A new approach to the assessment of odour nuisance

Thesis

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A NEW APPROACH TO THE ASSESSMENT OF ODOUR NUISANCE

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ABSTRACT

After reviewing the current situation with regard to the assessment of odour nuisance, the development of a new approach is presented.

Descriptions are given of the new techniques which have been developed for quantifying odour intensity, concentration, hedonic tone and annoyance. Statistical analyses of laboratory and field test data collected using these techniques provided mathematical relationships for the assembly of the odour nuisance assessment model. The nuisance criteria adopted was derived from various guidelines and standards from the U.S. and Europe. For completeness an atmospheric dispersion model was developed for estimating the behaviour of odours downwind of the source. This made it possible to assess the probability of an odour nuisance occurring, using any one of a number of different points of knowledge, e.g. existing or future situations.

The assessment method has been tested against independent historical data and been demonstrated to be an effective tool in predicting odour nuisance with a consistency better than any existing method.

A listing is provided for a computer program to enable the user to apply the model both quickly and effectively.

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Most of the original data used in this research were collected while carrying out projects for his employer.

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ABBREVIATIONS AND SYMBOLS

butanol	abreviation for butan-1-ol ($CH_3(CH_2)_3OH$), otherwise known as 1-butanol, n-butanol or butyl alcohol
cm	centimetres
cm^2	square centimetres
$^d/_c$	concentration ratio with reference to the threshold of complaints
$^d/_d$	concentration ratio with reference to the threshold of odour detection
$^d/_r$	concentration ratio with reference to the threshold of odour recognition
D/T	dilutions to detection threshold
ECI	effective continuous intensity
g/m^3	grams per cubic metre
g/s	grams per second
id	internal diameter

l	litres
log	logarithm to base 10
l/min	litres per minute
LTF	long term frequency
m	metres
mg/m^3	milligrams per cubic metre
ml	millilitres
ml/l	millilitres per litre
ml/min	millilitres per minute
m^2	square metres
mm	millimetres
m^3/s	cubic metres per second
m/s	metres per second
n	number of observations or psychophysical parameter depending upon context

nm	nanometres
NWA	numerically weighted average annoyance
NWI	numerically weighted average intensity
ppm_v	parts per million by volume
%T	percentage of observations greater than odour detection threshold
R	correlation coefficient
R^2	explained variance
RES.SD	residual standard deviation of statistical relationship
SD	standard deviation of data sample
SE	standard error of estimate
Sg	standard geometric deviation of a concentration distribution
STF	short term frequency
σ_y	standard deviation of crosswind direction of the plume concentration

σ_z	standard deviation in the vertical of the plume concentration
σ_{yp}	standard deviation of puff diffusion in crosswind direction
σ_{zp}	standard deviation of puff diffusion in vertical direction
σ_{yc}	standard deviation of centroid diffusion in crosswind direction
σ_{zc}	standard deviation of centroid diffusion in vertical direction
UNEP	United Nations Environment Programme
WSL	Warren Spring Laboratory

1. GENERAL INTRODUCTION

1.1. Introduction

Atmospheric pollution due to human activity has become one of the significant environmental health problems of our time. The rise in mortality and morbidity from this cause is demonstrated by the UK National Society for Clean Air (1978) which lists notable air pollution events and the effects on health.

Health hazards associated with air pollution have been investigated since Victorian times and a vast body of knowledge has been assembled on the subject, e.g. by the UK Health and Safety Executive (1985) and United Nations Environmental Programme (1979). Whilst not every hazard is understood or even identified, our knowledge is far in advance of that related to annoyance reactions produced by air pollution. Although people have always been concerned about odours even from the earliest times, as is evident by the development of perfumes, the workings of the human nose are the least understood of our senses (Ludel 1979).

A number of surveys in the United Kingdom by Department of Environment (1974) and Institution of Environmental Health Officers (1982), and in the United States by Flesh (1975) and National Research Council (1979) - have been conducted to identify the most common sources of odour. Tables 1.1 and 1.2 from Artis (1984) show that there is a wide range of industrial and rural activities that give rise to complaint.

Public concern over the years has resulted in legislation being enacted to control odour annoyance, both Leonardos (1974) and Artis (1984) give comprehensive reviews. There have also been significant technical advances reported by Warren Spring Laboratory in collecting, destroying, neutralising or masking odours (Anon 1980). However, our knowledge on assessment (Cheremisinoff 1975), which is the key to determining if complaints are justified and how much control is necessary, is very scanty in comparison to, say, dealing with a noise nuisance, another key environmental problem of our times.

One of the main problems of developing techniques to assess odour annoyance is our lack of detailed knowledge about the physiological mechanism of odour perception (Ludel) op. cit. The aim of this study was to establish a criterion or at least a method of assessing odours with respect to nuisance which is better than the system currently employed. The following study reviews the current situation and discusses possible approaches. The research then describes a new method of assessing odour nuisance which is tested against independent empirical data.

Table 1.1 Sources of odour emissions

Table 1.1 Sources of Odour Emissions

Sources	Number of Local Authorities where odour encountered[1]	Total Number of complaints in respect of each[2] source	
		1978	1979
1 Animal by product plants	26	>446	>408
2 Chemical plants	35	>578	>382
3 Refuse tips	24	>137	>198
4 Foundries	26	>237	>194
5 Intensive pig/poultry or other farms	38	>151	>158
6 Manure spreading	42	>185	151
7 Sewage disposal works/ pumping station	11	113	149
8 Food processing plants	23	>143	>128
9 Paint spraying/baking/ curing	14	98	122
10 Waste incineration plants	10	112	104
11 Cafes/restaurants/takeaways	10	> 62	> 61
12 Carbonisation plant (low temp)	2	28	57
13 Offensive trades	16	90	51
14 Animal feed manufacturers	14	>109	> 50
15 Solvent recovery works	1	40	50
16 Plastics (extrusion of) and PVC coatings	5	> 40*	> 40*
17 Quarry	1	—	34
18 Pharmaceutical industry	3	19	31
19 Rubber manufacture	2	41	29
20 Sewage sludge recycling	6	> 61	26
21 Laser engraving process on flexographic rollers	1	42	26
22 Defective drains	2	20	24
23 Launderettes/dry cleaners	3	11	17
24 Refineries	7	> 6	> 15
25 Dead rodents	1	6	15
26 Maggot breeding	6	22	14
27 Printing ink manufacture/ printing processes involving solvents	4	7	14
28 Polluted watercourse/rivers	4	15	13
29 Textile works	4	16	12
30 Seaweed fertilizer plant	1	10	10
31 Leather dressing	1	12	10
32 Purging LPG cylinders	1	5	7
33 Grass drying	1	14	7
34 Sewage effluent overflowing	1	4	7
35 Wool washing and combing	2	104	6
36 Vehicle exhaust emissions	1	0	6
37 Burning rubbish on industrial premises	1	2	6
38 Rubber reclamation industry	1	4	6
39 Abattoir	1	5	5
40 Electronics factory (dewaxing oven)	1	10	5
41 Heat treatment of metals	1	5	5
42 Expanded foam manufacture	1	10	5
43 Curing of adhesives on brake shoes/factories using adhesives	3	5	4
33 Heat treatment—oil quenching/oil blending	2	7	4
45 Papermaking	1	6	4
46 Tobacco factory	1	8	4

[1] This is the number of local authorities out of the 65 which responded to the survey.

[2] These figures represent the total number of complaints from each source, received by the 65 local authorities.

47	Aluminium can manufacture	1	6	3
48	Burning wood wastes containing "formica" offcuts	1	4	3
49	Galvanising	3	10	3
50	Lead works	1	4	3
51	Trade refuse	1	6	3
52	Cooking of food	1	1	2
53	Drum/container cleaning	3	7†	5†
54	Electroplating	1	0	2
55	Resin manufacturing industry	1	2	2
56	Roofing contractors/melting of bitumen	2	6	2
57	Stove enamelling	1	2	1
58	Farm sileage	2	8	2
59	Fumes from central heating system	1	—	1
60	Metal recovery (copper wire)	1	—	1
61	Blast furnaces	1	few	few
62	Brickworks	1	few	few
63	Colliery spoil heap	1	2	0
64	Coke ovens	1	few	few
65	Donkey stables	1	some	some
67	Expanded foam manufacture	1	few	few
68	Mushroom farm/manufacture of mushroom compost	2	some	some
69	Railways	1	1	0
70	Radiator manufacture	1	7	0
71	Straw burning after harvest	1	1	0
72	Miscellaneous	1	1	0

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*Source No. 16 In addition regular complaints received through the Area Residents Committee.

†Source No. 53 In addition complaints described as "numerous" received by one local authority.

Table 1.2. Odour Sources Affecting the Most Local Authorities

Source of Odour	Number of local authorities having encountered the odour[1]	% of those local authorities which took part in the survey
1. Manure spreading	42	65%
2. Intensive pig and poultry farms	38	58%
3. Chemical plants	35	54%
4. Animal by-product plants	26	40%
5. Foundries	26	40%
6. Refuse tips	24	37%
7. Food processing plants	23	35%
8. Offensive trades	16	25%
9. Animal feed manufacturers	14	22%
10. Paint spraying/baking/ curing	14	22%

A survey of this type, whilst useful to illustrate the extent of the odour problem in England does not, however, give an accurate picture and may even underestimate the problem, as it is apparent that in many cases the public, for various reasons do not complain. Often people become accustomed to odours especially those arising from works which have operated in a particular vicinity for a long time.

2. GENERAL PRINCIPLES

2.1. Definitions and Terminology

In order to be able to discuss odours it is necessary to introduce certain technical terms and definitions.

Acceptability	The scale of judgements with positive response (acceptance or pleasure or liking) at the one extreme and a negative response (non-acceptance, displeasure or rejection) at the other extreme. The position on the scale at which a given stimulus is placed may differ with different individuals, his condition, environment, attitudes, experience, etc. (Anon 1970).
Annoyance	Annoyance involves a negative factor for the individuals comfort and well being (Johnson 1984).
Concentration quotient z	Non-dimensional ratio of the odorant concentration (c) and the detection threshold concentration (Cd) (the concentration at which 50% of people can just detect the smell).

i.e. $$Z = \frac{C}{Cd} \qquad \text{E2.1}$$

However, since

$$\text{Concentration } (C) = \frac{\text{mass odorant } (M)}{\text{volume of odorant } (v)} \qquad \text{E2.2}$$

$$\text{and } (Cd) = \frac{\text{mass of odorant } (M)}{\text{volume of sample diluted to threshold } (Vd)} \qquad \text{E2.3}$$

then

$$Z = \frac{M}{v} \times \frac{Vd}{M} = \frac{Vd}{v} \qquad \text{E2.4}$$

Thus the concentration quotient is also equal to the non-dimensional ratio of the number of times a volume of odorous air must be diluted with non-odorous air before 50% of people can just detect the smell. Sometimes expressed as dilutions to threshold (D/T) (Anon 1970, Johnson 1984) op. cit.

In this thesis a distinction is made between which threshold (see below for definition). For example **d/d** is used to denote the concentration ratio with reference to the detection threshold. **d/r** is used to denote the concentration ratio with reference to the

	recognition threshold. The odour concentration is sometimes expressed as odour units (m^3)/m^3 or odour units (ft^3)/ft^3. This is identical to the concentration quotent.
Duration of odour	The duration of an odour is expressed in units of time and is often related to the long-term frequency, e.g. for 45 minutes twice per day.
ECI	Effective continuous intensity (see Section 8.2 for derivation).
Frequency of occurrence	It is convenient to consider the frequency of occurrence of odour events in the short and long term. The short term frequency (STF) can be defined as that percentage of time or number of breaths that the odour threshold is exceeded in a period of, say, 10-15 minutes. The long term frequency (LTF) is the rate of occurrence over a much longer period and is expressed as, say, twice a day or three times a week.
Hedonic tone	A psychological state attaching to a specific experience and ranging from pleasant to unpleasant. If, for example, the hedonic impact of a smell is positive, it has an associated connotation of pleasure, the negative impact leads to unpleasant associations (Anon 1970) op. cit.

