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UNIVERSITY OF LONDON
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THE PRACTICAL PREDICTION OF AIR
POLLUTION FOR INDUSTRIAL SITUATIONS

by

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ABSTRACT

By considering four case studies, several significant complicating factors in the application of air pollution dispersion models to industrial planning problems are identified, and methods are suggested for simulating them in the models. The first three case studies feature: local meteorological and topographic effects; off-design behaviour of sources; chimney downwash; problems of elevated receptors; and consideration of short-term peaks. The fourth case study (of a lead-acid battery factory) covers airborne lead, surface dust, lead in soil and in human blood.

In the battery factory study it is found that lead contamination of the air due to the works at distances of about 400 to 800 metres is only about one third to one half of the urban background levels, but lead in the blood of leadworkers' children is often significantly higher than average. The lead-in-air study of the battery factory involves wind and lead concentration measurements. It is found to be possible to correlate local winds at the factory (which is in a valley) with those at the nearest synoptic weather station and thereby to estimate long-term wind frequencies for the site.

A computer model of industrial pollution dispersion is constructed, taking into account the implications of the case studies and also the effect of inherent uncertainties in weather data. The model was used to simulate the battery factory during the lead monitoring period and the agreement between computed and measured concentrations was found to be encouragingly good (certainly sufficient for planning purposes) but by no means exact. The model was then used to predict long-term averages and frequency distributions, to illustrate its potential use in planning problems.

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1.0 INTRODUCTION

1.1 Objectives of this research

There is a pressing need for trustworthy means of predicting air pollution concentrations which might arise due to proposed industrial development. This need arises from several sources:

- (a) there is the obligation to the community to protect people living near to industrial plant from damage to health or property
- (b) excessive pollution of the air may impose constraints on future development, for example by creating an environment which is unacceptable to sensitive industries (food processing, instrument manufacture etc)
- (c) nuisance due to odour or dust may have a serious effect on the local community, for example by affecting property values, even though it may not be actually harmful to health or property
- (d) in planning situations the onus of proof rests on the developer and since the plant has not been built at this stage, theoretical calculations are the only method available
- (e) cases often arise when the cause of an air pollution problem is not immediately obvious; theoretical models can help apportion blame in such cases.

The present work is aimed particularly at planning situations and the starting point is the observation that in almost all real cases of which the author is aware the applicability of conventional dispersion models is clouded by the presence of a number of complicating factors. These might include : topographic effects,

variations in surface characteristics, presence of particles in the emission, weather effects (e.g. rain), human interference (e.g. vehicle motion) etc. These effects and others will be considered in greater detail later.

The plume dispersion models currently in use for studies of single industrial sources are founded on open air measurements of dispersion rates in situations which were deliberately selected for their fundamental simplicity (Pasquill(1961), Singer and Smith (1966)). That was of course absolutely correct, for it can be assumed, and it proved indeed to be the case, that many of the complicating factors which exist in real situations can be accounted for by relatively straightforward modifications of the 'ideal' models. These modifications should have a sufficiently convincing theoretical basis that further experimentation to validate them is unnecessary.

Unfortunately, however, it frequently happens that so many 'non-ideal' factors operate simultaneously that the overall accuracy of the prediction method now rests not so much on the niceties of the basic plume dispersion model but on the appropriateness of the modifications made in applying it to the case in hand. We now see that there is an imbalance between the precision of the dispersion model (for in the ideal case it is indeed very precise) and the inaccuracies surrounding the rest of the calculation. The overall objective of the present work is to contribute to the redressing of this imbalance by examining the methods involved in the light of specific case studies and developing guidelines for improved predictions as a result.

1.2 Complexity of dispersion mechanisms in real situations

Dispersion of a passive tracer or pollutant in the atmosphere occurs as a result of non-uniformities in the air flow. In principle, dispersion would not be observed if the air had at all points and all times the same velocity; however this situation never obtains in situations of practical interest in the atmosphere.

A number of mechanisms operate to distort the flow of the wind with respect to both time and space, notably the onset of turbulence, the shear of the flow associated with surface friction, and variations of density with height. For reasonably straightforward situations (e.g. in flat uniform terrain) the equations of motion for the time-dependent air flow can be written down (e.g. in differential form the Navier-Stokes equations), but they have no known analytical solutions and their solution by numerical methods is impractical by a very large margin on even the most powerful modern computers (except in simple cases at low Reynold's Number, which is not relevant to atmospheric flows).

Therefore, even in these relatively straightforward atmospheric flows, we are forced to rely either on gross simplification of the governing equations or on experimental results, or on a combination of both.

In theory, if we know the locations of all the sources of pollution and the temperature, velocity and nature of the emissions in an area, and if we had a complete picture of the airflow and the local topography, we would be able to deduce precisely what the concentration would be anywhere in the area at any time. Apart from being enormously expensive and time-consuming, such a calculation would cover only a particular locality and would be good for only a short time. Therefore it would have little value. At the other extreme a model

with a simplified airflow and topography (for example, uniform flow over a flat plain) would be likely to give unrealistic results.

The most significant single advance that was made in the development of predictive methods for dispersion was the perception that under certain circumstances the dispersion process could be essentially one of diffusion. This was first noted by Sutton (1932), who deduced that the cross-sectional concentration distribution in a plume from a point source in a uniform homogeneous wind field is asymptotically Gaussian in form at large distances from the source. This analysis assumed a constant diffusion coefficient (K) and it was clear that the specification of K would constitute in itself a major problem in any practical scheme.

The further development of this approach (so-called K -theory) has continued to the present day and models for practical cases are often very complex, involving variation of K coefficients with direction and position. It soon becomes apparent, in considering the applicability of this type of model to complex situations, that the specification of K , or indeed the specification of the turbulence field itself constitutes a major problem before any of the resulting equations can be solved. Moreover, any solutions eventually obtained by this method would be open to considerable doubt concerning the K values.

The next significant advance was the observation that the concentration profiles across many real plumes were adequately described by the Gaussian distribution even though Sutton's original analysis only predicted this form at very large distances. It was seen that the specification of the concentrations within the plume could be achieved more readily if the parameters of the

cross-sectional distribution (i.e. standard deviations σ_y, σ_z) could be specified than by specifying K values. Pasquill (1961) and Singer and Smith (1966) presented values of the standard deviations of plumes from point sources as functions of weather condition. The relevant weather condition was classified by Pasquill according to readily observable meteorological parameters (windspeed, insolation etc) and by Singer and Smith by the qualitative and quantitative analysis of the direction traces of a recording anemograph.

It can be seen that by this stage a complete prescription for predicting concentrations having an appealing ease of application had been achieved. However, the method was by now far removed from fundamental physical principles and the experimental data on which it was based were specific to rather special test situations. Nevertheless, the method is in many ways appropriately matched to the problem; it is neither too crude nor unnecessarily sophisticated. It forms the basis of the plume dispersion analysis used in this work.

Naturally, a model of this kind (which is essentially a device for correlating experimental results) will work most reliably when the prototype case to which it is applied corresponds closely to the original experimental conditions. A very good example where this condition is not met was the dispersion of a dense cloud of cold methane vapour formed during commissioning tests on the cargo jettison system of an LNG tanker (Kneebone and Prew, 1974). The investigators found in this case that the cloud standard deviations were well fitted by the following expressions:

$$\sigma_y = 1.384 x^{0.705}$$

$$\sigma_z = 0.0554 x^{0.705}$$

whereas Smith and Singer's standard results for dispersion from a point source are:

$$\sigma_y = 0.44 x^{0.705}$$

$$\sigma_z = 0.087 x^{0.705}$$

Clearly, in this case the density effects are tending to suppress vertical diffusion and enhance lateral spreading. It is obviously quite different from the original test case, yet it is a case of great practical significance.

Topographical effects are a major cause of departures from the 'ideal' case. Industrial plant is often sited in valleys or on coasts because of such factors as access to water supplies etc. Frequently, this means the airflow at the plant is significantly modified both in its average properties (direction and speed) and its fluctuating properties (turbulence). In these cases, it seems likely that suitable modifications of the Gaussian model (e.g. distortion of the plume centreline) would be applicable.

The presence of particles in the pollutant stream is a major complicating factor. While the behaviour of the particles in the air may be relatively well understood (and various authors have suggested models for the motion based, e.g., on terminal fall speed) their behaviour on the surface is extremely complex. In dry weather, particles may be intermittently airborne, sometimes settling during a lull in the wind or when they reach a sheltered place. Their motion is clearly dependent on the aerodynamics of surface obstacles, and the nuisance or other harmful effect they cause may relate to such subtle effects as optical quality rather than to their concentration per se (Hancock, Esmen and Furber, 1976).

Human interference may also cause variations in the dispersion pattern. For example, vehicle motions affect the distribution of dust. Abnormal emissions may occur due to human error; these are seldom predicted at the planning stage, yet they are frequently a major source of damage or nuisance (Cox, Shillito, Comer and Slater, 1977). Such emissions may have unusual dispersion characteristics by virtue of their bulk, density, momentum and other characteristics.

There is a further fundamental problem for planning situations concerning the weather.

In planning to keep down air pollution we try to design plant to last for 20 years or more without at any time causing unacceptable concentrations of pollution at ground level. It is quite impossible to predict weather so far into the future, so we have to look at past records and assume that future weather will be much the same. This assumption must be looked at very carefully for it is not quite as straightforward as it seems at first. For example, the average incidence of westerly-type weather in Britain from 1900 to 1950 was about 100 days per year, making it the most common of all weather types. However, over the period 1920-23 the average stood at 120 and in the years 1968-71 it fell to 66. These variations may be viewed either as inevitable random occurrences or as having distinct causes, according to taste. Whatever the reasoning, it makes little difference; the fact is that the weather is significantly variable, even when averages over quite long periods are compared.

The most intellectually honest approach is to describe the calculation not as a prediction but as a simulation.

We suppose that the proposed development had been built at some time in the past and calculate what pollution it would have caused since then. It is usual to take the weather over the past decade as the data, but there is no reason for believing that this is any more suitable than that over any other decade. Ideally, if the life of the plant it is proposed to build is to be T , we ought to have weather records for a period several times T and perform the simulation to find the worst pollution effects that would have occurred in any past period T . This is a good estimate of the worst possible result in the next T years.

Another problem with the weather is that the records themselves, though excellent for the purposes for which they were designed, are inadequate for pollution analysis. The best meteorological stations are located in open, flat country where the wind is not subject to local effects, whereas factories and towns are often built in valleys to be near a river. So the weather records may not represent conditions at the site being investigated. An important example of this is the 'katabatic wind' which occurs when the ground is cool at night and a shallow layer of cold, dense air drains downhill, often in a totally different direction from that of the wind measured in flat country. This is an extremely important factor affecting air pollution because the katabatic is a very even wind which carries pollution for great distances in a relatively undiluted state.

Local topography causes channelling effects in valleys and sheltering effects behind hills, but the magnitude of the variations depends critically on the wind direction and the temperature structure of the atmosphere. This temperature profile is often unknown, but is one of the most crucial factors in any air pollution model. Air which is being warmed from below becomes convective and is characterized by a great deal of

turbulence and strong mixing which rapidly dilute pollution; it is sometimes referred to as unstable. In contrast, stable, or 'stratified' air gradually decreases in density with height and therefore flows smoothly. It does not disperse much pollution; the katabatic wind is an example. The difficulty here is that existing records do not give a clear picture of temperature over the first few hundred feet from the ground, the region of most interest to the air pollution scientist.

The only way to get round this is to make observations of temperature at the site for long enough for all the important weather situations to be studied. It may be possible to find correlations between the weather observed on the site and that at a permanent weather station, and to estimate how often various local conditions happen by using long term data from the station.

1.3 Uses and accuracy of dispersion models

The accuracy and utility of an air pollution dispersion model is severely limited by the precision of the available meteorological data. One of the most important factors is wind direction, which is conventionally recorded by the Meteorological Office to the nearest 10° . Because the wind direction may vary with height and position, the effective accuracy of wind direction data is considerably worse than this in the usual case of a study area extending over many kilometres, and 45° has been suggested as a typical value for the total spread of possible plume positions for the same nominal wind direction.

It is clear that with such a large degree of uncertainty in the plume centreline no practical model can hope to predict the concentration at any fixed point (e.g. a monitoring site) at any one particular hour. It

could, however, predict the concentration pattern itself fairly well even though the location of the entire pattern may be wrong. If, however, the location error is small when averaged over a large number of occasions, then the time-averaged concentration should be well predicted provided that the calculated concentrations are appropriately averaged over the angular sector of uncertainty of wind direction (i.e., circumferential smoothing of the results).

This spatial averaging in the model may not make a significant difference to the answers if the plume width is not much smaller than the wind direction sector width and the frequencies of wind directions in adjacent sectors are comparable. Where the frequencies of peaks are concerned however, the circumferentially-smoothed model is inappropriate since it averages out peaks that do occur in real life.

We now consider the uses to which air pollution models may be put. The primary purpose, and the one to which the models are best adapted, is the prediction of long-term average concentrations and average frequencies of short-term peaks for planning purposes. Also, many workers have used models as part of a control system designed to keep ambient concentrations below some predetermined level.

For planning purposes either the standard or the circumferentially-smoothed model could be used to obtain average concentrations at any given point. Such a model could be validated by measurements at only a few fixed monitoring sites provided a sufficiently long validation period is used that the effects of plume location errors are averaged out. Average frequencies of peak values could also be obtained and validated in a similar way. Spot measurements are useless for validation; only average concentrations and average frequencies of peaks may be used.

In 'control' applications predictions of short term concentrations have to be made, and if concentrations at only a few fixed sites are of concern, the modelling task is an impossible one because both in reality and in the model the uncertainties of plume position will cause wide variations in concentrations. Furthermore, it will be impossible to validate these predictions. If, however, the worst concentration at any position is the parameter to be controlled, then the standard model should work satisfactorily, though it will again be impossible to validate it unless a very dense monitoring network is set up so that the maximum concentration can, in fact, be observed.

It should be noted that the utility of an air pollution model for planning purposes does not necessarily depend on its ability to predict absolute magnitudes correctly. It may be only the relative magnitudes which are important, for example, when assessing what additional contribution a proposed development would make as a fraction of the total contributions of existing sources as predicted by the same model. Such a model could also be used to estimate the proportions in which existing sources contribute to existing ground level concentrations.

1.4 Survey of previous studies in this field

While a vast literature exists having the same overall objective as the present work, i.e the development of improved predictive methods for air pollution, there has been an overwhelming prepondence of studies making use of essentially idealised models. Various studies have however attempted to cater for specific complications associated with particular case studies, and a selection of these is considered here. The purpose of reviewing these works at this stage is not so much to provide a critique, but to assemble a range

of techniques which are already available, in preparation for their joint application to our own case studies.

Pasquill, in the second edition of his book "Atmospheric Diffusion" (1974) has reviewed the state of the art of air pollution concentration prediction. He concludes that the available methods do not give reliable estimates when:

- (a) the wind is calm or very sluggish
- (b) there are marked local disturbances of the airflow, e.g. near buildings
- (c) the airflow is channelled or contains circulations and drainage due to differential heating and topography.

Pasquill goes on to consider the effects of varying surface roughness and vertical heat flux. He presents graphs showing the variations of the ratio (u^*/u) with these parameters, and then goes on to relate turbulence intensities to u_* and finally to give an expression for the variation of the dispersion parameters (Gaussian plume model) σ_y , σ_z in terms of u_* . Thus the effects of surface roughness can be taken into account. To develop this in a practical form, it is necessary to relate the vertical heat flux H to the standard atmospheric stability categories.

Pasquill proceeds to consider the representation of an elevated inversion and develops the various forms of the basic Gaussian equation relevant to various source geometries and time histories (e.g. continuous point source, infinite crosswind line source, etc). He then describes the 1958 Meteorological Office system, which was based on a Gaussian formula and incorporated simple rules or nomograms for estimating σ_y and σ_z as functions of distance. This system, or one essentially like it, was discussed and rationalised further by

Turner (1970) in his "Workbook of Atmospheric Dispersion Estimates", which again is based on an idealised model, although Turner also summarises some results which contribute to the problem of calculating concentrations in a 'fumigation' episode and provides some guidelines for dealing with certain topographic effects. These include hills downwind of the source, sloping ground and steep cliffs.

A substantial part of both Pasquill's and Turner's discussion is devoted to purely geometrical effects, of source characteristics such as line sources, area sources, instantaneous or continuous sources, multiple sources. These are all based on the principle of plume superposition, which is readily seen to be justified, and therefore these refinements are not subject to serious doubt. A typical example of the application of these ideas is the multiple-source algorithm developed by Novak and Turner (1976). It is worth noting that for the case of urban area sources, Hanna (1971) has suggested a very simple model based on Gaussian plume concepts which has demonstrated that local concentrations are mainly dependent on local emission strength and on the wind speed. Goumans and Clarenburg (1975) have gone further than this, by devising a model wherein the complexities involved in estimating source strengths are represented in a global fashion by correlation with numbers of residents and of workers, together with corrections for air temperature and wind. While these models are undoubtedly useful in urban situations, and provide some useful guidelines for development of models relevant to planning problems, they cannot cope with individual sources and therefore fall outside the scope of the present work.

Topographic effects remain the least well understood and most difficult to model. Britter, Hunt and Puttock (1976) have considered how mean streamline distortions and changes in turbulence intensities near obstacles cause variations in the spreading of plumes (measured by the cross-sectional standard deviations σ_y and σ_z). They draw attention to the strong influence of recirculating eddies which often occur in flows near buildings and cliffs. In such a region, pollutants rapidly become uniformly mixed. Rapid-distortion theory is invoked for predicting the effect of the obstacle on turbulence. This assumes that eddies do not interact with each other in the time scale of the mean flow near the obstacle. The authors go on to apply a diffusivity-based model to the problem and conclude that for a source on the upstream stagnation line, the concentration observed at the stagnation point is approximately equal to the concentration that would be observed there in the absence of the obstacle. Experiments confirmed this, and thus the authors were able to confirm the assumption to this effect inherent in a paper by Lucas (1972). Topographic effects will be among the most important of the topics studied in this thesis.

Apart from very localised effects on the airflow near a source or near a receptor point, topography on a large scale may influence the frequencies of different weather conditions. Gunn and Fumage (1976) have considered in particular the effect on surface wind, which is the most important effect on air pollution. They identified valley channelling effects on wind direction, and also noted that in cross-valley winds, gustiness is greater than in along-valley winds. These factors have obvious applications in air pollution prediction.

Effects due to downwash in the wakes of buildings or cliffs near to the source have been reviewed by McCormick (1971). He drew attention to the importance of siting chimneys carefully with respect to the buildings they serve. Halitsky (1963) presented results of extensive wind tunnel tests and resulting empirical formulae which can be used to predict concentrations within building wakes. Lord and Leutheusser (1966) presented wind tunnel results in the form of specified minimum stack heights for buildings such that the effluent is not entrained into any eddy zone or wake zone associated with the building. Snyder and Lawson (1976) considered the well-known " $2\frac{1}{2}$ times rule" and demonstrated that while this is reasonable for buildings with crosswind width at least twice their height, it is unduly conservative for tall buildings. These, and the many other experimental results addressed to the problem of short stacks near buildings, can be of help in developing predictive models for dispersion of pollution from such sources.

Effects due to the physical properties of the pollutants include, in particular, density effects and particulate fall-out effects. The latter has generally been dealt with by assuming particles are always falling through the air at their terminal velocity (e.g. Stukel, Solomon and Hudson, 1975). This approach contributes to the estimation of deposition, but contamination of the environment by dust is often affected strongly by the way the dust moves after its initial deposition. Cox et al (1977) have considered this, and suggest that the mechanism of saltation (Bagnold, 1941) may be a useful analogue for the behaviour of particles over 80 microns in diameter in the urban environment. Plume density effects were also considered by Cox et al (1977) and for ground level releases are represented by a density current model, based on earlier work done with cold fronts, lock interchanges and oil slick

spreading in mind. For elevated releases, Ooms (1972) and Ooms et al (1974) have presented a model which caters adequately for plume density effects by assuming a Gaussian cross-sectional distribution of plume concentration and density increment and calculating entrainment on the basis of contributions due to jet mixing, buoyancy or density and ambient turbulence, each based on constant entrainment coefficient concepts. This model gives excellent agreement with experiments, in both buoyant and dense plumes.

To summarise previous experience, we note that while considerable experience has been built up in certain specific areas, some problems remain, and little consideration has been given to possible interactions between different factors. An example of the latter is the problem of how particle fall-out is affected by building aerodynamics or flow round hills.

1.5 The approach adopted in the present work, and the format of the thesis

At the outset of this work, it was perceived that real planning situations frequently did not conform to the requirements of conventional plume dispersion models. It was therefore decided that as a first step some case studies based on real situations should be worked through in order to gain experience in the types of problems that arise and, it was hoped, to identify directions in which further effort should be made.

The result of this policy was that a total of four case studies was undertaken, of which three were of a preliminary nature, each being concerned with a limited range of phenomena. The fourth was a major undertaking in itself, consisting of a full and very

detailed survey of dissemination of lead into the environment near a battery factory, and encompassing every imaginable complication in the processes of this dissemination.

The first case study was concerned mainly with the local variations in weather patterns that can occur at specific sites (section 2.1). It identified important effects on the wind speed and direction due to meso-scale topography coupled with temperature stratification effects, and, by means of tracers, local aerodynamic features associated with a cliff and with the katabatic wind were revealed. Further work on the problems involved in predicting local weather given the synoptic scale frequencies at a site in a flat plain are developed partly from this study, and from the air pollution meteorology part of the battery factory survey.

The second case concerned an incinerator sited very close to a sharp cliff. Here the problems occurred in strong winds, unlike the first study where low wind/stable stratification appeared to be the major danger. Attention was drawn in this study to the inherent limitations of conventional Gaussian plume models in convective or highly turbulent airstreams. The looping plume behaviour that results in such conditions usually does not produce severe long term average concentrations but nevertheless can produce a nuisance or a hazard due to brief peaks of concentration.

The third and final preliminary case study involved a similar incinerator where the receptor point of concern was at an elevated position (it was in actual fact an electricity transmission line). The receptor point was so close to the source in this case that the plume was still rising under the influence of its buoyancy by the time it passed the receptor. Thus some

difficulty arose concerning the representation of the plume cross-sectional concentration distribution and degree of plume 'looping' that might occur within this buoyant phase.

The major case study concerned the battery factory. This plant incorporated scrap lead handling, smelting, oxide milling, plate manufacture and stacking as the major process operations. The emissions of lead, mostly in the form of oxide dust, were numerous and varied,

The situation was further complicated by the effects of vehicular and pedestrian movements, which tended to move dust in ways not normally anticipated in air pollution dispersion. The topography of the site was complex, it being in a valley with one steep side and one gently-sloping side.

This case study was carried out in cooperation with a number of other bodies and the overall objectives of the survey included a full analysis of lead levels in human blood, soil and vegetation as well as in dust and in the air. For reasons of consistency the statistical analyses relating to all of these factors were carried out by the present author and therefore the methods used have been described in this thesis (Appendix II) and the results are given in full in the relevant section (3.2).

The air pollution aspects of this case study were considered in considerable detail. It was recognised that the crucial factor for lead pollution was long-term average exposures rather than peaks, and therefore few conclusions could be drawn from a monitoring survey lasting only a few months since this would not be representative of all the possible weather conditions. Therefore it was decided to develop a dispersion model

(see chapter 5) and validate it (it was hoped) using the survey results, then apply the model to long-term average weather statistics to obtain an estimate of the desired average concentrations. This process, while simple in theory, proved very difficult in practice, one complicating feature being the marked topography and the lack of long term weather data for the specific site. Thus it was necessary to develop correlations between weather data measured at the site during the survey and weather data measured at one of the Meteorological Office synoptic stations (section 3.3).

Having completed these various studies, a review of the lessons learned was undertaken (chapter 4). This led to the formulation of a set of guidelines for the construction of air pollution models for general situations, which were then applied to the specific case of the battery factory (chapter 5).

2.0 Preliminary Case Studies

2.1 Field Studies of Local Weather and its effects on Air Pollution at a Proposed Industrial Site

2.1.1 Introduction

The effects of topography on local weather patterns are very considerable and become crucially important when an industrial process which emits pollutant gases is planned. In real situations, as opposed to simplified theoretical or wind tunnel models, the complexities are often so great that one cannot tell in advance what will occur locally in any given synoptic situation. For this reason there is much insight to be gained from field observations of the weather at the site in question for a sufficient period of time to ensure that all of the potentially hazardous weather situations have been observed. It should be possible to cater adequately for all of these situations by proper design of the plant, but there are rare cases when the problem is intractable and another site must be found. With these thoughts in mind, two short pilot studies have been made of a proposed industrial site called Forest Farm near Cardiff and, although admittedly not a comprehensive investigation, this work has revealed some potentially hazardous situations from which certain conclusions about plant layout and operation can be drawn.

The experiments were carried out in September, 1973, and August, 1974, as part of Field Study courses organised by the Royal Meteorological Society on the subject of "Air Pollution and Meteorology".

2.1.2 Description of Site

The study area was a flat-bottomed valley to the NW of Cardiff centre and the topography up to 4 km from the site is shown in Fig. 2.1.1. Fig. 2.1.2 shows the industrial site itself in larger scale and more detail. The site is enclosed by a sharp cliff (some 30 m high) to the west, by substantial hills to the north, and by some gently rising ground to the east. There is a narrow gap in the hills north of the site where the River Taff has cut through, while to the south the land falls away steadily to the sea. There are many houses on the high ground west of the cliff, some of which are close to the cliff edge.

The topographical feature which seemed most likely to affect the site aerodynamics was the cliff; it was felt that the complex of hills to the north was too far away (about 1.6 km) to have significant effect on the site itself, although the mountain range of which they are the foothills undoubtedly affects the meteorology of the whole of South Wales. Accordingly, the experimental investigation was designed to reveal the flow near the cliff in some detail, with special regard for any effect it might have on the effective heights of chimneys in the valley. The flow was expected to be dependent on the thermal structure of the atmosphere as well as on the wind speed and direction, so instruments were set up in the valley to measure these quantities.

Apart from these local aerodynamic effects, it is also of great importance to see if there are any larger-scale topographical influences which may make the weather in the valley (particularly the

wind direction) different from that in the surrounding countryside. Meteorological Office stations which report frequently enough for air pollution purposes (i.e. once per hour preferably) are of necessity fairly few in number and are almost always sited in large open spaces where topography does not affect them. Cities and industry, by contrast, are very often situated in river valleys where topography may have a major effect on the weather. In practice, any such effect is almost without exception an adverse one as far as air pollution is concerned. Thus the use of the nearest meteorological station's records in air pollution problems is a matter of considerable difficulty and part of the present field study was devoted to this question.

2.1.3 Experimental Methods

For the study of local airflows small rockets were used, each one fitted with a red smoke generator. These rockets create a vivid near-vertical streak of smoke extending to a height of about 110 m, and by photographing successive positions of the smoke trail from a position at right angles to the wind direction the velocity profile of the air flow can be estimated. The rockets used were the largest variety of ordinary firework rocket available in the U.K., modified quite simply by substituting a 'Day and Night' distress signal for the purely decorative pyrotechnics with which the rockets are originally equipped. The distress signal is of a type often used by yachtsmen and contains a flare for night-time use as well as the smoke for daylight hours. The night flare must be fired before the smoke generator can be fixed to the rockets. Because of their rather short shelf

life, time - expired red smoke generators of this type are available very cheaply and although presumably not reliable for emergency signalling they are perfectly adequate for meteorological experiments. Plate 2.1 is a photograph of the rocket trail and the anemograph mast (in 1974).

A continuous record was made of wind speed and direction using a portable 'Porton' anemograph which was mounted on a pole some 2m above a low building in Sept 73, and on a free - standing 7.3m mast in the middle of a field in August 1974. This instrument has the low threshold speed of 0.5 kt. (0.26 m/sec) which makes it very suitable for air pollution work, where low wind speed situations are often the most critical. It is, for example, particularly important to know accurately the distribution of wind direction in near-calm conditions because low level smells may then be carried for large distances in a relatively concentrated state. The Porton anemograph is capable of operating from two car batteries for a period of several weeks and this is another feature which makes it useful in air pollution work, where there may not always be access to mains electricity at the point of interest. In Sept 1973, there was also, adjacent to the anemograph, a simple wind vane (made by the Department of Geophysics at Reading University), this having a much shorter time constant than the Porton instrument, which was damped electronically to give greater clarity in the trace. This second vane was used to indicate gustiness or variability in the wind direction.

In September 1973, wet and dry thermometers were attached at four points between 1.2m and 7m from the ground on a pole on a derelict building, to give

an indication of the thermal stratification in the layer closest to the ground. In August 1974, dry thermometers only were attached to the anemograph mast. These thermometers consisted of thermistors connected by cables to a multi-channel Grant recorder, which was set to give one complete set of readings every 15 minutes. In both years, these sensors were set up on occasions of moderate wind and one would therefore expect a well mixed airflow with little difference in temperature between the top and bottom sensors. This was exactly what was found. Strictly, when considering atmospheric stability, potential temperature should be used, however over the small height range involved (about 6m) the adiabatic lapse rate would give a temperature difference of less than 0.1°C , which is not measurable with this system. Observed temperature differences were often of the order of 2°C and so the system did in practice give a good indication of the stability of the lowest layer of air. However, it was rather better at distinguishing between stable and neutral lapse rates than between unstable and neutral, because in stable air there is little turbulence and so heat is not readily transported vertically and big temperature differences can therefore be sustained. In convective conditions the heat transfer is so rapid that ground level temperatures can only slightly exceed those aloft.

In 1974 a wind vane was also set up at a hilltop site near Pentyrch (Fig.2.1.1) and this was expected to give readings which would be largely unaffected by topography. Wind data from the Meteorological Office station at Rhosce (Glamorgan Airport) has also been included in the analysis. This station is on the coast, some 20 km SW of Cardiff.

2.1.4 Local Weather Distortions at Forest Farm

Differences in the wind direction recorded at two not-too-distant sites are most likely to occur in a stable atmosphere because the level of turbulence is then low and so air at different heights can move in different directions without generating large shear stresses. In turbulent air these shear stresses would tend to unify the air mass and force all layers to move together. One of the most common causes of stable stratification is nocturnal cooling of the ground, which generates a shallow stable layer which may drift down-slope as a katabatic wind. At Forest Farm this situation was observed during the nights of the 4/5th September 1973, and the 27/28th August 1974. Figures 2.1.3 and 2.1.4 which give a complete record of all measured parameters during the two study periods, show clearly that the surface air was very stable on these two occasions. The wind direction was observed to shift to a point somewhat west of north on both nights, which is consistent with a katabatic wind draining down from the mountains. The wind direction at Glamorgan Airport, however, was quite different and is clearly associated with events on the synoptic, rather than local, scale. The shift in wind direction is well correlated with the onset of a stable temperature difference as measured between the highest and lowest points on the mast at Forest Farm, though there is a time lag of about 3 hours between the onset of stability and the appearance of the katabatic wind. In the early mornings of the 5th September 1973 and 28th August 1974 rocket experiments were made to investigate the velocity profile in the katabatic wind. Figure 2.1.5 shows tracings of the smoke trails as photographed during one such

experiment, together with a velocity profile derived from the successive positions of the smoke trail. The rocket was launched from point A (Fig.2.1.2) and the camera was at B. This velocity profile is characteristic of katabatic winds in that it has a maximum at quite a low altitude and the motion is largely confined to the dense air nearest to the ground. Some of the velocity profiles observed had a very sharp cut-off at about 30m altitude, with apparently stationary air above. On one occasion the upper air was observed to be moving at right angles to the katabatic layer.

The katabatic wind situation is a very important one in the context of air pollution. The most important conclusion is that when there is a ground level inversion the most likely direction of the wind at Forest Farm is between north and north west, so any smells or other pollutants emitted into the katabatic layer will tend to be carried to the south and south east. On these occasions, because the katabatic wind is not very turbulent and because it may undercut warmer air, creating a sharp inversion at a low altitude, these pollutants will probably not be well dispersed. As there are several houses further down the valley in this direction this is a point which should be watched and low level emissions must therefore be reduced to the minimum.

The effect of the katabatic on chimney emissions is quite different if the chimney protrudes through the stable layer. The emitted gases cannot be diffused back to the ground through the stable layer because of the low level of turbulence. Thus in general tall

chimneys are very satisfactory in this situation. Problems only arise when a tower block or a hill with houses on also protrudes through the stable layer because the lowest layers of air will go round rather than over such an obstacle and the upper layers will therefore impinge upon it. In such cases emissions must be so regulated that an adequate amount of dilution will have occurred before the plume reaches any houses.

A more complex situation occurred on the night of the 28/29th August 1974 when again the air was stable at low level, but now the general wind, as recorded at Rhoose, was not so weak as it had been the previous night and the katabatic wind was overwhelmed in an easterly airflow at about 5m/sec. However, the stable layers close to the ground are halted by the cliff at Forest Farm, so that the air in the valley stagnates and the wind recorded at Forest Farm is only around 1m/sec. It is quite likely in this case that effluent from a chimney protruding above the cliff but situated on the valley floor would travel nearly horizontally as it passes over the cliff instead of being deflected upwards as it would be in a neutral airstream. The effective chimney height as far as residents at Radyr are concerned would then be lowered by about the height of the cliff. Again, the only solution here is to place tall chimneys in the valley sufficiently far away from the cliff (either vertically or horizontally or a combination of the two) that the normal process of turbulent dispersion would render the pollution harmless by the time it reaches the houses. When calculations are being made for this case, a horizontal plume trajectory should be assumed after allowing for plume rise due to buoyancy and exit velocity.

Figures 2.1.3 and 2.1.4 demonstrate some of the differences which may occur between points which are only a few miles apart, but in general the wind direction and strength at Forest Farm is well correlated with that at Glamorgan Airport. The only exceptions observed were the occasions of prolonged stability at ground level or of very light wind, although from such a short study it is obviously not possible to be sure that other cases cannot occur. The wind speed at Forest Farm is less than that at Glamorgan Airport, partly because the anemometer was not so high (7m against 10m) and more importantly because of the rougher nature of the terrain and the presence of trees all round the test site. The wind direction trace from the vane at Pentyrch (1974 only) was very well correlated with Glamorgan Airport at all times, which indicates that it was not subject to local topographical effects. The diurnal cycle in ground level stability is clearly seen, though the very unstable lapse rates indicated in the afternoons of the 1973 experiments may be due to inadequate shielding of the sensors from direct sunlight, which was improved for 1974.

2.1.5 Aerodynamic Effects of the Cliff

Flow separation in the wake of the cliff in a westerly airstream was investigated using rocket smoke trails on several occasions during the two weeks of field study. Figure 2.1.6 which is derived from rocket experiments on the 2nd September 1973 at 4 p.m., shows clearly that there is a recirculating eddy in the lee of the cliff, which is characteristic of a separating flow. In this experiment the rocket was launched from point C (Fig 2.1.2) with the camera at D. The cloud of

smoke released before the rocket fired is also outlined and this reveals a reverse flow near the ground. A study of the differences between trails ① and ② shows that the centre of the eddy is about 15m above ground. The velocity profile indicates wind shear at all heights up to about 50m and there is no sudden discontinuity of wind speed ("shear layer") such as would be expected in a wind tunnel model of flow over a step (e.g Tani et al 1961). The absence of a pronounced shear layer is probably due to trees and other obstacles on the cliff top which generate turbulence and thicken the shear layer, making the velocity gradient more gradual. In an earlier experiment in the field at Oldham Edge, reported by Benjamin (1974) a very sharp shear layer was found but in that case the ground on the upwind side was devoid of trees and houses for a considerable distance and the remaining roughnesses were of the order of a few feet in dimension.

This type of separated flow is well known from wind tunnel tests to have a structure similar to that depicted in Fig.2.1.7(a), while the effect of such a flow on a chimney which is located within the eddy is shown in Fig.2.1.7(b). It is obvious that the effective chimney height is lower than it would otherwise have been, by an amount roughly equal to the depth to which the chimney is immersed in the eddy. The definition of the eddy depth is therefore a matter of some importance and it is clear from Fig. 2.1.6 that the boundary between the eddy and the outer flow is not always a distinct one. The best definition of eddy height for air pollution purposes appears to be that height below which there is no net horizontal flow in the mean. This is easy to determine from the velocity profiles, and in Figure 2.1.6 where the rocket trail is

close to the cliff, the eddy height is, not surprisingly, about equal to the cliff height of 30m. Repeat tests confirmed this general picture.

Further rocket tests were designed to show the variation of eddy height with horizontal distance from the cliff (Figure 2.1.8). These involved simultaneous firing of a number of rockets at various distances from the cliff (points E, Figure 2.1.2). The camera was placed at F. From Figure 2.1.8 it is estimated that 230m from the cliff the eddy height is reduced to 14m. The tests of Figure 2.1.6 were at a distance of 120m and since at the cliff itself the eddy height must equal the cliff height, a rough outline of the eddy shape which can be used for the purpose of correcting chimney heights can now be drawn (Figure 2.1.9). This diagram should be interpreted with flexibility; for example, the cliff may vary in height along its length and so an adjustment would be necessary.

The separating type of flow will occur only when the wind is blowing from the west. If the wind is not absolutely perpendicular to the cliff there will be an additional wind component along the cliff face which will make the eddy take on a spiral form at first, and at large angular differences from the perpendicular the eddy zone will break down completely. Thus the reduction in effective chimney height at Forest Farm would only be of concern to people living to the east.

Pollution sources which actually emit into the eddy zone itself are a different case, and because of the danger of accumulation in this poorly ventilated region such sources should not be allowed.

In the evening of the 29th August 1974, there was an opportunity for studying the motion of a stable easterly flowing towards the cliff. Unfortunately, no rockets were available by this time, and so static smoke generators had to be used. While out in the middle of the valley the anemograph was recording an easterly at about 4m/sec, the air at the base of the cliff was practically stationary. It appeared to drift slowly downhill like a katabatic, even though the sun had not been long gone. In view of the observation from the previous night that the air in the valley was moving far more slowly than that at Rhoose, discussed above, this indicates that as the ground cools after sunset the cold air piles up against the cliff and after a time it fills the whole valley. During the morning of the 29th the wind speed in the middle of the valley steadily increased towards the Rhoose value as the stability at ground level changed from stable to unstable. This daytime instability gives the wind a chance to fill the valley with a fresh body of air.

In a condition of stagnation in the valley, any chimney which is lower than the cliff height will contribute to an accumulation within the valley which is likely to persist until mid-morning. Even if the chimney protrudes through the stagnant region its effective height for people living above the valley will be reduced. Fortunately, however, most high chimneys emit quite hot gases, and the buoyant rise of the plume will be large, especially when the wind is light. Cool low level sources are the greatest problem and they must be sufficiently well filtered that they cannot cause harmful concentrations of pollution to accumulate.

2.1.6 Night Time Investigations of Flow round a Hill

This exercise was designed to show the effect of a hill in modifying wind speed and direction, and to this end four groups of volunteers made simultaneous measurements of wind speed and direction, temperature and humidity. The wind results are plotted on Figure 2.1.10, which is a contour map of Garth Hill (see Figure 2.1.3 for location relative to Forest Farm). The results of two of the groups only are plotted as there were gaps or inconsistencies in the results of the other groups. The first group traversed along AB starting at 20.45 hrs on the 26th August 1974 at A and arriving back at A at 22.20 hrs. The second group started at E at 20.45, proceeded to F where further progress towards the summit became impossible, so they went by car to C and traversed the route CD during the period 20.58 to 21.50 hrs.

The humidity measured at all points was consistently in the range 90 - 100% and no marked temperature inversion was observed at any stage, these results indicating a thick layer of well mixed air passing over the hill. The section AB, which is a ridge on the north side of the hill, is well exposed to the NW wind which prevailed at the time (see Figure 2.1.4 Glamorgan Airport measurement), therefore it is not surprising that the directions recorded along AB are not far from NW. However, along CD, which is on the west side of the ridge, it appears that the flow is being deflected around the hill so that sometimes it is almost at right angles to the main flow. At EF there is a calm which is certainly a consequence of the sheltering effect of the steep slope between the 61m and 152m contours near F. This is probably another example

of flow separation similar to that in the lee of the cliff at Forest Farm.

In air pollution problems such effects may be of great importance in that winds may be deflected along preferred directions near mountains and so pollution sources may affect some people very often and others not at all. The sheltering effect of hills is very significant and sources in a valley only occasionally enjoy the full benefits of a strong cleansing wind. A good example in this case is the lime kiln on the side of the hill immediately south of Garth Hill, which produces a pall of smoke which can often be seen drifting around in a concentrated mass in the lee of the hill. As shown in the field experiments, there may well be a calm in the valley even when there is a moderate wind aloft.

2.1.7 Conclusions

This study has shown how relatively brief field experiments can serve to identify some of the important weather situations which may cause local air pollution incidents. In particular it has drawn attention to the importance of atmospheric stability producing differences in wind direction between stations that are only a few miles apart. In stable conditions the wind may blow preferentially in one direction, so that a particular sector may be at risk from low level pollution sources. The mechanisms of stagnation in valley and flow separation may reduce effective chimney heights in certain weather conditions.

In all the situations observed during these field studies the adverse effects of weather could be allowed for in factory design by appropriate

location and height of chimneys and by filtering or elimination of low level emissions. There does not appear to be any fundamental meteorological reason why the industrial development of this site need cause any air pollution problem.



Plate 2.1 Rocket trail and
anemograph mast - August 1974

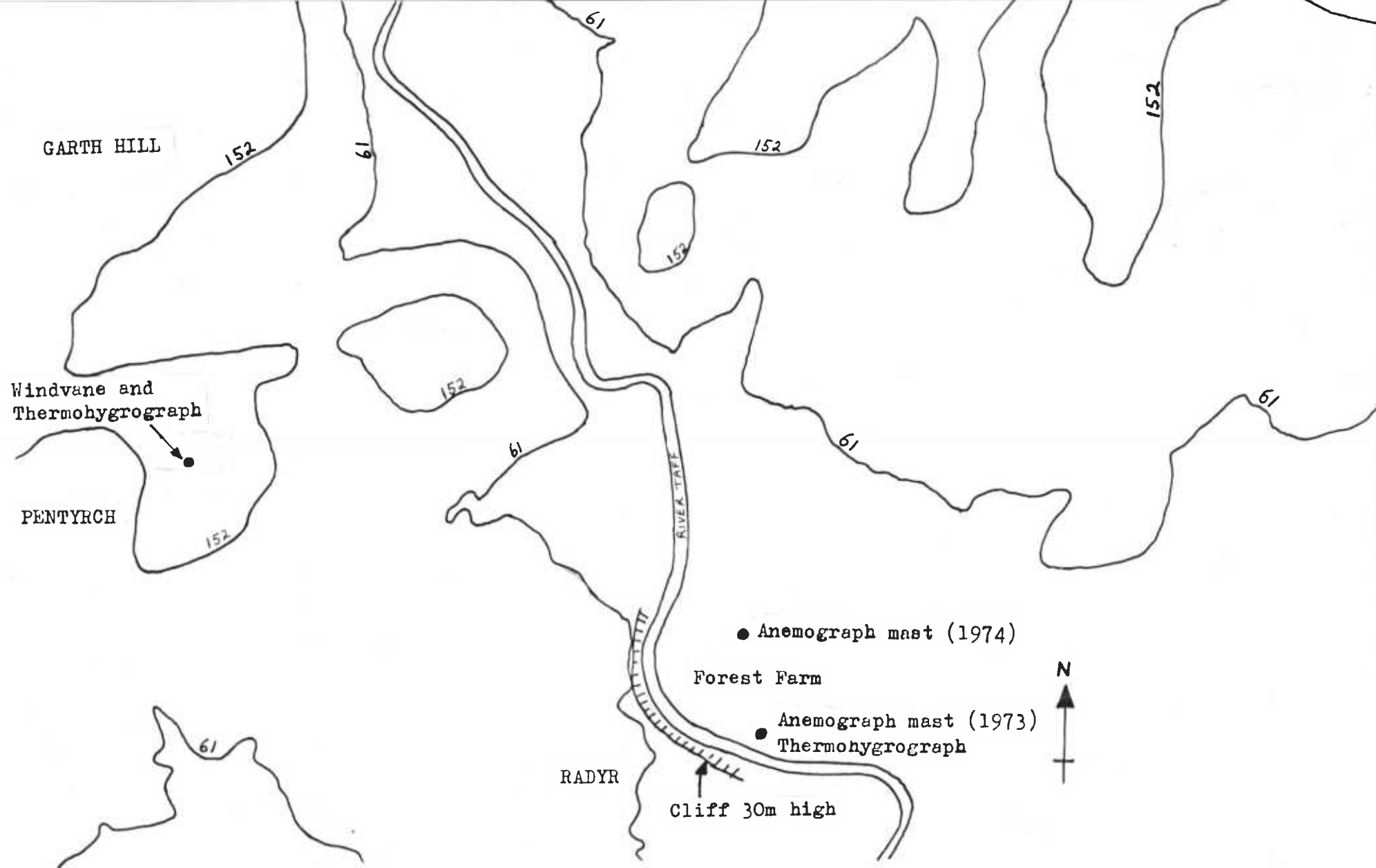


Fig2.1.1 Sketch map of study area showing contours at 61m and 152m

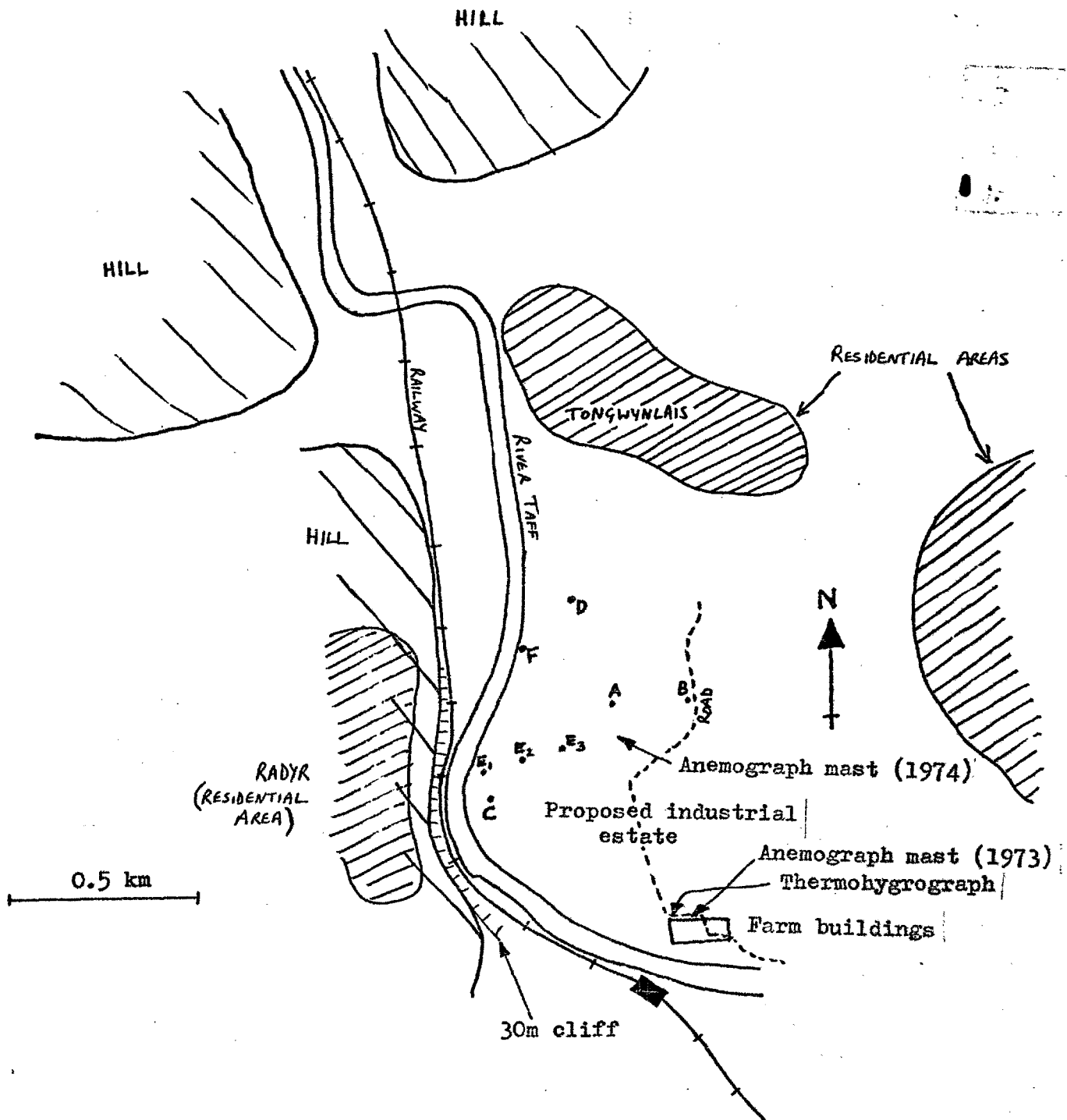
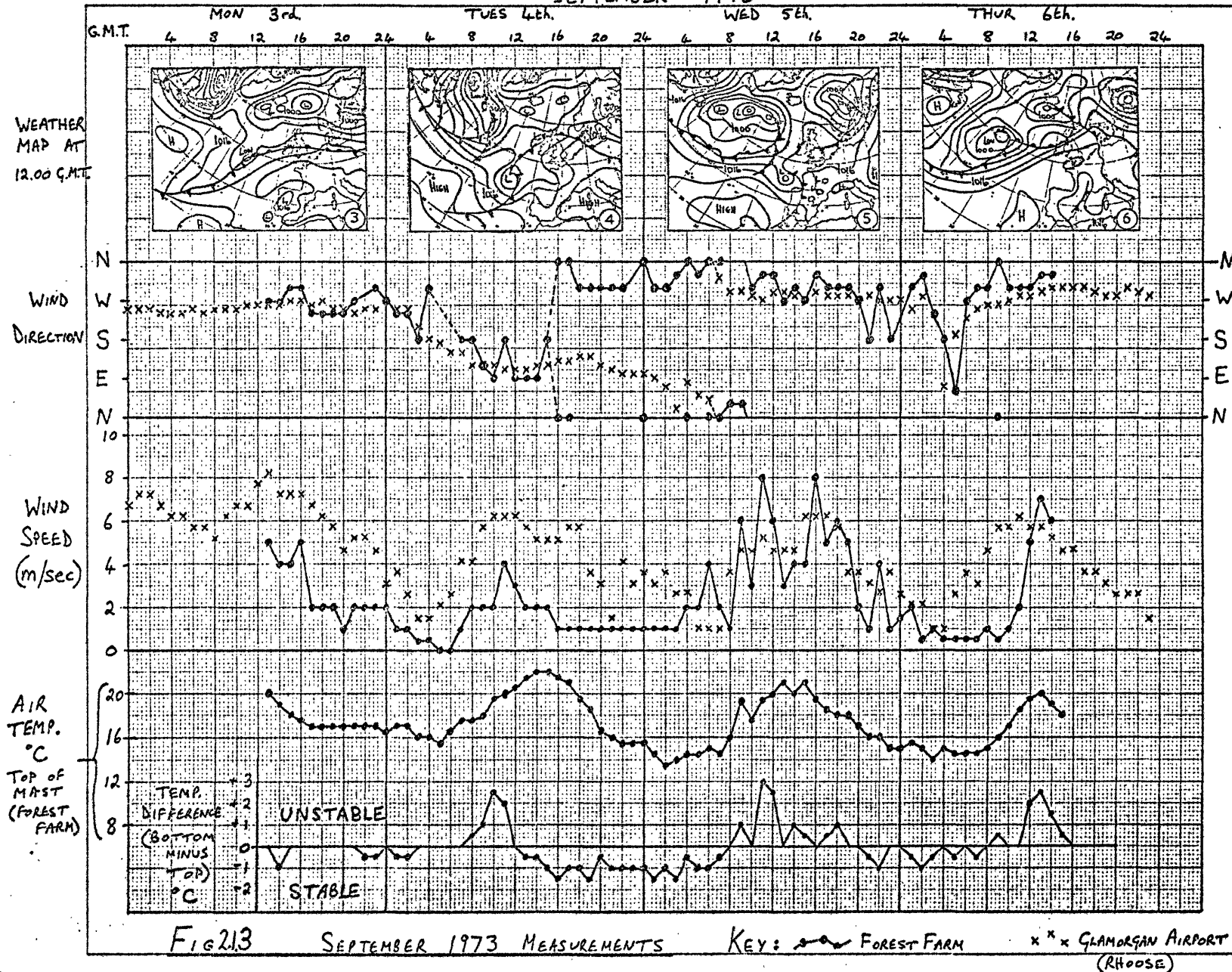
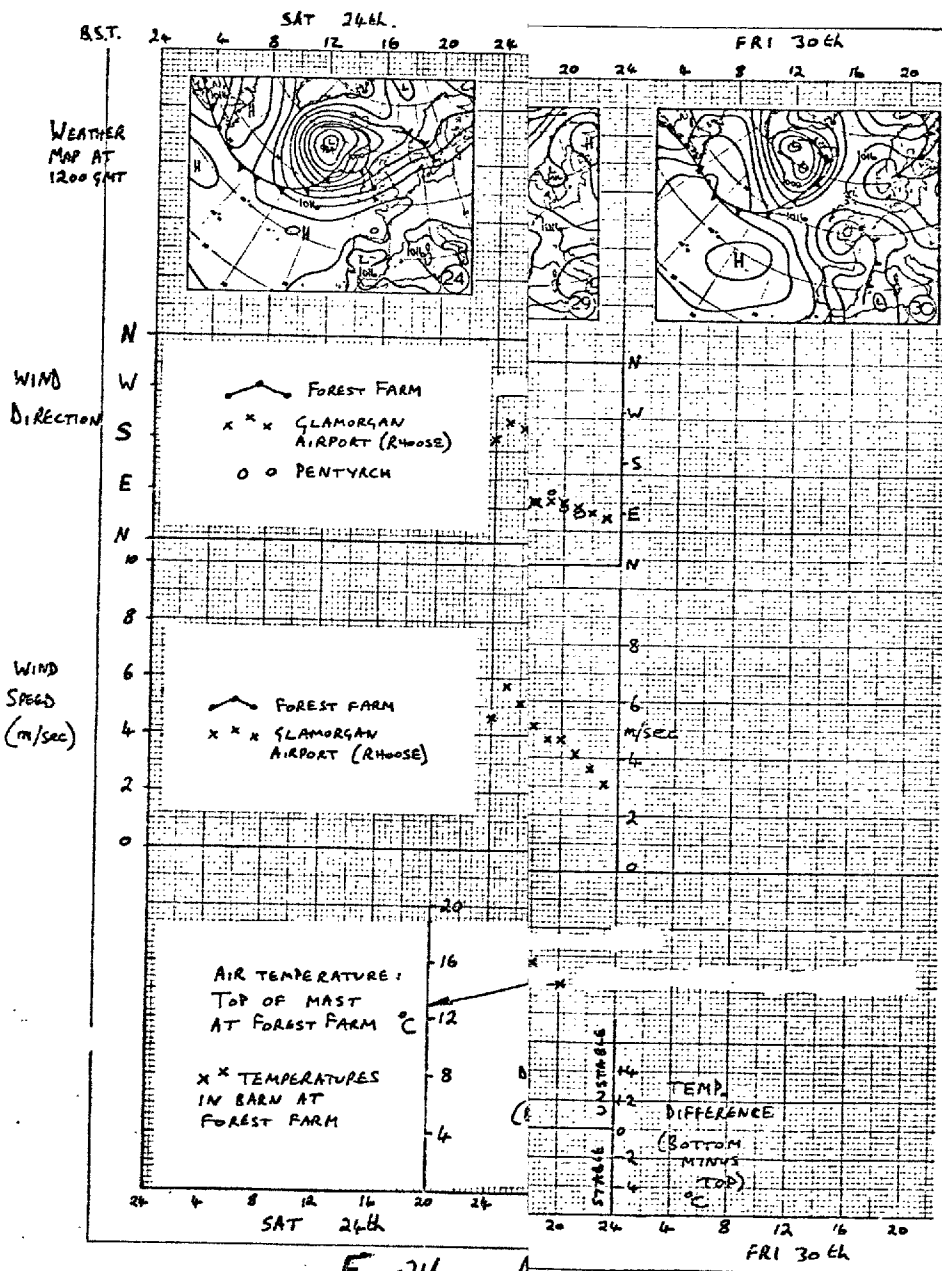


Fig 2.1.2 Sketch map of proposed industrial site at Forest Farm, Cardiff

Key : A, C, E, Rocket launching sites
 B, D, F, Camera positions

SEPTEMBER 1973





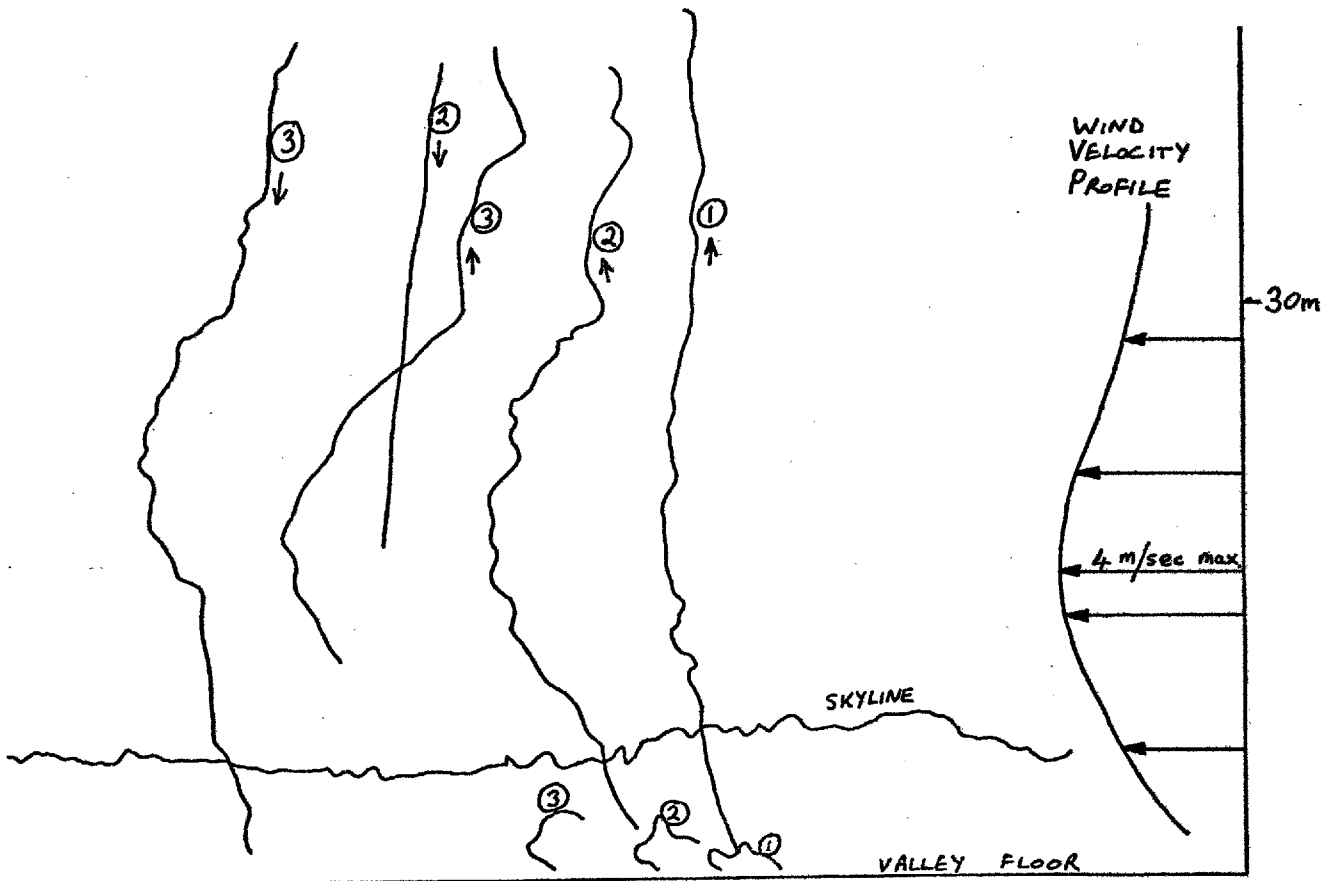


Fig 2.15 Wind velocity profile in a katabatic wind estimated from rocket experiments.

Key :

①	time = 0 secs
②	time = 3 secs
③	time = 6 secs
↑	trail from upward flight
↓	trail from downward flight

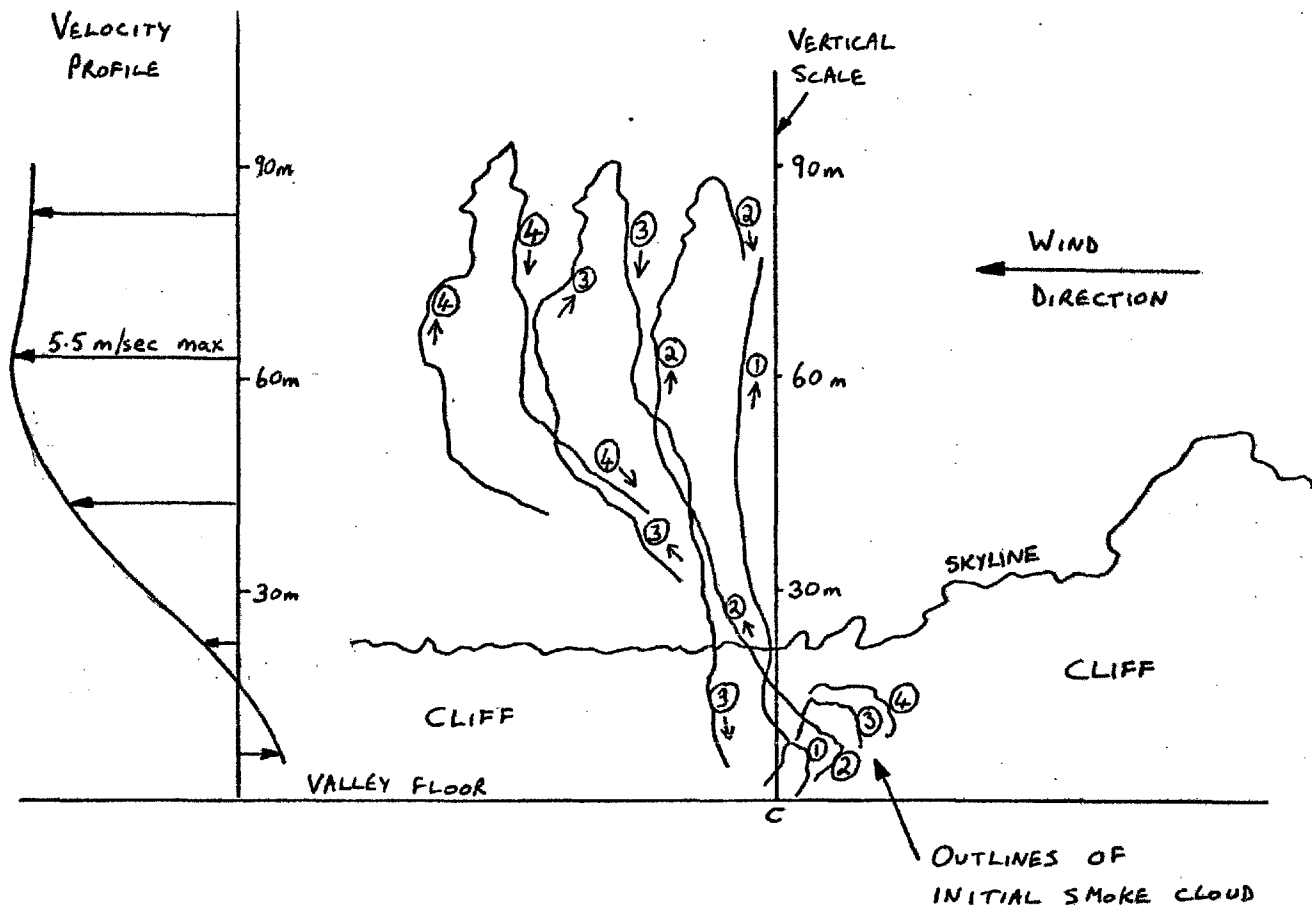


Fig 2.16 Successive positions of smoke trails. 2 Sept 1973 4p.m.
Velocity profile on left estimated from smoke trails. Rocket
launched from C (Fig 2) with camera at D.

