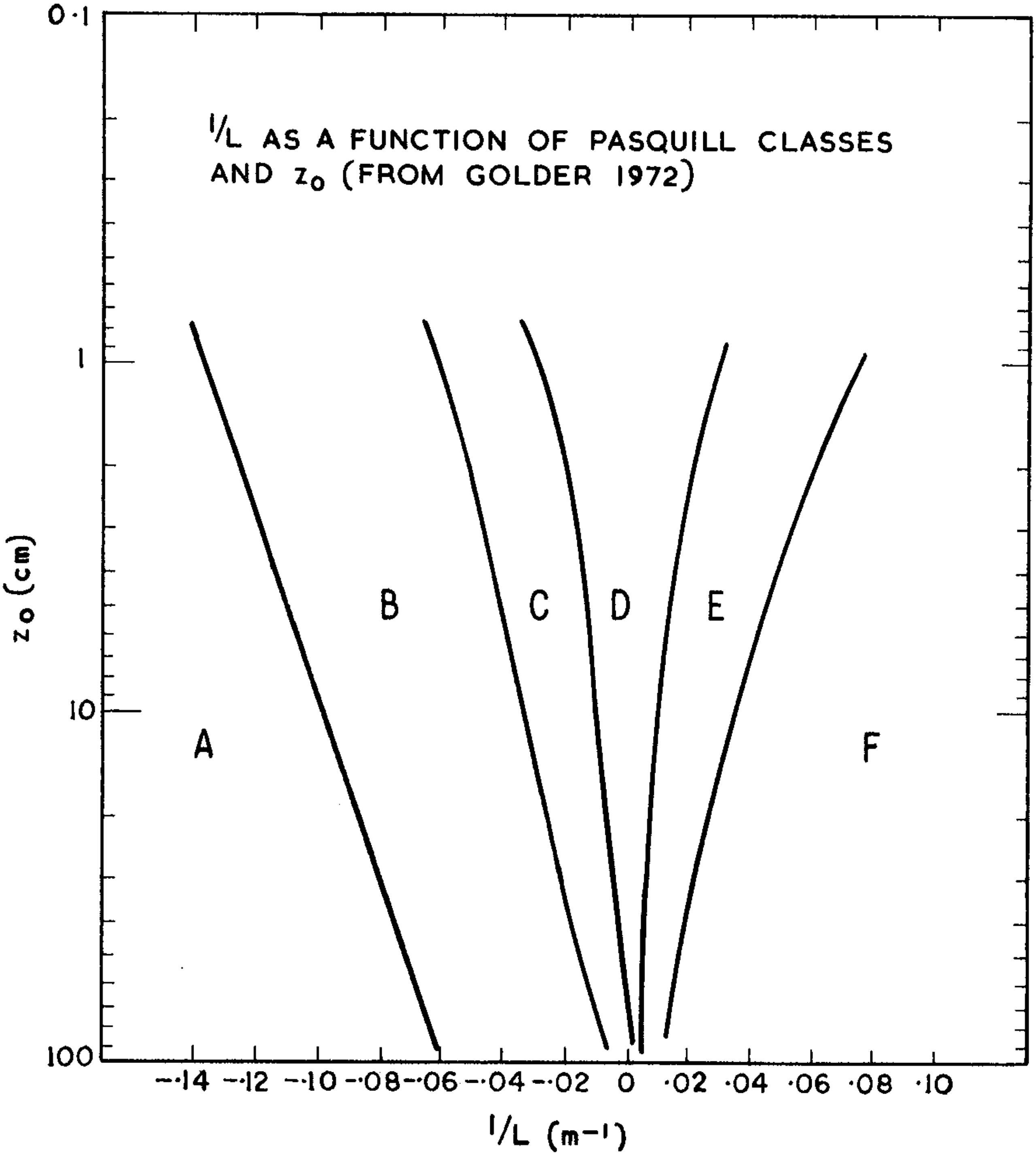


FIGURE 7. PASQUILL STABILITY CATEGORY AS A FUNCTION OF THE ROUGHNESS LENGTH (z_0) AND MONIN-OBUKHOV STABILITY LENGTH (L) (After Golder 1972)

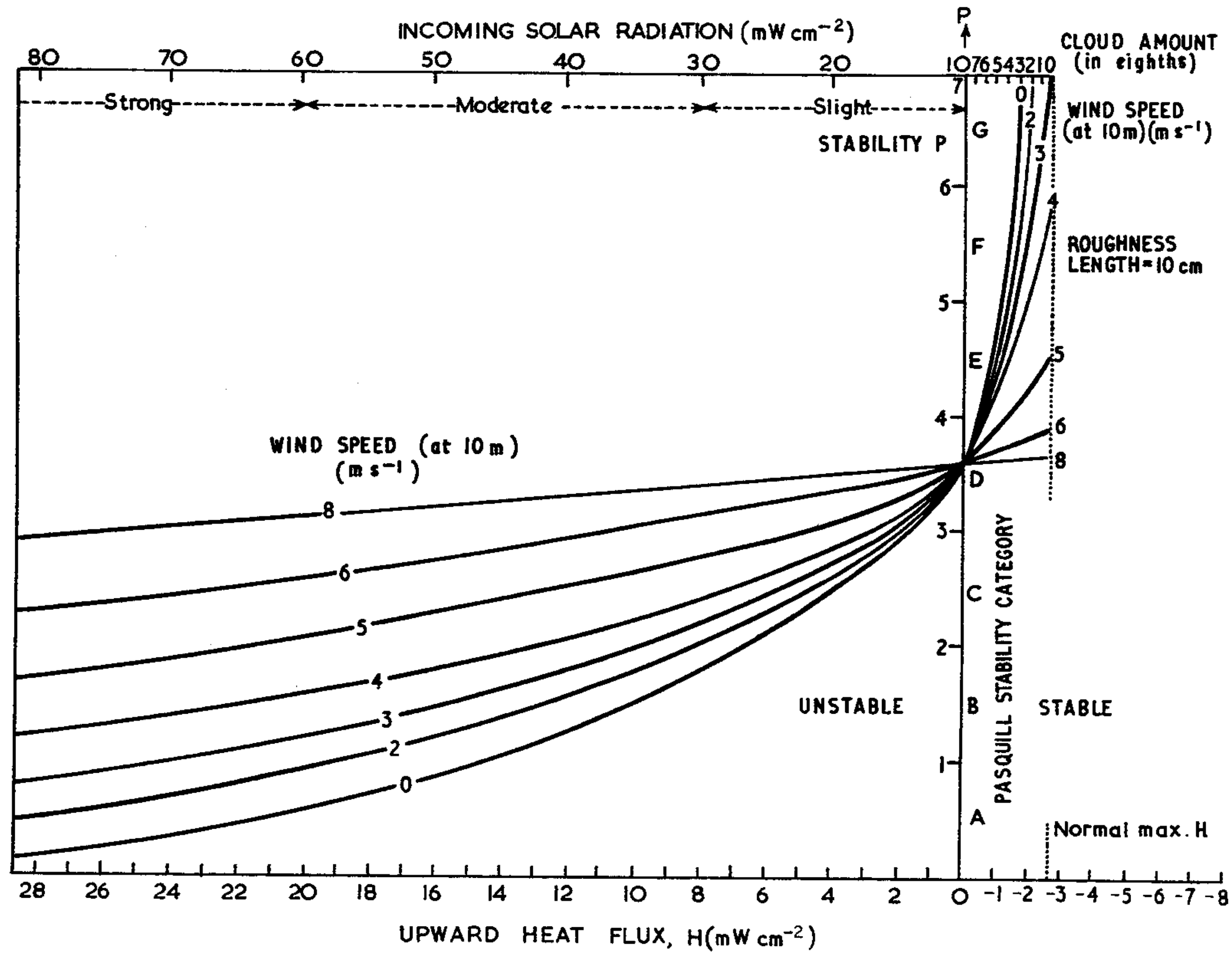
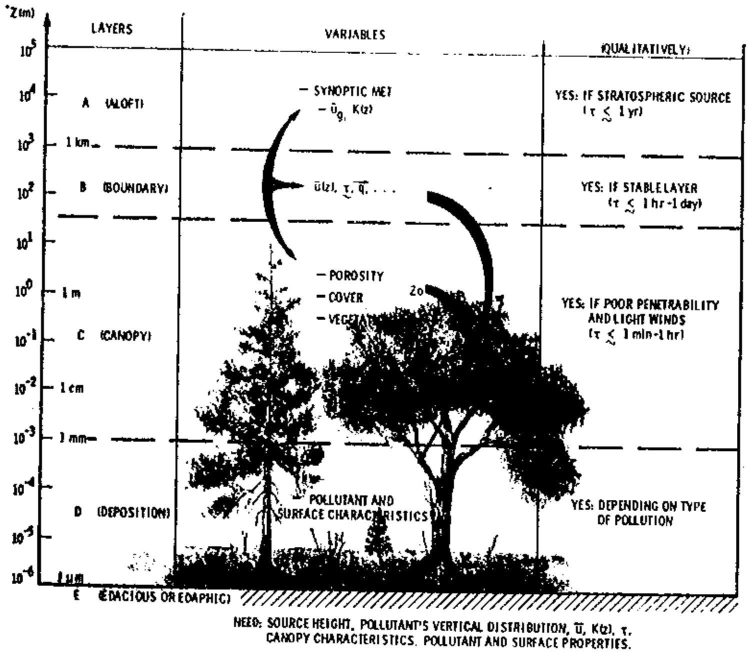
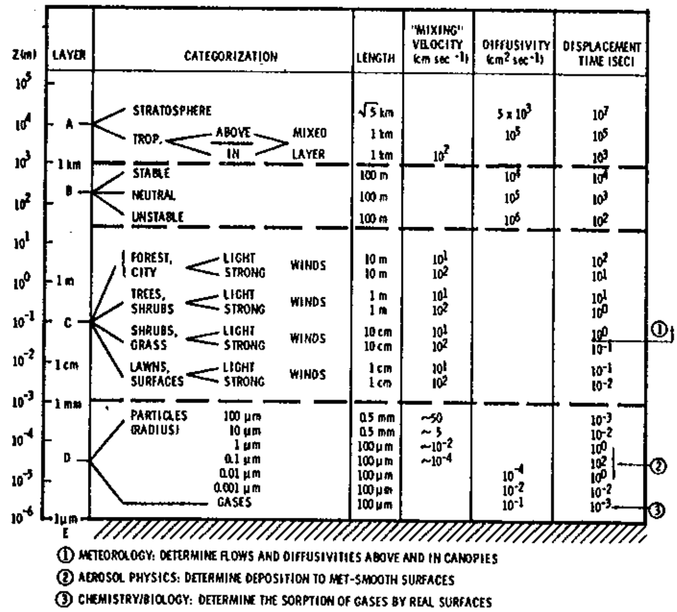


FIGURE 8. PASQUILL STABILITY CATEGORY AS A FUNCTION OF THE UPWARD SENSIBLE HEAT FLUX AND WIND SPEED (After Smith 1973)



A suggested division of the total dry deposition problem and a qualitative indication of where the process may be rate limited.