Intensity	The suprathreshold perceived intensity of an odour experience. It can be assessed through scaling or by comparison to reference standards (Anon 1970) op. cit.
Nuisance	A comprehensive definition of nuisance is given by Artis (1984). Briefly summarised this says that odours which can be described as disagreeable and cause annoyance are a "nuisance" in the ordinary meaning of the word. However this does not necessarily mean they are a nuisance in law. This is because when there is an actionable nuisance the law provides a legal remedy by way of injunction or damages but it is not prepared to do this in respect of every odour found to be annoying or objectionable. It is just not practicable, particularly as odours are notoriously subjective. Two types of legal nuisance are recognised in common law. They are private nuisance and public nuisance. A private nuisance may be and normally is, caused by a person doing on his own land something which he is entitled to do. This conduct only becomes a nuisance when the consequences of his acts are not confined to his own land but extend onto his

neighbour's land. For such action to be a tort, i.e. a civil wrong, the conduct must cause either:

1) physical damage to his neighbour's land or buildings or works or vegetation on it, or
2) unduly interfere with his neighbour in the comfortable and convenient enjoyment of his land. In other words action for private nuisance is designed to protect the use and enjoyment of land. Only the occupiers of that land may take this action.

A public nuisance is both a crime and a tort. The aim of the law of public nuisance is to prevent interference with the rights of the general public.

Odours can amount to a public nuisance if they substantially inconvenience a sufficient number of people. Lord Denning said that "A public nuisance is a nuisance which is so wide spread in range and so indiscriminate in its effect that it would not be reasonable to expect one person to take proceedings on his own responsibility to put a stop to it but that it would be the responsibility of the community at large." Anon (1957).

Nuisance is also recognised under Statute Law. The Public Health Act 1936 defines a statutory nuisance in Section 92(1) as -

(a) "Any premises in such a state as to be prejudicial to health or a nuisance"

(b) "any animal kept in such a place or manner as to be prejudicial to health or nuisance."

(c) "any accumulation or deposit which is prejudicial to health or a nuisance."

(d) "any dust or effluvia caused by a trade, business or manufacture or process which is prejudicial to health or are a nuisance [to the inhabitance of a neighbourhood]."

(f) "any other matter declared by the provision of this Act to be a statutory nuisance."

The words in the square brackets were repealed by Local Government (Miscellaneous Provisions) Act 1982.

Nuisance can also be thought of as unacceptable annoyance (author's definition).

Except where specified, e.g. when discussing the legal situation with regard to odours, nuisance in this report is taken as the ordinary meaning of the word.

NWA	Numerically-weighted average annoyance (see Section 8.2 for derivation).
NWI	Numerically weighted average intensity (see Section 8.2 for derivation).
Odorant	Any chemical compound which can stimulate the olfactory sense (Anon 1970) op. cit.
Odour	Product of the activation of the sense of smell on olfactory experience (Anon 1970) op. cit.
Odour descriptors	An adjective given to an odour note (see below) usually referring to an odour commonly experienced, e.g. floral, caramel, sewer odour (Johnson 1984) op. cit.
Odour emission rate	The product of the odour concentration ratio in dilutions to detection threshold and the volumetric flow rate at standard conditions in cubic metres per second (m^3/s).
Odour note	Unique olfactory sensation derived from specific chemical functional groups. They are subject to modification by variations in molecular structure and substituents (Johnson 1984) op. cit.
Odour profile	A plot of the frequency with which panel members assign individual descriptors of applicability to a test odorant (Johnson 1984) op. cit.

Odour unit	MKS system - 1 odour unit = 1 cubic metre of air at the odour threshold. FPS system - 1 odour unit = 1 cubic foot of air at the odour threshold (Johnson 1984).
Olfactometers	Instruments which are used to produce various concentrations of an odorous sample by mixing a known quantity of the sample with a known quantity of odourless air. The mixtures are then presented to a panel of noses to determine at which concentration 50% of the panel can only just detect the odour (some investigators work to a recognition rather than a detection threshold) (Johnson 1984) op. cit. See also Section 3.
Pervasiveness	The attribute of odour which pertains to the rate of change of odour intensity with change in odorant concentration, i.e. the slope of the intensity/concentration plot (Johnson 1984) op. cit.
Quality	The property which permits identification of a given odour characteristic through the perception of the unique balance of qualities comprising the experience (Anon 1970) op. cit., i.e. what it smells like.

Thresholds

Detection	A hypothetical lower or zero point on a scale. It is the lowest odour concentration capable of reliably exciting the sense of smell.
Recognition	Concentration at which recognition is possible.
Difference	Just noticeable difference in concentration.

All of these thresholds vary from observer to observer, from stimulus to stimulus, and from time to time, for a given observer (Anon 1970) op. cit.

2.2. Physiology of Olfaction

Before odour nuisance can be examined in detail it is necessary to consider the act of olfaction and the sense of smell.

Olfaction starts in the nose. Inhaled air enters the nostrils and passes through the nasal cavities - one set for the left nostril and one set for the right. These are complicated structures containing a number of bones and pieces of cartilage which are designed to remove dust, from the sampled air, and adjust its temperature and humidity.

Out of the main air stream at the top of each cavity is an area where the olfactory receptors are located. Normally only about 2% (Stuiver 1958), (Ludel 1974) to 5% (Douek 1974) of inspired air reaches the olfactory region but this can be increased to about 20% during sniffing (Anon 1980) op. cit. Air can also reach the olfactory region from the back of the throat.

The olfactory areas of the epithelia cover about 10 cm^2 in total. These are covered in mucus and contain 10-30 million receptor cells with corresponding numbers of supporting and basal cells. The receptor cells are just the naked dendritic endings of neurons. Each dendrite or rod ends in a knob with about ten cilia of diameter 0.1u and of length up to 100u. It is generally assumed (Anon 1980) op. cit. that the olfactory receptor sites are on the cilia surface membrane, as a result the effective total receptor bearing area is about 50 cm^2 (Anon 1980) op. cit.

The means by which some molecules stimulate the receptors and produce the sensation of odour while other molecules fail to do so is a complete mystery. It is generally believed that the smell stimulus is in some way related to the molecular characteristics, but exactly how is not known. Various theories have been put forward to explain the process of olfaction but so far none completely accounts for all of the observed phenomena. Five of the more important theories are described below.

2.2.1 Chemical Composition

One approach to understanding how olfactory receptors work was to list the chemical composition or formulae of odorous substances and to look for a pattern. Von Skramlik (1925) gives the chemical formulae for about 200 substances; Moncrieff (1944) gives more.

Of all the chemical elements only about 16 seem to play any role in the production of odours. Haycraft (1889). These 16, according to their chemical families, are:

a) hydrogen
b) carbon, silicon
c) nitrogen, phosphorus, arsenic, antimony, bismuth
d) oxygen, sulphur, selenium, tellurium
e) the halogens, fluorine, chlorine, bromine, iodine

Only the halogens and ozone are odorous as elements.

The great majority of odorous substances are organic containing hydrogen, oxygen and/or nitrogen.

Within each of the families similar compounds have similar odours. In the halogen family, for example, the elements theselves have similar odours. The compounds chloroform ($CHCL_3$), bromoform ($CHBr_3$) and idoform (CHI_3) also have similar odours. From chlorine through bromine to iodine the atomic weight and other atomic properties change progressively and to this chemical series there is a corresponding odour series. The odour of bromine is "heavier" than chlorine and the odour of iodine is heavier still. Similarly the odour of bromoform is midway between those of chloroform and iodoform.

There are many series of organic compounds which show a graduation of odour quality and also odorous intensity. The "lower" members of the series with small light molecules have little odour, the intermediate members have more while still higher members are non-volatile and have no odour. One such series is shown in Table 2.1.

Whilst this theory seems promising it fails to explain why similar substances give similar odours and at the same time dissimilar substances also give similar odours.

2.2.2 Molecular Structure

Passy (1892) suggested that this phenomenon could be explained by molecular structure. It was thought that the way atoms are arranged in the molecule was important.

Table 2.1. Organic compound series and odour threshold

Name of Acid	Formula	Threshold mg/m^3	Quality
Formic	CH_2O_2	25	Pungent
Acetic	$C_2H_4O_2$	5	Sour
Propionic	$C_3H_6O_2$	0.05	Sour
Butyric	$C_4H_8O_2$	0.001	Rancid
Valeric	$C_5H_{10}O_2$	0.01	Rancid
Caproic	$C_6H_{12}O_2$	0.04	Rancid/aromatic

Henning (1924) succeeded in demonstrating such a relationship for various organic compounds. Fragrant odours were associated with molecules that had two atom groups attached to adjacent members of an open chain or benzol ring. Spicy odour molecules were from a benzol ring with para substitution. Resinous odour molecules came from a benzol ring with cross link (or open chain with extra side link).

Etheral odour molecules comprised of a forked atom group attached to a ring or to an open chain. Burned odour molecules were based upon a hetrocyclic ring with a nitrogen member.

This theory was never taken seriously as it had many difficulties. Inorganic substances did not fall so neatly into the method of classification. As with the chemical composition theory, even if odours could be classified by their chemical structure it would not explain how the receptors operate.

2.2.3 Ultra-violet Theory

Haycraft (1889) and Zwaardmaker (1922) suggested that vibrations of the atoms or groups of atoms or the vibrations of the electrons could be detected by the olfactory receptors. Different vibration rates would lead to different responses.

Heyninx (1919) succeeded in showing a correlation between vibrations in the ultraviolet region, i.e. 360 to 200 nm with known odorous responses. He produced a complete odour spectrum with the following classes in order, in Table 2.2.

Table 2.2. Odour spectrum

Type of smell	Typical compound	Wavelength (nm)
Putrid	Carbon disulphide	320
Rancid	Butyric acid	280
Burned	Phenol	270
Spicy	Caraway	255
Fragrant	Acetone	210

But like other rules that have been suggested it appears to have had many exceptions. Quite different odours such as acetone and camphor were found to have the same wavelength.

2.2.4 Infra-red Theory

The infra-red theory is based on the fact that the human body is warm and emits radiation in the wavelength range 4-20 microns. In addition most odorous substances absorb selected wavelengths in this range. The theory suggests that when an odorous substance comes into contact with the olfactory receptors some of the heat rays are preferentially absorbed. As a result the olfactory cells lose heat and this selective cooling stimulates them to send a response to the brain. It is believed that olfactory cells of different size and shape are tuned into different wavelengths thereby having the ability to respond to different odours.

In its simplest form this theory does not account for the fact that certain optical isomers have the same absorption spectrum but different odours, e.g. d- and l- dimethyl-octonol and d- and l- dimethylcyclohexanone -5 (Young, Fletcher and Wright 1948). By taking account of the solubility of the odorant in the receptor cell surface this exception can be partially explained (Beck 1950).

2.2.5 Stereo-chemical or Steric Theory

As most substances with similar smell have molecules that are similar in shape it has been suggested that the stereo-chemical theory applies to olfaction (Amoore 1970) in the same way as enzymes work.

Different enzymes have different geometric structures and the various locations where enzymes can exert influence are thought to contain receptor sites of particular shapes. In the lock-and-key view of enzyme function the enzymes are the keys and the receptor sites that they precisely fit are the locks.

In olfaction the cillia are presumed to contain receptor sites that respond to specific molecular shapes. They are only triggered when a complementarily shaped molecule comes into contact. Basing calculations upon the relative areas involved, Davies and Taylor (1959) estimated that there might be about 44000 "potential sites" per receptor each having an area of about 64 A^2 (square Angstroms). This, of course, is just too small to be observed even with an electron microscope. These sites are therefore still hypothetical and their existence still has to be confirmed. In Davies' steric theory the molecular sites are involved in some form of rupturing of the molecular cell membrane allowing ionic changes to take place which in turn lead to electrical activity.

Yet another interpretation of the steric theory has been given by Dravnieks (1964). He suggested a hypothetical mechanism for primary stimulation which is based upon a change in coupling between an electron donor/acceptor pair of large molecules that occurs when an odorant is absorbed at the composite junction. The altered charge transfer balance or capacitance effect would be monitored by the appropriate nerve fibres.

Although the steric theory is the most promising theory of olfaction it fails to explain several olfactory phenomena, e.g. why some odours change their characteristics with concentration.

Regardless of how the receptors work, information travels from the cilia along the olfactory rod towards the brain in bundles of axons called the olfactory nerves. These are short and pierce the cribiform plate (a piece of bone that forms the roof of the nasal cavity) and enter the olfactory bulbs. Several hundred primary olfactory axons converge on the bulbs and this convergence is considered to be the main cause for the high sensitivity of the sense of smell. The olfactory bulbs serve as integration and relay centres for sending information to different locations within the brain. Olfactory information unlike other sensory information is not ultimately sent to any particular region of the cortex. Olfaction is completed by the brain when it interprets the information it receives.