Key :

①	time = 0 secs	↑ up trail
②	time = 3 secs	↓ down trail
③	time = 6 secs	
④	time = 9 secs	

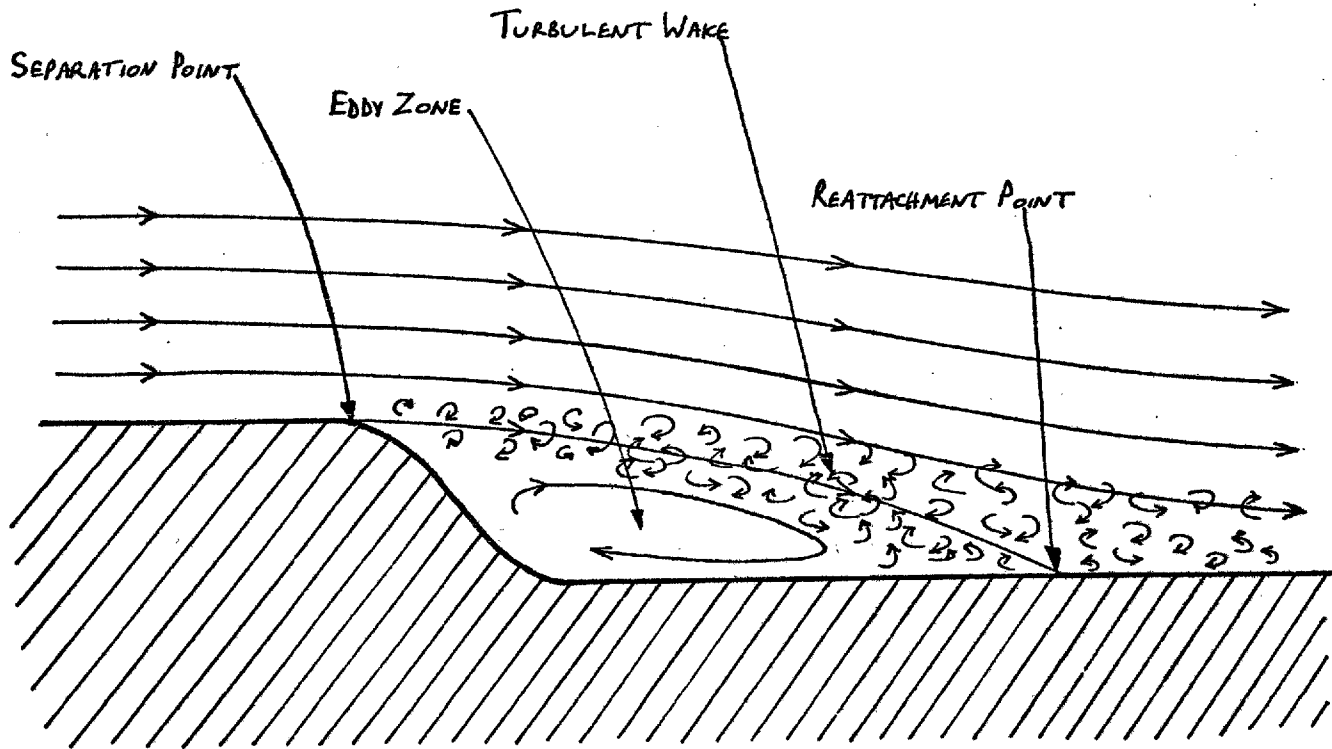


FIG 2.1.7(a) SEPARATING FLOW DOWN A CLIFF

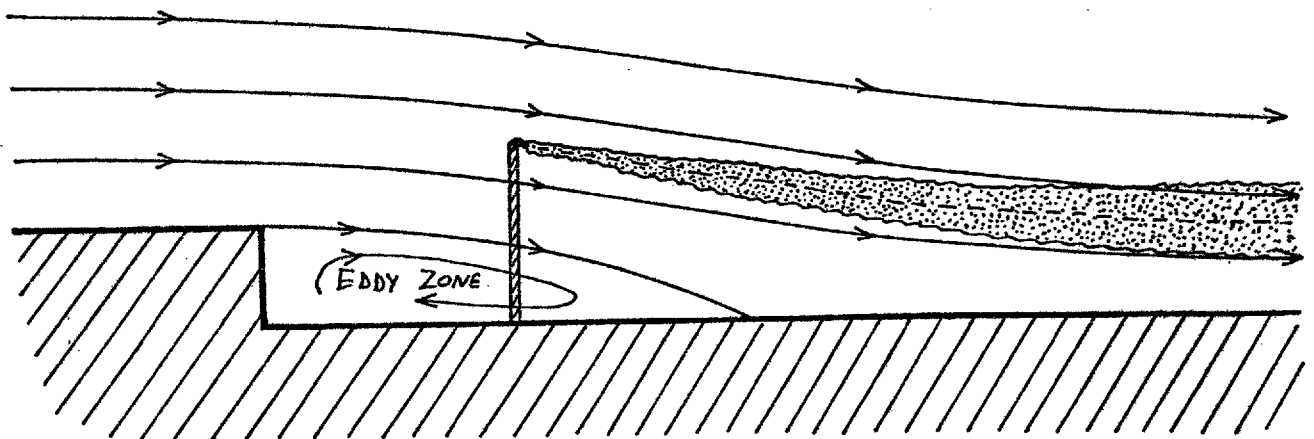


FIG 2.1.7(b) DOWNWASH OF CHIMNEY PLUME CAUSED BY PROXIMITY
TO CLIFF. EFFECTIVE CHIMNEY HEIGHT IS REDUCED

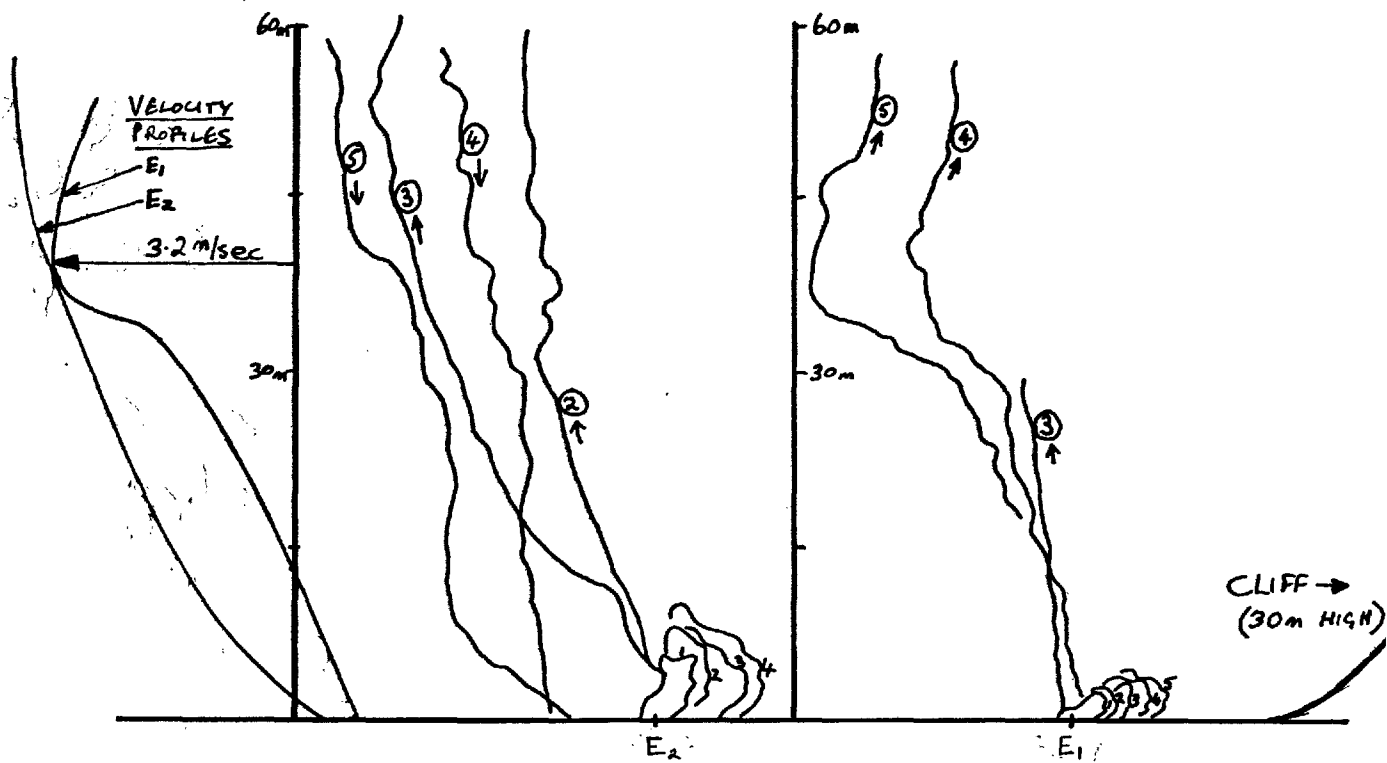


Fig 2.13 Successive positions of smoke trails 4th Sept 1973

Point E_2 - 230m from cliff ; Point E_1 - 120m from cliff

Key: ① time = 0 secs ↑ up trail
 ② time = 3 secs ↓ down trail
 ③ time = 6 secs
 ④ time = 9 secs
 ⑤ time = 12 secs

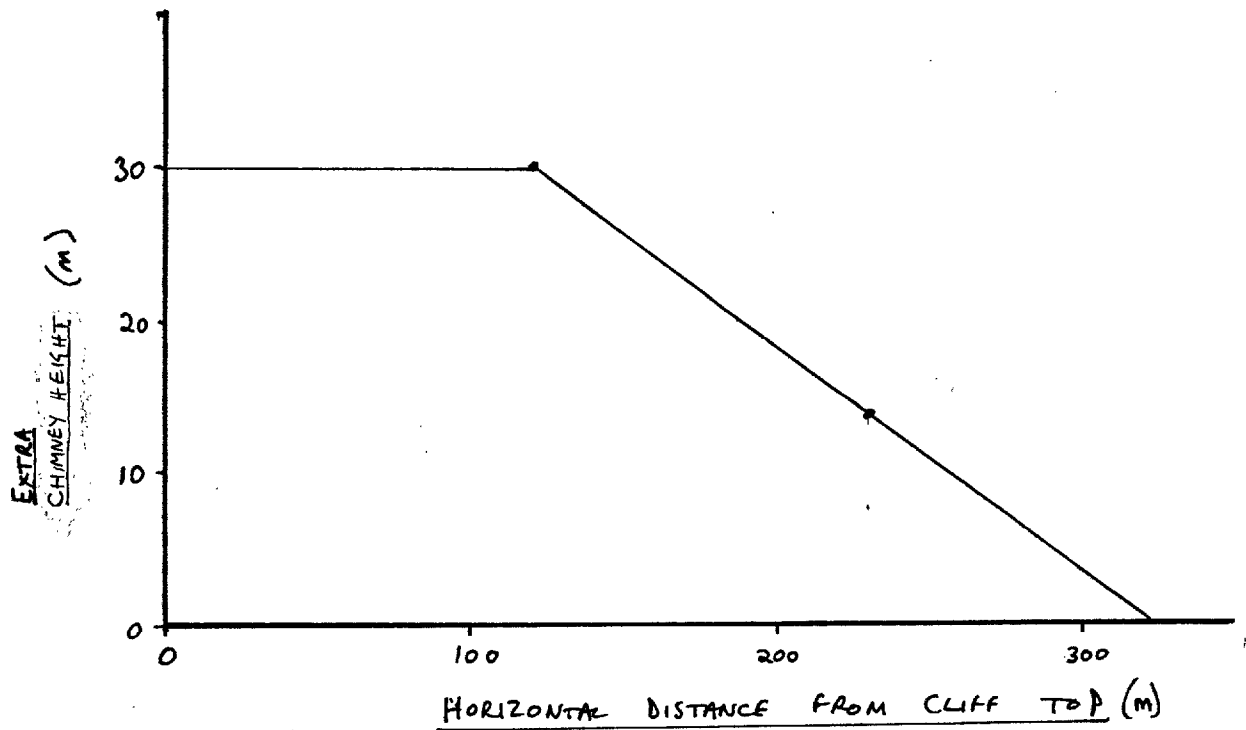


Fig 2.19 Extra chimney height required due to flow separation near a cliff (guideline only)

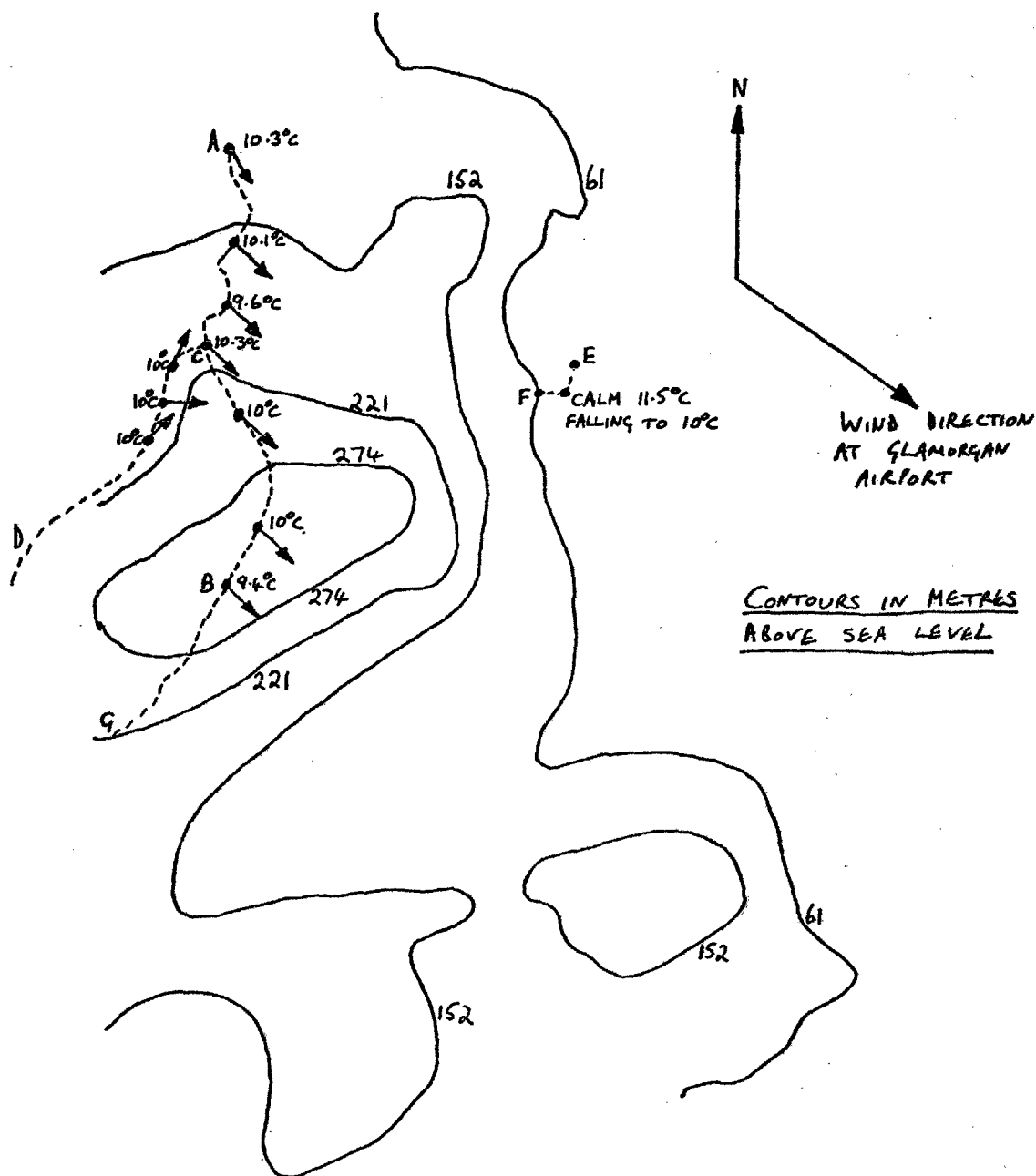


Fig 2.1.10 Results of traverse of Garth Hill Monday 26th August
at 20.45 hrs to 22.30 hrs.

Wind direction and dry bulb temperature shown thus: ↗ 9.5°C

2.2 Air Pollution due to a Chemical Waste Incinerator

2.2.1 Introduction

Chemical waste incinerators for specific industrial applications are not new, but in the U.K. following the passage of the Deposit of Poisonous Wastes Act 1972, a number of multi-purpose chemical waste incinerators have been constructed by various waste disposal companies as an alternative to tipping on land sites. Not surprisingly, in view of the hazardous nature of the materials handled, these installations have been closely scrutinized for their potential air pollution impact and in general this has resulted in designs in which a conscious effort to minimise air pollution has been made.

One case in which serious air pollution has nevertheless occurred is described in this study and some suggested remedies are discussed.

2.2.2 The Incinerator Site and its Environs

Figure 2.2.1 is a plan of the incinerator site showing all the significant buildings and the contours at 23m and 31m. A section on AA is also shown, in Figure 2.2.2, to the same scale vertically and horizontally. The most notable feature is the steep cliff which is no more than 50m away from the 39m chimney. This cliff is some 21m high in the part of its length between bearings of 153° and 213° from the chimney and by chance it curves round at an approximately constant radius from the chimney.

The plant buildings are quite low in relation to the chimney and were not expected to influence the plume although they would obviously generate turbulence in the first 10m or so above ground. A railway cutting just south of the cliff is the

most notable of several undulations in the higher ground to the south, and the topography on a larger scale (shown in Fig. 2.2.3) also undulates very considerably. The golf course (Figs. 2.2.1 & 2.2.2) is devoid of trees, but the top edge of the cliff has several medium size trees on it.

2.2.3 Emissions from the incinerator

The incinerator is designed to operate at a combustion temperature of 1000-1200°C with a residence time of 3 seconds and 300% excess air, conditions which should guarantee the elimination of smells and the complete oxidation of all chemicals. The gases are passed through an afterburner and a scrubber before being exhausted via the chimney at a temperature of about 250°C. The chimney functions by natural draught as this was felt to be more reliable than forced draught, and would furthermore ensure a negative pressure in the incinerator so that incompletely burnt gases would not escape at low level. The designed chimney efflux velocity was 7.6m/sec, emerging through an orifice 2.75m in diameter formed by placing a truncated cone on top of the 4.27m diameter chimney stack. This arrangement was adopted so that a second incinerator could be installed later, to use the same chimney with the cone removed.

Not all of these desirable features have been realized in practice. Perhaps the most interesting and illuminating reason for this is the advent of the fuel shortage from 1973 on. This has resulted in a drastic slump in the calorific value of industrial wastes due to the use by industry of waste liquids as fuel. This has resulted in a

reduction in throughput and temperature and in some cases intermittent working on waste incinerators. In the present case, the incinerator is divided into several combustion cells and the temperature in each cell is controlled independently so that on part load some cells are turned off completely while in others the temperatures are still adequate for removal of smell. Nevertheless, the effect of part-load running on the plume buoyancy and the natural draught is considerable, and evidently the design efflux velocity is not always being achieved (see Fig. 2.2.4 which is drawn from photographs of the plume). The poor natural draught is also having an adverse effect on low level emissions because transient positive pressures can occur at various points in the furnace when for example a large door is opened to allow charging of solid wastes into the incinerator. These pressure pulses cause smoke to be emitted from various points (notably the other doors) and this is very noticeable as it has a pungent smell.

The plume buoyancy is not what it should be and this is exacerbated by the effects of dilution just after emission caused by the low efflux velocity allowing the plume to be caught in the chimney wake. Thus there is practically no buoyant plume rise to offset the likely adverse effects of the topography.

2.2.4

Investigation of Air Pollution Incidents

Air pollution incidents so far observed have been of two distinct kinds. The first occurs only in winds which blow from the direction of the cliff, i.e. roughly from the SSW, and then only in moderate or strong winds. It is observed that

intermittently the plume is brought down to ground level within the confines of the incinerator site, even though the mean plume centreline is apparently nearly horizontal. The second has been observed in a wind blowing towards the cliff and is characterized by smells occurring at ground level while the main chimney plume can be seen to be well clear of the ground at all times. This is probably due to the low level incinerator emissions.

The intermittent chimney downwash problem has been investigated using smoke generators placed on the cliff and on a "crow's nest" halfway up the chimney to make the airflow visible. Figure 2.2.5 shows the smoke trails arising from these smoke generators, and was drawn by tracing on the same sheet of paper photographs of the same experiment at three different times. The outlines of the smoke clouds are readily visible and their movement indicates the direction of the local airflow. In all cases the camera was positioned approximately at right angles to the mean wind direction though in the cliff wake region there was sometimes some three-dimensional motion which was not recorded. The outstanding feature is the sluggish nature of the flow near the crow's nest. The cliff generator indicates that there is a recirculating eddy in the lee of the cliff which is causing the smoke there to move upwards until it reaches the cliff top when it is entrained into the horizontal wind and is carried out over the site. Clearly, the chimney is immersed to at least half its height in the turbulent wake of the cliff. Notice that the plume from the chimney is somewhat more smooth and steady than the flow at the crow's nest.

The smoke generator in the latter position was held well away from the chimney so that it would not be entrained in the chimney wake. The experiment was repeated several times during a period of one hour in which the wind did not change appreciably in strength or direction (moderate SSW) and it was found that the flow at the crow's nest was constantly swinging in all directions (see Figs. 2.2.6 & 2.2.7). Observations of the flow of the chimney plume shortly after emission revealed that successive portions of the plume could also travel in different directions, (though not to the same extent as at the crow's nest) and that once clear of the chimney they tended to move in a nearly straight trajectory. In other words, the vertical velocity appeared to be advected with the horizontal flow so that an individual particle tended to keep its initial vertical velocity. Figure 2.2.4 shows two extreme positions adopted by the plume shortly after emission and illustrates that the distortions of the plume by atmospheric turbulence extended right back to the chimney orifice. This figure was traced from two of a series of photographs.

2.2.5 Causes of downwash phenomena

2.2.5.1 Chimney wake effects

When the horizontal wind speed is higher than the efflux velocity from the chimney there is a strong probability that all or part of the plume will be entrained into the chimney wake. The frequency distribution of different wind directions for speeds greater than 8.2m/sec

(c.f. efflux velocity of 7.6 m/sec) is shown in Fig. 2.2.8. It is notable that such strong winds only occurred about 12.4% of the time during 1960-1969 and when they did occur the overwhelming tendency was for the direction to be between S and W. Thus by an unfortunate coincidence strong winds almost always blow from the direction of the cliff, which is the most dangerous quarter from the point of view of the cliff wake effects which are discussed below. There is no doubt that some chimney wake effects are operating in this case, as Figure 2.2.4 shows clearly that the smoke sometimes curls round the edge of the venturi cone so that it appears in the figure to be emitted through the side of the chimney. However, such downwash does not occur all the time, nor does it affect all of the plume. The intermittent nature of this wake effect must be due to a high level of turbulence in the oncoming air stream. The design of the venturi cone probably contributes to the probability of chimney downwash. The cone is rather short, and so the effluent is emitted quite close to the wake of the main part of the chimney. The momentum deficit in the chimney wake is that of a large chimney while the efflux momentum is appropriate to a small one. This can only increase the chances of downwash occurring. A far better design would include a parallel section of the smaller diameter on top of the cone.

2.2.5.2 Cliff wake effects

When the wind blows from the direction of the cliff the air flow from the golf course separates from the surface at the cliff edge and then gradually re-establishes itself as normal attached flow on the lower ground in the valley.

This area of transition extends some 10-15 cliff heights down wind, and up to about 7 cliff heights down wind there is a recirculation of the mean flow in the form of a closed eddy. At any instant, however, the flow will be greatly disturbed by turbulence, and the eddy may not be very steady.

Considering first the mean flow, that is, averaged over a time period of, say, 10 minutes, it is clear that to a first approximation the centreline of a passive plume emitted from a chimney protruding through the eddy will be deflected downwards by an amount roughly equal to the eddy height at the chimney. In the present case this distortion of the mean plume centreline undoubtedly occurs but it has proved very difficult to observe because the plume is so rapidly distorted by turbulence that it cannot be seen far enough downwind.

The effect of the cliff on the turbulence encountered by the plume is very great. By lowering the effective chimney height the plume is brought into a more turbulent part of the air flow. In the case in question the undulating terrain beyond the cliff and the trees on the cliff edge act as powerful generators of turbulence and are responsible for the fluctuating behaviour of the plume near the chimney exit. It is noticeable that when the wind blows towards the cliff this fluctuation is almost absent. It would appear therefore that a form of plume 'looping' caused by mechanically generated turbulence is responsible for the presence of concentrated whiffs of chimney fumes on the ground near the chimney. There is a distinct possibility that in strong winds such turbulence may trigger intermittent chimney wake downwash, thus exacerbating the problem.

The mean streamline at the chimney top will be at a small angle below the horizontal, due to cliff downwash, and this will increase the probability of the plume being caught in the chimney wake. Conversely, when the flow is towards the cliff the streamline will be angled upwards, which may cause the complete suppression of chimney downwash. The upward angle in this case would be much larger than the downward one in the previous case because when the flow is towards the cliff there is no eddy zone in the valley, so the streamlines are more sharply deflected.

The vertical component of the mean wind at the chimney top may also have an effect on the natural draught of the chimney, assisting it when the flow is towards the cliff and opposing it when the flow is from the cliff.

2.2.6 Summary of adverse circumstances contributing to the downwash phenomena in winds from the cliff

- (i) The mean streamline is deflected downwards, bringing the plume down with it.
- (ii) The pollutants are emitted into an usually turbulent part of the airflow, resulting in rapid break-up of the plume and consequent loss of buoyancy and reduction of plume rise.

- (iii) Due to the turbulence individual parts of the plume are detached and brought down to ground level shortly after emission, where they cause intermittent smells.
- (iv) The downward component of the mean wind at the chimney top opposes the natural draught and thus reduces the efflux velocity.
- (v) Three factors, namely the design of the exit venturi cone, the low exit velocity, and the downward component of the mean wind all combine to increase the likelihood of chimney wake downwash.
- (vi) Strong winds, which are the most likely to produce chimney downwash, most frequently come from the direction of the cliff.

2.2.7 Recommendations for the Improvement of the Plant

It is obvious that an increase in chimney height would have a greatly beneficial effect. It would offset the downward deflection of the mean airflow and would reduce the level of turbulence into which the pollution is emitted. The downward component of the mean wind would also be reduced. As the eddy height near the chimney appears from the smoke generator experiments to be about equal to the cliff height it would be reasonable to increase the chimney height by that amount, giving a total height of 60m. This would give the chimney a performance roughly equivalent to what would have been achieved by the existing chimney if sited in an open plain. A further possibility which would allow a slightly lower chimney would be to remove the trees from the cliff top and level the top of the cliff on the incinerator side of the railway cutting. It is probable that eddies are shed from the rather sharp cliff top (see Figure 2.2.2) and the smoothing of this feature would probably lower the turbulence levels, though it might not affect significantly the eddy height at the chimney because there is still high ground on the other side of the cutting.

These modifications are however not enough because they still leave a severe risk of chimney downwash due to the low efflux velocity and the aerodynamics of the chimney top. The latter could be dealt with by making a part of the increase in chimney height consist of a smaller diameter section above the venturi cone. Such an arrangement would place the plume well clear of the wake of the larger part of the chimney and would have the incidental advantage of minimizing the wind loading on the

chimney, which is critical for the overturning moment on the foundations.

The low efflux velocity is an unhappy consequence of the decision to use natural draught. It is very difficult to get more than about 8m/sec velocity from a natural draught chimney because the frictional losses increase rapidly with speed. Thus even with a well-designed chimney exit there is still a likelihood of downwash occurring whenever the wind is above about 8m/sec. Such winds occur quite often at 10m above ground (see Figure 2.2.8) and would occur even more frequently at the chimney top because of the wind shear. The ideal solution from the air pollution point of view would therefore have to involve the abandonment of natural draught and in view of the need to have negative pressures in the incinerator chambers the required fan would be an induced draught type located just before the chimney. It is however possible that such a scheme would not be viable because of its energy consumption and an alternative scheme would be a system for shutting down the combustion of hazardous or smelly wastes whenever the wind is strong enough to cause chimney downwash. Downwash is however a phenomenon that has a gradual onset as wind speed increases, so that the precise moment for shut-down would be hard to determine. It would be helpful to have an anemograph in a suitably well-exposed position above the height of the cliff so that judgments of this kind could be made. This is incidentally something which all industries that emit air pollution should have as a matter of course, so that subsequent analysis of pollution incidents can be more easily made. Another way of detecting chimney downwash would be to have temperature sensors outside and below the chimney top. These would detect the presence of incinerator gases in the

chimney wake and could be linked automatically to shut down devices.

2.2.8 Implications for Prediction Models of Air Pollution Concentrations

This short study has only considered the aerodynamic and meteorological aspects of this air pollution problem, yet the great complexity of the case is evident. Other relevant matters which have not been assessed here include the efficiency of operation of the wet scrubber (into which gases are fed at temperatures approaching 1000°C), the completeness of combustion and the open-ended question of what flue gas composition might result from all possible combinations of industrial wastes being destroyed.

The result of this complexity is that predictions of ground level concentrations by conventional plume models before the actual construction of the plant would be very unlikely to be reliable. Because almost all the unexpected effects were adverse, any such prediction would have been grossly optimistic and it is clear that before planners can have a realistic guide to likely air pollution concentrations new methods which take into account the interacting effects of topography, chimney aerodynamics and atmospheric turbulence must be developed.

In the present case, a simple comparison of concentrations predicted on the basis of different assumptions about plume behaviour serves to illustrate the point. Let us take a Gaussian plume model in the form

$$P = \frac{Q}{U\pi\sigma_y\sigma_z} \exp(-h'^2/2\sigma_z^2)$$

for concentration P on the ground assuming no absorption of the plume at the ground. By way of example we assume $\sigma_y = \sigma_z = kx$ where k is a constant depending on the intensity of atmospheric turbulence. Then we obtain

$$P = \frac{Q}{U\pi k^2 x^2} \exp(-h'^2/2k^2 x^2)$$

This is for the plume average over 3 minutes, that is, for present purposes it is the 'mean' plume. On a conventional basis, topography being neglected, and buoyant plume rise taken into account, we would obtain at a distance of 128m with $k = 0.05$ (a typical value for high sources) a concentration given by

$$P = \frac{Q}{41 U \pi} \exp(-h'^2/82)$$

The height of the plume at $x = 128m$ in a typical wind (say 8m/sec) would be 62m and hence $P = 4.2 \times 10^{-24} \times Q$. For realistic values of Q this is of course a negligible concentration, but as we are here concerned only with the sensitivity of the concentrations to different assumptions we may use it as a reference level against which to compare later results. We designate this reference level P_{ref} .

Firstly, adjusting the effective chimney height to take account of distortion of the mean plume centreline, we subtract the cliff height from h' and obtain $P = 2.8 \times 10^{11} \times P_{ref}$.

Then removing the allowance for plume rise because of the dilution due to excess turbulence destroying the buoyancy we find $P = 3.8 \times 10^{18} \times P_{ref}$.

Finally, letting $k = 0.2$ instead of 0.05 to take account of the enhanced rate of spreading due to the turbulence, $P = 9.5 \times 10^{18} \times P_{ref}$. Note that

these figures all relate to the 3-minute averaged plume, so that the effect of strong turbulence in causing intermittent high concentrations is ignored. A crude way of assessing this is to assume that the 'normal' plume with $k = 0.05$ is distorted so that it impinges on the ground prematurely. For this case $h' = 0$, so that

$$P = 2.0 \times 10^{20} \times P_{\text{ref}}.$$

The effect of such alterations in the assumptions on long term average values and the frequency of peaks has been investigated by computer simulation using the actual wind records from Edinburgh (Turnhouse) Airport for the decade 1960-1969. The plume model used was a conventional Gaussian type matched to a plume rise formula by Briggs (1970). The concentrations predicted were integrated for all occasions during the decade to give frequency tables and average concentrations at all points round the source. A summary of the results is given in the following table:

Table 2.2.1

	Case A: buoyant plume unaffected by topography	Case B: buoyancy destroyed by turbulence and plume affected by topography
Max. average ground level concentration (Max G.L.C.)	P	15.4P (at 610m distance)
Average G.L.C. at 420m on bearing of 030°	virtually zero	3.9P
3-minute aver- age concen- tration which is exceeded 0.1% of the time in the worst place	39P	615P

N.B. These figures are for 3-minute average peaks and therefore do not take into account plume looping due to the larger turbulent eddies; this would produce still higher peaks of rather shorter duration.

It can be seen from this that quite reasonable alterations of the assumptions may produce drastic changes in the predicted concentrations. This is not just a feature of the particular model used; it is an inherent characteristic of real plumes. Thus the lesson which is to be drawn from this exercise is that conventional plume models may sometimes be virtually useless for prediction purposes and the real challenge is to determine the nature of the atmospheric flow into which the pollution is being emitted. A further complication in the particular case under consideration is that

changes in the properties of wastes arising can be caused by political or economic events and specifically a reduction in calorific value will lead to progressively worse dispersion due to lower plume rise. Since energy is clearly set to become steadily more expensive we must expect a long-term downward trend in calorific value and this should be taken into account when estimating the air pollution impact of proposed waste incinerators.

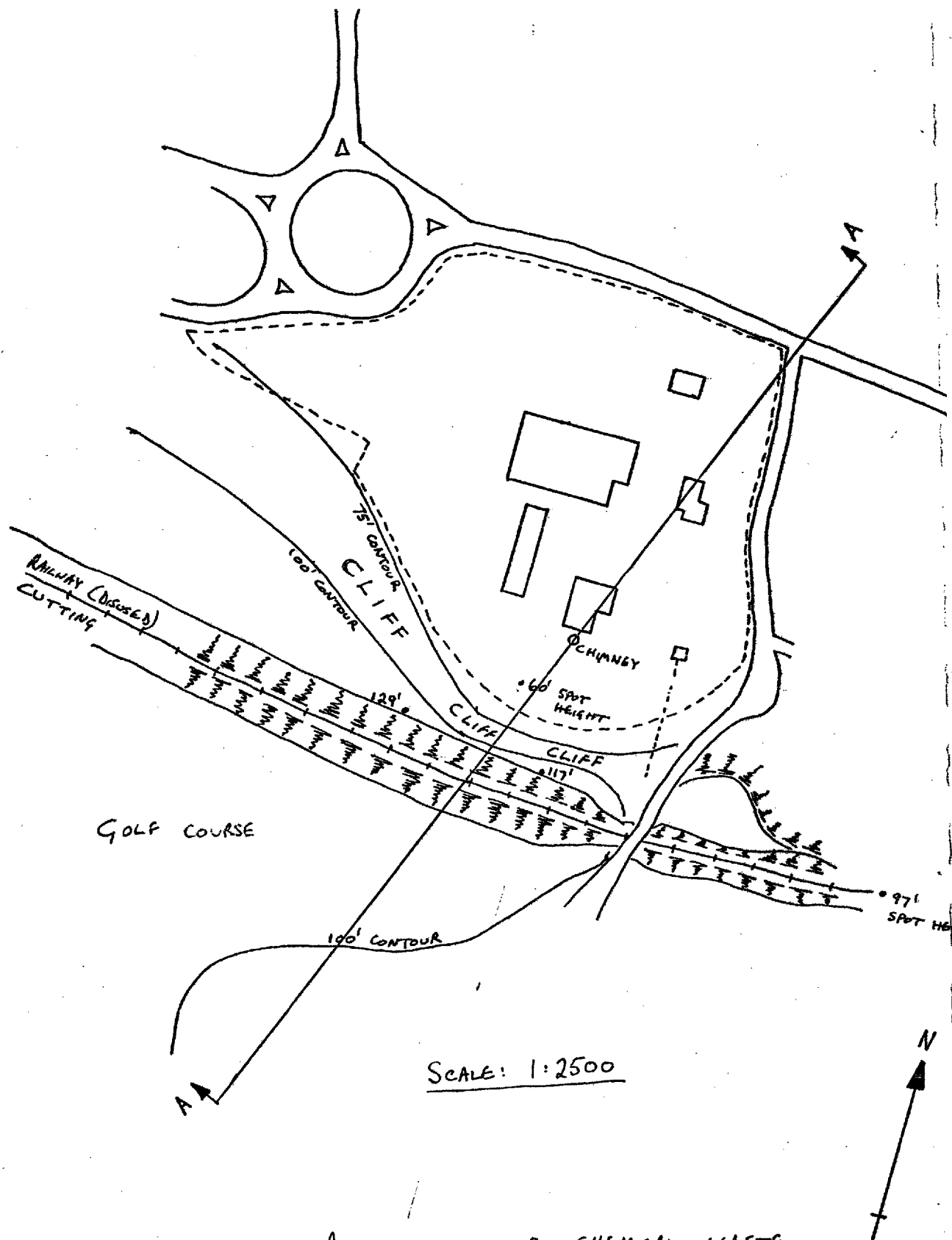


Fig 2.2.1 GENERAL ARRANGEMENT OF CHEMICAL WASTE INCINERATOR. FOR SECTION ON 'A-A', WHICH LIES ON THE SSW-NNE DIRECTION, SEE FIG 2.

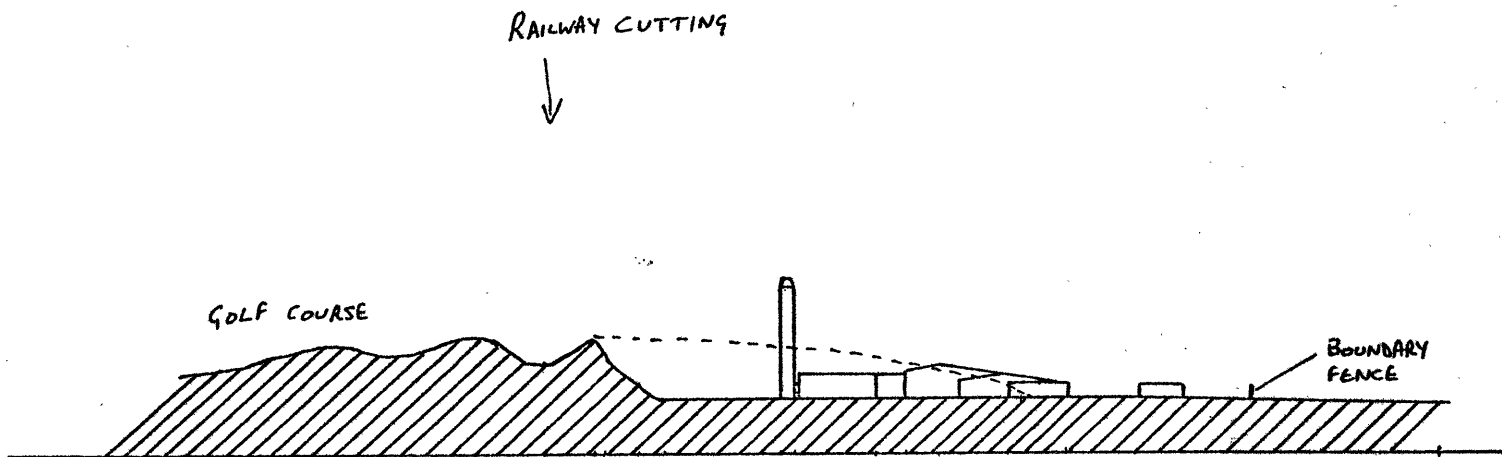


Fig 2.2.2 SECTION ON 'A-A' (Fig 2.2.1). THE DOTTED LINE SHOWS THE APPROXIMATE EXTENT OF THE RECIRCULATING EDDY IN THE LEE OF THE CLIFF. SCALE 1:2500

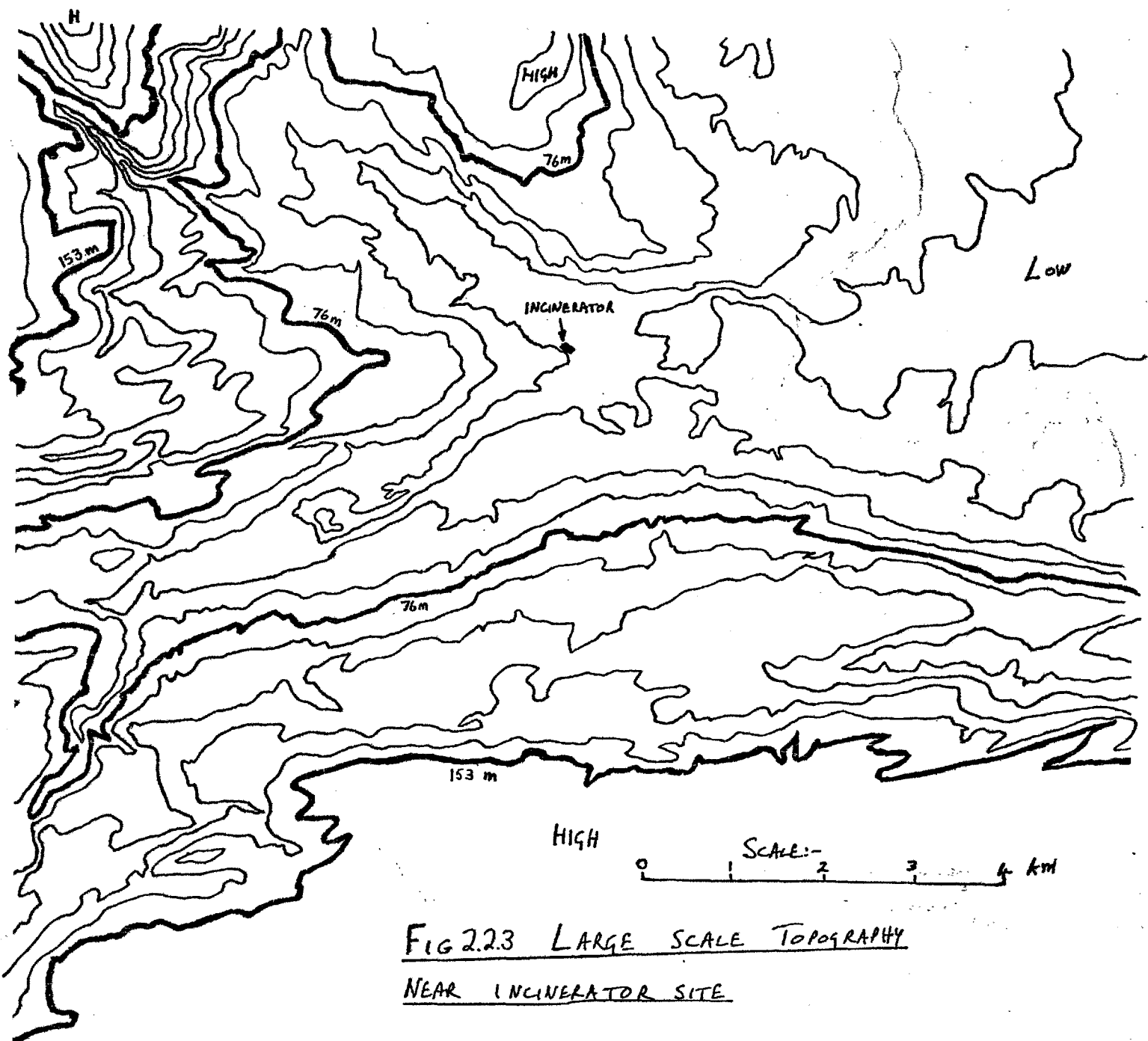


FIG 2.2.3 LARGE SCALE TOPOGRAPHY
NEAR INCINERATOR SITE

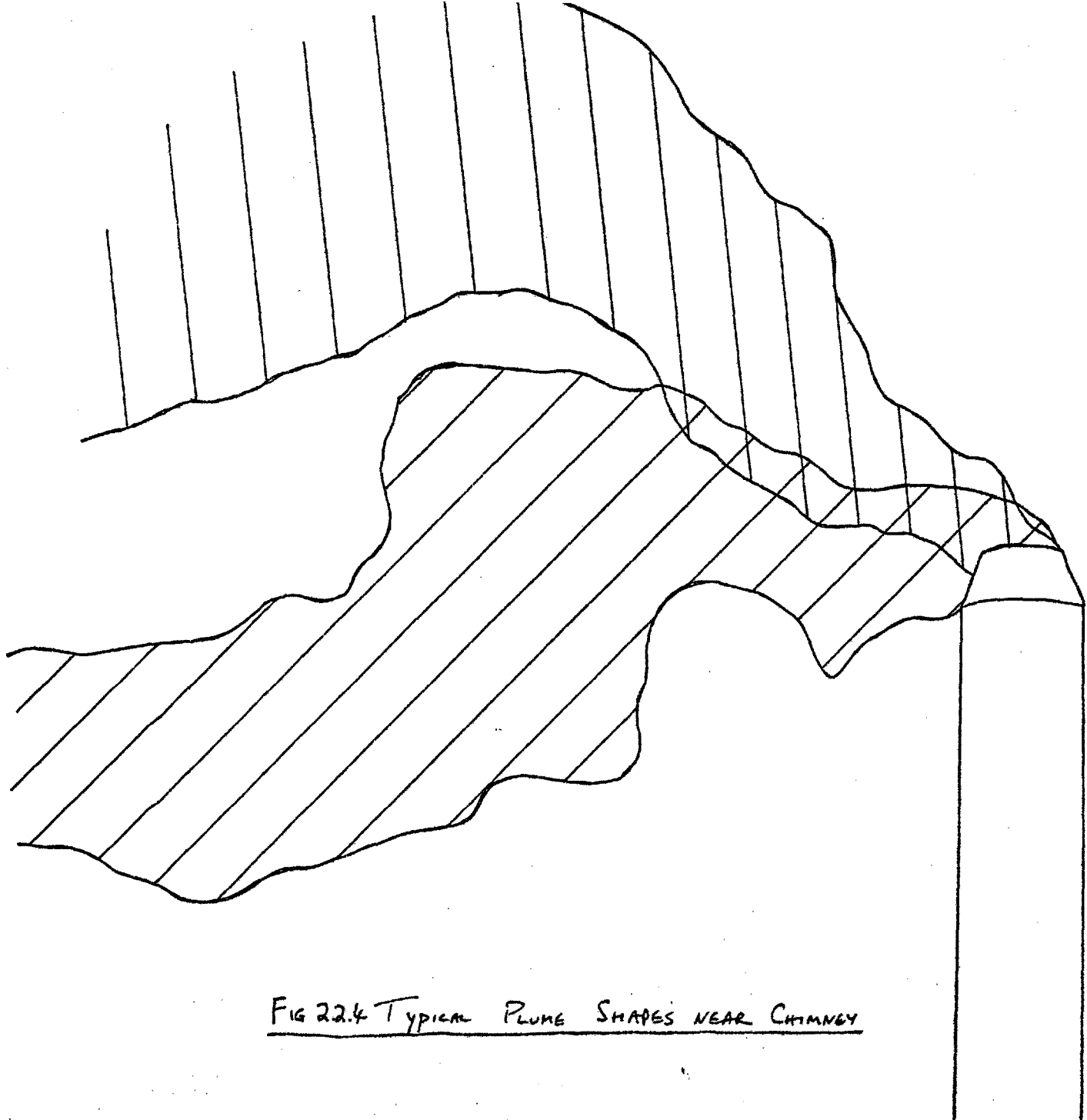


FIG 22.4 Typical PLUME SHAPES NEAR CHIMNEY

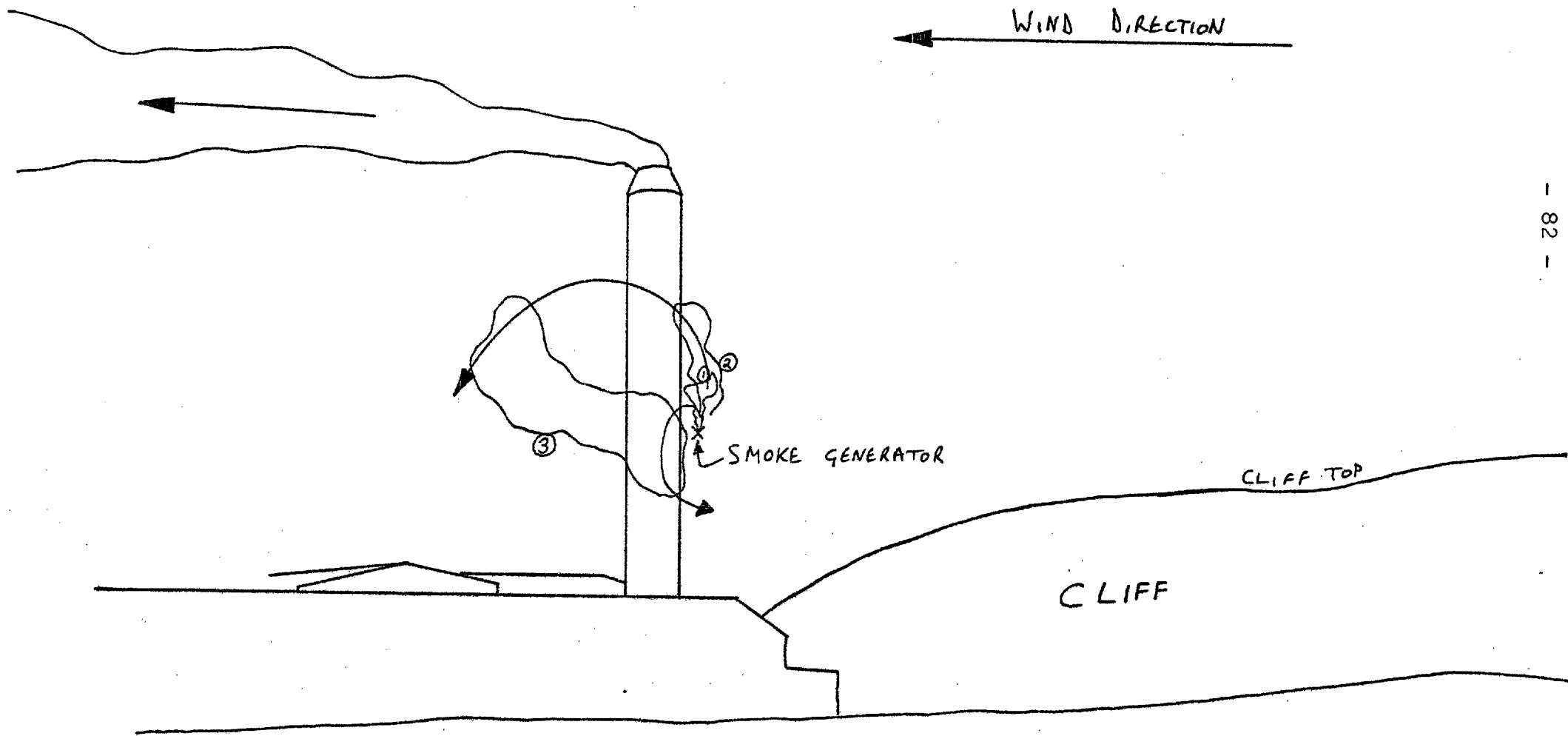


FIGURE 2.2.5

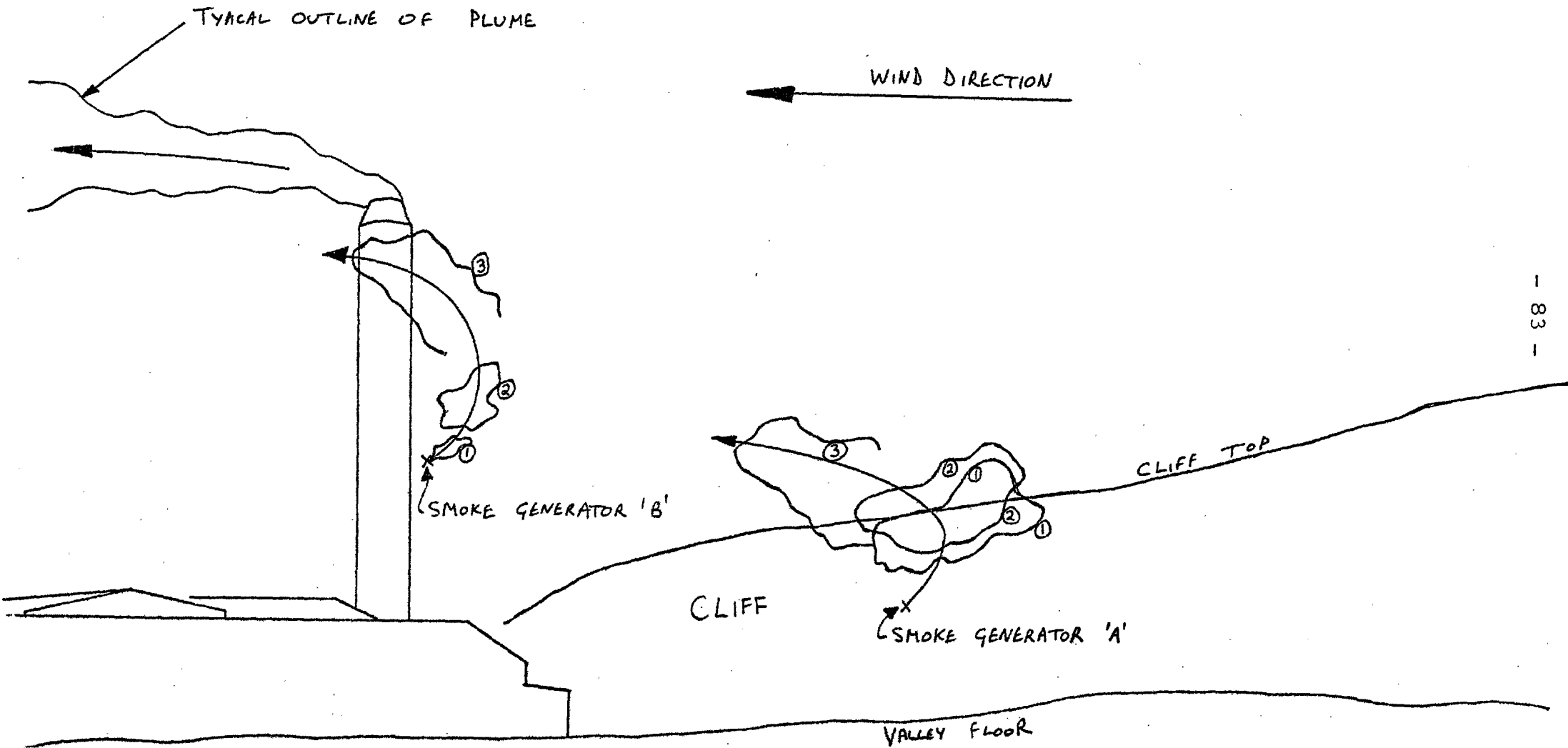


FIGURE 2.2.6

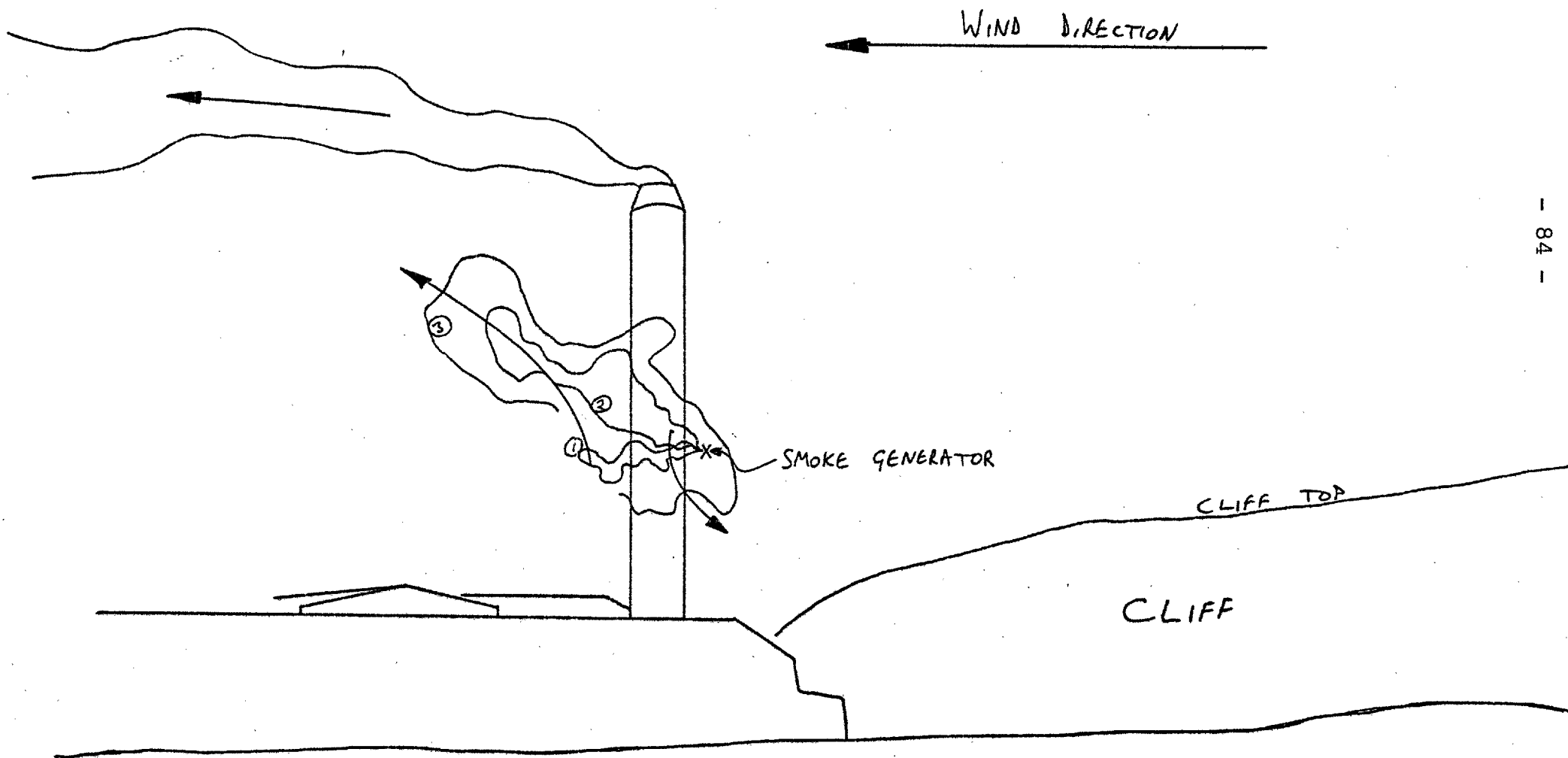


FIGURE 2.2.7

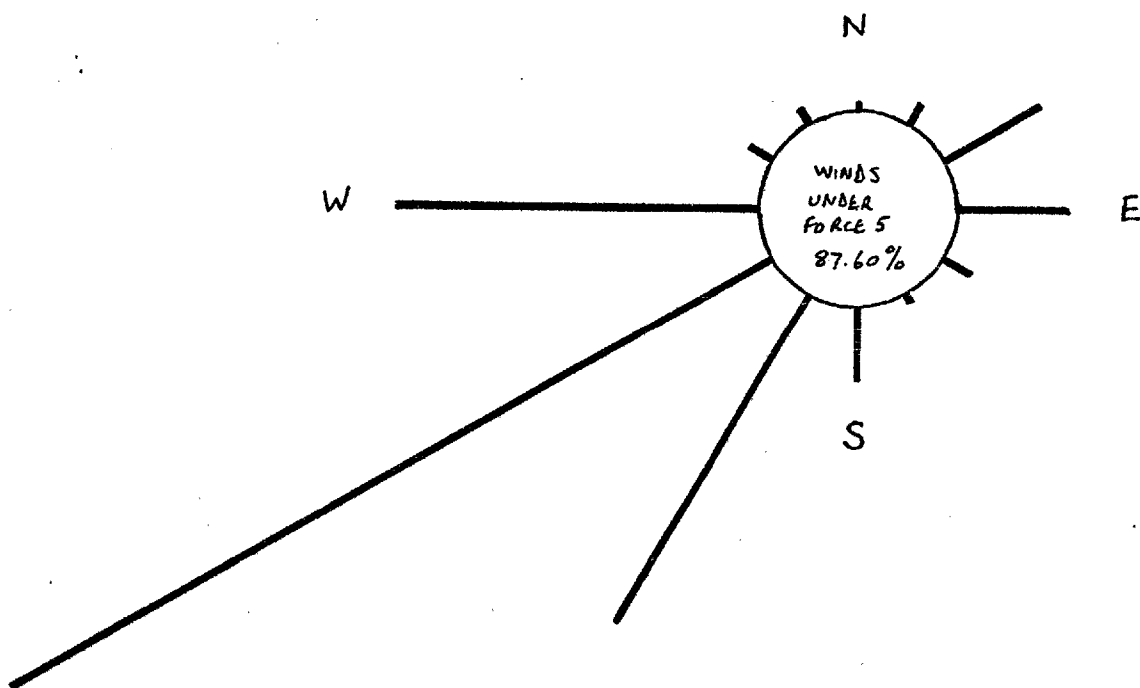


FIGURE 2.2.8

WIND ROSE FOR WINDS ABOVE FORCE 4 (i.e. > 16 kts)
AT EDINBURGH (TURNHOUSE). PERCENTAGE FREQUENCY DURING
1960-1969. SCALE: 2 cms REPRESENTS 1%. DIRECTIONS
SHOWN ARE THOSE FROM WHICH WINDS BLOW.

2.3 Peak and Mean Concentrations at an Elevated Receptor Point Close to a Chimney

2.3.1 Introduction

The source of pollution in this case was a chemical waste incinerator similar in most respects to the one described in the preceding study (section 2.2). Concern arose because of the proximity of a major electricity transmission line to the incinerator, and it was feared that corrosion problems might arise, or that maintenance crews might experience difficulty or even serious danger due to the effluent.

The proposed plant was situated in a flat plain, the nearest significant topographical feature being a 20 m high cliff some 200 m away from the chimney. Previous studies using smoke tracer, similar to those described in Section 2.1.5, had shown that this cliff did not affect the airflow at the site significantly, although there is a likelihood of increased gustiness in winds from the direction of the cliff.

A plan view of the transmission line is given in Figure 2.3.1, with the chimney position and wind direction sectors marked. The stack was to be 55 m high and the height of the pylon numbered 12 (Figure 2.3.1) is 62 m. Thus, the plume rise due to momentum and buoyancy would be a vital factor in the analysis, since it would be solely through plume rise that

the plume could avoid impinging upon the transmission line. An elevation showing the relative heights of the chimney and the pylon and conductors is given in Figure 2.3.2.

A practical aspect which placed constraints upon the height allowable for the chimney was that any tall structure near to transmission lines must be located such that if it were to fall over it would not touch the lines. The calculations for this case are based on the assumption that the falling structure rotates about its base on the ground as a rigid body, and that the conductor cables are displaced towards the structure due to wind forces. A safety margin is allowed in addition to these pessimistic assumptions. The result of this is that a further 24 m but no more could be allowed on the stack height if a remedial measure of this kind were deemed necessary.

2.3.2 Concerns Regarding Peak and Mean Concentrations on the Transmission Line

The specific reasons for concern in this case fell into two categories: firstly short-term peaks and secondly, long-term averages.

Peak values were of interest because of:

- a) flashover on insulators due to plume wetness or to acid gases dissolved in condensation.

- b) increased rates of corrosion, possibly caused by the non-linear relationship between pollution concentration and corrosion rate, with associated hysteresis effects
- c) danger to personnel working on the line, due to sudden peaks, of SO_2 , CO_2 , mixed flue gases and metallic dusts.

Average values gave concern because of:

- a) flashovers due to metallic dusts accumulating on insulators over a period of time
- b) accelerated corrosion due to prolonged exposure to chlorides, especially HCl , which attack aluminium conductors, and to the acid gases
- c) danger to personnel due to contact with accumulations of metallic dusts.

Some of these points of concern involve complex mechanisms at the receptor point (e.g. corrosion and health effects) for which there is wholly inadequate basic information. They remain, therefore, distinctly speculative; however, since the line itself is a very important one in the electricity supply network, it seemed reasonable to aim to design the chimney such that plume impingement on the transmission lines would never occur. This point is reinforced by the knowledge that the basically similar plant considered in Section 2.2 gave rise to a distinctly smelly and unpleasant effluent. Mixed flue gases are believed to be potentially more hazardous than the sum of their respective components would indicate, i.e. synergistic effects take place.

In view of the nature of their work, it would clearly be dangerous for linesmen to work at tower height when such a plume is impinging on the line, and a similar danger could conceivably exist for helicopter pilots and observers monitoring the line.

2.3.3 Mechanisms Contributing to Short-Term Peaks

A number of mechanisms could lead to short-term peaks on the transmission line. We consider first those which could occur while the plant is functioning at its design condition with an efflux velocity of 7.5 m/sec. at a temperature of 400°C.

The first mechanism to be considered is the reduction of plume height which occurs in strong winds and could cause the lower part of the plume to intersect the transmission line when the wind is in the right direction. From an analysis of the plume trajectory using the model of Briggs (1970), in the first 120 m from the chimney it is apparent that such peaks will occur if the wind is of the order of 9 m/sec. or more. Figure 2.3.2 shows calculated plume trajectories diagrammatically. In a 3 m/sec. wind the plume rise carries the pollution well clear of the pylon, and the vertical velocity at all points is sufficiently high that plume looping caused by convective conditions will not be significant. In a 9 m/sec. wind, however, the bottom edge of the plume is very close to the top of the pylon, and the slightest atmospheric subsidence in looping conditions will cause the top of the pylon to be immersed intermittently in the plume. In such a situation the dilution at the pylon distance

would be about 50 times based on a Gaussian model in neutral stability, Pasquill 'D'. On this basis, for stack emissions of SO_2 , HCl , and Cl_2 at the Alkali Inspector's limits (Table 2.3.1) would give instantaneous pylon concentrations of 1.0, 1.1, 1.4 times the relevant TLV (Table 2.3.1) respectively. From peak-to mean data of Martin and Barber (1973) it is estimated that the 8 hour exposure will be at least 6 times lower than this, on the assumption that the wind strength and direction remain steady throughout this period. Such a meteorological event is improbable since in this sector, winds greater than 8.5 m/sec. only occur about 7 hours per year per 10° sector. If the plume spreading angle is 30° then there are about 21 hours per year when the potential for short peaks around the TLV will occur, and in the remote chance that 8 of these 21 hours are consecutive, the average concentration over these 8 hours will be 0.17, 0.18, 0.23 of the TLV for the pollutants SO_2 , HCl , and Cl_2 . In view of the fairly narrow margin of safety which this provides, and with special regard for the synergistic effects between toxic gases in a mixed incinerator effluent, it might well be necessary for work to be carried out on the line only when the wind is in another direction or the incinerator is shut down.

Table 2.3.1
Alkali Inspector's Emission Limits,
and TLV's for Chemical Waste
Incinerator Stack Gases

Pollutant	Emission Limit			TLV ppm
	A.I. Value	Kg/hr	ppm v/v (=P _O)	
SO ₂	300 lb/hr	136	250	5
HCl	0.2 grain/cu.ft.	74.4	280	5
Cl ₂	0.1 grain/cu.ft.	37.2	70	1

The second mechanism for producing peaks is the fragmentation of the plume by vortices shed from the chimney. Provided that the efflux velocity is maintained, this does not appear to be a major threat, since Figure 2.3.2 shows that in light or average winds (up to 3 m/sec.) the plume should leave the stack top cleanly. However, as in the case described in Section 2.2, this effect could occur in strong winds or when the efflux velocity falls.

The essential difference between this case and that in Section 2.2 is that here the plume is still dominated by buoyancy in the area of interest, whereas in the earlier case plume looping in the passive phase had to be considered.

If the efflux velocity or the temperature fall below their design values (as was the case in Section 2.2) then the plume may behave effectively passively, and impingement on the lines is a certainty, and both peak and average

concentrations will be high.

2.3.4 Plume Dispersion Modelling of Peak and Mean Values

Calculations have been made of the annual average concentrations expected to occur at various points along the transmission line, due to emissions at the Alkali Inspector's limits from the proposed 62 m chimney.

Because the plume passes over the transmission line while still rising because of buoyancy, the Pasquill-Gifford fluctuating plume model used here will not be very accurate as it amounts to an extrapolation into an uncertain region. The results should therefore be considered only as a first approximation.

The problem here is that in a buoyant plume there is usually a well mixed region of nearly uniform composition, with a fairly sharp edge outside which is the ambient air. Thus, a Gaussian cross-section does not describe the plume very well. This is a weakness of Ooms' (1972) model which makes a similar assumption.

The plume model used here involves the division of the plume into two connected regions: the bent-over plume which rises through the surrounding air but has the same horizontal velocity; and the passive plume which has no buoyancy and disperses under the action of atmospheric turbulence. The transition between these two regions is somewhat arbitrarily accomplished by assuming that the standard deviation of the cross-sectional concentration distribution in the passive fluctuating plume is equal to the radius of the buoyant plume at

the transition point. An alternative assumption would be to match the centreline concentration at this point. The transition is assumed to occur when the upward velocity of the plume falls to 1/10 of the wind speed, this being a typical value of the turbulence velocity. In real life, of course, the transition is gradual, with turbulence having negligible effect, then increasing in importance as the buoyant velocity falls, and finally dominating the dispersion.

For the very hot effluent expected, the final plume rise will be very substantial and for this reason the ground level concentrations predicted are very satisfactory. In the vast majority of the plume calculations this final rise is all that matters and the actual trajectory is irrelevant, but on examination it is found in this case that the predicted trajectory for the high wind speed cases is quite shallow, even though the final rise may be large. Typical trajectories for wind speed ($= U$) of 3 m/sec. and 9 m/sec., are shown in Figure 2.3.2. It is clear that while the lower wind speed is quite satisfactory, at $U=9$ the slightest deviation of the plume from the theoretical trajectory would cause the pylon to be immersed in the incinerator effluent.

The basic plume model used gives three minute average concentrations and it is necessary to combine these results with meteorological data (wind frequencies) to obtain annual average values. In each sector the estimate has been made for the part of the line nearest to the chimney, and allowance has been made where appropriate for the sag of the cables between

the pylons.

2.3.5 Results of Calculations

Results of the calculations are given in the following table:

(N.B. P_o = concentration in stack - see Table 2.3.1).

Table 2.3.2

Sector (see Fig. 2.3.1)	Distance of nearest part of cable (m)	Height above stack top (m)	Estimated Pollution Concentration Ratio (P/P_o)		Average Concentration (pphm)		
			Peak 3-min. at 9 m/sec.	Annual Average	SO_2 $P_o =$ 250ppm	HCl $P_o =$ 280ppm	Cl_2 $P_o =$ 70ppm
1	275	7.0	.0049	8×10^{-6}	.20	.22	.06
2	134	-6.7	.012	9.2×10^{-6}	.23	.26	.06
3	100	-1.5	.018	42×10^{-6}	1.1	1.2	.29
4	100	7.0	.018	120×10^{-6}	3.0	3.4	.84
5	100	7.0	.018	170×10^{-6}	4.2	4.8	1.2
6	122	-3.4	.013	31×10^{-6}	.77	.86	.22
7	220	7.0	.0065	30×10^{-6}	.74	.83	.21

The average concentrations are highest at sector 5, for which the actual point considered was the most westerly in that sector, where the cables are nearest to the chimney. This point is very close to pylon 12, as shown in Figure 2.3.1, although the pylon itself is in sector 4. The different results for sectors 4 and 5 are due to different wind frequencies. The peak values in Table 2.3.2 were obtained by assuming the effluent to be uniformly distributed across the buoyant plume and that

the centreline of the plume is distorted so that it intersects the transmission line while the average values assume a Gaussian cross-section. By looking in more detail at the behaviour in all wind speeds, using a Gaussian model, the frequency of exceeding pollution concentration ratios of 1/100 and 1/50 have been determined and these are given in the following table:

Table 2.3.3
Number of Hours per Year of
 $P_{\max}/P_o$ exceeding 1/100 and 1/50

Sector	1	2	3	4	5	6	7
1/100	0	.24	18	59	88	3.3	0
1/50	0	0	.7	3.6	6.5	0	0

A comparison of these results with experiments in the field would be useful, but the only data readily available are for SO_2 :

Table 2.3.4
Results Compared with National Survey Data

Peak 3-min (Pylon 12)	Average (Pylon 12)	Castle Bromwich 1 1968/9 (A)		Coleshill 16 1968/9 (B)		Peak/ mean ratio, (C) 3-min: day (Martin & Barber)	A or B xC approx.
		peak daily	average	peak daily	average		
500pphm	4.2pphm	18.6pphm	4.6pphm	19.5pphm	3.1pphm	20 approx.	400pphm

The essence of the results is contained in this table. It may be summarised by saying that the annual average concentrations due to the incinerator if operated at the Alkali Inspector's limits will be about equal to the existing background. Thus, the effect of the plant will be to double the mean concentration experienced near pylon 12. The same is not true of peaks, however, since the circumstances which cause peaks from the incinerator plume are not the same as those which cause peaks from other sources. For example, if a peak were caused by the plumes from a nearby power station to the east, an easterly wind would have to be present carrying the effluent towards Pylon 12. This would blow the incinerator effluent harmlessly away to the west. Alternatively, if the peak were due to low-level domestic sources we would expect this to be in inversion conditions and still air, when the hot incinerator plume would climb well away from the transmission line. So the effect of the new plant on peak values will not be to increase the magnitude of the peaks but roughly to double their frequency.

2.3.6 Conclusions and Recommendations

Whether or not these results are of concern depends on data on corrosion rates etc., which are at present unavailable: however, it is worth considering ways in which the problem, if any, might be ameliorated. In view of the fact that concentrations due to the chimney are in general very low, it would seem wasteful to install further fume cleaning equipment purely to cope with a small area of high concentration. Better by far would be to

increase the stack height so as to lift the plume clear of the pylon under all conditions. This would not greatly affect ground level concentrations, since these depend mainly on the thermal rise of the plume and not on the physical stack height, but the effect near the source would be large. For example, a calculation has been done for $U=9$ m/sec. at different stack heights:

Stack height (m)	55	61	67	73	79
Average P/P_0 ($\times 10^{-6}$)	170	71	39	25	17

The frequency of peaks is curtailed even more drastically, and even a 6 m increase in chimney height makes peaks $> 1/100$ practically impossible.

The question of giving adequate safety clearance between the (hypothetically) falling chimney and the power line now arises. As mentioned in 2.3.1, there is a clearance of 24 m between the falling 180 ft. stack and the safety clearance line for the bottom conductor in 45° swing. This 24 m could be used if necessary giving a 79 m chimney height. If this were not adequate, the stack would have to be repositioned further away.

To conclude, it cannot be stated on the sole basis of dispersion estimates that the effluent from the incinerator will not cause damage to the transmission line, though the converse is unproven also. The effects will

be no greater in magnitude than those already occurring due to ambient pollution levels. The possibility of reducing concentrations due to the incinerator exists through appropriate design and location of the chimney.

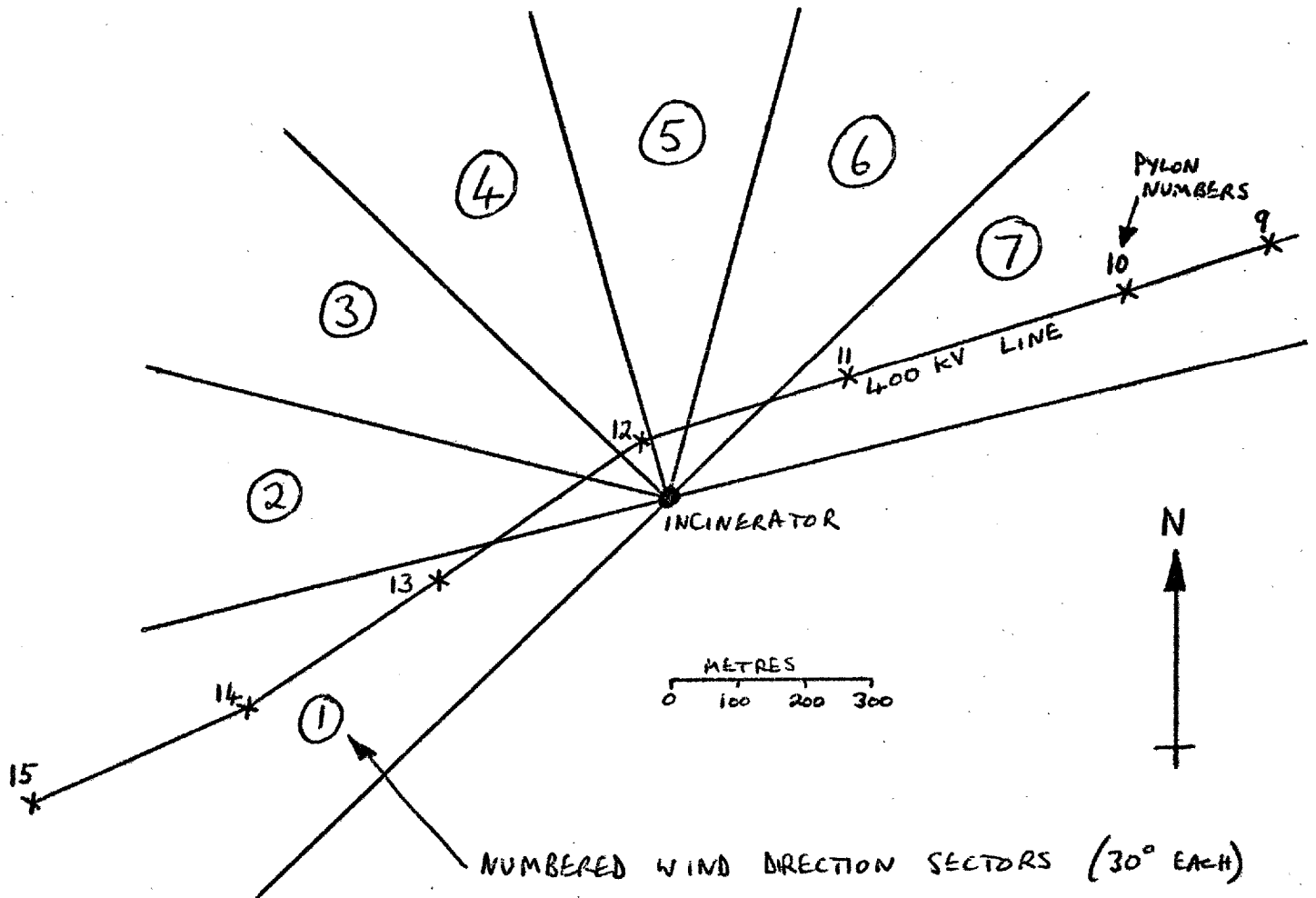
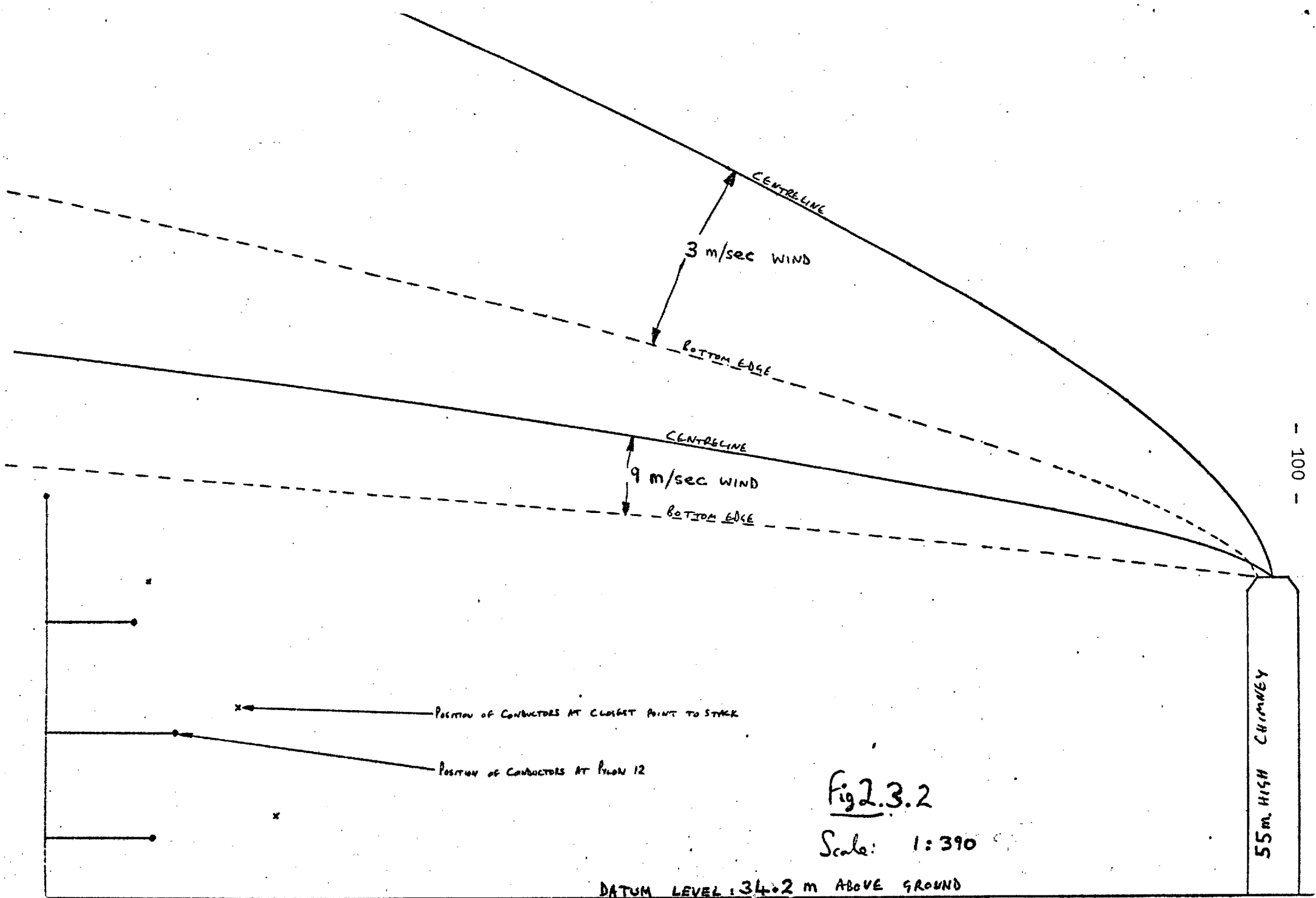


Fig 2.3.1 RELATIVE POSITIONS OF TRANSMISSION LINE
AND INCINERATOR CHIMNEY ; DEFINITION OF WIND DIRECTION SECTORS



3.0 MAIN CASE STUDY - BATTERY FACTORY LEAD EMISSIONS

3.1 General description of the factories studied and their environs

3.1.1 The Clifton factory

3.1.1.1 Processes carried out on site and the associated emissions of lead

The battery factory at Clifton produces a wide range of lead-acid batteries covering both automotive and industrial applications. Raw materials vary according to supply and demand, but the basic supply of lead is from scrap, which is smelted and refined on site. Refined lead and antimony, or alternatively lead/antimony alloy, may be brought in by road, as may various minor alloying constituents needed for plate manufacture. Refined lead or lead/antimony is supplied in the form of ingots and does not give rise to any lead containing dust in transport or handling. The scrap, however, which consists mostly of battery plates of a friable nature, is stored in the open and, undoubtedly, contributes to the spread of lead dust through the action of the wind.