Indications of the time scales involved in the dry deposition process, evaluated either from $\delta t = \delta z/v$ or $\delta t = [\delta z]^2/D$, and illustrating that the process may be rate limited in various layers, depending on where the displacement time is largest.

FIGURE 9. DRY DEPOSITION-PROCESSES, TIME AND LENGTH SCALES (After Slinn 1975a)

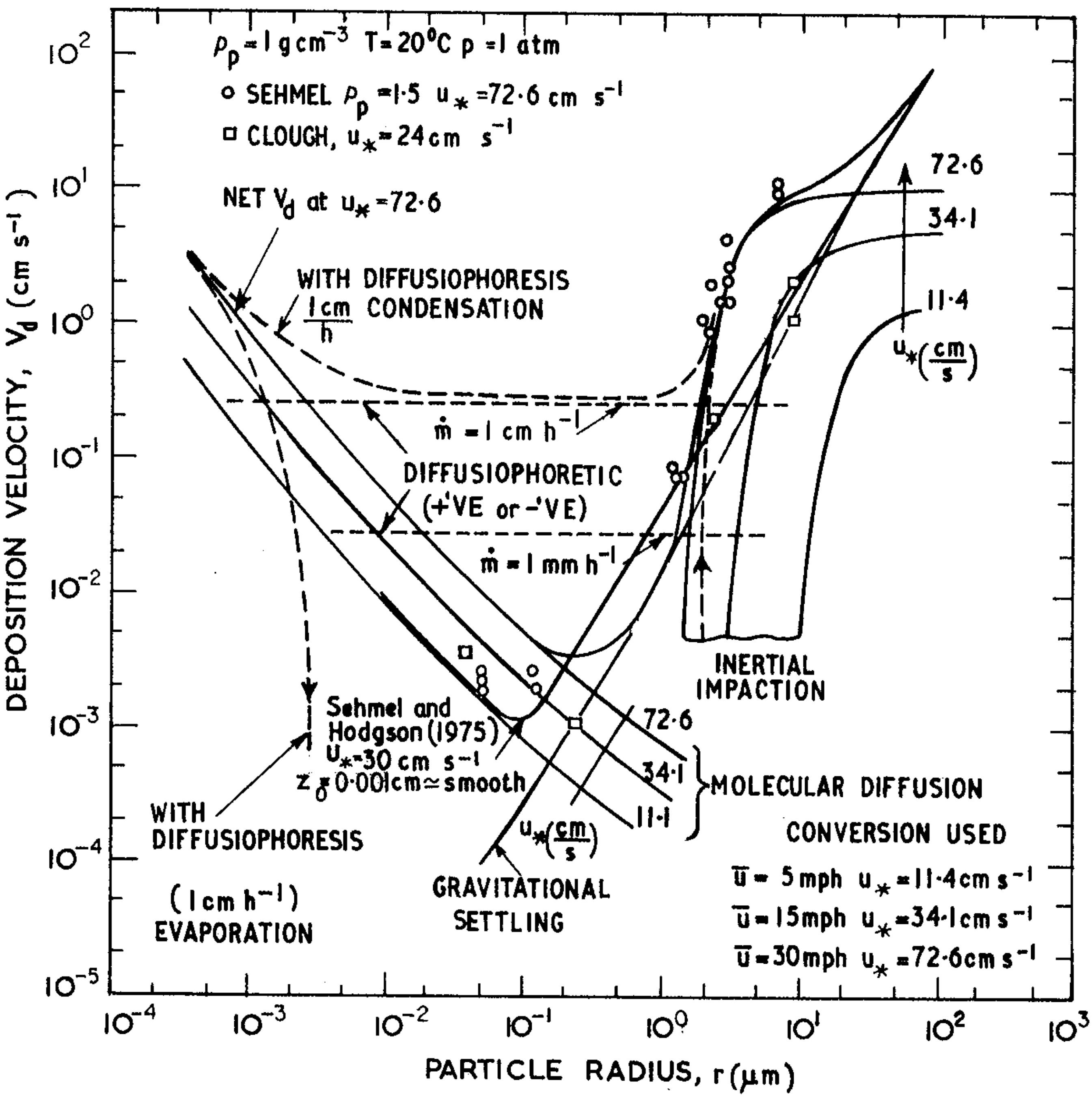
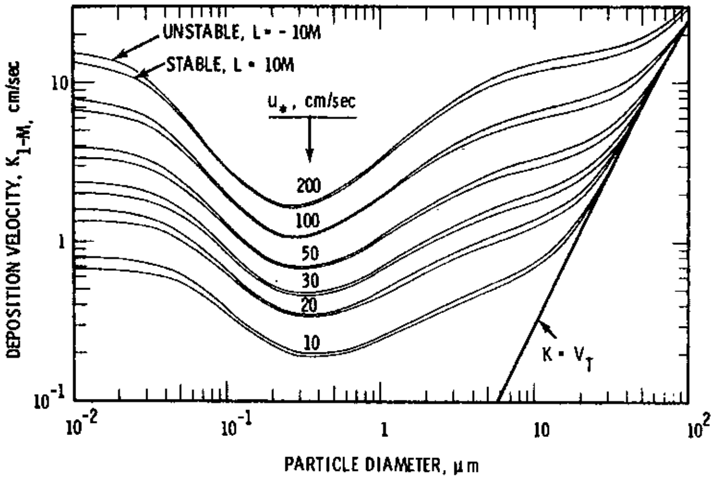
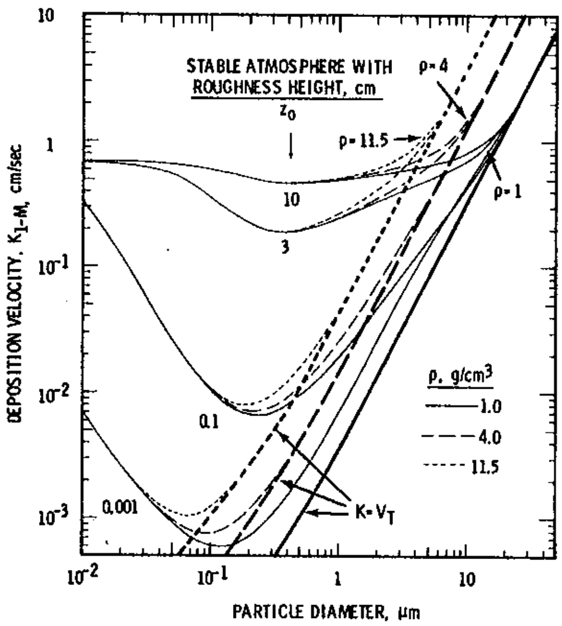


FIGURE 10. DRY DEPOSITION VELOCITIES OVER SMOOTH SURFACES AS A FUNCTION OF PARTICLE RADIUS (r) AND FRICTION VELOCITY (u_*) (After Slinn 1975a)

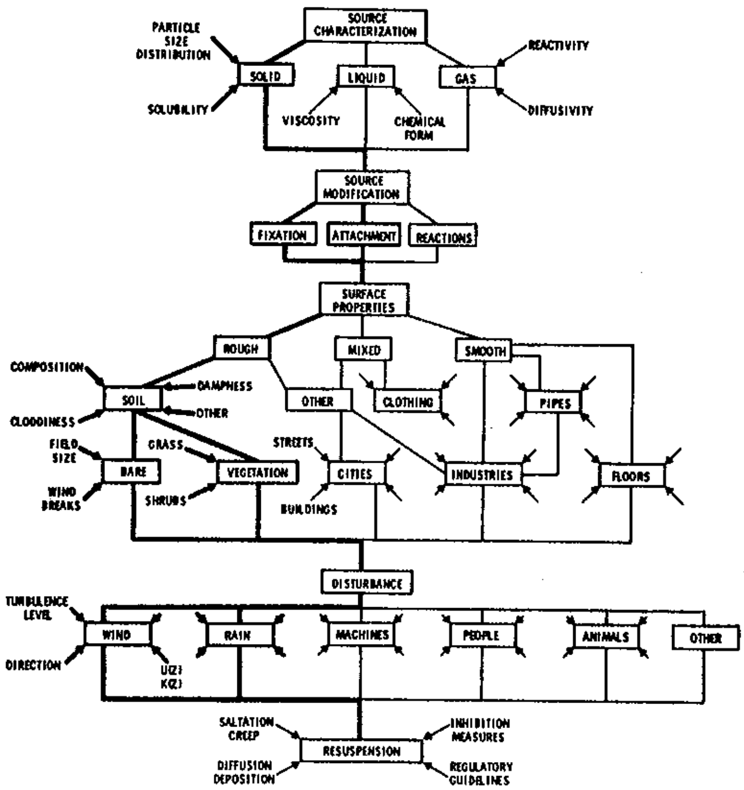


Predicted deposition velocities at 1 m height for particle density of 1 g/cm³ and z_o = 3.0 cm.



Predicted deposition velocities at 1 m for u_* = 10 cm/sec and particle densities of 1, 4, and 11.5 g/cm³.

FIGURE 11. DRY DEPOSITION VELOCITIES AS A FUNCTION OF FRICTION VELOCITY (u_*), ROUGHNESS LENGTH (z_o), PARTICLE DENSITY (ρ), PARTICLE DIAMETER (d) AND STABILITY LENGTH (L) (After Sehmel and Hodgson 1975)



An indication of some of the complexities of the resuspehsion problem.

FIGURE 12. SOME COMPLEXITIES OF THE RESUSPENSION PROCESS (After Slinn 1975b)