The interior of the nose is also provided with cutaneous senses of touch, pain, warmth, cold and the throat which receives the inspired air from the nose is provided with taste buds (Woodworth 1954). As a result inhaled substances may "smell" sweet, sour, prickly, warm or cold, etc. The sharp pungent "smell" of ammonia arises from the stimulation of the pain receptors and the cool or fresh "smell" of menthol arises from the cold receptors. Von Skramlik (1925) made a special study of smell-accompanying sensations and found that over 75% of odorous samples tested gave recognisable sensations besides odour.

2.3. Perception

For perception to be possible it is necessary for a sufficient number of odour molecules to reach the olfactory epithelium. The minimum perceptible number of molecules in the volume of inspired air, at the detection threshold concentration, depends both on the chemical nature of the molecules and on the physiology and psychology of the human receptor. DeVries and Stuiver (1961) estimate that a single molecule may be sufficient to excite a single receptor and 40 molecules of various mercaptans would be sufficient for perception. All normal people have a sense of smell unless they have had some form of damage to the relevant areas of the brain or to the olfactory system. The acuity of the sense increases with age until the early teens, then there are 30 or more years with the full sense until in old age there is a gradual failure (presbyosmia); this results in anosmia (complete loss of sense of smell) for roughly one third of octogenarians. While anosmia is rare except in old people, specific or selective anosmias are probably fairly common, because studies with single substances have shown that a few per cent of the population are unable to detect specific odorants. There may be temporary or permanent specific or general hyperosmia (heightened sensitivity) or hyposmia (lowered sensitivity). When the sense of smell is not normal qualitatively it is a case of parosmia, or cacosmia if the distorted perceptions are unpleasant. The cause of parosmia can be due simply to an infection, or to defects in the olfactory organs. However, physical damage to the brain or psychological disorders can cause parosmias that take the form of illusions or hallucinations of smell. These can be genuine in that an odorant is believed to be present; or knowing that no odorant is present a person can have a psuedo-hallucination of smell, perhaps as the side effect of certain drugs (Anon 1980).

Persons with a normal sense of smell are well aware of the fact that the perceived intensity of smell fades if the stimulus is received continuously. This phenomenon of olfactory fatigue, or self-adaptation to an odorant, is generally specific in that the ability to detect other odours in not impaired.

A.A. North (1980) states that "For persons with a normal sense of smell the sensations produced by inhaled odorants have four definite characteristics; detectability, intensity, quality and acceptability. Although descriptions of experience of smells might use the terms persistence and pervasiveness, these are not definite characteristics of odorants. Persistence can result from the way the perceived intensity relates to the concentration of odorant, so that it depends on the chemical nature as well as on the rates of production and dispersion of odours. Pervasiveness depends, in addition, on the adsorption or absorption of odours by, and subsequent release from, various materials."

2.3.1 Scaling

The classical way to measure sensory magnitude or perceived intensity by indirect means was devised by Gustav Fechner (Cain & Moscowitz (1974)). He began with Weber's observations that the ability to resolve small differences between stimuli is approximately proportional to the magnitude of stimulation Φ i.e. $\Delta\Phi = K\Phi$, $\Delta\Phi$ is the smallest difference in stimulation that can be perceived (the just noticeable difference or jnd). Fechner then assumed that, whenever stimulation was changed by an amount equal to a jnd, the sensation magnitude was changed by a constant amount. This assumption gave the jnd a status of a unit of sensation magnitude and allowed a scale of sensation to be erected by the summation of jnd's from one end of the sensory continuum to the other. When summation is begun at the level of the absolute threshold (zero sensation level), the resulting scale is assumed to be a ratio scale; when summation is begun at some point above the threshold the scale is assumed to be an interval scale.

A common way to construct a scale of perceived intensity from direct interval judgements is to use the method of category estimation. In some cases of category scaling, the observer has been presented with a response scale that includes an absolute zero, i.e. a category to represent "no odour". Inclusion of an absolute zero does not, however, automatically bestow ratio properties upon the scale. Katz and Talbert (1930) used a scale with an absolute zero:

> "0, or no odour requires no amplification; No. 1 is the threshold odour, just perceptible. Consider now the opposite end of the scale. No. 5, or very strong, is the most intense odour without regard to quality and perceived aside from any other physiological effects such as irritation or nausea. No. 3, or easily noticeable, is the median odour midway between Nos. 1 and 5. No. 2, or faint, is conceived as midway between Nos. 1 and 3; similarly No. 4, or strong, is conceived as midway between Nos. 3 and 5."

2.3.2 Relationship between Intensity and Concentration

Odour intensity and concentration are not the same but they are related by the Weber-Fechner law and the Stevens power law as are other psychological sensations.

The Fechner law (Wagenaar, 1975) states that the perceived intensity of an odorant is a linear function of the logarithm of suprathreshold concentration. Thus:

$$I_i = K_i \log\left(\frac{C_i}{C_{oi}}\right) \qquad \text{E2.5}$$

where

I = Perceived intensity measured in jnd's
k_i = Constant of proportionality for i
C_i = Concentration of odorant i
C_{oi} = Threshold concentration of i

Stevens' law (Wagenaar, 1975) describes the relation between perceived intensity and physical intensity as a power function,

$$I_i = a_i\,(C_i - C_{oi})^{n_i} \qquad \text{E2.6}$$

where

I_i = Perceived intensity measured by direct estimation
a_i = Constant of proportionality for i
C_i = Concentration of odorant i
C_{oi} = Threshold concentration of i
n_i = Exponent for odorant i

The exponent n or the psychophysical constant is of particular importance as it is a measure of the pervasiveness of the odour. It is obtained from the slope of the curve when the stimulus or concentration and the perceived intensity are plotted on log coordinates. This constant varies between different odorants. For example, Cain (1969) reported values of 0.28 for geraniol and 0.71 for acetone, Patte et al (1975) gave values for 110 substances ranging between 0.12 and 0.87. No odorants give values greater than 1.

A low value indicates a lower human sensitivity to increases or decreases in concentration of that odorant and hence a more difficult abatement and dispersion problem.

For an odorant with n equal to 0.2 a ten-fold reduction in concentration decreases the perceived intensity by a factor of only 1.5; whilst for an odorant with n equal to 0.8 a ten-fold reduction in concentration lowers the perceived intensity by a factor of 6.3. Thus in ambient air the presence of an odorant with a low value for the exponent could result in a much more persistent odour than would be the case for an odorant with a high value for n.

2.3.3 Odour Classification

In taste we have the common names, sweet, sour, bitter and salt which are found to be adequate for scientific classification. Woodworth and Schlosberg (1954). In colour we have a similar set of common names, i.e. hue, value and chroma, Munsell (1915). In sound there is the scale of pitch but with smell there is no such sample classification system.

The first serious attempt to classify odours was by Linnaeus (1756). He distinguished seven classes of odours - as indicated in Table 2.3.

Table 2.3. Linnaeus odour categories

Aromatic	- as carnation
Fragrant	- as lily
Ambrosial	- as musk
Alliaceous	- as garlic
Hircine	- as valerian
Repulsive	- as certain bugs
Nauseous	- as carrion

Zwaardemaker (1895-1925) sought to perfect the systems by subdividing some of the classes and adding two new classes - the etherial and empyreumatic.

Zwaardemaker's (1925) classification had nine classes and many sub-classes. Henning (1915-16, 1924) revised the classes to six given in Table 2.4.

Table 2.4. Henning's odour categories

Fragrant
Etherial/fruity
Resinous
Spicy
Putrid
Empyreumatic/burned

The classification was developed into an odour quality system.

This was achieved after extensive tests on 415 different odours which were presented to a number of observers.

Henning eventually ended up with a prism that was supposed to represent the similarities and differences between odours as shown in Figure 2.1.

The corners are not elementary odours but turning points in the qualitative continuum. Starting at the bottom of face FERS of Figure 2.2 at sassafras and working left, nutmeg, pepper and cinnamon seem to be coming more spicy but then you seem to turn a corner and cassia, cloves, bay, thyme are becoming distinctly fragrant.

Figure 2.1. Henning's odour prism

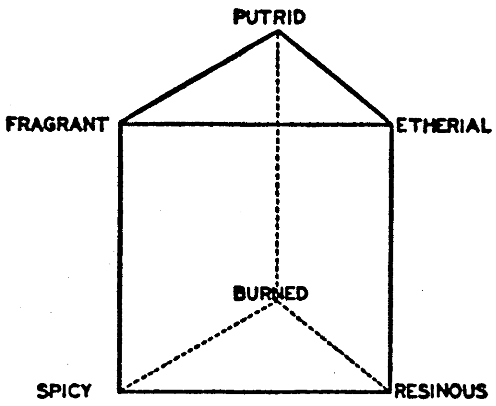
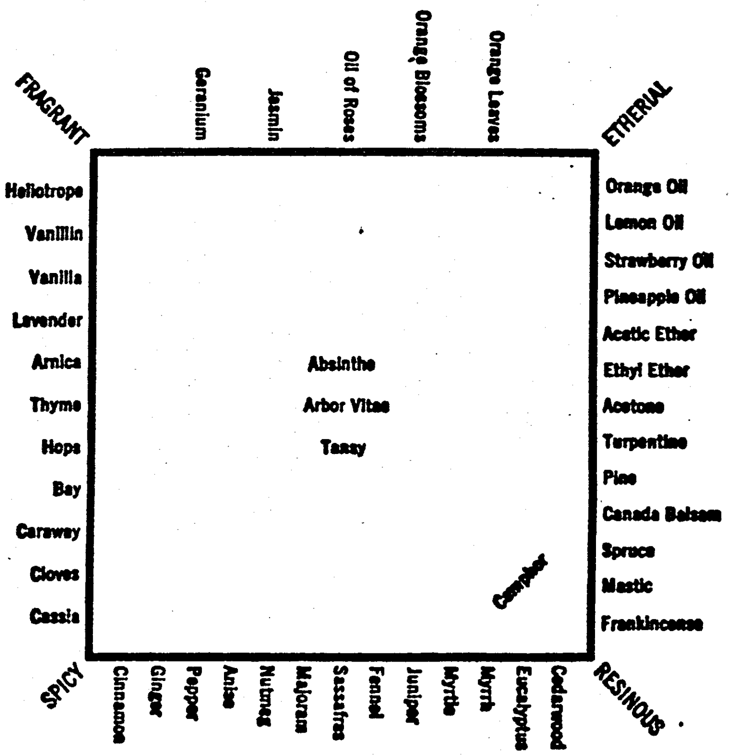


Figure 2.2. Part of Henning's odour prism



The FERS odor square, a part of Henning's smell prism.

Certain odours belong to the edge while others have resemblance of all four classes and therefore fit on the face. Every "pure" odour would be on a face or edge while a mixed odour would be inside the prism. According to Henning every "pure" odour is simple and cannot be produced from a mix of the others.

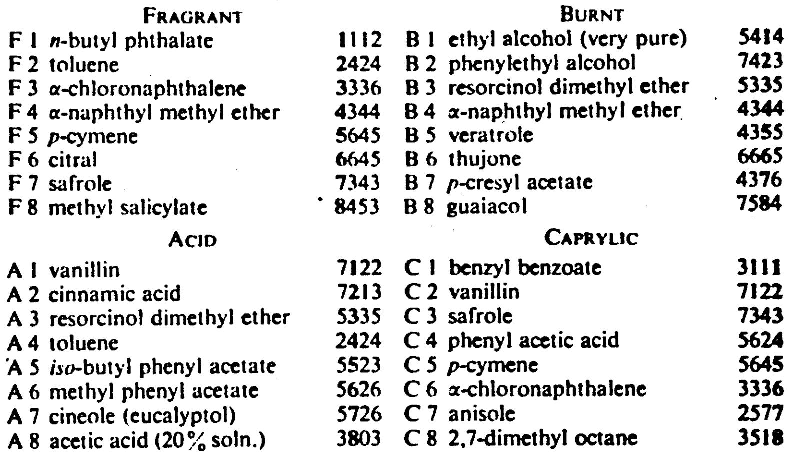
This is comparable with pitch where the note D is part of a series BCDEF etc. but cannot be produced from a mix of the other notes. Henning suggested that there are many different types of receptor cell each of which are "turned" to a different stimulus.