Scrap lead arriving by road is first deposited on the pile, which is near to the site entrance. It was observed that the manoeuvring area for lorries bringing in scrap was very badly contaminated with lead and littered with scrap plates. It seemed inevitable that these vehicles would carry lead dust out of the site on their tyres. Scrap batteries must be split open and the plates separated from the casings, and this is carried out manually with the aid of an axe - probably the

most primitive operation in the entire process, and one which it is alleged cannot yet be carried out mechanically.

Scrap invariably contains a large proportion of oxide and, therefore, it must be smelted before it can be re-used. It is fed to one of two blast furnaces on the site, each of which exhausts through a fume control system consisting of the following elements in series: expansion chamber, air cooler in the form of zig-zag ducting, bag filter house, induced draft fan and chimney (37m and 47m high respectively). In addition to the main furnace exhausts, there are auxiliary fume control systems which extract fume-laden air from the vicinity of furnace doors (which must be opened for slagging and charging), and lead refining pots where alloying is carried out. These fumes need no cooling but pass through bag filters before emission from a short stack in the older installation and from the 47m chimney in the newer one. The emissions are quantified in Section 3.3.

Lead produced in the smelter is used in two ways: first, as lead/antimony alloy, it is cast into the form of a grid, which is used as the structural basis for the battery plates and second, it is partially oxidised to produce Pb/PbO granules (about 60% by weight PbO), which can be pasted onto the grids and subsequently electrolysed to form positive and negative plates. Grid casting machines are supplied with alloy from individual melting pots at a modest temperature. Although fume extraction equipment is used to preserve industrial hygiene in this process, the amount of lead present in the fume from relatively cool molten alloy is negligible and the emissions are

of no concern in this study.

The oxide mills are a major potential emitter of dust and like the smelters are a scheduled process under the Alkali Act regulations. Lead in the form of ingots or specially cast balls about 8 cm in diameter is fed to a rotary kiln which is supplied with hot air from a furnace. The oxide (PbO) formed on the surface of the lead is abraded under the action of collisions between lead ingots and falls into a hopper below after passing through an 80 mesh screen (corresponding to 180 micron particle size). Inevitably, some of the oxide dust is carried away in the kiln exhaust and this is therefore passed through a bag filter, sometimes with a preliminary cyclone stage, before emission to atmosphere. The solids collected in the hopper and in the filters and cyclone constitute the oxide product from the mill.

The flash from the plate grid casting process must be removed and there are both mechanical and manual processes for this. Essentially, these consist of offering the plates up to a shaped former and grinding off any excess material. Fume extraction equipment is installed and the emissions are found to be quite significant.

The next process is the pasting of oxide (as a slurry in water and sulphuric acid) onto the lead/antimony grids. Since this is carried out wet, it does not cause any significant emission of dust. The paste now consists of a mixture of Pb , PbO and PbSO_4 which has the particular physical properties required (i.e. porosity and strength). The plates are left to 'mature' for about three days in a building having carefully controlled

ventilation designed to keep the humidity up. The remaining Pb in the oxide granules is oxidised slowly to PbO . Matured plates are then passed to the electrolysis vats in which the oxide is transformed to form positive and negative plates depending on the polarity of the electrolysis. Positive plates are transformed into PbO_2 , and negative ones to Pb, both having the necessary spongy structure. The emissions from these steps are very small, but once the plates are dry they become liable to generate dust if roughly handled and so care must be taken when transporting them. Positive and negative plates must be assembled together with the corresponding insulating separators and this may be done manually or by one of two Reed stacking machines. Manual stacking tends to be a cleaner process than mechanical stacking, apparently because the human hand is capable of more sensitive control of the plates. Both processes require comprehensive fume extraction equipment and give rise to significant emissions (unfiltered). Stacks of plates are inserted into their cases and the final process involving a fume emission is the "burning" (i.e. melting and welding) of battery connection fittings prior to sealing with pitch. The emissions here are rather small and are not filtered.

Batteries normally leave the works dry and require only filling with acid before they are put into service.

As can be seen from the foregoing, this plant contains a wide variety of emission sources for lead and the degree of control applied in the form of filtration plant varies considerably. Many of

the emissions are of a type which would be difficult to control or even to quantify (e.g. dust from transport of dry plates, or from scrap piles). However, due to the need for control of air quality within workplaces, fume extraction ducting abounds, and measurements of lead in these ducts has enabled most of these emissions to be quantified. This is discussed in detail in Section 3.3.

3.1.1.2 Factory location and surroundings

Figure 3.1.1 shows the Clifton factory site in relation to its surroundings up to 3-5 km distance. The works is in the valley of the Irwell river and is in a long-established industrial setting which now includes a tile works, a dye works, the Agecroft colliery and the Agecroft power station. It is believed that the tile works uses a limited amount of lead, but the emissions from these operations are negligible compared with those from the battery factory. The M62 motorway passes close by the site and a number of other roads in the area carry heavy volumes of traffic. The nearest residential property is the housing on Pepper Hill, some 400m from the centre of the factory site.

The main topographical feature which appeared likely to affect dispersion of airborne dust was the steep cliff on the north side of Pepper Hill. The housing on this promontary is nearly level with the tops of the factory chimneys. To the north-east the ground rises relatively slowly towards Whitefield and no major topographic

effects should be felt there. These aspects will be considered in greater detail in connection with local meteorological effects in Section 3.3.

3.1.2 The Dagenham factory

3.1.2.1 Process and emissions

The basic processes carried out at Dagenham are the same in principle as those at Clifton and therefore will not be described in detail here (see Section 3.1.1.1 for general description of Clifton process). The major differences between the two factories are as follows:

- (i) all production is automotive batteries,
- (ii) there is only one lead smelting furnace, having a stack 19m high,
- (iii) the handling of scrap lead is generally more satisfactory than at Clifton, since scrap is held in purpose-built bunkers with brick sides, from which it should be less easy for lead to escape,
- (iv) the overall level of emission control at Dagenham is superior to that at Clifton, with the result that, relative to production rates (which are smaller at Dagenham) the emissions are lower.

3.1.2.2 Factory location and surroundings

Figure 3.1.2 shows the Dagenham factory and its environs. The battery works is located in an area which is exclusively given over to industrial purposes. The nearest residential area is about 700m away. The industrial activity is dominated by the large Ford manufacturing plant, and this is also significant as there is an

emission of lead from the car body shop of this plant, due to the operation of grinding and smoothing of lead filler applied to car bodies. This emission has been quantified (see Section 3.3) and turns out to be considerably smaller than the battery factory emission.

The River Thames is about 1 km south of the plant at its nearest approach, and Barking power station lies on its north bank, some 3 km to the west. The river is nearly 1km wide at this point.

Heavy traffic flows are experienced on the A13 trunk road which passes close by the site. Several other roads within the residential areas also carry substantial volumes of traffic. Most of the Borough of Barking is built-up, with the area north of the A13 largely residential and the area to the south almost exclusively industrial.

3.1.3 Assessment of mechanisms likely to play a part in disseminating lead into the environment

Lead emissions are all in solid form and may consist of elemental lead, but predominantly of lead oxide PbO_2 . Generally, lead in elemental form is sufficiently soft that it does not readily form dusts, and the only point where elemental lead dust could form is in plate cleaning.

Oxide dust is readily generated because of the friable nature of the compound. The particle sizes may vary up to millimetre dimensions, but are mostly in the range 1 micron to 1 mm.

Particles in these sizes will be carried around by the air, at least intermittently. The fact that such dust cannot always be treated as a passive tracer diluting into the air makes the analysis of dispersion very difficult. Some of the mechanisms which may be involved in dust dispersion are discussed in Appendix I. The emissions concerned must each be examined in turn to establish (a) the particle size spectrum, (b) emission location and (c) exit conditions.

3.1.3.1 Elevated emissions

At the Clifton factory, only two emissions can be considered "elevated" in the sense that they are not affected by the aerodynamic effects of buildings, etc. These are the two smelter chimneys of 37 and 47 m height. Since the exhausts from these stacks are first passed through a bag filter, it would be expected that the only particles likely to be emitted would be in the range below about 0.1 microns. The bulk of these particles would probably be below 0.01 micron and would behave essentially as if they were gaseous tracers and, therefore, passive dispersion models should apply. Because the emissions are elevated, the immediate aerodynamic effects of buildings will not be important although the general topography of the site on a larger scale (i.e. one comparable with the distance to maximum ground level concentration) may have an important effect.

The Dagenham smelter chimney is only about twice the height of the buildings nearby, and therefore it is possible that building wakes do interfere somewhat with the plume. Nevertheless, it seemed reasonable to treat it as an elevated source in the first instance.

3.1.3.2 Low-level designed emissions

"Designed" emissions are those for which purpose-made ducting or chimneys have been provided. They are to be distinguished from "adventitious" emissions described in the next section.

Apart from the main smelter chimneys, all designed emissions at the two factories have rather short stacks, invariably fitted with a "Chinese hat" or similar device to prevent rain ingress. These effectively kill any vertical momentum that the emission might have had, and, moreover, disperse it radially so that rapid dilution occurs in the first few seconds. This means that these emissions inevitably become entrained in building wakes, so that for the purpose of estimating concentrations at points beyond the site boundary, they may be assumed to be diluted uniformly through a depth equal to a typical building height, and through a width comparable with the total width of the factory building complex. Table 3.1.1 gives a general description of the nature of the emissions.

Table 3.1.1 Low-level designed emissions

Source	Emission Characteristics
Clifton old furnace fume extraction system	Mostly 0.1 micron fume
Casting shop, final) assembly of fittings)	Fine fume from molten Pb
Oxide mills exhaust	Fume and dust up to 5 microns
Plate cleaning	Dust up to 100 microns Pb or PbO
Reed stacking machine) Hand stacking benches)	Dust up to 20 microns PbO ₂

3.1.3.3 "Adventitious" or unintentional emissions

Unintentional emissions are by far the most difficult to predict or to treat analytically. In the present context they include: blow-off from scrap stores, escapes of dust from lead oxide storage (or from bagging operations), spills or losses from plate transport within factory, dust carried on shoes of leadworkers or on vehicle wheels, etc.

It is customary in certain parts of the plant to keep floors and roadways constantly doused with water, to keep dust from rising into the air and wash it down the drain to sumps from which it can be periodically emptied (producing a valuable smelter feed). In practice, it was observed that these areas were not being kept wet all of the time, and lead dust was in evidence at many points around the site. In particular, the scrap

piles are not wetted, and so emissions from this area are totally uncontrolled.

Particle sizes involved in adventitious escapes range up to grit sizes (say 10mm) typically, but occasionally exceptional occurrences arise, such as whole plates being carried out of the works on vehicles, or falling from incoming scrap loads.

3.1.3.4 Particle fall-out

Most of the 'design' emissions should consist mainly of fume with a typical particle size of 0.1 microns or lower. This would certainly apply to any emission which had passed through a bag filter, and to fume generated over melting pots containing relatively cool molten lead. These emissions would not fall out significantly in the time scales of interest in the dispersion process (i.e. the time to travel with the wind to the edge of the study area some 5 km away). A few design emissions involve larger particles (say up to 20 microns) and these would settle significantly within this time scale. Appendix I gives values for the settling rates of particles of different sizes on the assumption of specific gravity of unity and spherical particle shape. It is uncertain what density the oxide particles will have, since they are loosely structured, however it seems likely that they will be considerably denser than water, and therefore their fall speed will be higher than given in the Appendix.

The major contributors to large particle emissions are the various varieties of adventitious release. Most of these are from dust

accumulations at or near ground level, and therefore must of necessity include dusts which are liable to settle rapidly, otherwise they could not have accumulated in the first place. The prime example is blow-off from scrap piles. These particles will probably fall out so rapidly that they are never airborne for very long, and their motion in the environment proceeds as a series of hops, according to the onset of gusts and lulls in the wind.

3.1.3.5 Particle deposition and accumulation

Particles that are being carried by the air may be deposited onto surfaces and held there by a number of mechanisms. The shearing of the wind velocity profile has a major effect on the motion and allows particles to adopt a near-vertical trajectory in the final stages of descent. This increases the chances of being captured on the surface rather than bouncing off.

The nature of the surface is clearly critical in determining whether or not the particle will be retained. On grass or soil surfaces the likelihood of lead dust particles being able to escape after deposition is low, and depends primarily on the degree of wetness. Dust travels furthest in urban environments where it cannot be so easily trapped in this way (unless it is raining).

Accumulation of dust may also occur where there are standing eddies in the air, associated with flows round buildings or other obstacles. This leads, for example, to the accumulation of dust in roadside kerbs. Appendix I discusses these

phenomena in more detail.

3.1.3.6 Particle saltation

The process of dust particle movement known as saltation has been examined in a classic analysis by Bagnold (1941) who was concerned with the movement of desert sands. This process involves the following steps:

- (i) a particle is dislodged by some means from the surface on which it rests
- (ii) it follows a trajectory through the air which first lifts it into a faster-moving airflow, then accelerates it nearly up to the horizontal windspeed, and finally allows it to subside back to the surface due to the settling process, but now with increased horizontal momentum.
- (iii) on colliding again with the surface, the particle cannons other particles into the air, or bounces off itself to repeat the cycle.

This process is only possible when the average number of particles thrown up due to one particle impact exceeds unity. This criterion will depend on the windspeed and on the distribution of particle coverage over the ground and therefore it is uncertain to what extent it would be relevant in an urban situation.

3.1.3.7 Transport on vehicles

Vehicles which are driven over roads or ground contaminated with lead dust will pick up quantities of lead on their tyres. Lead containing mud can also be thrown up into wheel arches. Lead picked up in these ways will probably be deposited subsequently as the dust dries out, or by being

washed off by rain water. As discussed in Appendix I, the airflow pattern round cars is such as to sweep any dust deposited in the road to the edge, where it accumulates in the kerb.

In the case of the battery factory, lead may be deposited onto roadways from vehicles bringing in scrap for smelting. These vehicles are not always securely covered, especially when returning empty, and lead may readily fall from them.

Thus, in the survey work described in Section 3.2, special attention has been paid to transport routes, and to dust found in the kerbs.

3.1.3.8 Transport on the persons of factory workers

The employees of the battery factory must be considered in three classes: "high risk" leadworkers, "low risk" leadworkers and office staff. The first of these groups comprises those who work in the most heavily contaminated environments, notably the smelters, oxide mills, stacking, etc. These workers are subject to the closest medical surveillance and have blood tests at least once every three months. The "low risk" leadworkers include those who are involved only with low temperature casting operations, welding of fittings, handling of finished batteries and the like. They have less frequent medical checks. All manual leadworkers are encouraged to observe strict rules of personal hygiene, including thorough washing, changing of shoes and, in some cases, of clothing. It is believed, however, that the majority do not in fact carry out the

full range of such precautionary actions, and therefore there exists the possibility that they may carry lead out of the factory on their persons.

The roadway within the works at the time of the survey were observed to be contaminated with lead dust quite often, although the roads were occasionally watered to wash this material to the drains. Thus, even an employee who conscientiously washed himself and changed clothing on leaving the works would probably pick up some lead on his shoes. If he travels by car, this could readily be transferred to the carpets of the car, where it could accumulate. Equally, such lead could readily be transferred from the car to the home, and indeed this is possible, though less likely, to occur in cases where no car is involved. Soft clothing, e.g. socks, sweaters, etc., can act like a filter and accumulate dust particles from the air. Such particles may become dislodged only when the clothing is removed and hence a fairly efficient transfer of lead from factory to home is possible. Lead on the soles of shoes of workers who walk all the way home is, by contrast, unlikely to survive the journey.

3.1.3.9 Absorption by the human population

In itself, lead on clothing is a minor hazard; ingestion may occur if the hands become contaminated during handling of clothing, and inhalation is possible if the dust is shaken out. Thus, some degree of exposure of all members of the family is inevitable. A particular concern, however, relates to young children, since the dust can be expected to accumulate in the carpets

of the home, whence it may contaminate toys and other objects on the floor, or directly contaminate the skin. The lead may then be ingested if any of these objects is put in the mouth. Children are thus suspected to be particularly likely to ingest lead, and, furthermore, are considered at increased risk due to their low body weight and, speculatively, to the critical stage of development of their nervous systems, which it seems likely could be impaired by lead poisoning.

Thus a major part of the survey described was devoted to identifying whether effects like these were occurring, and to assessing their magnitude.

The general population is exposed to lead from a number of sources. In air, lead exists in significant quantities due to the lead content of petrol and, as will be seen later, the battery factory also contributes significantly. Much of this lead will be in the respirable range (under 5 microns) but some of this (that under 0.5 microns) may well be breathed out again rather than absorbed. Typically, 25 to 50% of the dust is absorbed. Ingested lead arises from contamination of food and of other objects that may be placed in the mouth. Some 5 to 10% of ingested lead is absorbed.

Lead contamination in the home may arise from such sources as lead water pipes and flaking lead paint, either of which may cause significant ingestion. Thus it is seen that the population in general is subject to a wide variety of possible sources of lead and the emissions from the battery factory will be only part of the total.

The interpretation of blood lead concentrations is not altogether simple. A considerable proportion of ingested or inhaled lead can be stored in the bone tissue, having first been absorbed into the blood. Following chemical changes in the blood (exemplified by chelation therapy) this stored lead may be released again into the blood stream. At all times, there may be excretion of lead in the urine. Thus the level of lead in blood is in a sense a reflection of the amount of lead flowing through the body, and not necessarily of the total body burden. Since the damage caused by lead is believed to occur mainly in the brain and nervous system, it seems reasonable to conclude that the average blood lead level is indeed the crucial factor rather than the total burden, although the latter may contribute to maintaining the former for a prolonged period after exposure ceases.

3.1.4 Review of previous studies of lead in the environment and in human blood

3.1.4.1 Lead in the environment

A number of authors have investigated the 'natural background' of lead in the environment and the general conclusion has been that hardly any point on earth is uncontaminated with lead from Man's activities. Fox and Ludwick (1976) have shown, however, that the total current global background is still very low compared with typical concentrations within cities. Janssens and Dams (1975) consider that the background in Belgium is about $0.23 \mu\text{g}/\text{m}^3$ of lead in air, while in sparsely populated parts of Europe and Scandinavia the levels are about 100 times

lower. Thus we can expect a general background much above the 'natural' level in the context of the battery factory study.

Hudson et al (1975) studied airborne lead levels in a small urban community and found very similar levels ($0.227 \mu\text{g}/\text{m}^3$) and Solomon and Hartford (1976) presented results for the same city for lead in dust and soil. Outdoor dust was found to contain between 600 - 1950 ppm while soil contained 250 - 1100 ppm Pb. Their work indicated that traffic exhaust was the main source of lead contamination and concentrations fell away with increasing distance from the road. Ward et al (1975) studied a remotely-located road and confirmed this result, noting in addition that elevated levels in soil were only detectable up to 100 m from the road and to a depth of 5 cm. They estimated that the total amount of lead in the soil up to 250 m from the road and to a depth of 6 cm represented over 50% of the total lead emitted by traffic on this road since the introduction of leaded petrol. This implies that removal processes for lead in soil are very slow.

Heichel and Hankin (1976) showed that roadside trees could cause increases in lead deposition compared against open country. Within a belt of trees, deposition rates could be doubled. Servant (1974) found a mean deposition velocity for lead particulates of 0.13 cm/sec in a residential section of Toulouse.

A number of specific studies have been made near to major lead works, e.g. McClannan and Rossano (1975) who found $1.4 \mu\text{g}/\text{m}^3$ lead in air near the Tacoma smelter but only $0.39 \mu\text{g}/\text{m}^3$ while the smelter was not operating, an interesting result

which indicates that in this case process emissions dominate casual sources such as wind-whip of accumulated surface dust. Dorn et al (1976) found that approximately 66% of lead emissions from a smelter in Missouri were composed of particles below 4.7 microns in size (the upper limit of respirable particles) and presented some detailed particle size spectra. The mean concentration about 800 m from the smelter stack was found to be about $1.04 \mu\text{g}/\text{m}^3$ compared with a 'control' value of $0.11 \mu\text{g}/\text{m}^3$.

In the specific context of the Clifton battery factory, Ratcliffe (1975) has presented results for lead in vegetation, showing a consistent pattern of reducing concentration in mosses with increasing distance from the works. There appeared to be a significant effect of the prevailing wind, and of channelling in the valley. Pollitt (1976a) presented results of air sampling in nearby Salford, indicating a mean figure of $1.25 \mu\text{g}/\text{m}^3$ while lead in dust ranged up to 5000 ppm, with most results in the range 200 - 1000 ppm.

Figures have been reported for lead in air at Tower Hamlets ($3 \mu\text{g}/\text{m}^3$), Avonmouth ($2.2 - 6.0 \mu\text{g}/\text{m}^3$) and Fleet Street ($5.0 - 9.0 \mu\text{g}/\text{m}^3$). For dust, other published figures range over 500 to 40000 ppm and for soil a similar range. Thus considerable variability of the results can be expected and comparisons between different studies may be difficult.

3.1.4.2 Effects on the human population

The effect of environmental contamination on human populations has been the subject of extensive study. Thomas et al (1967) found

substantially higher blood leads ($22.7 \mu\text{g}/100\text{ml}$) in male populations living near a Los Angeles freeway than in a control population ($16 \mu\text{g}/100\text{ml}$). The result was also significant in women, but the levels were generally lower (16.7 and $9.9 \mu\text{g}/100\text{ml}$). Corresponding mean lead-in-air values ranged from 4.6 to $13.25 \mu\text{g}/\text{m}^3$ near to the freeway.

Manton (1973) while attempting to use isotope ratios to identify sources of lead in blood, found that the response time for the isotope ratio in blood to change following a change in the isotope ratio of the lead to which the subject is exposed is of the order of one or two decades, thus implying a substantial reservoir of lead within the body. For this reason, his original objective was unfortunately not achieved, because none of his subjects had been living for long enough in the same place.

Barltrop (1975) studied blood lead levels in children and mothers living in an area with a high natural content of lead (some over 10000 ppm) and found that for children the blood lead levels increased from 20.7 to $29.0 \mu\text{g}/100 \text{ ml}$ between the least and the most heavily contaminated areas. No difference could be found for the mothers, however.

The California Department of Public Health (1967) reviewed investigations of lead in the environment and assessed its relevance to public health. They presented approximate relationships between blood lead level and ambient air concentration, showing a significant effect of air pollution over the commonly-observed range. They also

reviewed lead concentrations in food, examined the particle size spectrum and carried out extensive analysis of blood and urine samples from various populations. They concluded that lead levels in petrol were the most significant source of lead in air and recommended that permissible lead levels in petrol should not be increased and indeed the feasibility of reducing them should be examined. (This was, of course, eventually proven feasible and implemented).

A previous major study reported by Ludwig et al (1965) also covered lead in air and in blood and urine (this provided some of the source material for the California Department of Public Health work). A detailed breakdown of blood lead levels was given for different occupations, which clearly showed that occupations relating to cars carried a high risk (e.g. car drivers, traffic police, garage mechanics, etc.).

Hammond (1976), discussing the results of a follow-up study involving seven U.S. cities, reports that this later work failed to identify any significant correlation between blood lead and lead in air, although he goes on to quote two laboratory studies which indicate about $1.5\mu\text{g}/100\text{ml}$ in blood for every $1.0\mu\text{g}/\text{m}^3$ in air. This figure would appear to be in agreement with the California Department of Public Health data based on environmental exposure.

Beattie et al (1975) found that lead levels in water in the homes of a group of mentally retarded children were higher than in the homes of a matched control group. In some cases the water lead figures were as high as 800ppb (compared with a W.H.O. acceptable limit of 100ppb). Blood lead levels were also significantly higher in the retarded group.

The most important series of researches into the metabolism of lead were those of Kehoe and his co-workers and are summarised in Kehoe's Harben Lectures (Kehoe, 1961). By carrying out careful lead balance observations on a small number of subjects, it was demonstrated that at normal levels of lead ingestion the rate of excretion of lead in faeces and urine closely matches the rate of ingestion. Thus the total body burden remains approximately constant. When, however, an individual subject is caused to ingest lead at abnormally high rates, it is found that this lead balance is disrupted and accumulation within the body occurs. It is found from cadaver studies that this is mostly in the bone structure.

Kehoe reports that in the extensive experience of his team, no cases of lead intoxication have come to light in which the concentration of lead in blood was less than 80 $\mu\text{g}/100\text{ ml}$. This applied both to children and to adults. However, because of the special factors which could theoretically render children more susceptible (see section 3.1.3.9), it is generally held that blood lead levels in children should not be allowed to exceed 40 $\mu\text{g}/100\text{ ml}$ if at all possible. The level of 80 $\mu\text{g}/100\text{ ml}$ has been used for occupational hygiene purposes for many years, and appears to be effective in eliminating lead intoxication in lead-working populations.

This inevitably incomplete review of the literature of environmental lead research has indicated the broad front along which progress is being made. The present work has a specific objective within

this overall picture, namely to examine mechanisms of dispersion of lead in the environment and to study its absorption in the population (particularly in children).

3.2 Survey of Lead in Human Blood and in the
Environment Near Battery Factories

3.2.1 Preface

The work described in this section was carried out with the co-operation of the Boroughs of Swinton and Pendlebury, Prestwich, Whitefield and Barking and of the Chloride Group Ltd. The study consisted of surveys of lead in human blood, dust, soil, air and tap water and the part played by the author in this massive programme was as follows:

- i) Design of the environmental part of the survey, incorporating a number of suggestions by Mr. E. King, whose laboratory undertook the chemical analysis.
- ii) Supervision of sampling by Public Health Inspectors in the boroughs concerned.
- iii) Certain specific investigations such as the one-day study of lead concentrations downwind of the Dagenham factory were carried out under the sole direction of the author.
- iv) Statistical analysis of both human blood and environmental results.

It has been necessary for the sake of completeness to include descriptions of the work of others and in particular Dr. W. J. Elwood of the North-Western Regional Health Authority and Dr. D. Malcolm, consultant to the Chloride Group Ltd., were largely responsible for the design of the blood sampling survey and advice was sought from a number of specialists including notably Mr. E.

King of the National Occupational Hygiene Service Ltd. and Dr. J. F. Taylor of Chloride Group Ltd. The Local Authorities concerned provided the greater part of the manpower required for sampling and visiting blood lead subjects. The description of all this work is entirely in the present author's words.

3.2.2 Introduction

The survey described in this section was primarily designed to show whether or not the blood lead levels of children living near two particular battery factories or whose parents are employed there are significantly higher than those of a suitable control group. Further objectives included a study of adult blood lead levels and an investigation of lead levels in air, soil, dust and tap water, as a means of identifying mechanisms which might transport lead dust from the factories into the home.

The two battery factories are located at Clifton Junction near Manchester and at Barking, Essex near London, and both have lead smelters. The survey at Barking was not as comprehensive as that at Clifton and furthermore due to shortcomings in the techniques used there the Dagenham results are not as dependable as those from Clifton. Unless otherwise stated, results quoted in this section refer to the Clifton survey and Dagenham figures are given only where comparisons between the two factories are concerned. The Dagenham results all agreed qualitatively with those from Clifton but do not carry the same degree of statistical confidence.

Children under five years of age are regarded as being particularly at risk from lead contaminated environments because they are in close proximity to dusty floors and have a tendency to put objects in their mouths which may have become contaminated while on the floor. It is also possible that a high lead intake may be more harmful during the years of the most rapid mental development than it is in adults. The most reliable information available to date on the metabolism of lead (Kehoe, 1961) relates to adults only and the effects in children are largely unknown.

The mothers of each of the survey children were also examined, to see whether these ideas about increased intake rates in children were justified. A problem arose at this juncture because it was accepted that to take venous blood samples from very small children was both impractical and unethical, though perfectly acceptable with adults. The only alternative was to take capillary samples by finger or heel prick, but this method is inherently less reliable than venous sampling because of the danger of contamination by lead on the skin and the difficulty of handling and analysing the very small sample of blood. It was therefore decided to keep a check on the reliability of the capillary (micro) samples by

- (a) taking capillary samples from some of the adults and comparing with the venous samples and,
- (b) making up some micro samples by subdivision of venous samples.

The venous and capillary samples were analysed at two separate laboratories, which will be referred to here as "Lab 'A'" and "Lab 'B'" respectively. Lab 'A' used anodic stripping voltametry for their analysis, checking by dithizone and by atomic absorption methods on a proportion of the samples. Lab 'B' used the Delves Cup method with atomic absorption spectrophotometry (Delves, 1970).

Samples of soil and dust were taken at all points on a grid system extending to two miles distance from the factories along 8 radial directions. The object here was to quantify any fall-off of lead concentrations with distance and to examine the effect of prevailing wind. It was also felt that there might be some correlation with human blood levels. In addition to the grid point measurements, dust samples were taken along transport routes frequently used by factory traffic, and along roads not so used but similar in traffic volume. This was done to establish whether material falling from or swept along by vehicles constituted a significant transport mechanism for lead dust.

While soil samples may be expected to represent accumulations over a period of at least a few months, dust is likely to be of much more recent origin, say a few days old. For this reason individual dust measurements will have considerable scatter and can only be used as a rough guide. Air sampling is indicative only of current levels and is so dependent on the weather that an

*Footnote:

Lab 'A' = National Occupational Hygiene Service Ltd
Lab 'B' = Great Ormond Street Hospital

elaborate analysis involving simultaneous weather monitoring has to be made before the results can be usefully interpreted. In the case of the present survey it was decided to utilise existing National Survey air pollution samplers by analysing the smoke filters for lead content. To examine possible effects near the source three extra samplers of similar design were installed about 800 m away. The full analysis of these results will not be given in this chapter as it merits separate discussion, but for present purposes the results of a much less comprehensive study of downwind lead concentrations in air will be presented.

Tap water samples were taken from a few of the homes of survey subjects. This was done primarily to establish whether there was a difference between lead levels in the drinking water in the vicinity of the Dagenham and Clifton factories.

In a parallel survey, the results of which have been published (Ratcliffe 1975) samples of grasses and mosses from around the Clifton factory were analysed for lead and some of the relevant figures have been included in this section for comparison with the other measurements.

3.2.2.1 Note on units of distance

For administrative reasons it was necessary to organise the reference grid used in lead sampling on the basis of the mile as the distance unit, and therefore miles have been used for reporting distances from the works in this section. Kilometre equivalents are, however, also given in most cases.

3.2.3 Methods used in Human Blood Lead Survey

For each of the two factories groups of test and control subjects were defined as follows:

- i) Children under five years of registered battery factory leadworkers
- ii) A random sample of children under five who are not children of any type of leadworker or battery factory employee and who have lived within one mile (1610 m) of the factory all their lives
- iii) As (ii) but who have always lived more than one mile from the factory
- iv) Three groups consisting of the mothers of subjects in (i), (ii) and (iii) above.

Group (iii) and their mothers were regarded as the 'control' groups, however as they share a geographical boundary (the circle radius one mile (1610 m) from the factory) with one of the test groups the controls should not be taken as representative of background blood lead levels such as one would expect to find many tens of miles away from sources of lead. They are simply a standard for comparison against which the test groups (i) and (ii) are measured.

The registered leadworkers' children were identified by means of a census of employees which asked for names and dates of birth of all children under five years among other administrative information. The response rate to this questionnaire at Clifton was 65% and it is thought likely that many of those who did not respond were older employees who did not have young children and may have felt that there was therefore little point in their completing the form.

The random samples of other children were made by adopting as a sampling frame the Register of Births in the four boroughs concerned, namely Swinton and Pendlebury, Prestwich, Whitefield (all near Clifton) and Barking (including Dagenham). From these sampling frames the following groups were eliminated:

- (i) children who had died
- (ii) children whose families were known to have changed address during the previous five years
- (iii) children of leadworkers or battery factory employees.

In order to achieve a satisfactory number of subjects at all distances the random selection process picked out a higher proportion of the population living nearer than of those further away. The random selection was carried out simply by picking cards at regular intervals from a shuffled deck, each card having one child's name written on it. This was repeated as required until the numbers in the random test and random control groups were about equal to the number of leadworkers' children. The present address and the names of any siblings under five were obtained from Health Visitors' records. Siblings were included partly to increase the numbers of subjects available for certain parts of the analysis (such as laboratory reproducibility) and partly to avoid upsetting the randomly selected children, who might otherwise be frightened at having been singled out for special examination.

The sampling at Clifton was carried out in phases, using successively the Births Registers for 1971, 1970 and 1972, this making possible some interim analyses which indicated whether or not sufficient numbers had been examined to give a significant result. At Dagenham, however, the numbers of children in all groups were much lower and so Births Registers for 1971, 1970, 1972, 1969 and 1973 were all used at once. At Clifton any siblings examined were removed from the sampling frames for subsequent phases of the survey.

The resulting lists of test and control subjects were worked through simultaneously so that each batch of specimens sent to the laboratories would contain a cross-section of different types, there being no means of identification by which the laboratories could tell the type of any individual sample.

Each mother was invited to attend a local clinic for blood sampling, both by introductory letter and by a personal visit from a Public Health Inspector. The degree of co-operation received from mothers in Clifton was very good: the overall response rate among Births Register subjects was 60%, with 49% in the group inside one mile (1610 m) and 70% in the controls. The response of families among the 65% of leadworkers who completed census returns was nearly 100%. In Dagenham the performance was quite poor at 25% overall. Strenuous efforts were made by Health Visitors and others to persuade waverers to come forward for sampling.

It was thought much better to get subjects to the clinics (which were all remote from the factories) rather than sample in the homes because of the risk of contamination when taking samples in an unsuitable place, and so a taxi service was employed for transporting families to and from the clinics.

Public Health Inspectors visited a proportion of the homes to record possible sources of lead (e.g. lead pipes, flaking paint and traffic fumes) and in a small number of cases they took a sample of tap water in the early morning.

From each family the following samples were normally taken:

Mother: 5 ml venous blood, 0.2 ml capillary by fingerprick

Survey child: 0.2 ml capillary by finger or heel prick

Siblings (where relevant): as survey child

Optional samples: replicates of any of the above were taken when the subjects concerned were willing, and these were used as a check on the reproducibility of results. In addition, micro-aliquots of the venous sample were sometimes made and these were put in capillary containers.

As a further check on the laboratory work samples of 'Standard Blood' containing measured amounts of lead (and supplied by the Employment Medical Advisory Service of the Department of Employment) were made up in syringes and capillary tubes identical with those used for the human sampling,

and these were inserted at random among the survey samples sent for analysis.

The numbers of blood samples of various kinds taken during the two surveys are shown in Table 3.2.1.

Note that the Dagenham survey did not include any replicates, and that in the Births Register families some 29% of the children sampled were siblings of randomly selected children. The abbreviations for blood types given in the first column will be used throughout the remainder of this report and in addition 'B.R.' will be used for 'Births Register'.

Each mother was asked to supply information of a general kind about the family and home (e.g. age of house, car ownership, etc.) and in addition records were made of such data as social class (based on employment of head of household), age, sex, location and reason for inclusion in the survey. All of this information was recorded on computer cards along with the results of the laboratory analysis.

Great care was taken to ensure that all samples were properly identified in a way that did not permit the laboratories to know or guess what category of sample they were analysing. The sampling was done in accordance with a pre-arranged detailed programme which specified the number and types of samples to be taken from each subject, and a set of envelopes was prepared, one for each sample, marked with the name of the subject and the sample type. As each sample was taken it was

TABLE 3.2.1 Numbers of Subjects and Blood Samples Giving Useable Results

Type	Clifton				Dagenham	
	No. of subjects	No. of samples	% of total	% of subjects giving replicates	No. of subjects	% of total
Standard Blood (S.B.)	-	124	6.8%	-	30	7.0%
Childrens Blood (C.B.)	465	554	30.4%	19%	141	33.1%
Adult Venous Blood (A.V.B.)	340	407	22.3%	20%	115	27.0%
Adult Capillary Blood (A.C.B.)	341	516	28.3%	51%	112	26.3%
Microaliquots of Venous Blood (MA)	130	222	12.2%	71%	28	6.6%
Totals	1276	1823	100.0%	-	426	100.0%

put in the appropriate envelope and later allocated a serial number by which it would subsequently be identified when sent for analysis. The samples were put in a refrigerator overnight and despatched to the laboratories the next day.

Any blood leads reported over 60 $\mu\text{g}/100\text{ ml}$ (a figure later revised to 50 $\mu\text{g}/100\text{ ml}$) were referred for repeating. If the repeat samples confirmed the first then a letter was sent to the family doctor concerned reporting the results and suggesting that the subject should be referred for clinical investigation. (Note: in the event, only three such cases were found and in none of these was any clinical evidence of ill-health detected).

The technique used in obtaining samples of capillary blood was that established by the Department of Clinical Pathology, Hospital for Sick Children, Great Ormond Street, London, with certain refinements to reduce the chance of contamination. At all stages equipment which could come into contact with the sample (e.g. the lancet, bottle stopper, etc.) were kept covered while not actually in use.

A pilot survey was carried out before any of the sampling for which results are quoted in this paper. This was intended to ensure that the main survey would be free of initial troubles due to lack of familiarity with procedures. The pilot survey revealed that Lab 'A' was giving consistently lower results than Lab 'B'. This applied both to adult capillary and to micro-aliquots when compared against the corresponding venous samples, and so it was not simply due to

contamination of the capillary samples as had been thought possible. Both laboratories gave consistent reproducibility of results where replicate samples were taken, and so it was decided to proceed to the main survey and allow for the consistent difference between the two laboratories at a later stage. The total number of subjects in the pilot survey was 22 and from them some 44 samples in all were obtained.

The statistical analysis of the thousands of individual sampling results obtained during the survey necessitated computer methods. This analysis consisted of two main steps: first a validation stage in which all of the cards were checked for inconsistencies, both within and between data cards; and second, the analysis stage in which such statistical variables as means and standard deviations were computed. Due to the variety of classes into which the samples were divided, this analysis was highly complex. The computer programmes developed for this work are fully described in Appendix II.

3.2.4 Results of Blood Analyses

3.2.4.1 Tests of Adequacy of Sampling and Analytical Procedures

For each sample a computer card was punched giving all available information about the subject including the blood lead result. Codes indicating relationships with other survey subjects in the same family and referring to other samples taken from the same subject were incorporated into each card and a large proportion of the information was

deliberately repeated in an implicit way so that checks on the consistency and compatibility of the data could be made. For example, there was a code indicating whether the subject was a child or an adult, and also another code for age. A computer programme was written to check the data cards for compatibility and this successfully identified a significant number of punching and administrative errors which would otherwise have gone unnoticed. All of these errors proved to be rectifiable as comprehensive hand-written records were kept at all stages. See Appendix II for a description of the computer programmes used.

3.2.4.2 Assessment of Laboratory Performance

Specially prepared 'standard' blood specimens were included in each batch of human blood sent for analysis. These numbered about 7% of the total. The suppliers of the standard blood quoted a value for the lead concentration which was the average of measurements they had made by three different methods. The standard concentration varied between 39 and 110 $\mu\text{g}/100\text{ ml}$ but was supplied in batches of around 20 samples of the same concentration. For each batch an analysis was made of the significance of any differences found between the results of Lab 'A' and Lab 'B' and the quoted standard value. It was found that in most cases there was no statistically significant difference at the 95% confidence level and the agreement was particularly good at the higher lead levels, which were however much higher than those normally found in human blood.

In the following table the standard blood results are summarised:

TABLE 3.2.2 Standard Blood

Batch Number	Quoted Standard Concentration	Lab 'A'			Lab 'B'		
		No.	Mean	S.D.	No.	Mean	S.D.
1	105	3	79.7	25.7	6	119.2	9.1
56	105	2	102.0	1.4	4	92.8	5.3
378	110	15	114.4	11.1	8	121.6	15.3
698	39	11	33.0	3.8	14	39.9	5.7
1023	79	11	78.8	6.2	10	78.4	5.0
1487	46	0	-	-	10	49.3	4.6
1974	108	10	101.1	5.8	20	98.6	7.8

Of these, two by Lab 'A' are significantly lower than the standard value (batches 698 and 1974), while four by Lab 'B' are significantly different from standard with two above (batches 1 and 1487) and two below (batches 56 and 1974). Thus it seems that if the quoted standard is taken as the most reliable measurement, being the average of three different analyses, it would appear that while Lab 'B' is more variable than Lab 'A', it is better calibrated on average. Lab 'A' on the other hand could be reading slightly low on average. It is important to note that only two of the standard blood batches were in the range of human blood results, and for these two it appeared that Lab 'B' was high by 1 to 3 $\mu\text{g}/100\text{ ml}$ and Lab 'A' low by around 6 $\mu\text{g}/100\text{ ml}$. The numbers of samples involved here were too low for the figures to be used with confidence but they do agree fairly well with later analyses of inter-laboratory differences using human blood samples from the survey.

In spite of these discrepancies, the two laboratories appeared to be equally consistent within themselves and this was further confirmed by an analysis of the correlation between replicate samples (i.e pairs of similar samples taken from the same subject.) This indicated correlation coefficients of 0.80 and 0.87 respectively for Lab 'A' and Lab 'B' and standard deviations within samples of 2.9 and 2.8 respectively. In both cases the between samples variance exceeded the within samples variance by a factor of the order of 10, which indicates that the analysis was well capable of giving a reliable measure of the sample variance.

The difference between the two laboratories was first investigated by regression analysis of venous blood results by Lab 'A' and corresponding micro-aliquot samples analysed by Lab 'B'. This yielded the following best-fit relationship between the two analyses:

Result 'B' (micro-aliquot) = $6.9 + 0.97x$ (Result 'A' (venous))

All units for blood lead are of course $\mu\text{g}/100\text{ml}$. This regression had a very high degree of statistical significance (99.9% confidence) and the correlation coefficient between 'A' and 'B' was found to be 0.96. The mean difference between the pairs of samples was 6.0; note that this is slightly less than the intercept of the regression relation because the calculation of mean difference assumes in effect that the slope of the regression line is unity. The implication of these results is that Lab 'B' gives results that are 6 to 7 $\mu\text{g}/100\text{ml}$ higher than those of Lab 'A'. This must be borne in mind when considering any of the absolute values quoted for human blood elsewhere in this report.

Questions arose as to the possible effects of the use of different sample containers on this comparison and so a further analysis was made using micro-aliquot analyses made by Lab 'A' compared against the same laboratory's venous results. These micro-aliquots were not originally intended to be used in the analysis of the main survey results, but they proved useful in this instance because the only difference between them and the venous samples lay in the container and in the techniques for extracting the aliquot sample. It was found as expected that there was a very pronounced correlation between these pairs of samples (coefficient = 0.84) and the mean difference was found to be 2.7 $\mu\text{g}/100\text{ml}$ (micro-aliquots high, significant at 99.9% level). By comparing the 'A' micro-aliquots with the corresponding 'B' micro-aliquots it was possible to make a direct assessment of laboratory difference and this yielded a mean difference of 3.4 $\mu\text{g}/100\text{ml}$ (Lab 'B' high, significant at 99.9% level), again with a high degree of correlation (coefficient = 0.76). Thus the total mean difference of 6.0 is accounted for in approximately equal shares by laboratory analytical differences on the one hand and by container and aliquot handling differences on the other.

A further analysis of the inter-laboratory differences revealed that the difference declined in magnitude during the course of the survey. Most of this change appears to have occurred between the first and second of the three phases into which the survey was divided for administrative reasons. The following table gives the relevant details:

Table 3.2.3

AVERAGES OF RANDOMLY-SELECTED ADULT BLOOD RESULTS

PHASE OF SURVEY	LAB 'A' VENOUS BLOOD	LAB 'B' MICRO-ALIQUOT	DIFFERENCE
I	14.3	22.2	7.9
II	13.3	18.0	4.7
III	13.2	17.6	4.4

It is clear from this that the greater part of the change between Phases I and II is accounted for by the change in Lab 'B', however Lab 'A' also recorded a fall, which suggests that the population mean may have dropped. A further possibility is a change in specification of the microsample containers or in the technique for extracting the aliquot. At present these possibilities are not resolved and they may well prove impossible to resolve. No attempt has been made to "correct" the main survey results to allow for these features of the analytical methods, as it was felt that this could be misleading, especially on the sensitive issue of the absolute magnitude of the human blood results. Instead, the reader is left to make his own assessment of the results in the light of all the known facts about the sampling and laboratory work.

3.2.4.3 Physiological effects on blood lead level

An investigation was made into the differences between venous and capillary blood in adult subjects. The purpose of this, apart from its fundamental interest, was to facilitate discrimination between behavioural and physiological effects on any differences that might be found between adults and children. This was necessitated because it had been decided that venous samples could not be taken from children; adult samples were however to be venous ones at these were thought likely to be more reliable because of greater volume. The comparison for physiological differences was made by looking at results by Lab 'B' only on micro-aliquots of venous blood and on capillary blood taken from the same subject. This analysis revealed a mean difference of $1.6 \mu\text{g}/100\text{ml}$ (capillary high, significant at 99.9% level) and a correlation coefficient between pairs of samples of 0.79. A part or all of this difference could be due to differences in handling technique between the two types of sample; it might be expected that in spite of the elaborate precautions taken the capillary samples would be more easily contaminated. The effect is certainly small in any event and for the purposes of reviewing the later results of the survey the actual cause of this difference is not important.

3.2.4.4 Results of Human Blood Lead measurements

The total numbers of subjects and samples (including replicates) used in the Clifton survey are given in the following table:

Table 3.2.4 NUMBERS OF SUBJECTS AND SAMPLES

SPECIMEN TYPE	No. OF SUBJECTS	No. OF USEABLE SAMPLES
Standard Blood (SB)	-	124
Children's Blood (CB)	465	554
Adult Venous Blood (AVB)	340	407
Adult Capillary (ACB)	340	516
Adult Micro-Aliquots (MA)	340	222
Others (volunteers etc.)	14	0

In this context, useable samples means those not in the following categories: repeat samples (generally taken if the first was high); clotted samples; micro-samples analysed by Lab 'A'; and any result over 100 $\mu\text{g}/100\text{ml}$. The exclusion of the last category was arbitrary but justified by the fact that only 4 such cases arose and in each of these a repeat sample gave a normal result.

All subjects were initially classified into four basic groups, namely (i) Chloride "High Risk", (ii) Chloride "Low Risk", (iii) Births Register living within one mile (1610 m) of the factory and (iv) Births Register living outside one mile.

The last group was treated as a control group although in fact it is possible that they are not far enough away from the works to be strictly representative of the population background. This compromise was necessary because of serious administrative complications and expense that would otherwise have been incurred. The B.R. children were further subdivided into groups containing only the randomly selected children and groups containing the siblings of those children. It was subsequently found that there was no detectable difference between these two subdivisions and on reflection it was decided to treat them together in the final presentation of the results. Table 3.2.5 summarises the results for childrens' blood.

Table 3.2.5.
RESULTS FOR CHILDRENS' BLOOD

	Chloride Employees' Children						Births Register Children					
AGE	HIGH RISK			LOW RISK			< 1 MILE			> 1 MILE		
	No	Mean	S.D.	No	Mean	S.D.	No	Mean	S.D.	No	Mean	S.D.
0	5	24.2	12.1	5	26.0	9.7	7	25.0	14.7	11	19.7	9.7
1	6	33.8	13.6	14	33.4	9.9	18	26.3	5.4	20	31.2	9.2
2	35	32.6	9.5	38	34.2	8.7	37	27.8	6.6	70	28.1	8.8
3	28	35.6	8.8	35	34.2	6.3	27	27.0	6.2	43	23.2	6.4
4	12	32.0	7.1	14	30.1	4.9	14	29.0	5.9	26	28.3	7.9
all	86	33.1	9.6	106	33.1	7.9	103	27.3	6.9	170	26.7	8.7

It should be noted that the inclusion of siblings could slightly bias the sample because (a) the number of children in a family might be correlated with the degree of lead contamination in the home through some common causative factor and (b) families which agreed to have siblings sampled as well as the random child might be the more hygiene-conscious ones. Point (a) does not seem very likely and would presumably result in larger families having higher blood leads if the popular theory that affluence leads to smaller families is correct. This would make the siblings' results higher than the random ones but in fact they are marginally lower though not significantly so. Thus point (a) does not seem to be important. On point (b) mothers were not told who was the randomly selected child and who the sibling, lest this should lead to misunderstandings. As there is in any case no significant difference between the random and sibling children the argument for amalgamating the two groups seems very strong.

An analysis was made of the significance of the differences between means in this table, using the untransformed data (the use of the log-transform is discussed later). This showed that there was no detectable difference between High Risk and Low Risk subjects at any age, but there was apparently a significant difference between 'near' and 'far' B.R. subjects at age 3 years. This point did cause some concern at first, however it is thought that the result is spurious because the 'far' result at age 3 is exceptionally low and does not match at all the other 'far' results. The 'near' result at this age is no higher than at ages 2 and 4 and so it is not likely that this significant result is due to an effect of the factory.

The main feature of the table is the unquestionable difference between Chloride and B.R. groups at ages 2 and 3. To look more closely at this the High and Low Risk groups were merged, as were the 'near' and 'far' groups. The next table gives the results:

Table 3.2.6.

RESULTS FOR CHILDRENS' BLOOD

Age	Chloride			B.R.			Difference of means	Significance
	No.	Mean	S.D.	No.	Mean	S.D.		
0	10	25.1	11.0	18	21.8	11.8	3.3	not sig
1	20	33.5	11.1	38	28.9	7.6	4.6	not sig,
2	73	33.4	9.1	107	28.0	8.1	5.4	SIG at 99.9%
3	63	34.8	7.5	70	24.7	6.3	10.1	SIG at 99.9%
4	26	31.0	6.0	40	28.6	7.3	2.4	not sig
all	192	33.1	8.6	273	27.0	7.8	6.1	SIG at 99.9%

Note here that the lack of significance at age 1 is largely due to the small numbers of subjects and large variances, while at age 4 it is due to the small difference between the means. It appears that age 3 is the most critical, for the Chloride children have maximum blood lead levels then and also the difference between them and the B.R. children is greatest (but remember the anomalous low result for 'far' B.R. children at age 3).

Turning now to the results for adult venous blood taken from the mothers, it was found that as for children there were no significant differences between High Risk and Low Risk Chloride categories, nor between 'near' and 'far' B.R. categories. Furthermore, in contrast to the case of the children, there was no significant difference between Chloride and B.R. subjects. The following table summarizes these results:

Table 3.2.7
RESULTS FOR ADULTS

SUBJECT CATEGORY	NUMBER	MEAN	S.D.
Chloride Mothers (High Risk)	65	15.4	6.7
Chloride Mothers (Low Risk)	82	14.6	4.9
B.R. Mothers (near)	71	13.9	4.6
B.R. Mothers (far)	122	14.7	6.1

The above analysis of the gross effects of the battery factory on the local population and on leadworkers' families has, therefore, revealed only one significant effect, namely an increase of about 5 to 10 $\mu\text{g}/100\text{ ml}$ in children aged 2 or 3 years having a parent who is a leadworker at the battery factory. No effects on mothers could be detected, nor was there any consistent difference in mean blood lead levels between randomly selected populations living within and outside the one-mile circle.

3.2.4.5 Frequency Distribution of Human Blood Lead Levels

It has been noted above that the significance tests reported above were carried out on the untransformed data. The test used was Student's 't' test, which assumes that the probability distributions of the tested variables are normal. In the case of blood lead measurements this cannot be strictly true because they cannot take negative values whereas the normal distribution would imply a finite probability of negative values. It is found that concentrations of pollutants in the environment often have a lognormal distribution (i.e. the logarithm is distributed normally) because they are generally the result of diluting processes which have a dividing rather than subtracting effect on the concentration. The blood lead results were, therefore, examined to see whether they would fit a lognormal distribution. Figures 3.2.1, 3.2.2, 3.2.3 and 3.2.4 show the cumulative frequency distributions for Chloride and B.R. children and adults plotted on linear-probability and log-probability paper respectively. Ignoring the extremities of the plots (which are unreliable

because they depend on one or two isolated results) we can see that the results plot as a straight line on log-probability paper, but have a definite curvature on the linear-probability paper; this confirms that the distributions are indeed lognormal. It follows therefore that the significance tests should be carried out on the logarithms of the results rather than on the untransformed data. This has been done for all the human blood results and produced significant results in exactly the same cases as reported above. It appears, therefore, that the use of untransformed data does not lead to any appreciable error in this case.

The following table lists the geometric means for children and adults:

Table 3.2.8 Geometric means for human blood

Subject	Chloride		B.R.	
	Number	Geometric Mean	Number	Geometric Mean
CHILDREN				
age 0	10	23.3	18	19.5
age 1	20	32.1	38	28.0
age 2	73	32.3	107	26.9
age 3	63	34.1	70	23.9
age 4	26	30.4	40	27.7
all ages	192	32.1	273	25.7
ADULTS	147	14.0	193	13.5

These figures are quoted to facilitate comparison with other reported results. The geometric means, being the antilogs of the mean logarithm, are more appropriate for lognormal variables than arithmetic means.

It is often of interest to know the percentages of subjects whose blood lead falls in various ranges and for this purpose Figures 3.2.5 and 3.2.6 have been prepared in which the data has been grouped in ranges with a width of 5 $\mu\text{g}/100\text{ ml}$. The laboratory reports were to the nearest whole $\mu\text{g}/100\text{ ml}$ and so the range shown as, say, between 10 and 15 on the abscissae actually corresponds to reported results between 11 and 15 inclusive; a result of 10 would be counted in the next lower range. The lognormality of the distribution is reflected in the skewness of these distributions.

It is interesting to note that in adults results of 15 and 16 $\mu\text{g}/100\text{ ml}$ were reported abnormally rarely, while results of 17 and 18 were surprisingly common. That this is a feature of both Chloride and B.R. results suggests some kind of systematic error which has not as yet been identified. This oddity actually results in the mean values occurring relatively infrequently!

The following table, derived from these figures, gives the percentages of children with blood lead results (Lab 'B') over 40 $\mu\text{g}/100\text{ ml}$:

Table 3.2.9 Frequency of childrens' blood over
40 μ g/100 ml

Age	Chloride	B.R.
0	10% approx	11% approx
1	15% approx	5%
2	19%	6%
3	19%	1%
4	8% approx	8%
all	17%	5%

As might be expected, there are marked differences between Chloride and B.R. subjects, with ages 2 and 3 again standing out. Examination of frequency of high values will tend to emphasise differences between populations because of the shape of the probability distributions near the extremes, and this is why these rates are much more sharply differentiated than the mean values quoted earlier. It must be remembered that the figures given are based on measurements by Lab 'B', which consistently give high results compared with Lab 'A'. Thus while the frequencies in this table may be compared with each other they cannot straightforwardly be compared with the results of other surveys using different laboratories or sampling techniques.

3.2.5 Analysis of correlations between blood lead results and possible causative factors

3.2.5.1 Study of very young children

In view of the results in Table 3.2.6, which indicate that very young children (aged 0 years) have low blood lead levels, it was decided to look at the relationship between blood lead and age in months up to one year. Figure 3.2.7 shows all of the individual results, 28 in number. Unfortunately, the number of subjects is insufficient for a conclusive statement, however the data is consistent with the supposition that lead levels are low at birth and rise to a fairly constant level after one year or thereabouts. None of the eight children under 5 months had a blood lead level over 30 $\mu\text{g}/100\text{ ml}$, whereas a glance at Figure 3.2.5 will show that in both B.R. and Chloride children of all ages under 5 years such levels are commonplace.

3.2.5.2 Differences between sexes

The following table shows results for children classified by sex:

Table 3.2.10

Sample	Sex	No.	Mean	S.D.
B.R.	M	140	28.1	8.7
B.R.	F	133	25.7	7.2
Chlor.	M	97	33.0	9.2
Chlor.	F	98	33.0	8.2

For B.R. children the difference of $2.5 \mu\text{g}/100 \text{ ml}$ is significant at the 97.5% level, but for Chloride children there is no significant difference, in spite of adequately large numbers. It is not easy to explain the difference between B.R. and Chloride children in this respect. The implication is that the 'Chloride effect' is greater in girls than in boys, while paradoxically in B.R. subjects boys have higher results. This could imply that the means by which Chloride lead enters the body is different from general lead, or it could imply that the relationship between blood lead and lead intake is very nonlinear, so that in Chloride children the intake of Chloride lead swamps all other lead intakes, while only increasing blood lead by about 20%.

3.2.5.3 Classification by social class

The following tables give the results for all subjects classified by social class. The figures in the 'Social Class' columns are as punched on the data cards and have the meanings given below:

1 social class I	; 2 social class II
3A social class III non-manual;	3B social class III manual
4 social class IV	; 5 social class V
6 student	; 7 housewife
8 unemployed	;

Table 3.2.11 Classification by social class

	CHILDREN					
	Births Register			Chloride		
Social Class	No. of subjects	Mean	Confidence level (if significant)	No. of subjects	Mean	Confidence level (if significant)
1	12	25.8	not sig	0	-	-
2	34	26.7	not sig	0	-	-
3A	35	27.9	not sig	0	-	-
3B	108	27.5	not sig	0	-	-
4	65	26.8	not sig	193	33.0	not sig
5	4	24.3	not sig	0	-	-
6	0	-	-	0	-	-
7	0	-	-	0	-	-
8	7	24.4	not sig	2	37.0	not sig
all	265	27.1	-	195	33.0	-

	ADULTS					
	Births Register			Chloride		
Social Class	No. of subjects	Mean	Confidence level (if significant)	No. of subjects	Mean	Confidence level (if significant)
1	10	13.6	not sig	0	-	-
2	25	13.5	not sig	0	-	-
3A	25	16.6	not sig	0	-	-
3B	75	14.0	not sig	0	-	-
4	47	14.7	not sig	146	14.7	not sig
5	2	13.3	not sig	0	-	-
6	0	-	-	0	-	-
7	0	-	-	0	-	-
8	4	15.8	not sig	1	48	not sig
all	188	14.5	-	147	14.9	-

Note that in the above tables, the significance tests were between each social class and the averages for all social classes. None of the social classes showed any significant difference from the average. It is notable that the Chloride families are almost all from class 4 while the B.R. ones are drawn from a wide range of classes. This mismatch between the control and test groups might be thought to invalidate the comparison, however the lack of any statistically significant effect of social class on the B.R. results indicates that this does not matter. In particular, class 4 of the B.R. results is well in line with the average of all B.R. subjects. If class 4 alone be taken as the control there is a difference of $6.2 \mu\text{g}/100 \text{ ml}$ between Chloride and B.R. children and this is significant at the 99% level.

3.2.5.4 Effect of specific lead hazards

Lead hazards other than having a leadworker in the family were assessed by a Public Health Inspector on his visit to each home. The presence of a lead hazard was coded on the data cards as follows:

0 no lead hazard	; 1 lead water pipes
2 flaking paint	; 3 traffic
4 other	; 5 more than one of the above hazards

The following tables give the blood lead results for all subjects classified under these six headings:

Table 3.2.12 Correlation with presence of lead hazards

	CHILDREN					
	Births Register			Chloride		
Hazard	No. of subjects	Mean	Confidence level (if significant)	No. of subjects	Mean	Confidence level (if significant)
0	85	25.6	-	13	39.1	-
1	40	29.8	99.5%	5	35.3	not sig
2	2	27.0	not sig	0	-	-
3	44	27.7	not sig	4	37.8	not sig
4	0	-	-	0	-	-
5	33	28.1	not sig	11	36.6	not sig
all (except haz=0)	119	28.5	97.5%	20	36.5	not sig
all	204	27.3	-	33	37.5	-

Table 3.2.12 (continued)

	ADULTS					
	Births Register			Chloride		
Hazard	No. of Subjects	Mean	Confidence level (if significant)	No. of Subjects	Mean	Confidence level (if significant)
0	60	13.8	-	9	14.2	-
1	28	14.1	not sig	4	14.1	not sig
2	1	13.0	not sig	0	-	-
3	33	14.0	not sig	2	11.5	not sig
4	0	-	-	0	-	-
5	23	16.7	97.5%	6	17.9	not sig
all (except haz=0)	85	14.7	not sig	12	15.6	not sig
all	145	14.3	-	21	15.0	not sig

From these tables, the following points should be noted:

- (i) the marked effect of lead pipes in B.R. children, which is not evident in the much smaller sample of Chloride children;
- (ii) in general the lack of significance in the Chloride children is due to the small number of Chloride homes which were reported on by P.H.I., thus we cannot conclude that these children are not also affected by (e.g.) lead pipes;
- (iii) in adults no significant effect is found unless more than one hazard is present, but children under more than one hazard are not affected.

3.2.5.5 Effect of Car Ownership

One of the questions asked of all mothers sampled in the survey was whether or not the family owned a car. The blood lead levels for groups with and without a car were examined and the following table lists the results:

Table 3.2.13 Effect of Car Ownership

	Children				Adults			
	B.R.		Chloride		B.R.		Chloride	
	No	Mean	No	Mean	No	Mean	No	Mean
No car	90	24.8	77	34.3	59	13.7	56	15.8
+ car	182	28.0	114	32.1	133	14.7	88	14.3
Sig?	yes at 99.5%		no		no		no	

As before, B.R. children seem to be the more sensitive to the hypothetical effect. Here we see that the ownership of a car apparently raises blood lead levels by over 3 $\mu\text{g}/100\text{ml}$ in this category. The numbers of Chloride children were sufficient in this case to have detected a difference between the means of 2.4 $\mu\text{g}/100\text{ml}$, but this was not in fact found, the actual different being 2.2 (but in the opposite direction, i.e. 'no car' high).

3.2.5.6 Detailed Analysis of Effect of Distance and Direction from the Factory

This is a complex question because distance and direction are mutually correlated due to the very non-uniform distribution of housing density around the works. Thus it may be meaningless to assess the effect of distance alone because particular distances will tend to be associated with particular directions. Furthermore, the spatial distributions for B.R. and Chloride families are quite different, presumably because the employees prefer not to live too close to their work. For example, only 17 Chloride families live within one mile, as against 71 B.R. ones. Table 3.2.14, which follows, gives detailed results for all groups.

Table 3.2.14(a) B.R. CHILDREN

N.B. Figures underlined are averages for 10 or more subjects.

Key:

number
mean $\mu\text{g}/100\text{ml}$

Dir Dist	North 1	2	East 3	4	South 5	6	West 7	8	All	Sig. difference from Average?
1	0	0	0	0	1 34.0	1 27.5	2 27.5	0	4 29.1	no
2	0	0	0	0	13 <u>33.4</u>	14 <u>24.6</u>	13 <u>27.9</u>	0	40 <u>28.6</u>	no
3	0	0	18 <u>27.1</u>	0	1 20.0	18 <u>27.3</u>	22 <u>25.2</u>	0	59 <u>26.3</u>	no
4	6 25.3	12 <u>26.3</u>	28 <u>29.0</u>	3 27.7	22 <u>23.7</u>	37 <u>24.9</u>	11 <u>28.0</u>	0	119 <u>26.1</u>	no
5	4 24.0	25 <u>26.2</u>	7 36.1	0	0	12 <u>30.2</u>	0	0	48 <u>28.5</u>	no
6	0	3 21.7	0	0	0	0	0	0	3 21.7	no
all	10 <u>24.8</u>	40 <u>25.9</u>	53 <u>29.3</u>	3 27.7	37 <u>27.3</u>	82 <u>26.2</u>	48 <u>26.7</u>	0	273 <u>26.9</u>	-
sig?	no	no	yes, 95%	no	no	no	no	-	-	

Table 3.2.14(d)

CHLORIDE ADULTS

Dir Dist	North 1	2	East 3	4	South 5	6	West 7	8	all	sig. diff. from avge?
1	0	0	0	0	2 21.5	1 9.0	1 18.0	0	4 17.5	- no
2	0	0	0	0	0	4 9.4	2 11.5	0	6 10.1	no
3	0	0	0	0	0	5 16.6	2 9.0	0	7 14.4	no
4	0	1 18.0	1 17.0	0	7 16.4	29 <u>15.2</u>	6 13.0	4 13.4	48 <u>15.1</u>	no
5	1 13.0	0	0	0	1 17.0	4 12.8	0	0	6 13.5	no
6	0	0	2 14.0	5 11.0	1 13.0	0	22 <u>17.4</u>	46 <u>14.8</u>	76 <u>15.3</u>	no
all	1 13.0	1 18.0	3 15.0	5 11.0	11 <u>17.1</u>	43 <u>14.5</u>	33 <u>15.8</u>	50 <u>14.7</u>	147 <u>14.9</u>	-
sig?	no	no	no	no	no	no	no	no	-	

It is difficult to draw clear conclusions from these results because the numbers of subjects in some locations are very small. Considering first the averaged results for each distance separately and each direction separately we observe immediately that there is no detectable effect of distance. Thus the significant results for random subjects in the two directions E and NE are not confused by coupling between distance and direction. It appears, therefore, that children in the east have markedly higher blood lead levels than the average, while adults in the northeast have low ones. Unfortunately, the complementary groups (i.e. northeast children and east adults, and all Chloride subjects) do not confirm this picture so these results must be regarded as questionable. Especially perplexing is the fact that in the east children are high but adults are low; these results cannot be explained simply in terms of wind direction. Another point is that out of so many significance tests it is quite likely that one or two would appear significant even if the data were totally random. In all, these tests have not demonstrated any effect of the factory on the spatial distribution of blood lead levels.

Taking the results for each distance/direction location we again find no patterns which are consistent over all four groups of subjects, however, at location 45 both Chloride and B.R. children are low, while at location 25 B.R. children and adults are high. As will be seen later, there is a high degree of correlation between blood leads from different subjects in the same family.

The data indicate that fears of high blood lead levels being found within the first $\frac{1}{4}$ mile are without foundation and, furthermore, that people living in the prevailing wind directions do not in general have higher blood leads, though the evidence on this last point is conflicting. The effect of direction, if any, is certainly far less than the effect of having a Chloride employee in the family.

3.2.5.7 Regression analyses of associations between blood lead and other factors

Simple bivariate regression analyses have been made taking blood lead as 'dependent' variable and considering in turn the following factors: age, length of residence, age of house, rateable value of house, distance and direction from the works, length of time for which there had been a leadworker in the family. The use of the word 'dependent' above should not be taken to imply a cause and effect relationship although this may in some cases be the reason for finding a significant correlation.

Children and adults were considered separately in most cases, but in the correlation with age they were also taken together, using the capillary samples from the adults. Some of these regressions yielded significant relationships, but in many of these cases a cubic polynomial was required in order to fit the data, the measure of fit being that the variance due to the highest order term is significantly larger than the residual variance of the measured values about the fitted line, using the F-test. The results are given in Table 3.2.15.

Table 3.2.15 Regression Relationships

Blood Cate- gory	Random or Chloride?	'inde- pendent' vari- able(=x)	Correl- ation Coeff.	Best-fit relation	Confidence Level
CB	R	age	0.26	$21.6 + 14.9x - 8.48x^2 + 1.30x^3$	99%
CB	C	age	0.22	$27.5 + 4.9x - .921x^2$	99%
AVB	R	age	< .1	not sig	
AVB	C	age	0.22	$49.3 - 2.64x + .0610x^2 - .000386x^3$	95%
ACB	R	age	< .12	not sig	
ACB	C	age	0.15	not sig	
CB & ACB	R	age	0.31	$27.3 - .178x$	> 99%
CB & ACB	C	age	0.49	$34.0 - .439x + .0033x^2$	>> 99%
CB	R	length of res.	0.22	$33.3 - 1.91x + .124x^2 - .00212x^3$	95%
CB	C	length of res.	< .1	not sig	
AVB	R	length of res.	< .16	not sig	
AVB	C	length of res.	0.25	$17.2 - 1.21x + .114x^2 - .00233x^3$	99%
CB	R	age of house	0.18	$25.8 + .0622x$	99%
CB	C	age of house	0.11	not sig	
AVB	R	age of house	0.19	$12.4 + .0364x$	95%
AVB	C	age of house	0.33	$12.7 + .0654x$	99%
CB	R	R.V.	< .19	not sig	
CB	C	R.V.	0.27	not sig	
AVB	R	R.V.	0.27	$.157 + .238x - .00118x^2 + .00000172x^3$	95%
AVB	C	R.V.	0.39	not sig	
CB	R	distance	0.1	not sig	
CB	C	distance	0.13	not sig	
AVB	R	distance	0.15	$6.73 + 4.67x - .654x^2$	95%

Table 3.2.15 cont.