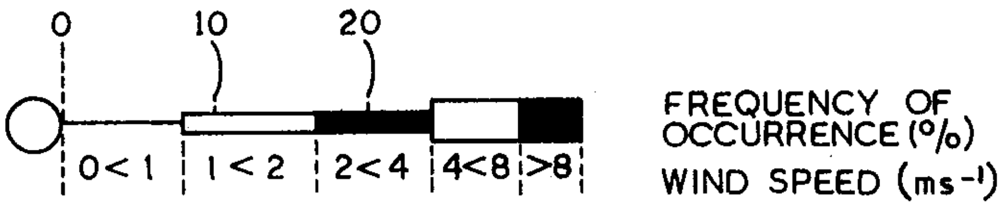


FIGURE 13. THE BAILLEY-TYPE WIND ROSE

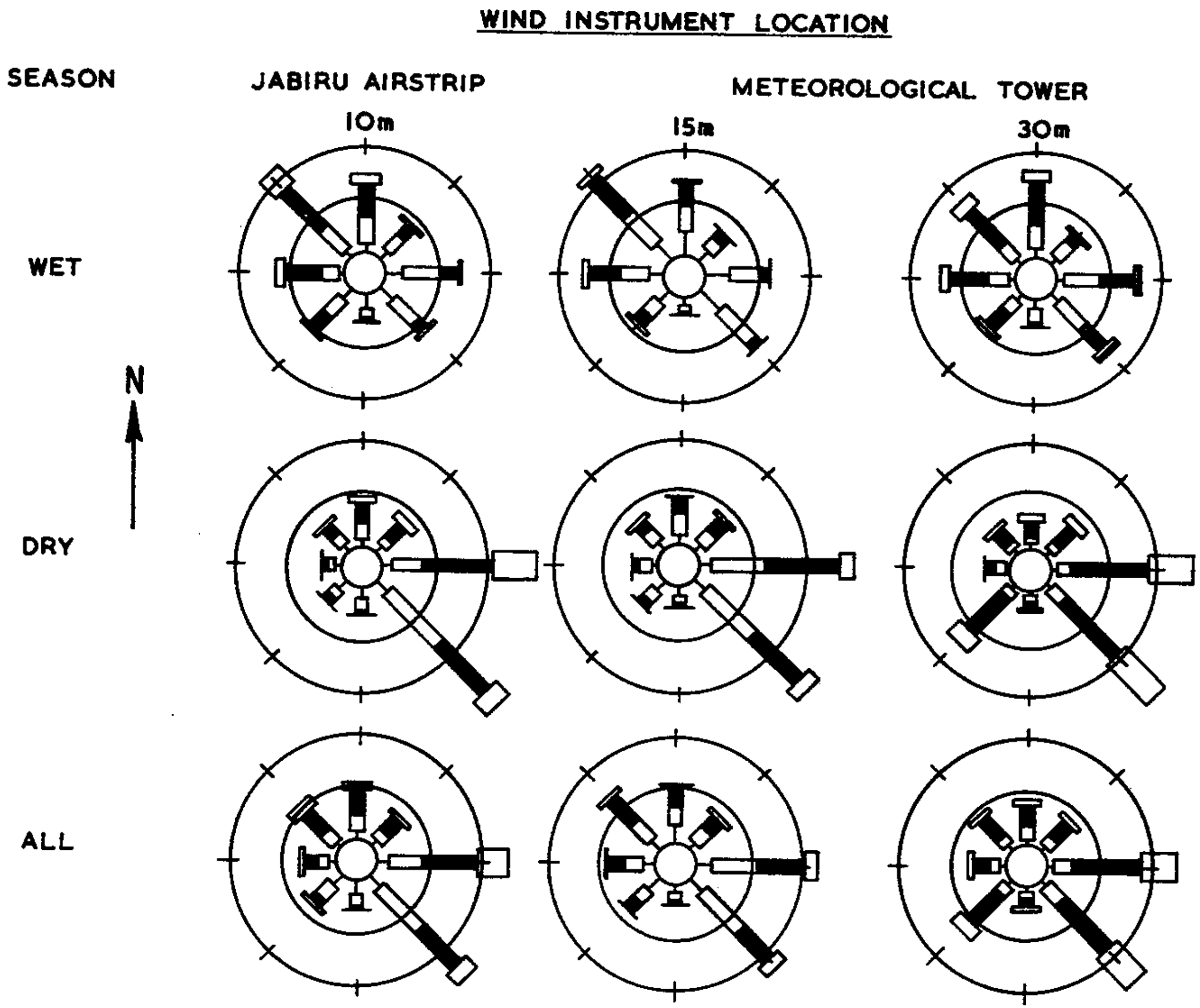


FIGURE 14. SEASONAL WIND ROSES FROM THE JABIRU REGION - ALL TIMES OF OBSERVATION COMBINED

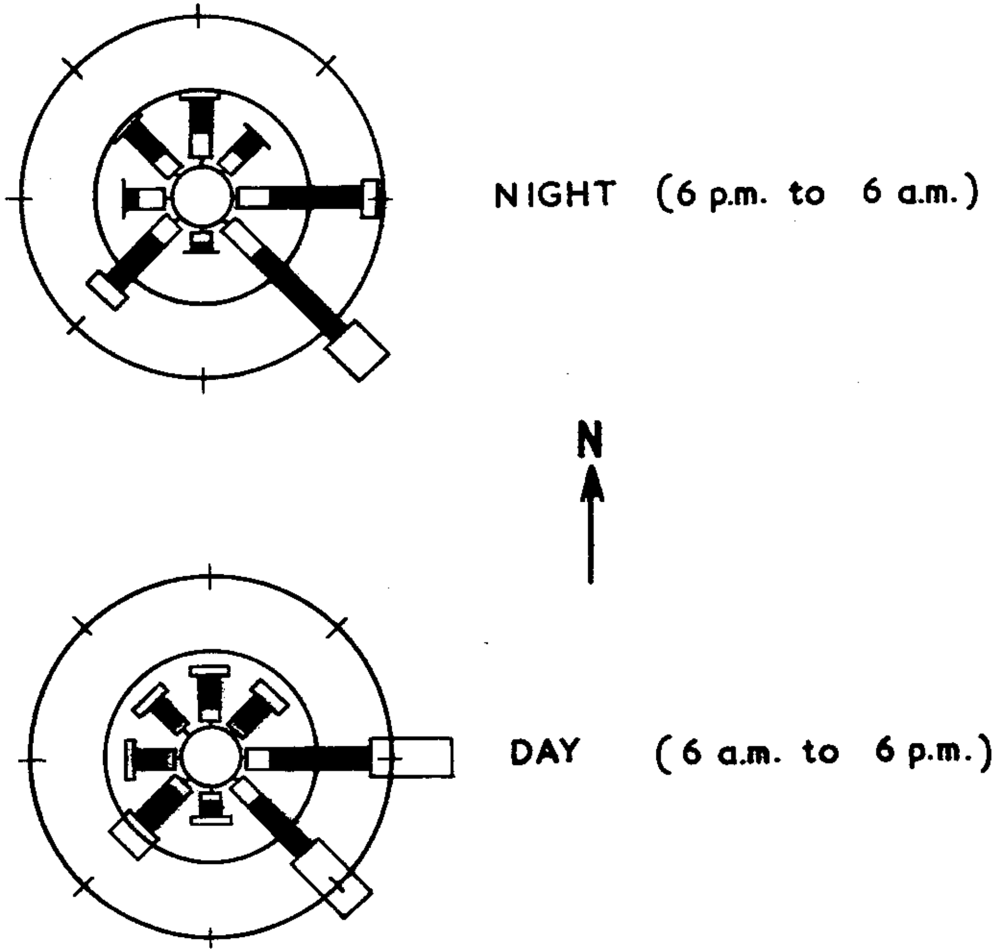


FIGURE 15. DAY AND NIGHT WIND ROSES FOR THE 30 METRE TOWER LEVEL - ALL SEASONS AND TIMES COMBINED

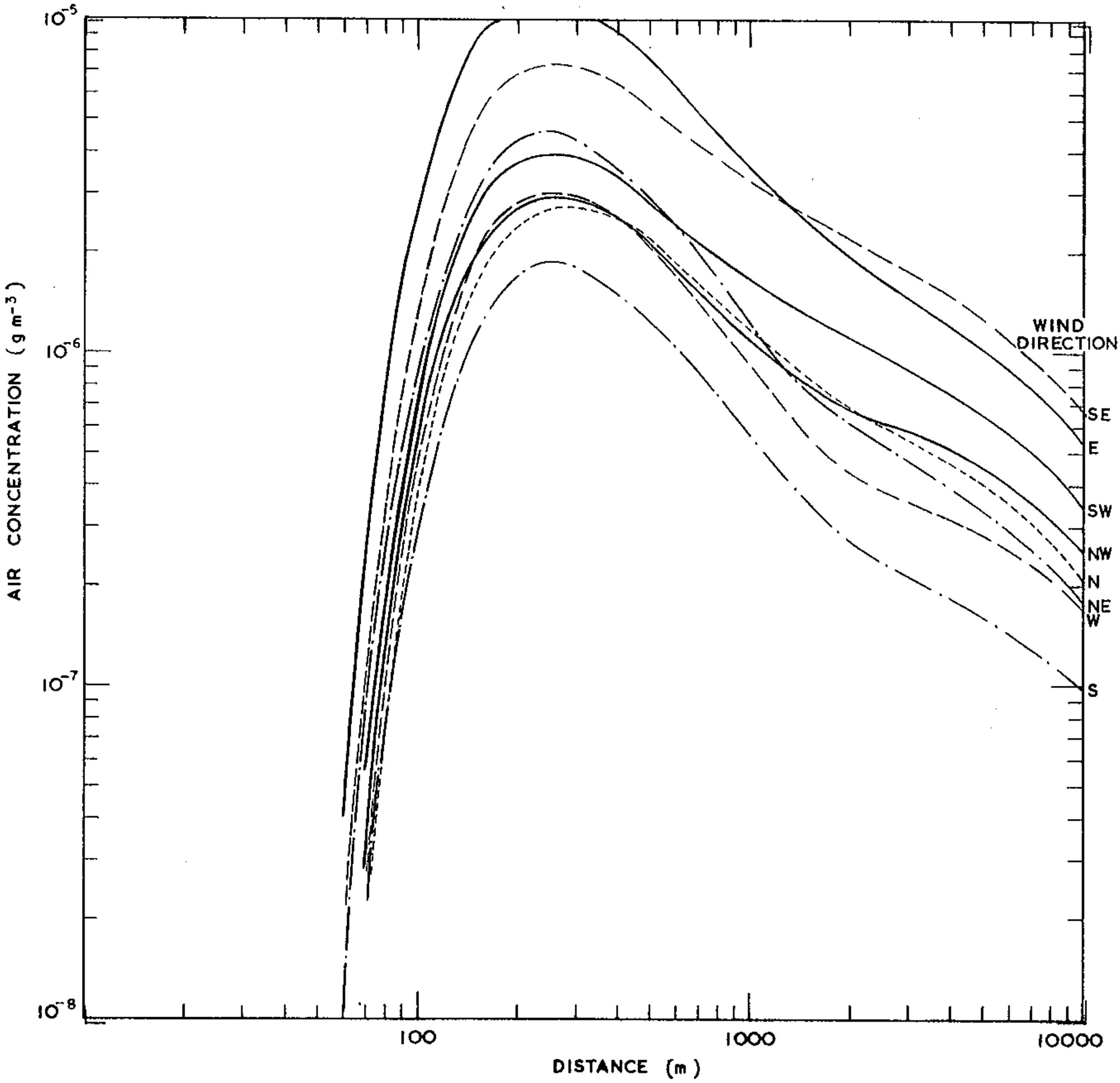


FIGURE 16. SULPHUR DIOXIDE AIR CONCENTRATIONS (AT 1 METRE ALTITUDE) AS A FUNCTION OF DOWNWIND DISTANCE (X) AND WIND DIRECTION – USING THE PASQUILL DIFFUSION CURVES (TABLE 4)