Further work on Henning's classification system by MacDonald (1922) and Findley (1924), Hermann (1926), Hazzard et al (1930) found that this theory needed a lot of revision. The system was complicated by mixed substances, nearly all of which belonged inside. Some others could not be fitted into the prism at all. Non-olfactory sensations such as the sensation of cold, warm, sharp, etc. did not fit into the system at all. Hazzard (1930) op. cit. found that well practiced observers could locate odours on ten non olfactory scales in addition to the six Henning categories.

Henning found that untrained observers did not separate odour from other sensations obtained during smelling. He mentions the prickly sensation of oil of mustard, the cold of garlic and the sweet of jasmine, etc. Komuro (1921) and Ohma (1921) suggested that the presence of smell-accompanying sensations made it imperative that the classification of odours should be revised or at least re-examined experimentally with the object of factoring out the non olfactory components. They contend that certain classes might coalesce if the non-olfactory components were eliminated. The whole FERS face of Henning's prism could simplify into a single class if pungency (pain sense), freshness (cold sense) and sweetness (taste) could be factored out. The outcome would be a complete and simplified system of classification of odours or the recognition of fundamental odours which fail to be "outstanding" when blended with non olfactory components.

The Crocker-Henderson (C-H) (1927) system of odour classification was developed on the basis of their experience as flavour and cosmetic chemists. They selected four of Zwaardemaker's terms - fragrant, acid, burnt and caprylic or goaty and proceeded to represent each of these qualities as far as their own experience was concerned by four series of odour samples of high purity and stability. Each separate quality was represented on an 8 point scale. Both the reference series and subsequently unknown odours were characterised by a four figure number representing the perceived intensities of each of these selected components in the order given. For example, in Table 2.5 which shows the standards for the C-H system, vanillin has the number 7122. Its characteristics are predominantly fragrant though there are other detectable components of the other qualities. Similarly acetic acid is class 3803, i.e. primarily acid. There is no substance in the system which exclusively represents one quality. Secondly several

Table 2.5. Crocker Henderson Odour Classification Standards



FRAGRANT			BURNT		
F 1	*n*-butyl phthalate	1112	B 1	ethyl alcohol (very pure)	5414
F 2	toluene	2424	B 2	phenylethyl alcohol	7423
F 3	α-chloronaphthalene	3336	B 3	resorcinol dimethyl ether	5335
F 4	α-naphthyl methyl ether	4344	B 4	α-naphthyl methyl ether	4344
F 5	*p*-cymene	5645	B 5	veratrole	4355
F 6	citral	6645	B 6	thujone	6665
F 7	safrole	7343	B 7	*p*-cresyl acetate	4376
F 8	methyl salicylate	8453	B 8	guaiacol	7584
ACID			**CAPRYLIC**		
A 1	vanillin	7122	C 1	benzyl benzoate	3111
A 2	cinnamic acid	7213	C 2	vanillin	7122
A 3	resorcinol dimethyl ether	5335	C 3	safrole	7343
A 4	toluene	2424	C 4	phenyl acetic acid	5624
A 5	*iso*-butyl phenyl acetate	5523	C 5	*p*-cymene	5645
A 6	methyl phenyl acetate	5626	C 6	α-chloronaphthalene	3336
A 7	cineole (eucalyptol)	5726	C 7	anisole	2577
A 8	acetic acid (20% soln.)	3803	C 8	2,7-dimethyl octane	3518

substances, e.g. vanillin, appear as reference standards in different positions in more than one series, e.g. position 1 on the acid scale and position 2 on the caprylic scale.

Since its development the system has been highly criticised. Ross and Harriman (1949) were particularly critical on the grounds that it failed to give consistent results when used by untrained subjects.

In a review of odour classification Harper, Bate-Smith and Land (1968) described many other approaches. These included methods adopted by biologists, perfumists, chemists, and behavioural scientists. Several quantitative approaches using factorial and multi-dimensional similarity analysis were also examined. However, they could only conclude that there was no universally effective classification system which had an agreement terminology. Odour classification continues to be an intellectual challenge.

2.3.4 Odour Profiling

The difficulty with the systems of odour classification described above is that only a few odours such as vanillin and isovaleric acid are so characteristic that they fit into a specific class without compromise. Most odours exhibit several odour notes, each belonging to another class (Dravnieks 1979).

In recognising this Dravnieks and others (1978, 1979) have developed the comprehensive list of odour notes given in Table 2.6. These can be used in a multi-dimensional scaling method for describing the quality of an odour.

For the reasons given in Section 3 this would be assessed by an odour panel. A member considers each descriptor separately and judges its applicability to the test odour on a 0-5 point scale, i.e. 0 for absent, 1 for slight, 3 moderate, 5 extreme with 2 and 4 as intermediate values.

The result is an odour profile. Profiles can be compared and analysed by methods which produce similar ratings correlated to direct similarity comparisons. The profiles also indicate the nature of the difference, if there is a significant difference and if there are specific odour notes. A typical profile is shown in Table 2.7 (Dravnieks 1979) op. cit.

2.3.5 Hedonic Tone

In working towards defining annoyance Dravnieks et al (1982) identified odour intensity, odour character and hedonic tone as the primary factors. Working with the Sensory Evaluation Committee E18 of the American Society for Testing and Materials they developed a relationship between odour character; as derived from odour profiling, and the hedonic tone of an odour, i.e. the degree of pleasantness or unpleasantness.

ODOUR QUALITY EVALUATION

- * SMELL SAMPLE. YOU CAN RE SMELL IT AS NEEDED FOR EVALUATION.
- ** GO THROUGH LIST BELOW. FOR EACH DESCRIPTOR, *ENCIRCLE* THAT SCORE NUMBER WHICH BEST CHARACTERIZES THE *DEGREE OF PRESENCE* OF THAT ODOR NOTE IN THE SAMPLE ODOR. IF ABSENT, *DO NOT ENCIRCLE ZERO*
- *** INITIAL OR SIGN, AND DATE.

Initial or Signature .... Date ....

MEANING OF THE ODOR QUALITY SCALE:

ABSENT	SLIGHTLY		MODERATELY		EXTREMELY
0	1	2	3	4	5

DESCRIPTORS

Index	NAME	SCORE	Index	NAME	SCORE
001	FRAGRANT	0 1 2 3 4 5	031	OILY, FATTY	0 1 2 3 4 5
002	SWEATY	0 1 2 3 4 5	032	LIKE MOTHBALLS	0 1 2 3 4 5
003	ALMOND-LIKE	0 1 2 3 4 5	033	LIKE GASOLINE,SOLVENT	0 1 2 3 4 5
004	BURNT, SMOKY	0 1 2 3 4 5	034	COOKED VEGETABLES	0 1 2 3 4 5
005	HERBAL,GREEN,CUT GRASS	0 1 2 3 4 5	035	SWEET	0 1 2 3 4 5
006	ETHERISH, ANAESTHETIC	0 1 2 3 4 5	036	FISHY	0 1 2 3 4 5
007	SOUR,ACID,VINEGAR	0 1 2 3 4 5	037	SPICY	0 1 2 3 4 5
008	LIKE BLOOD, RAW MEAT	0 1 2 3 4 5	038	PAINT-LIKE	0 1 2 3 4 5
009	DRY, POWDERY	0 1 2 3 4 5	039	RANCID	0 1 2 3 4 5
010	LIKE AMMONIA	0 1 2 3 4 5	040	MINTY, PEPPERMINT	0 1 2 3 4 5
011	DISINFECTANT,CARBOLIC	0 1 2 3 4 5	041	SULPHIDIC	0 1 2 3 4 5
012	AROMATIC	0 1 2 3 4 5	042	FRUITY (CITRUS)	0 1 2 3 4 5
013	MEATY (COOKED, GOOD)	0 1 2 3 4 5	043	FRUITY (OTHER)	0 1 2 3 4 5
014	SICKENING	0 1 2 3 4 5	044	PUTRID,FOUL,DECAYED	0 1 2 3 4 5
015	MUSTY,EARTHY,MOLDY	0 1 2 3 4 5	045	WOODY, RESINOUS	0 1 2 3 4 5
016	SHARP,PUNGENT,ACID	0 1 2 3 4 5	046	MUSK-LIKE	0 1 2 3 4 5
017	CAMPHOR LIKE	0 1 2 3 4 5	047	SOAPY	0 1 2 3 4 5
018	LIGHT	0 1 2 3 4 5	048	GARLIC, ONION	0 1 2 3 4 5
019	HEAVY	0 1 2 3 4 5	049	ANIMAL	0 1 2 3 4 5
020	COOL, COOLING	0 1 2 3 4 5	050	VANILLA-LIKE	0 1 2 3 4 5
021	WARM	0 1 2 3 4 5	051	FECAL (LIKE MANURE)	0 1 2 3 4 5
022	METALLIC	0 1 2 3 4 5	052	FLORAL	0 1 2 3 4 5
023	PERFUMERY	0 1 2 3 4 5	053	YEASTY	0 1 2 3 4 5
024	MALTY	0 1 2 3 4 5	054	CHEESY	0 1 2 3 4 5
025	CINNAMON	0 1 2 3 4 5	055	HONEY-LIKE	0 1 2 3 4 5
026	POPCORN	0 1 2 3 4 5	056	ANISE (LICORICE)	0 1 2 3 4 5
027	INCENSE	0 1 2 3 4 5	057	TURPENTINE (PINE OIL)	0 1 2 3 4 5
028	CANTALOUPE,HONEY DEW MELON	0 1 2 3 4 5	058	FRESH GREEN VEGETABLES	0 1 2 3 4 5
029	TAR-LIKE	0 1 2 3 4 5	059	MEDICINAL	0 1 2 3 4 5
030	EUCALYPTUS	0 1 2 3 4 5	060	ORANGE (FRUIT)	0 1 2 3 4 5