Blood Cate- gory	Random or Chloride?	'inde- pendent' vari- able(=x)	Correl- ation Coeff.	Best-fit relation	Confidence Level
AVB	C	distance	0.19	not sig	
CB	R	direction	0.1	not sig	
CB	C	direction	0.19	$25.1+1.20x$	99%
AVB	R	direction	0.25	$16.1-4.53x+1.64x^2$ $-.149x^3$	95%
AVB	C	direction	0.06	not sig	
CB	C	time lead- worker in	0.11	not sig	
AVB	C	family	0.02	not sig	

Of these, the significant relationships for random subjects are plotted in Figure 3.2.27 and for Chloride subjects in Figure 3.2.28. In addition, by way of example, the original data for the effects of age and age of house on Random subjects are plotted with the (linear) regression lines in Figures 3.2.8 and 3.2.9.

It is instructive to compare some of these figures. It appears that while there is no consistent trend with age in the adults, the trend taking capillary samples from children and adults together is significant and consistent. Figure 3.2.10 shows the regression for Chloride and Random subjects on the same graph. It confirms that the differences are much greater in children than in adults, and also that children have generally higher blood leads than their parents. The following table summarises the effect of age by classifying the subjects as adults and under-fives (girls only):

Table 3.2.16 Effect of age

Subjects	Number	Mean ($\mu\text{g}/100\text{ml}$)	difference	confidence level
B.R.girls	133	25.7	3.8	>99%
B.R. mothers	193	21.9		
Chloride girls	98	33.0	9.4	>>99%
Chloride mothers	148	23.6		

These figures are for capillary blood only, analysed by Lab 'B'. Thus, it would appear that B.R. girls have lead levels about $4 \mu\text{g}/100 \text{ ml}$ higher than their mothers and that if in addition there is a Chloride leadworker in the family the blood lead will be higher again by about $7 \mu\text{g}/100 \text{ ml}$.

Taking Chloride and Random results together, there seems to be no consistent effect of length of residence on children or adults, but in B.R. children age of house matters to the extent of $6 \mu\text{g}/100 \text{ ml}$ for a 100 year old house compared against a new one. The relationship for Chloride children is, however, not significant. In both groups of adults, age of house is significantly correlated and Lab 'A' AVB results are increased by $4-6 \mu\text{g}/100 \text{ ml}$ for a 100 year old house.

Rateable value is not correlated with blood lead except in the one case of B.R. AVB results, but here a cubic polynomial had to be invoked to effect the fit. This lack of correlation supports previous findings which indicated no relationship with social class. The length of time a leadworker had been in the house was also not correlated with blood lead.

3.2.5.8 Correlation of blood lead within families

It was noticeable throughout the survey that blood lead levels were well correlated between subjects in the same family. Correlation coefficients for results from pairs of siblings and mother/child pairs are given in this table:

Table 3.2.17 Correlation of blood lead within families

	Correlation coefficients	Significance
Chloride sibling pairs	0.80	99%
B.R. sibling pairs	0.79	99%
B.R. mothers/children	0.15	95%

3.2.5.9 Summary of magnitudes of possible effects on blood lead

Whilst there are still a few contradictions in the data, it is, nevertheless, possible to give some upper limits to the possible effects of various factors on blood lead level when each factor acts alone. The following table summarises this:

Table 3.2.18

Supposed cause	magnitude of effect (maximum)	comments
Physiological difference between sexes	2.4. $\mu\text{g}/100 \text{ ml}$	males high
lead pipes	4.2	
car ownership	3.2	
direction from Chloride	2.4	conflicting evidence
age of subject	3.8	children high
age of house	6.0 per 100 years	
Chloride lead-worker in family	6-7	

Note that the figure for Chloride families is a well established one which seems to be common to all subdivisions of childrens' groups, while the other figures are maxima and some subdivisions may show lower results. This table should, however, be a reasonable guide to the relative magnitude of the supposed effects. Note that saturation effects may result in lower levels when two or more effects act simultaneously.

One noteworthy feature of the results is that in several cases a significant result in B.R. children is not repeated in the Chloride results, even though the numbers of subjects may have been adequate. Examples can be found in the effects of sex, car ownership, age and age of house. This suggests that the effects are not additive to the effects of being a Chloride child.

Lead intake by ingestion or inspiration must clearly be strictly additive as regards different sources of lead, so what is suggested is that blood lead does not follow lead intake linearly; if it did, the effects would be additive. A possible interpretation, which is advanced tentatively as it is only based on mathematical observations incorporating several assumptions, is that in Chloride children the intake of Chloride lead dominates all other intakes, so that the latter do not have a significant effect. Because of the non-linear relation between blood and intake lead this only increases blood leads by about 20% ($6 \mu\text{g}/100 \text{ ml}$). This hypothesis needs checking against physiological work.

3.2.6 Sampling of lead in the Environment

3.2.6.1 Air Sampling Methods and Results

It was recognised from the start that the concentration of lead dust in air at any given point would be very strongly dependent on the weather and so no experiment of short duration could possibly give meaningful average values. An anemograph was therefore set up on the roof of one of the Clifton factory buildings so that the lead concentrations observed could be related to the local wind speed and direction. This factory is in a fairly deep valley and so the local winds are not always the same as those at the nearest Meteorological Office stations (e.g. Manchester Weather Centre or Ringway Airport), and so the estimation of long term average concentrations involves correlating the local winds with winds at stations for which long records are available and this complex calculation will be the subject of a separate section (3.3).

Apart from the measurement by fixed air samplers at Clifton, mentioned earlier, two further studies of lead-in-air concentrations were made at Dagenham, and these are reported here. The first was carried out by selecting from the meteorological records from the London Weather Centre days on which the wind was constantly blowing either along or across two lines of National Survey of Air Pollution air samplers which lie to the north and west of the factory. The air samples, consisting of filter papers through which a known quantity of ambient air had been drawn, were analysed by Lab 'A' using the monocolour dithizone method for total lead content. Each filter was exposed for 24 hours.

Figure 3.2.11 shows the positions of the sampling sites and the factory. It was fortunate that so many of the National Survey sites happened to lie roughly along radial lines from the works. Figure 3.2.12 shows lead concentration plotted against position in northerly and

southerly winds. Note that site 3 actually lies some way off the north-south line through the factory and is included for comparison as it should be unaffected by the battery works emissions. The straight line interpolation between points is simply for clarity and is not to be taken as an estimate of concentrations at intermediate points. Figure 3.2.13 is similar to figure 3.2.12 but for east and west winds, and in this case it is site 4 that is to one side of the line and indicates the background.

The most notable feature of figures 3.2.12 and 3.2.13 is the apparent uniformity of lead concentrations at all sites. The values observed vary considerably from day to day but not from place to place. From the north wind results it is especially clear that lead levels upwind of the factory are much the same as those downwind. There is no consistent increase of concentration close to the works. Even in southerly winds, the upstream lead levels are as high as elsewhere, and this is especially surprising because the air has arrived from over the Thames estuary and one would have expected fallout of particles and capture at the water surface to have cleansed the air. It would appear therefore that the lead observed is in very fine particulate form which does not settle quickly, and moreover the source must be widespread. This evidence suggests that traffic exhaust may be responsible. The day-to-day variations are probably due to the weather, in particular to the height of the lowest inversion, which traps low level pollution below it.

An inventory of known lead emissions at the two works is available and the break-down between high level (i.e. tall chimney) emissions and low level ones (e.g. ventilator exhausts) is as follows:

Table 3.2.19 - Emissions of Lead to Air

Dagenham	High level (18.9m chimney)	35.5	
	Low level	92.2	
	Total	127.7kg Pb per week of 168 hours	
Clifton	High level (i) (47m chimney)	172.5	
	High level (ii) (37m chimney)	33.1	
	Low level (incomplete information)	80.8 +	
	Total	286.4 + kg per week	

The low level sources are considered to be all those which do not have chimneys at least $1\frac{1}{2}$ times the nearest building height; the probable true total of low level emissions at Clifton is much greater than that shown because many of the exhausts had not been measured and blow-off from the scrap pile is likely to be greater as it is larger than at Dagenham and rather more exposed to the wind. A simple dispersion model based on conventional (Briggs 1969) plume rise formulae and Gaussian dispersion (Pasquill 1974) has been applied to these emissions data and shows clearly that as far as ground level concentrations are concerned the effects of high level sources, which give their maximum concentrations some distance from the chimney, are completely overshadowed by the effects of low level sources. The net effect is that the concentration decreases monotonically with distance.

The second investigation made use of a number of Casella portable air samplers which were set out for an 8-hour period along a radial line downwind of the factory. A portable 'Porton' anemograph was also installed to provide a continuous check on wind direction and strength. The Casella samplers employ a filter principle similar to that of the National Survey

instruments already described and are in regular use monitoring the lead-in-air concentrations to which leadworkers are exposed. They were calibrated for flow rate before and after the experiment, and this revealed that in one case the battery was becoming discharged towards the end of the experiment, however the error was not large and could be allowed for because the total volume drawn in is proportional to a counter reading on the instrument. Provided that the air quality did not change much in the last part of the experiment this correction will be accurate, and the wind records support this contention. The counter readings were checked throughout the experiment and proved to be proportional to time for the remaining six samplers, indicating a satisfactory constant sampling rate.

The wind direction records yielded the frequency rose shown in Figure 3.2.14 for the sampling period. As the samplers had been set out along a bearing of 30° a wind on 210° would be desired, and allowing for a reasonable angle of spread of the plume this indicates that the samplers were immersed in air which contained emissions from the factory for over half the time. The wind speed was between 4 and 6 m/sec throughout.

Figure 3.2.15 shows the concentrations found, as a function of distance downwind. The highest result came from a sampler on the factory fence, at nearly $20 \mu\text{g}/\text{m}^3$. This may have been because the factory subtends a large angle at this site and so the instrument may have been exposed for effectively longer than the others. This argument, however, also applies to the second nearest site, which gave a much lower reading. The first sampler was near a sports ground, which was mown during the experiment; this may well have dislodged accumulations of lead dust and thus affected the results. In general, however, the measurements confirm that lead concentrations do not appear to be significantly affected by the factory, except perhaps at extremely close range. The fall-off with distance between the second site and the most distant one (at 4.6 km) is barely detectable and it would appear that background levels had been

reached by about 2 km at the most. It must be remembered that this is in the downwind direction only and does not represent the average concentration fall-off.

3.2.6.2 Dust Sampling Methods and Results

Battery manufacture requires lead in the form of oxide dust because this material, suitably pasted onto a lead/antimony frame, makes a porous structure which gives a large area of contact between the plates and the electrolyte. This dust is unfortunately difficult to handle because it crumbles easily and of course it is also toxic. All significant emissions of lead from the factories are in the form of dust, and typical sources include the contaminated air extracted by fans from workplaces, filtered exhausts from the smelter and oxide mills, and particles blown off the scrap store by the wind.

A typical dust particle has a complicated behaviour because it may be airborne only intermittently and it never gets very far away from the ground. Its track may be quite different from that of the upper wind because of obstructions on the ground and the aerodynamic effects of traffic. The lead-in-air concentrations discussed above clearly measure partly the very fine particles which for practical purposes behave like a gas and partly larger particles which may have settled temporarily and then been picked up again by the wind. Settling is more likely in sheltered pockets in corners and so accumulations of dust often occur there. The dust measurements now to be described simply provide a guide to the levels of lead in such accumulations. The inherent variability of dust measurements, caused by highly complex aerodynamic sorting mechanisms which favour settling of particular varieties of particle, means that only the broadest of conclusions can be drawn.

The dust survey was in two parts: firstly a general survey on a fixed grid covering 8 directions at 45° separation and 5 distances from the factory up to over 2 miles, and secondly a survey alongside roads known to be used by battery factory traffic and along 'control' roads known not to be so used. The purpose of the factory transport route study was to determine whether lead dust was getting into the environment by being picked up on tyres or by falling from lorries loaded with battery scrap.

For the grid system survey, samples were taken from suitable flat surfaces such as window ledges, which had to be at least 20m from the nearest road. Two samples were taken from each site. On the roadside sites two samples were taken from the kerb and another two from the back of the pavement. Notes were made of the distance along the road from the factory gate, where relevant. The samples were taken by brushing surface dust onto paper and then transferring to a plastic container, previously identified by a serial number. Sampling was only carried out on dry days. The laboratory analysis of lead in dust was done by polarographic methods after passing the dust through a 200 mesh sieve to remove the large particles which might otherwise make the sample unrepresentative. Absence of tin was confirmed by atomic absorption spectroscopy.

Figure 3.2.16 shows the distribution of lead in dust near the Clifton works, each number shown being the average of two measurements. The variability of the results is notable, though a general decline in concentration with distance is evident. In the raw data the highest individual result was over 66% lead content and the lowest 0.03%. Out of 34 samples, 8 were over 1% lead though two of these were just inside the works boundary, due to distances on the sampling grid having been taken from a central point in the factory. Of the rest of the samples over 1%, four were inside $\frac{1}{4}$ mile, one between $\frac{1}{4}$

and $\frac{2}{3}$ mile and one between $\frac{2}{3}$ and 1 mile. Of the 8 samples taken outside the works but inside $\frac{1}{3}$ mile radius, half were over 1% lead.

Figure 3.2.17 shows the concentration as a function of distance after averaging over all directions, and demonstrates that there is a substantial reduction in concentration at around $\frac{2}{3}$ mile.

The variation of lead concentration in dust along the transport routes at Clifton and Dagenham is shown in Figures 3.2.18 and 3.2.19 respectively. There is no consistent difference between results for kerb and rear of pavement, nor incidentally between left and right sides of the road (which might have been important if for example only outgoing traffic were contaminated) and so in this discussion they will be treated together. At Clifton there is a fairly sharp drop from very high levels near the factory gate to moderate levels (about ten times those found on the 'control' roads) and then a slower fall-off. The average figures for the control roads are shown dotted on the diagrams. It is notable that the Clifton transport route dust between 350m and 1450m is consistently around 10 times the 'control' concentration, while at Dagenham it is only about twice as high and falls away to the control level more quickly. The control values for roadside dust were 1900 and 2600 ppm respectively at Clifton and Dagenham, each of these figures being an average of at least 40 measurements. It seems therefore that rather more dust is escaping from the works at Clifton than at Dagenham, while a comparison between Figures 3.2.17 and 3.2.18 confirms that transport routes are more polluted by lead dust than other parts of the surroundings.

An investigation was made to see whether families living directly on Chloride transport routes were affected by the high lead levels in dust. There were only 8 Births Register families in this category and as the children's blood results were only up by $2 \mu\text{g}/100\text{ml}$ over the average this study did not yield a statistically

significant result. The effect, if any, is therefore small and likely to be submerged under other forms of lead contamination.

3.2.6.3 Soil Sampling Methods and Results

The determinants of lead concentration in soil are as complex as those for dust, and contain at least as many unknown factors. One helpful feature, however, is that soil concentrations represent average values which depend on the exposure of the surface to lead over a period of a year or more. Thus they are not very sensitive to recent weather. Such factors as acidity will affect the solubility of lead compounds and therefore the rate at which lead is leached out of the soil. A balance develops in which lead is deposited on the surface from the air and is washed down through the soil by rain, a reduction in concentration with depth being the usual result.

For this survey, soil samples were taken at each of the grid points previously specified for dust sampling, each core being about 15cm long by 2.5cm in diameter. At each site four such cores were obtained, one at each corner of a 1m square, from undisturbed soil of long standing (typically a lawn). Cores were transferred to numbered polythene bags. The laboratory identified the tops and bottoms of the cores by the vegetation and carried out separate analyses on pieces 2.5cm long cut from the two ends and dried at 105°C. Analysis was by polarographic methods, absence of tin being confirmed by atomic absorption.

The results obtained for soil were less variable than those for dust, apparently because of the greater ease of selecting consistent types of sampling site and the larger number of samples taken. Figures 3.2.20, 3.2.21, 3.2.22 and 3.2.23 show the spatial distribution of lead in surface and deep soil at Clifton and Dagenham. Again, there is a general reduction in concentration with

distance but the most notable feature is the variation between directions at Clifton. In particular, the W, SW and S sectors have markedly low levels, which may well be the result of prevailing wind effects. In every case but two the surface figures exceed the deep ones, which suggests that there is an accumulation of lead dust on the surface. The two exceptions were in soils which were very low in lead anyway. The highest figure for surface soil was 4120 $\mu\text{g}/\text{Pb}$ per gram of soil, which may be compared with 74000 $\mu\text{g}/\text{g}$ for dust.

Figures 3.2.24 and 3.2.25 show the variation with distance averaged over all directions. Excepting the very high surface value close to the works at Clifton, the variation is quite gradual, with a steady reduction from about 300 $\mu\text{g}/\text{g}$ at 0.8 km to about 100 $\mu\text{g}/\text{g}$ at 4 km.

Unfortunately, the scatter in the results is large and moreover only two sampling sites beyond 2 miles (3.22 km) were used at Clifton and both of these were in directions where lead levels were generally low. Thus the only conclusion that can reliably be drawn is that lead levels in soil do measurably increase near the factory. The extent of the affected area is not known with certainty.

3.2.6.4 Tap Water Sampling methods and results

Some 47 tap water specimens (including replicates) were taken from both hot and cold taps in 18 homes in the Clifton area, while at Dagenham only 18 samples in all were taken. Laboratory analysis was by monocolour dithizone method. The average results are summarised in the following table:

Table 3.2.20 Tap Water Results

	Clifton	DAGENHAM
Cold tap	47	7.6
Hot tap	49	8.3
Both taps	48	8.0 mg/1000 litres (=0.001 ppm)

It is interesting that although the overall means for hot and cold samples are evidently consistent, the values are not in fact correlated when taken house by house. It appears that high lead is often found in one tap or the other but less frequently in both. The consistent difference between Clifton and Dagenham undoubtedly reflects a genuine difference in water quality, probably due to the softer Manchester water dissolving lead compounds more readily.

Figure 3.2.26 shows the frequency distributions of lead in Clifton tap water. It can be seen that intermediate values (of the order of 100 mg/1000 litres) hardly ever occur. This suggests that the lead source is not present in all houses,

but if present it always causes lead levels well above background. Lead pipework, particularly with joints with pipework in a dissimilar metal, could well be the explanation.

An investigation was made into the blood levels of families living in houses with high tap water lead, and who were not Chloride subjects. Only four such families were found, and so it is not possible to draw statistically significant conclusions, however further investigation might be worthwhile in view of the fact that the blood lead levels were indeed high, adults by 2 $\mu\text{g}/100\text{ml}$ above average and children by 6 $\mu\text{g}/100\text{ml}$. One family in particular had consistently high blood lead levels among three children and their hot water lead was over 250 $\mu\text{g}/1000$ litres, the highest value found. In this case a child aged 0 years (i.e. under one year) had a blood lead of 41 $\mu\text{g}/100\text{ml}$, which is extremely high for its age.

3.2.6.5. Correlations between environmental samples

No significant correlation was found between dust and soil results, which presumably reflects the very different time scales for variation of dust and soil lead concentrations (the former in hours, the latter in years). However, a strong correlation exists between surface and sub-surface lead in soil, the correlation coefficient being 0.79. This supports the idea that lead in deep soil originates from lead dust deposited at the surface.

No correlation could be found between soil or dust samples and the grass results by Ratcliffe (1975) but this was probably due to the sampling sites not being the same for grass as for the other specimens.

3.2.6.6 Summary of environmental results

- (i) Lead concentrations in air fell away very rapidly with distance and the effect of the factory at Dagenham is only measurable at the factory fence itself. The behaviour of lead concentrations in general is characteristic of a widespread source (probably road traffic) rather than an isolated source.
- (ii) Dust is significantly contaminated with lead from the battery factories but particularly so on transport routes used by factory vehicles. The effects are detectable up to one mile from the Clifton works on transport routes.
- (iii) Soil is also affected by the factories up to one mile away, surface soil lead levels within one mile being about twice those between one and two miles.
- (iv) Elevated tap water lead levels are probably due to lead pipework and may explain some cases of high blood lead levels.

3.3 Detailed study of airborne lead near a battery factory.

In this section we will restrict attention to the Clifton battery factory, on the grounds that a more extensive survey of airborne lead was made there than around the Dagenham plant. In addition, an anemograph was installed on site, which was not the case at Dagenham.

The methods used in air sampling have been described in section 3.2.6.1. We will only be concerned with measurements made using National Survey Type daily sampling equipment. Some 265 air samples were obtained from six fixed sites around the Clifton works during the period April-May 1974. The sampling method used was by analysis of the particulate filters on standard U.K. National Survey of Air Pollution instruments. These samplers draw about 2 cubic metres of air each day through a Whatman No. 1 filter paper. Biles and Ellison (1975) have examined the efficiency of cellulose filter papers (including Whatman No. 1) with respect to lead particles in ambient air in London and conclude that of the filters they studied (Whatman Nos. 1, 4 and 541) the No.1 filter was the most efficient. However, even this filter exhibited a fairly low efficiency (about 50%) when clean. The efficiency approached 100% as the degree of soiling with particulates increased. Unfortunately, insufficient information is given to enable an assessment to be made of the efficiency likely to obtain for a 24 hour sample in typical ambient air at Clifton. However, Pollitt (1976b), working in nearby Salford, sampled an urban atmosphere containing about $1.3 \mu\text{g}/\text{m}^3$ of lead, using both Whatman No. 1 and a more efficient millipore paper. Out of 14 pairs

of samples the largest difference he found was only $0.2 \mu\text{g}/\text{m}^3$, and only 4 pairs differed by more than $0.1 \mu\text{g}/\text{m}^3$. It is therefore felt that the use of National Survey filters in this type of work is likely to be satisfactory. At Clifton, in addition to three existing National Survey sites, each about 2 km from the factory, a further three similar samplers were set up about 800 metres away, to give a measure of distance effects.

A check was made of the background levels of lead in unexposed Whatman No. 1 paper, which yielded an average value of $0.002 \mu\text{g}/\text{cm}^2$, which corresponds to less than 1% of the values found after exposure. Errors due to blank values have therefore been ignored in the analysis.

This section is concerned with the analysis of the results of these measurements and with their relationship to local weather conditions. There is no attempt at this stage to relate concentrations to emissions via a dispersion model; this is treated in section 5.

3.3.1 Quantification of emissions

Unfortunately, the magnitudes of the emissions at Clifton are not as well documented as are those at Dagenham. A summary of the known totals for both plants is given in section 3.2.6.1 (Table 3.2.19) and it will be observed that the data in the table for low level emissions at Clifton are marked as incomplete. The reason for this was simply that the majority of low level emissions at Clifton had never been measured in any way. Only the obvious major

sources had been studied and Table 3.3.1 gives the breakdown of source strengths for these emissions, along with certain other information relevant to the emission (e.g. temperature, height, etc). The table also includes such information as is available concerning the remaining, unmeasured, sources, and to complete the table, estimates have been made of the unmeasured emissions, based on the data from Dagenham, scaled up in the ratio of the respective production rates at the two factories. These estimates are identified with an asterisk.

It can be seen from Table 3.3.1 that the new blast furnace emission is the largest individual contributor to the total but that substantial emissions also arise from the old furnace and from the totality of the remaining sources. The low level emissions total over 167 kg/week and such adventitious escapes as scrap pile blow-off may be expected to add substantially to this. The total for high level emissions is of the same order (206 kg/week) but will be more effectively dispersed, and therefore it is to be expected that low level sources will dominate the concentration pattern experienced in neighbouring areas. These emission rates will be used in the dispersion calculations of section 5 .

TABLE 3.3.1 EMISSIONS AT CLIFTON

SOURCE	AVERAGE NO. OF UNITS IN SERVICE	EMISSION (kg/WEEK) EACH UNIT	EFFECT- IVE HEIGHT (m)	VOLUME FLOW RATE (m ³ /SEC) PER UNIT	TEMP °C	PARTICLE SIZE RANGE (MICRONS)	CONCENT- RATIONS μg/m ³
Scrap piles	1	medium ?	0	?	amb- ient	0.1-1000	?
Old blast furnace	1	33.1	37	5.0	50	< 0.1	10.1
Old blast furnace fume extraction	1	45.4	low	6.4	22	< 0.1	10.8
New blast furnace Plus its fume extraction	1	172.5	47	26.0	45	< 0.1	10.8
Casting shop ventilation	?	small ?	low	?	amb- ient	~ 0.1	?
Tudor oxide mill	2.5	13.6	low	10.0	80	< 0.1	9.3
Hardinge oxide mill	1	1.5	low	1.0	80	< 0.1	3.0
Plate cleaning	?	<u>all units</u> 47*	low	<u>all units</u> 11.8*	amb- ient	1-100	40*
Reed stacker	2	8.2*	low	0.37*	amb- ient	0.1-10	130*
Hand stacking benches	?	<u>all units</u> 18.2*	low	<u>all units</u> 11.8*	amb- ient	0.1-10	9*
Pack burning	?	<u>all units</u> 4.5*	low	<u>all units</u> 13*	amb- ient	~ 0.1	2*

* signifies estimate based on Dagenham plant figures appropriately scaled.

3.3.2 Examination of topography and local meteorology

Figure 3.3.1 shows the location of the battery factory in relation to the western seaboard, the high land of the Pennines and to the largest of the urban areas.

The works is about 50 km inland from the Irish Sea and therefore it is expected that coastal effects will be rare. There is a possibility, however, that during very prolonged spells of warm windless weather, primarily when there is a well-established anticyclone, sea breezes would be set up which would persist far inland. This would probably induce a westerly wind at the site, but such occasions are almost certainly too rare to have much influence on the overall pattern of pollution dispersion.

More significant is the proximity of the Manchester conurbation. There will undoubtedly be heat island effects which will cause inflow towards the urban centre in otherwise calm conditions. Moreover, the airflow over the city will be convective and highly turbulent. The works is surrounded on most sides (except the north) by heavily built-up terrain and thus a strongly turbulent airflow will persist for much of the time. In situations where stability sets in at ground level, the urban heat island will probably assist the generation of a katabatic wind flowing down the Irwell valley.

The proximity of the Pennine hills to the north and east of the site can be expected to have an effect on the local weather. There may be some channelling along a generally north-south direction, and in stable weather katabatic drainage from these hills

may cause local winds from the quadrant between north and east.

Thus the local winds at the battery factory site are likely to be affected in a complex way by both topographic and urban heat island effects, and it is expected that the local variations will depend on the atmospheric stability and wind direction.

The nearest meteorological station giving a full set of measurements is at Ringway airport, on the southern edge of the Manchester conurbation. This site, while not subject to local topographical effects on the micrometeorological scale (as is the Clifton site), is still affected by mesoscale influences of the Pennines and the Manchester heat island. Here, one would expect: a) north-south channelling due to the Pennines; b) southerly winds induced by the heat island; (c) easterly katabatics flowing off the Pennines. In the sub-sections which follow, these aspects are investigated in more detail.

3.3.2.1 Installation of an anemograph on the battery factory site

In order to obtain direct experimental evidence about micro-and meso-scale winds at the battery factory, an anemograph was set up in a well-exposed position 5.5m above a flat-roofed office building within the site. This building is the tallest building in the immediate vicinity apart from chimneys and the installation was deemed to be uninfluenced by building aerodynamic effects.

The instrument used was a standard Casella recording anemometer and wind vane, on hire from the Meteorological Office and identical in every respect to standard Meteorological Office equipment. Plate 3.3 is a photograph of the cup anemometer and wind vane as installed on an open framework on the building roof.

The chart recorder was installed in an office within the building and was maintained by the staff therein, who attended to routine matters such as changing charts, inking pens, annotating the charts with dates and times etc. The alignment of the wind vane was effected by visual sighting against landmarks identifiable on an Ordnance Survey map. The overall accuracy of the direction measurements was estimated to be better than $\pm 5^{\circ}$, which is within band of accuracy involved in subsequent reading of the charts.

3.3.2.2 Analysis of anemograms

The anemograms resulting from the measurements on site were analysed in two ways: firstly according to standard Meteorological Office practice, to obtain hourly mean values for direction and speed; and secondly according to the methods of Singer and Smith (1966) to obtain Brookhaven atmospheric gustiness categories. The Singer and Smith technique consists of characterising the appearance of the wind direction trace and divides the possible states of the atmosphere into five categories, as follows:

- A Fluctuations of direction exceeding $\pm 90^\circ$
- B₂ " " between $\pm 40^\circ$ and $\pm 90^\circ$
- B₁ " " " $\pm 15^\circ$ and $\pm 45^\circ$
- C trace has an unbroken solid core, such that a straight line may be drawn through it without touching "open space".
- D the trace approximates to a wavy line; short term fluctuations do not exceed $\pm 15^\circ$.

For certain anemographs having a slow response rate (e.g. some instruments which are deliberately damped for clarity of the trace) these definitions would be unsatisfactory because the high frequency information would not be recorded. However, provided the equipment has a response rate of the order of 10 seconds or better the Brookhaven categories can be assessed without trouble and the equipment actually used easily meets this requirement with its response time of the order of one second. Singer and Smith have shown that the dispersion coefficients in a Gaussian model can be correlated with the gustiness category, and this allows prediction of concentrations if the gustiness category is known.

It was found helpful in analysing the traces to study at the same time the daily weather charts for the eastern Atlantic area. This provided a useful check on chart timing, where occasionally the markings were ambiguous, and also gave supporting evidence in the selection of gustiness categories (e.g by indicating the likely cloud cover etc).

The anemograph was run for a total of seven months, covering the period November 1973 to May 1974 inclusive. The data was recorded by hand in tables for each hour, then transferred to a magnetic cassette data file on a Hewlett-Packard desk-top programmable calculator by means of which subsequent analyses (section 3.3.2.4) were made. Appendix III describes the programmes used in detail.

3.3.2.3 Records from Ringway airport

The standard Meteorological Office "Analysis of Anemograms" forms were obtained for Ringway Airport for the period November 1973 to May 1974. These forms give details for each hour of the hourly mean windspeed and direction, and the direction and speed of the maximum gust. In the analysis of the battery factory dispersion, however, only the hourly averages were used since the "gustiness category" was to be determined from the one-site anemograph as described in section 3.3.2.2.

The average frequencies of wind speeds and directions for Ringway were also obtained from the Meteorological Office. These were based on data from the decade 1960-1969 and included a breakdown by calendar months. These records showed that the prevailing wind direction at Ringway is southerly, which suggests that either the channelling effects of the Pennines or the heat island effect of Manchester (or both) are very significant. The wind direction rose is shown in Figure 3.3.2. This shows up minor peaks in the westerly and easterly directions, with minimum frequency of northerly winds. This last observation may indicate an effect of the Manchester conurbation in blocking northerly winds. The average frequencies are to be used later in the estimation of long term average lead concentrations.

3.3.2.4 Correlation of local wind with synoptic scale wind

Figures 3.3.4.1 to 3.3.4.5 are scatter diagrams relating wind directions at Clifton Junction to those at Ringway. The numbers within the body of the tables are frequencies of occurrence of each combination of wind directions at the two sites, normalised so that the total frequency excluding calms is 10,000. This normalisation is done purely for convenience in presenting the data. The scatter diagrams are presented separately for five particular conditions, i.e.:

- (i) strong winds (greater than 7 kts)
- (ii) each of the Brookhaven gustiness categories except Class A (for which insufficient data were available). The remaining categories are: B2 (strong instability), B1 (weak instability), C (neutral), D (stable).

The scatter diagrams were generated by a computer programme which is described in detail in Appendix III. This method of analysis was necessitated by the very large number of data points which had been obtained during the six month anemograph run at Clifton.

The scatter diagram for strong winds (Figure 3.3.4.1) shows that there is a high degree of correlation between the wind directions at the two sites, as would be expected in these conditions. There are signs, however, of a systematic deviation from the diagonal, which is indicative of a consistent topographical effect such as channelling in the valley. This is best studied in Figure 3.3.5, in which the mean veer of the Clifton wind relative to the Ringway wind is plotted against the Ringway direction. The veer has maximum values at

Ringway directions around 04 (40°) and 25 (250°) and minima at 17 (170°) and 33 (330°).

A partial explanation for these deviations in the wind veer can be derived from consideration of the orientation of the valley of the Irwell (approximately NW-SE). It is likely that winds aligned along or across the valley would be relatively unaffected in direction, but winds from other directions would be subject to valley channelling effects. Southerly and northerly winds would be backed and easterlies and westerlies would be veered. Thus, the veer would be near zero at directions 45, 135, 225 and 315, maximal at 90 and 270 and negative maximal at 360 and 180 degrees. Study of the graphs in Figure 3.3.5 shows that this behaviour is a major component of the observed deviations, although it is clearly not the only factor involved. The 'strong winds' category in this figure shows the effect most clearly and Class C also indicates minimal veer in southerly and northerly winds as expected.

In the two 'unstable' categories B1 and B2, where the wind direction is variable, the degree of correlation between the two wind directions, as shown in Figures 3.3.4.2 and 3.3.4.3, is smaller than for strong winds, especially for the most variable class, B2. There is a notable and consistent tendency for winds at Clifton to be clustered around directions 250 and 330 and veered by 20 to 30 degrees in Class B1 conditions. The latter peak is almost certainly a channelling effect, but there is no obvious explanation for the distinct peak at 250 degrees (Clifton, Figure 3.3.4.2).

Despite the relatively large scatter in Class B2 conditions (Figure 3.3.4.3) the mean wind directions appear to be consistent. Note that the high veer recorded in Figure 3.3.5 in Class B2 for northerly winds at Ringway is based on only two data points and, therefore, has no real significance.

In Class C and B1 the scatter diagrams show an absence of winds in the direction band 210-220 at Clifton, but this effect is not seen in the other gustiness classes. The winds that would have been expected in this sector appear to have been displaced towards a westerly direction (270 degrees). Class C in general shows less scatter than Classes B1 and B2.

In Class D, Figure 3.3.4.5 shows as expected a marked loss of correlation between the wind directions at the two sites. This is because in stable weather with light winds, the local wind direction may be affected greatly by local topography, heat island effects and katabatic winds. Despite the wide scatter of the data in Figure 3.3.4.5, it is possible to identify one distinct cluster of points off the diagonal which is significant.

This cluster is of NW winds at Clifton coinciding with S or SW winds at Ringway. It is likely that this combination of wind directions occurs as a result of the inflow towards Manchester that will tend to occur in times of slack wind.

In general, the figures indicate that the correlation of wind direction between the sites is reasonably good, but that different gustiness

classes should be treated separately.

3.3.2.5 Use of results in air pollution prediction applications

Any model designed to calculate long-term averages or frequency distributions for air pollutants from an industrial source will require data on the frequencies of wind strengths and directions and stability classes. This information is normally only available in the U.K. for major climatological stations, such as Ringway, and, therefore, it will be necessary to use the correlations determined above (Section 3.3.2.4) to adapt the long-term Ringway data to make it relevant to the Clifton Junction site. There are two ways in which this could be done: first, the graphs in Figure 3.3.5 could be used to give a fixed veer value for each direction at Ringway, or, alternatively, the distribution of veer as given in the scatter diagrams (Figures 3.3.4.1 et. seq.) could be used directly. The latter method would more accurately reflect the cases where one wind direction at Ringway is associated with a variety of possible directions at Clifton, as is the case in Class D conditions particularly. In the present work, this last method has been adopted and a computer programme was developed to carry out the computations.

The method used in this process was as follows: First, the frequency table for wind speeds, directions and stability categories (Pasquill) was obtained for Ringway from the Meteorological Office. This data is generated by a computer

programme which uses such information as wind speed, cloud cover and time of day to estimate Pasquill categories. There is no facility for generating Brookhaven gustiness categories, since these are essentially defined in terms of the appearance of a wind direction trace and cannot be directly inferred from normal meteorological observations, unlike the Pasquill categories. Therefore, since the correlations were based on Brookhaven categories using the anemograph traces from the Clifton site, some means of relating Pasquill categories to Brookhaven categories needed to be defined. The relationships used for this are specified in Table 3.3.2.5.

Table 3.3.2.5 Atmospheric Stability Categories

<u>Brookhaven</u>	<u>Pasquill</u>	<u>Description</u>
A	A	Strong convection
B2	B	Moderate convection
B1	C	Weak convection
C	D	Neutral
D	E/F	Stable

The Ringway frequency tables are then examined taking each stability category in turn. The scatter diagram for Clifton Junction for the stability category under consideration is consulted and for each wind direction at Ringway the frequency distribution of corresponding Clifton wind directions is extracted from the diagram. This frequency distribution is then normalised to give a total frequency of unity. Then for each wind speed at Ringway, the frequency of occurrence is factored by the

normalised frequencies and the result is added into the Clifton wind frequency table at the wind speed and stability existing at Ringway but at the wind direction corresponding to each individual normalised frequency. When all of the Ringway weather conditions have been covered in this way, the Clifton frequency table is complete and this constitutes the weather data input needed for the dispersion modelling programme when used to predict long-term average concentrations and frequency distributions of concentration.

The practical application of these concepts in the particular case in question is covered in detail in Section 5.

3.3.3 Discussion of air sampling results with reference to current weather

3.3.3.1 Sampling Sites

Figure 3.3.3 shows the location of the six sampling sites in relation to the factory. The three town hall sites were existing National Survey of Air Pollution sampling sites, while the three inner sites were specially set up for the present work. The sampling equipment at Whitefield and Swinton Town Halls was the original one-day sampler requiring daily attendance by staff to change the filter papers etc. This meant in practice that at weekends the samples were often averages for two or occasionally three consecutive days. The remaining instruments were all of the automatic 8-day variety and therefore a complete set of daily results was obtained. In all cases the filters were changed at mid-day and the volume of air drawn in was noted. This information was recorded on punched cards along with the date, time and site location code and the laboratory results (obtained by monocolour dithizone methods).

The sites were considered to be unaffected by any particular individual local sources of lead, although it was perhaps inevitable that the town hall sites would be within heavily built-up areas and would therefore register contributions from petrol engine emissions. These sites were each near to roads carrying significant traffic volumes, but the sampler location in each case was on the side of the building remote from the road.

3.3.3.2. Average results for each site

Because of the short period of time available for sampling, it was not possible to study concentrations under all possible weather conditions. The wind speed and direction was however monitored at the Clifton works and these records have been used to estimate the number of hours for which each sampling site was within 15° of the downwind direction from the factory on each day. This number of hours is referred to here as the 'downwind exposure time', and is naturally a nominal figure only, owing to the arbitrary nature of its definition.

It is of interest to compare the average results for the six different sites at Clifton, and Table 3.3.2 summarises these:

TABLE 3.3.2 AVERAGE RESULTS FOR INDIVIDUAL SITES AT CLIFTON

Distance from Works	Direction from Works	Average downwind time per day (hours)	Mean Concentration $\mu\text{g}/\text{m}^3$	Standard deviation	No. of samples
800m	45°	0.71	0.60	0.29	59
800m	90°	0.63	0.48	0.30	38
800m	205°	2.63	0.65	0.43	61
2400m	45°	0.82	0.46	0.26	52
2400m	90°	0.86	0.40	0.27	59
2400m	205°	3.43	0.81	0.58	24

A slight effect of downwind time relative to the factory is indicated by these results, but no consistent effect of distance can be discerned. No attention should be paid to any apparent effects of direction since this would be strongly influenced by the particular wind patterns which existed during the two months of the survey.

3.3.3.3 Analysis of concentrations against downwind exposure times.

The average values presented in Table 3.3.2 are difficult to interpret because of the influence of the weather. A more illuminating analysis is provided by taking the results for all sites together and analysing with respect to downwind times.

Table 3.3.3 gives results for lead concentrations at Clifton on days with different downwind times:

TABLE 3.3.3

Downwind Time (Hours)	Mean Concentration $\mu\text{g}/\text{m}^3$	Standard Deviation $\mu\text{g}/\text{m}^3$	Number of samples
0	0.45	0.27	178
≥ 0	0.53	0.36	265
≥ 1	0.69	0.45	87
≥ 6	0.66	0.36	21

From this it can be seen that the general background is about $0.45 \mu\text{g}/\text{m}^3$ (based on zero exposure time). Though there is considerable variability, as indicated by the standard deviation results, it can also be said that the downwind sites are on average higher in lead by some $0.2 \mu\text{g}/\text{m}^3$. The effect of increasing exposure time from 1 to 6 hours is however unclear, presumably because of the small number of samples and the high variability.

The overall average result of $0.53 \mu\text{g}/\text{m}^3$ may be compared with the equivalent Dagenham figure of 0.60 (standard deviation 0.32), based on 79 samples.

These results suggest that the factory is contributing a significant amount of lead to the atmosphere near the plant, specifically about half of the background levels. Due to the magnitude of the background levels in relation to the factory contribution, problems may well arise in proving the validity of a dispersion model using these data, and this aspect is dealt with in section 5.0.

3.3.3.4 Examination of individual high results and long downwind times

Results over $1.0 \mu\text{g}/\text{m}^3$ have been examined individually in an attempt to identify specific causes of high concentrations. Out of 20 such results 70% were associated with exposure times of at least 1 hour, but the converse relationship did not hold, since of some 17 samples with over 8 hours exposure only 2 gave results over $1.0 \mu\text{g}/\text{m}^3$. It was thought that the weather may have been a contributory factor in this variation and so a preliminary examination of the current weather was made. This seemed to indicate that high concentrations were more likely to occur on calm days, but owing to the small number of samples this could not be established as an inviolate rule.

3.3.3.5 Summary of air sampling results

The initial analysis presented in this section has been somewhat inconclusive, primarily because the effect of the factory does not dominate the background

(although it is detectable and significant). The correlations carried out so far are of the simplest kind (i.e. with wind direction only) and do not take into account the many other complicating features of the topography and weather which are expected to affect concentrations. Thus it seemed worthwhile to construct a more sophisticated model of the transport of airborne lead and to see how high a correlation could be achieved between predicted and measured values. This is described in section 5.



Plate 3.3 Anemograph mast
at Clifton Junction Site

Fig 3.1.1 CLIFTON FACTORY SITE

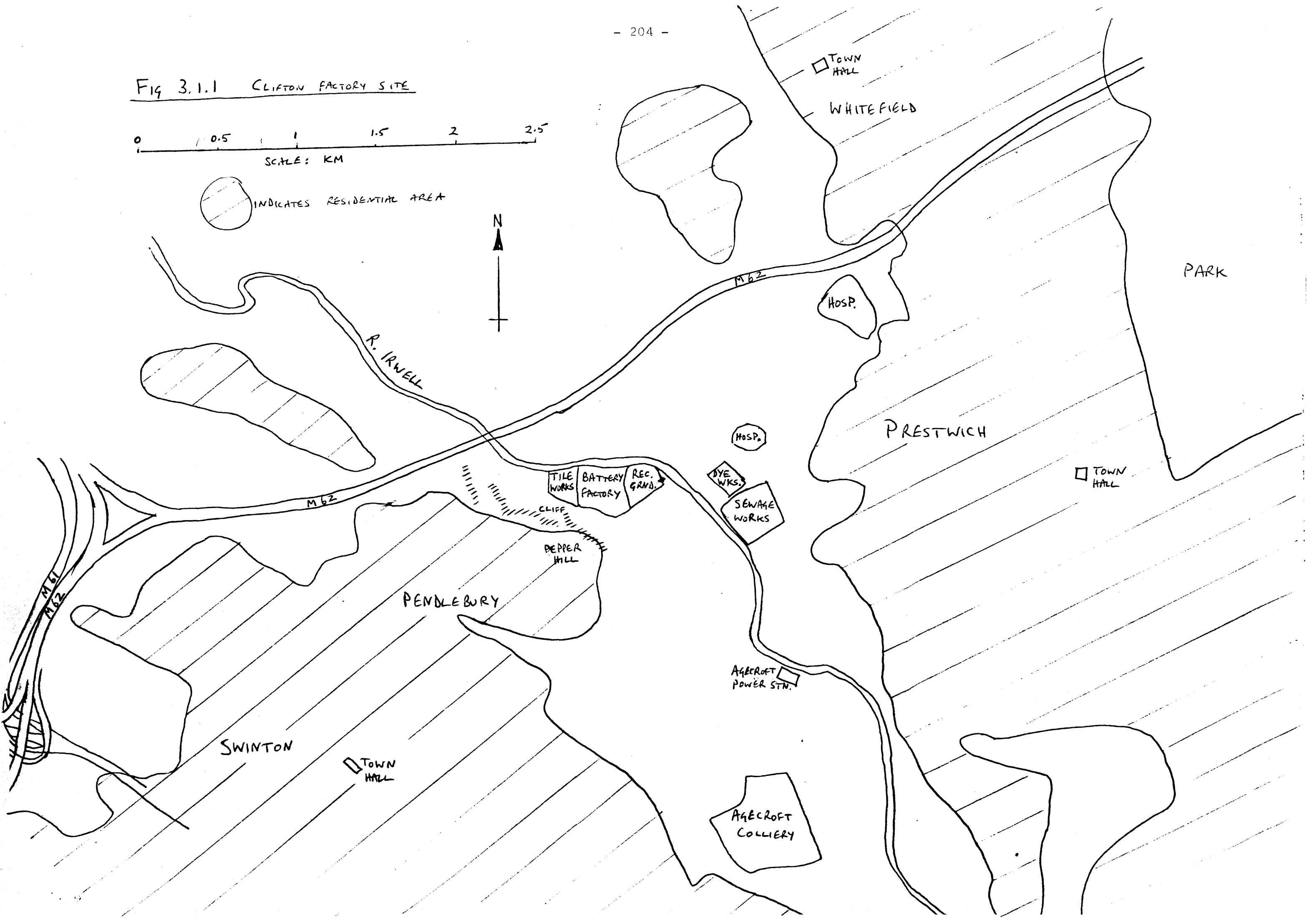
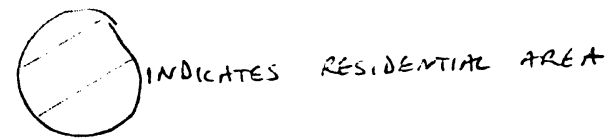
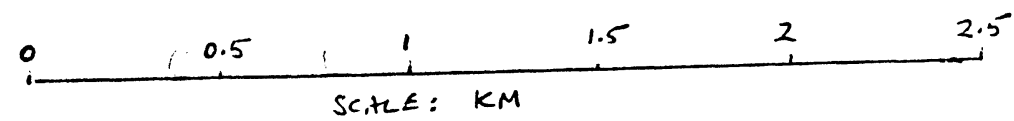
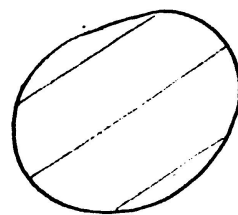
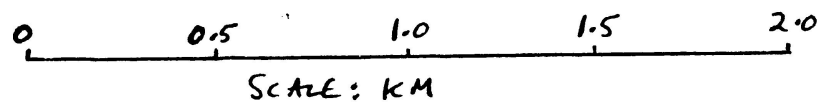


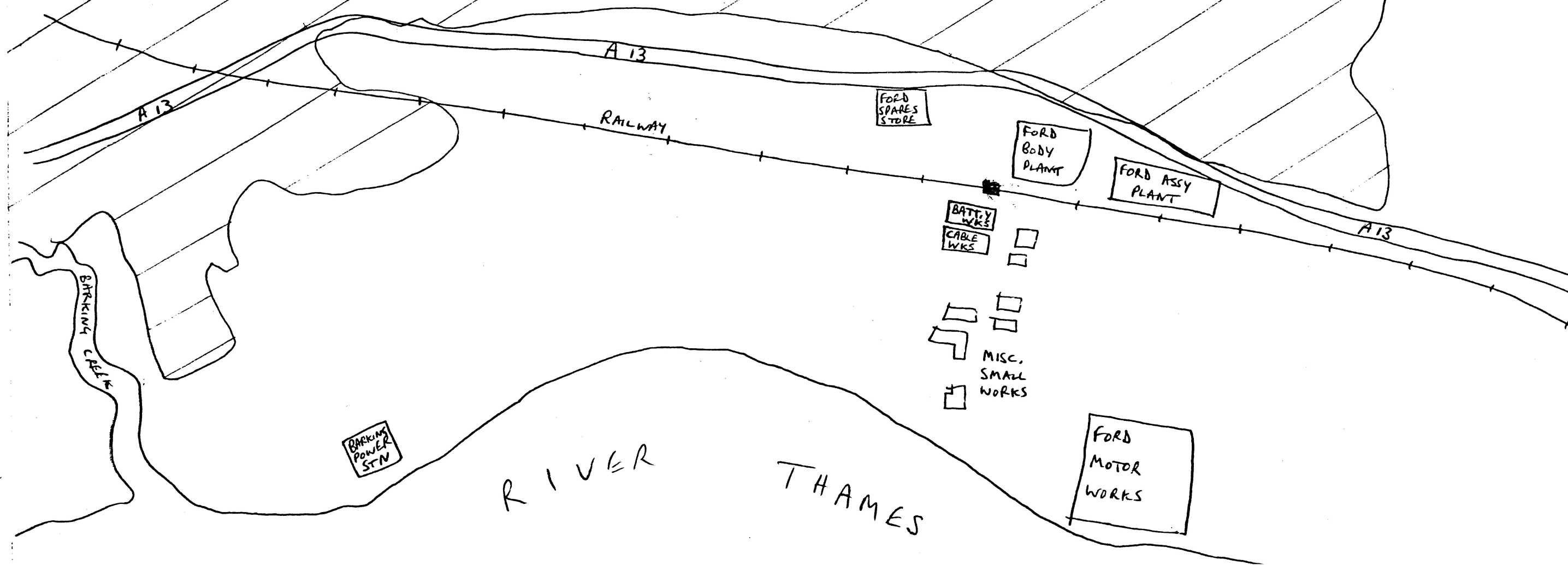
Fig 3.1.2 DAGENHAM FACTORY SITE

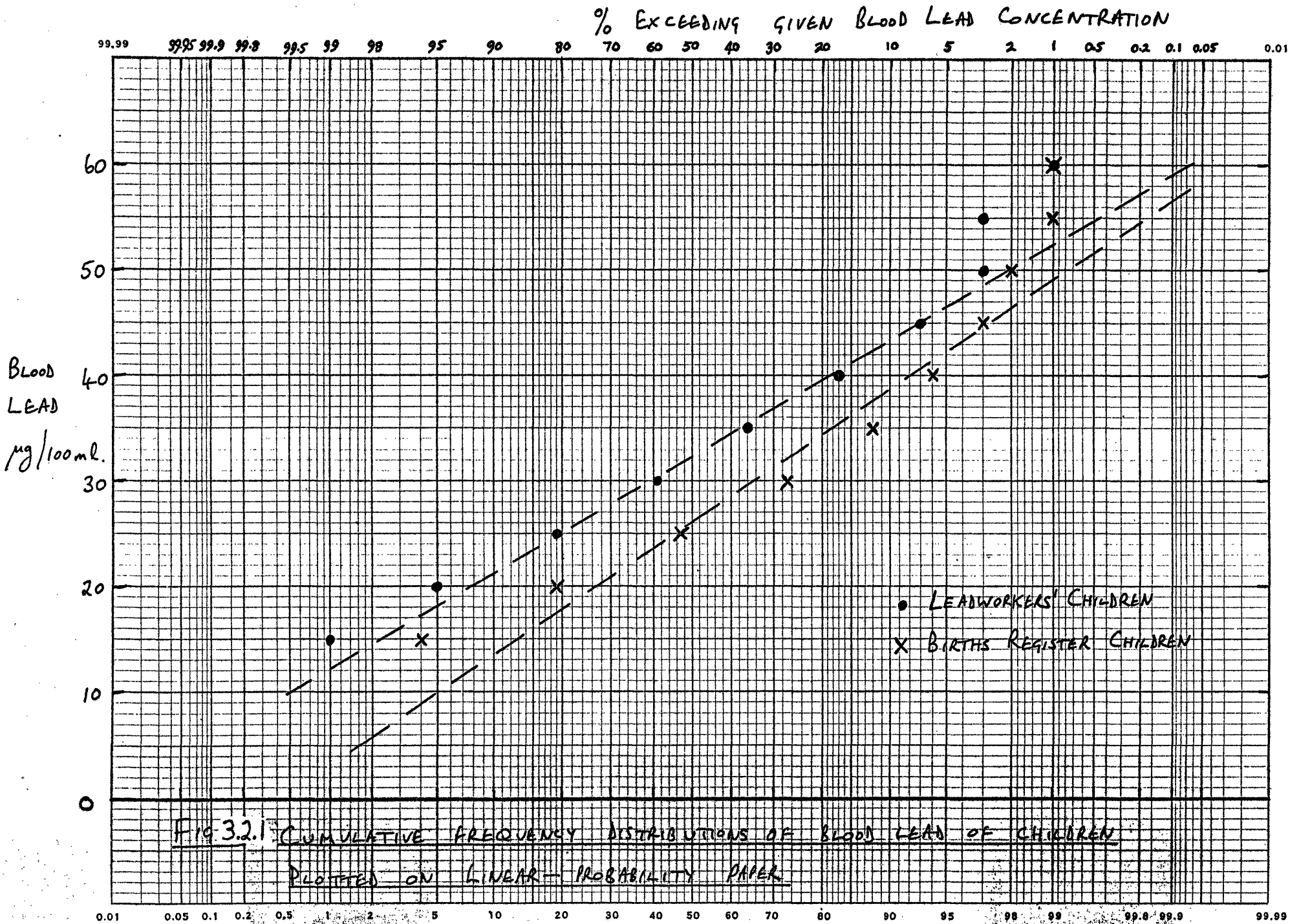


INDICATES RESIDENTIAL AREA

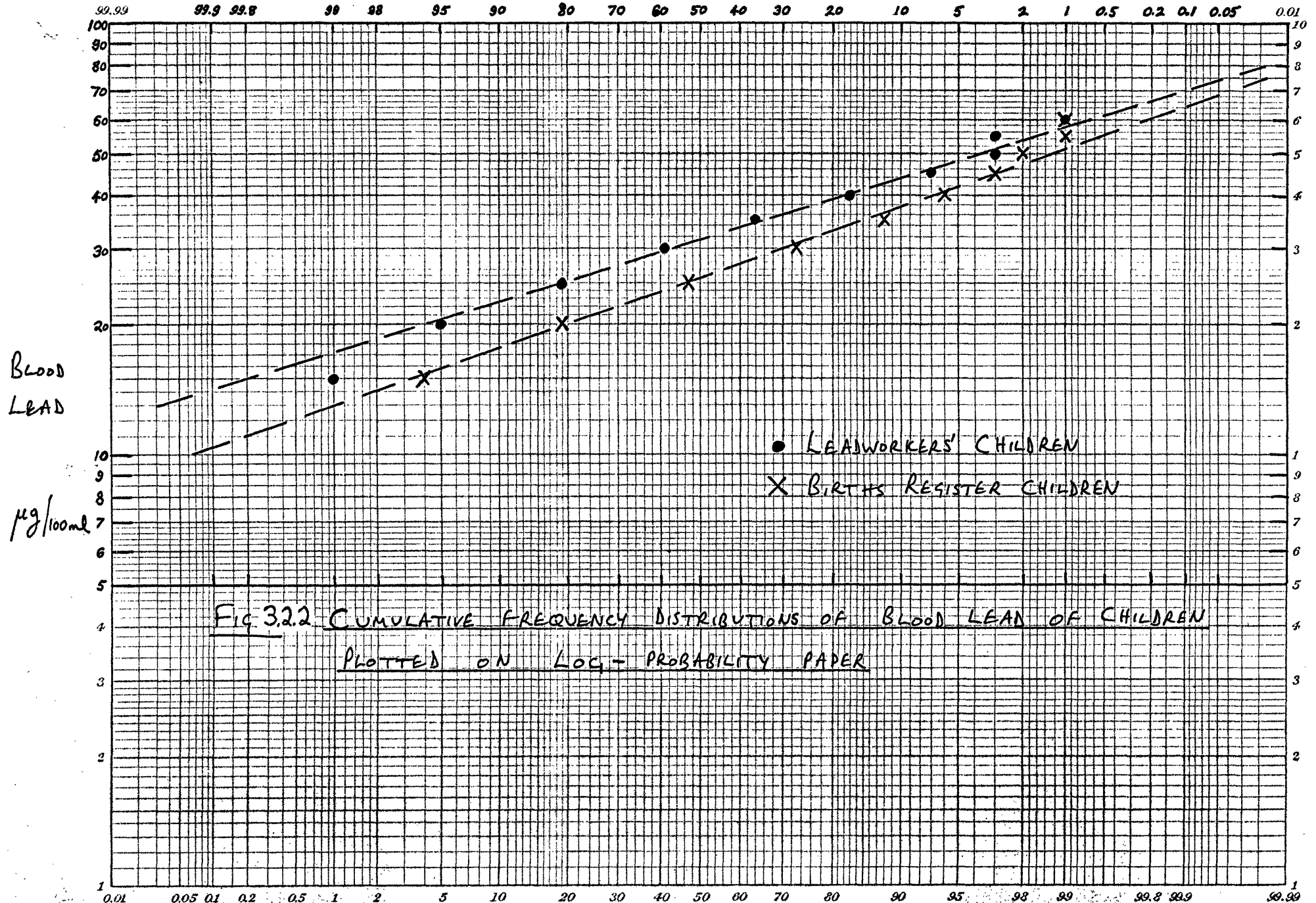
BARKING

DAGENHAM

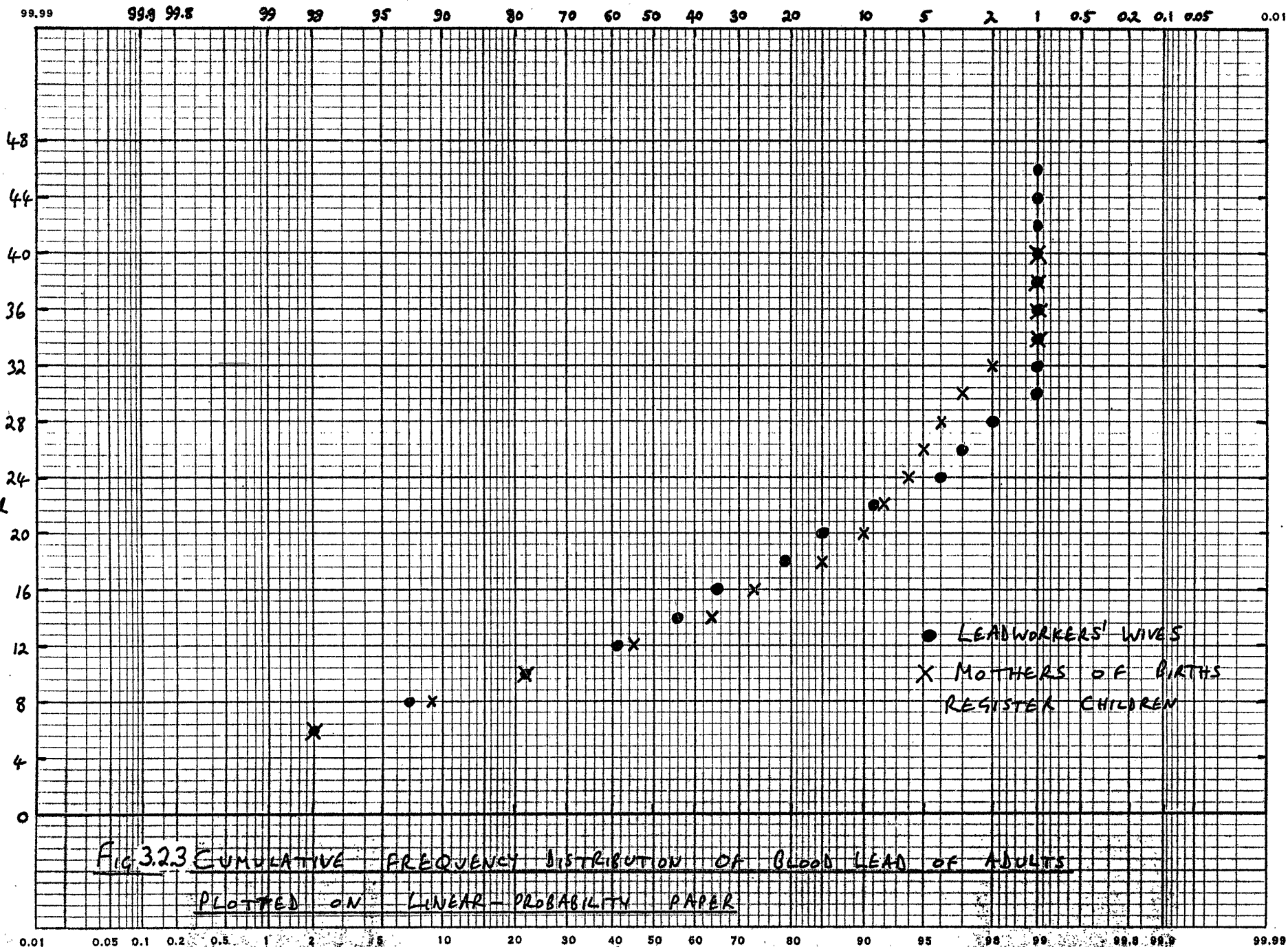




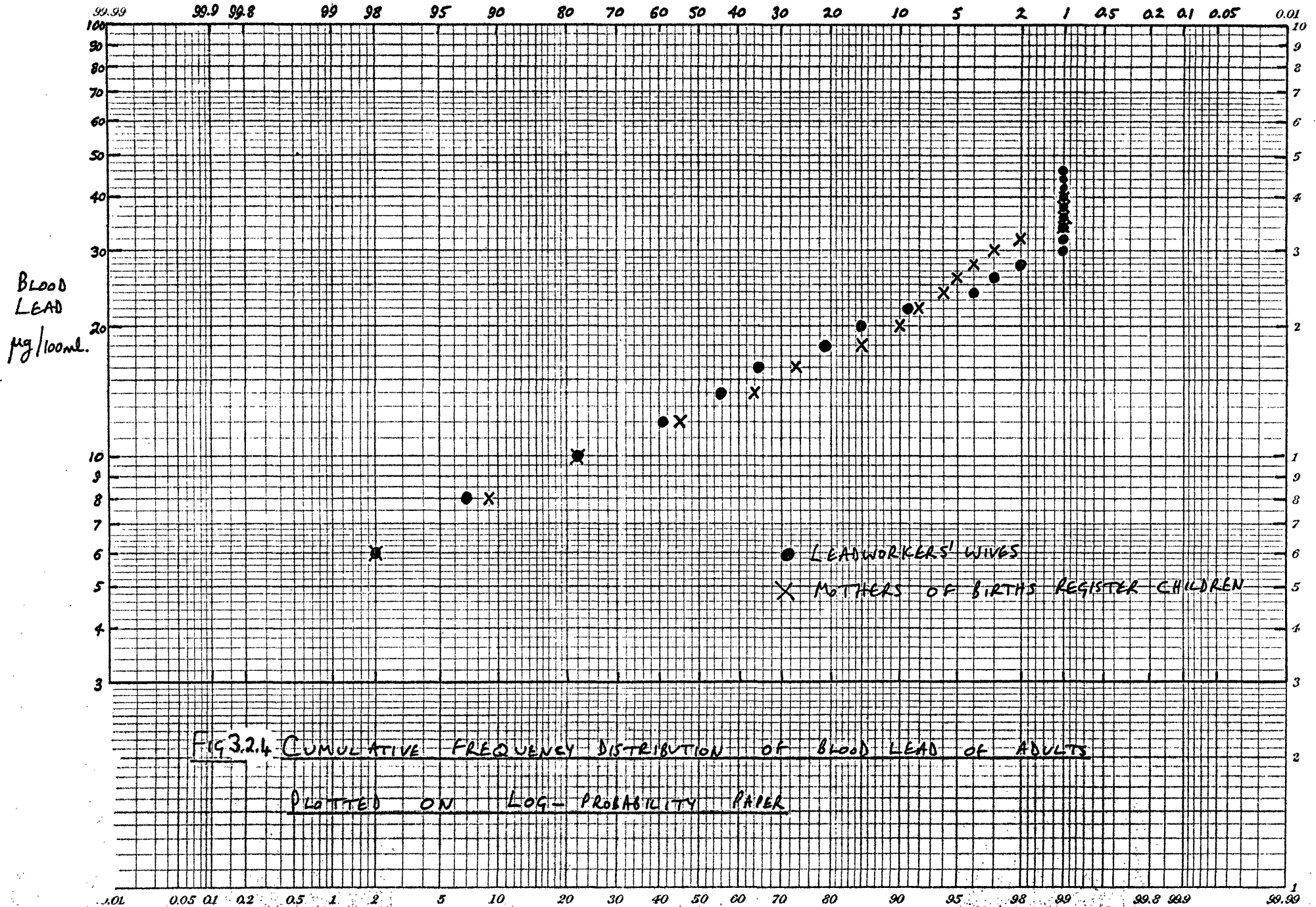
% EXCEEDING GIVEN BLOOD LEAD CONCENTRATION



% EXCEEDING GIVEN BLOOD LEAD LEVEL

BLOOD
LEAD
mg/100 ml

% EXCEEDING GIVEN BLOOD LEVEL



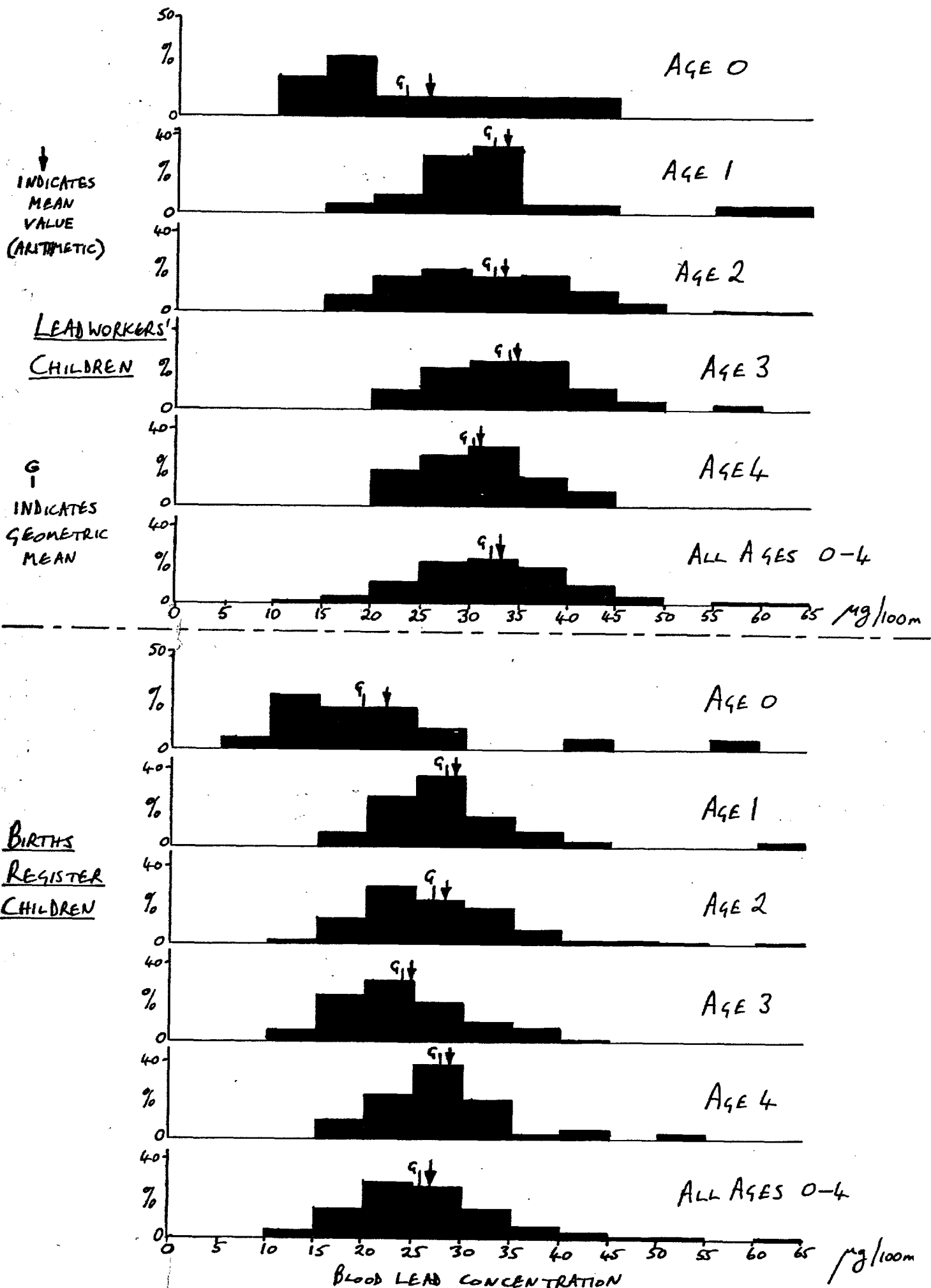
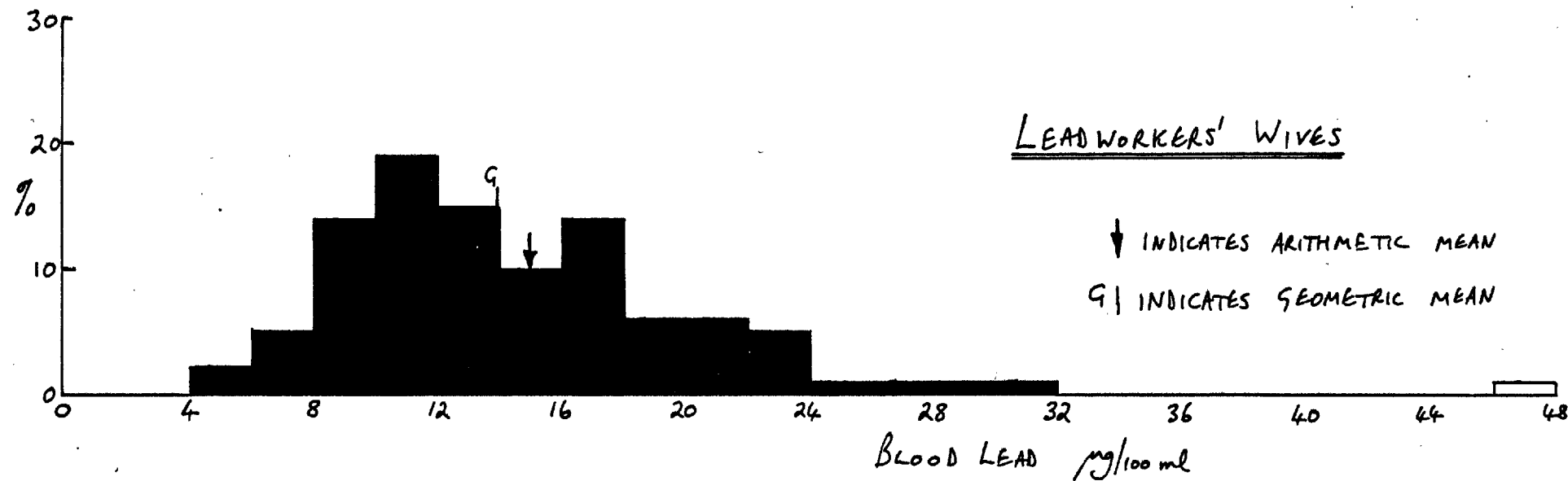