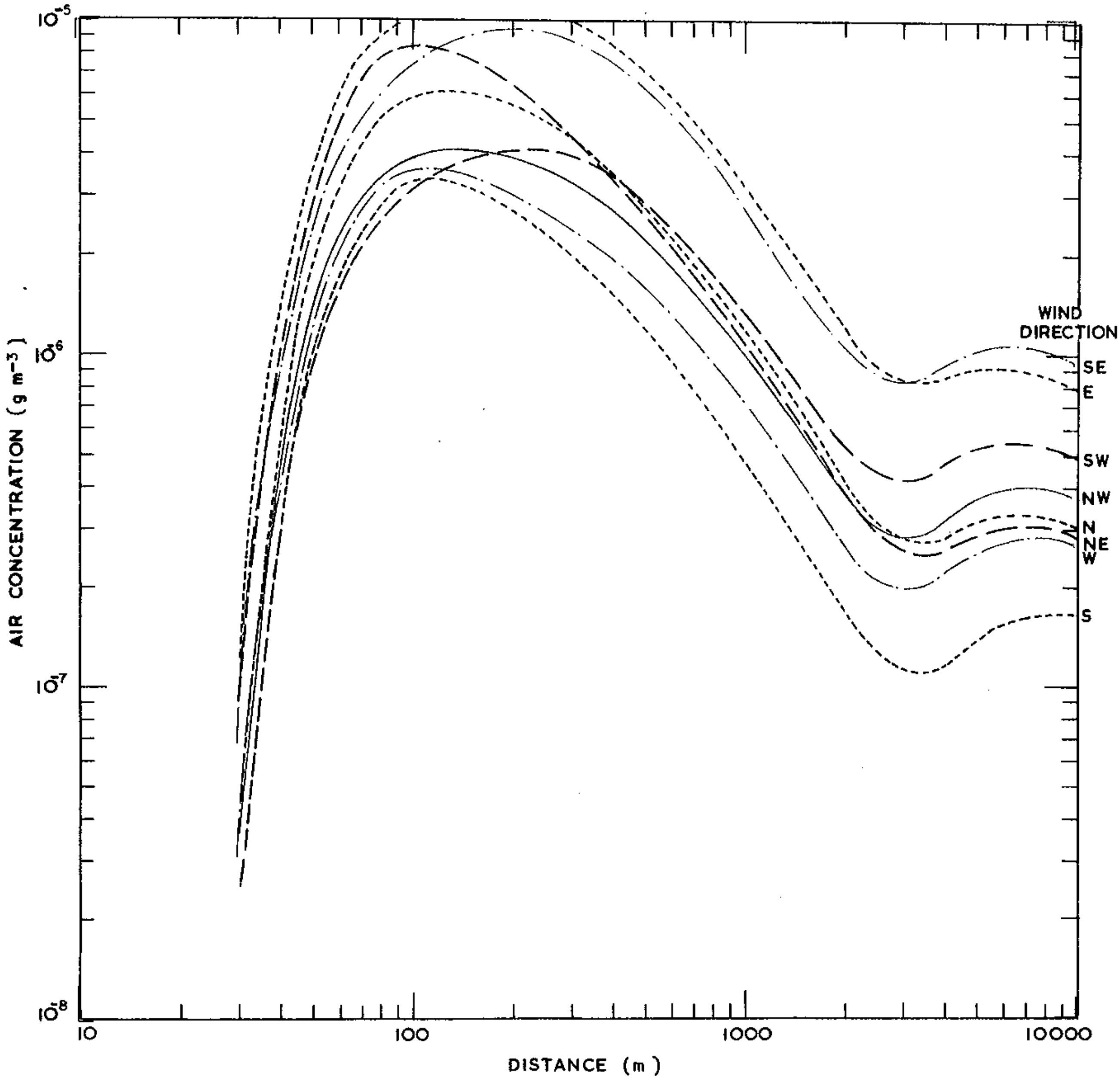


FIGURE 17. SULPHUR DIOXIDE AIR CONCENTRATIONS (AT 1 METRE ALTITUDE) AS A FUNCTION OF DOWNWIND DISTANCE (X) AND WIND DIRECTION – USING THE WIND DIRECTION TURBULENCE DIFFUSION CURVES (TABLE 7)

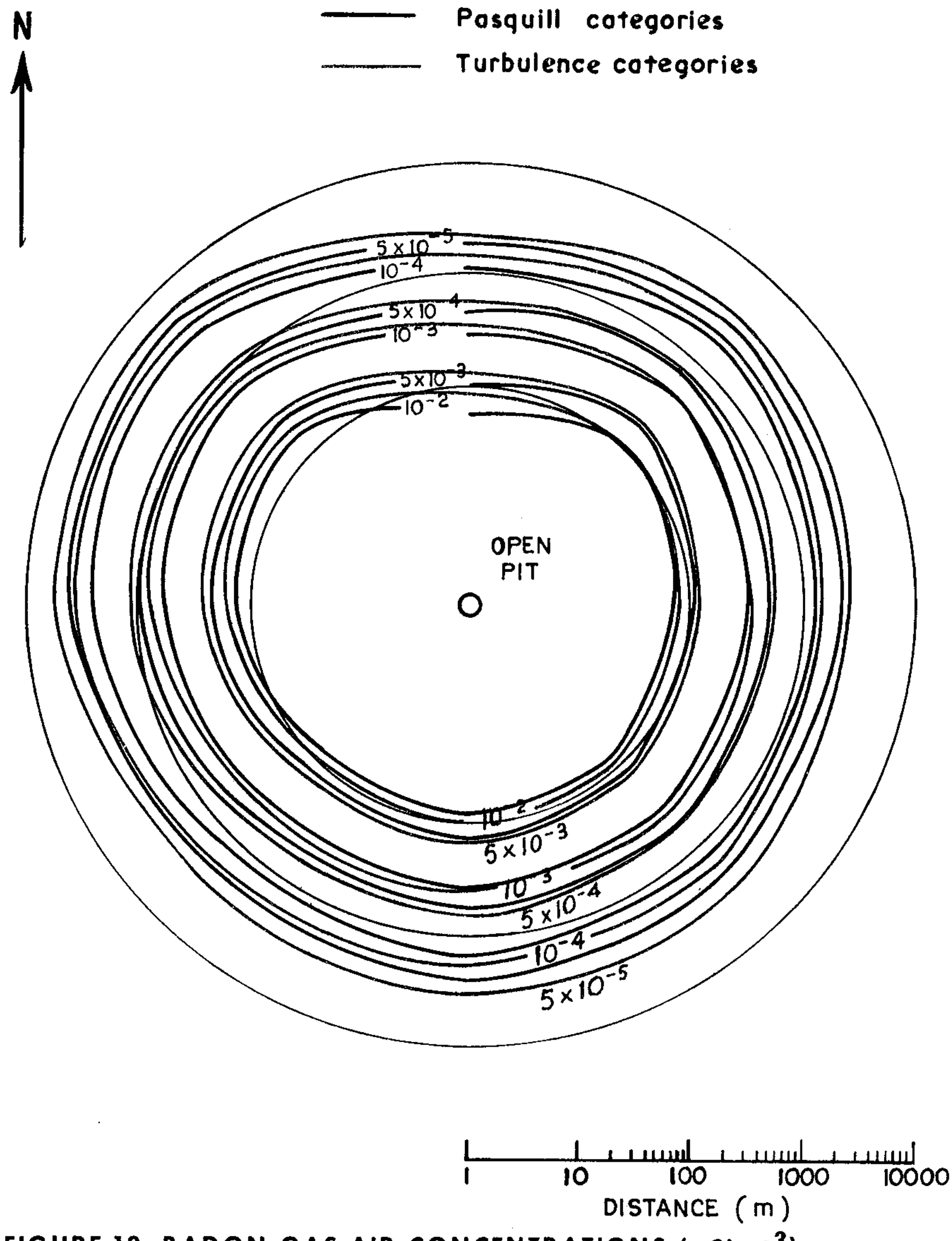


FIGURE 18. RADON GAS AIR CONCENTRATIONS (μCi m^{-3}) ASSUMING ALL SOURCES ARE LOCATED AT THE OPEN PIT — 3000 t y^{-1} PLANT

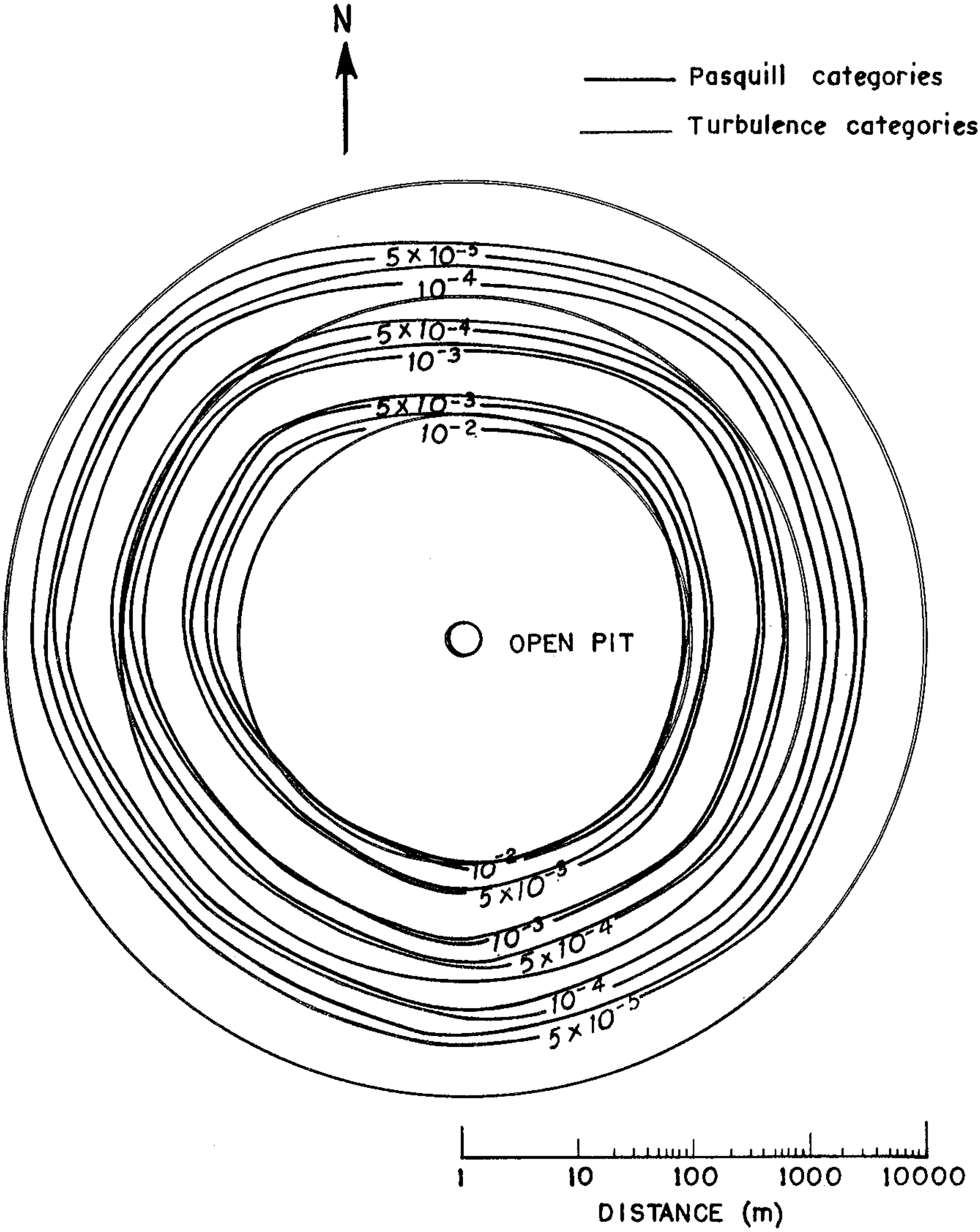


FIGURE 19. RADON GAS AIR CONCENTRATIONS (μCi m^{-3}) ASSUMING ALL SOURCES ARE LOCATED AT THE OPEN PIT – 6000 t y^{-1} PLANT