DESCRIPTORS

Index	NAME	SCORE	Index	NAME	SCORE
061	BUTTERY (FRESH)	0 1 2 3 4 5	104	HOUSEHOLD GAS	0 1 2 3 4 5
062	LIKE BURNT PAPER	0 1 2 3 4 5	105	PEANUT BUTTER	0 1 2 3 4 5
063	COLOGNE	0 1 2 3 4 5	106	VIOLETS	0 1 2 3 4 5
064	CARAWAY	0 1 2 3 4 5	107	TEA-LEAVES-LIKE	0 1 2 3 4 5
065	BARK-LIKE,BIRCH BARK	0 1 2 3 4 5	108	STRAWBERRY-LIKE	0 1 2 3 4 5
066	ROSE-LIKE	0 1 2 3 4 5	109	STALE	0 1 2 3 4 5
067	CELERY	0 1 2 3 4 5	110	CORK-LIKE	0 1 2 3 4 5
068	BURNT CANDLE	0 1 2 3 4 5	111	LAVENDER	0 1 2 3 4 5
069	MUSHROOM-LIKE	0 1 2 3 4 5	112	CAT-URINE-LIKE	0 1 2 3 4 5
070	WET WOOL, WET DOG	0 1 2 3 4 5	113	PINEAPPLE (FRUIT)	0 1 2 3 4 5
071	CHALKY	0 1 2 3 4 5	114	FRESH TOBACCO SMOKE	0 1 2 3 4 5
072	LEATHER-LIKE	0 1 2 3 4 5	115	NUTTY (WALNUT, ETC.)	0 1 2 3 4 5
073	PEAR (FRUIT)	0 1 2 3 4 5	116	FRIED CHICKEN	0 1 2 3 4 5
074	STALE TOBACCO SMOKE	0 1 2 3 4 5	117	WET PAPER-LIKE	0 1 2 3 4 5
075	RAW CUCUMBER-LIKE	0 1 2 3 4 5	118	COFFEE-LIKE	0 1 2 3 4 5
076	RAW POTATO-LIKE	0 1 2 3 4 5	119	PEACH (FRUIT)	0 1 2 3 4 5
077	MOUSE-LIKE	0 1 2 3 4 5	120	LAUREL LEAVES	0 1 2 3 4 5
078	BLACK PEPPER-LIKE	0 1 2 3 4 5	121	BURNT MILK	0 1 2 3 4 5
079	BEAN-LIKE	0 1 2 3 4 5	122	SEWER ODOR	0 1 2 3 4 5
080	BANANA-LIKE	0 1 2 3 4 5	123	SOOTY	0 1 2 3 4 5
081	BURNT RUBBER-LIKE	0 1 2 3 4 5	124	CRUSHED WEEDS	0 1 2 3 4 5
082	GERANIUM LEAVES	0 1 2 3 4 5	125	RUBBERY (NEW RUBBER)	0 1 2 3 4 5
083	URINE-LIKE	0 1 2 3 4 5	126	BAKERY (FRESH BREAD)	0 1 2 3 4 5
084	BEERY (BEER-LIKE)	0 1 2 3 4 5	127	OAK WOOK,COGNAC-LIKE	0 1 2 3 4 5
085	CEDARWOOD-LIKE	0 1 2 3 4 5	128	GRAPEFRUIT	0 1 2 3 4 5
086	COCONUT-LIKE	0 1 2 3 4 5	129	GRAPE-JUICE-LIKE	0 1 2 3 4 5
087	ROPE-LIKE	0 1 2 3 4 5	130	EGGY (FRESH EGGS)	0 1 2 3 4 5
088	SEMINAL,SPERM-LIKE	0 1 2 3 4 5	131	BITTER	0 1 2 3 4 5
089	LIKE CLEANING FLUID(CARBONA)	0 1 2 3 4 5	132	CADAVEROUS,LIKE DEAD ANIMAL	0 1 2 3 4 5
090	CARDBOARD-LIKE	0 1 2 3 4 5	133	MAPLE (AS IN SYRUP)	0 1 2 3 4 5
091	LEMON (FRUIT)	0 1 2 3 4 5	134	SEASONING (FOR MEAT)	0 1 2 3 4 5
092	DIRTY LINEN-LIKE	0 1 2 3 4 5	135	APPLE (FRUIT)	0 1 2 3 4 5
093	KIPPERY (SMOKED FISH)	0 1 2 3 4 5	136	SOUPY	0 1 2 3 4 5
094	CARAMEL	0 1 2 3 4 5	117	GRAINY (AS GRAIN)	0 1 2 3 4 5
095	SAUERKRAUT-LIKE	0 1 2 3 4 5	118	CLOVE-LIKE	0 1 2 3 4 5
096	CRUSHED GRASS	0 1 2 3 4 5	139	RAISINS	0 1 2 3 4 5
097	CHOCOLATE	0 1 2 3 4 5	140	HAY	0 1 2 3 4 5
098	MOLASSES	0 1 2 3 4 5	141	KEROSENE	0 1 2 3 4 5
099	ALCOHOL-LIKE	0 1 2 3 4 5	142	NAIL POLISH REMOVER	0 1 2 3 4 5
100	DILL-LIKE	0 1 2 3 4 5	143	FERMENTED (ROTTEN) FRUIT	0 1 2 3 4 5
101	CHEMICAL	0 1 2 3 4 5	144	CHERRY (BERRY)	0 1 2 3 4 5
102	CREOSOTE	0 1 2 3 4 5	145	VARNISH	0 1 2 3 4 5
103	GREEN PEPPER	0 1 2 3 4 5	146	SOUR MILK	0 1 2 3 4 5

Table 2.6. Odour profiling descriptors

Table 2.6. Odour profiling descriptors

Table 2.7. Odour Descriptor Profiles of Dredged Mud Samples

Descriptors	Degree of Descriptor Applicability		
	Active Harbor I (Sea)	Active Harbor II (Lake)	Less Active Sea Harbor
Fruity (citrus)			
Fruity (other)			
Floral			
Musky	X		
Fragrant			
Aromatic		X	
Almond-like			
Spicy			
Woody, resinous		XX	
Minty			
Camphor			
Vanilla			
Sweet	X		
Etherish, anesthetic			
Herbal, cut grass			
Soapy			
Stale	X		X
Musty, earthy	X		X
Mushroom			
Burnt, smoky	XX	XXX	
Burnt rubber		X	
Tar		XXX	
Disinfectant, carbolic			
Mothballs			
Sharp, pungent	XX	XXX	
Sour, acid, vinegar		X	XXX
Ammonia			
Fishy			
New rubber		X	
Gasoline, solvent	XXXXXXX	XXXXXXX	
Kerosene	XXX	X	
Oily, fatty	XXXX	XXX	
Paint-like			
Cooked meat			
Cooked vegetables			
Rancid		X	
Sweaty		XX	
Household gas	XXX		X
Sulfidic	XX		XXX
Garlic, onion			
Metallic	X	X	
Blood, raw meat			
Animal			
Sewer			
Putrid, foul			XX
Fecal (like manure)			
Sickening	XXXXX	XXXXX	XX
Dry, powdery			X

An assumption was made that if hedonic weights were assigned to each profile descriptor then a link would be found between the applicabilities of the specific descriptors and the overall hedonic tone. The values of these hedonic weightings were found by conducting a survey of 429 subjects. Each was given the descriptor list of 146 terms and asked to rate the hedonic tone of every descriptor on a scale of 1 to 9 with 5 as the mid point. Values above 5 indicated increasing unpleasantness with 1 indicating the most pleasant.

Using the results of this survey together with those from earlier studies by Woskow (1964), Doty et al (1978) and Dravnieks and O'Neill (1979) they derived a full set of hedonic weightings. These were normalised to give neutral unpleasantness of value of zero so that the scale went from -5 (very unpleasant) to +5 (very pleasant).

Table 2.8 which lists these weightings should be read in conjunction with Table 2.6. Thus the weighting for "fishy", i.e. index 36 (Table 2.6) is -1.88 (Table 2.8).

The method of assessing hedonic tone from the odour profile was as follows.

1) Members of an odour panel (see Section 3) are asked to classify an odour using any number of the 146 standard descriptors listed in Table 2.6. Each of the descriptors is rated on a scale of 0-5 as to the presence of that odour note.

Table 2.8. Hedonic tones of descriptor indices

INDEX	H	INDEX	H	INDEX	H	INDEX	H
1	2.51	41	-2.42	81	-2.88	121	-2.16
2	-2.44	42	2.67	82	0.63	122	-3.61
3	1.92	43	2.17	83	-3.29	123	-1.66
4	-1.33	44	-3.67	84	0.10	124	-0.17
5	2.03	45	0.97	85	2.04	125	-0.87
6	-1.33	46	0.38	86	1.90	126	3.44
7	-1.30	47	0.84	87	-0.10	127	1.27
8	-1.42	48	-0.29	88	-1.03	128	1.90
9	-0.10	49	-1.08	89	-1.60	129	2.00
10	-2.39	50	2.50	90	-0.49	130	0.41
11	-1.50	51	-3.29	91	2.4	131	-1.35
12	1.52	52	2.75	92	-2.42	132	-3.67
13	2.32	53	0.07	93	-0.47	133	2.24
14	-3.36	54	0.92	94	2.23	134	1.26
15	-1.82	55	2.09	95	-0.65	135	2.55
16	-2.28	56	1.18	96	1.19	136	1.07
17	-0.50	57	-0.57	97	2.72	137	0.61
18	0.84	58	2.10	98	1.00	138	1.56
19	-0.76	59	-0.81	99	-0.26	139	1.53
20	1.53	60	2.81	100	0.74	140	1.24
21	0.79	61	1.99	101	-1.51	141	-1.52
22	-0.80	62	-1.44	102	-1.23	142	-0.76
23	1.96	63	2.10	103	1.27	143	-2.63
24	1.12	64	0.98	104	-2.17	144	2.51
25	2.47	65	1.16	105	1.88	145	-0.69
26	2.36	66	3.06	106	2.57	146	-2.85
27	1.06	67	1.26	107	1.36		
28	2.31	68	-0.12	108	2.89		
29	-1.47	69	0.52	109	-1.99		
30	0.96	70	-2.20	110	0.24		
31	-1.31	71	-0.83	111	2.18		
32	-1.21	72	1.30	112	-3.6		
33	-1.03	73	2.20	113	2.49		
34	1.50	74	-2.69	114	-0.67		
35	2.05	75	1.18	115	1.80		
36	-1.88	76	0.19	116	2.48		
37	1.88	77	-2.11	117	-0.87		
38	-0.72	78	0.18	118	2.23		
39	-3.08	79	0.49	119	2.59		
40	2.47	80	1.95	120	0.97		

2) % A is calculated for each descriptor where

a) number of panellists = n

b) total score = T

c) $\%S = \frac{T}{n} \times \frac{100}{5}$ E2.7

d) $\%P = \frac{\text{number of results}}{n} \times 100$ E2.8

e) $\%A = \sqrt{(\%P \times \%S)}$ E2.9

3) The profile-derived hedonic tone is then calculated from the relationship given in equation E2.10

$$PH = \frac{\sum \%A \times H}{\sum \%A} \qquad \text{E2.10}$$

where H = hedonic tone of individual descriptor or index (Table 2.8).

The profile-derived hedonic tone PH is a single number describing the unpleasantness of the odour sample.

Laing, Panhuber and Baxter (1978) have shown that the hedonic tone and intensity are not governed by the same psychophysical laws whilst intensity is a linear function of concentration on a log-log scale, pleasantness or hedonic tone was curvilinear. Moskowitz and Gerbers (1974), Moskowitz et al (1974) and Moskowitz et al (1976) reported that

i) pleasant odours grow less rapidly in effect than intensity;

ii) odour unpleasantness grows more rapidly than intensity; and

iii) unpleasant odours are judged at high intensities to be substantially more intense than other odorants.

The pleasantness of butanol was essentially the inverse of intensity. Intensity - concentration and hedonic tone are therefore closely interrelated and any assessment of tone should be conducted at a standard intensity or concentration.

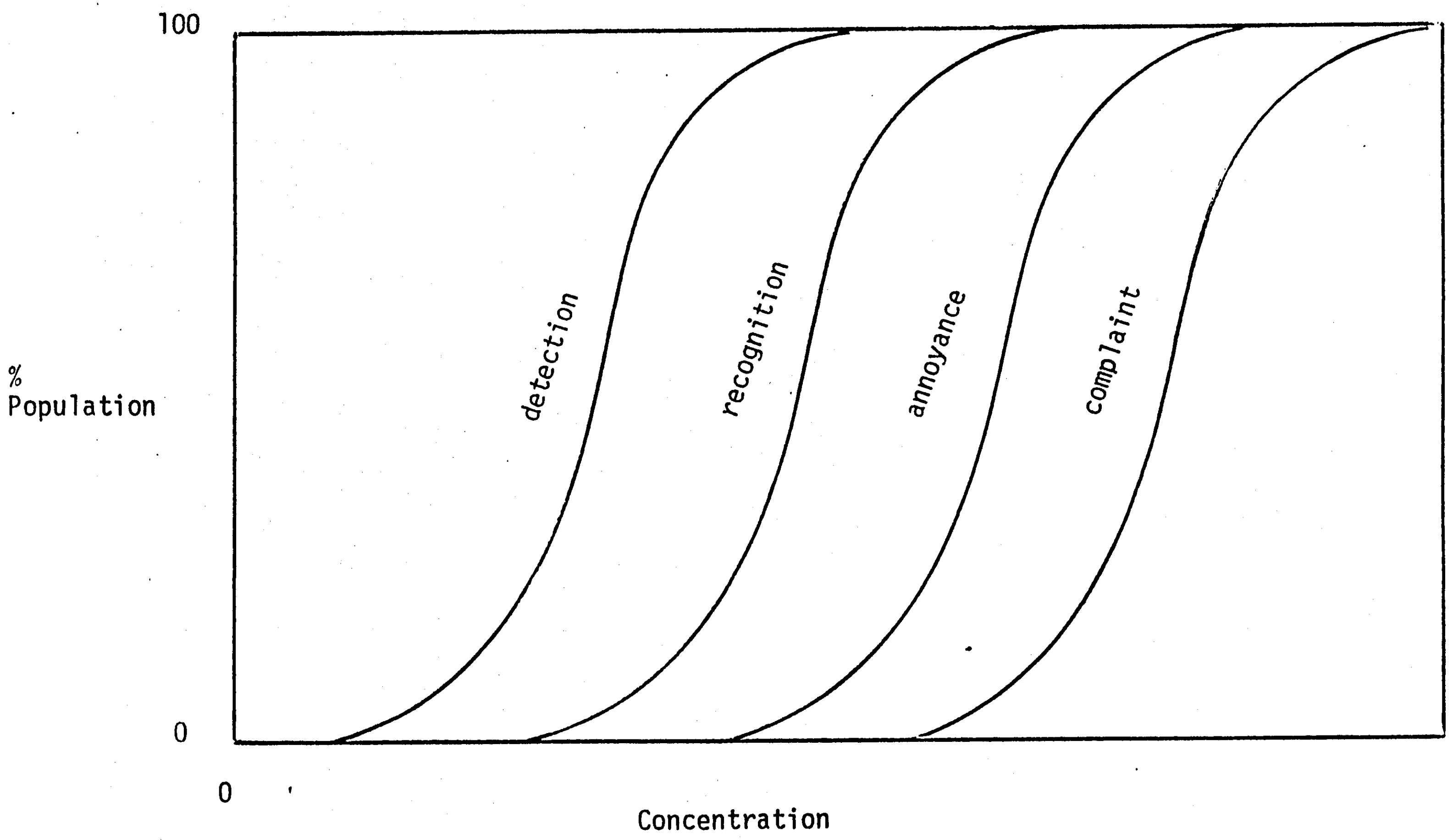
2.3.6 Dose Response Relationships

If people are exposed to a steady odour, i.e. not fluctuating, and if the concentration of the odour is gradually increased from zero there will be a progressive series of responses. What tends to happen is indicated in Figure 2.3.