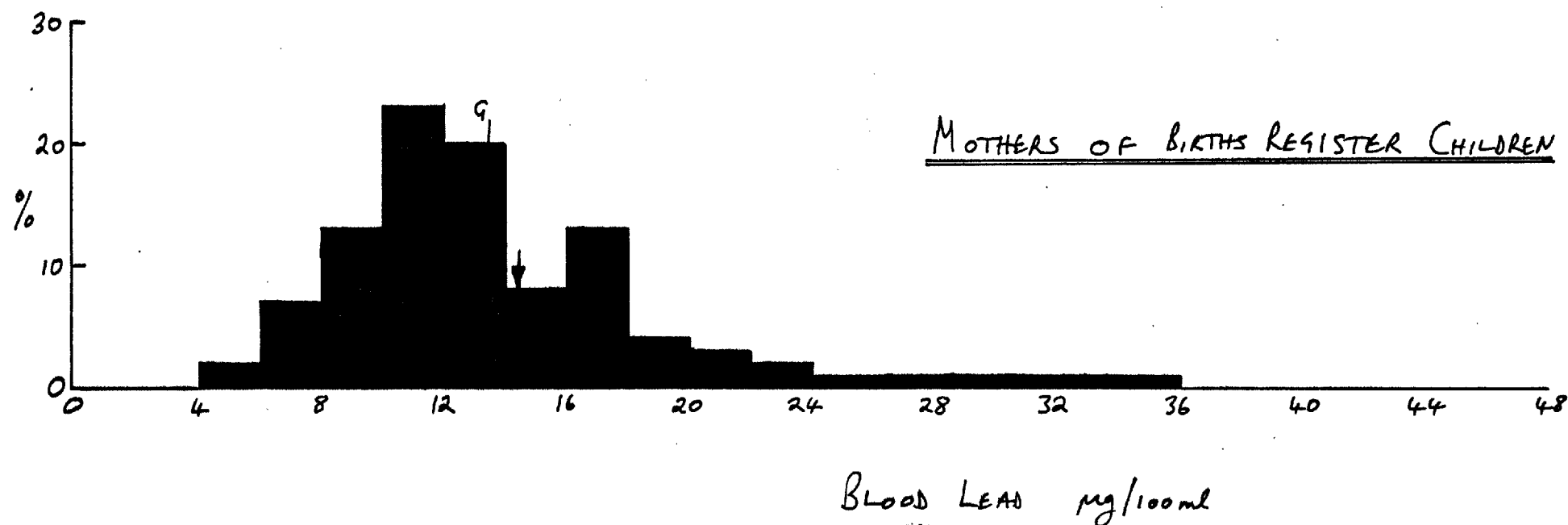
Fig 3.2.5 FREQUENCY DISTRIBUTIONS OF BLOOD LEAD OF CHILDREN

FIG 32.6 FREQUENCY DISTRIBUTIONS OF BLOOD LEAD OF ADULTS

LEADWORKERS' WIVES



MOTHERS OF BIRTHS REGISTER CHILDREN



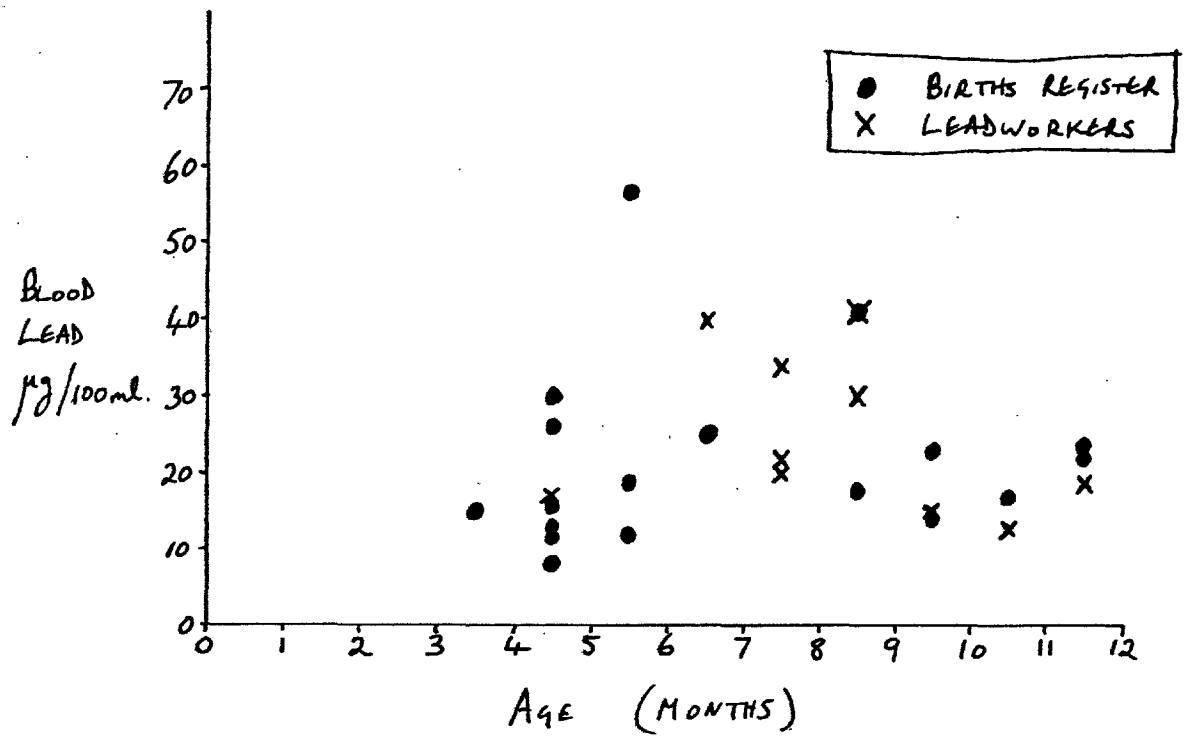


Figure 3.2.7) Results for Children Aged 0 years

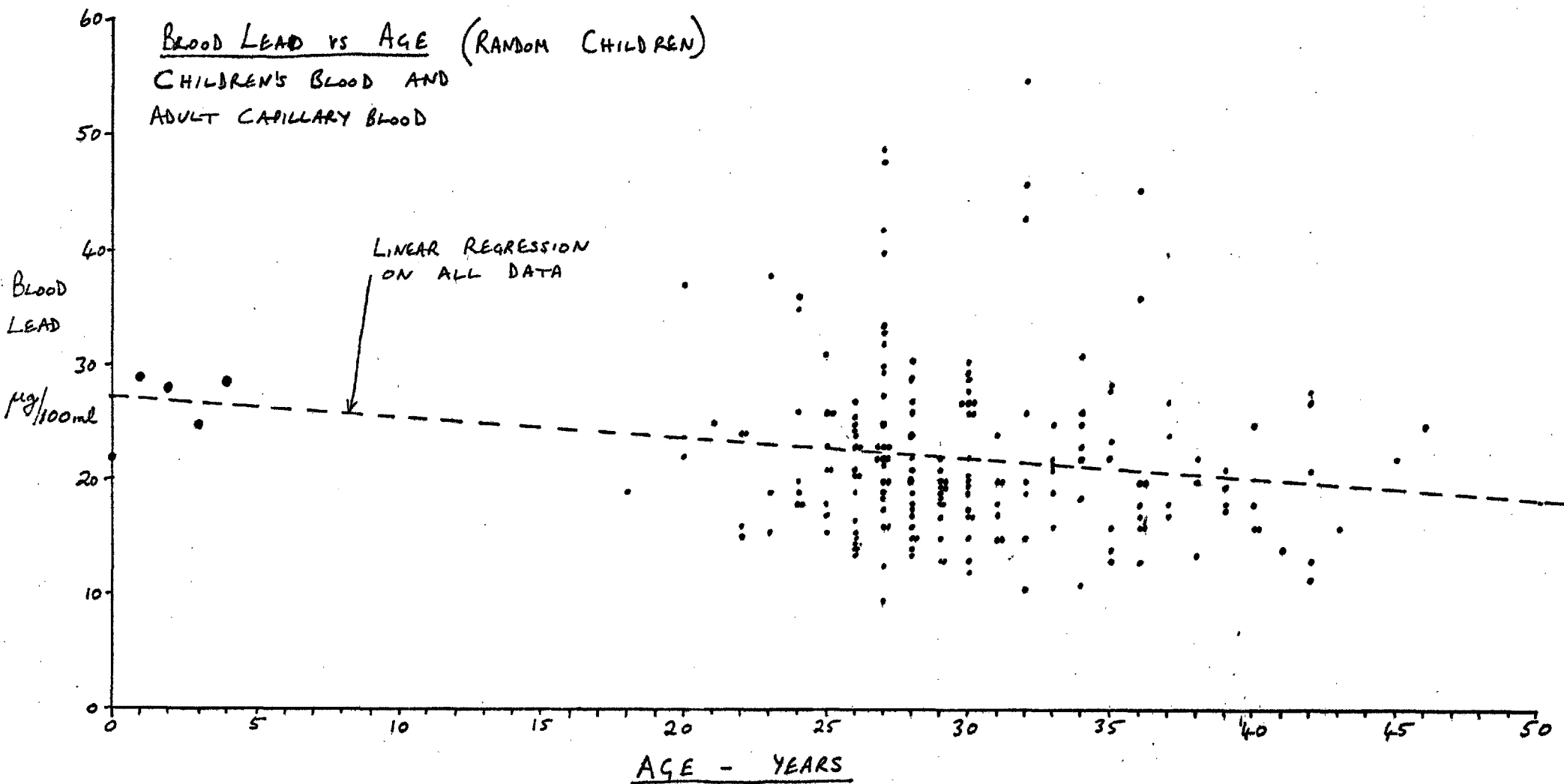
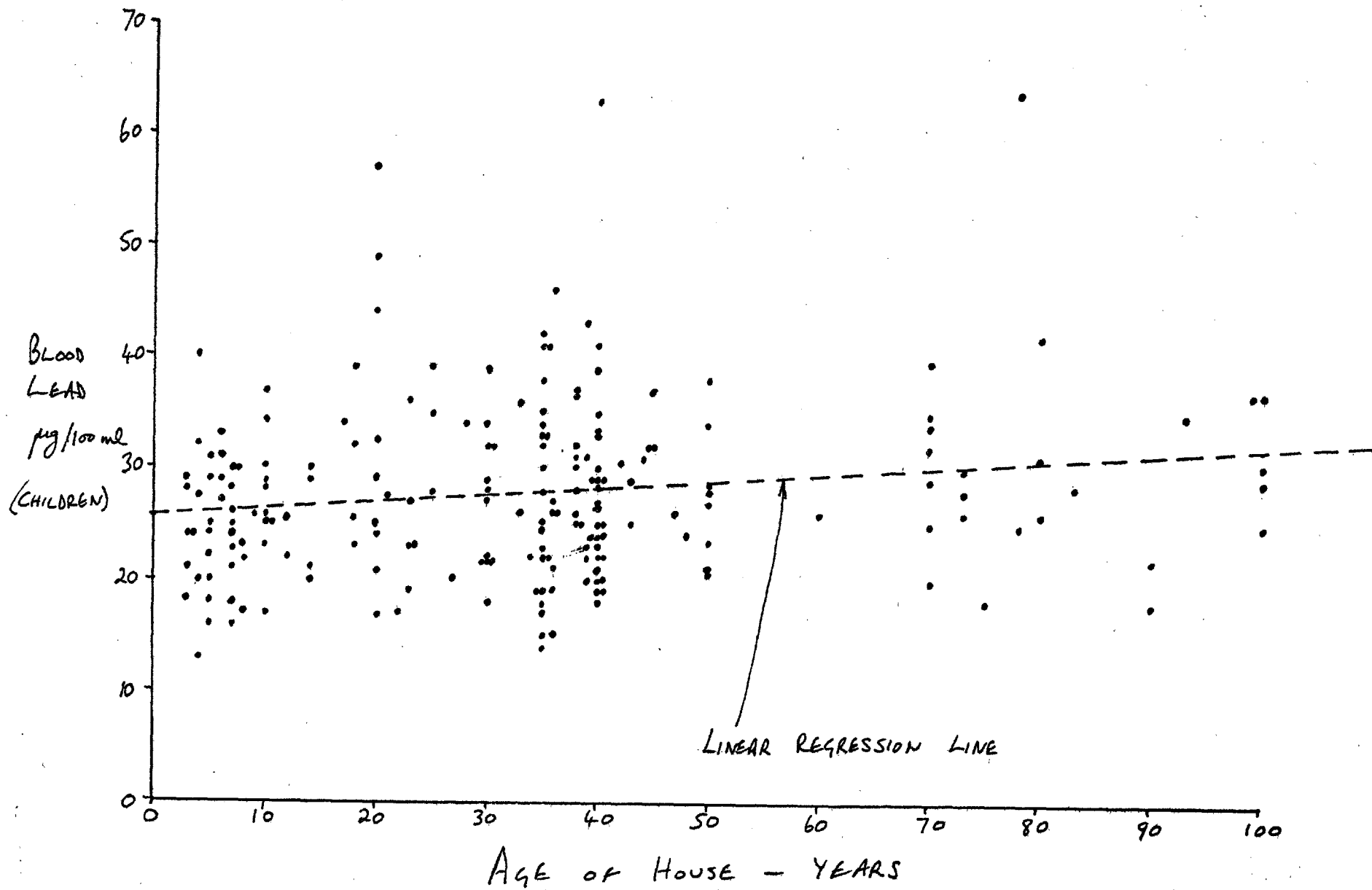


Fig 3.2.8 LINEAR REGRESSION OF BLOOD LEAD AGAINST AGE



BLOOD LEAD OF BIRTH REGISTER CHILDREN VS. AGE OF HOUSE

FIG 3.2.9 / LINEAR REGRESSION OF BLOOD LEAD AGAINST
AGE OF HOUSE

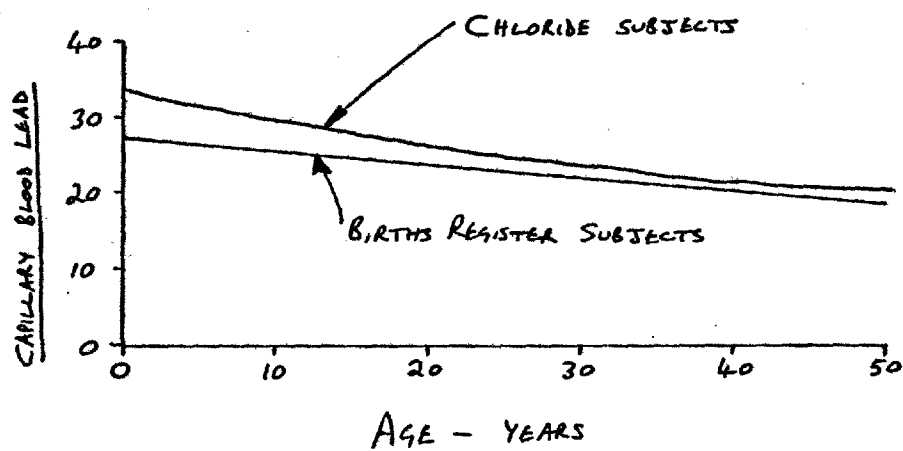


Fig 3.210 - REGRESSION OF BLOOD LEAD AGAINST AGE

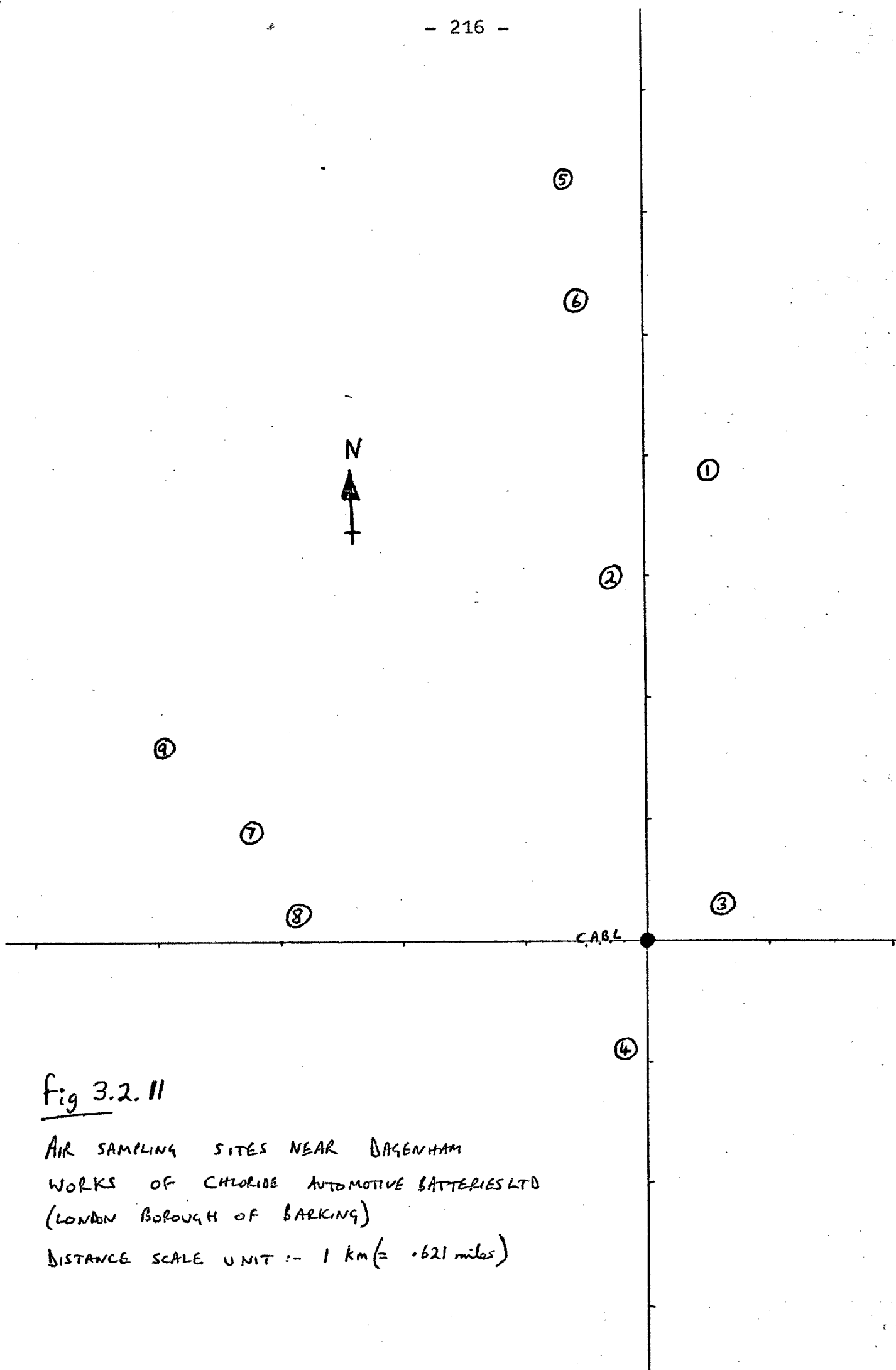


Fig 3.2.11

AIR SAMPLING SITES NEAR BAGENHAM
WORKS OF CHLORIDE AUTOMOTIVE BATTERIES LTD
(LONDON BOROUGH OF BARKING)

DISTANCE SCALE UNIT :- 1 km (= 0.621 miles)

Fig 3.2.12

WIND FROM LEFT TO RIGHT (APPROXIMATELY)

SCALE 1" = 1 km

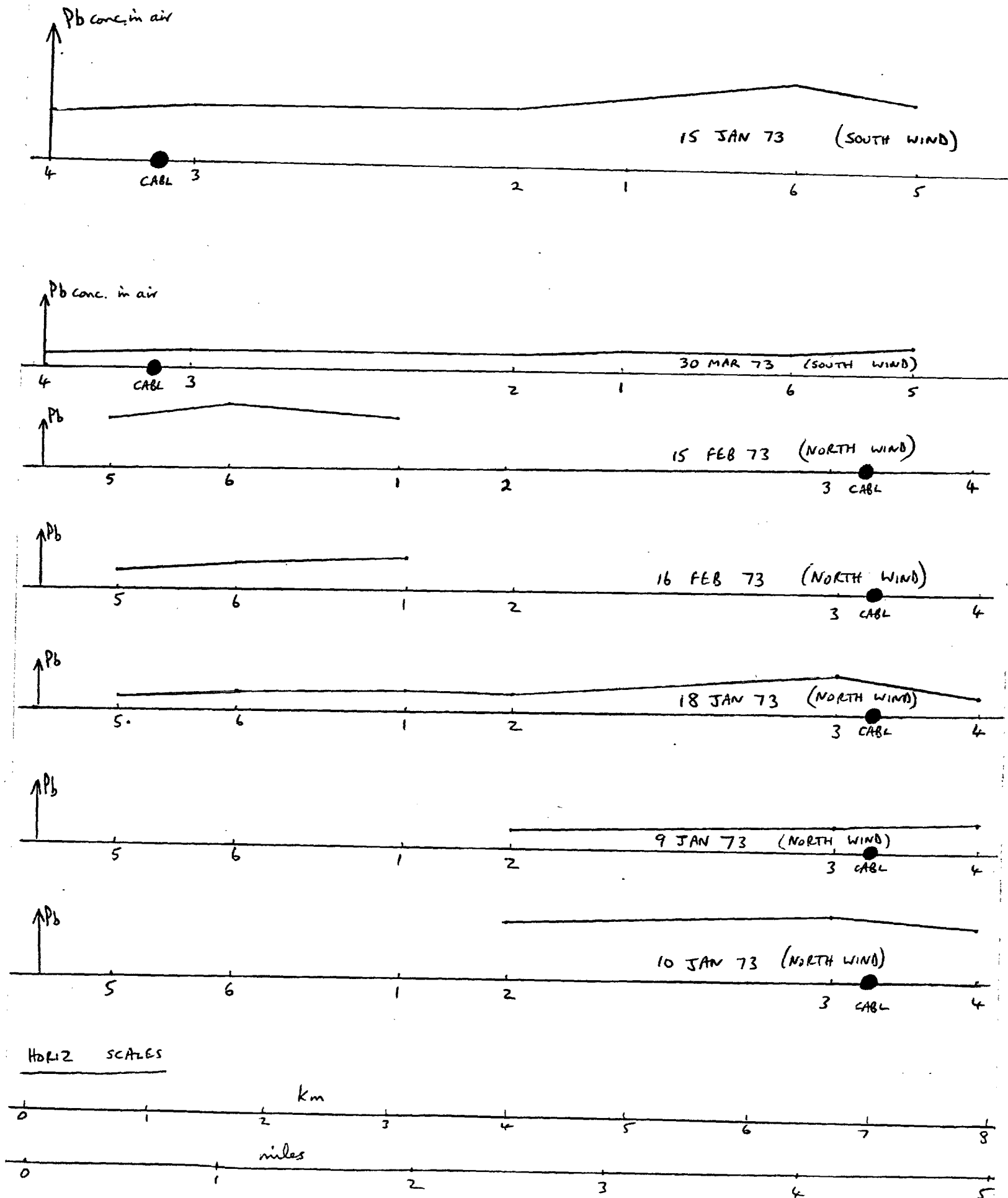
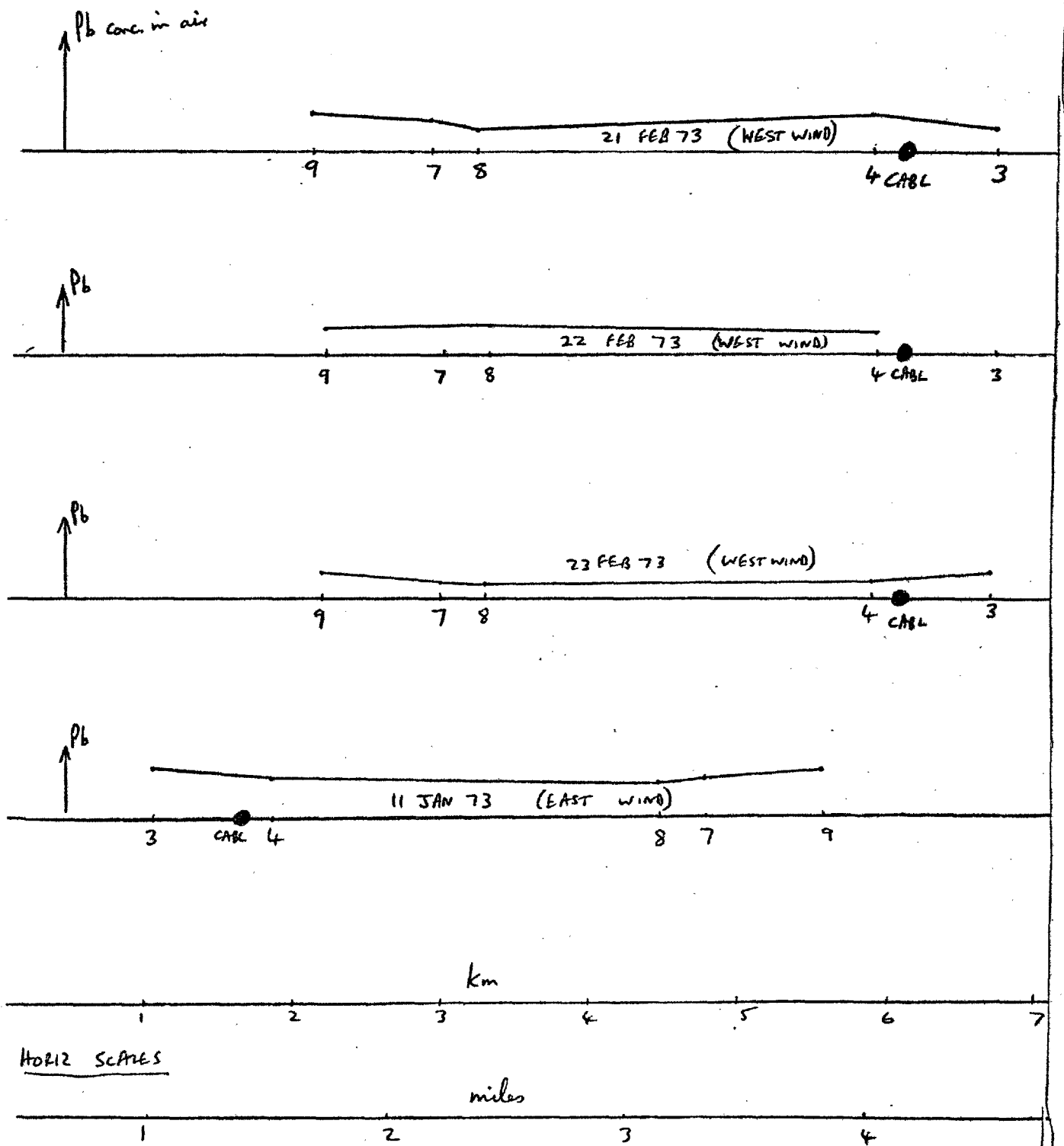


Fig 3.2.13

WIND from LEFT TO RIGHT (APPROXIMATELY)

SCALE 1" = 1 km



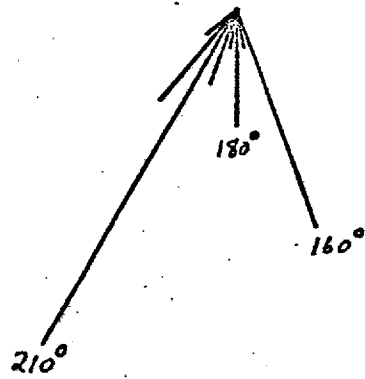


Fig 3.2.14 Wind rose for Dagenham air sampling

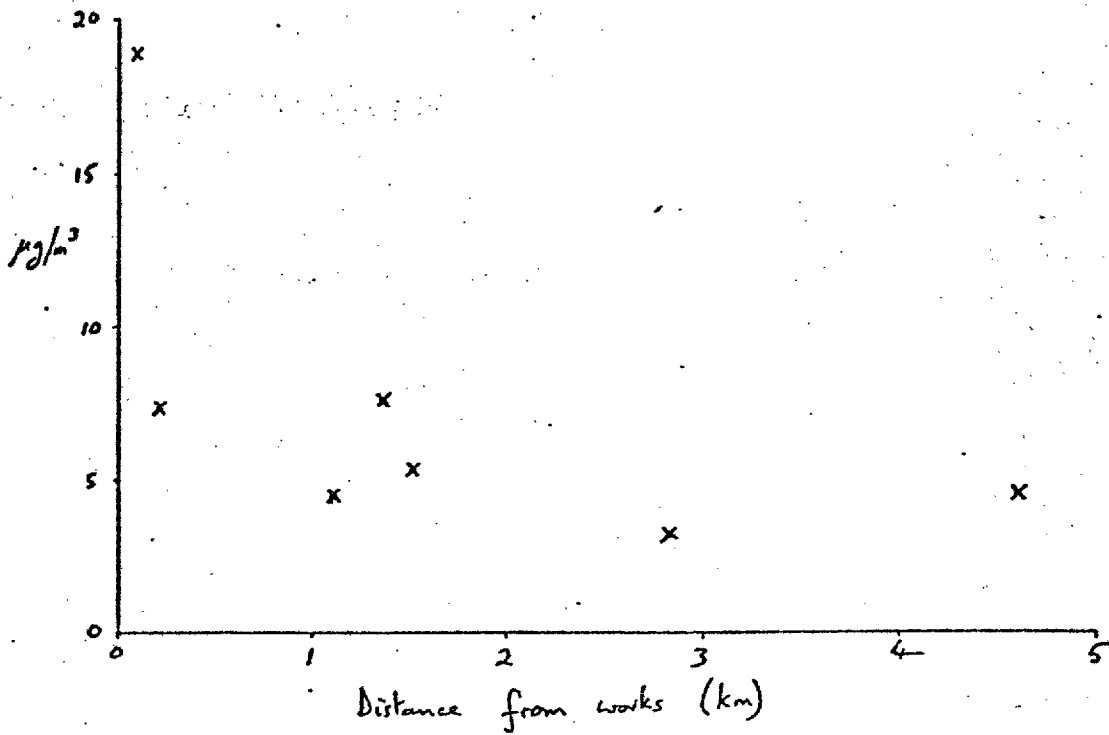


Fig 3.2.15 Variation of concentration with distance

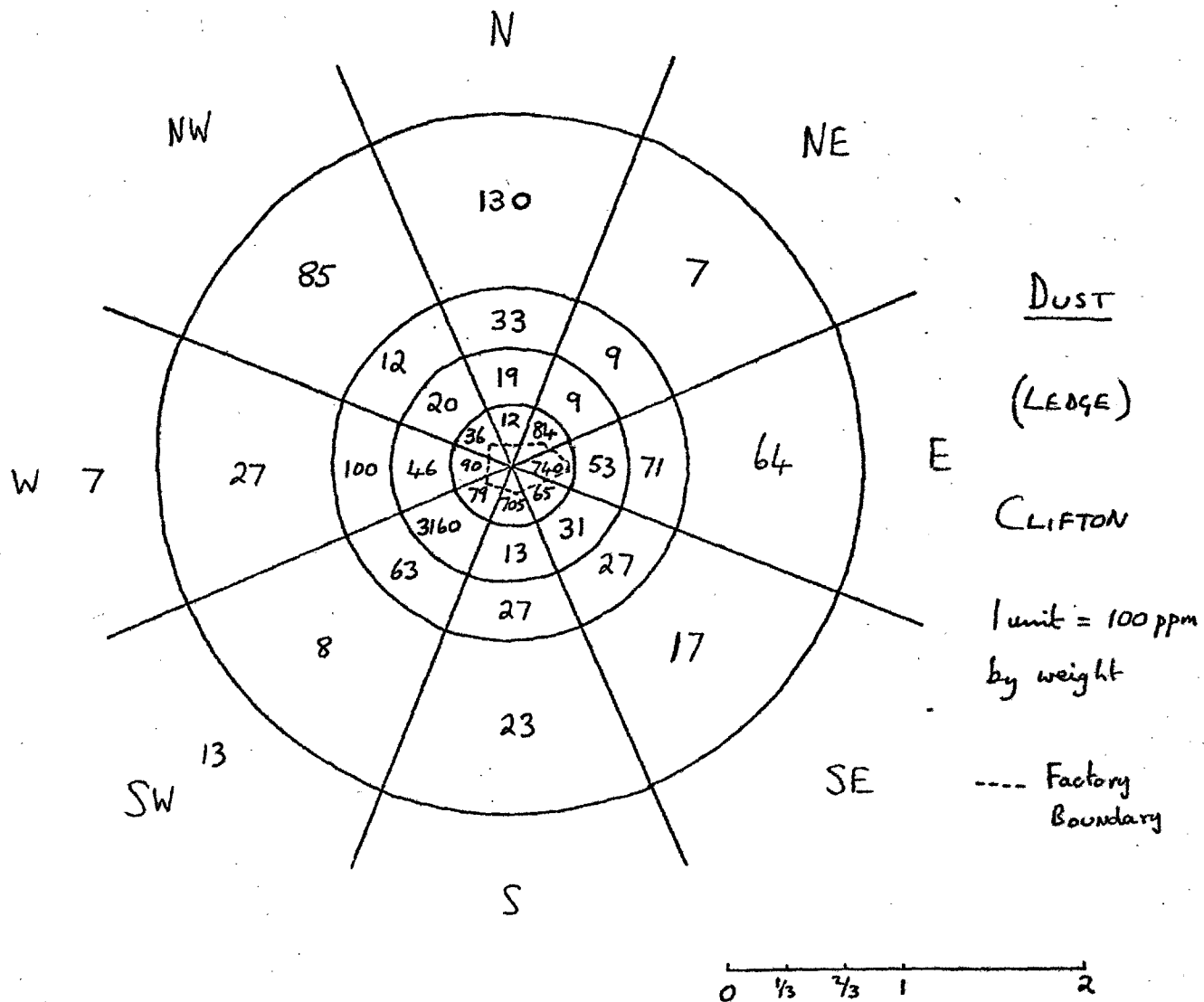


Fig 3.2.16

FIG 3.2.17 LEAD IN DUST VS. DISTANCE

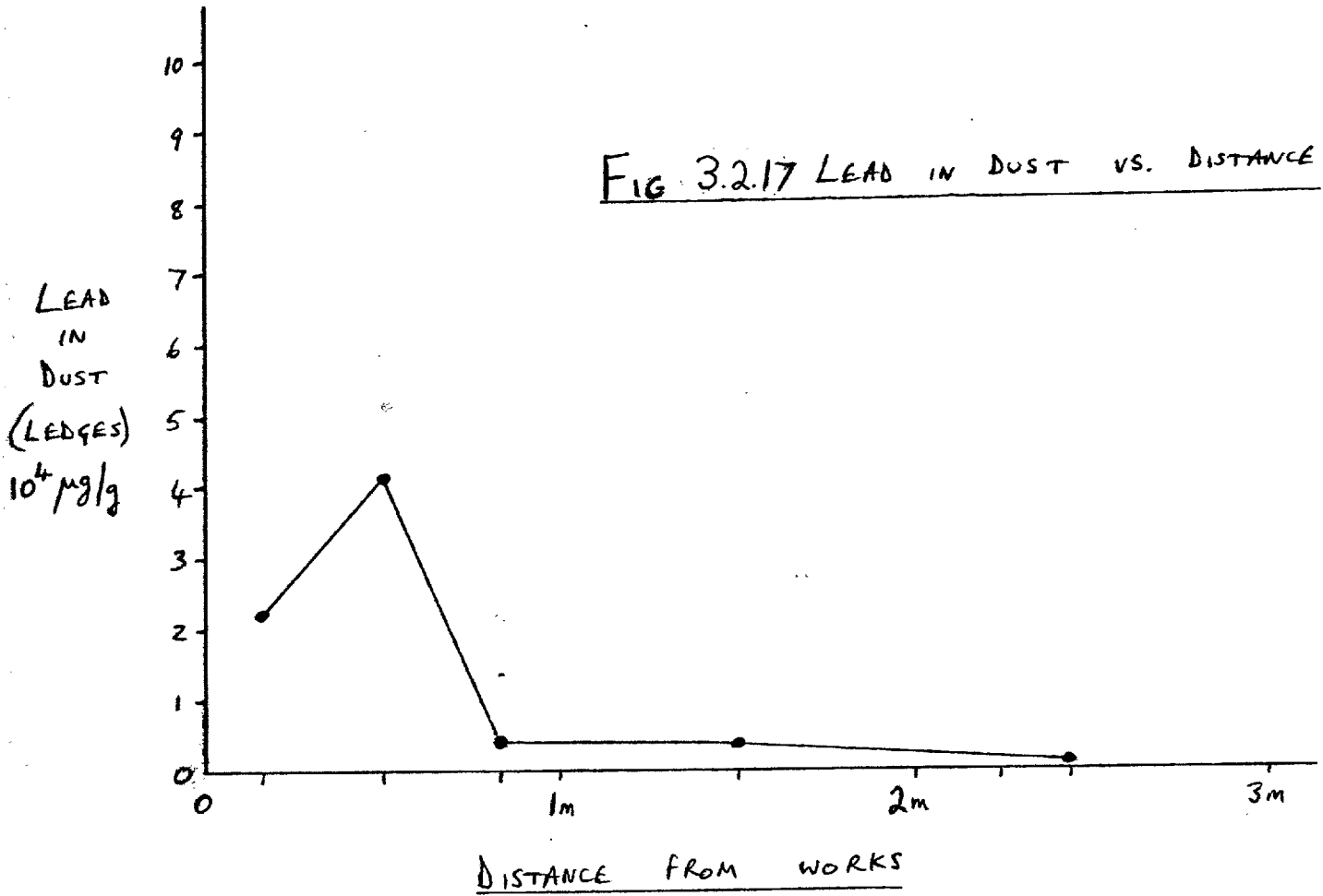


Fig 3.2.18

DUST ON CHLORIDE TRANSPORT ROUTES

CLIFTON

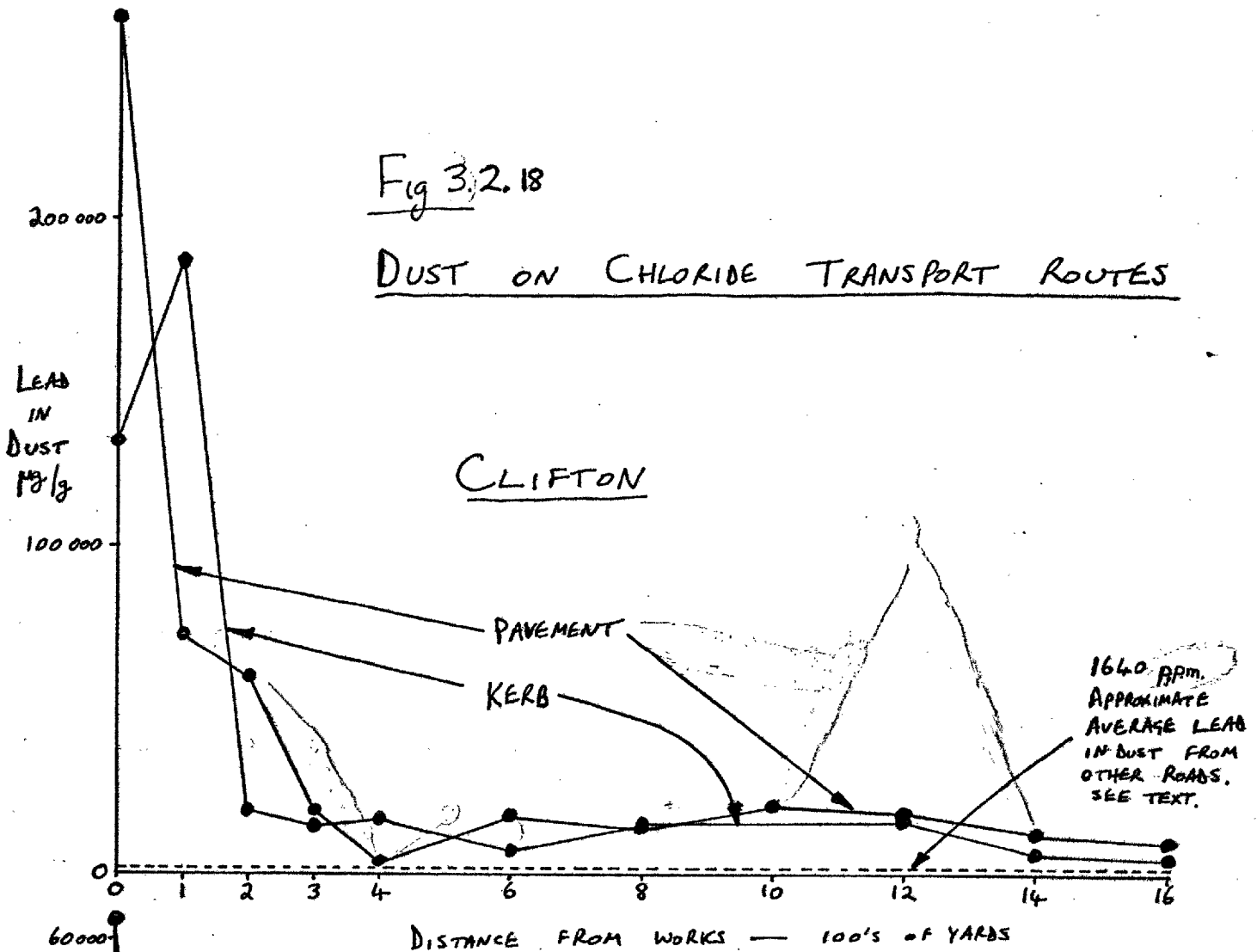
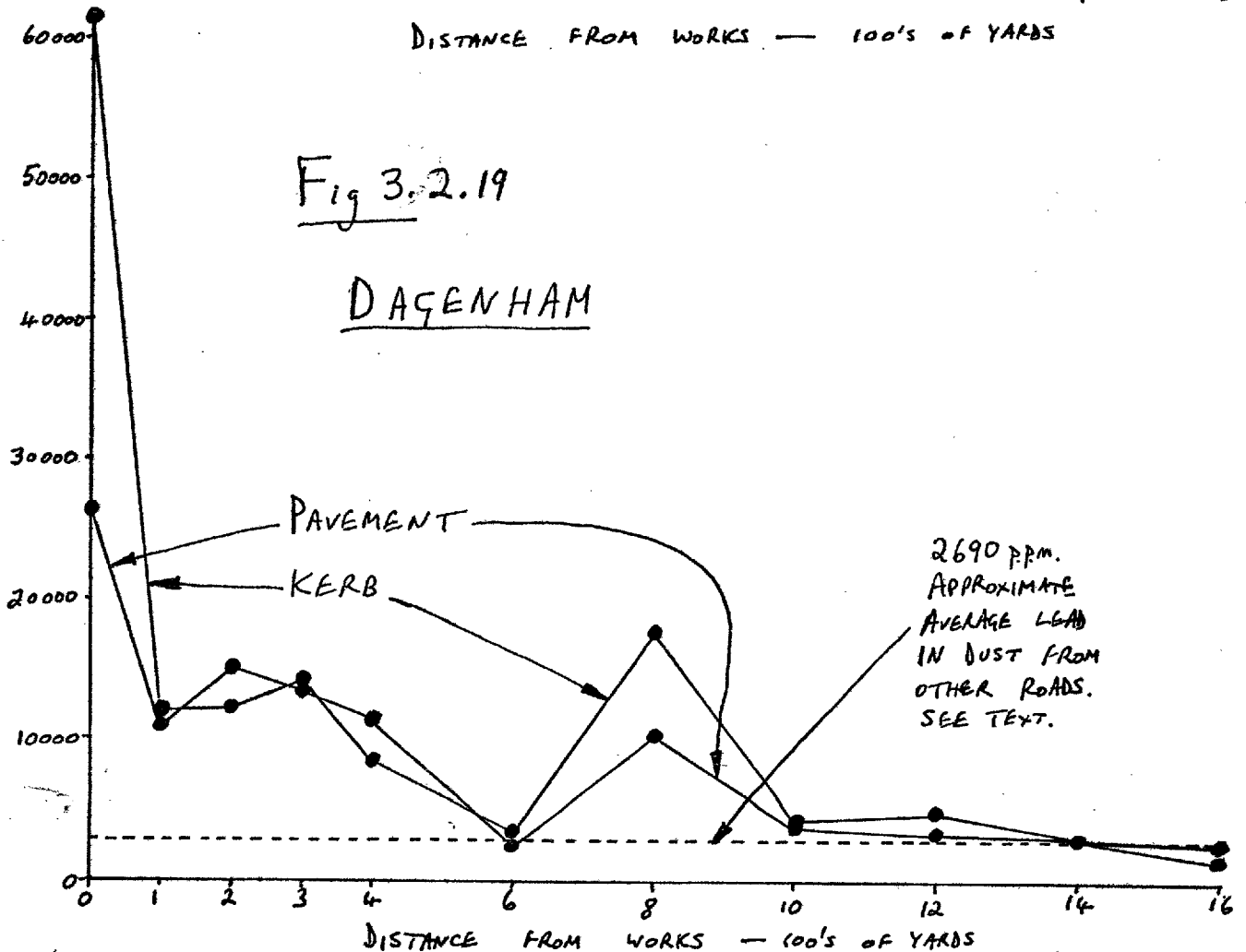
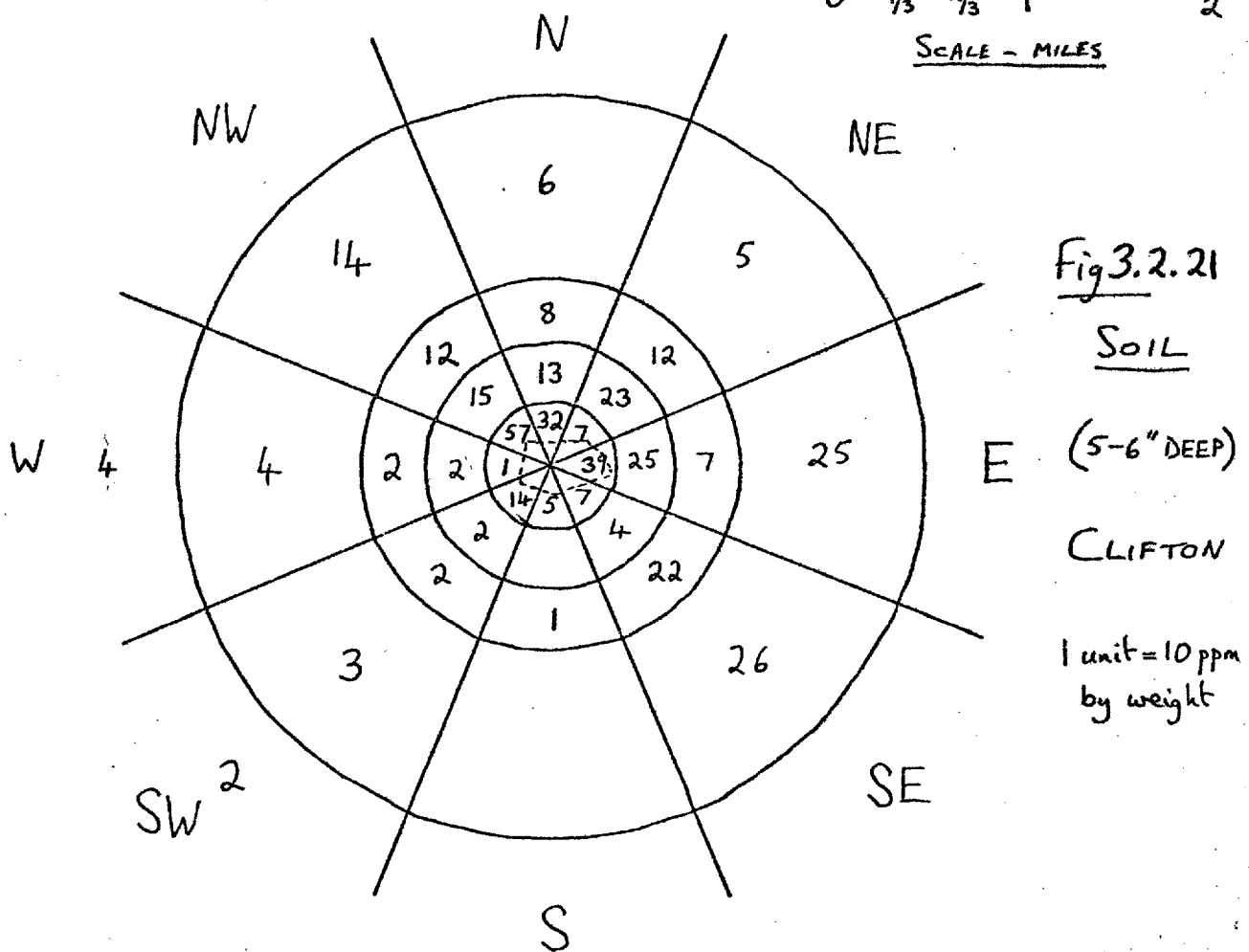
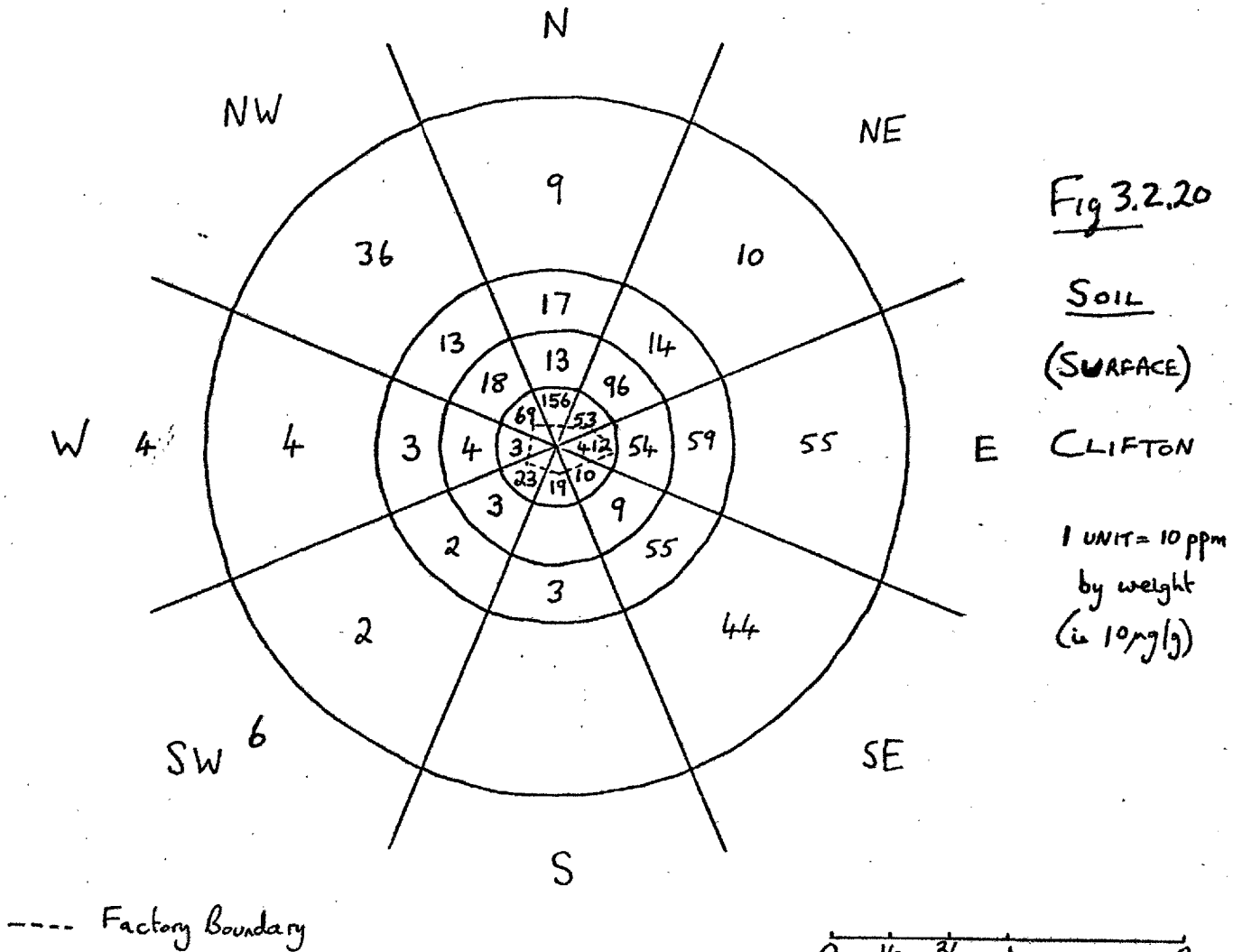
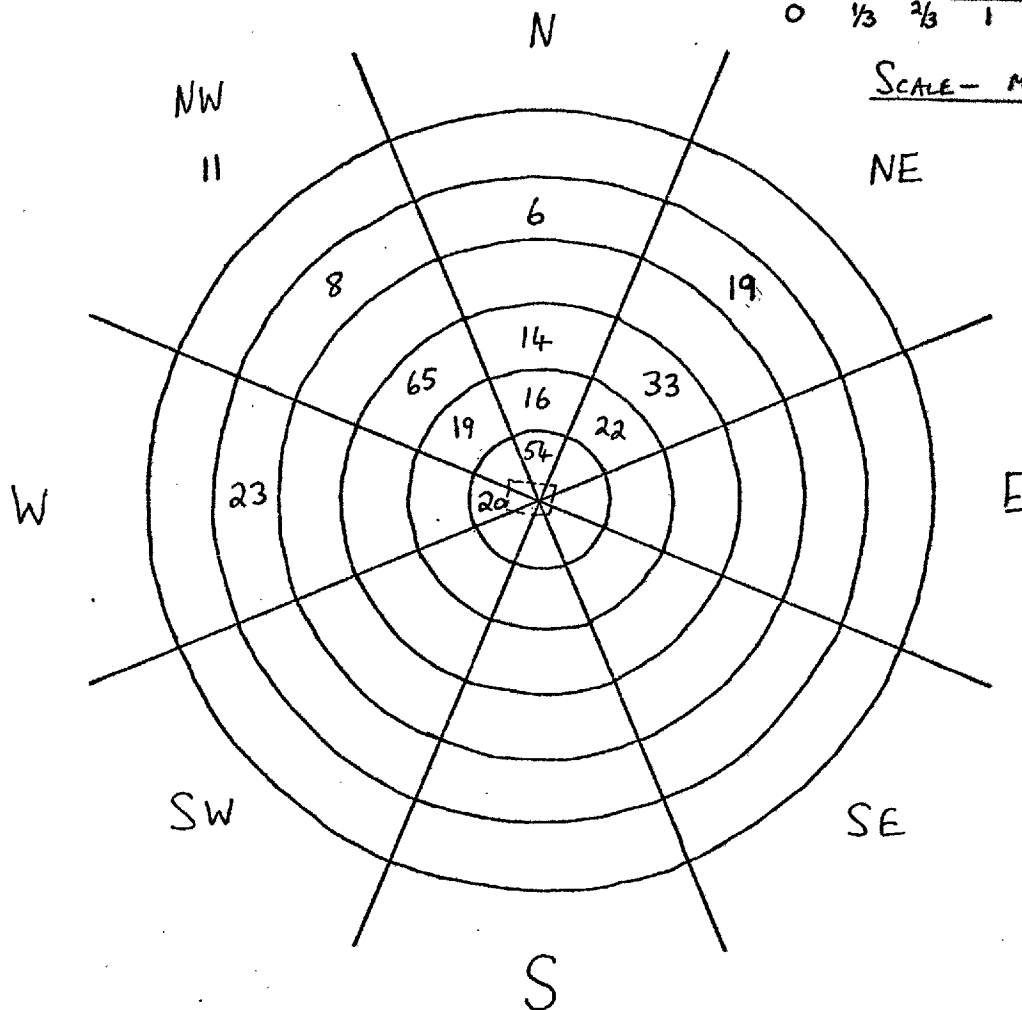
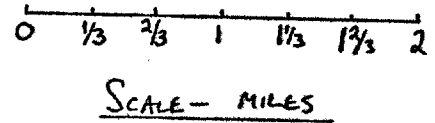
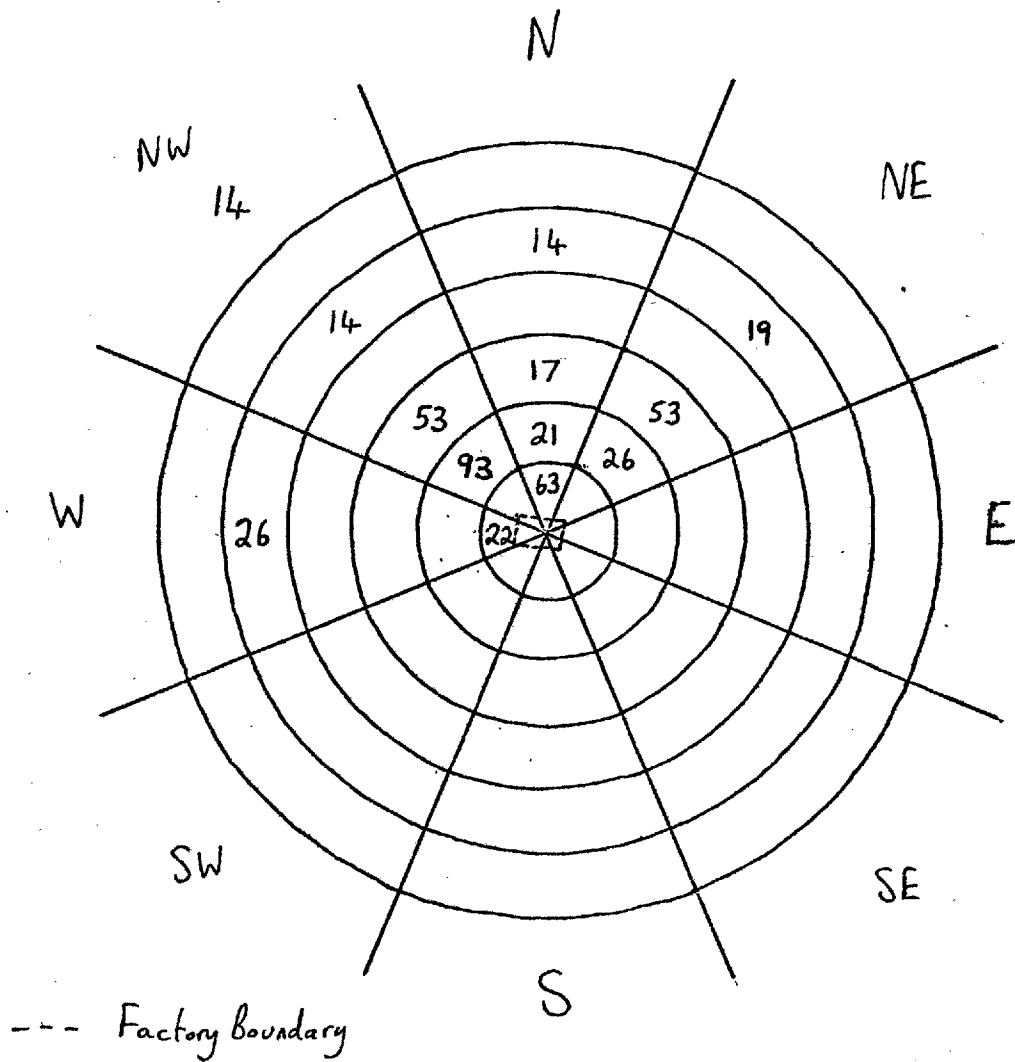


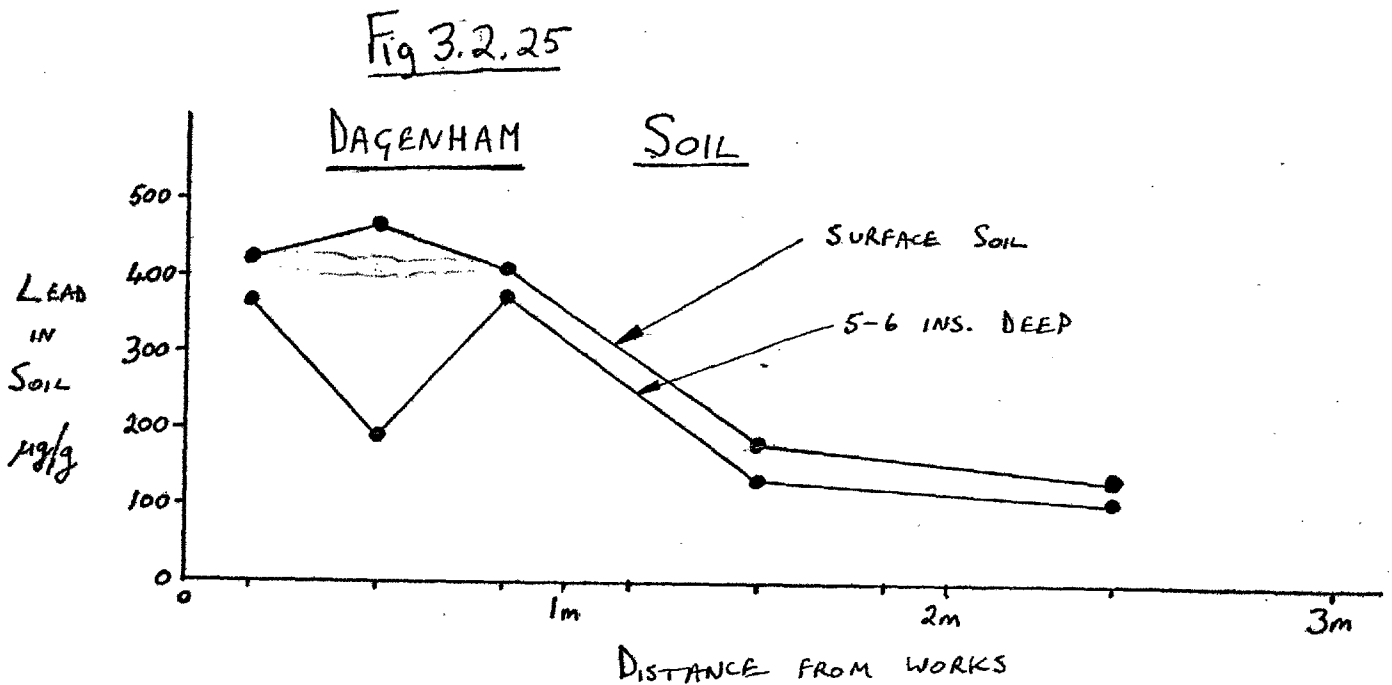
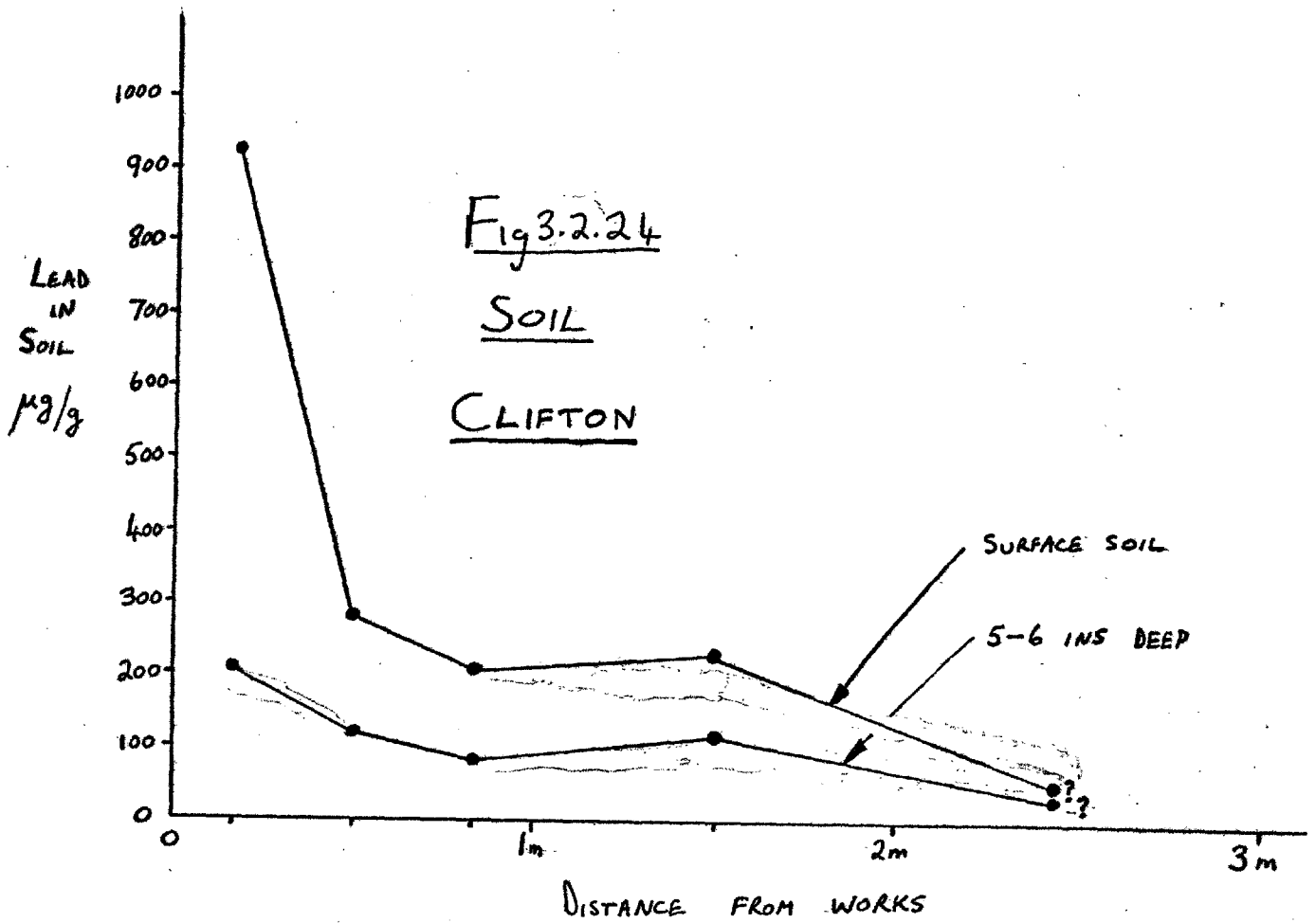
Fig 3.2.19

DAGENHAM









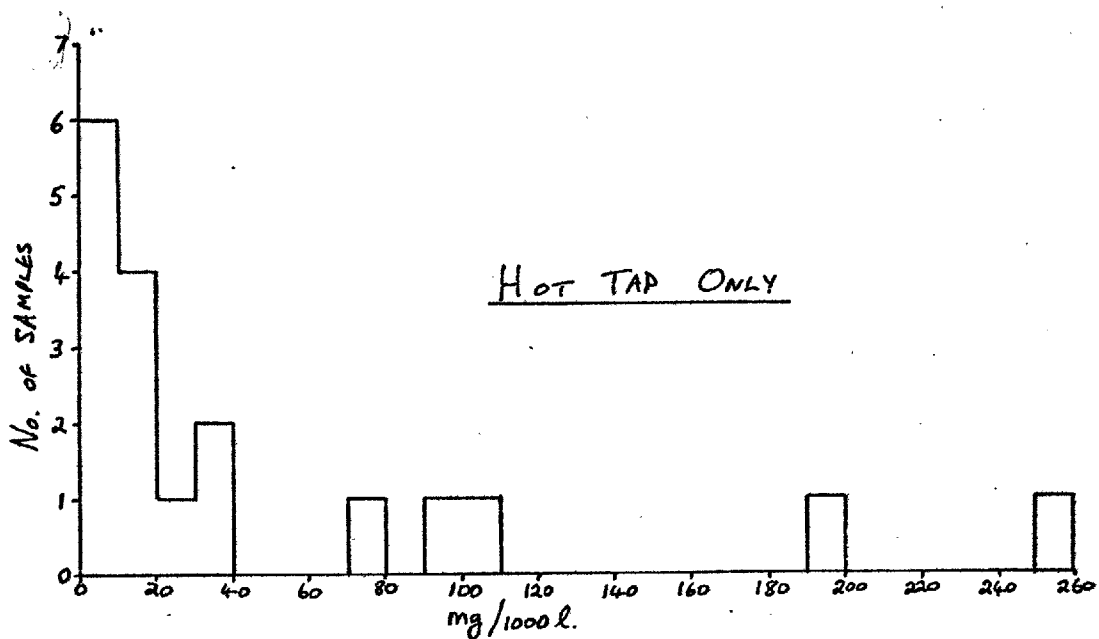
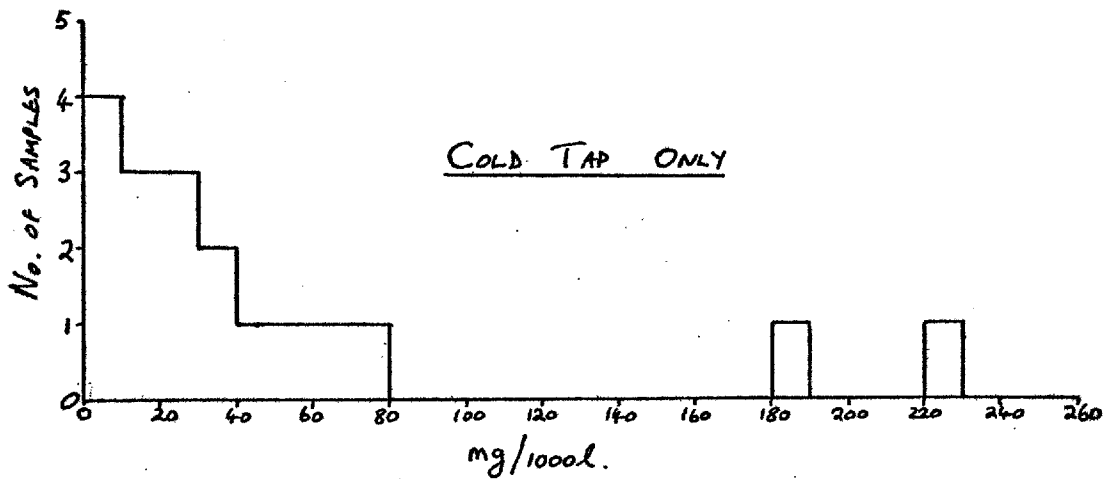
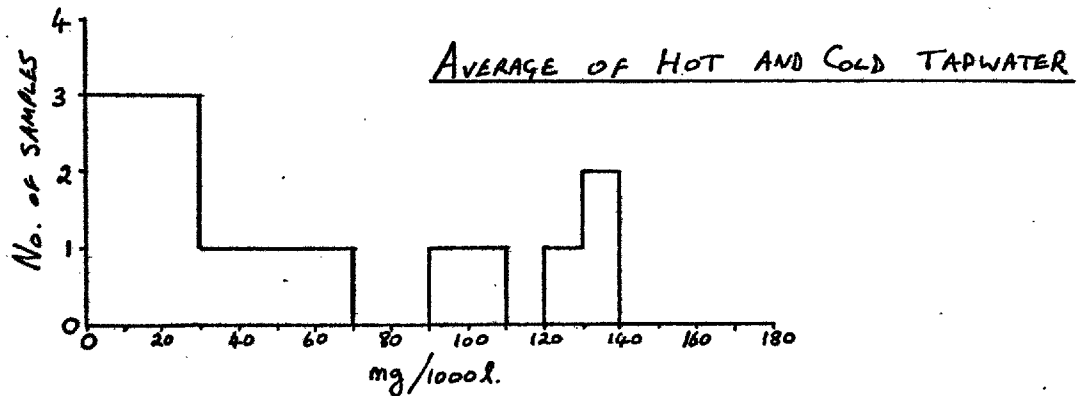


Fig 3.2.26 FREQUENCY DISTRIBUTION OF LEAD CONCENTRATION IN TAP WATER

SAMPLES FROM 18 HOMES IN CLIFTON JUNCTION SURVEY.

1 mg/1000l. = 0.001 ppm.