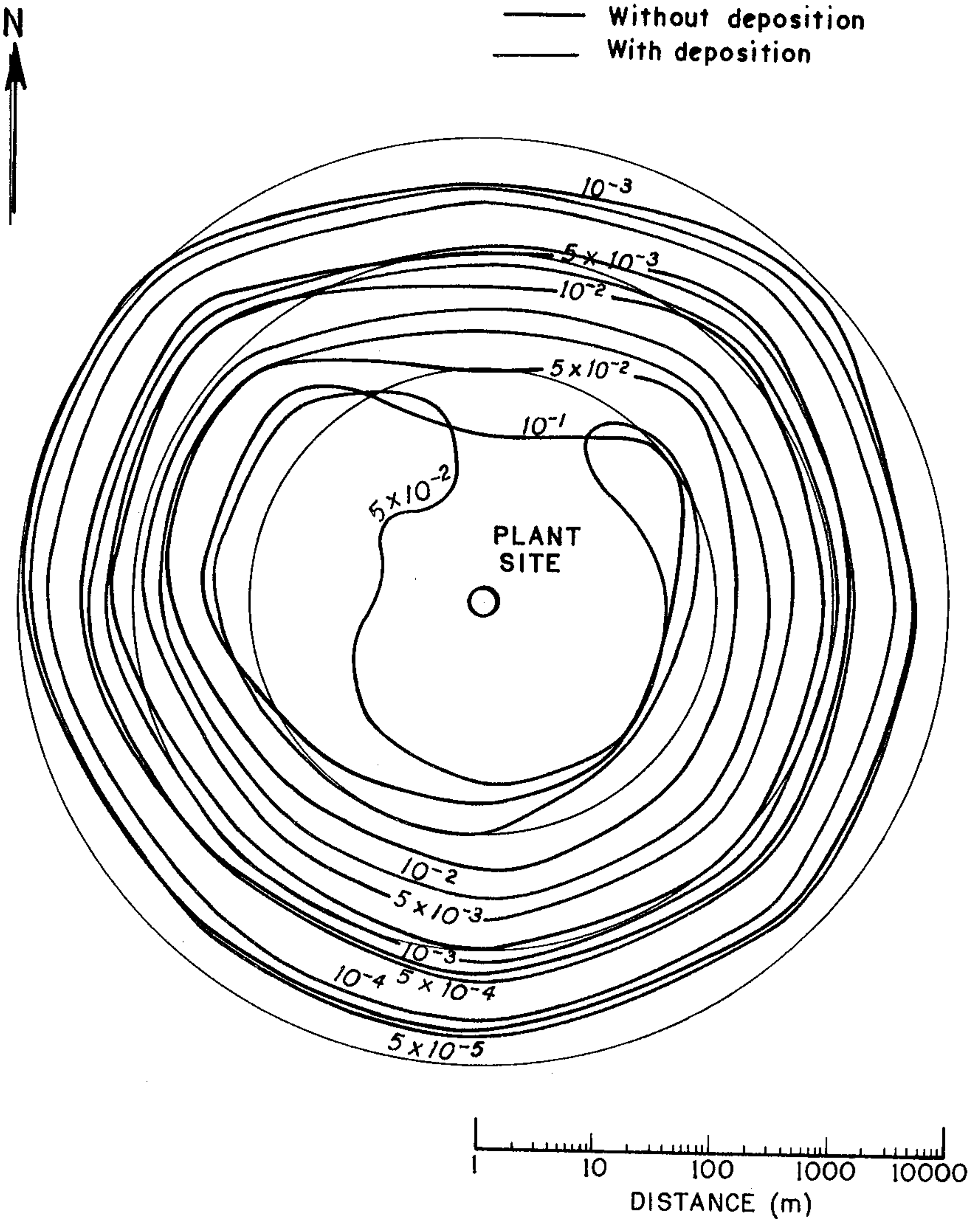


FIGURE 20. URANIUM DUST AIR CONCENTRATIONS (pCi m^{-3}) (AT 1 METRE ALTITUDE) USING SOURCE INVENTORY No. 1 WITH THE PASQUILL METHOD — 3000 t y^{-1} PLANT

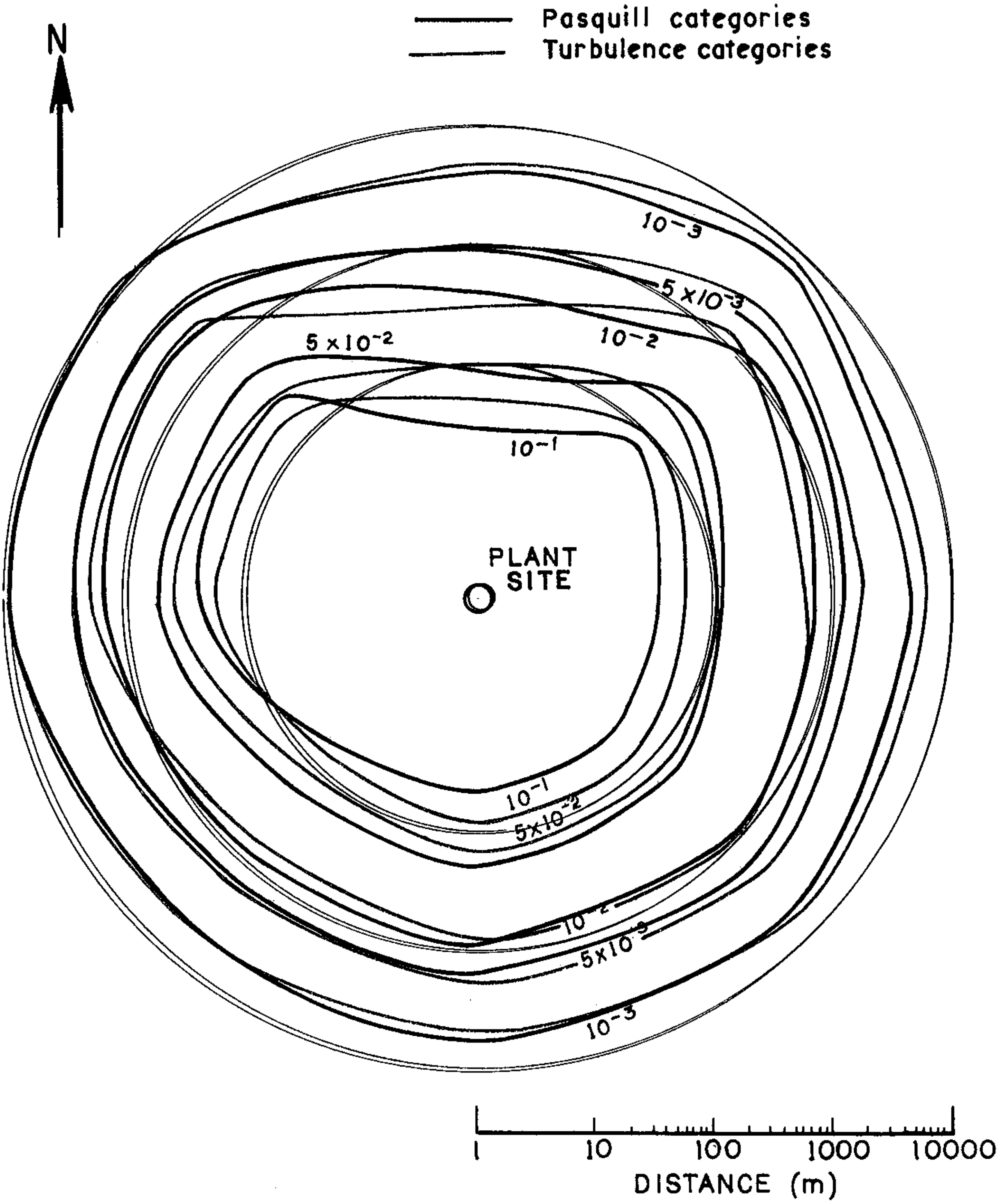


FIGURE 21 URANIUM DUST AIR CONCENTRATIONS ($pCi\ m^{-3}$) (AT 1 METRE ALTITUDE) USING SOURCE INVENTORY No. 2 – 3000 $t\ y^{-1}$ PLANT

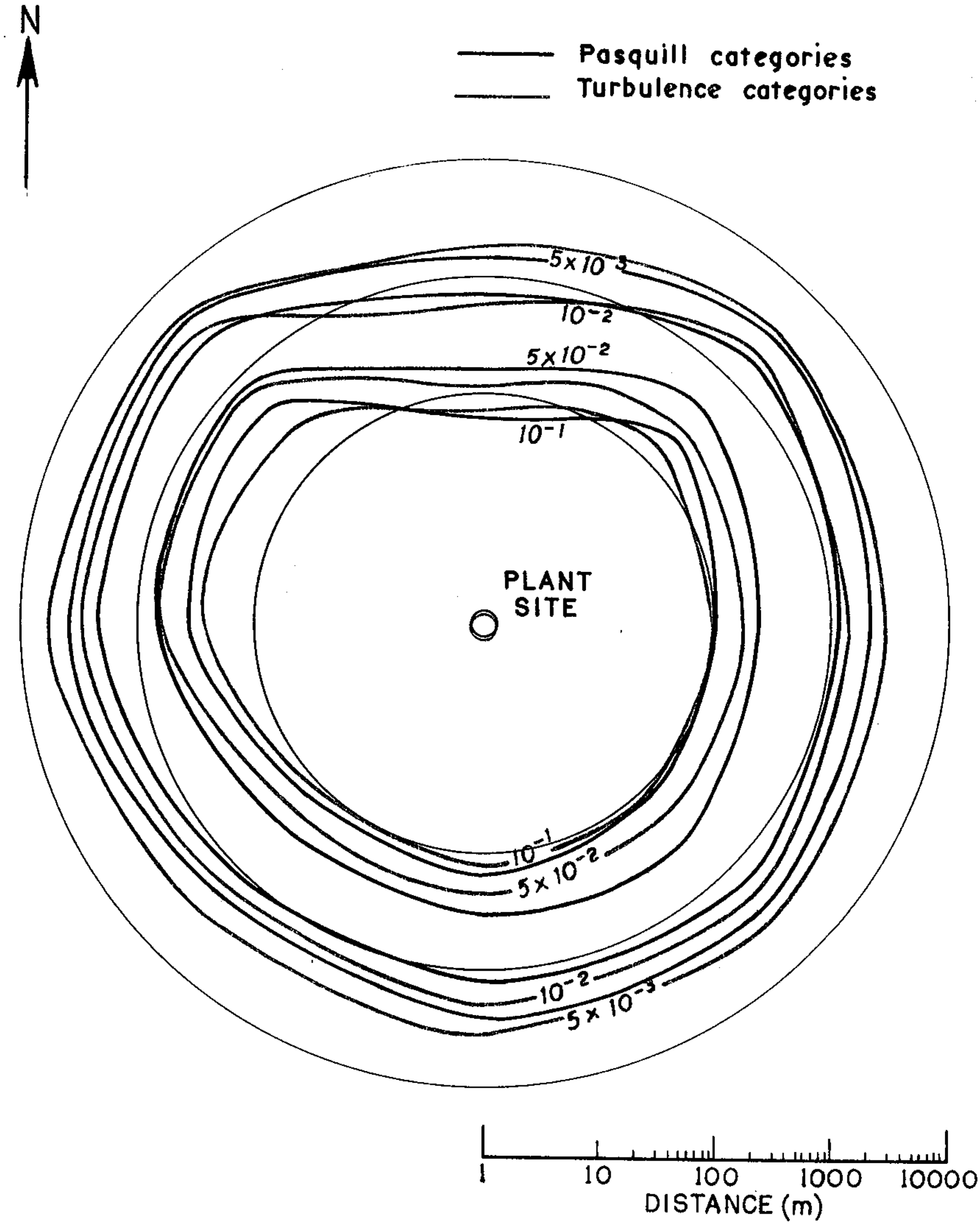


FIGURE 22. URANIUM DUST AIR CONCENTRATIONS (pCi m^{-3}) (AT 1 METRE ALTITUDE) USING SOURCE INVENTORY No. 2 – 6000 t y^{-1} PLANT