Initially those people with the most acute sense of smell will begin to detect the odour. With a further increase more and more people can detect the odour until every one can excluding anosmics. Meanwhile the most sensitive subjects have started to recognise the odour. By the time all can recognise the odour a high proportion will probably be finding it annoying. When the annoyance reaches a certain value it causes the subject to complain.

FIGURE 2.3

Human Response to Increasing Odour Dose
(Concentration)



In practice complaints about odour nuisance are not received until the odour concentration is greater than 3-6 times the detection threshold Anon (1980). Huey (1960) suggested that concentrations greater than 7 times the detection threshold would probably cause complaint. Since the ratios of odour recognition threshold to detection threshold lie between 2 and 10 times depending upon the type of odour (Hellman and Small 1974) it would appear that complaints arise when an odour is high enough to be recognised (Keddie 1984).

Because of the effort necessary to complain, few of those annoyed actually complain. In a survey of public attitudes to industrial odours carried out by Basarin and Cook (1982) it was found that only 0.5% of those annoyed actually complained. Complaints are therefore not a good indicator of annoyance.

2.4. Summary

Many theories have been proposed to explain olfaction but none of them completely accounts for all of the observed phenomena. In short, we still do not know exactly how olfaction takes place. However, we are beginning to understand some of its characteristics. Concentration, intensity and unpleasantness can be quantified, but the character of an odour can only be qualified by comparisons with inadequate classifications or categories.

To complicate matters, olfactory activity or sensitivity varies from individual to individual, so to, does the point at which an odour becomes a nuisance.

3. METHODS OF MEASUREMENT

3.1. Background

The response to odours is a subjective reaction. No instrument can incorporate the human psychological factor. In addition to this, the human olfactory system is several orders of magnitude more sensitive in detecting odours than even the most sensitive instrumental techniques.

For this reason most odour measurement techniques rely on human judgement or the opinions of a panel of judges. The most often measured odour parameters are its strength in terms of concentration or intensity.

When an odour panel is used in this way the assessment technique is designated organoleptic. The reason for using an odour panel is that there is considerable variation in response to odours by an individual and between individuals. Wilby (1969) reports measuring a variation in individuals of +/- 900%.

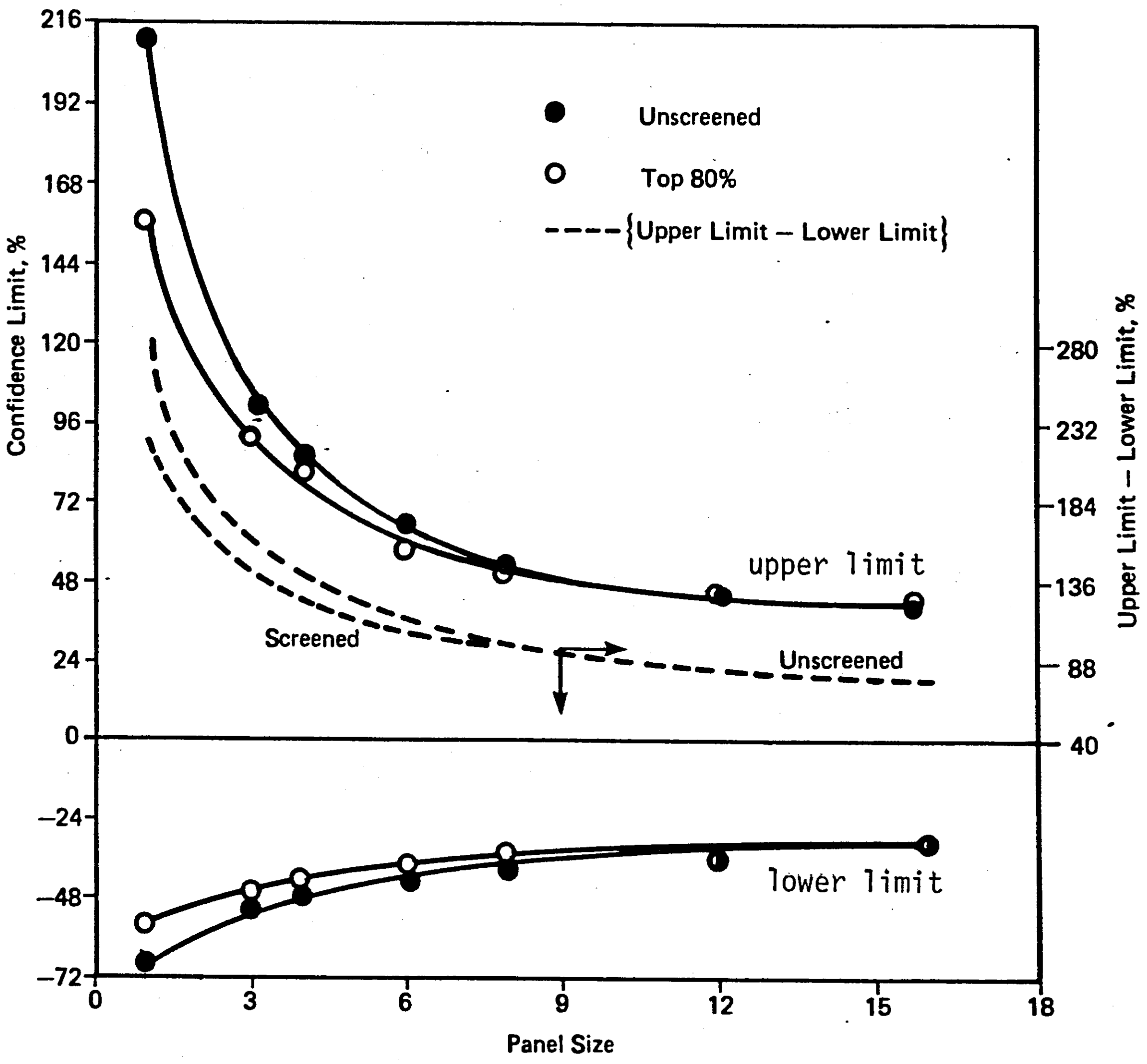
Therefore, statistically it is better to have as large an odour panel as possible in order to obtain the best estimate of the mean. In practice a compromise is necessary because of the cost and management of large numbers of people. The Karolinska Institute (Anon 1970) op. cit. recommend 5-10. Dravnieks and Jarke (1979) recommend using 9 or more if the sample is assessed only once. For smaller panels, say five or less, the samples should be evaluated two or three times. Molton and Cash (1978) use a panel of eight. Hemeon (1968) claimed that differences between individuals were normally less than +/- 300% and used only 3 panel members with repeat evaluations. Warren Spring Laboratory (Anon 1980) op. cit. give a statistical analysis of the errors involved for various panel sizes based on dilution steps of 30% and 60%. Figure 3.1 which is reproduced from Anon (1980) op. cit. shows the spread in 95% confidence limits for different panel sizes, screened and unscreened, for a single sample and 30% dilution steps. A screened panellist was one who was selected because their individual threshold value to either a sample of the odour to be tested or a key component of that odour lay in the top 80% of the panel thresholds.

It can be seen from Figure 3.1 that there is no point screening panels larger than 8 members. In addition, 3 screened or 4 unscreened panellists produce the same precision with 95% confidence according to Figure 3.1 to obtain a result within +/- 60% with a 95% confidence you would need 7 unscreened or 6 screened panel members.

3.2. Concentration

A very dilute concentration of the odorous sample is prepared in an olfactometer (see below) and presented to the odour panel for assessment. The number that can detect the smell is noted. The concentration is increased progressively and at each step the

Figure 3.1. Spread in 95% confidence limits for dilution factor against panel size



number of positive responses is recorded. The dilution at which 50% can just detect the odour is taken as the concentration quotient Z, i.e. a measure of the concentration of the odour.

Some typical odour concentrations at the point of emission as measured by Warren Spring Laboratory Anon (1980) are reproduced in Table 3.1.

3.3. Intensity

Odour intensity is also assessed by means of the human nose or panel of noses. However, for intensity the assessment is made on suprathreshold concentrations of odours. The observer(s) report their subjective impression in relation to the physical stimuli, either by comparative scaling (indirect), e.g. weaker or stronger than standard or by category scaling, e.g. weak, moderate, intense, etc.

When comparative scaling is carried out the subjects use reference odours of known concentration. These are either contained in the head space of an odorous liquid in a bottle or presented in an odorous airstream from an olfactometer as will be described under dynamic dilution techniques.

Butan-1-ol ($CH_3(CH_2)_3OH$) otherwise known as 1-Butanol, n-butanol or butyl alcohol and referred to in this thesis as butanol is the most widely used reference odorous material for assessing intensities. It is neutral in terms of unpleasantness but slightly carcinogenic.

Table 3.1. Typical odour concentrations at the point of emission

Industry		Dilution Factor	Flowrate ($m^3 s^{-1}$)	Odour Emission ($m^3 s^{-1}$)
Rendering				
100 t/wk	Ventilation	20,000	8.5	
	Process	42,000	0.75	Total 202,000
200 t/wk	Ventilation	333,000	1.2	
	Process	217,000	0.35	Total 476,000
350 t/wk	Ventilation	6,000	13.5	
	Process	1,350,000	0.5	Total 756,000
Approx 600 t/wk	Ventilation	28,000	10.5	
	Process	420,000	0.55	Total 525,000
Approx 1500 t/wk	Ventilation	42,000	20	
	Process	340,000	0.45	Total 993,000
Feather Hydrolysis				
20 t/wk		4,000,000	0.018	72,000
200 t/wk		500,000	0.21	105,000
400 t/wk		4,000,000	0.08	320,000
Maggot Farm				
2.5 to 3 x 10^3 gal/wk (October)		5,000	6	30,000
Farming				
Pig Pens		400 to 600	–	–
Chicken House (15,000 birds)		600	4.2	2,520
Fishmeal				
White fish		150,000	7.9	1,185,000
80% oily fish		400,000	7.9	3,160,000
Poultry Manure Drying				
8 t/h		200,000	6	1,200,000
1 t/h		43,000	1.5	65,400
Less than 1 t/h		22,000	0.5	11,000
Swill Boiling				
2.5 ton Pressure cooker		17,000	0.95	16,200
Blood Drying				
500 gal batch		50,000	0.25	12,500
Pharmaceuticals				
Sterilization of fermenter		715,000	0.75	536,000
Potato Crisps				
30,000 t/yr		250,000	–	–
100,000 t/yr		30,000	14.5	435,000
		275,000	2.4	660,000
Printing				
Web-offset		40,000	1.5	60,000
Low Pollution inks		2,000	2.0	4,000
Textile Stentering				
Nylon		18,000	2.0	36,000
Polyester cotton		1,200	0.6	720

A comparison between intensity, concentration of butanol and the corresponding category scale is given in Table 3.2.

Table 3.2 Butanol concentration, intensity and category scales

ppm_V	Intensity S	Category
1713	35	Very strong
472	15	Strong
250	10	Substantial but not strong
117	6	Easily noticeable
22	2	Faint
1	1	Threshold

ppm_V parts per million by volume

S defined as 10 at 250 ppm_V

Reference Dravnieks & O'Neill (1979)

3.4. Olfactometers

Olfactometers are basically of two types.