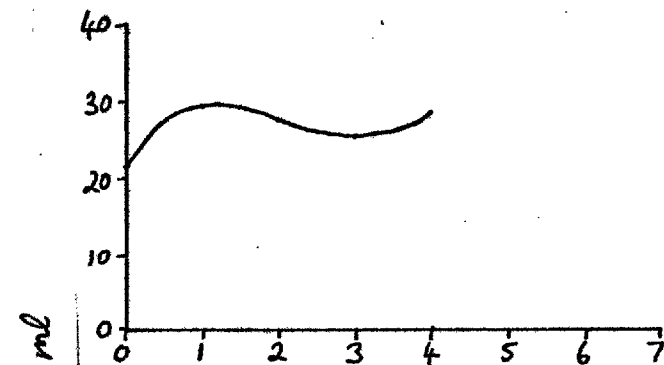


Fig 27a
C.B. vs AGE

$r = 0.26$

99% confidence

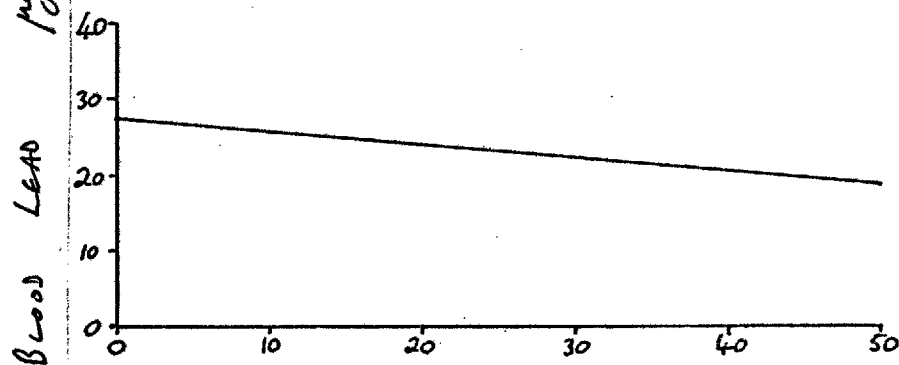


Fig 27b
C.B. and A.C.B. vs AGE

$r = 0.31$

99% confidence

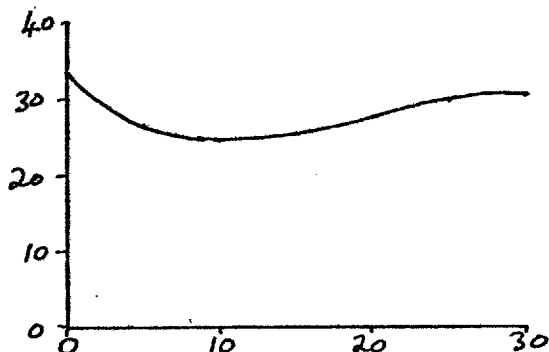


Fig 27c
C.B. vs LENGTH OF RESIDENCE

$r = 0.22$

95%

FIG 3.227 REGRESSIONS OF BIRTHS REGISTER RESULTS

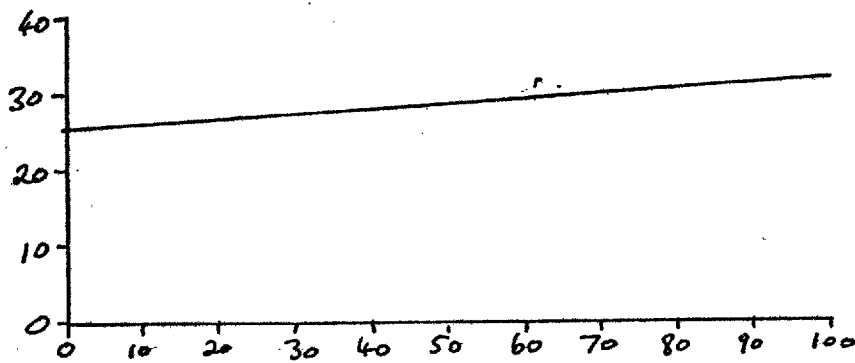


Fig 27d
C.B. vs AGE of House

$r = 0.18$

99%

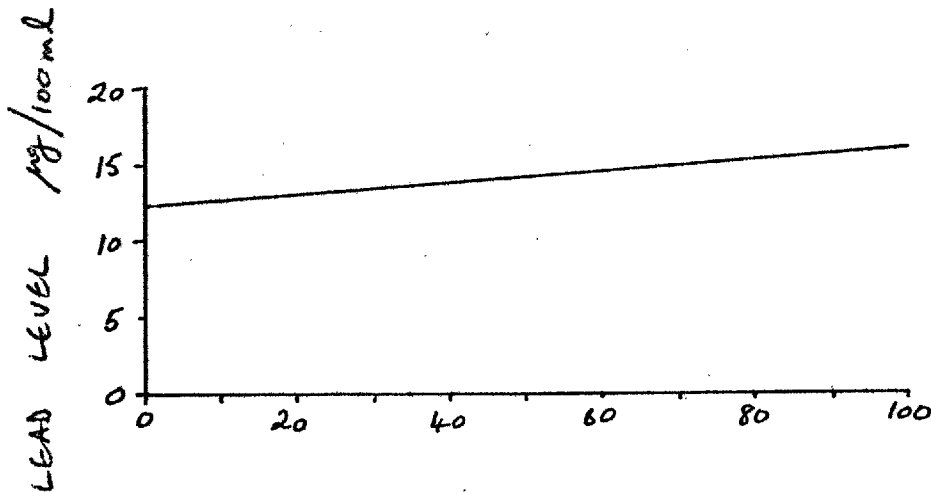


Fig 27e
AV.B. vs AGE of House

$r = 0.19$

95%

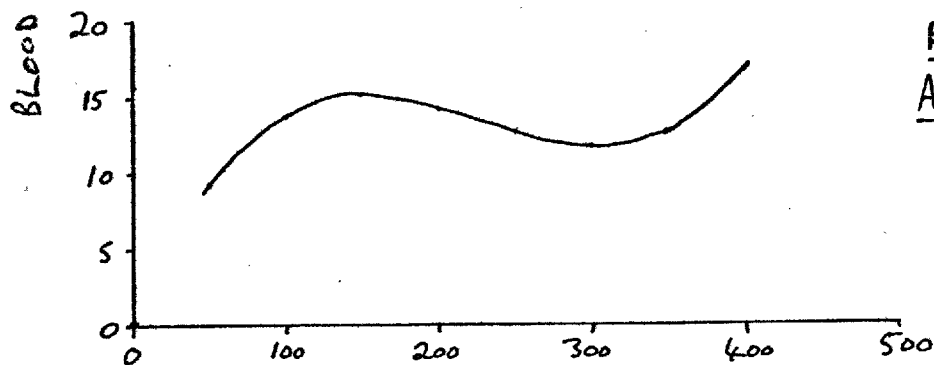


Fig 27f
AV.B. vs RATEABLE VALUE

$r = 0.27$

95%

Fig 3.2.27 - contd.

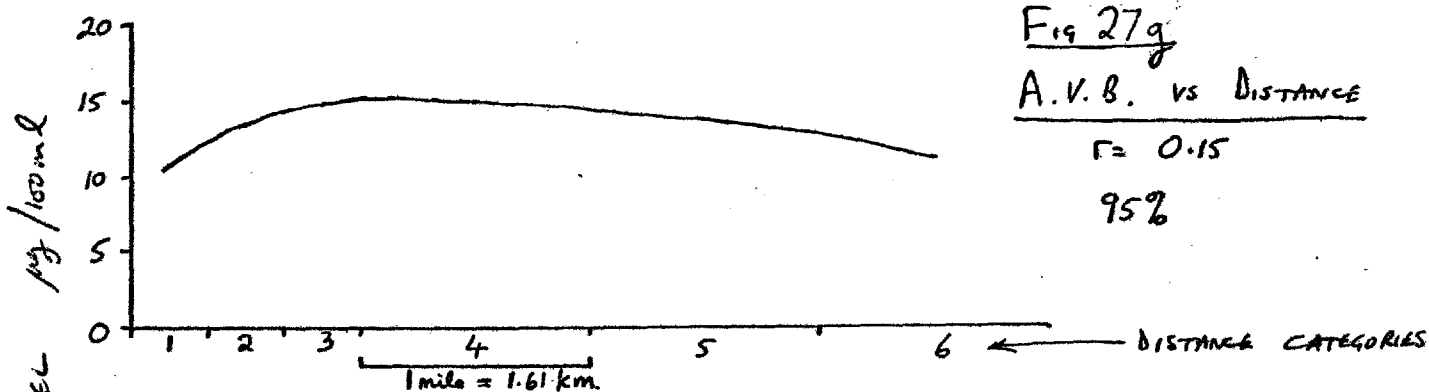


Fig 27g
A.V.B. vs DISTANCE
 $r = 0.15$
95%

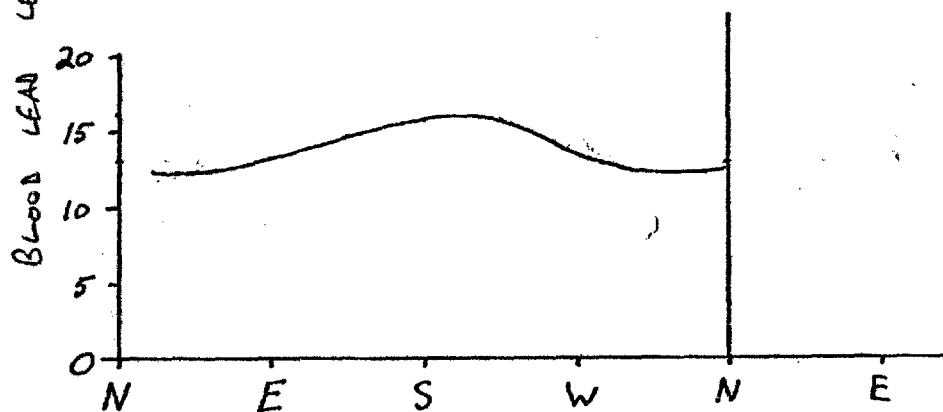


Fig 27h
A.V.B. vs DIRECTION
 $r = 0.25$
95%

Fig 3.2.27 - contd.

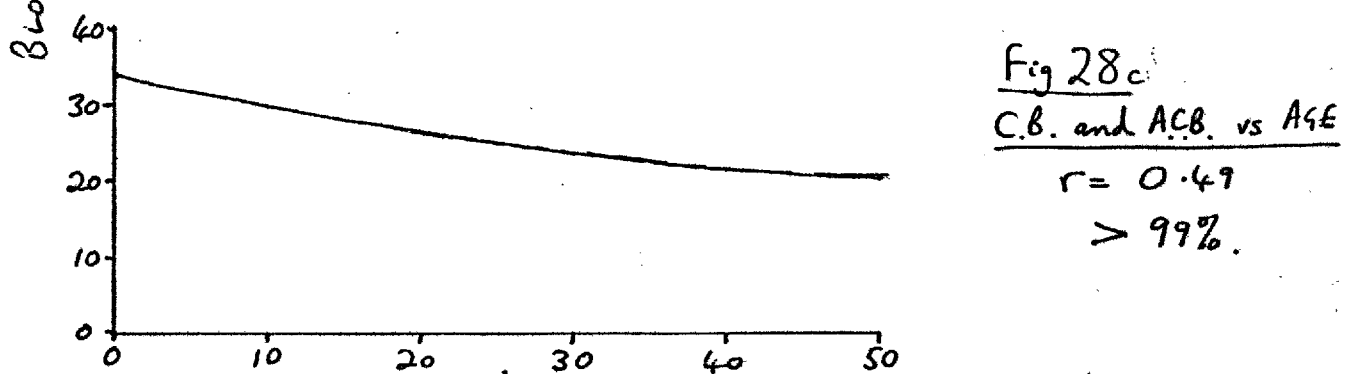
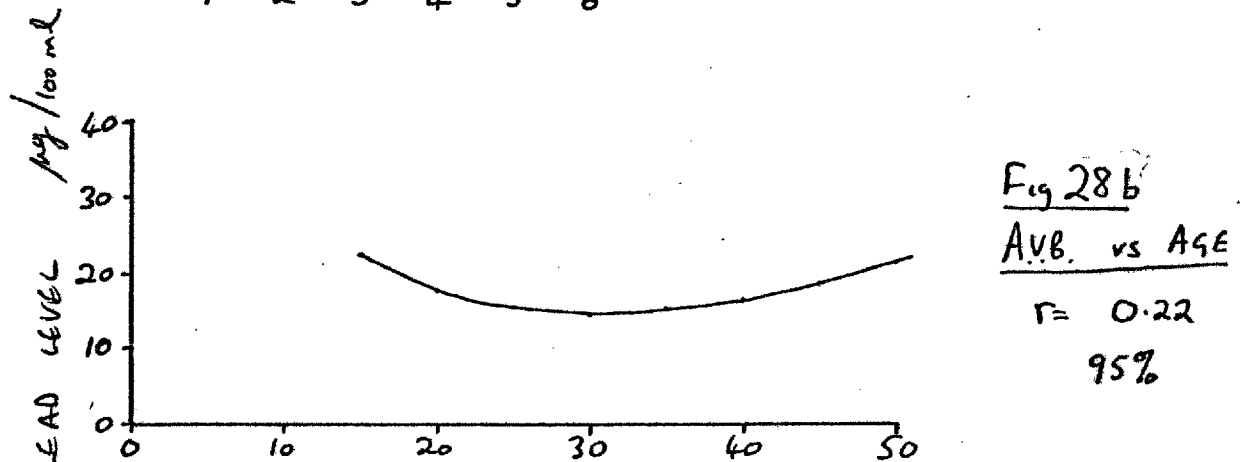
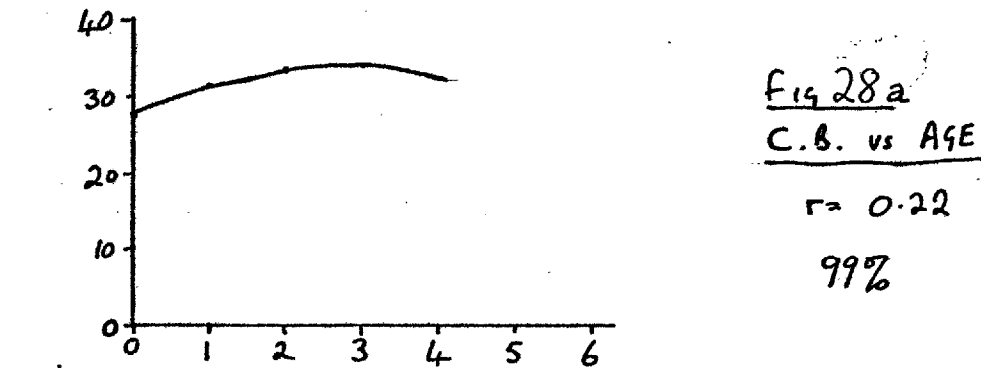


FIGURE 3.2.28 REGRESSIONS OF LEADWORKER'S FAMILIES RESULTS

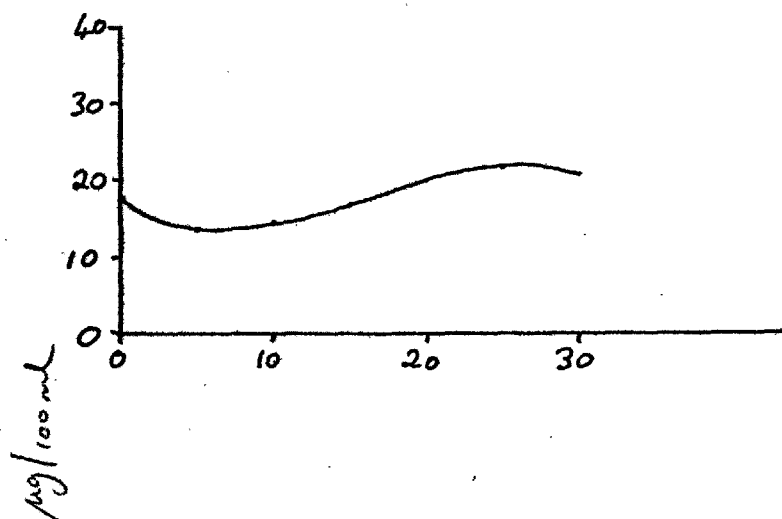


Fig 28d
A.V.B. vs LENGTH OF RESIDENCE

$$r = 0.25$$

99%

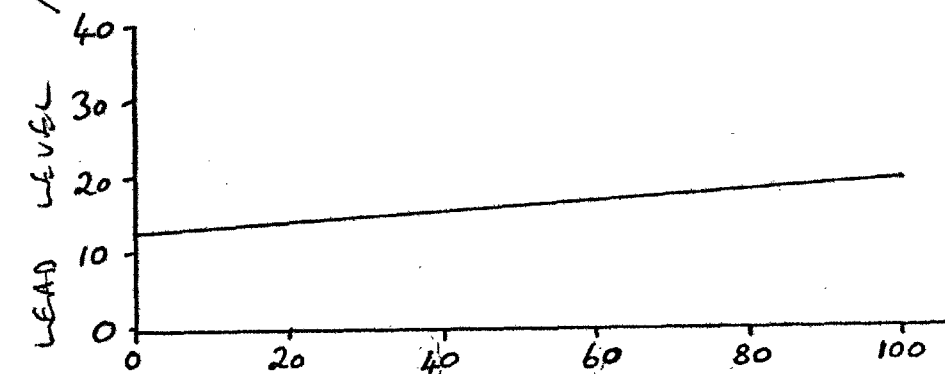


Fig 28e
A.V.B. vs AGE OF HOUSE

$$r = 0.33$$

99%

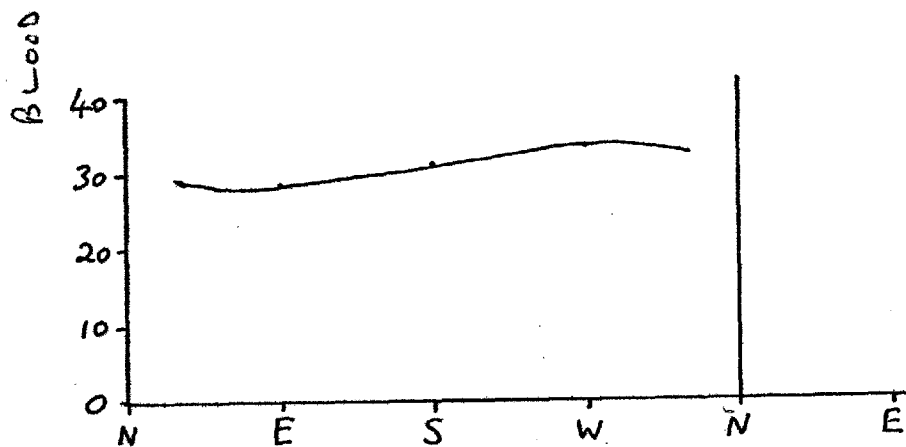
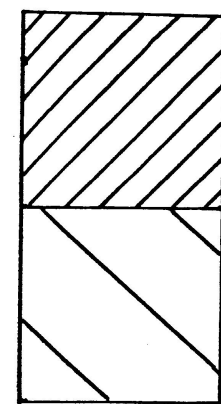


Fig 28f
A.V.B. vs DIRECTION

$$r = 0.19$$

99%

Fig 3.2.28— contd.



BUILT-UP AREAS

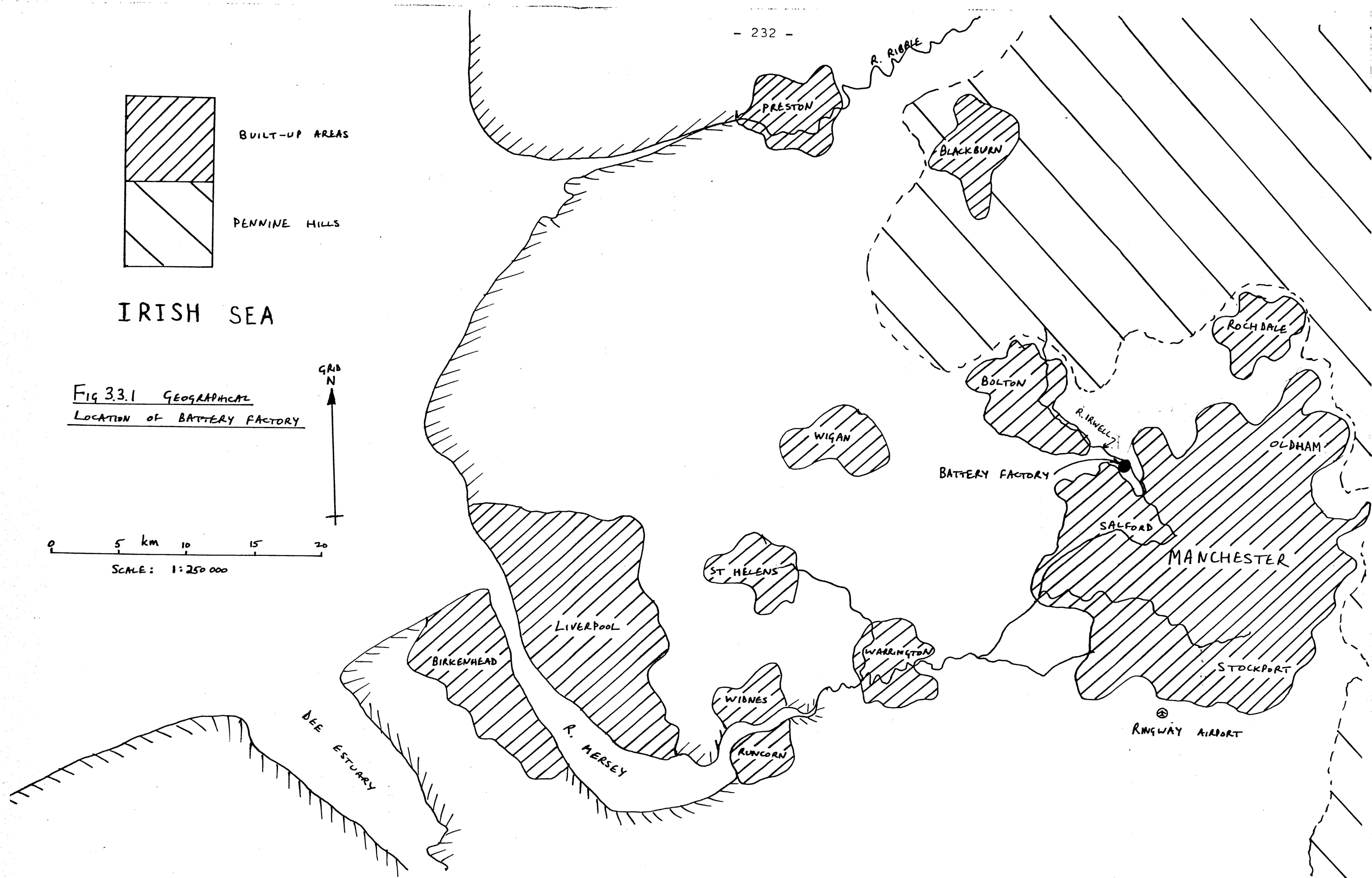
PENNINE HILLS

IRISH SEA

Fig 3.3.1 GEOGRAPHICAL
LOCATION OF BATTERY FACTORY



0 5 km 10 15 20
SCALE: 1:250 000



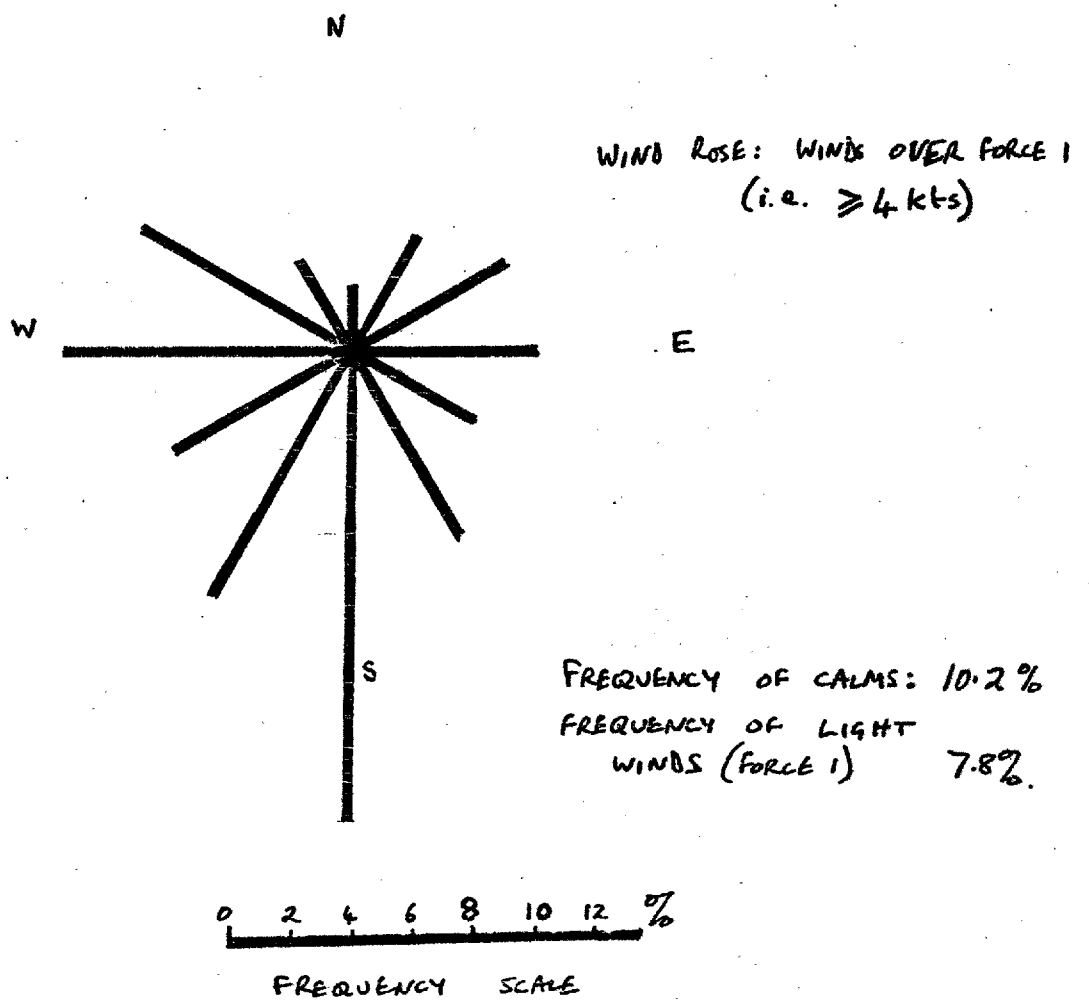


Fig 3.3.2 WIND ROSE FOR RINGWAY AIRPORT 1960-9

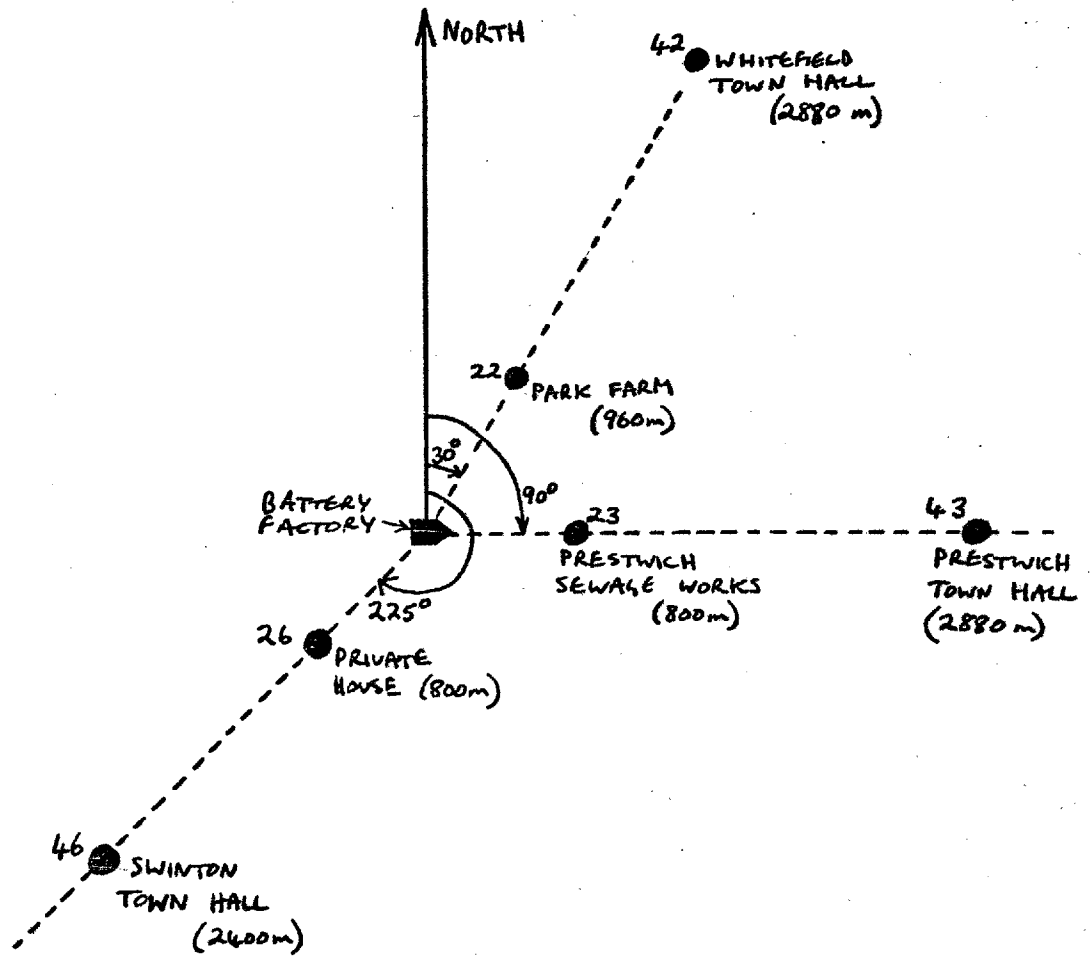


Fig 3.3.3. Location of Air Sampling Sites.

N.B. Code letters adjacent to site markers were used to identify site during computer analysis. Distances to battery factory in brackets.

FIGURE 3.3.4.1

STRONG WINDS (FILE 12)

RINGWAY DIRECTION

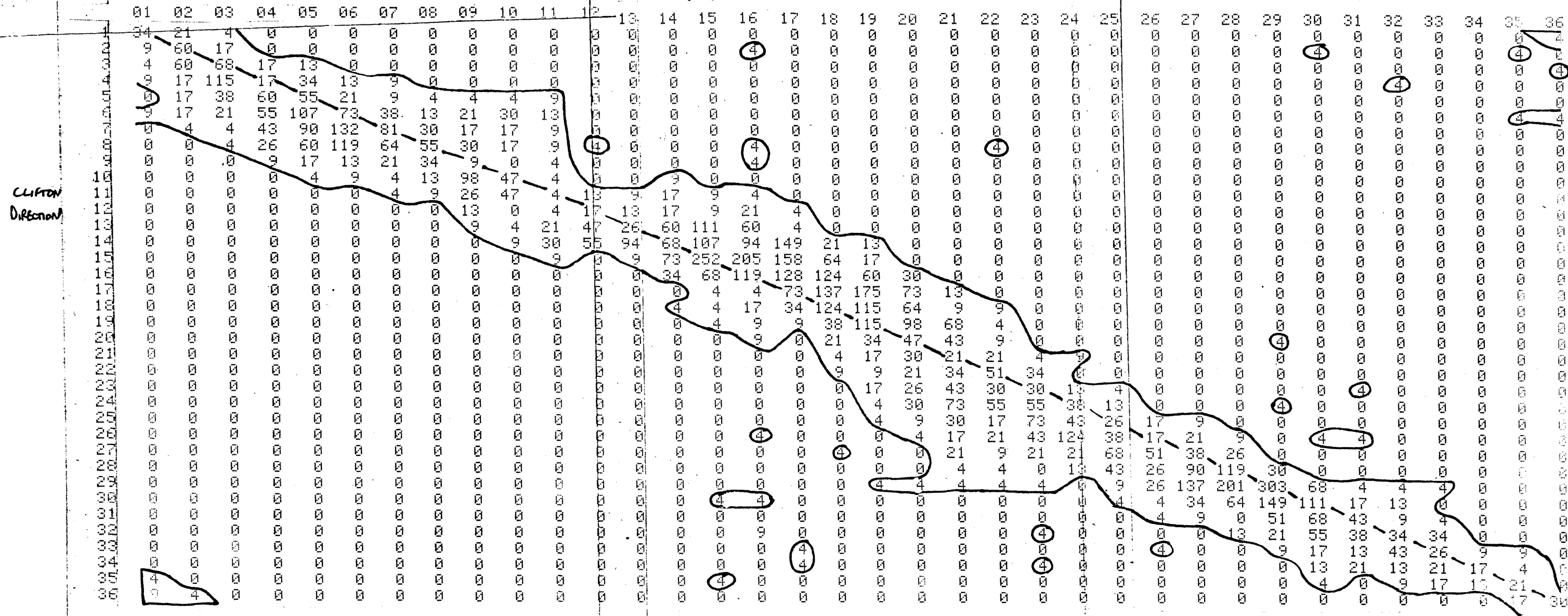


FIGURE 3.3.4.2

CLASS B.1 (FILE 14)

[illegible]

FIGURE 3.3.4.3

CLASS B2 (FILE 15)

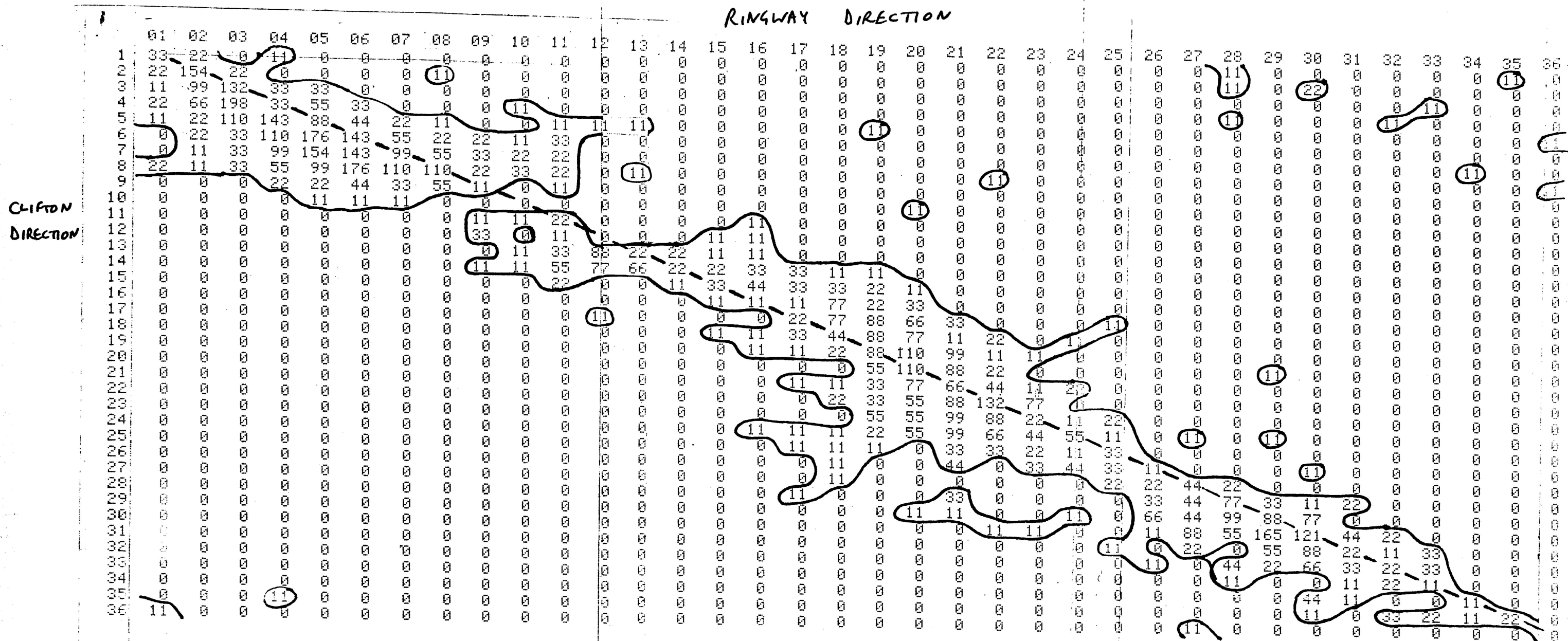


FIGURE 3.3.4.4
CLASS C (FILE 16)

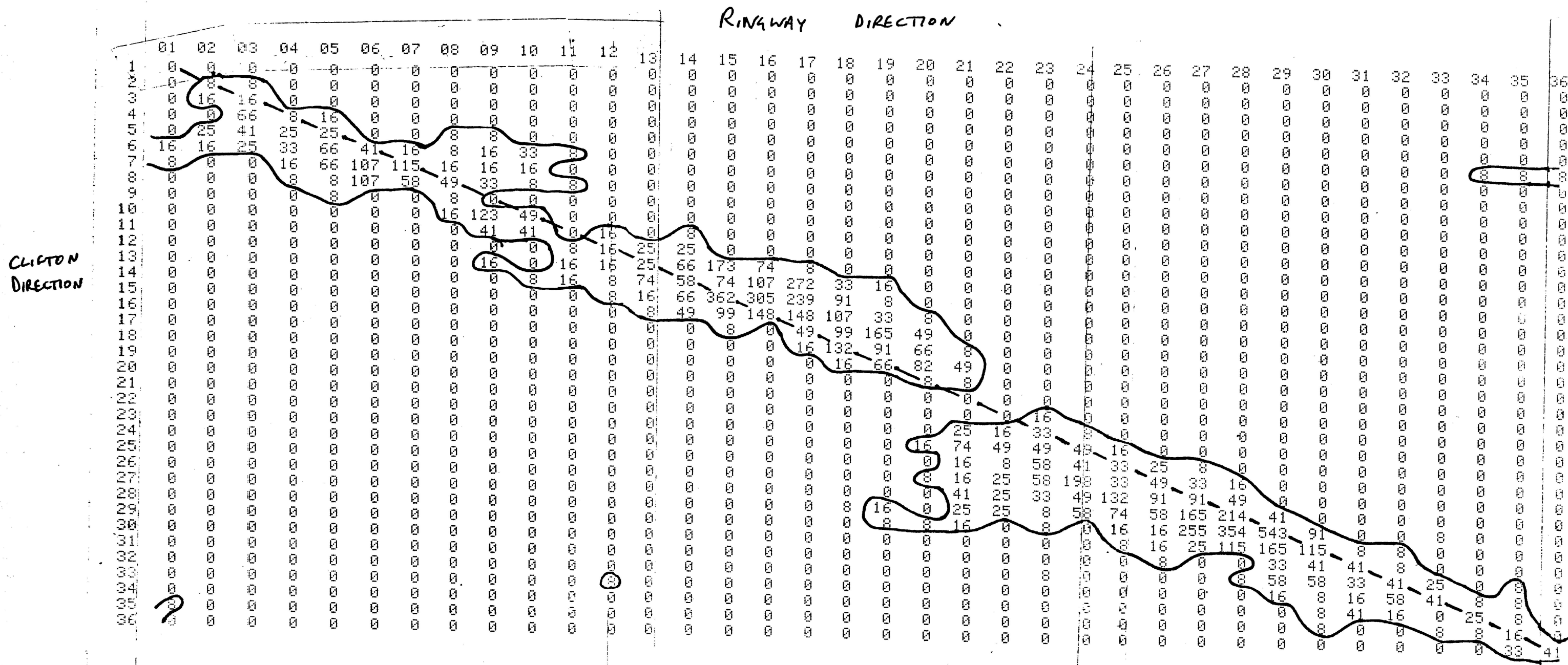


FIGURE 3.3.4.5

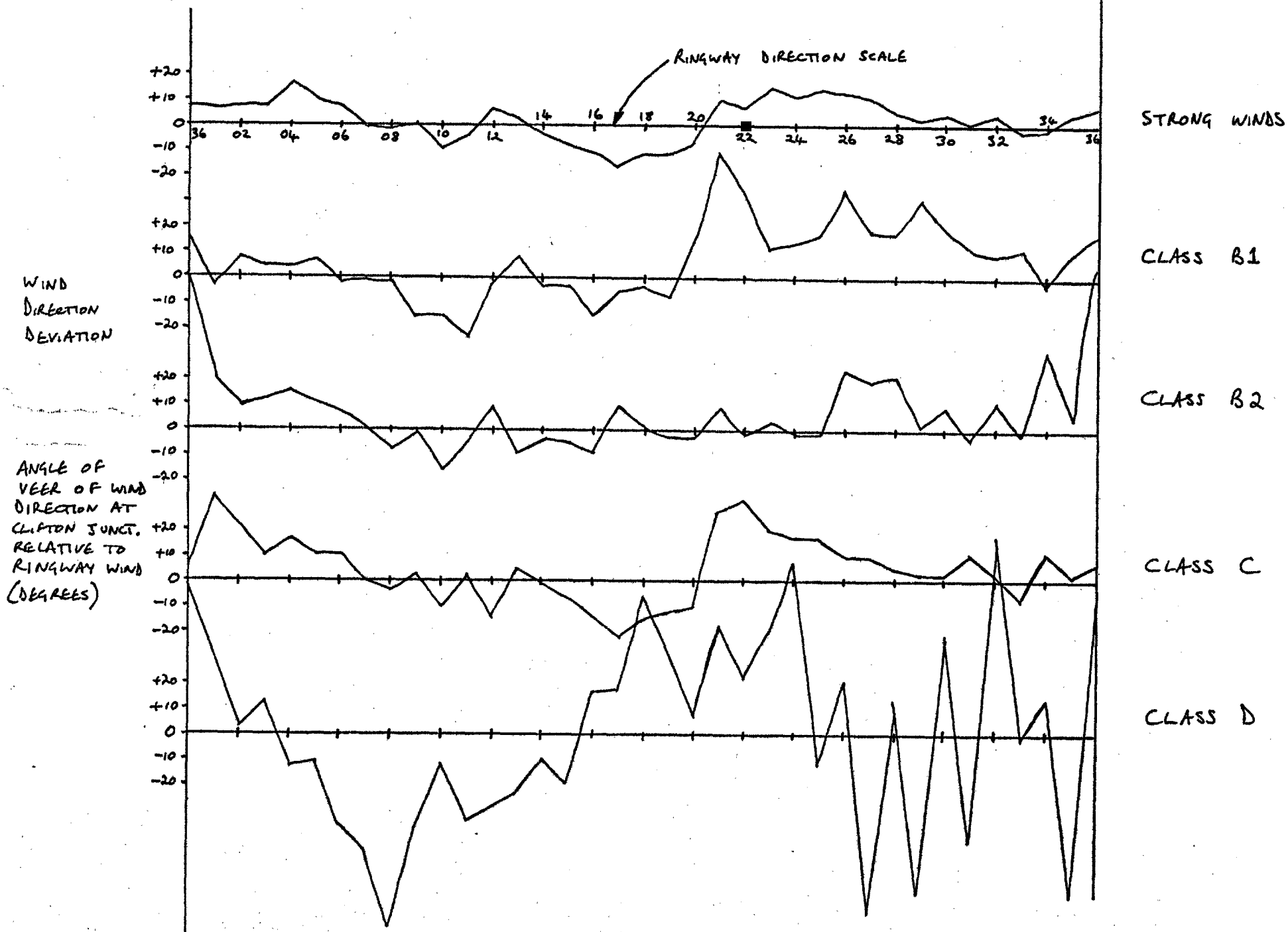
CLASS D (FILE 17)

RINGWAY DIRECTION

CLIFTON
DIRECTION

[illegible]

FIGURE 3.3.5 WIND DIRECTION DEVIATIONS



4.0 REVIEW OF IMPLICATIONS OF THE CASE STUDIES FOR AIR POLLUTION PREDICTION MODELS

4.1 Local Meteorological Effects

In an air pollution model designed for use in planning industrial developments, we are clearly concerned with long-term impact, expressed both as average concentrations and as average frequencies of peaks. For predictions in this form, the expected pattern of local weather is required as a data input and several of the case studies have indicated that the generation of an accurate description of local winds may not be straightforward.

4.1.1 The Importance of Local Weather Deviations

In the battery factory study (Section 3.3) a detailed analysis of the differences in wind frequencies at two different sites near Manchester was made. This showed that while a high degree of correlation was in evidence most of the time, in certain weather conditions there were significant departures, and these included the case of stably stratified atmosphere, which is important because of the associated poor dispersion characteristics. The Forest Farm study (Section 2.1) also identified this case and provided direct experimental (rather than statistical) evidence of it using simultaneous measurements of wind and temperature profiles as well as wind strength and direction measurements. The incinerator study (Section 2.2) showed that the distribution of wind directions at a site could be significant in exacerbating an existing air pollution problem.

Aspects of local meteorological effects and the implications for theoretical models are discussed in detail in the following subsections.

4.1.2 Katabatic Wind Effects

In stable weather, katabatic winds may be expected to develop and these will often cause the wind direction to align itself in the down-slope direction. Unfortunately, the evidence of Sections 3.3 and 2.1 tends to show that the onset of these conditions is not uniquely related to any particular set of routinely-observed parameters, although the probability of such winds increases towards certainty as the duration of a period of surface cooling increases. It would seem from the records in Section 2.1 that the katabatic wind may start some 3 hours after the onset of stable conditions and this could be used in a model in the absence of any direct observations at the site.

Alternatively, statistical correlations can be used to indicate the frequency of katabatic wind effects, and indeed such methods can be used as a general tool to handle all local variations. The limiting factor in this approach lies in the statistical significance of the correlations. In the context of stable conditions and katabatic winds this is illustrated by Figure 3.3.4.5 which gives the scatter diagram between Clifton Junction and Ringway wind directions for Brookhaven D conditions. For Ringway directions around $160-180^{\circ}$ there are two probable situations at Clifton: firstly winds around 160° to 170° and secondly winds between 290 and 350° . The

latter winds may be either katabatics or heat island effects or both, while the former indicate a relatively strong general wind which dominates local effects over a large area. It is not possible from the data used to know which of these conditions will occur at Clifton on any particular occasion. Moreover, it is not even certain that the relative frequency of these two states is correct, since the correlation has been evaluated over a necessarily short observation period.

To resolve this it would be necessary to go back to the raw data and attempt to find a weather parameter which is observed at Ringway which is strongly correlated with the Clifton wind direction in these conditions. New scatter diagrams could then be constructed for different values of this parameter and these scatter diagrams would be expected to exhibit a higher degree of correlation. For the present study, however, this was thought unlikely to be successful because of the small number of observations available, and so the statistical approach was used, based on the original scatter diagram. This is equivalent to assuming that the split between the two Clifton Junction wind directions would be the same over a long time span as it was observed to be in the six month observation period.

4.1.3 Stagnation in Valleys

The observations in the Forest Farm study (Sections 2.1.4 and 2.1.6) indicated that valleys can have a considerable sheltering effect which is likely to be dependent on the synoptic scale wind direction and the stability. This effect is again not easily predicted from first principles and in particular it is unlikely that a reliable and generally applicable method for predicting the magnitude of reductions in wind speed could be developed. There is a possibility however that flat calms in valleys could be associated with particular synoptic situations. For the present study the statistical approach has again been used.

4.1.4 Heat Islands

The battery factory study (Section 3.3.2.4) drew attention to a possible effect of the Manchester heat island on the correlation of wind directions at two sites. This effect will be stability dependent and should exhibit a consistent behaviour. In the absence of any direct observations it may be assumed that for sites near to the edge of a city the wind will be flowing inwards when the synoptic situation is calm.

4.1.5 Channelling in Valleys and by Mountain Ranges

Section 3.3.2.4 identified significant deviations from the synoptic wind direction which were explicable in terms of valley channelling effects. It seems intuitively likely that these deviations would occur in a systematic manner, particularly in strong winds,

and this is what was observed. Although the statistical method has been used in the present work, it would seem likely that the deviations in wind direction could be represented as a sinusoidal function having zeroes along and across the valley direction, and an amplitude of the order of $\pm 15^\circ$.

4.1.6 Use of Temporary On-Site Weather Observations and Records from Permanent Climatological Stations

Because of the complexity of the physical phenomena which are involved in determining local winds it has been found that only a few special circumstances are capable of being predicted with any degree of reliability. Moreover, even in these cases there remain unexplained variations which are undoubtedly the result of local perturbations. A good example of this is the case of channelling of wind in valleys, where the deviation in wind direction is very consistent in strong winds but only a part of the observed deviation pattern is explicable in terms of a simple channelling effect. For such reasons, it is preferable to use observed wind correlations rather than the rules of thumb which would constitute the only alternative.

In order for the correlations to have significance it is necessary that the observation period should be sufficiently long to cover all of the likely weather conditions with a reasonable number of observations. The six month period used in the present work (Section 3.3.2.4) appears to be long enough for this purpose as most of the stability categories and wind speeds and directions have been covered.

It remains to be decided how to organise the correlations and here the crucial decision is which of the observed parameters to use to classify the synoptic situation. The airflow should in principle be fully determined by what might be regarded (following wind tunnel terminology) as the "upstream" or "undisturbed" flow. This would be specified in terms of its direction relative to the local topographical features, and the vertical profiles of flow characteristics including speed, turbulence velocities and density profile (stability). If it is assumed that turbulence is, in any given application, determined by the other parameters, the characteristic properties reduce to: direction, stability and speed. These are also the properties which are required as input to the dispersion model and therefore the objective would ideally be to find a relationship based on these values. If we denote the direction, stability and speed at location i by the vector (d_i, s_i, u_i) and define location 1 to be the "upstream" or "synoptic" location and location 2 to be the site of interest, then the problem can be stated thus:

"For every possible value of (d_1, s_1, u_1) determine the frequency distribution of (d_2, s_2, u_2) ."

The difficulty with this ideal approach is that the length of the observation period required to define the frequency distribution with any accuracy at this level of detail would be of the order of several years. For the present study, therefore, it was necessary to discard one of the variables in the state vector (d_i, s_i, u_i) .

Since d_i is totally independent of S_i and u_i it had to be retained, but the windspeed and stability are related in that (for example) strong winds are always close to neutral stability, and therefore it was decided to discard one of these values. The windspeed was therefore dropped, on the grounds that the stability classes were discrete rather than continuous functions and therefore were more easily used in the correlation, and that the windspeeds should be nearly proportional in any given situation. It was also necessary to assume that the stability category would be the same at the two sites at all times, because there were no direct measurements of stability category available for Ringway, comparable with the gustiness categories determined for Clifton. The application of these ideas in a practical example is covered in Section 5.

4.2 Aerodynamic effects of site topography

In this section we consider topographical effects operating on a smaller scale than those discussed in Section 4.1. These effects do not influence local weather in a general sense, but may affect the wind pattern experienced at a source and will in that case affect the dispersion of pollutants. The chief effects are reduction of the effective chimney height and enhancement of turbulence levels.

4.2.1 Alteration of effective chimney height

The Forest Farm study (Section 2.1) identified two situations in which the effective height of a chimney might be reduced. These were in the lee of a cliff, and when a stable wind blows towards a cliff. For the former case, the reduction in effective chimney height could be related to the cliff height and the horizontal distance of the chimney base from the salient edge at the cliff top (Figure 2.1.9. illustrates this). The effect would be limited to the case of winds blowing towards the chimney from the direction of the cliff, and for the purposes of modelling this effect it seems reasonable to reduce the chimney height by the amount indicated in Figure 2.1.9, scaled by cliff height, for all wind directions within the angle subtended by the cliff at the chimney base. For sources which do not extend outside the eddy zone, reverse flow may occur and the pollutant will ultimately mix into the surrounding air through the shear layer (Figure 2.1.7(a)). Provided that this condition persists for sufficient time (roughly one hour), an equilibrium condition will be obtained in which the sources are balanced by losses through the

shear layer and in this state these sources are best represented as a vertical area source with a height equal to the cliff height.

When a stable wind blows towards a cliff the lowest layers may be arrested by the cliff and the upper layers will then travel nearly horizontally rather than being deflected upwards by the cliff. In a somewhat different way, a stable flow approaching an isolated hill will tend to travel round it rather than over the top. Here again, the upper layers may travel horizontally and impinge on the hill. This tendency to flow round hills is present to a lesser extent even in neutral stability.

The Forest Farm study (Section 2.1.5) provided some observational evidence of the stagnation produced by cliffs in stable conditions and indicated that the concentrations at points on the higher ground beyond the cliff edge would be best calculated by reducing the effective chimney height by an amount equal to the cliff height. A similar rule applies for stable flow towards an isolated hill or a tower block but in the latter case the rule is only applicable for receptor points on the tower, not for ground level receptors beyond the tower.

4.2.2 Effects on turbulence levels

The present work has not provided any quantitative evidence linking increases in turbulence levels with specific topographical features but the incinerator study (Section 2.2) confirmed that wake effects in the lee of cliffs may be a cause of such increases. The effects would be expected to persist some 10 to 15 cliff heights downwind. In the absence of any detailed information, it would seem reasonable to use dispersion coefficients appropriate to strongly unstable atmospheric conditions when calculating hourly (and longer) average values. For short-term peaks (of the order of 10 seconds in duration) clearly some high concentrations can be experienced at ground level due to an effect similar to plume 'looping' and for this it would appear reasonable to calculate plume centreline concentrations (i.e. take effective chimney height of zero for ground level concentrations).

4.3 Representation of the Source

The case studies have drawn attention to several different aspects of typical industrial sources which cause difficulties in mathematical modelling. These include: chimney aerodynamic effects (downwash, etc), low level emissions and effects of nearby buildings, and off-design behaviour of sources.

4.3.1 Chimney aerodynamic effects

The chemical waste incinerator study (Section 2.2) revealed the sensitivity of ground level concentrations to the effective height of a chimney plume. In particular, for the low-speed but high-buoyancy plume in question, the danger of the plume being affected by the chimney downwash before it had a chance to gain height due to buoyancy was identified. It appeared that this effect resulted in the absence of any significant plume rise.

Following the widely-used assumption that chimney downwash becomes important when the efflux velocity falls below the windspeed, it seems reasonable to take into account buoyant plume rise only when the efflux velocity is greater than the wind speed.

The vortex shedding in the wake of a chimney has a relatively minor effect on ground level concentrations, although wisps of material can be drawn from the underside of the main plume and these can occasionally cause brief peaks at ground level. Usually, however, the rate of dilution in the near wake is very high and therefore these concentrations are less of a problem than those due to the downwash effect of the wake on the main plume.

4.3.2 Off-design behaviour of sources

This is probably the most difficult problem in the specification of data for an air pollution prediction model, especially when the calculations are being made at the planning stage. The only way to make headway involves the inclusion of a detailed technical audit of the plant design in the air pollution assessment. While this type of audit is beyond the scope of the present work, it may be helpful to set out some general guidelines.

The primary consideration must be the predictability of plant performance. The chemical waste incinerator (Section 2.2) is perhaps the classic example of an installation in which there are so many unknowns at the planning stage that extreme caution should be used on all points.

The following factors serve to increase uncertainty about plant operating conditions:

- (i) multi-fuel operation,
- (ii) use of waste as all or part of fuel,
- (iii) furnace used to consume contaminated air streams (eg to eliminate odours),
- (iv) variable throughput in process (ie large 'turn-down' ratio)
- (v) provision for future expansion made in existing equipment
- (vi) presence of 'difficult' air pollutants in exhaust stream which may necessitate changes to pollution control equipment in the future causing changes in emission rates and temperatures

(vii) scrubber liquor obtained from another part of the process, which may not perform as expected, or may be changed in the future, etc.

(viii) intermittent or batch operation

In cases where doubts arise, the worst case must always be assumed.

Factors leading to confidence in performance specification include the following:

- (i) proven design already operating elsewhere in essentially the same form (e.g. power station
- (ii) continuous, steady load operation
- (iii) single fuel design
- (iv) simple process
- (v) no interactions with other processes, etc.

In case where these criteria are met, it will be reasonable to accept the design figures as the basis for the source specification.

4.3.3 Low Level Emissions

The chemical waste incinerator study (Section 2.2) identified the importance of low level emissions from the incinerator charging doors as a source of air pollution, and the battery factory study (section 3.3.1) quantified the low level emissions and showed that these were at least as large in magnitude as the high level chimney emissions.

For chimneys fitted with 'chinese hats', where the chimney exit is within the roof top eddy zone, ie. no higher above the roof than 0.4 times the building height or crosswind width (whichever is less), then the source will be trapped in the building wake and must be treated as a low level source. If there is an unimpeded vertical orifice, then chimney plume rise may be taken into account but if this is insufficient to allow the plume to clear the building wake and the rooftop eddy zone, then again the source must be treated as low level.

The representation of low level sources in air pollution models is relatively straightforward. Where the source is associated with a building, it can be assumed that the emitted material will become uniformly distributed over the crosswind area of the building. This can usually be represented quite accurately by defining a virtual source upstream of the building such that the plume dimensions match those of the building at the crosswind plane on the downstream side of the building.

If there are many buildings in the path of a plume from a low level source, then unstable dispersion coefficients should be used to take account of the increased levels of turbulence.

In the absence of buildings, low level sources can be treated as chimneys with zero height but in most cases due to the low temperature of most low level sources and their customary lack of ordered vertical momentum, plume rise is negligible.

4.4 Factors involved in dispersion of dust

The complexities of the motion of dust are discussed in Appendix I and Section 3.1.3 (battery factory study), and experimental evidence which strongly suggests that unconventional transport mechanisms are at work has been described in Sections 3.2.5 and 3.2.6, which covered human blood lead levels and environmental lead levels respectively. The chief conclusion that can be drawn is that some of these mechanisms, while very important in themselves, are best treated as special cases and do not fall within the class of air pollution problems as such. For this reason, generalised methods of approach should not be sought and some of these features of dust motion are not treated in the air pollution prediction model developed in Section 5 of this work.

4.4.1 Transport on vehicles and persons

In Section 3.2.6.2 it was shown that lead levels in dust alongside roadways used by battery factory vehicles were markedly higher than alongside 'control' roads. This clearly indicates that lead dust is being transported by vehicles, but the precise mechanism is far from clear. Possible explanations include:

- (i) lead components or scrap falling from loaded vehicles
- (ii) lead in mud carried on vehicle tyres
- (iii) lead in mud spattered on the undersides of vehicles

Each of these mechanisms will vary greatly in their ability to transport lead as the weather changes, for wind strength is a factor in blow-off from vehicle loads, and the rainfall history and humidity have a profound effect on the take-up and dropping of mud from vehicles.

In the case of lead dust carried on the person, again the mechanisms are quite varied:

- (i) lead in mud can be carried on the soles and outsides of shoes
- (ii) airborne lead dust can be trapped in absorbent clothing such as woollens, socks, etc., and carried home to be dislodged when the garments are changed.
- (iii) where individuals travel to and from work by car, the chance of carrying dust home is greatly increased because they walk a relatively short distance to their cars and lead can accumulate on the car floor and be carried home without further loss, such as would occur during walking or bicycling.

The quantification of these mechanisms by theoretical calculation would obviously be a very difficult task and it is evident that more satisfactory results can be obtained by direct experimental methods. Since these processes do not really fall within the scope of the air pollution modelling procedures to be developed in Section 5, they are not considered in detail here, but it seems relevant to point out some of the factors that should be taken into account at the planning stage rather than dealt with after the event.

First among these is the identification of possible routes for pollutant dust transport. Any person, vehicle or piece of equipment which is regularly transported to or from the works must come under scrutiny. Wherever possible, these people or vehicles must be kept separate from contaminated parts of the plant, and if this is not possible, then decontaminating procedures must be used (e.g. wheel washing, changing rooms, etc.). Such aspects are undoubtedly best dealt with at the preliminary planning stage, not after the plant is built.

Another important issue is the design of pollution monitoring programmes. It will be important to identify the 'unconventional' emission routes prior to commissioning so that baseline studies (designed to define the state of the 'undisturbed' environment) can be properly designed in relation to post-commissioning monitoring programmes. Therefore, where dust is involved, transport routes must be monitored, and clothing and vehicles should be examined.

4.4.2 Dust fallout and deposition

Appendix I has detailed various mechanisms by which dust may move in a different way from a passive tracer in the atmosphere. The mechanisms involved include particle fallout, deposition, accumulation and re-suspension, and we now consider the implications of these processes for concentration of dust in the air and, hence, for air pollution prediction models.

Consider first the surface deposition (or absorption) process for a passive tracer, such as a

dilute gas. We can readily identify two extreme cases: one in which the surface is a perfect absorbent for any pollutant that reaches it, and another in which the surface does not absorb the gas at all.

In the first case, the concentration pattern in the air and the rate of deposition at the surface can be predicted in principle by use of passive dispersion plume theory, allowing the plume to pass through the ground to simulate surface absorption. The air concentrations are, therefore, exactly the same as if the ground were not present.

In the second case (total reflection), the boundary condition at the surface is one of zero vertical mass flux and this is calculated using the customary 'image source' method. The air concentrations are then the same as they would have been if (a) there were no ground surface and (b) there had been an additional source equal to the actual source, but located at the point where the real source is reflected in the ground. At the surface, this means that concentrations are exactly twice those that would have been obtained in the 'total absorption' case.

Clearly, the true situation, in which the surface is neither perfectly reflective nor perfectly absorptive, gives concentrations somewhere between these values, and the method which has been used for handling such situations makes use of the concept of 'deposition velocity' (Chamberlain, 1953). The deposition velocity is defined as the rate of deposition per unit area divided by the concentration of pollutant per unit volume at a reference point just above the surface. Slade (1968) gives a useful brief review of the method

and makes the point that this concept does not attempt to describe the physics of the deposition or absorption processes; it is merely a convenient way of summarising a number of complex interactions. In principle, if the value of deposition velocity for a particular species of pollutant over a particular surface has been measured, then deposition rates can be predicted if the air concentration is known or can be estimated.

Consider now how this concept can be applied in a predictive dispersion model, still taking the case of a passive tracer. Assuming that the deposition velocity is known, all that is required is to predict surface concentrations, but clearly these will depend on the rate of deposition at all upstream sections. Three models have been proposed for dealing with this problem.

The first, by Chamberlain (1953), is still in widespread use and simply assumes that the amount deposited can be subtracted from the original source strength, and concentrations at the next downstream distance increment can be calculated using the original plume geometry (e.g. σ as function of x in the Gaussian model) but with the lower source strength value.

The Chamberlain model led to some useful analytical and graphical solutions for ground level and elevated sources, but was criticised because it extracted material from the plume throughout the plume cross-section instead of at the surface only. It, therefore, underestimated concentrations at higher levels.

Two types of surface-absorption model have been proposed as a solution to this problem. The first of these (Horst, 1974) used negative ground level sources of Gaussian type and a step-by-step calculation along the downwind direction starting from the actual source location. The second variant uses a similar negative source representation in a K-theory framework (e.g. Draxler and Elliott, 1977).

These models show, as expected, considerable divergence from the Chamberlain (1953) type and they have reached a level of development at which no further improvement is warranted, other than better definition of the deposition process itself.

If we now turn to the case of non-passive pollutants, of which particulates are the most common example, the additional complication of fallout is introduced. This results in the plume centreline being distorted towards the ground, thus increasing ground level concentrations and, hence, the deposition rate. None of the three deposition models described above will simulate this effect, and therefore they tend to underestimate deposition of dusts.

Very little work has been done on the modelling of dust fallout from plumes and for the present it appears reasonable, in view of the limited accuracy expected (or required), to assume that the plume centreline descends towards ground level at an angle $\tan^{-1}(v/u)$, where v is the average terminal velocity of the particles and u is the mean windspeed.

The deposition could in principle be calculated using the deposition velocity concept with ground level concentrations calculated using the descending plume model. For the present application, however, where the ground surface over most of the study area is open countryside or relatively low density low-rise residential areas, with a high capacity for absorbing lead dust in grass and soil, complete absorption of lead dust at the ground has been assumed.

Dust accumulation and re-suspension has a local effect only, and results primarily in a flux of dust along the surface which persists only until it reaches an absorbent surface such as a garden or field. Therefore, while these mechanisms may strongly influence individual buildings or roads, they have a negligible effect on lead-in-air concentrations generally and, therefore, they have not been included in the model which is described in Section 5.

4.5

Prediction of the Frequency of Peak Concentrations

'Peak' concentrations are often discussed in a very loose way which may lead to difficulties in formulating the air pollution prediction problem correctly. The discussion of this aspect of air pollution necessarily starts from the definition of pollutant concentration at a point, which can be expressed thus:

'the average concentration of a pollutant at a point P over a period of time, t , is defined as the limit of the average partial volume (or mass) of the pollutant in the period t in a volume V which includes P divided by the total volume (or mass) in V over the same period, as V tends to zero around P'.

This somewhat cumbersome definition clearly assumes that the fluids in question can be regarded as continua. In reality, this means that the limit must be considered to be reached before molecular effects become significant.

The first point to note is that the definition remains valid as t tends to zero, and therefore it is possible to speak of instantaneous concentrations. From this definition, the theoretical upper limit to the instantaneous concentration can be identified, and this is equal to the source concentration, for in a continuum, there is no mechanism by which the fluid can concentrate. It is interesting to note that in a real, molecular, fluid very small volumes of fluid may contain concentrations much higher than the average source concentrations, but this will not be important for

most practical purposes.

Given this view of the theoretical limits to peak instantaneous concentrations, it is evident that the peak concentration averaged over a time t observed in any observation period T will tend to increase as the length of T increases. This will be true for all averaging times t , and therefore it is not possible to speak of 'the peak value of concentration averaged over a time t ', except in the context of a particular (and therefore essentially untypical) period of observation.

Quite clearly, then, a statistically repeatable measure of peak values is required, and this must take the form of an ensemble average. The most convenient statistical form is the average frequency distribution of concentrations, but other statistics could be defined, for example, the ensemble average of the highest concentration averaged over t in a large number of observation periods of length T . In this context, it may be noted that the oft-mentioned 'peak-to-mean' ratio is only meaningful on an ensemble average basis, but is rarely estimated in this way.

4.5.1 The Need for Consideration of Peak Values

Many air pollutants have acute short-term effects which may be important even though the long-term average is acceptable. Examples of this include acute poisons such as chlorine or odiferous substances (food flavourings, mercaptans, etc.) or pollutants which may have acute effects in a minority of individuals or in vegetation (e.g. smoke and SO_2). For reasons such as these, peak

values must be predicted by air pollution planning models, and in practice the frequency distribution provides a useful form for presenting the results and assessing acceptability of the impact.

4.5.2 Methods of Calculation in Practical Models

4.5.2.1 Weather data limitations

If the prediction model is intended to take into account the weather pattern (as it must in industrial planning applications), then the shortest averaging time for which the model can predict peak values will be limited by the averaging time implicit in the meteorological data, and that implicit in the basic dispersion model.

Practical dispersion models such as the Gaussian are framed in such a way as to give accurate values of concentrations within a plume provided that the general meteorological situation remains steady for a sufficient time for the average concentration to stabilise, typically 3 to 10 minutes at distances of the order of one kilometre from the source. Weather data suitable for use in a practical model are, however, typically averaged over at least one hour and, therefore, when such data are applied with a Gaussian model, the implicit assumption is that the quoted weather for a particular hour actually persisted throughout that hour without change. In fact, examination of wind traces from an anemograph show that this assumption is often, but not always, accurate. For prediction of concentration values at a particular point in time, then, the weather data

may not be fully trustworthy. On the other hand, for prediction of average statistics such as long-term means or average frequency distributions the errors in each individual hour will tend to cancel out and, therefore, these calculations should be relatively accurate.

The effect of averaging of weather data is that fluctuations which occur in reality are smoothed out and do not appear in the model. For example, variations in wind direction are possible which would cause the concentration at a point downwind to vary considerably. The proper representation of these fluctuations in the model is important in the prediction of the frequency distribution because a receptor point directly downwind will probably be crossed several times by the plume centreline during the course of one hour. Therefore, the maximum 3-minute value observed there during that hour will be the plume centreline value even though the hourly average at that point will be much lower. Thus, by careful treatment of plume fluctuations within each one-hour period it is possible to make approximate calculations of the frequency distributions of 3-minute average concentrations. This is discussed in more detail in the following subsection.

4.5.2.2 Consideration of Off-centreline Concentrations and Plume Overlapping

Consider a particular hour in which the meteorological records indicate a wind in a particular direction. The wind data is necessarily grouped into direction ranges, usually 10, 20 or 30 degrees wide, and, therefore, we can think of the mid-point of the recorded

direction range as the most likely wind direction, with the actual wind direction having a probability distribution centred around this. Therefore, at any fixed receptor point the concentration at any one time depends on how far the plume centreline is from the receptor. For this reason it is necessary to consider the full range of off-centreline concentrations. Provided that suitable assumptions can be made about the probability distribution of wind direction in any individual one-hour period, then the probability distribution of 3-minute concentration levels for that hour can be calculated. The details of a calculation on these lines are given in Section 5. The average frequency distribution for the specified receptor point is found by summing over the whole time period for which observations are available.

Where there are several sources at the same location, as is the case at Clifton Junction, where there are both low level and high level sources, the plumes must be superimposed before the frequency distribution calculation is made. If the sources are at multiple locations the same applies, but there are considerable complications because if the meteorological data is coarsely grouped (say in 30 degree sectors of wind direction) the pattern of pollution concentration will change shape significantly as the direction varies through the sector. For 10 degree sectors, however, the changes in the extent of overlapping are small enough to be ignored, with consequent major savings in computing time.

5.0 A PREDICTION MODEL FOR THE CASE OF THE CLIFTON BATTERY FACTORY

5.1 Objectives of the Model

The dispersion model described in this chapter has a dual purpose: firstly, to illustrate the practical application of some of the modelling techniques which have been discussed in previous chapters; and secondly to complete the study of the Clifton battery factory by facilitating the estimation of long-term average lead-in-air concentrations.

The Clifton battery factory is a challenging subject for air pollution dispersion modelling, because many complicating factors are present. These include topographic effects, particulate emissions, aerodynamic effects of buildings, and the variety and large number of individual sources. It is in many ways typical of many real industrial pollution sources and it therefore provides a useful test case for modelling techniques. As it is a plant which is already in existence, however, a great deal more information is available than is normally the case in the planning situations which are the primary subject matter of this thesis. This is particularly true in regard to the specification of emission sources, since actual emission rate measurements were available for the majority of the designed emissions. In a planning situation this would obviously be impossible, and the best approach would be to use measured data from comparable plant, suitably factored in proportion to (say) production capacity; it is wise to take a cautious view of design calculations, which tend to be optimistic in this respect.

For the battery factory, lead is by far the most important pollutant and by the nature of lead toxicology, the concern is more about long term average concentrations than short term peaks, and so attention has been focused on this issue. In the battery factory air sampling study (Section 3.3) it was only practicable to take measurements over a relatively short period (actually two months) and clearly this survey could not be representative of long term average values, since the weather in so short a period would not be typical. Thus the air sampling results can only be used if it proves possible to correlate them with the local weather and then use the correlation in conjunction with long-term weather statistics to estimate average concentration levels. In principle, a dispersion model should facilitate the development of the required correlations and this is the approach that is used here.

The model is therefore designed to be run in two modes: first a validation mode in which a time-history of weather data over a particular period of time is used in a direct simulation of the pollutant emission and dispersion during the air sampling period; and second, a prediction mode in which average weather statistics are used and average concentrations or frequency distributions are calculated.

5.2 Features to be Included in the Model

The model was specially developed for the battery factory case and incorporates many, but not all, of the features discussed in Section 4. It is not the purpose of this study to reexamine the strengths and weaknesses of the various competing plume rise and dispersion models that are available, but rather to see how such models can

be integrated into a model of the overall climatology, topography, emission, dispersion and fallout. For this reason, conventional basic dispersion models which have gained broad acceptance for general purpose work in this field have been used, ie. Briggs (1970) model for buoyant plume rise, and the Gaussian dispersion model with Pasquill's original dispersion coefficients (Pasquill, 1961). The details of the complete model are described in the following sub-sections. Figure 5.2.1 illustrates the general form of the buoyant plume, and gives details of the Gaussian dispersion equation for the case of a non-absorbing ground surface (ie. total reflection at ground). Details of the plume rise formulae used are given in Section 5.2.4. below.

5.2.1 Simulation of Pollution Time History

In this mode of operation of the program, the pollution concentrations at each of six specified ground level receptor points corresponding to the six sampling stations in the Clifton survey are calculated for each hour of a two month period, April-May 1974, during which time concentration measurements had been made. The program evaluates the contribution from each of the sources separately, then sums them since overlapping plumes are simply additive in this context. The hourly concentrations thus obtained are based on the records of wind strength, direction and gustiness as measured directly at Clifton during the study period.

The hourly concentration values are then averaged over all 24 hour periods starting and ending at 12 noon which was the change-over time of the daily average sampling equipment used in the Clifton Survey. In this mode of operation the program does not print out any hourly values since these were not measured, nor does it calculate the

frequency distribution of hourly concentrations because this would not be statistically significant on the basis of a two-month simulation period. A flow diagram of the model in this mode of operation is given in Figure 5.2.4.