APPENDIX A

EXPANSION OF DATA USED IN THE ATMOSPHERIC DISPERSION PREDICTIONS AT JABIRU

Two methods were used for atmospheric dispersion estimates of aerosols released from the uranium mining operations at Jabiru. These were defined as the 'Turbulence' and 'Pasquill' methods. As described in Sections 3 and 12, wind data were re-analysed by 1 hour averages of speed, direction and the turbulent nature of the direction trace for the period May 1973 to May 1975. The 30 metre level on the meteorological tower at the mining site was chosen as the most representative place for wind measurements over the area.

The annual frequency of Pasquill stability categories is summarised by wind speed class, wind direction and time of day (day = 6 a.m. to 6 p.m.; night 6 p.m. to 6 a.m.) (Tables A1 to A4). Tables A5 to A10 give similar data on the frequency of occurrence of the wind direction turbulence classes defined by Clark & Bendun [1974]. These data were then applied to the Gaussian diffusion model and source emission inventories for the various aerosols to give the downwind estimates of air concentrations as a function of distance and wind direction sector.

In preparing estimates of the annual radiation doses to individuals on the SML boundary and at other locations in the region, it was necessary to separate the source types for uranium dust according to either the ore or yellowcake production process. In Tables A11 and A12 the air concentrations for uranium dust are separated by the type of production process. Because estimates using the Pasquill method were lower, only those from the Turbulence method are presented.

TABLE A1

FREQUENCY (%) OF OCCURRENCE OF PASQUILL STABILITY CATEGORIES
JABIRU METEOROLOGICAL TOWER ... 30M

NOTE : TOTAL IN LOWER RIGHT HAND CORNER OF THE TABLE IS THE NUMBER OF HOURLY OBSERVATIONS

TIME = NIGHT WIND DIRECTION = N

	WIND SPEED (M/S)					
PASQUILL	0-1	1-2	2-4	4-8	>8	TOTAL
A	0.00	0.16	0.70	0.24	0.00	1.11
B	0.00	0.80	4.70	1.35	0.00	6.85
C	0.21	3.53	10.37	3.62	0.00	17.74
D	0.37	5.82	14.33	4.58	0.00	25.11
E	1.55	13.42	11.73	0.15	0.00	26.85
F	0.15	2.64	2.43	0.00	0.00	5.22
F1	7.33	8.48	1.33	0.00	0.00	17.13
TOTAL	9.61	34.85	45.60	9.93	0.00	614.

TIME = NIGHT WIND DIRECTION = NE

	WIND SPEED (M/S)					
PASQUILL	0-1	1-2	2-4	4-8	>8	TOTAL
A	0.00	0.20	0.76	0.17	0.00	1.13
B	0.00	0.67	2.93	0.34	0.00	3.93
C	0.25	3.91	8.70	0.71	0.00	13.57
D	0.52	7.83	14.33	0.93	0.00	23.60
E	1.75	17.44	15.17	0.10	0.00	34.46
F	0.40	3.98	2.63	0.00	0.00	7.02
F1	5.83	9.01	1.45	0.00	0.00	16.29
TOTAL	8.74	43.05	45.96	2.24	0.00	446.

TIME = NIGHT WIND DIRECTION = E

	WIND SPEED (M/S)					
PASQUILL	0-1	1-2	2-4	4-8	>8	TOTAL
A	0.00	0.07	0.68	0.18	0.00	0.94
B	0.03	0.20	2.36	0.81	0.00	3.40
C	0.18	1.82	8.39	2.53	0.00	12.92
D	0.25	3.91	15.98	6.22	0.00	26.35
E	0.68	9.16	19.36	3.33	0.00	32.53
F	0.07	3.88	8.29	0.46	0.00	12.71
F1	2.34	5.27	3.48	0.06	0.00	11.15
TOTAL	3.54	24.32	58.54	13.60	0.00	1242.

TIME = NIGHT WIND DIRECTION = SE

	WIND SPEED (M/S)					
PASQUILL	0-1	1-2	2-4	4-8	>8	TOTAL
A	0.00	0.00	0.59	0.04	0.00	0.63
B	0.01	0.09	1.94	1.41	0.00	3.45
C	0.13	1.30	7.07	5.09	0.04	13.63
D	0.24	2.88	14.94	10.50	0.07	28.62
E	0.74	7.05	18.37	3.89	0.00	30.05
F	0.26	2.23	8.59	0.48	0.00	11.56
F1	2.88	5.39	3.69	0.09	0.00	12.05
TOTAL	4.26	18.95	55.17	21.50	0.12	1736.

TABLE A2

FREQUENCY (%) OF OCCURRENCE OF PASQUILL STABILITY CATEGORIES
JABIRU METEOROLOGICAL TOWER ... 30M

NOTE : TOTAL IN LOWER RIGHT HAND CORNER OF THE TABLE IS THE NUMBER OF HOURLY OBSERVATIONS

TIME = NIGHT WIND DIRECTION = S

WIND SPEED (M/S)

PASQUILL	0-1	1-2	2-4	4-8	>8	TOTAL
A	0.00	0.47	0.40	0.35	0.00	1.21
B	0.00	0.37	1.36	0.21	0.10	2.04
C	0.47	3.62	4.39	0.51	0.60	9.60
D	0.98	7.34	7.48	0.33	1.17	17.29
E	3.32	17.87	8.39	0.00	0.00	29.58
F	0.84	3.93	2.52	0.00	0.00	7.29
F1	13.08	17.34	2.57	0.00	0.00	32.99
TOTAL	18.69	50.93	27.10	1.40	1.87	214.

TIME = NIGHT WIND DIRECTION = SW

WIND SPEED (M/S)

PASQUILL	0-1	1-2	2-4	4-8	>8	TOTAL
A	0.00	0.00	0.09	0.17	0.00	0.26
B	0.00	0.16	1.63	0.76	0.00	2.56
C	0.08	1.62	7.61	3.22	0.00	12.53
D	0.16	3.35	16.15	7.00	0.00	26.66
E	0.56	8.30	19.91	2.68	0.00	31.44
F	0.10	3.00	7.53	0.36	0.00	10.98
F1	3.78	6.59	5.11	0.09	0.00	15.57
TOTAL	4.67	23.02	58.04	14.28	0.00	899.

TIME = NIGHT WIND DIRECTION = W

WIND SPEED (M/S)

PASQUILL	0-1	1-2	2-4	4-8	>8	TOTAL
A	0.00	0.00	0.44	0.19	0.00	0.63
B	0.00	0.15	1.37	0.30	0.00	1.82
C	0.23	3.44	5.22	0.76	0.00	9.65
D	0.49	8.49	9.77	0.81	0.00	19.56
E	1.65	21.10	11.89	0.00	0.00	34.64
F	0.46	7.65	3.39	0.00	0.00	11.51
F1	6.96	14.06	1.17	0.00	0.00	22.19
TOTAL	9.79	54.90	33.25	2.06	0.00	388.

TIME = NIGHT WIND DIRECTION = NW

WIND SPEED (M/S)

PASQUILL	0-1	1-2	2-4	4-8	>8	TOTAL
A	0.00	0.00	0.13	0.24	0.00	0.37
B	0.00	0.13	3.96	0.76	0.00	4.84
C	0.16	2.46	10.29	2.13	0.00	15.03
D	0.34	5.78	16.65	2.96	0.00	25.73
E	1.17	14.77	17.09	0.35	0.00	33.38
F	0.85	5.01	2.54	0.00	0.00	8.40
F1	3.92	7.33	0.99	0.00	0.00	12.24
TOTAL	6.44	35.48	51.65	6.44	0.00	637.

TABLE A3

FREQUENCY (%) OF OCCURRENCE OF PASQUILL STABILITY CATEGORIES
JABIRU METEOROLOGICAL TOWER ... 30M

NOTE : TOTAL IN LOWER RIGHT HAND CORNER OF THE TABLE IS THE NUMBER OF HOURLY OBSERVATIONS

TIME = DAY WIND DIRECTION = N

	WIND SPEED (M/S)					
PASQUILL	0-1	1-2	2-4	4-8	>8	TOTAL
A	1.10	14.60	30.70	4.15	0.00	50.56
B	0.79	1.65	8.22	2.55	0.00	13.21
C	2.05	3.50	8.22	3.90	0.00	17.67
D	1.12	2.11	6.17	4.59	0.00	14.00
E	0.24	0.40	0.00	0.00	0.00	0.64
F	2.40	1.52	0.00	0.00	0.00	3.92
F1	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	7.71	23.79	53.30	15.20	0.00	454.

TIME = DAY WIND DIRECTION = NE

	WIND SPEED (M/S)					
PASQUILL	0-1	1-2	2-4	4-8	>8	TOTAL
A	0.37	12.99	38.32	13.44	0.00	65.12
B	0.44	1.67	6.54	3.84	0.00	12.48
C	1.12	3.05	5.05	3.16	0.00	12.37
D	0.64	1.71	3.28	2.56	0.00	8.20
E	0.13	0.05	0.11	0.07	0.00	0.36
F	1.15	0.32	0.00	0.00	0.00	1.47
F1	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	3.85	19.78	53.30	23.08	0.00	546.

TIME = DAY WIND DIRECTION = E

	WIND SPEED (M/S)					
PASQUILL	0-1	1-2	2-4	4-8	>8	TOTAL
A	0.23	4.09	25.58	18.80	0.07	48.78
B	0.15	1.34	6.30	6.28	0.03	14.10
C	0.41	2.93	8.27	6.69	0.10	18.40
D	0.27	1.86	6.01	6.12	0.15	14.41
E	0.09	0.41	0.51	0.50	0.00	1.51
F	0.83	1.34	0.56	0.08	0.00	2.80
F1	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	1.98	11.95	47.23	38.48	0.35	1715.