1) batch or static dilution.
2) dynamic dilution.

There are techniques which are closely related to olfactometers and for the sake of completeness some of these have been included below. The various forms of presentation of the odour sample are indicated in Figure 3.2.

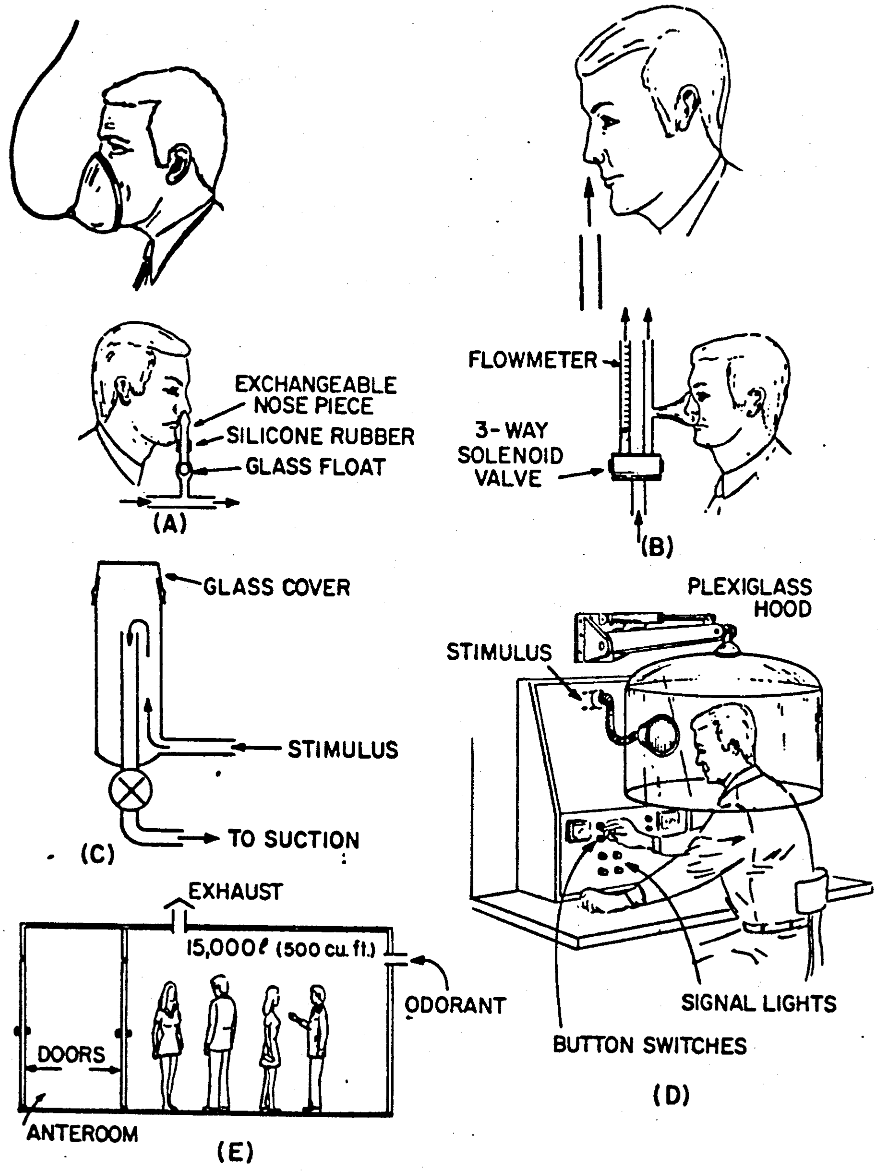
3.4.1 Batch or static dilution

Syringe dilution

This method is described by American Society for Testing and Materials ASTM D-391-57 (1972).

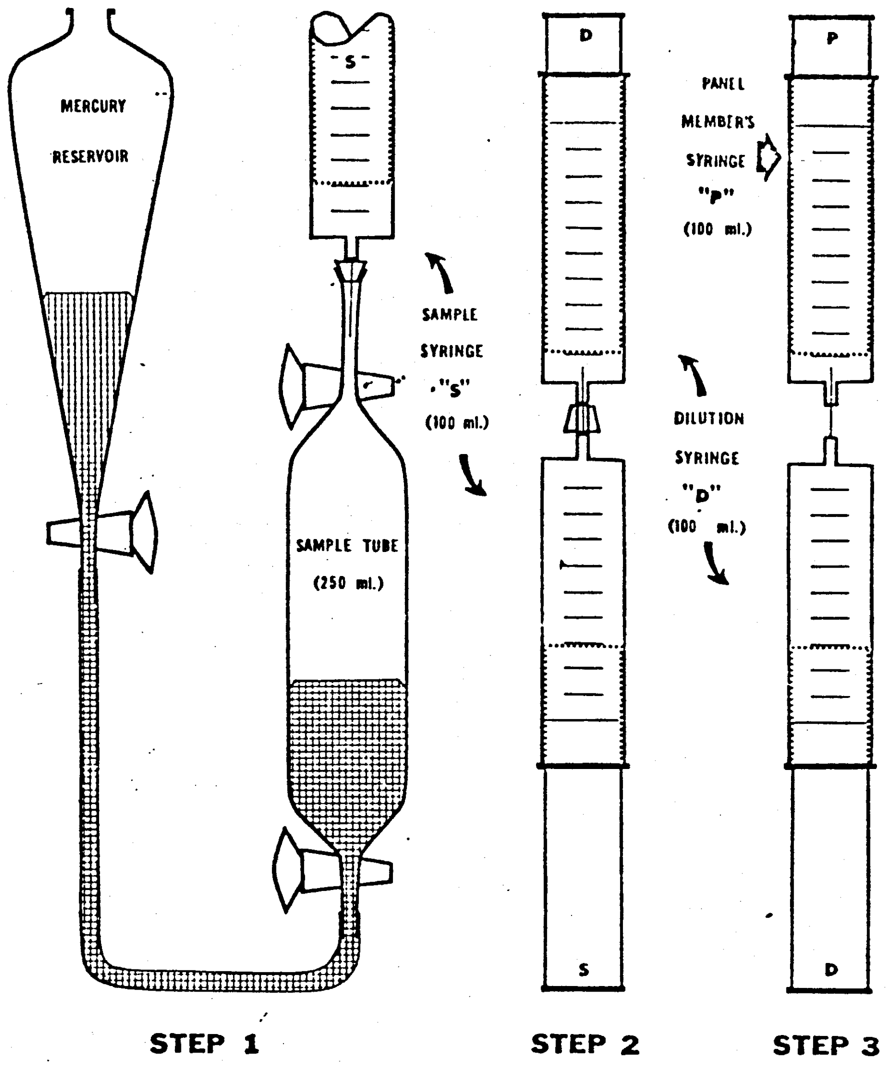
Using this technique a 250ml odour sample is collected in a glass gas-sampling tube and transferred to a 100ml glass syringe as indicated in Figure 3.3. A proportion of this, usually 50%, is transferred to a second syringe. The rest of the 100ml in the second syringe is made up with odour-free air. The process is repeated between the second and a third syringe, and again between the third and a fourth syringe and so on until a very dilute sample is obtained. The samples in each syringe are then discharged into the nostrils of an odour panel in succession as indicated in Figure 3.4. The intention is to maintain a trend in the order of presentation but to prevent a predictable sequence by frequent presentations of out-of-order concentrations.

Figure 3.2. Presentation of odour samples to odour panels



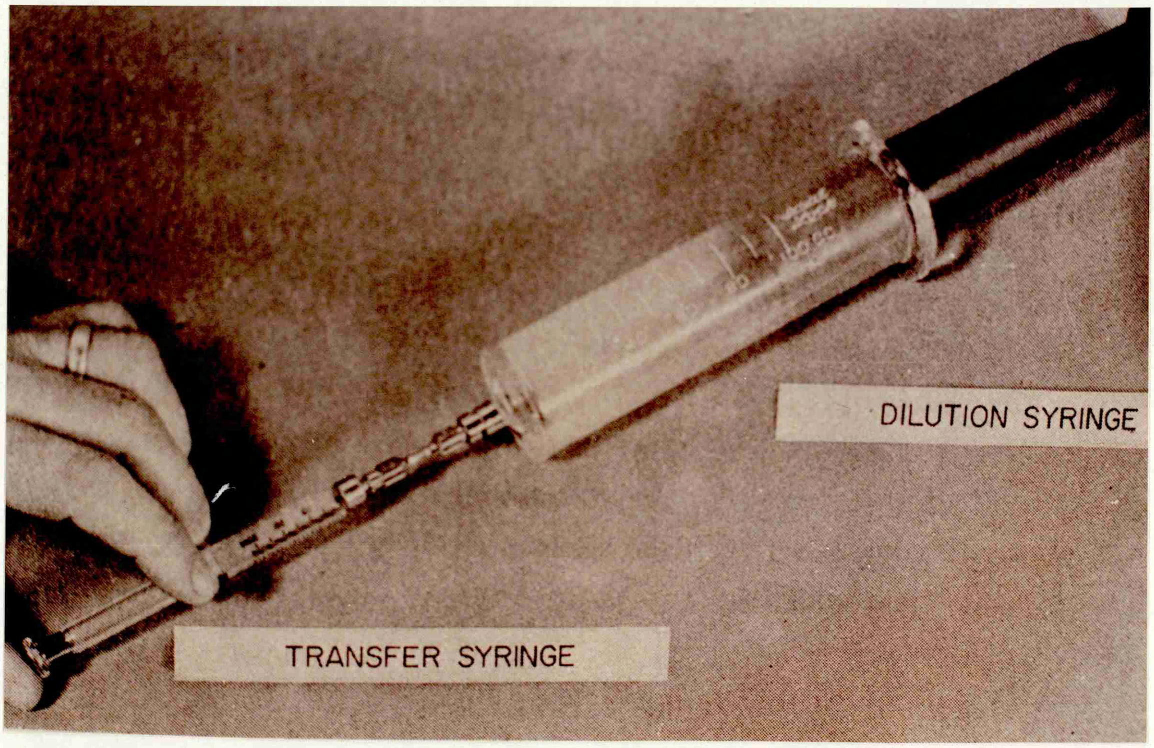
Various forms of presentation of odour stimulus to panellists. The two upper and funnel in B are the most commonly used.

Figure 3.3. Dilution of odour sample by syringe



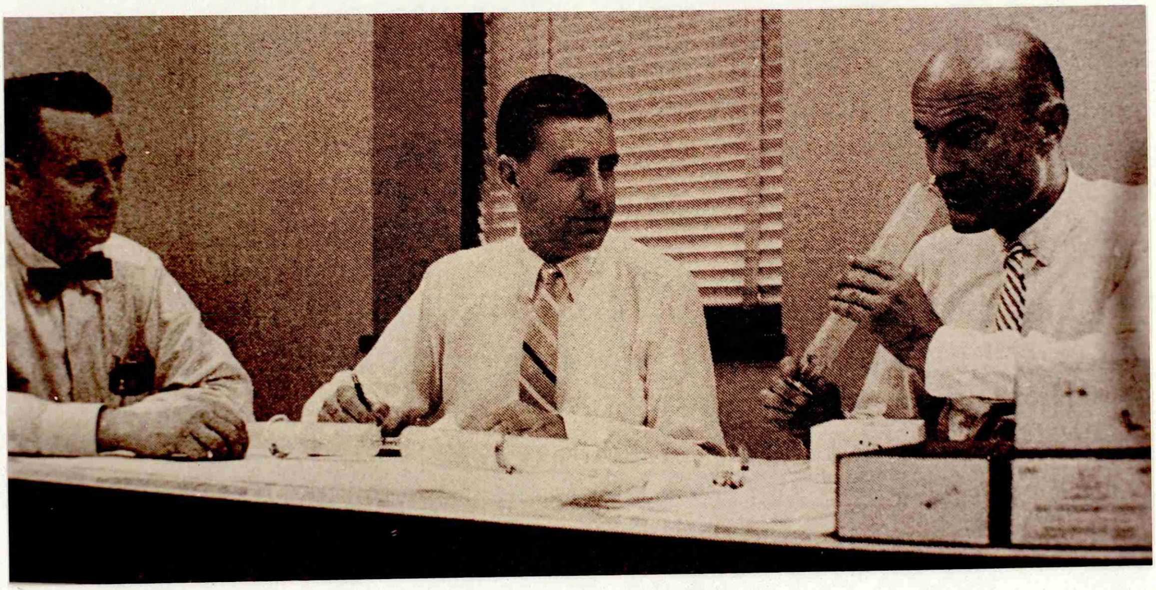
Odour samples are transferred to the sample syringe by mercury displacement. Dilution is accomplished by withdrawing the plunger of the dilution syringe to the 100ml mark after injecting part of the sample. Additional dilution is then made similarly in the panel member's syringe.