5.2.2 Calculation of the Geographical Distribution of Long-Term Averages and Frequency Distribution of Hourly Concentrations

In this mode of operation the weather data is input in the form of a frequency table of wind speed and direction and atmospheric stability class estimated for Clifton Junction as described in Section 5.4.1.1 below. For each weather condition the hourly concentration is calculated at each point on a regular radial grid having six distances and nine directions in this application. This concentration pattern is then multiplied by the fractional probability (ie. hours per year for that condition divided by the total hours per year), and a summation is then carried out for all weather conditions. This sum is the long term average concentration distribution for the sources in question and it is in a form which can be used directly for industrial planning purposes.

To calculate the long-term average frequency distributions of different concentration ranges, the program evaluates the probabilities of each concentration range at each grid point for each weather condition using the methods described in Section 5.2.7 below. These probabilities are then summed for all weather conditions and these sums (one for each concentration range at each grid point) constitute the calculated long term average frequency distributions. These

distributions are also useful for planning purposes; for example the geographical area in which certain concentrations are exceeded with more than a specified frequency can be identified. The flow diagram for this mode of operation appears in Figure 5.2.5.

5.2.3 Multiple Sources

In this model each source is characterised by its lead emission rate, buoyancy flux, height above ground and typical particle size. No account is taken of the different locations of the sources on the factory plot because at the distances of the receptors considered this would not be significant. This simplification results in considerable gains due to the possibility of adopting a polar coordinate system for all computations. However, it would not introduce any fundamentally new principles if different source locations were used; it would simply necessitate the use of a cartesian coordinate system, and in practical computational terms a considerable increase in the size of arrays required.

5.2.4 Effective Height of Chimneys

In this model the height of the plume above ground at some downwind station is composed of several factors: the physical stack height, plus any buoyant plume rise, less any reduction due to topographical effects (Section 4.2.1), less any particle fallout.

The physical stack height is taken as zero for any sources which are classed as 'low-level' in Section 3.3.1, ie. those which are actually at ground level or which emit into the wakes of buildings.

Plumes may rise above the physical stack height due to their momentum and buoyancy but in the case of low level emissions this effect is taken to be negligible in the present model, due to the effects of low level turbulence and building wakes, and (in many cases) the use of "Chinese hats". For high level emissions, the model of Briggs (1970) is used for the buoyancy effect. In this model, the equation

$$Z = 1.6 \frac{F^{\frac{1}{3}}}{u} x^{\frac{2}{3}} \quad \text{-----} \quad 5.2.4.1$$

(See Notation - Appendix IV)

describes the early part of the plume rise, out to a distance of x^* , where

$$x^* = 2.16 F^{\frac{2}{5}} h^{\frac{3}{5}} \quad \text{-----} \quad 5.2.4.2$$

Beyond x^* , the plume trajectory is given by

$$Z = 1.6 \frac{F^{\frac{1}{3}}}{u} x^{\frac{2}{3}} \left\{ 0.4 + 0.64 \left(\frac{x}{x^*} \right) + 2.2 \left(\frac{x}{x^*} \right)^2 \right\} \\ \times \left\{ 1 + 0.8 \left(\frac{x}{x^*} \right) \right\}^{-2} \quad \text{-----} \quad 5.2.4.3$$

Equation 5.2.4.1 is based on solution of the equations of motion of a plume slice which is assumed to have uniform properties in the cross-section. The only empirical element is the factor 1.6, which Briggs found gave better agreement with observation than the theoretical figure of 1.8. Equation 5.2.4.3, however, is not based on physical principles but is simply a correlation of observational data.

The reduction in effective height by topographical effects has been described in Section 4.2.1. In the present application there is a sharp cliff 26m high, to the southwest of the Clifton factory. However, the cliff is some 300 metres away, and therefore on the basis of Figure 2.1.9 (page 60) no correction is necessary for the case of wind blowing from the direction of the cliff. This is because any separated flow due to the cliff would reattach before it reached the factory. For stable winds blowing towards the cliff, however, the effective plume height is reduced by the cliff height in stable weather. In the model, this will occur for winds between 5° and 75° , which are the opposites of the limiting bearings subtended by the cliff at the factory.

Particle fallout causes the plume to lie below the position it would have adopted if the pollutant were a passive tracer. The modelling of this effect is a somewhat complex issue due to the necessity of representing depletion of the pollutant at the surface. This has been discussed at length in Section 4.4.2, where it was concluded that the most appropriate way to model both fallout through the air and deposition at the surface would be to angle the plume downwards by an angle appropriate to the terminal velocity of the particles and the wind speed, and assume total absorption at the ground. This has been done in the present model. Thus, the Gaussian equations used do not include the customary factor of 2 for total reflection at the surface. The terminal velocity was calculated by Stokes' equation taking average density for PbO .

5.2.5 Local Climatology

Local meteorological effects are not included explicitly in the dispersion model but appear in the weather data used. For the simulation mode, this weather data consists of anemograph records from the site in question and therefore fully takes into account any local weather distortions. For the other operating mode of the model, ie. prediction of long term statistics, the weather frequency tables are estimated for the site as described in Section 5.4.1.1 below.

5.2.6 Area Source Effect of Buildings for Low Level Sources

If a low level source emits into an area which has many buildings nearby, then the emissions will become well mixed into wakes of at least some of these buildings. In the case of the Clifton Factory, there are many buildings, mostly about 15 metres high, covering a horizontal extent of some 350 metres. The combined wake of these buildings is therefore roughly 350×15 metres, however, it is not correct to assume that each individual source will be diluted into a plume with this large cross-section, since the lateral rate of spreading in the wake zone is not sufficiently rapid. Therefore, in the present model, the effect of initial dilution by building wakes is allowed for by reference to building height only.

The specific method employed is to postulate a virtual source upstream of the building such that σ_z is equal to the building height at the location of the building. Since the variation of σ_z with distance depends on the stability class, the location of the virtual source must also vary with stability.

Since most of the buildings at Clifton are around 15 metres in height, this length has been used for all low level sources. No initial mixing correction is applied for high level sources. The dispersion co-efficient σ_z is described by Pasquill's (1974) graphs as expressed in analytical form by McMullen (1975). This analytical expression takes the form

$$\sigma_z = \exp (I + J \ln (x) + K (\ln(x))^2)$$

where the coefficients I, J, K are functions of Pasquill stability class only. Thus, to find the location of the initial source, all that is necessary is to solve the quadratic equation in $\ln(x)$ which results when σ_z is set equal to 15 metres.

5.2.7 Effects Due to Changes of Wind Direction Within Individual One-Hour Periods

The Pasquill dispersion coefficients which are used in this model are based on the plume geometry averaged over a time of the order of 3 to 10 minutes. We will refer to this plume geometry as the "3 minute plume" for simplicity in the following discussion, which has been previously introduced in its basic principles in section 4.5.2.

It is clear that the 3 minute plume will wander to some extent during any one-hour period. Moreover, the original meteorological observations are lumped into finite ranges of say 10° or 20° , so that the actual position of the plume centre line could be in error by 5° or 10° as appropriate.

These wind direction variations, both real and artificial, must be taken into account in the model. A simple argument to demonstrate this fact is as follows.

Consider a 3 minute plume which is narrow compared with the sector of wind direction uncertainty, as is usually the case. If the receptor point happens to be on the centre line of the plume, a high concentration will result both in real life and in the model. If on the other hand the receptor lies to one side of the plume, a low concentration will result. This again is equally true in real life as in the model. In real life, the short-term concentration at a single fixed point at a specified time is therefore essentially unpredictable without better knowledge of the position of the plume centreline at that time. All we can hope to do is to predict the most likely value, or the average value over a large number of realisations of this same experiment.

In the present model, this problem has been handled by calculating for each hour at each receptor point the average concentration and the probability of the chosen concentration ranges on the assumption that the probability distribution of plume centreline positions within the hourly average wind direction sector as recorded is uniform. Thus, if the recorded direction is 50° and the meteorological record is lumped in 20° sectors, it is assumed that the plume centreline is actually equally likely to lie anywhere within the sector 40° to 60° . The average concentrations and frequencies can be computed by integration.

For the simulation mode of operation, only averages are of interest, and the computation proceeds as follows. The concentration distribution at a particular down-wind cross-section of the plume is given by

$$c = \frac{Q}{2\pi u \sigma_y \sigma_z} \text{Exp} \left(-\frac{z^2}{2\sigma_z^2} \right) \text{Exp} \left(-\frac{y^2}{2\sigma_y^2} \right) \\ = k \exp \left(-\frac{y^2}{2\sigma_y^2} \right), \text{ say.}$$

For the angles involved, no significant error is introduced by assuming that the crosswind coordinate y is equal to the angular deviation in radians multiplied by the distance from the source. Thus $y = r (\theta + d\theta)$ where θ is the angle between the receptor and the centreline of the wind direction sector, and $d\theta$ represents the deviation of the actual wind direction from the latter centreline. Hence, the average concentration is given by

$$\bar{C} = \frac{k}{r \Delta\theta} \int_{r(\theta - \Delta\theta/2)}^{r(\theta + \Delta\theta/2)} \exp \left\{ -\frac{y^2}{2\sigma_y^2} \right\} dy$$

where the width of the wind direction sector is $\Delta\theta$. This is illustrated in Figure 5.2.2 and it should be noted that the expression above is equally valid whether the receptor point is inside or outside the wind direction sector.

For the calculation of the frequency of concentrations within fixed ranges, the same assumptions are made, thus for any given receptor point in one particular hour, the concentration may vary between limits which depend on the range of possible positions of the plume. The probability of concentration lying between two values C_1 and C_2 can be calculated by the method illustrated in Figure 5.2.3. The "3 minute" cross-sectional distribution of concentration is represented by the Gaussian function $C(y)$. The values of y for which $C(y)$ equals C_1 and C_2 can be calculated (y_1 and y_2). The angle subtended by the line y_1, y_2 is approximately,

$$\delta\phi = |y_2 - y_1| \div r$$

and hence the probability that $C_1 < C < C_2$ in that

hour is equal to the probability that the plume centre-line lies within the required sector of width $\delta\phi$.

If the whole of this sector is inside the then-current wind direction sector, this probability will be $\delta\phi/\Delta\theta$

If it is wholly outside, the probability is zero, and if only an angle $\delta\omega$ lies inside the probability is $\delta\omega/\Delta\theta$.

5.2.8 Miscellaneous Factors not Included in Model

Some of the factors discussed in previous chapters have not been explicitly included in the model. These include: dust transport other than by atmospheric dispersion with fallout; increases in turbulence due to aerodynamic effects; downwash effects due to low efflux velocity.

The non-aerodynamic dust transport mechanisms were not included primarily because the model was designed to predict the airborne lead burden and it was felt that such mechanisms as transport of lead on clothing and vehicles and by saltation should not greatly increase the long-term average airborne lead levels, observed at sampling sites which were all several metres above ground.

Increases in turbulence due to topographical effects were not explicitly included primarily because the wind observations at the site itself already include this effect to a large extent.

Downwash effects due to low efflux velocity are taken into account in the sense that all of the low stack emitting near roof level, often with "Chinese hats", are assumed to be severely affected by building or chimney downwash and are therefore taken as low level sources. For the two high level chimneys, the exit conditions are satisfactory and no downwash would be expected.

5.3 Validation of Model by Operation in Simulation Mode

5.3.1 Data Base

5.3.1.1 Emission Sources

The full set of available details of the emission sources at Clifton Junction is contained in Table 3.3.1 (page 186). Since some of the emissions have identical characteristics (particle size, effective height, etc.) it was possible to combine them to give a reduced number of sources as indicated in Table 5.3.1. In most of these cases, the opportunities for combination arose from the fact that low level sources are assumed to have negligible plume rise even if the emission is in fact buoyant, due to building wake effects. The methods used for determining source parameters in Table 3.3.1 have been discussed in Section 3.3.1.

TABLE 5.3.1
SOURCE GROUPINGS FOR COMPUTER SIMULATION

Source	Particle size (μm)	Effective height (m)	Emission rate gPb/sec	Buoyancy flux F m^4/sec^3
Scrap pile; Plate cleaning	10	0	0.144	0
Old blast furnace	0.1	37	0.0547	1.7
Old blast fur- nace fume ex- traction; casting shop ventilation; pack burning.	0.1	0	0.0825	0
New blast furnace	0.1	47	0.285	7.58
Tudor mill; Hardinge mill	0.1	0	0.0587	0
Reed stacker; hand stacker	0.3	0	0.0572	0

5.3.1.2 Weather Data

Sections 3.3.2.1 and 3.3.2.2 have described the wind measurements made directly on the site throughout the air sampling period April/May 1974, and the use of the Singer and Smith (1966) methods for establishing gustiness categories hour-by-hour. The computer model obtains its weather data for each hour from the data file for the Clifton Junction records, set up as described in Appendix III.

The particular two-month period used for lead-in-air sampling was untypical because of a predominance of easterly and northeasterly winds. For this reason, the sampling site in the south west was more frequently exposed to pollution from the battery factory than were those in the east and north east. The predominant gustiness category was Brookhaven B₂ (approximately Pasquill B), occurring about 40% of the time, with neutral conditions (Brookhaven C), occurring about 27% of the time. Table 5.3.2 gives full details. The bias in weather conditions experienced during this rather short period is to be expected and does not in itself create any major problems, except that the process of validation of the dispersion model cannot be considered equally comprehensive for all weather conditions. Thus, for example, no occasions of gustiness category Brookhaven A occurred, and therefore there was no opportunity to verify the accuracy of the model in this weather condition.

Table 5.3.2 % Frequencies of Weather Types
During April-May 1974

Brookhaven Gustiness: Frequency:	A	B ₂	B ₁	C	D	Defective	Trace
	0%	40%	16.5%	27%	7.5%		9%

Wind Direction: Frequency	N	NE	E	SE	S	SW	W	NW	Def.
	2.3%	20.8%	25.4%	10%	5.4%	10%	3.8%	13.1%	9.2%

5.3.1.3 Air Sampling Data

The lead-in-air data was obtained by methods described in Section 3.3. A crude analysis of the results with respect to current weather was also included in Section 3.3 and this indicated that a general background of about $0.45 \mu\text{g}/\text{m}^3$ existed and that the battery factory added about $0.2 \mu\text{g}/\text{m}^3$ to this figure in the downwind sector. Thus it is clearly important to remove the "background" from the observations before attempting any comparison with model predictions.

It has already been established (Section 3.2.6.1) that the "background" (or "upstream") concentrations may vary considerably from day to day and therefore it was necessary to make an assessment of the background value for each day of the sampling period. This was done by determining from the wind direction records which of the six sampling sites lay upwind of the site throughout the major part of each 24 hour sampling period. The average concentration recorded at this site (or sites) was taken as the best estimate of the background and this value was then subtracted from all of the recorded concentrations for that day.

In some cases, measured concentrations at downwind sites were less than those at upwind sites, due to unknown causes. This was assumed to occur only on days of very low contribution from the battery factory, and therefore this contribution was set to zero on such occasions. The raw data and the estimated background values are presented in Table 5.3.3.

The re-worked data with the background subtracted appears in Table 5.3.4.

TABLE 5.3.3

RAW AIR SAMPLING DATA ($\mu\text{g}/\text{m}^3$) AND ESTIMATED BACKGROUNDS

Site (see Fig 3.3.3) Date	22	42	23	43	26	46	Esti- mated Back- ground
April 1	0	.939		.336	.688	1.430	.336
2	.454	.413		.224	.780	.452	.224
3	.555	1.128		.828	1.192	1.556	.842
4	.959	.795		.662	1.376	1.024	.877
5	.706	.895		.497	1.055	.776	.801
6	.555	.358		.386	1.147	.294	.457
7	.454	.358		.386	.596	.294	.406
8	.605	.358		.276	.642	.294	.482
9	.404	.604		.441	.780	2.207	.504
10	1.009	.749		.828	2.201	2.207	.828
11	1.864	1.468		1.821	1.902	.696	1.299
12	.540			.331	.136		.540
13	.441			.221	.272		.441
14	.490			.221	.226		.490
15	.981			.552	.362		.981
16	.834			.331	.498		.834
17	.736	.573	.353	.342	.724	.454	.655
18	.382	.239	.353	.342	1.675	.530	.311
19	.430	.268	.247	.342	.860	.530	.349
20	.620	.479	.777	.456	.770	.623	.550
21	.573	.479	.636	.456	.906	.623	.526
22	.573	.479	.600	.456	.688	.623	.526
23	.620	.332	.565	.114	.815	.791	.803
24	.382	.224	.600	.513	.815	.448	.303
25	.418	.235	.318	.114	.589	.312	.327
26	.418	.258	.177	.285	1.177	.628	.338
27	.511	.233	.106	.171	.504	.280	.372
28	.325	.233	.141	.114	.596	.280	.279
29	.651	.233	.530	.570	.634	.280	.442
30	1.115	.565	.848	.797	.770		.770

TABLE 5.3.3 (contd).

Sites: Date	22	42	23	43	26	46	Estimated Background
May 1	.465	.581	.035	.911	.453		.453
2	.910	.465	.530	.637	.321		.321
3	.696	.589	.247	.579	.642		.413
4	.642	.272	1.801	.347	.504		.457
5	.482	.272	.247	.579	1.376		.377
6	.482	.272	.636	.463	.734		.377
7	.642	.843	.565	.289	1.055		.427
8	.963	.558	.589	.463	.596		.761
9	.696	.642	.277	.448	.232		.232
10	.375	.386	.277	.249	.186		.186
11	.482	.239	.280	.497	.465		.465
12	.696	.239	.277	.298	.372		.372
13	.482	.239	.277	.199	.929		.929
14	.054	.298	.594	.056	.325		.325
15	.214	.316	.777	.199	0.0		.265
16	.264	.334		.114	.465		.114
17	.422	.540	.530	.456	.790		.481
18	.685	.507	.636	.228	.372		.372
19	.633	.507	.600	.456	.186		.186
20	1.212	.507	.530	.456	.465		.456
21	1.054	.770	.706	.057	.232		.232
22	.527	.224	.594	.627	.232		.232
23	.404	.245	.280		.235		.325
24	.555	.283	.350		.612		.419
25	.353		.280	.171	.377		.353
26	.908			.171	.283		.908
27	.605			.171	.283		.283
28	.504			.171	.471		.471
29	.555	.290		.399	.188		.188
30		.252		.399	.706		.706
31		.471		.228	.286		.471

TABLE 5.3.4

MEASURED CONCENTRATIONS - LESS ESTIMATED BACKGROUNDS

Sites: Date	22	42	23	43	26	46
April 1	0	.603	-	0	.352	1.094
2	.230	.189	-	0	.556	.228
3	0	0	-	0	.279	.714
4	0	0	-	0	.499	.147
5	0	0	-	0	.254	0
6	0	0	-	0	.690	0
7	0	0	-	0	.190	0
8	0	0	-	0	.160	0
9	0	0	-	0	.276	1.703
10	.181	0	-	0	1.373	1.379
11	.565	.169	-	.522	0	0
12	0	-	-	0	0	-
13	0	-	-	0	0	-
14	0	-	-	0	0	-
15	0	-	-	0	0	-
16	0	-	-	0	0	-
17	0	0	0	0	.069	0
18	0	0	.042	.031	1.364	.219
19	0	0	0	0	.511	.181
20	0	0	.227	0	.220	.073
21	0	0	.110	0	.380	.097
22	0	0	.074	0	.162	.097
23	0	0	0	0	0	0
24	0	0	.297	.210	.512	.145
25	0	0	0	0	.262	0
26	0	0	0	0	.839	.290
27	0	0	0	0	.132	0
28	0	0	0	0	.317	.001
29	0	0	.088	.128	.192	0
30	.345	0	.078	.027	0	0

TABLE 5.3.4 contd.

MEASURED CONCENTRATIONS - LESS ESTIMATED BACKGROUNDS.

Sites: Date	22	42	23	43	26	46
May 1	.012	.128	0	.458	0	-
2	.589	.144	.209	.316	0	-
3	.283	.176	0	0	.229	-
4	0	0	1.344	0	.047	-
5	0	0	0	.202	.999	-
6	0	0	.259	.086	.357	-
7	.215	.416	0	0	.628	-
8	0	0	0	0	0	-
9	.464	.410	.045	.216	0	-
10	.189	.200	.091	.063	0	-
11	.017	0	0	.032	0	-
12	.324	0	0	0	0	-
13	0	0	0	0	0	-
14	0	0	.269	0	0	-
15	0	0	.512	0	0	-
16	.150	.220	-	0	.351	-
17	0	0	.049	0	.309	-
18	.313	.135	.264	0	0	-
19	.447	.321	.414	.270	0	-
20	.747	.042	.065	0	0	-
21	.822	.538	.474	0	0	-
22	.295	0	.362	.395	0	-
23	0	0	0	-	0	-
24	0	0	0	-	.193	-
25	0	-	0	0	.024	-
26	0	-	-	0	0	-
27	.322	-	-	0	0	-
28	.033	-	-	0	0	-
29	.367	.102	-	.211	0	-
30	-	0	-	0	0	-
31	-	0	-	0	0	-

5.3.2 Discussion of Results

The 24 hour averaged concentrations calculated by the model are tabulated in Table 5.3.5 and can be compared with the measured values in Table 5.3.4. The measured and calculated values are also presented graphically in Figures 5.3.1 to 5.3.6 and it is very much easier to assess the results from these Figures.

Figures 5.3.1 to 5.3.3 show the results from the three nearest sites (22, 23 and 26). The calculated and measured values are generally of similar magnitude throughout these Figures although there are cases where substantial discrepancies arise, for example: May 9, 14, 27 and 29 at Site 22; April 23, May 4 at Site 23; April 13, 14, 15, 16, 21, 22 and May 26 at Site 26. These discrepancies could be due to local disturbances similar to the grass mowing which may have influenced lead-in-air measurements at Dagenham (Section 3.2.6.1). Another possibility is abnormal variation in source strength; normally the battery factory operates continuously and so for planning purposes this factor is not important but it could have a substantial influence on the validation exercise under discussion.

Of the anomalous results for these three sites, two extreme cases have been examined in detail. The first of these was the predicted peak of about $1.9 \mu\text{g}/\text{m}^3$ on April 23 at Site 23. It transpired that the weather record for the period 12 noon at the 22nd to 12 noon on the 23rd was defective for much of the time; in fact

TABLE 5.3.5 CALCULATED 24 HOUR CONCENTRATIONS $\mu\text{g}/\text{m}^3$

	SITE:	22	42	23	43	26	46
APR	1/ 2	99.999	99.999	99.999	99.999	99.999	99.999
APR	2/ 3	0.000	0.000	0.000	0.000	0.840	0.102
APR	3/ 4	0.000	0.000	0.000	0.000	1.434	0.399
APR	4/ 5	0.000	0.000	0.000	0.000	0.869	0.203
APR	5/ 6	0.000	0.000	0.000	0.000	1.150	0.285
APR	6/ 7	0.000	0.000	0.000	0.000	0.715	0.139
APR	7/ 8	0.000	0.000	0.000	0.000	0.518	0.098
APR	8/ 9	0.000	0.000	0.000	0.000	0.897	0.210
APR	9/ 10	0.097	0.008	0.000	0.000	1.582	0.366
APR	10/ 11	0.283	0.023	0.212	0.012	0.918	0.268
APR	11/ 12	0.000	0.000	0.000	0.000	0.048	0.002
APR	12/ 13	0.000	0.000	0.000	0.000	0.690	0.149
APR	13/ 14	0.000	0.000	0.000	0.000	1.105	0.233
APR	14/ 15	0.000	0.000	0.000	0.000	1.007	0.154
APR	15/ 16	0.000	0.000	0.000	0.000	0.809	0.115
APR	16/ 17	0.000	0.000	0.000	0.000	0.372	0.054
APR	17/ 18	0.000	0.000	0.000	0.000	1.748	0.282
APR	18/ 19	0.000	0.000	0.000	0.000	0.673	0.009
APR	19/ 20	0.000	0.000	0.000	0.000	0.860	0.185
APR	20/ 21	0.000	0.000	0.000	0.000	1.424	0.310
APR	21/ 22	0.000	0.000	0.000	0.000	1.757	0.286
APR	22/ 23	0.000	0.000	1.935	0.220	0.000	0.000
APR	23/ 24	0.000	0.000	0.000	0.000	0.504	0.079
APR	24/ 25	0.000	0.000	0.000	0.000	0.552	0.077
APR	25/ 26	0.000	0.000	0.000	0.000	1.269	0.254
APR	26/ 27	0.000	0.000	0.000	0.000	0.452	0.086
APR	27/ 28	0.000	0.000	0.000	0.000	0.650	0.094
APR	28/ 29	0.000	0.000	0.000	0.000	0.874	0.141
APR	29/ 30	0.333	0.060	0.627	0.088	0.000	0.000
MAY	1/ 2	0.131	0.011	0.705	0.093	0.000	0.000
MAY	2/ 3	0.113	0.014	0.735	0.086	0.000	0.000
MAY	3/ 4	0.106	0.014	0.000	0.000	0.010	0.001
MAY	4/ 5	0.000	0.000	0.000	0.000	0.495	0.123
MAY	5/ 6	0.000	0.000	0.000	0.000	0.845	0.150
MAY	6/ 7	0.000	0.000	0.000	0.000	1.052	0.174
MAY	7/ 8	0.098	0.017	0.000	0.000	1.714	0.308
MAY	8/ 9	0.062	0.006	0.179	0.021	0.019	0.001
MAY	9/ 10	0.068	0.007	0.000	0.000	0.000	0.000
MAY	10/ 11	0.000	0.000	0.000	0.000	0.000	0.000
MAY	11/ 12	0.033	0.003	0.000	0.000	0.000	0.000
MAY	12/ 13	0.180	0.028	0.005	0.000	0.000	0.000
MAY	13/ 14	0.052	0.007	0.000	0.000	0.000	0.000
MAY	14/ 15	0.352	0.047	0.636	0.063	0.000	0.000
MAY	15/ 16	0.000	0.000	0.091	0.006	0.404	0.090
MAY	16/ 17	0.000	0.000	0.000	0.000	0.738	0.177
MAY	17/ 18	0.006	0.000	0.000	0.000	0.000	0.000
MAY	18/ 19	0.192	0.037	0.717	0.077	0.000	0.000
MAY	19/ 20	0.603	0.099	0.271	0.024	0.000	0.000
MAY	20/ 21	0.519	0.084	1.315	0.248	0.000	0.000
MAY	21/ 22	0.742	0.156	1.934	0.347	0.000	0.000
MAY	22/ 23	0.000	0.000	1.005	0.197	0.000	0.000
MAY	23/ 24	0.000	0.000	0.000	0.000	0.102	0.011
MAY	24/ 25	0.000	0.000	0.000	0.000	0.284	0.047
MAY	25/ 26	0.000	0.000	0.597	0.076	0.742	0.150
MAY	26/ 27	0.000	0.000	0.981	0.141	0.000	0.000
MAY	27/ 28	0.000	0.000	1.839	0.344	0.000	0.000
MAY	28/ 29	0.000	0.000	0.653	0.109	0.000	0.000
MAY	29/ 30	0.000	0.000	0.108	0.007	0.000	0.000
MAY	30/ 31	0.0	0.000	0.0	0.0	0.587	0.121

the only valid weather measurements which were submitted as data to the program were for the first 5 hours of this 24 hour period, in which the wind direction was towards site 23 and varied by no more than 20 degrees. The computer prediction was based on this 5 hour period only, for want of any better data. The undoubtedly explains the anomalous result.

The second extreme case was the four-day period 13-16 April for Site 26. During this period the measured values were zero but the program calculated levels consistently in the range 0.7 to 1.1 $\mu\text{g}/\text{m}^3$. There is no reason for this that is apparent from the weather records for this period and the matter remained very perplexing until it was realised that Easter Day fell on the 14th April in 1974, so that this anomaly can be attributed with confidence to plant shutdown for the holiday period 12 to 15 April.

For the three sites furthest from the factory the results are given in Figures 5.3.4 to 5.3.6. The concentrations are generally lower than for the nearer sites, as would be expected, and therefore there is a danger that these sites would not provide a good test of the model because the effect of the factory would be somewhat smaller in relation to the background levels. In fact, however, the results do confirm again that the calculated values are of approximately the right magnitude, and that the variation with time is followed as well as could be expected.

As with the closer sites, there are some discrepancies, notably in the magnitude of the results for Site 42 where the calculated values are generally lower than the observed ones, and in the different shape of the records for the period 6 to 12 April at Site 46. There is, however, good agreement at Site 46 for April 17-27. It is encouraging to find that, in general, the prediction of zero values for concentration is consistently borne out by the observations.

It is, of course, entirely possible that a major factor causing discrepancies between measured and predicted values is the lack of accuracy of the measured values. These values, are moreover, the result of subtracting the estimated background (itself a measured value) from the actual observations at each site. Thus, it is pointless to seek a high level of agreement throughout the available record. In the main, therefore, the results presented in Figures 5.3.1 to 5.3.6 are considered encouraging.

It must be stressed, moreover, that the calculation model was in no way "matched" or "fitted" to the observed results; the results presented were calculated entirely on the basis of the methods developed and described in earlier sub-sections of Section 5 and it uses standard Pasquill dispersion coefficients. No extra "refinements" were incorporated into the model in the light of earlier prediction runs; in fact the results presented are those

of the first (and only) computation free of programming errors. This aspect of the results is considered very important, for it indicates the degree of accuracy which is likely to be achievable in typical "difficult" planning cases when no actual measurements are available.

In order to make a quantitative assessment of the differences between measured concentrations (C_m) and calculated ones (C_c), a linear regression of C_m on C_c was carried out. This was done separately for each site and also for all six sites together and for two of the sites together. Anomalous cases for which good explanations had been found were excluded. The computer program used for this analysis (REG) is described briefly in Appendix II.

The results of these analyses are given in Table 5.3.6. In this table the "F" parameter is the ratio of the variance associated with the linear variation to the variance associated with the residual variations about the fitted line. High values of "F" therefore imply a high degree of statistical significance in the fitted relationship. If we examine first the results for the individual sites, it is apparent that the degree of correlation at sites 42, 23, 43 and 46 is relatively poor, while that at sites 22 and 26 is good.

TABLE 5.3.6 RESULTS OF REGRESSION ANALYSES

Site	No. of Points	Regression Coefficient	"F" value	"best fit" relationship
22	58	0.77	47	$C_m = 0.054 + 0.898 C_c$
42	51	0.48	3.1	$C_m = 0.046 + 1.03 C_c$
23	36	0.54	1.6	$C_m = 0.119 + 1.21 C_c$
43	58	0.48	4.7	$C_m = 0.040 + 0.429 C_c$
26	56	0.82	63	$C_m = 0.0009 + 0.434 C_c$
46	24	0.52	2.4	$C_m = 0.021 + 1.16 C_c$
all	283	0.64	98	$C_m = 0.064 + 0.366 C_c$
22 & 23	114	0.78	100	$C_m = 0.048 + 0.418 C_c$

The "best fit" relationships have the expected low values of the intercept of the $C_c = 0$ axis, but the slopes vary. Several sites (22, 23, 42, 46) have slopes close to the desired value of 1.0 but the others, including site 26 for which good correlation was obtained, give slopes around 0.43.

Of all the results for individual sites, the only significant ones are those for sites 22 and 26, which give slopes of 0.898 and 0.434 respectively. The regression for all sites taken together gives a high degree of correlation and a slope of 0.366. For sites 22 and 26 only, taken together, the slope is 0.418. That this is nearer to the result of Site 26 than to that for Site 22 is due to the greater number of non-zero values of concentration at Site 26. The slope for the two sites combined is, moreover, actually lower than for Site 26, due to a change in the intercept on $C_c=0$. This result, as first perplexing, is made possible by the circumstance that the Site 26 results are richer in high values than the Site 22 results, so that the two sets of results cover somewhat different ranges of C_c and C_m .

Thus the overall impression gained at the end of this examination of the results is that the model produces calculated values which are broadly correlated with the measured ones, at least as far as the accuracy of the measurements themselves will allow. The results are, however,

apparently too high in general, which indicates that further scope for refinement of the model exists.

However, since one of the two sites for which good correlation was obtained also gave results only some 10% too high, and since the slope of the relationship was close to 1.0 for four out of the six sites, it was decided to leave the model unmodified on the grounds that the discrepancy could be due to unknown highly localised influences on the measuring sites, rather than a fault in the model. Thus the results obtained later, in the application of the model to the calculation of long term averages, should be considered carefully in the light of the above evidence. The indications are that the computer model may predict somewhat high on average, but by no more than a factor of 2.5 at the most.

5.4 Predictions of long-term air pollution impact

This mode of operation of the model has been described in section 5.2.2 and is illustrated in flow diagram form in Figure 5.2.5.

5.4.1 Data Base

Apart from the details of the sources, outlined in section 5.3.1.1 above, this version of the model only requires the long term weather statistics as data.

5.4.1.1 Long-term wind frequencies

The methods used for correlating local winds at Clifton Junction with those at Ringway have been described in Section 3.2.2.4. The correlations obtained were used to generate estimates of the frequencies of wind speeds, directions and stabilities at Clifton as described in Section 3.3.2.5. The frequency tables thus generated followed a similar format to that generated by the standard Meteorological Office frequency program, except that certain stability categories were treated differently.

The Meteorological Office's program generates frequencies of weather situations classified by 5 wind speeds, 18 directions (sector width 20 degrees) and 9 stability classes, designated as follows: A, A/B, B, B/C, C, C/D, D, E, F/G.

Since the classes designated A/B, B/C, and C/D could not be readily used, because of the lack of dispersion coefficient data, these classes were split between the two nearest "single" classes, the frequencies being added equally to each. Thus, for example, the frequencies finally allocated to class C included the original allocation plus half the allocation to B/C and C/D. Class F/G was allocated entirely to class F, since G is relatively rare.

The estimated frequency tables were stored on magnetic tape cassette for later use in the dispersion program.

5.4.2 Discussion of Results

The computer program output took the form of long term average values and frequencies of concentrations in specified ranges for each of 144 points on a polar grid centred on the battery factory. This polar grid comprised 8 distances at 400 metre intervals, and 18 directions spaced at 20° intervals. In order to make the results more readily comprehensible, the mass of output has been condensed for presentation here, and the summarised results take the following forms:

- (i) Table 5.4.1, which shows the average concentrations at each of the grid points,
- (ii) Table 5.4.2, showing the percentage frequency of exceeding $1.0 \mu\text{g}/\text{m}^3$ lead-in-air at each grid point,
- (iii) Figures 5.4.1 to 5.4.3 which show typical calculated frequency distributions at selected grid points.

The long-term average figures in Table 5.4.1 all show steadily decreasing concentrations with distance and since the range of distances considered includes the distance at which the maximum effect of the high level sources would be expected, it can be concluded that the low-level sources dominate the picture. If high level sources were significant, a maximum would be seen at some distance from the source.

The most interesting variation is with direction from the source. At 400 metres distance the maximum effect is in direction 330, which is the most frequent direction for winds in the commonest stability classes (C and D). The contribution of the factory at this distance is

Table 5.4.1 Calculated Long-Term Lead-in-Air

Concentrations ($\mu\text{g}/\text{m}^3$)

Distance from source (m) Direction (degrees)	400	800	1200	1600	2000	2400	2800	3200
10	.314	.114	.065	.044	.032	.025	.020	.016
30	.160	.045	.023	.014	.010	.008	.006	.005
50	.444	.177	.103	.069	.051	.040	.032	.026
70	.524	.199	.116	.078	.057	.044	.036	.029
90	.580	.217	.126	.087	.064	.050	.041	.034
110	.674	.265	.156	.108	.080	.063	.051	.042
130	.525	.194	.110	.074	.054	.042	.033	.027
150	.507	.199	.115	.078	.057	.044	.035	.029
170	.347	.129	.073	.049	.035	.027	.022	.018
190	.148	.062	.039	.028	.021	.017	.014	.012
210	.228	.090	.055	.038	.029	.023	.019	.016
230	.432	.175	.105	.073	.055	.043	.035	.029
250	.446	.178	.106	.074	.055	.043	.035	.029
270	.298	.104	.058	.039	.028	.022	.018	.014
290	.365	.132	.074	.049	.036	.028	.023	.019
310	.642	.242	.140	.096	.071	.056	.045	.037
330	.867	.340	.199	.136	.101	.079	.064	.053
350	.658	.252	.147	.100	.074	.058	.047	.039

estimated as $0.8 \mu\text{g}/\text{m}^3$, falling to 0.34 at 800m, 0.2 at 1200 m and 0.14 at 1600 m. These figures appear broadly compatible with the estimates from the lead-in-air measurements reported in Section 3.3.3.

Table 5.4.2 records the frequencies of exceeding $1 \mu\text{g}/\text{m}^3$ at each of the sites and, again, a steady decrease with distance is registered in all directions. The direction having the maximum likelihood of exceeding $1 \mu\text{g}/\text{m}^3$ is 330 degrees (as for the average concentrations) and in general the pattern of frequencies of high values is much the same as that for averages. This is probably mainly due to the predominance of low level sources, which do not exhibit plume rise and are therefore mostly sensitive to wind direction rather than speed. For high level sources, by contrast, it can happen that if the frequency distribution of the directions of high speed winds is quite different from that of average winds, then the distribution of peak frequencies is also different from that of average values. This is clearly not the case in the present example.

Figure 5.4.1 shows the probability density function of calculated concentrations at a typical location (actually direction 110° distance 800m). The computations were made for very narrow concentration ranges ($0.02 \mu\text{g}/\text{m}^3$ wide) in the part of the graph between 0 and $0.2 \mu\text{g}/\text{m}^3$, and this explains the high degree of scatter in this region. The range widens to $0.2 \mu\text{g}/\text{m}^3$ between 0.2 and $2.0 \mu\text{g}/\text{m}^3$, and again to $1.0 \mu\text{g}/\text{m}^3$ from 2 to $10 \mu\text{g}/\text{m}^3$. If the scatter is neglected, it can be seen that the probability density function decreases steadily and there is no evidence of any 'bimodal' tendency, which sometimes shows up in models for single sources in which, to put it simply, the receptor is either within or outside the plume, leading to a bimodal distribution. The lack

of bimodality in this case is believed to be due to the care taken to represent plume swinging properly, and to the presence of multiple sources with superimposed concentration patterns which probably have less pronounced crosswind concentration gradients.

It is of interest to examine the form of the frequency distribution function. It was thought likely that the distribution would be log-normal, since this is usually found to be the case for measured air pollution concentrations, for similar reasons to those for the log-normality of blood lead levels (Section 3.2.4.5). The cumulative frequencies for the same site as in Figure 5.4.1 were therefore plotted on log-probability paper (in figure 5.4.2) and it was found that the distribution was in fact far from log-normal, although three distinct parts of the distribution could be identified each of which approximated to lognormality ($0-2 \mu\text{g}/\text{m}^3$, $2-7 \mu\text{g}/\text{m}^3$ and $7-9 \mu\text{g}/\text{m}^3$). No obvious explanation for this behaviour could be found.

The same data were therefore re-plotted on linear-probability paper (Figure 5.4.3) and a much better straight-line fit was obtained, with the only major (and inevitable) deviation occurring near the zero concentration level. In Figure 5.4.3, data are plotted for two sites and both show the same general behaviour, but have different means and standard deviations.

The results presented in this sub-section are typical of those that can be generated by a suitably-constructed dispersion model. Such results can be directly applied in planning studies provided that criteria exist for acceptable concentrations either on a long-

TABLE 5.4.2 Calculated frequencies of exceeding $1\mu\text{g}/\text{m}^3$ Lead-in-Air
(percent)

DIRECTION (DEGREES) \ DISTANCE FROM SOURCE (M)	400	800	1200	1600	2000	2400	2800	3200
10	5.99	3.42	2.48	1.64	1.13	.76	.36	.32
30	3.30	1.03	.55	.38	.25	.15	.13	.10
50	6.15	4.36	3.22	2.26	1.60	1.15	.72	.60
70	8.79	5.64	4.25	2.82	1.88	1.30	.68	.59
90	11.06	6.59	4.83	3.25	2.41	1.63	.74	.67
110	11.67	7.83	5.78	3.94	2.94	1.99	.95	.84
130	8.25	4.84	3.56	2.43	1.62	1.18	.74	.61
150	6.79	4.84	3.71	2.54	1.70	1.28	.82	.68
170	4.26	2.65	1.98	1.44	.98	.77	.59	.47
190	3.18	1.62	1.20	.87	.60	.52	.40	.40
210	4.56	2.52	1.87	1.31	.93	.72	.48	.47
230	7.54	5.23	4.03	2.75	1.99	1.44	.83	.79
250	7.78	5.38	4.09	2.83	2.14	1.48	.80	.76
270	4.75	2.54	1.81	1.25	.87	.65	.41	.35
290	5.05	2.72	1.95	1.44	1.06	.84	.62	.50
310	10.53	6.86	5.19	3.61	2.68	1.88	1.01	.90
330	13.92	9.78	7.49	5.15	3.74	2.68	1.40	1.25
350	11.46	7.44	5.61	3.81	2.74	1.90	.93	.84

term basis or on the basis of acceptable frequency of exceeding a peak value. It would be a relatively easy matter to compute the individual contribution of each source to the total and thereby provide guidance for the design and application of emission control equipment. This, however, has not been attempted in the present case, since the main concern here is to establish principles rather than to analyse any specific case exhaustively.

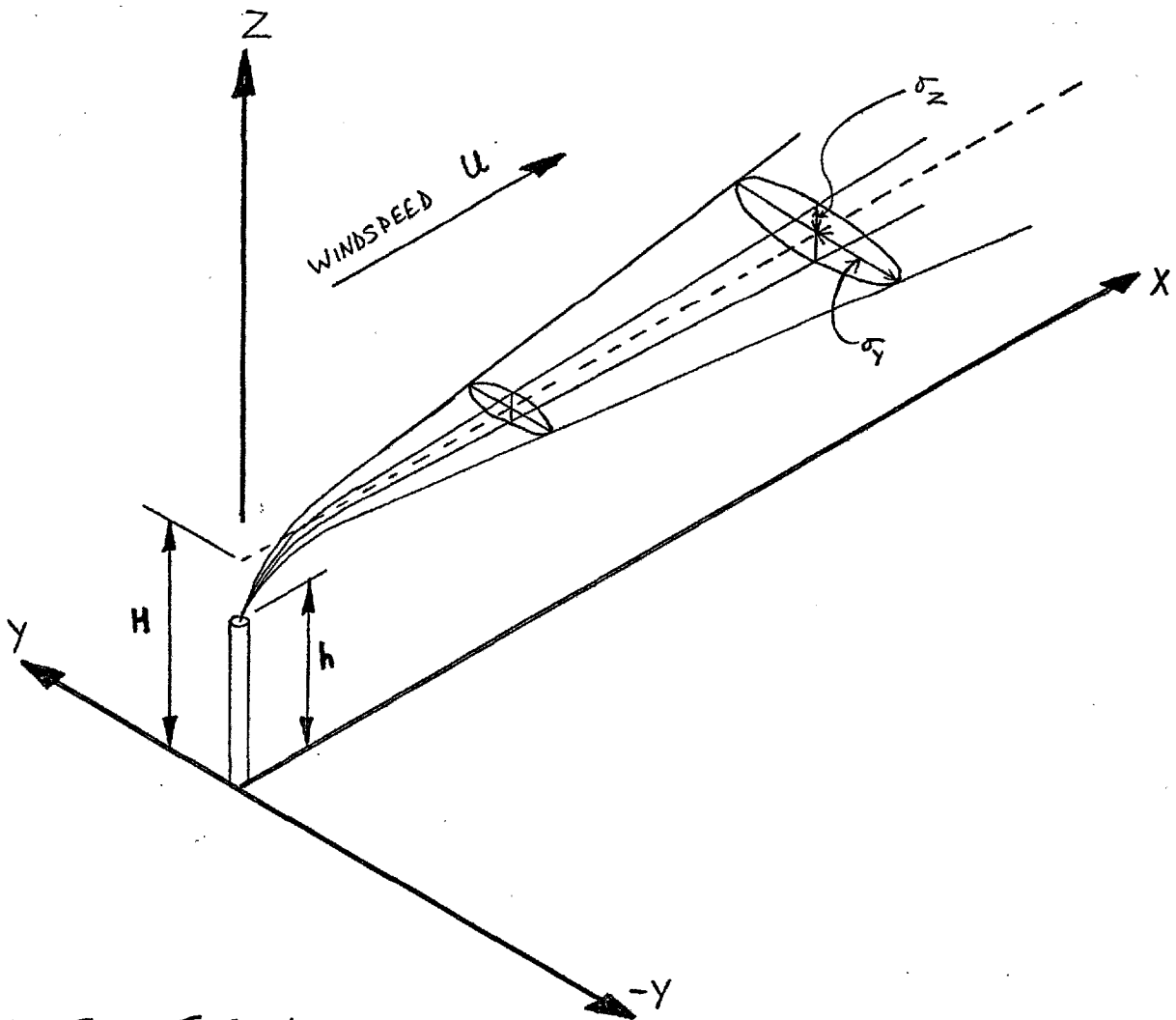


FIG 5.2.1

GAUSSIAN PLUME MODEL

IN THE PASSIVE PART OF THE PLUME, I.E. AFTER PLUME HAS STOPPED RISING, CONCENTRATION X IS GIVEN BY

$$X = \frac{Q}{2\pi\sigma_y\sigma_zU} e^{-\frac{y^2}{2\sigma_y^2}} \left\{ e^{-\frac{(z-H)^2}{2\sigma_z^2}} + e^{-\frac{(z+H)^2}{2\sigma_z^2}} \right\}$$

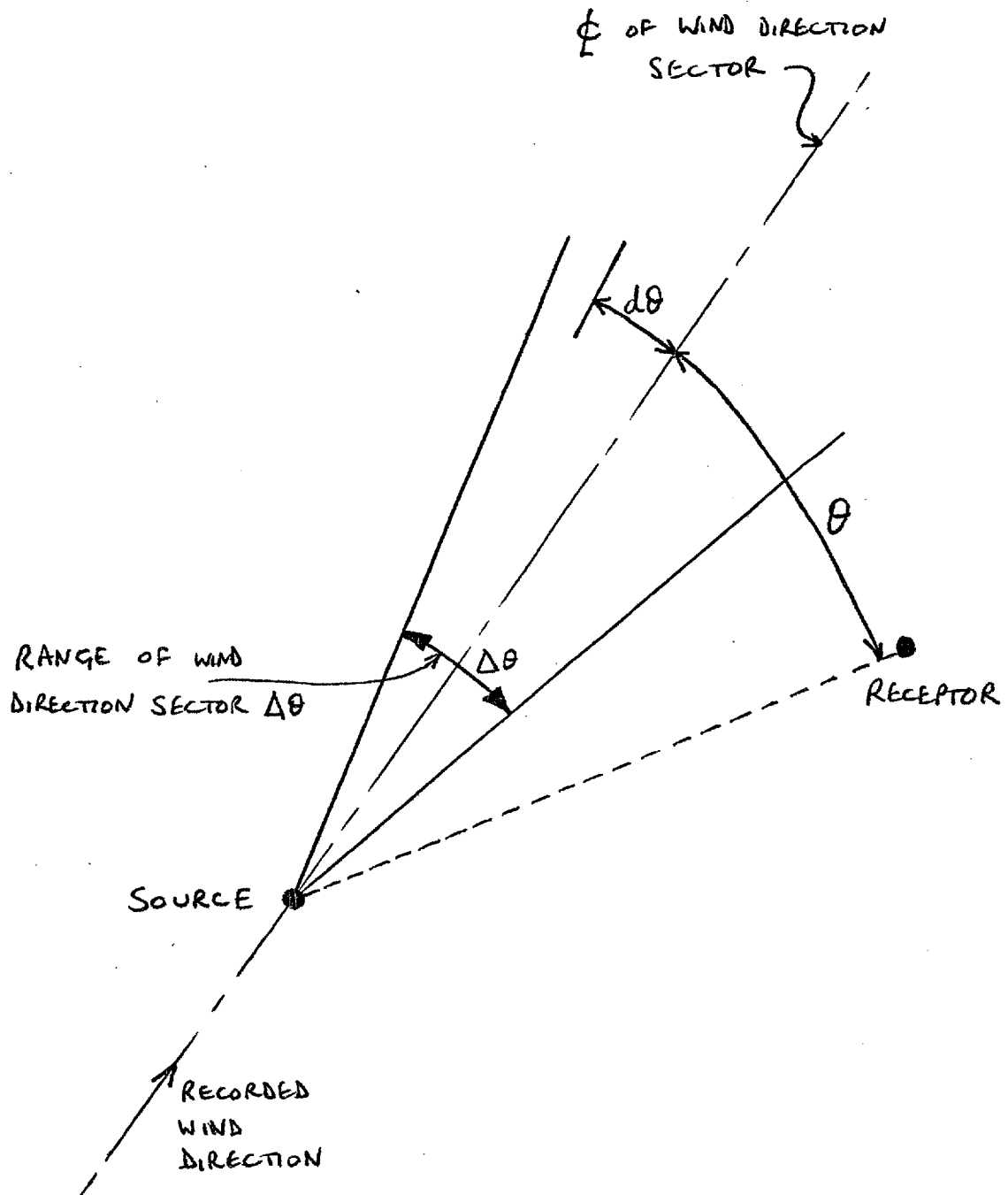
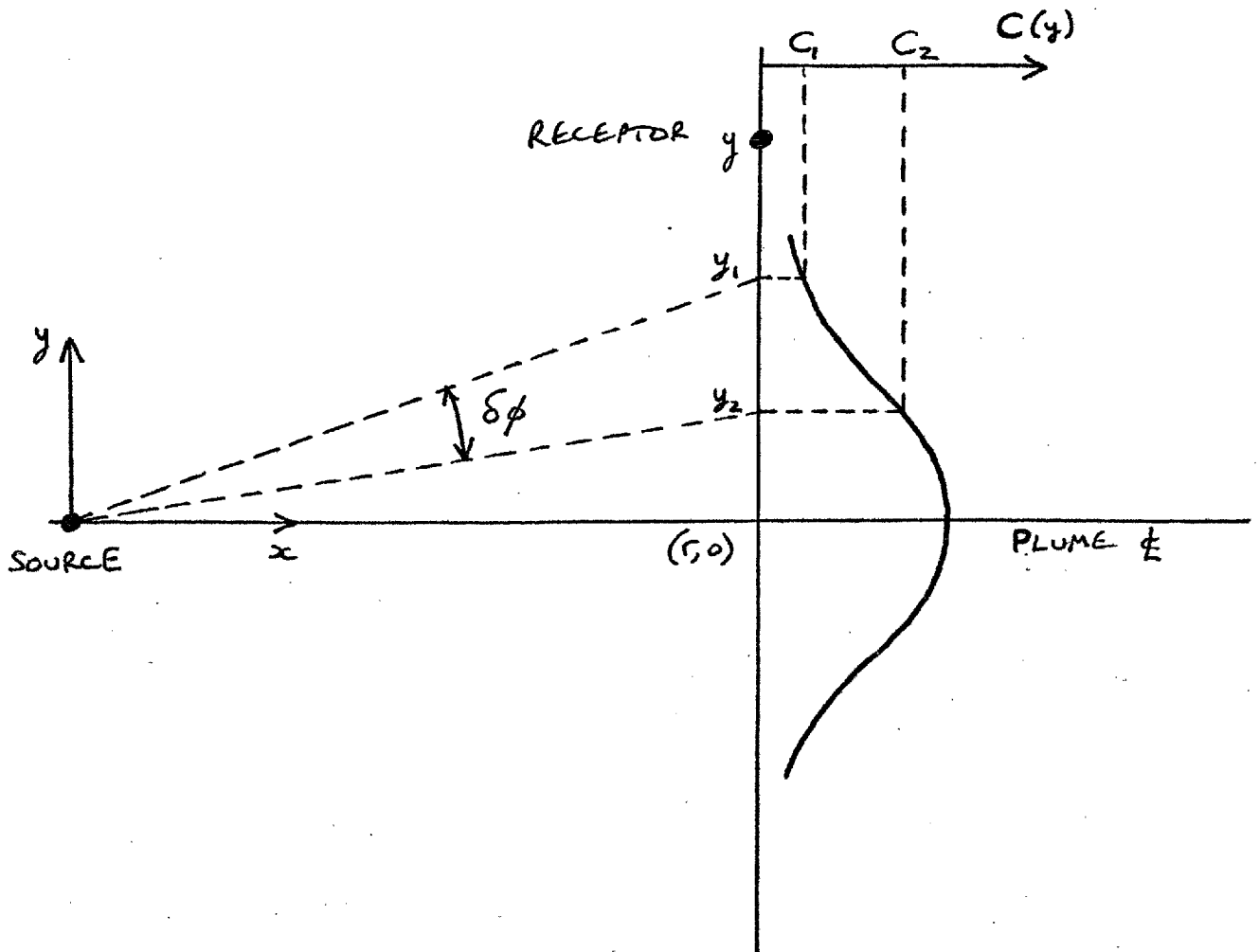


FIGURE 5.2.2 DEFINITION OF ANGLES IN CALCULATION
OF AVERAGE CONCENTRATION DURING ONE HOUR



$$\text{Prob}\{C_1 < C < C_2\} = \text{Prob}\{y_2 < y < y_1\} = \frac{\delta\phi}{\Delta\theta}$$

FIGURE 5.2.3 PROBABILITY ASPECTS OF PLUME SWINGING

FIG 5.2.4. DISPERSION

PROGRAM (VALIDATION)

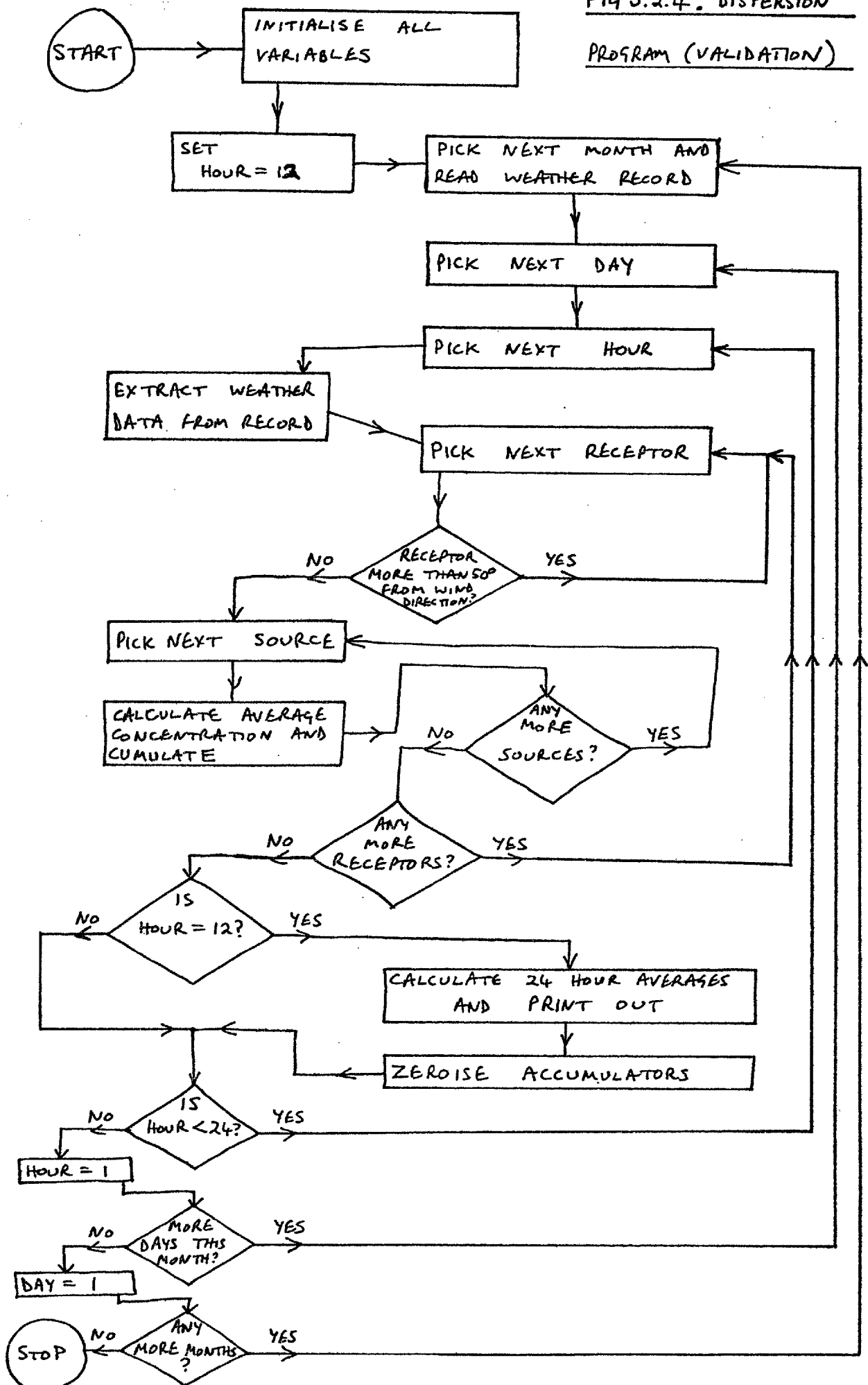


FIG 5.2.5 . DISPERSION
PROGRAM (CALCULATION OF
LONG TERM AVERAGES AND
FREQUENCIES)

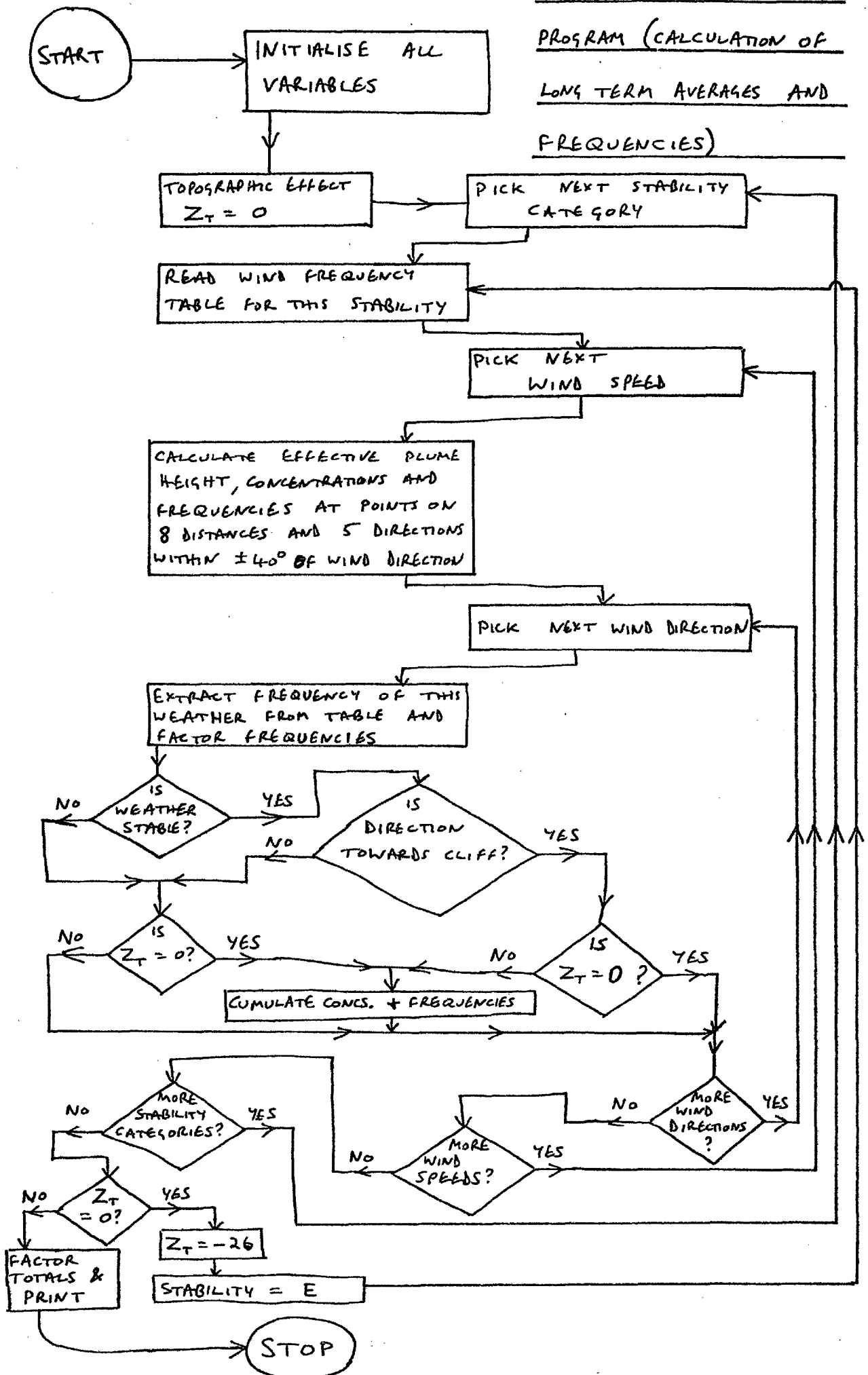


FIG 5.3.1 MEASURED AND CALCULATED CONCENTRATIONS AT SITE 22

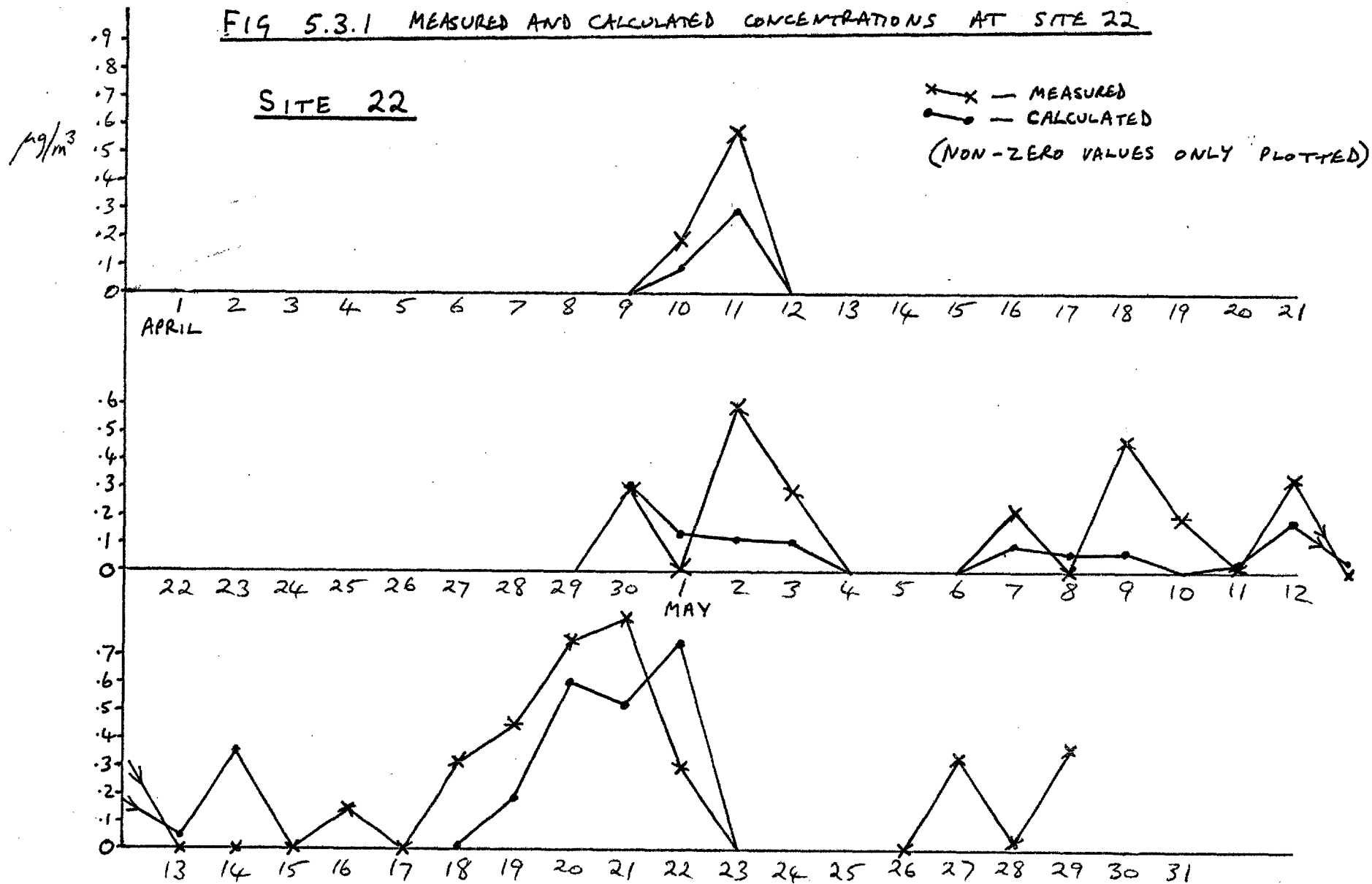
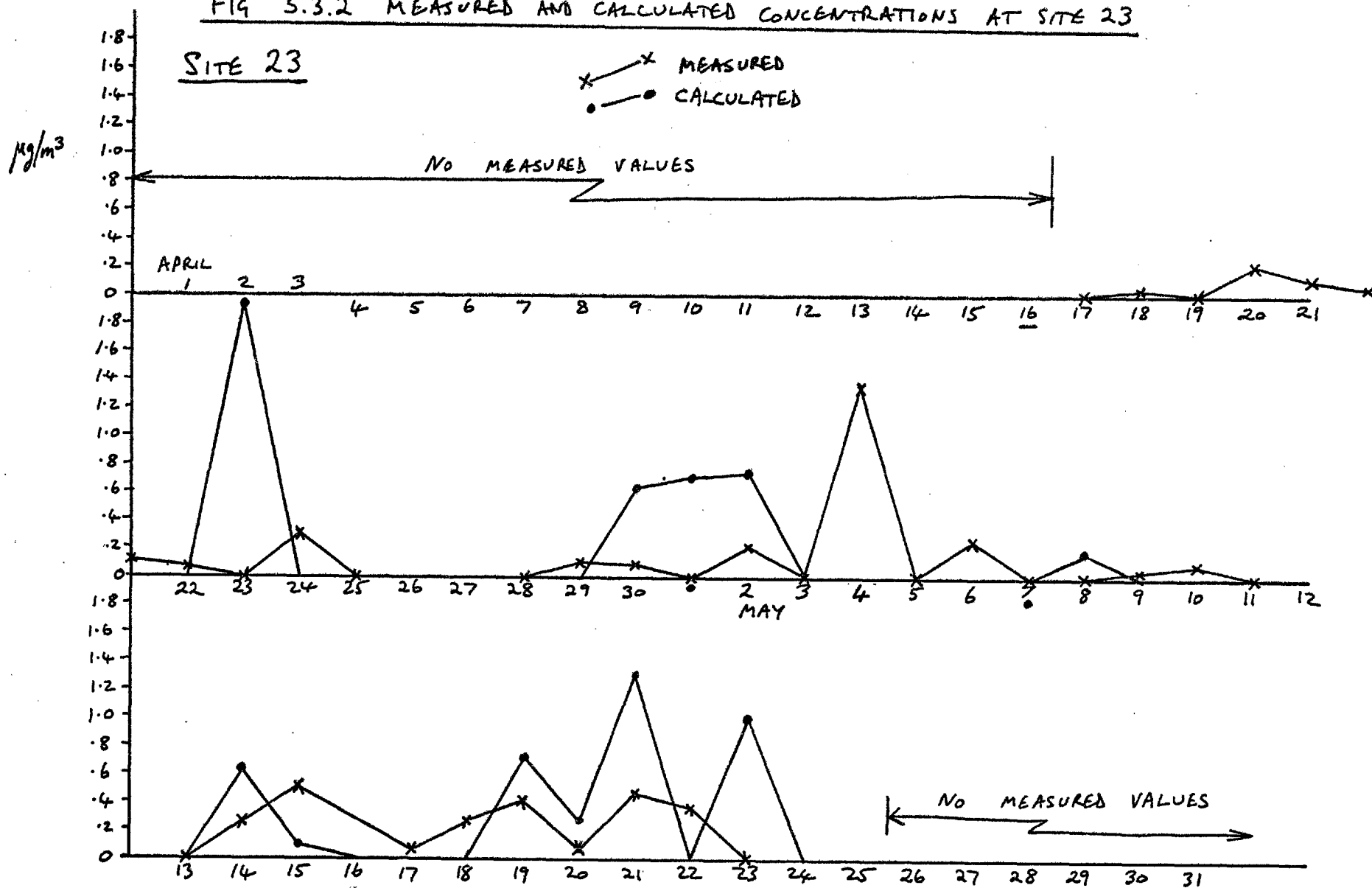