TIME = DAY WIND DIRECTION = SE

	WIND SPEED (M/S)					
PASQUILL	0-1	1-2	2-4	4-8	>8	TOTAL
A	0.27	4.65	18.34	12.37	0.00	35.63
B	0.34	1.98	5.46	6.75	0.01	14.52
C	0.84	4.24	8.64	9.77	0.04	23.54
D	0.53	2.54	6.97	11.02	0.09	21.14
E	0.18	0.37	0.93	0.64	0.00	2.11
F	1.27	1.08	0.70	0.00	0.00	3.05
F1	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	3.42	14.86	41.03	40.55	0.14	1460.

TABLE A4

FREQUENCY (%) OF OCCURRENCE OF PASQUILL STABILITY CATEGORIES
JABIRU METEOROLOGICAL TOWER ... 30M

NOTE : TOTAL IN LOWER RIGHT HAND CORNER OF THE TABLE IS THE NUMBER OF HOURLY OBSERVATIONS

TIME = DAY WIND DIRECTION = S

PASQUILL	WIND SPEED (M/S) 0-1	1-2	2-4	4-8	>8	TOTAL
A	0.99	14.50	28.54	6.95	0.00	50.99
B	0.86	2.72	5.07	3.03	0.02	11.69
C	2.22	5.86	4.74	3.46	0.10	16.37
D	1.42	3.94	2.95	3.97	0.22	12.50
E	0.40	0.81	0.23	0.13	0.00	1.57
F	4.04	2.30	0.53	0.00	0.00	6.87
F1	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	9.93	30.13	42.05	17.55	0.33	302.

TIME = DAY WIND DIRECTION = SW

PASQUILL	WIND SPEED (M/S) 0-1	1-2	2-4	4-8	>8	TOTAL
A	0.39	4.91	23.32	8.75	0.00	37.37
B	0.21	1.79	6.92	5.06	0.01	13.99
C	0.55	3.93	10.52	8.37	0.09	23.47
D	0.37	2.46	7.62	9.18	0.16	19.79
E	0.24	0.41	0.74	0.09	0.00	1.47
F	2.04	1.05	0.81	0.00	0.00	3.91
F1	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	3.80	14.55	49.93	31.45	0.26	763.

TIME = DAY WIND DIRECTION = W

PASQUILL	WIND SPEED (M/S) 0-1	1-2	2-4	4-8	>8	TOTAL
A	0.47	9.06	41.00	7.20	0.00	57.73
B	0.23	2.22	6.86	2.56	0.00	11.89
C	0.59	4.77	6.42	2.65	0.00	14.41
D	0.35	3.21	3.59	2.81	0.00	9.96
E	0.21	0.67	0.30	0.00	0.00	1.18
F	2.83	1.62	0.37	0.00	0.00	4.82
F1	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	4.68	21.55	58.55	15.22	0.00	427.

TIME = DAY WIND DIRECTION = NW

PASQUILL	WIND SPEED (M/S) 0-1	1-2	2-4	4-8	>8	TOTAL
A	0.22	6.99	33.18	6.49	0.00	46.88
B	0.48	2.14	7.67	3.19	0.00	13.48
C	1.23	5.04	8.68	4.07	0.00	19.03
D	0.80	3.47	5.75	4.87	0.00	14.89
E	0.30	0.79	0.13	0.00	0.00	1.22
F	2.38	2.12	0.00	0.00	0.00	4.50
F1	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	5.41	20.56	55.41	18.61	0.00	462.

TABLE A5

FREQUENCY (%) OF OCCURRENCE OF WIND DIRECTION TURBULENCE CLASSES
JABIRU METEOROLOGICAL TOWER ... 30M

NOTE : TOTAL IN LOWER RIGHT HAND CORNER OF THE TABLE IS THE NUMBER OF HOURLY OBSERVATIONS

TIME = NIGHT WIND DIRECTION = N

	WIND SPEED (M/S)					
TURB.	0-1	1-2	2-4	4-8	>8	TOTAL
1	0.00	0.16	0.49	0.00	0.00	0.65
2	0.00	0.65	14.98	6.51	0.00	22.15
3	0.00	0.00	2.12	0.65	0.00	2.77
4	0.00	0.16	1.14	2.28	0.00	3.58
5	1.63	3.09	1.47	0.00	0.00	6.19
6	0.00	2.93	3.09	0.00	0.00	6.03
7	0.49	6.51	11.40	0.16	0.00	18.57
8	1.14	9.93	3.75	0.00	0.00	14.82
9	0.49	5.70	7.00	0.33	0.00	13.52
10	5.86	5.70	0.16	0.00	0.00	11.73
TOTAL	9.61	34.85	45.60	9.93	0.00	614.

TIME = NIGHT WIND DIRECTION = NE

	WIND SPEED (M/S)					
TURB.	0-1	1-2	2-4	4-8	>8	TOTAL
1	0.00	0.22	0.00	0.00	0.00	0.22
2	0.00	0.45	8.07	1.57	0.00	10.09
3	0.00	0.22	1.57	0.45	0.00	2.24
4	0.00	0.00	0.22	0.00	0.00	0.22
5	1.35	3.81	0.90	0.00	0.00	6.05
6	0.45	4.93	4.48	0.00	0.00	9.87
7	0.00	4.04	14.57	0.00	0.00	18.61
8	2.24	16.59	6.28	0.00	0.00	25.11
9	0.22	6.95	9.19	0.22	0.00	16.59
10	4.48	5.83	0.67	0.00	0.00	10.99
TOTAL	8.74	43.05	45.96	2.24	0.00	446.

TIME = NIGHT WIND DIRECTION = E

	WIND SPEED (M/S)					
TURB.	0-1	1-2	2-4	4-8	>8	TOTAL
1	0.00	0.00	0.08	0.00	0.00	0.08
2	0.00	0.00	5.55	4.42	0.00	9.98
3	0.00	0.08	2.09	0.64	0.00	2.82
4	0.00	0.00	0.40	0.64	0.00	1.05
5	0.80	4.10	4.02	0.08	0.00	9.01
6	0.08	4.67	11.83	0.88	0.00	17.46
7	0.00	3.54	25.91	7.00	0.00	36.44
8	0.97	6.52	3.22	0.00	0.00	10.70
9	0.16	3.94	5.39	0.00	0.00	9.49
10	1.53	1.45	0.00	0.00	0.00	2.98
TOTAL	3.54	24.30	58.49	13.68	0.00	1243.

TABLE A6

FREQUENCY (%) OF OCCURRENCE OF WIND DIRECTION TURBULENCE CLASSES
JABIRU METEOROLOGICAL TOWER ... 30M

NOTE : TOTAL IN LOWER RIGHT HAND CORNER OF THE TABLE IS THE NUMBER OF HOURLY OBSERVATIONS

TIME = NIGHT WIND DIRECTION = SE

WIND SPEED (M/S)

TURB.	0-1	1-2	2-4	4-8	>8	TOTAL
1	0.00	0.00	0.12	0.00	0.00	0.12
2	0.00	0.00	5.29	7.25	0.00	12.54
3	0.00	0.00	1.04	0.17	0.00	1.21
4	0.00	0.12	0.92	4.83	0.12	5.98
5	0.75	3.91	3.97	0.12	0.00	8.75
6	0.23	2.47	12.49	0.92	0.00	16.11
7	0.00	2.65	25.20	8.06	0.00	35.90
8	1.09	5.75	2.53	0.06	0.00	9.44
9	0.00	2.19	3.45	0.17	0.00	5.81
10	2.19	1.84	0.12	0.00	0.00	4.14
TOTAL	4.26	18.93	55.12	21.58	0.12	1738.

TIME = NIGHT WIND DIRECTION = S

WIND SPEED (M/S)

TURB.	0-1	1-2	2-4	4-8	>8	TOTAL
1	0.00	0.47	0.00	0.00	0.00	0.47
2	0.00	0.00	3.27	0.00	0.47	3.74
3	0.00	0.00	1.40	1.40	0.00	2.80
4	0.00	0.00	0.00	0.00	1.40	1.40
5	2.80	9.35	1.87	0.00	0.00	14.02
6	0.93	2.34	4.21	0.00	0.00	7.48
7	0.00	2.34	6.07	0.00	0.00	8.41
8	4.67	18.69	2.80	0.00	0.00	26.17
9	0.00	7.48	6.54	0.00	0.00	14.02
10	10.28	10.28	0.93	0.00	0.00	21.50
TOTAL	18.69	50.93	27.10	1.40	1.87	214.

TIME = NIGHT WIND DIRECTION = SW

WIND SPEED (M/S)

TURB.	0-1	1-2	2-4	4-8	>8	TOTAL
1	0.00	0.00	0.11	0.00	0.00	0.11
2	0.00	0.00	3.89	3.00	0.00	6.89
3	0.00	0.11	0.78	0.33	0.00	1.22
4	0.00	0.00	2.22	4.56	0.00	6.78
5	1.44	4.22	5.89	0.11	0.00	11.67
6	0.00	3.11	10.22	0.67	0.00	14.00
7	0.00	4.11	25.33	5.22	0.00	34.67
8	0.67	5.11	2.78	0.00	0.00	8.56
9	0.11	3.22	6.56	0.44	0.00	10.33
10	2.44	3.11	0.22	0.00	0.00	5.78
TOTAL	4.67	23.00	58.00	14.33	0.00	900.

TABLE A7

FREQUENCY (%) OF OCCURRENCE OF WIND DIRECTION TURBULENCE CLASSES
JABIRU METEOROLOGICAL TOWER ... 30M

NOTE : TOTAL IN LOWER RIGHT HAND CORNER OF THE TABLE IS THE NUMBER OF HOURLY OBSERVATIONS

TIME = NIGHT WIND DIRECTION = W

	WIND SPEED (M/S)					
TURB.	0-1	1-2	2-4	4-8	>8	TOTAL
1	0.00	0.26	0.26	0.00	0.00	0.52
2	0.00	0.00	2.84	1.03	0.00	3.87
3	0.00	0.00	1.55	0.77	0.00	2.32
4	0.00	0.00	0.52	0.26	0.00	0.77
5	2.84	7.47	1.29	0.00	0.00	11.60
6	0.52	7.73	4.38	0.00	0.00	12.63
7	0.00	6.19	9.02	0.00	0.00	15.21
8	1.80	17.01	3.61	0.00	0.00	22.42
9	0.52	7.99	9.54	0.00	0.00	18.04
10	4.12	8.25	0.26	0.00	0.00	12.63
TOTAL	9.79	54.90	33.25	2.06	0.00	388.

TIME = NIGHT WIND DIRECTION = NW

	WIND SPEED (M/S)					
TURB.	0-1	1-2	2-4	4-8	>8	TOTAL
1	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	12.56	3.61	0.00	16.17
3	0.00	0.00	1.41	0.47	0.00	1.88
4	0.00	0.00	0.63	1.57	0.00	2.20
5	1.26	4.40	1.41	0.00	0.00	7.06
6	0.47	5.65	3.45	0.00	0.00	9.58
7	0.00	6.12	21.04	0.78	0.00	27.94
8	1.57	10.36	3.77	0.00	0.00	15.70
9	0.00	5.49	7.22	0.00	0.00	12.72
10	3.14	3.45	0.16	0.00	0.00	6.75
TOTAL	6.44	35.48	51.65	6.44	0.00	637.