FIG 5.3.2 MEASURED AND CALCULATED CONCENTRATIONS AT SITE 23



$\mu\text{g}/\text{m}^3$

SITE 26

X — X MEASURED
● — ● CALCULATED

FIG 5.3.3 MEASURED AND CALCULATED
CONCENTRATIONS AT SITE 26

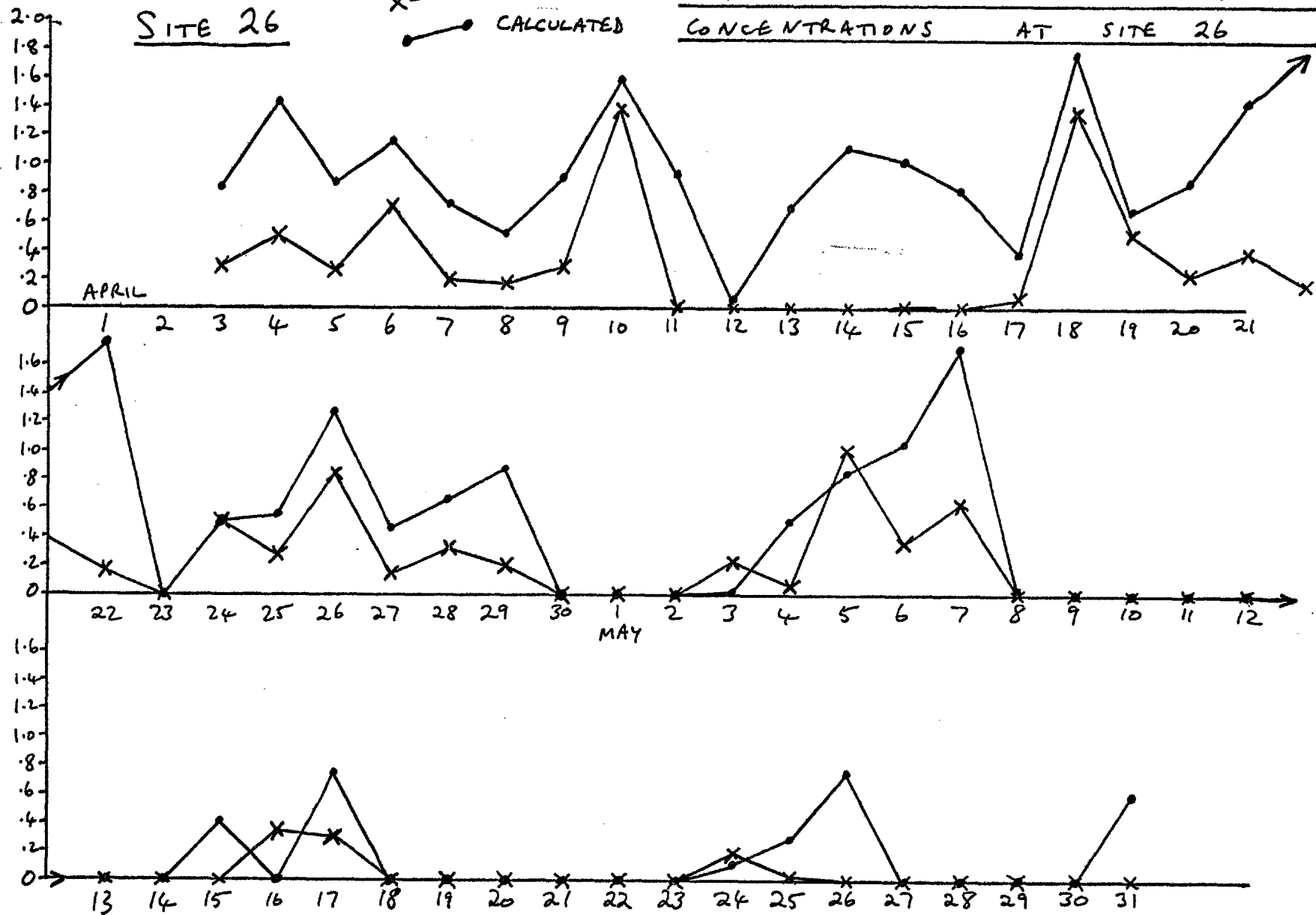


FIG 5.3.4 MEASURED AND CALCULATED CONCENTRATIONS AT SITE 42

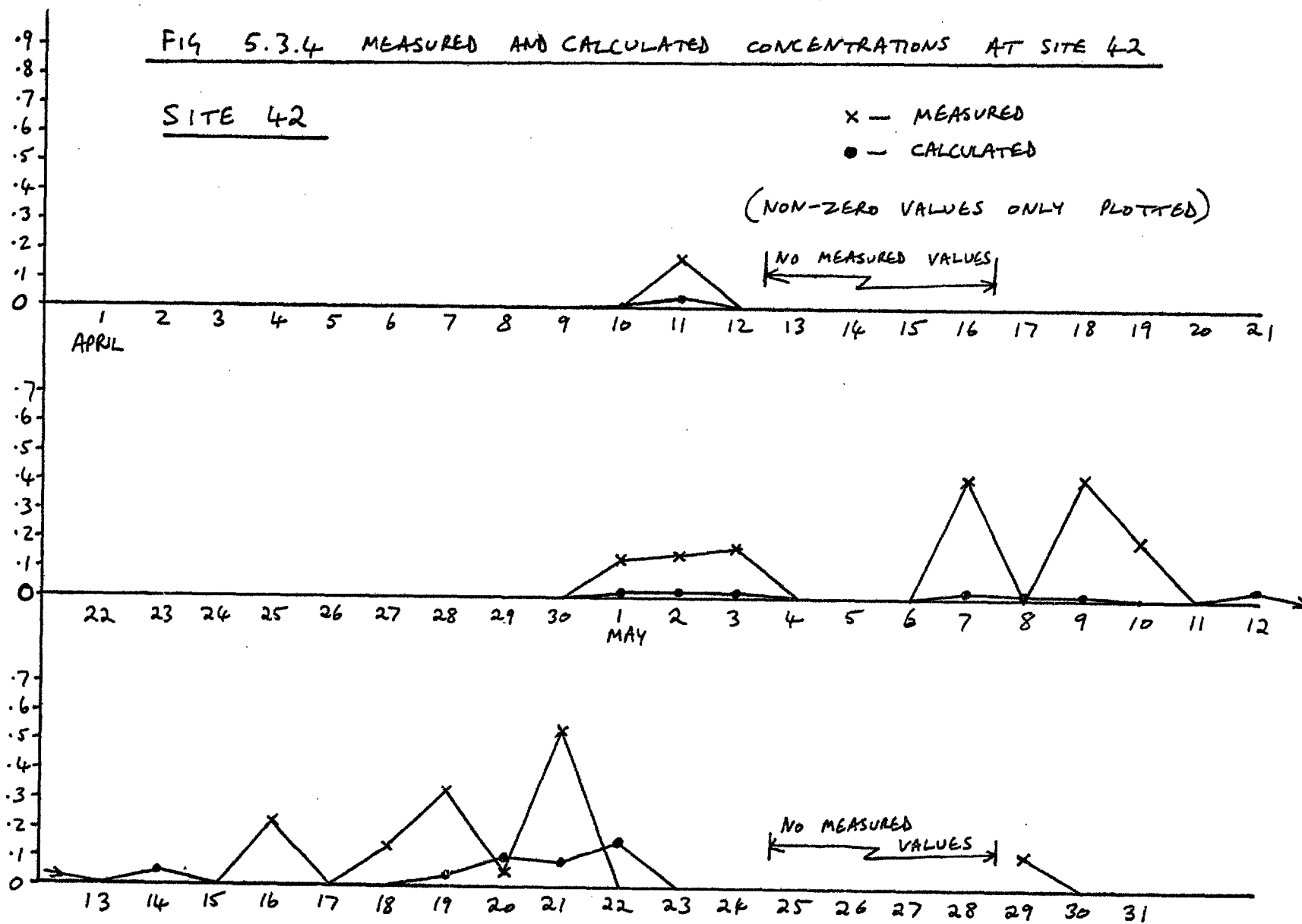
$\mu\text{g}/\text{m}^3$

SITE 42

x — MEASURED

● — CALCULATED

(NON-ZERO VALUES ONLY PLOTTED)



SITE 43

x — x MEASURED
 ● — ● CALCULATED

FIG 5.3.5 MEASURED AND CALCULATED
CONCENTRATIONS AT SITE 43

µg/m³

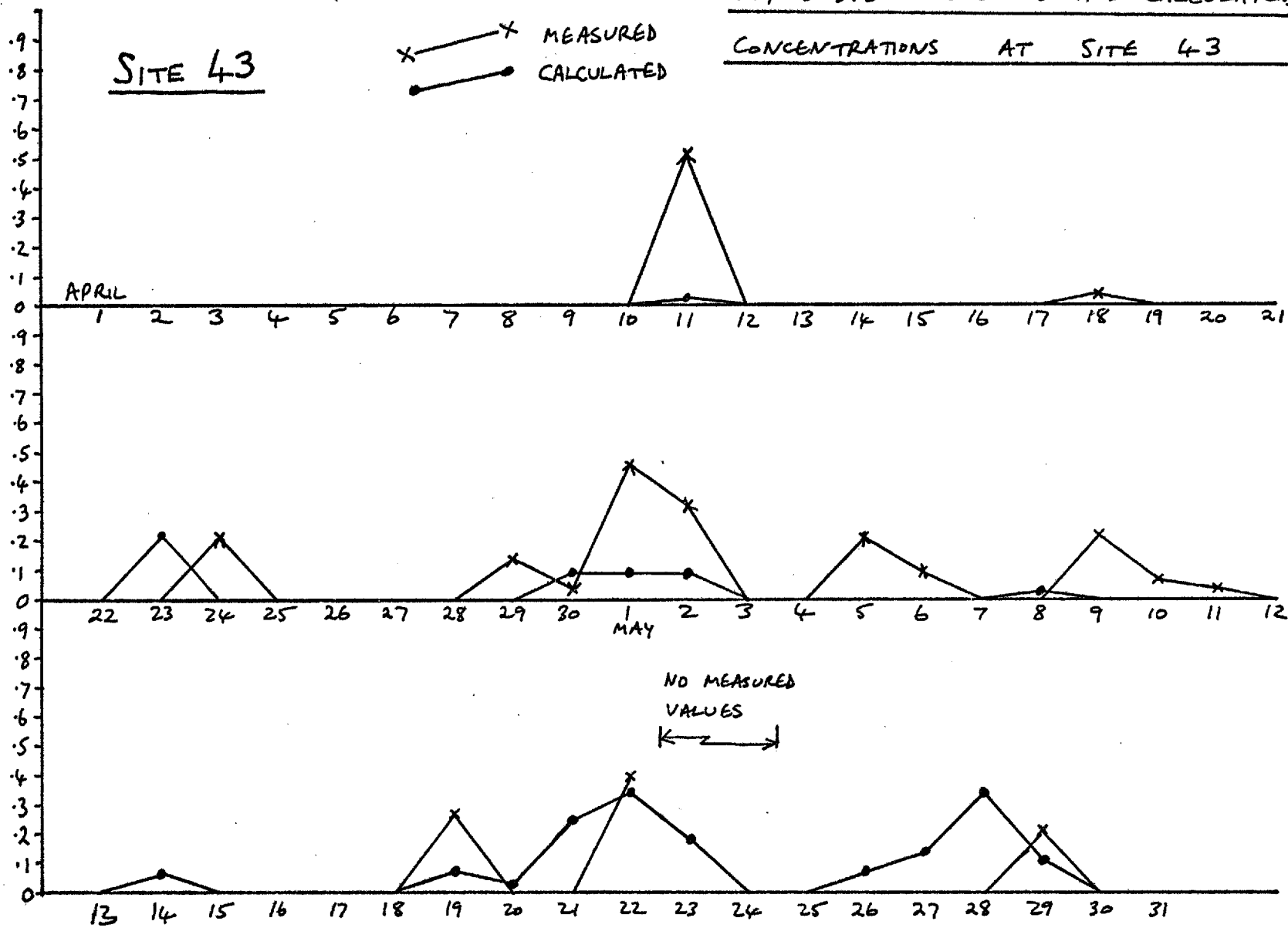
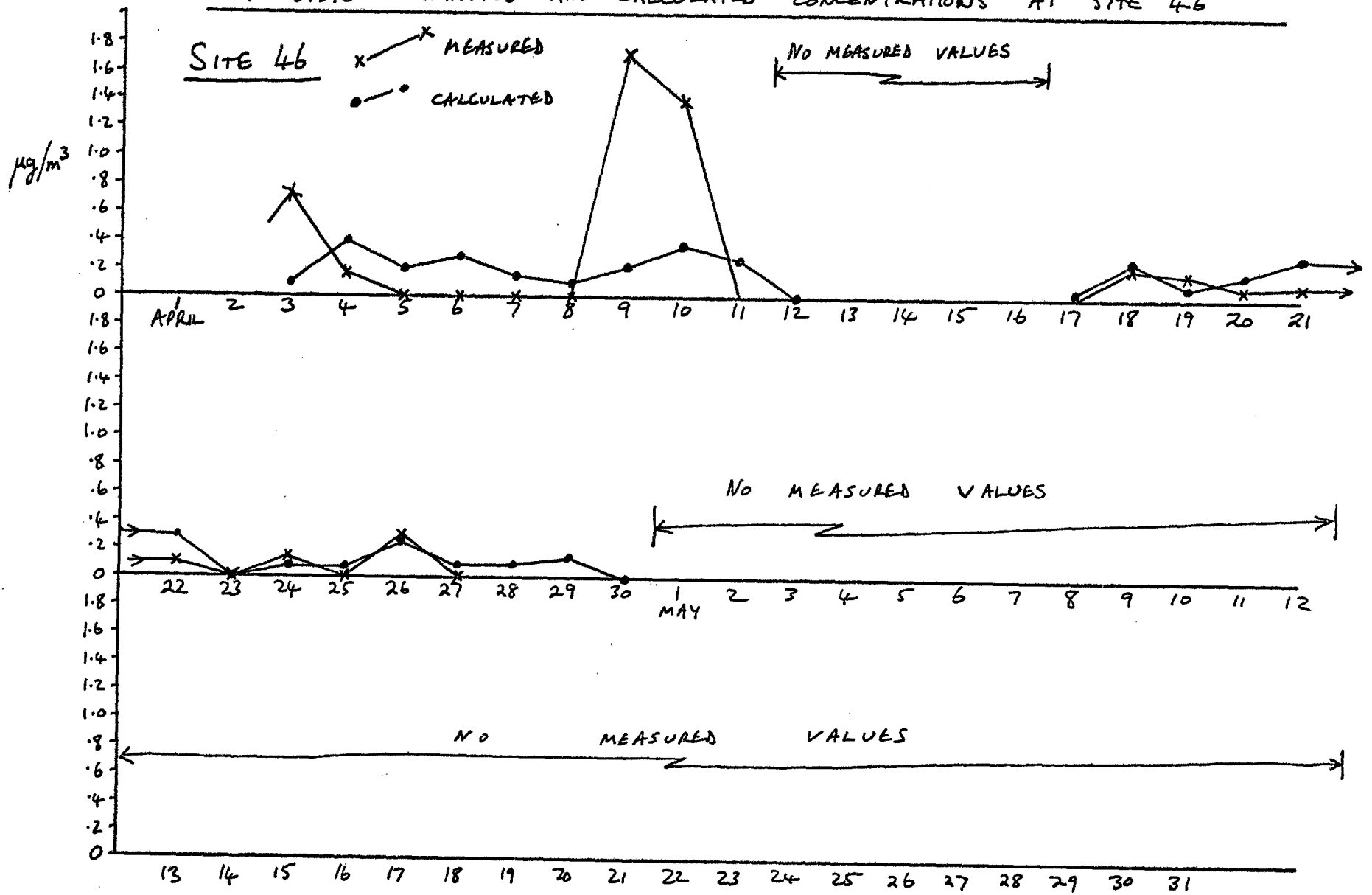


FIG 5.3.6 MEASURED AND CALCULATED CONCENTRATIONS AT SITE 46



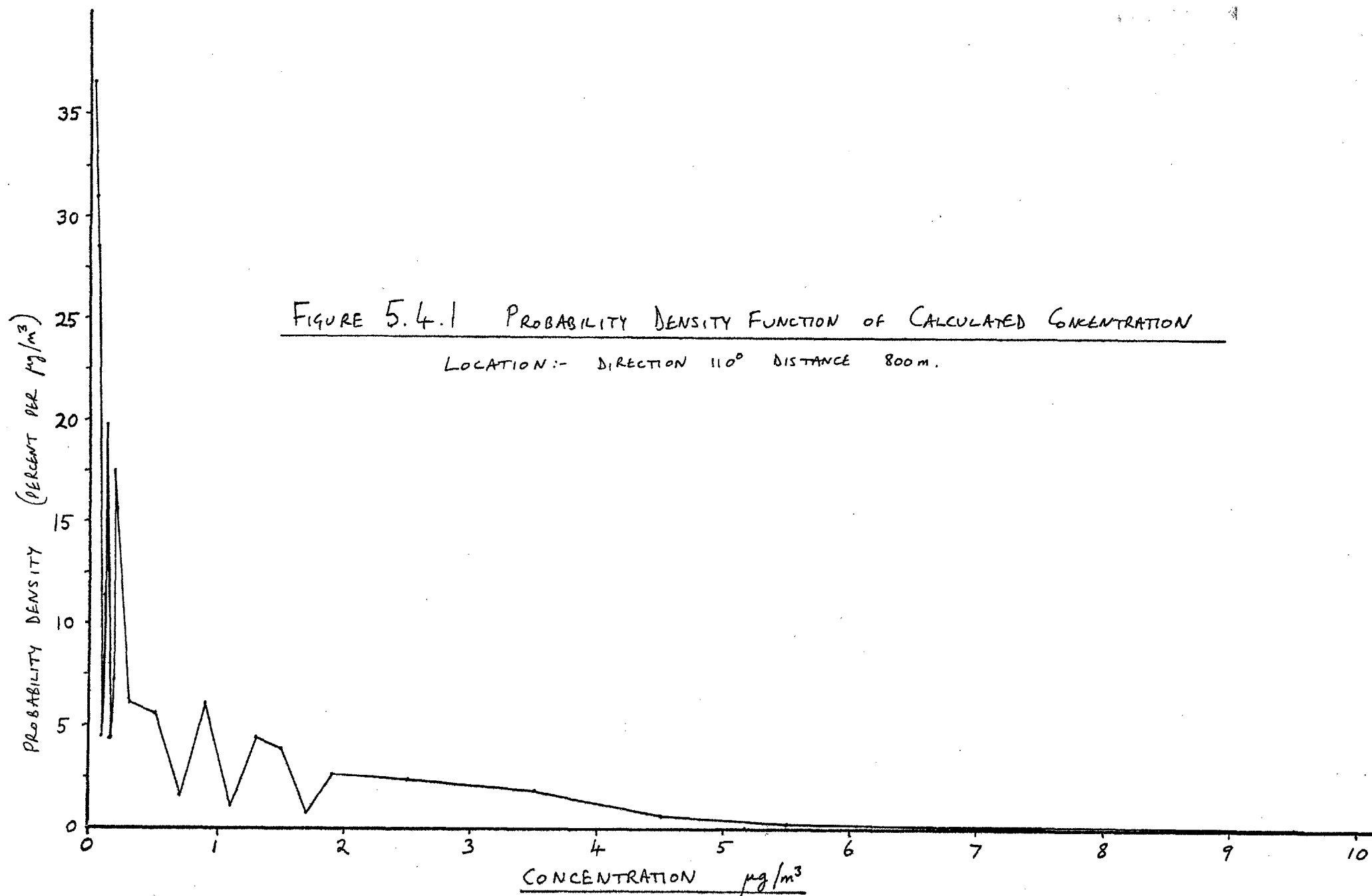


FIG 5.4.2 PROBABILITY DISTRIBUTION ON LOG-PROBABILITY PAPER

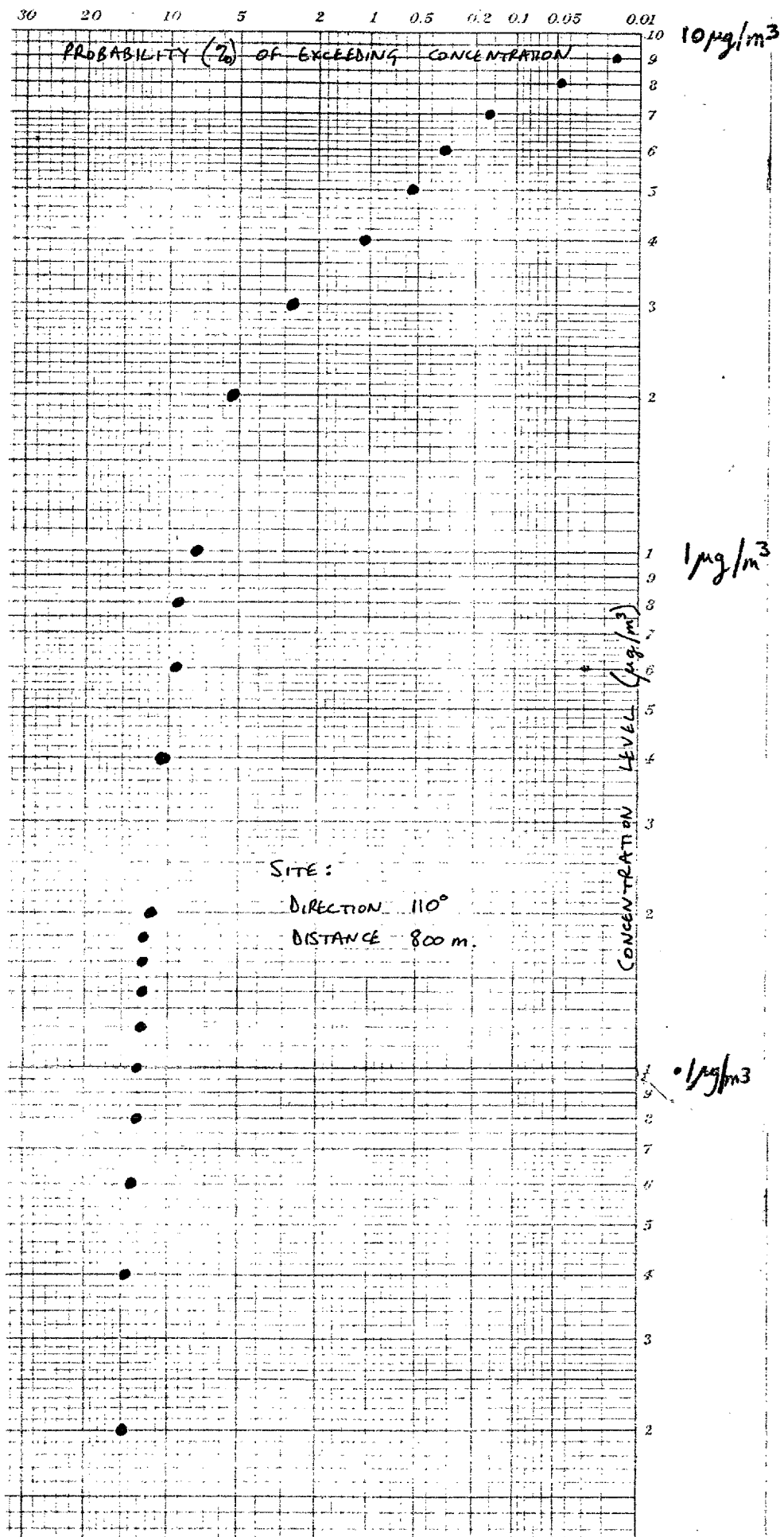
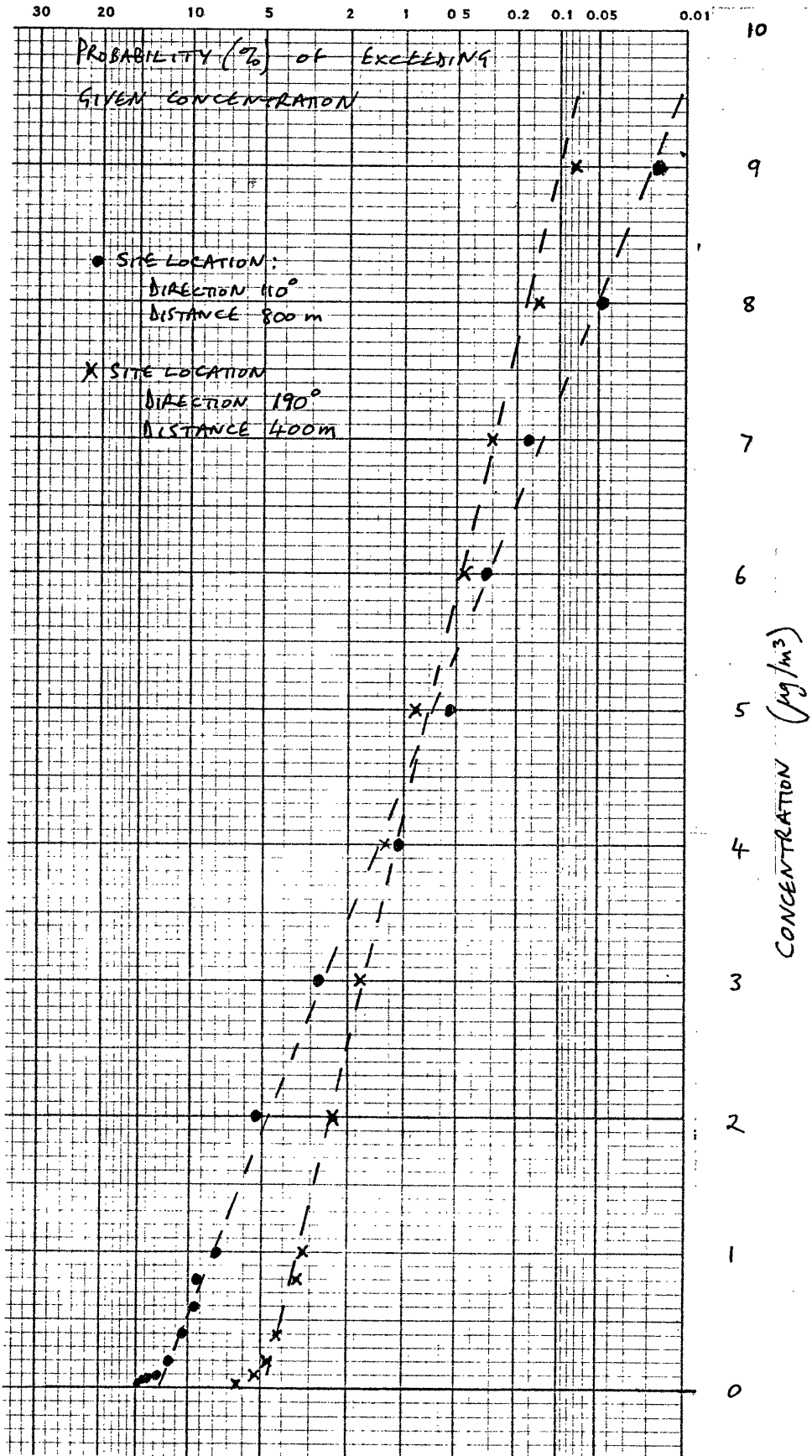


FIG 5.4.3 PROBABILITY DISTRIBUTIONS ON
LINEAR-PROBABILITY PAPER



6.0 CONCLUSIONS

6.1 Principal Conclusions

- (i) Local weather distortions due to topography and heat islands can make significant differences to the frequency distribution of winds at potential or actual industrial sites as compared with the distribution at the nearest synoptic meteorological station (Sections 2.1.4; 2.1.5; 4.1.2). These local distortions can be assessed by correlating on-site observations with the synoptic ones over a period of six months or more (Section 3.3.2.4). The resulting correlations can be used to provide better estimates of the long-term weather frequencies at the site of interest, for use in air pollution predictions (Sections 3.3.2.5; 4.1.6).
- (ii) Local topographical effects can cause changes in the effective chimney height through such mechanisms as flow separation (Sections 2.1.5; 2.2.5.2; 4.2) and stagnation (Section 2.1.5). Since the concentration observed is highly sensitive to the position of the plume centreline (Section 2.2.8) these factors must be taken into account in prediction models.
- (iii) Industrial sources may not perform as originally intended by design (Section 4.3.2), for example the buoyancy may be different (Section 2.2.3) or chimney downwash may occur (Section 2.2.5.1). Where insufficient experience exists for a particular design (not yet actually constructed) it may be preferable to use observed emission rates from other broadly comparable equipment rather than rely on design calculations (Sections 3.3.1; 4.3.2).
- (iv) Certain receptors may be more sensitive to short duration peaks in concentration rather than the overall average (Section 2.3.2). Therefore, models for planning purposes must be capable of predicting peak values, which are best expressed in the form of a probability distribution at each receptor point. This calculation must take into account concentration levels at points off the ground-level plume centreline, plume overlapping for multiple sources and inherent uncertainties in lumped wind frequency data (Section 4.5).

- (v) It is practicable to construct an air pollution dispersion model for a complex industrial source which will give predictions within a factor of about 2 of the actual values at the worst, with better results to be expected in many cases. This level of performance can, however, be expected only when the local weather is well understood and the emissions are reasonably accurately quantified (Section 5.3.2).
- (vi) A dispersion model can be used in conjunction with estimated frequencies of local weather to predict both long term average concentrations and the probability distribution of concentrations. For the illustrative example considered in this thesis (a lead-acid battery factory) the predicted probability distributions approximated to the normal distribution rather than the expected log-normal. The pattern of average concentrations indicated that low-level emissions dominated those from high chimneys, in terms of ground level concentrations (Sections 3.2.6.1; 5.4.2).

6.2 Secondary Conclusions

- (vii) Particle fallout, combined with surface absorption, is best represented by an inclined plume rather than by a horizontal plume with a surface deposition velocity (Sections 3.1.3.4; 3.1.3.5; 4.4.2).
- (viii) Results of laboratory analyses of lead in human blood may vary considerably and due care must therefore be taken in the analysis of results, for example by looking for spurious trends. Direct comparisons between results of surveys analysed by different laboratories may be invalid (Section 3.2.4.2).
- (ix) The probability distribution of lead concentrations in human blood is log-normal (Section 3.2.4.5).
- (x) For children, the maximum increases in blood lead level ($\mu\text{g}/100\text{ml}$) associated with different circumstances were found to be as follows: leadworker in family, 7; 100-year-old house, 6; lead pipes, 4.2; car in household, 3.2; sex, 2.4 (males high); direction from lead works, 2.4. The effect of a leadworker in the family was greatest in children of ages 2 and 3 years.

- (xi) Capillary blood lead levels are about $1.6 \mu\text{g}/100\text{ml}$ higher than the corresponding venous blood leads in adults (Section 3.2.4.3).
- (xii) The battery factory studied as an example caused significant increases in lead levels in air, dust and soil. These effects decrease steadily with distance, except that lead in dust is particularly high on routes followed by vehicles leaving the works (Sections 3.2.6.1; 3.2.6.2; 3.2.6.3).
- (xiii) Lead levels in tap water show large variations from house to house, and between hot and cold water systems in the same house (Section 3.2.6.4).
- (xiv) The effect of the battery factory on lead-in-air concentrations is of the order of 0.2 to $0.3 \mu\text{g}/\text{m}^3$ at a distance of about 800 metres, as compared with an estimated urban background of about $0.45 \mu\text{g}/\text{m}^3$ (Sections 3.3.3.3; 5.4.2).

REFERENCES

- Bagnold, R.A.(1941) The physics of blown sand and desert dunes, Methuen.
- Barltrop, D. (1975) Significance of lead-contaminated soils and dusts for human populations. Arh. Hig. Rada Toksikol 26 (supplement), 81-96.
- Beattie, A.D. et al (1975) Role of chronic low-level lead response in the aetiology of mental retardation. Lancet March 15, 1975, 589-592.
- Benjamin, S.F. (1974) An Assessment of Atmospheric Dispersion Theory. University of London Ph.D. Thesis, Mathematics Dept., Imperial College.
- Britter, R.E., Hunt, J.C.R. and Puttock, J.S. (1976) Predicting pollution concentrations near buildings and hills, Symp. Systems and models in air and water pollution, Institution of Measurement and Control, London, Sept 22-24 1976.
- California Department of Public Health (1967) Lead in the environment and its effects on humans. Air resources Board, Sacramento, California.
- Chamberlain AC (1953) Aspects of travel and deposition of aerosol vapour clouds. AERE HP/R 1261 H.M.S.O.
- Cox, R.A., Shillito, D.E., Comer, P.J., Slater, D.H., (1977) Novel methods for assessment of air pollution in planning situations where conventional dispersion models are inapplicable, 4th Int. Clean Air Congress, Tokyo, May 16-20, 1977.

REFERENCES (CONT.)

- Dorn, C.R., Pierce, J.O., Phillips, P.E., and Chase, G.R. (1976), Airborne Pb, Cd, Zn and Cu concentration by particle size near a Pb smelter. Atm. Env. 10, 443-446.
- Draxler, R.R. and Elliot, W.P. (1977) Long range travel of airborne material subjected to dry deposition. Atm. Env. 11, 35-40.
- Fox, T.D. and Ludwick, J.D. (1976) Lead concentrations associated with 1000 mb geostrophic back trajectories at Quillayute, Washington. Atm. Env. 10, 799-803.
- Gunn, D.M. and Furnage, D.F. (1976) The effect of topography on surface wind, Met. Mag. 105, 8-23.
- Halitsky, J. (1963) Gas diffusion near buildings, Am. Soc. for heating and Refrigg. Air Engr. Trans. 69, 464-485.
- Hancock, R.P., Esmen, N.A., Furber, C.P. (1976) Visual response to dustiness, J.A.P.C.A. 26(1), 54-57.
- Hanna, S.R. (1971) A simple method of calculating dispersion from urban area sources, J.A.P.C.A. 21(12) 774-777.
- Heichel, G.H., and Hankin, L., (1976) Roadside coniferous windbreaks as sinks for vehicular lead emissions. J.A.P.C.A. 26(8), 767-770.
- Horst, T.W. (1974) A surface depletion model for deposition from a gaussian plume. Proc. Symp. Atmospheric-Surface Exchange of Particulate and Gaseous Pollutants. ERDA Symp. Series. Conf. 740921 Richland, WA 4-6 Sept. 1974.

REFERENCES (CONT.)

- Hudson, J.L., Stukel, J.J. and Solomon, R.L. (1975).
Measurement of the ambient lead concentration in the
vicinity of Urbana-Champaign, Illinois. Atm. Env.
9 1000-1006.
- Janssens, M. and Dams, R. (1975) Man's impact on
atmospheric lead concentrations - pollution sources
and baseline levels in Western Europe. Water, Air
and Soil Pollution 5, 97-107.
- Kehoe, R.A. (1961) The Harben Lectures, 1960 - The
Metabolism of Lead in Man in Health and Disease.
J. Roy. Inst. Public Health and Hygiene.
- Kneebone, A. and Prew, L.R. (1974) Shipboard jettison
tests of LNG onto the sea. 4th Int. Conf. on LNG
Algiers, June 1974.
- Lord, G.R. and Leutheusser, H.J. (1966) Minimum stack
heights for apartment buildings, Univ. of Toronto,
Dept. Mech. Engg. TP 6602.
- Lucas, D.H. (1972) Choosing chimney heights in the presence
of buildings, Int. Clean Air Conf. Melbourne University,
proceedings publ. by Clean Air Soc. of Aus. and NZ.
- Ludwig, J.H., Diggs, D.R., Hesselberg, H.E., and Maga, J.A.
(1965) Survey of lead in the atmosphere of three urban
communities. Ind. Hyg. J. May-June 1965, 270-284.
- Manton, W.I. (1973) Significance of lead isotope composition
in blood. Nature 244, 165-167.
- Martin, A. and Barber, F.R. (1973) Further measurements
around modern power stations I, II and III, Atm. Env.
7, 17-37.

REFERENCES (CONT.)

- McClannan, H., and Rossano, A.T., (1975) Arsenic and lead exposures in the vicinity of the Tacoma smelter. *Trend. Engineering.* 27, 8-13.
- McCormick, R.A. (1971) Air pollution in the locality of buildings, *Phil. Trans. Roy. Soc. Lond. A* 269, 515-516.
- McMullen, R.W. (1975) The change of concentration standard deviations with distance. *J.A.P.C.A.* 25, No. 10, 1057-1058.
- Novak, J.H. and Turner, D.B. (1976) An efficient Gaussian-plume multiple-source air quality algorithm, *J.A.P.C.A.* 26(6), 570-575.
- Ooms, G. (1972) A new method for the calculation of the plume path of gases emitted by a stack. *Atm. Env.* 6, 899-909.
- Ooms, G., Mahieu, A.P., and Zelis, F. (1974) The plume path of vent gases heavier than air. 1st Int. Loss Prevention Symposium, The Hague/Delft May 1974.
- Pasquill, F. (1961) The estimation of the dispersion of windborne material, *Met. Mag.* 90, 33.
- Pasquill, F. (1974) *Atmospheric diffusion*, 2nd edition, publ. Ellis Horwood Ltd. Chichester.
- Pollitt, J.G. (1976a) Atmospheric lead pollution - some observations. *Clean Air*, Summer issue 1976.
- Pollitt, J.G. (1976b) Personal communication, August 1976.

REFERENCES (CONT.)

- Ratcliffe, J.M. (1975) An evaluation of the use of biological indicators in an atmospheric lead survey. *Atm. Env.* 9 623-629.
- Servant, J. (1974) Deposition of atmospheric lead particles to natural surfaces in field experiments. E.R.D.A. Symposium series 38, Atmosphere-Surface Exchanges of Particulate and Gaseous pollution.
- Singer, I.A. and Smith, M.E. (1966) Atmospheric dispersion at Brookhaven National Laboratory, *Int. J. Air & Water Pollution* 10, 125-135.
- Slade (1968) Meteorology and Atomic Energy 1968, US A.E.C. Division of Technical Information TID-24190.
- Snyder, W.H. and Lawson, R.E. (1976) Determination of a necessary height for a stack close to a building - a wind tunnel study, *Atm. Env.* 10, 683-691.
- Solomon, R.L. and Hartford, J.W. (1976) Lead and cadmium in dusts and soils in a small urban community. *Env. Sci. and Tech.* 10 (8), 773-777.
- Stokes (1850) *Trans. Cambridge Philosophical Society* 9, p8.
- Stukel, J.J., Solomon, R.L. and Hudson, J.L. (1975) A model for the dispersion of particulate or gaseous pollutants from a network of streets and highways, *Atm. Env.* 9, 990-999.
- Sutton, O.G. (1932) A theory of eddy diffusion in the atmosphere, *Proc. Roy. Soc. A*, 135, 143.
- Tani, I., Tuchi, M. (1961) Experimental Investigation of Flow Separation Associated with a Step or Groove. University of Tokyo Aeronautical Research Institute Report No.364.

REFERENCES (CONT.)

Thomas, H.V., Milmore, B.K., Heidbreder, G.A., and Kogan, B.A. (1967) Blood lead of persons living near freeways. Arch. Env. Health. 15, 695-702.

Turner, D.B. (1970) Workbook of atmospheric dispersion estimates E.P.A. Office of Air Programs Publication No. AP-26.

Ward, N.I., Reeves, R.D., and Brooks, R.R. (1975) Lead in soil and vegetation along a New Zealand state highway with low traffic volume. Environ. Pollut. 9, 243-251.

APPENDIX I

I.0 THE BEHAVIOUR OF DUST IN THE ENVIRONMENT

I.1 Introduction

The substances we call pollutants come in two varieties: those whose chemical nature is novel and incompatible with some components of the biosphere, and those that occur naturally but cause trouble through being present in such quantity that the natural cycles cannot cope with them. In general, dust problems are of the second kind, but the variety of types of dust pollution is very great and the generalization might mislead. For example, dust produced by a manufacturing process may simply overload the environment, while dust problems in towns are often caused when grass, which traps dust, is replaced by concrete, which does not. In this case the natural cycle has been directly damaged by Man's action, and a material which would otherwise be quite harmless becomes a pollutant.

Dust can have two kinds of harmful effect: physical and chemical. Physical effects include such things as making buildings dirty, erosion of stonework, and haze. In these cases the particle size is of more importance than its composition. Chemical effects will not concern us much in this discourse, except in considering as an example the important case of toxic lead dust and the transport mechanisms which make lead emissions dangerous. It is the physical effects of dust that make it one of the air pollutants people most frequently complain of, for it is tangible and visible, and gases can only be detected as easily when they are smelly. These characteristics make dust a good example for study

and the observant amateur can see for himself the various aerodynamic and hydrodynamic mechanisms by which dust is transported, accumulated, and dispersed. But we should always bear in mind that in the wider context of pollution and resource problems, dust pollution cannot be portrayed as a great threat to human society by any stretch of the imagination; we simply use it here as an illustration of the complex interactions between human society and the physical world.

I.2 Definition of Dust

Dust is, literally, a household word. The all-too-familiar operation of dusting the house suggests a useful broad definition of dust: dry particles of such size and weight that in typical gusts or draughts they become airborne, while in calm air they settle within the time scale of interest. This definition allows the range of particle sizes considered as dust to vary from case to case according to differences in time scales and gust velocities. To take the example of household dust, we might well concern ourselves only with particles which settle out overnight, which are those bigger than 1 micron (1μ) while for industrial emissions particles up to 5μ may travel quite a long way before settling in significant amounts, and the falling speed through the air is largely ignored.

Particles which do not settle significantly are often referred to as fume, while those that are hardly ever airborne are called grit. A useful guide to sizes for out-of-doors dust is as follows:

fume	:	up to 1μ
dust	:	1μ to 1mm
grit	:	1mm. and above.

These figures are only given to provide a sense of the scale of the particles and the interpretation of them must be flexible, especially because particles can be of very variable shape. For example, household dust tends to include fibrous material which settles much more slowly than spherical particles of the same weight. Our definition of dust is based on sinking rate rather than on particle size because that determines that particle trajectory in a given wind and hence how dust is distributed around the source producing it. It is worth noting that where the problem of people getting dust in their eyes is concerned the range of particle sizes of importance is limited because only those particles which are too small to be seen can normally get in the eye.

The material which dust consists of also has other forms, such as mud, dried mud cake, etc., and is often transformed between these states in the course of its existence. Thus, rather as we have to know the life cycle of an insect pest before we can confidently set about eradicating it, so we must study the 'life cycle' of dust if we are to reduce the pollution problem which it causes. The mechanics of the cycle has three components - sources, transport, and sinks - and we will find that the worst effects of dust occur while it is being transported through the air, because aerodynamic mechanisms accumulate it, and then dislodge it again by a change in wind direction or a strong gust. When wet, dust is relatively well-behaved and is simply carried around by the water flow, for which gutters, drains and sumps have been thoughtfully provided in our cities.

Although transport mechanisms determine the effects of dust, the solution of the problem may often lie with the dust source itself. Human activity has a tendency to stir up dust, but Nature can do much more on occasions. Desert dust storms surpass anything Man can do, but these occur mainly in remote regions, while the urban areas of temperate countries with which we are mainly concerned, Man's impact on the existing dust pattern has been overwhelming. We have constructed huge areas of concrete on which dust has no stable refuge such as it has on soil or vegetation. Then we drive around in all kinds of vehicles which stir up the air so that the dust never settles for long. Cities are constructed with a total disregard for local aerodynamic phenomena, so that exceptionally high winds are caused near tall buildings and any dust that may be around gets picked up. But most of this urban dust is in fact soil, and not of our creation at all. We have simply turned it into a nuisance.

I.3 Industrial Sources of Dust

Many artificial sources of dust are obvious. Several industrial processes generate dust and disperse it into the air; for example coal burning invariably produces some ash, and nowadays power stations burning pulverized coal have to filter the exhaust using electrostatic precipitators to keep ash fall-out down to acceptable levels. Even now it occasionally happens that with power stations of obsolete design tiny ash particles may be deposited over a wide area under certain weather conditions, or when a rapid start-up of a boiler is required (because the precipitators cannot be operated when cold due to condensation on the high voltage insulators). Sometimes conglomerations of ash particles are emitted when surface conditions inside the chimney permit accumulation of ash on the walls.

Dust is an unavoidable intermediate material in many industrial processes, notably mineral processing. Cement manufacture is a specially interesting example because the emission from stacks which are obvious to the eye are often not the ones which cause the worst effects. Chalk quarrying is a very dusty process in itself and there is usually visible evidence of this in the deposits covering vegetation near a quarry. The incoming materials must be crushed and mixed and the dust produced by these processes has to be handled very carefully to avoid hazard to operators as well as excessive emission to the local environment. Air extraction equipment which is designed to improve conditions within buildings must be fitted with filters to ensure that conditions outside are not adversely affected. The larger particles are removed in cyclones and the smaller ones by bag filters. When the chalk is fired, cement clinker is formed and some dust is carried away up the chimney. This dust can be seen in the plume from the main works chimney, but in most cases much of the dense white appearance of this plume is due to water clouds, which can be seen to evaporate as the plume dilutes into the atmosphere, leaving only the much less visible dust plume. Because of the very large quantity of dust lost from the process in this way there has been a very proper emphasis on adequate filtration of this emission, and modern cement kilns do not cause much pollution at ground level by their high-level chimney emissions.

The next stage is transporting the clinker to a place of storage. This is a very dusty operation because the clinker must inevitably fall some distance from the conveyor or crane into the storage area, and so dust is raised. This produces some of the worst internal atmospheres to be found in a cement works, and any operators in the area must wear masks or be located in

sealed cabins supplied with fresh air. Naturally it is essential that the building be properly sealed, but this is not always easy or cheap to do. To make the final product, the clinker is ground to powder and blended with gypsum, both very dusty operations requiring tight environmental control. Loading of cement into bags or vehicles must be done in fume-extracted areas with adequate filtration of the extracted gases. Nowadays cement lorries are washed down after loading to eliminate the serious offence which would be caused by dust blowing off moving vehicles, though it must also be said that clean lorries are helpful to public relations and this was probably the major factor in the decision to wash them.

Despite these apparently comprehensive measures, the cement industry still releases dust from a great variety of minor sources, all at low level, which continue to be a major cause of complaint from nearby residents. We shall see later that there may be ways of trapping this low level dust after emission as an alternative to eliminating each source one by one.

Cement making is a typical industrial source of dust. There are many others which the reader may observe in his travels and it will be found that they all share the characteristic that the worst effects are due to a multiplicity of small, low level sources while any chimney emission is usually well controlled. Another very important artificial source is demolition, which has serious effects because of its proximity to population. Houses are made largely of dust particles stuck together, and when a building is demolished a tremendous amount of this material is released. In fact some of this is cement dust in an unwelcome reincarnation. When demolition is

finished the site frequently remains empty for several months and this in itself causes dust problems because the ground, having no topsoil, is liable to erosion in the high winds which are often encountered in open areas in towns. This nuisance can be prevented by erecting a solid fence around the site which will trap dust in the eddy zones which form near the base. Another abuse in this connection is the release of dust from lorries carrying demolition materials. These can often be seen being driven with no tarpaulin or other protective cover. This puts the dust where it is least wanted - in busy streets - and is totally unnecessary.

It is commonly thought that roads are a source of dust. This is because they are invariably dusty places, but in fact normal road traffic does not itself generate dust. By calculating the rate of wear of tyres it can be shown that even on the most densely trafficked road this could not account for more than about 1% of the observed roadside dust. Wear of the road surface itself is very slow and even on the most pessimistic assumption its contribution is even smaller. Other possible sources, such as brake and clutch linings, are totally negligible. Thus we conclude that the effect of traffic is mainly to transport dust, not create it. Microscopic examination shows that the dust which is found in kerbs is almost always ordinary soil, or constituents of soil, which has been carried along either by the repeated aerodynamic patterns of the stream of traffic or as mud spattered on the undersides of vehicles. The true source in these cases may be hard to determine, but typical examples can easily be found by the observant investigator. Sometimes the wakes of vehicles cause soil to be picked up from nearby verges or borders, and mud is often carried onto road from building sites and fields.

We have considered so far some examples of the range of dust sources which give cause for complaint in contemporary situations. It is not an exhaustive list by any means, but these examples should prove adequate to illustrate the principles of the argument. We must now consider the behaviour of the dust once it has been released.

I.4 Transport of Dust in the Environment

Dust transport occurs both in water and in air and the actual effects of dust on any given day depend on which of these media is dominant. The presence or absence of water is the major determinant. On a rainy day we have the phenomena of washout and rainout of particles from the atmosphere. The first of these - washout - is the removal of particles by collision with falling raindrops. This is not a very effective removal mechanism although we commonly find that the air after a rainstorm is completely clear of haze because the dusty air has been replaced by a fresh body of air brought down by the rain. The larger the particle the more likely it is to be removed by washout because its mass is increased more than its area and so it is less likely to be carried round a raindrop by the airflow. The same mechanism operates in the gas scrubbers commonly used for cleaning industrial exhausts, and so the finest particles are not trapped.

Rainout is the result of the formation of cloud droplets on the dust particles, which act as condensation nuclei. The droplets coalesce and eventually fall as rain, taking the particles with them. This is a much more effective cleaning mechanism, and it removes the smallest particles as effectively as the large ones.

Just as water is the crucial factor in the air, so it is on the ground. It is obvious that on wet days dust on the ground will not become airborne at all, but will form mud or be transported in the water run-off as a fine slurry, possibly silting up at certain points where the flow slows down. Many of the phenomena of dust transport in the air may be observed in microscale in water, and in particular there is an aerodynamic counterpart of silting up which we will be concerned with below.

Generally, water-borne dust is not a problem. It is certainly a form of dust which is common in Nature, and provided the dust is non-toxic no hazards have arisen from it in this form. One important consequence, however, may be the clogging of drains taking storm water from roads. This possibility necessitates regular road sweeping, especially in sensitive areas such as the approach road to a tunnel (since tunnels are of course the lowest point in the road system for a considerable distance in all directions and water and dust therefore collect from a large area). Because of the need for sweeping, roads are in fact a sink for dust but this should not be taken to imply that they therefore have a beneficial effect on the dust nuisance in the neighbourhood. The adverse effect of roads comes about because traffic brings with it intermittent gusts of wind which disturb dust which has accumulated in corners, and unfortunately roads are inevitably places where there are people. Social surveys taken before and after the building of urban motorways have indicated an increase in annoyance caused by dust, which is due to these effects and to the replacement of dust absorbing surfaces such as foliage by asphalt and concrete. Another possible factor is a heightened awareness of dust due to the gross dust pollution which accompanies site clearance and road construction.

For dust to become airborne it must be dry and quite finely divided. For the particle sizes which are of most interest in this problem the analysis by Stokes (1850) of the flow around a sphere falling through a viscous fluid is a good model of dust behaviour and gives us a means of estimating the falling speed of different sizes of particle through the air. The viscous drag force in Stokes' flow is proportional to the particle size and exactly balances the weight; from this we find that the terminal velocity of the particle is proportional to the square of the particle size (for a fixed particle density). For comparison, the following table gives the times taken for typical particles of various sizes to fall through one metre of air:

<u>Particle Size</u>	<u>Time to fall 1m.</u>	<u>Remarks</u>
0.1 μ	800 hours	fume
1 μ	8 hours	dust
5 μ	20 minutes	dust
10 μ	5 minutes	dust
100 μ	3 second	Stokes law not strictly valid due to turbulence in the airflow. For guidance only.

For many purposes we treat particles smaller than 5 μ as behaving like a gas, i.e. having zero fall speed, but in general the validity of this depends on the scale and intensity of the motion we are interested in. For example, if we are calculating the dust distribution from an isolated industrial source with a 30 metre chimney and we are interested in distances up to 4km away, the order of time for the wind to travel this distance is about 12 minutes, in which time a 5 μ particle will have fallen about 0.5m relative to the air. In the context of a 30m chimney and eddies which carry the air up and down over even greater heights

settling is clearly not significant. A 20μ particle would however have dropped 10m, so this would certainly invalidate any calculation that assumed the particles to behave like a gas, unless the air were fairly turbulent. In problems concerned with deposition near buildings, however, this same 20μ particle might well be considered to behave like a gas particle because it will not have time to fall out nearby.

The effect of atmospheric turbulence on the fall behaviour is to scatter the particles more widely. If we imagine a high level source of dust particles of a single size in a smooth airstream, the particles will all follow the same path and would reach the ground at the same point. The lighter the particles the further away this point would be. In turbulence, however, each individual particle would experience a different sequence of eddies and hence would follow different paths, so that they would reach the ground in a spread centred on the original smooth flow point. We can easily see that for a source which produces a wide variety of different particle sizes, in turbulent wind every point on the ground will receive a mixture of particle sizes and the distribution of these sizes will be different from place to place.

It is a fairly straightforward matter to estimate the dispersion of dust from an isolated high level source such as a cement works chimney in a uniform wind using the concepts described above together with some meteorological data for the locality. Such estimates are used to decide how much dust should be allowed to be emitted from a works. As a result electrostatic precipitators or other filtration apparatus are usually required to be incorporated in the design. Such filters cannot be 100% efficient but the particles that escape

are mostly those of the smallest size, which travel furthest in the atmosphere and are therefore well dispersed. Calculations and measurements show that for typical industrial emissions the main stacks contribute far less dust to the environment than do the low level sources within the factory. If stack emissions were the dominant factor we would expect dust concentrations to be greatest at some distance from the works where the plume from the stack actually reaches the ground. In fact, for such works as cement factories or battery factories it is invariably found that concentrations decrease with distance and this indicates that low level sources dominate. Unfortunately, the calculation of dispersion of air pollutants at low level is bedevilled by all manner of uncertainties, particularly the effect of ground obstacles on the mean flow and turbulence. Much dust motion close to the ground is determined by the flow characteristics of buildings and vehicles. One important example of this is that the larger dust particles are transported preferentially along roadways rather than across them.

I.5 Aerodynamic Mechanisms of Dust Accumulation

The flow approaching a rectangular building is shown schematically in Figure A1. Note the regions of separated flow (eddy zones) in which the air recirculates. Any dust which falls into the eddy zone will not escape until there is a substantial change in wind direction which causes the entire flow to change and the eddy to be carried downwind. If there is a corner which contains such a standing eddy in all wind conditions then a major dust accumulation will take place. This situation can often be found in built-up areas, and the effect is made much worse by the gustiness which is found near the tall blocks which are a feature of modern urban

architecture. A sudden gust may pick up a pile of dust which has accumulated in an eddy zone for a few minutes and blow it in the faces of pedestrians. The accumulation of dust is often a nuisance because it makes the place look untidy and dirty, necessitating more frequent cleaning. It would be preferable in most cases if the dust simply blew away until it found a stable resting place in the soil or vegetation where it is not a nuisance. However, in some situations the accumulation process is a useful one because it concentrates the dust in a manner suitable for sweeping. The best example of this is the roadside kerb. The pattern of airflow round passing cars is repeated again and again and drives any dust that may be in the road towards the kerb, where a separation zone is set up similar to that caused by a rectangular building. Thus the dust is trapped at the kerb but dragged along it by the wakes of vehicles. This is a very effective transport mechanism and has been found to be of importance in the distribution of lead dust from lead-acid battery factories; in several studies, roads used by vehicles serving such works had high lead contents in the kerb dust, while other roads were not so contaminated.

I.6 Dust Sinks

The ultimate fate of airborne dust in the natural cycle is of importance because it may suggest countermeasures against dust pollution. We have already noted the mechanisms of washout and rainout, which introduce airborne dust into the water cycle. This dust may ultimately become part of the topsoil through which the water drains or it may form silt on the river bed, but these mechanisms serve only to clean up a widely dispersed particulate aerosol; they cannot contribute to the localised problem of wind-blown dust on a dry day. In this case we are concerned with larger particles than those which form aerosols. These particles are carried along

close to the ground and are only intermittently airborne, and the cycle of settling when the wind drops and being picked up again in gusts is repeated for as long as the dust alights on a relatively smooth and impervious surface, such as concrete. This cannot go on for ever, and eventually the dust reaches a surface from which it cannot be dislodged by normal gusty winds. Such surfaces include grass, soil and open surface water.

A grass verge by a road will effectively absorb the dust which is repeatedly dislodged and displaced laterally by gusts from passing vehicles. Careful layout of gardens or grass could contribute to solving the local nuisance caused by a cement works, and is especially important in residential areas. Another example where the same processes operate is the case of the sandhills produced by grasses which continually grow upwards through the sand accumulated when the wind blows it from the open beach.

The correct choice of countermeasures for combatting dust will depend on the particular circumstances of each case. A distinct individual source such as a factory chimney is best dealt with by the well-established dust extraction techniques, but for certain processes adequate dust suppression is either impracticable or uneconomic, and so it would be preferable to throw some kind of dust trap around the entire operation. This might be a grass verge or an open channel of running water, or a low wall from the foot of which accumulated dust could be regularly swept. The last of these functions in the same way as the kerb of a road, trapping the dust in the eddy zone where the air recirculates. The general dust found in cities, which comes from a multitude of sources which it would be impossible to suppress individually must be handled by interspersing

grass and gardens between the tracts of concrete and by avoiding building layouts which cause strong gusts at ground level, particularly on hard surfaces. Tall buildings close together or buildings on stilts are particularly bad in this respect.

As a matter of interest, there is a precedent for the idea of dust-controlling walls or fences which has been applied to the control of snow drifts. To prevent snow collecting on roads it has long been common practice to place fences a few yards away from the road so that most of the snow in the lower layers of air crossing the road falls out in the region of reduced velocity around the fence.

I.7

Conclusions

Perhaps because it is a natural feature of our environment, dust is not generally regarded as a serious pollutant. It seems on the contrary to be thought of as an inevitable feature of the world about which nothing can be done. While there is some truth in this, many artificial causes of dust nuisance exist and it may be possible, by studying the natural processes of dust transport and removal, to devise means of reducing the annoyance. These methods often use aerodynamic processes of dust accumulation to concentrate the material in places where it is absorbed by the environment or can be easily swept up. Many dust problems are made worse by modern urban structures which do not allow in their design for the inevitable presence of dust.

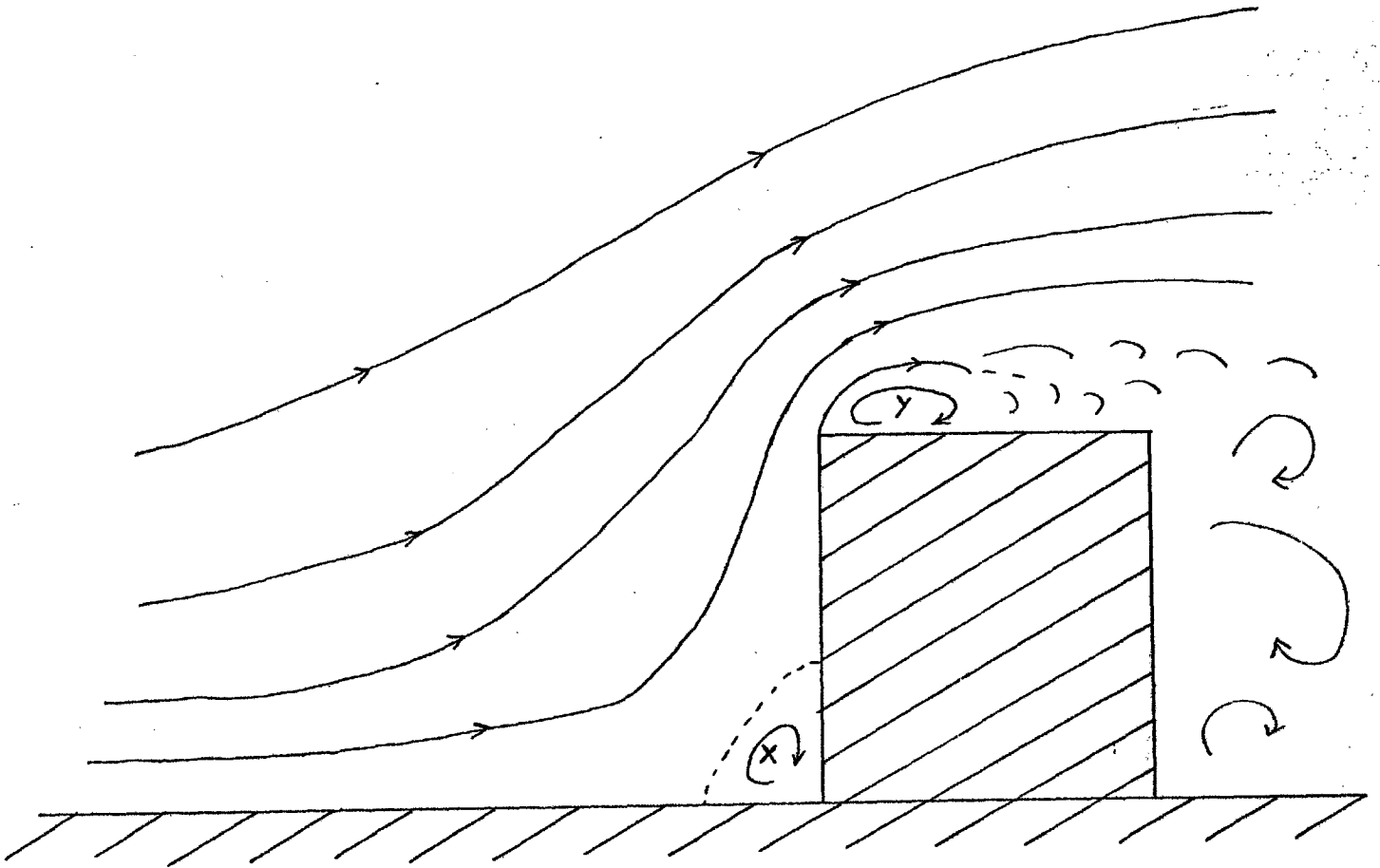


FIGURE A1 · FLOW ROUND A RECTANGULAR BUILDING

NOTE: STANDING EDDIES (RECIRCULATING) AT 'X' AND 'Y'

APPENDIX II

II.0 COMPUTER METHODS USED IN STATISTICAL ANALYSIS OF LEAD SURVEY DATA

The very large number of human subjects in this survey necessitated the use of a computer for the analysis of the results. For each sample (both human blood and environmental samples) a data card was punched giving relevant details, which would be used later in the analysis.

For human blood, the data card included the following information: sample identifying number; type of sample; cross reference to any other samples from the same subject; age of subject; sex; category of subject; relationship to any leadworker in family; lab. result; cross reference to 'Family Index'. The Family Index provides further information relating to an entire family rather than to individual subjects. This includes: location of home; age and rateable value of house; period of residence in the house; social class; presence of any overt lead hazard (e.g. lead pipes, paint).

In order to compress all of this information onto a single data card, it was necessary to encode it and this was done using a straightforward record sheet for each subject, which was filled in by the person responsible for taking the sample.

Much the same approach was also adopted for handling the environmental survey data, but in the event it proved possible to analyse this data manually rather than by computer, since the number of categories involved was smaller.

II.1 Checking the data base - Programme CHECK

The data cards were first reviewed by a specially developed programme (CHECK) which was designed to identify any contradictions in the data. This was possible because a large measure of redundancy had been built into the record sheet information from the start (for example, the age of the subject would provide a partial check on the sample type, i.e. child's blood or adult's blood, etc.). The checks carried out involved both internal checks, that is, checks on the consistency of information within a single card, and external checks - those involving conflicts between two cards.

Among the internal checks were the following:

- (i) valid specimen serial number
- (ii) specimen type valid
- (iii) valid repeat and replicate cross references
- (iv) cross reference between adult capillary blood and micro aliquots of venous blood consistent with specimen type.
- (v) age of subject consistent with specimen type, e.g. no venous blood from children, etc
- (vi) sex of adults always female
- (vii) presence of leadworker consistent with specimen category
- (viii) school reference consistent with age of subject
- (ix) lab. (Lab 'A' or Lab 'B') consistent with sample type
- (x) only one lab. result per sample, result in range
- (xi) valid family index

Internal checks on the Family Index data were made for consistency with each individual card:

- (i) home location valid
- (ii) leadworker in family consistent with specimen category
- (iii) age of house in range
- (iv) valid coding of lead hazards in house

Standard blood cards were also checked for internal consistency.

The external checks included the following:

- (i) all relevant personal information identical on pairs of cards relating to the same subject
- (ii) family index identical on cards from related subjects
- (iii) relationships within families consistent, i.e. siblings all associated with same mother, etc
- (iv) Repeat and replicate samples mutually consistent, i.e. only one primary sample of each type from one subject, any others being repeats or replicates.

Programme CHECK was run for each batch of cards as they were received from the personnel carrying out the sampling. As mistakes were revealed (mostly punching errors) these were reported back and eventually corrected. The checking process was then repeated and the cycle of checking and correction continued until no known errors remained in the data.

II.2 Analysis of human blood results - Programme AN2

The purpose of the analysis programme AN2 is to sort the data into consistent groups, find mean and standard deviation values and present the data in a form suitable for tests of statistical significance.

The programme first reads all of the data cards and decodes and edits them, sending the edited version to a working file on disc. This working file was needed because the volume of information was too great to be held at one time in the central core memory. The Family Index data is then set up; due to its relatively small size, this can be held in core. Another index which is set up in core at this stage is a 'Results' index, which simply records the lab. result corresponding to each sample. This greatly improves the efficiency of the programme since it avoids having to go to disc for these values, which are referred to repeatedly.

The process of sorting can now begin. For each blood type (i.e. standard blood, children's blood, adult venous blood, adult capillary blood and micro-aliquots) the entire data file is scanned and the relevant cards are extracted and held in core.

For standard blood, the means and standard deviations in each batch are calculated for comparison with the quoted standard blood lead level.

For children's blood, the samples are further sub-divided by age in years, and then again by subject category (i.e. Chloride High Risk, Low

Risk, Births Register Near and Far) and for each of these sub-groups the means and standard deviations are output. The totals for all ages are also calculated.

In the case of adults, the same general procedure is followed except that sub-division by age is not relevant. These samples are, however, divided into venous blood, capillary blood and micro-aliquots.

There is an option to present the logarithm of the results instead of the reported result, which is useful in generating geometric means and standard deviations.

Tests of significance were carried out manually by Student's t-test method using the output from AN2.

II.3 Analysis of associations between blood lead and other factors

II.3.1 Extraction of data for correlation - Programme ASSOC

A computer programme (ASSOC) was used to extract laboratory results from the records and sort them according to various factors having possible connections with blood lead. These analyses were of two kinds: firstly, those for which the data could be split into distinct groups (for example, the various social classes) and, secondly, those where the correlation between two variables was to be examined (for example, blood lead and age of house).

In the first of these cases, programme ASSOC simply prints out the values in each group and

calculates means and standard deviations. This was done for the following sub-groups: children separately by sex; children attending various schools; children and adults by social class; children and adults by lead hazard in home; children and adults by ownership of a car in the family.

For the second class of analysis, the programme printed out paired values of lead level and the parameter supposedly associated with it. This same information was also output to a temporary working file which would subsequently be used as input to programme REG (see III.3.2). Paired values examined in this way were as follows:

children's blood lead versus:	age of house
	rateable value of house
	distance from the battery factory
	direction from the battery factory
	length of employment as leadworker
adult venous blood versus:	the same parameters as for children

II.3.2 Regression analysis - Programme REG

In view of the different nature of the various parameters which it was believed could have an effect on blood level (i.e. some having a few discrete values, others being continuously variable) it was not possible to apply a full multiple regression procedure on all of these factors simultaneously. For this reason, it was deemed sufficient for the purposes of gaining an approximate estimate of the relative

importance of different factors to consider the correlation of each one separately. For this purpose a conventional bivariate regression analysis programme was written. This was capable of fitting polynomials up to quartic to given data in the form of a set of paired values of the two variables.

Programme REG reads the data prepared by ASSOC, and uses conventional least squares best fit methods to obtain the co-efficients of the fitted polynomial. The output consists of these co-efficients and the sums of squares and variances associated with each term of the polynomial and the F value corresponding to the highest power used. The F value is the ratio of the variance attributable to the highest power term to the residual 'unexplained' variance. From this F value the statistical significance of the highest order term is readily obtained. By carrying out the fit for linear, quadratic, cubic and quartic fitting in turn, the appropriate order of fitted polynomial is thus readily determined.

APPENDIX III

Computer Methods in Wind Data Analysis

III.1 Purpose of Analysis

In the Clifton battery factory survey an on-site anemograph was set up as a means of investigating topographical influences on wind strength and direction. The primary consideration was whether a way could be found of relating winds at the site to winds at a distant Meteorological Office station for which long-term data were available.

It was expected that the most significant influence of topography would be to change the wind direction at the site from the value that would be expected in flat country. This change would be dependent both on the atmospheric stability and on the synoptic scale wind direction.

The anemograph was run for seven months and the corresponding data from Ringway Airport were obtained for the same period. The latter were in the form of tables of hourly mean values and therefore comparable tables were drawn up from the on-site anemograph traces, along with Brookhaven gustiness categories as described in Section 3.3.2.2. The total number of data points thus accumulated was about 26,000 and therefore a computer analysis was clearly necessary. This analysis was designed to show, for each gustiness category (corresponding roughly to stability categories) the relationship between wind direction at the site and that at Ringway.

III. 2 Data Handling, Storage, Checking and Editing

The computations were carried out on a desk-top Hewlett-Packard 9830A programmable calculator. This machine has some 3800 words of core storage and a facility for storing data on magnetic tape cassettes. Since the whole of the wind data could not be held in core, it was decided to analyse the data in seven blocks, each relating to one month. Even with this provision, some care was needed in encoding the data in order to make the programme efficient in its storage requirements. The difficulty here was that while floating-point variables occupy 4 words of core, integers occupy only one. Unfortunately however, such integers would have to lie in the range - 32767 to + 32767, thus allowing only five digits per word, and it would clearly be desirable to store both direction and speed as well as gustiness category within the same word. The wind direction and force were each given as two-digit numbers, representing wind bearing in units of 10° and wind speed in knots. These were stored as the least significant four digits in the word. If calm, 0000 was registered, while 99 represented defective trace in either direction or speed. For the gustiness categories the following codes were used and formed the most significant digit, together with the sign bit:

<u>Gustiness Category</u>	<u>Code</u>
A	1
B1	-1
B2	-2
C	2
D	3
Defective	0

Thus by the use of integer rather than character representation of the gustiness category (and by using the sign bit) it was possible to get all of the information of the site anemograph into one word for each hour. The Ringway data was encoded similarly but did not include the gustiness category.

Each month of data thus comprised two arrays, each of 744 points (for a 31 day month). These arrays were set up using a specially written programme which read in the data from the keyboard and transmitted it to the cassettes. This programme also provided a de-coded output on the printer at the end of each month of data, so that the stored values could be readily checked against the written tables. Any errors thus found could be corrected by running the programme in its "EDIT" mode, in which the specified element in any array could be changed to any desired value simply by specifying the month, site, day, hour and the new value.

III.3 Analysis Programme

The analysis of local effects on wind direction was carried out by a separate computer programme which read the wind data from the cassette in monthly blocks. Each hour of data was examined in turn. If either of the direction records was defective the data was discarded.

The analysis consisted of counting the frequency with which all pairs of direction values (ie. direction at site and direction at Ringway) occurred, subject to certain qualifying conditions. The qualifying conditions comprised (i) moderate to strong wind force (ie ≥ 7 kts) or (ii) the five Brookhaven gustiness categories. For each qualifying condition an array dimensioned 37 x 37 was set up with all elements initially zero. The ordinate and abscissa of this array were the wind directions at Ringway and the site respectively, and thus each element of the array represented the frequency with which two particular directions at the two stations coincided in the same hour. As the program executed, each hour's data satisfying the specified qualifying condition was used to increment the values of the corresponding element of the array. If the winds at the site were always the same as those at Ringway, then all of the non-zero values in the frequency array would lie on the diagonal, and thus the departure of the actual results from this condition is a measure of the degree of local influences on the wind direction.

After going through the entire seven-month record, the programme printed out the frequency arrays for each qualifying condition for subsequent analysis by manual methods.

III.4

Estimation of Frequencies at Clifton Junction

The final step in the computer analysis of winds at Clifton and Ringway consisted of the generation of long-term average frequency tables using the Meteorological Office records from Ringway in combination with the correlations calculated as described in III.3 above.

In carrying out this computation, the program takes in turn each stability class and selects the corresponding 37 x 37 frequency array relating Clifton wind directions to Ringway wind directions. Then for each wind speed and direction the average frequency is extracted from the long-term frequency data. This frequency is then apportioned between the various directions at Clifton in proportion to the frequency values in that column of the 37 x 37 array which corresponds to the selected Ringway direction. This procedure is then repeated for all directions and speeds at Ringway in that stability class. The next stability class is then considered, and the corresponding 37 x 37 array is used. The frequencies apportioned to each Clifton Junction weather condition are summed and the resulting array constitutes the desired "best-estimate" weather frequency table for Clifton Junction.

APPENDIX IV - NOTATION

SECTION 1.0

K	diffusion coefficient (m^2/sec)
u	mean wind speed (m/sec)
u_*	friction velocity (m/sec)
x,y,z	distances downwind, crosswind and vertically, from source (m)
σ_y, σ_z	standard deviations of concentration distribution in a plume, in y and z directions (m)
σ_θ	standard deviation of wind direction (radians)

Section 2.2

h'	effective source height above ground (m)
k	function of stability (dimensionless)
P	concentration (kg/m^3)
P_{ref}	reference concentration (kg/m^3)
Q	source strength (kg/sec)
U	wind speed (m/sec)
σ_y, σ_z	as for Section 1.0

Section 2.3

P	concentration (ppm by volume)
P_{max}	maximum concentration at receptor (ppm by volume)
P_o	initial concentration (ppm by volume)
U	wind speed (m/sec)

SECTION 4.0

d_i	wind direction at location i (degrees)
S_i	stability class at location i (Pasquill or Brookhaven class)
u_i	wind speed at location i (m/sec)

SECTION 5

C	concentration (kg/m^3)
$\bar{C}$	average concentration taking into account wind direction variations (kg/m^3)
C_c	calculated concentration ($\mu\text{g/m}^3$)
C_m	measured concentration ($\mu\text{g/m}^3$)
C_p	specific heat of emitted gases (kcal/kg)
C_1, C_2	concentration levels specifying a selected concentration range $C_1 < C < C_2$ (kg/m^3)
F	buoyancy flux ($= 3.7 \times 10^{-5} \pi w_o r_o^2 \rho_o C_p (T_o - T)$ (m^4/sec^3))
h	physical stack height (m)
I, J, K	coefficients in expression for σ (dimensionless)
k	coefficient (dimensionless)
Q	source strength (kg/sec)
r	radial distance from source (m)
r_o	stack radius at exit (m)
T	atmospheric temperature ($^{\circ}\text{C}$)
T_o	stack gas temperature ($^{\circ}\text{C}$)
U	wind speed (m/sec)
w_o	efflux velocity (m/sec)

x	distance downwind from source (m)
x^*	characteristic downwind distance (m)
y	distance across wind from plume centreline (m)
y_1, y_2	crosswind displacements from plume centreline corresponding to C_1, C_2 (m)
z	height of plume centreline above ground (m)
$\delta\phi$	angle $ y_2 - y_1 \div r$ (radians)
ρ_0	density of emission (kg/m^3)
σ_y, σ_z	as for section 1.0
θ	angle between receptor and centreline of wind direction sector (radians)
$d\theta$	deviation of actual wind direction from centreline of wind direction sector (radians)
$\Delta\theta$	width of wind direction sector (radians)
$\delta\omega$	angle subtended by that part of the line y_1, y_2 lying inside the wind direction sector (radians)