TABLE A8

FREQUENCY (%) OF OCCURRENCE OF WIND DIRECTION TURBULENCE CLASSES
JABIRU METEOROLOGICAL TOWER ... 30M

NOTE : TOTAL IN LOWER RIGHT HAND CORNER OF THE TABLE IS THE NUMBER OF HOURLY OBSERVATIONS

TIME = DAY — WIND DIRECTION = N

WIND SPEED (M/S)

TURB.	0-1	1-2	2-4	4-8	>8	TOTAL
1	0.88	13.22	14.98	0.44	0.00	29.52
2	0.00	0.66	13.22	7.71	0.00	21.59
3	0.22	1.54	20.26	5.07	0.00	27.09
4	0.00	0.00	0.00	1.76	0.00	1.76
5	0.22	0.44	0.00	0.00	0.00	0.66
6	0.00	0.44	0.00	0.00	0.00	0.44
7	0.66	1.10	1.76	0.00	0.00	3.52
8	2.64	2.42	0.22	0.00	0.00	5.29
9	0.66	2.64	2.86	0.22	0.00	6.39
10	2.42	1.32	0.00	0.00	0.00	3.74
TOTAL	7.71	23.79	53.30	15.20	0.00	454.

TIME = DAY — WIND DIRECTION = NE

WIND SPEED (M/S)

TURB.	0-1	1-2	2-4	4-8	>8	TOTAL
1	0.18	9.52	22.34	2.38	0.00	34.43
2	0.00	0.37	5.31	5.13	0.00	10.81
3	0.18	3.85	21.43	15.38	0.00	40.84
4	0.00	0.00	0.18	0.00	0.00	0.18
5	0.00	0.18	0.00	0.00	0.00	0.18
6	0.00	0.00	0.37	0.00	0.00	0.37
7	0.18	0.92	1.47	0.18	0.00	2.75
8	1.83	1.47	0.00	0.00	0.00	3.30
9	0.18	3.30	2.20	0.00	0.00	5.68
10	1.28	0.18	0.00	0.00	0.00	1.47
TOTAL	3.85	19.78	53.30	23.08	0.00	546.

TIME = DAY — WIND DIRECTION = E

WIND SPEED (M/S)

TURB.	0-1	1-2	2-4	4-8	>8	TOTAL
1	0.12	2.57	8.10	1.75	0.00	12.54
2	0.00	0.29	6.65	11.08	0.17	18.19
3	0.12	1.69	21.52	23.21	0.12	46.65
4	0.00	0.00	0.29	0.99	0.06	1.34
5	0.41	0.93	0.70	0.12	0.00	2.16
6	0.12	0.64	1.22	0.29	0.00	2.27
7	0.06	1.52	6.30	0.99	0.00	8.86
8	0.64	1.28	0.41	0.00	0.00	2.33
9	0.06	2.45	2.04	0.06	0.00	4.61
10	0.47	0.58	0.00	0.00	0.00	1.05
TOTAL	1.98	11.95	47.23	38.48	0.35	1715.

TABLE A9

FREQUENCY (%) OF OCCURRENCE OF WIND DIRECTION TURBULENCE CLASSES
JABIRU METEOROLOGICAL TOWER ... 30M

NOTE : TOTAL IN LOWER RIGHT HAND CORNER OF THE TABLE IS THE NUMBER OF HOURLY OBSERVATIONS

TIME = DAY WIND DIRECTION = SE

	WIND SPEED (M/S)					
TURB.	0-1	1-2	2-4	4-8	>8	TOTAL
1	0.27	2.74	5.75	0.89	0.00	9.66
2	0.07	0.68	5.89	18.77	0.14	25.55
3	0.00	2.12	15.48	15.55	0.00	33.15
4	0.00	0.00	0.34	3.49	0.00	3.84
5	0.41	0.68	0.82	0.00	0.00	1.92
6	0.21	0.62	2.47	0.48	0.00	3.77
7	0.14	2.19	7.95	1.30	0.00	11.58
8	1.16	2.40	0.41	0.00	0.00	3.97
9	0.21	2.88	1.85	0.07	0.00	5.00
10	0.96	0.55	0.07	0.00	0.00	1.58
TOTAL	3.42	14.86	41.03	40.55	0.14	1460.

TIME = DAY WIND DIRECTION = S

	WIND SPEED (M/S)					
TURB.	0-1	1-2	2-4	4-8	>8	TOTAL
1	0.99	10.93	13.58	0.00	0.00	25.50
2	0.00	0.33	3.64	7.95	0.33	12.25
3	0.00	3.97	19.21	9.27	0.00	32.45
4	0.00	0.00	0.00	0.00	0.00	0.00
5	1.66	0.99	0.66	0.00	0.00	3.31
6	0.33	1.32	0.33	0.00	0.00	1.99
7	0.00	0.99	1.99	0.33	0.00	3.31
8	3.97	6.62	0.66	0.00	0.00	11.26
9	0.33	3.31	1.99	0.00	0.00	5.63
10	2.65	1.66	0.00	0.00	0.00	4.30
TOTAL	9.93	30.13	42.05	17.55	0.33	302.

TIME = DAY WIND DIRECTION = SW

	WIND SPEED (M/S)					
TURB.	0-1	1-2	2-4	4-8	>8	TOTAL
1	0.39	3.15	5.11	0.00	0.00	8.65
2	0.00	0.52	8.39	14.42	0.13	23.46
3	0.00	1.97	22.02	11.66	0.00	35.65
4	0.00	0.13	1.18	5.11	0.13	6.55
5	0.39	0.92	0.92	0.00	0.00	2.23
6	0.13	0.79	1.70	0.13	0.00	2.75
7	0.00	1.44	6.03	0.13	0.00	7.60
8	0.92	2.88	0.39	0.00	0.00	4.19
9	0.13	2.49	4.06	0.00	0.00	6.68
10	1.83	0.26	0.13	0.00	0.00	2.23
TOTAL	3.80	14.55	49.93	31.45	0.26	763.

TABLE A10

FREQUENCY (%) OF OCCURRENCE OF WIND DIRECTION TURBULENCE CLASSES
JABIRU METEOROLOGICAL TOWER ... 30M

NOTE : TOTAL IN LOWER RIGHT HAND CORNER OF THE TABLE IS THE NUMBER OF HOURLY OBSERVATIONS

TIME = DAY   WIND DIRECTION = W

	WIND SPEED (M/S)					
TURB.	0-1	1-2	2-4	4-8	>8	TOTAL
1	0.23	6.32	11.71	0.00	0.00	18.27
2	0.00	0.47	4.22	5.62	0.00	10.30
3	0.23	3.04	35.83	9.60	0.00	48.71
4	0.00	0.00	0.00	0.00	0.00	0.00
5	0.94	0.47	0.47	0.00	0.00	1.87
6	0.00	1.17	0.70	0.00	0.00	1.87
7	0.00	0.94	0.94	0.00	0.00	1.87
8	1.17	2.81	0.70	0.00	0.00	4.68
9	0.00	4.92	3.98	0.00	0.00	8.90
10	2.11	1.41	0.00	0.00	0.00	3.51
TOTAL	4.68	21.55	58.55	15.22	0.00	427.

TIME = DAY   WIND DIRECTION = NW

	WIND SPEED (M/S)					
TURB.	0-1	1-2	2-4	4-8	>8	TOTAL
1	0.00	5.63	12.34	0.00	0.00	17.97
2	0.00	0.43	9.09	9.09	0.00	18.61
3	0.22	1.52	25.97	8.66	0.00	36.36
4	0.00	0.00	0.43	0.87	0.00	1.30
5	0.43	1.95	0.00	0.00	0.00	2.38
6	0.22	1.52	0.43	0.00	0.00	2.16
7	0.00	1.52	1.52	0.00	0.00	3.03
8	1.95	3.46	0.87	0.00	0.00	6.28
9	0.43	4.11	4.76	0.00	0.00	9.31
10	2.16	0.43	0.00	0.00	0.00	2.60
TOTAL	5.41	20.56	55.41	18.61	0.00	462.

TABLE A11

ANNUAL AVERAGE URANIUM DUST AIR CONCENTRATIONS (AT 1 metre ALTITUDE) ON THE SML BOUNDARY; ASSUMING ALL SOURCES LOCATED AT THE PLANT SITE, NO DRY DEPOSITION INCLUDED

Source information	Source type	Direction from Plant Site							
		N	NE	E	SE	S	SW	W	NW
		Annual Average Air Concentrations (pCi m^{-3})							
Uranium dust 3000 t y^{-1}	Ore	$0.88x10^{-3}$	$2.03x10^{-3}$	$1.53x10^{-3}$	$1.84x10^{-3}$	$0.77x10^{-3}$	$0.25x10^{-3}$	$1.68x10^{-3}$	$1.65x10^{-3}$
Turbulence method	Yellowcake	$1.87x10^{-3}$	$4.47x10^{-3}$	$3.32x10^{-3}$	$2.5x10^{-3}$	$1.96x10^{-3}$	$0.73x10^{-3}$	$4.02x10^{-3}$	$4.65x10^{-3}$
Uranium dust 6000 t y^{-1}	Ore	$1.57x10^{-3}$	$3.64x10^{-3}$	$2.55x10^{-3}$	$2.2x10^{-3}$	$1.26x10^{-3}$	$0.50x10^{-3}$	$3.0x10^{-3}$	$3.3x10^{-3}$
Turbulence method	Yellowcake	$3.33x10^{-3}$	$8.16x10^{-3}$	$5.85x10^{-3}$	$5.5x10^{-3}$	$3.54x10^{-3}$	$1.28x10^{-3}$	$7.2x10^{-3}$	$8.5x10^{-3}$

TABLE A12

ANNUAL AVERAGE URANIUM DUST AIR CONCENTRATIONS (AT 1 metre ALTITUDE)

USING THE TURBULENCE METHOD; ASSUMING ALL SOURCES LOCATED AT THE PLANT SITE,

NO DRY DEPOSITION INCLUDED

Source type	Regional centre		Mudginberri Pastoral Lease				Plant Size ($t\ y^{-1}$)
			Homestead		Closest boundary		
	West	North-west	North-west	North	North-west	North	
	Maximum Annual Average Concentrations ($pCi\ m^{-3}$)						
Ore	$3.6x10^{-4}$	$0.43x10^{-3}$	$3.65x10^{-4}$	$1.07x10^{-4}$	$1.10x10^{-3}$	$0.51x10^{-3}$	3000
Yellowcake	$8.41x10^{-4}$	$1.05x10^{-3}$	$8.85x10^{-4}$	$2.45x10^{-4}$	$2.63x10^{-3}$	$1.09x10^{-3}$	
Ore	$0.64x10^{-3}$	$0.78x10^{-3}$	$0.66x10^{-3}$	$1.90x10^{-4}$	$1.98x10^{-3}$	$0.91x10^{-3}$	6000
Yellowcake	$1.5x10^{-3}$	$1.87x10^{-3}$	$1.57x10^{-3}$	$4.35x10^{-4}$	$4.68x10^{-3}$	$1.97x10^{-3}$	
Distance from plant site (km)	9		10		5	3.5	