Figure 3.3. continued   Dilution of odour sample by syringe



Transfer of odour sample to dilution syringe. Sample in transfer syringe was measured out of a sample syringe, which is identical with dilution syringe.

Figure 3.4. Presentation of odour sample in syringe to panellist



Evaluation of diluted odour sample. Panellist is injecting contents into nostril to determine if any odour is present at this dilution.

The method has many disadvantages including laborious preparation of samples, poor presentation, adsorption of the odour on the internal surface of the syringe and cleaning difficulties afterwards.

Some idea of the problems involved in using this technique can be gained from the recommendations of a task group of the ASTM D22 (1977) Committee, ASTM (1977) which reviewed the principles applicable to the D1391-57 test. They recommended that:

"1) Panel threshold for the sample should be the geometrical average of the panellists' thresholds.

2) Odours should be presented in ascending concentration, and the concentration should be doubled for each successive presentation.

3) At each concentration one odour-containing and one odourless syringe should be presented. The panellist would smell both and then indicate to the panel leader which is the odour sample. The blank syringe would be randomised as being the first or the second to be sampled.

4) Panellist's threshold should be considered reached at the lowest of those three successive concentrations at which all of the panellists make the correct choice; or at the lowest of those two when the second, higher concentration the panellist's response was very positive and correct."

Odour room

An odour room is a specially designed room lined with aluminium walls (Figure 3.2) and equipped with fans for rapid air mixing. An odour sample of known volume is introduced into the room and the air is mixed while the panellists wait in an adjoining odour free room. The concentration is derived from the volume of the sample and the volume of the room.

Under the sponsorship of the manufacturing chemists association Arthur D. Little (1969) made a study of the odour threshold of 53 chemicals by the use of an odour room of $14m^3$ ($500ft^3$) volume.

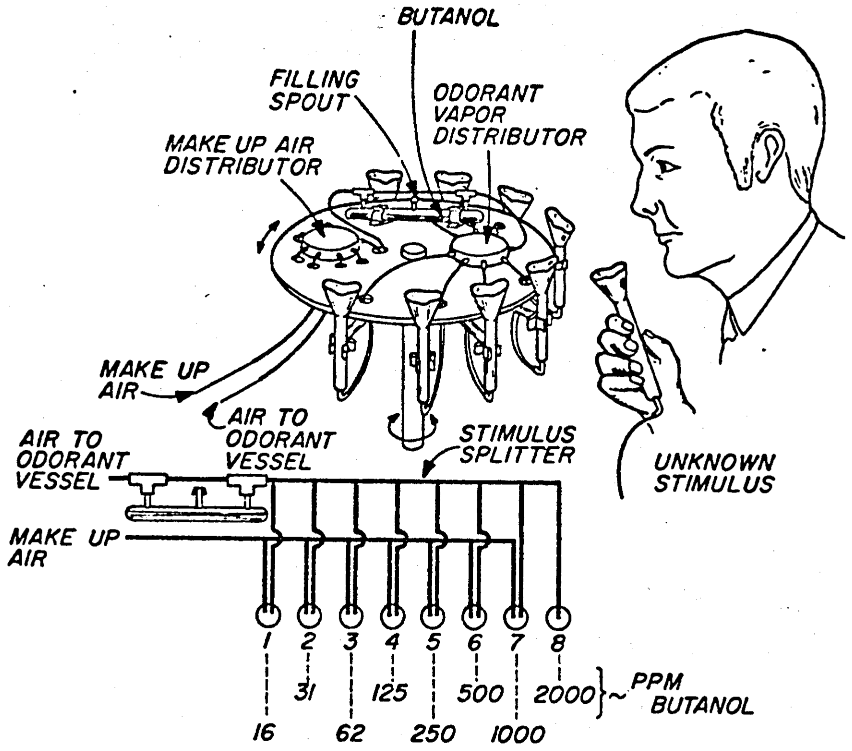
The main disadvantages of this method are that it is not possible to change the concentration in the room rapidly and it is hard to use many panellists while providing conditions that prevent panellists influencing one another.

3.4.2 Dynamic dilution techniques

Dynamic manifold olfactometer

The American Society for Testing and Materials developed an apparatus for producing suprathreshold concentrations of butanol for assessing odour intensity (ASTM E544-75). Figure 3.5 shows the instrument consists of two parts - an air supply manifold and an odorant manifold. Capillary tubes connect the manifolds to eight sample ports. The flow to each port is controlled by

Figure 3.5. ASTM apparatus for producing supra threshold concentrations of butanol



Odour intensity reference scale based on butanol.

different lengths of capillary tubing such that undiluted odorant leaves the first port. Equal quantities of odour sample and clean air are exhausted through the second port (dilution of 2). At the third port there is three times as much air as odorant (dilution of 4). At the fourth port there is seven times as much air as odorant (dilution of 8). The eight ports give a dilution rate of up to 128. At each port there is the same total sample flow rate.

Although this apparatus was designed for producing known concentrations of butanol it lends itself to modification for producing known concentrations of any odour. Such an instrument is shown in Figure 3.6 and was constructed by the author of this report during the course of his professional work.

One of the disadvantages of this type of instrument is that it is difficult to clean after use. A very large internal surface area has been in contact with the odour. In addition, this instrument has a limited range of only 128 dilutions. The odorous mixtures emitted from the ports either contaminate the test room if they have high flow rates (see Table 3.4), thus making it necessary for the operator to use a face mask, or the mixtures are at risk of being diluted in air before they reach inside the nostril if the flow rates are too low.

Another type of manifold olfactometer described by Mills et al (1963) is shown in Figure 3.7. Dilution is achieved by continuously mixing odour sample and odour-free air under the control of needle valves and flow meters to obtain the desired

Figure 3.6. Manifold olfactometer based on the ASTM apparatus

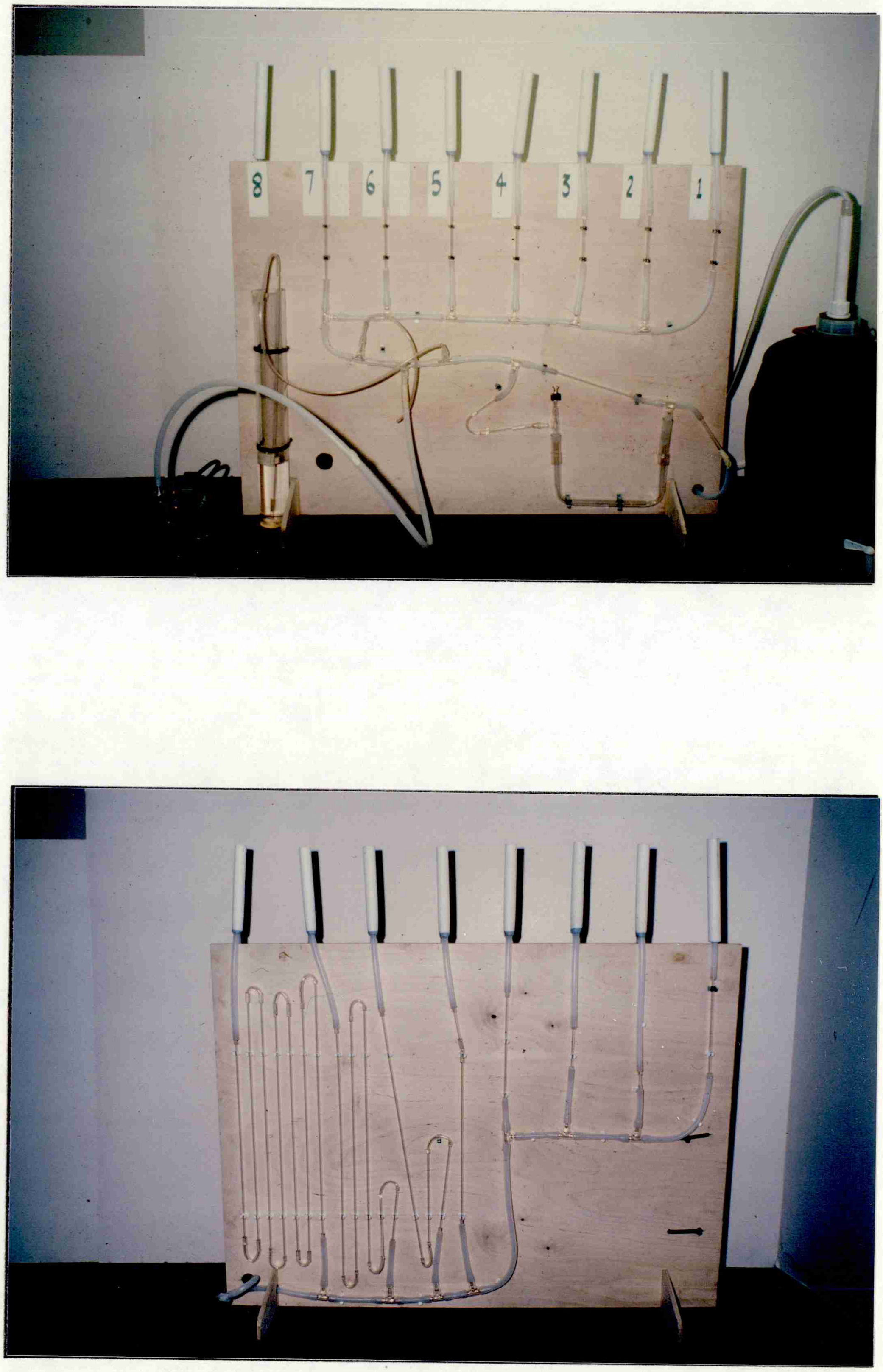


Figure 3.7. Manifold olfactometer

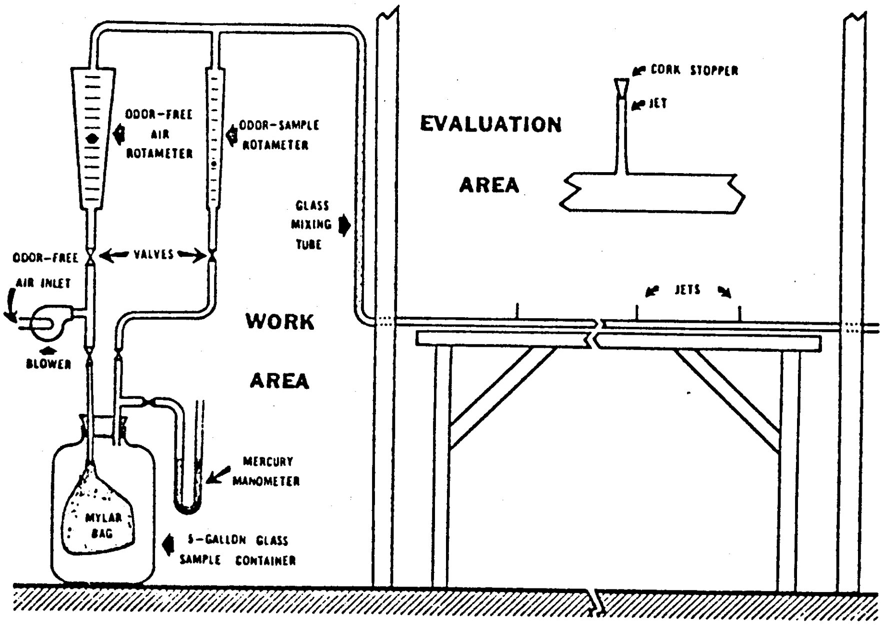


Diagram showing equipment assembly for continuous dilution of an odour sample for evaluation of odour concentration by the dynamic method.

dilution. The mixture is pumped at a pressure slightly above atmospheric through a glass manifold equipped with eight glass ports separated from the manifold by glass stoppers or stopcocks. The panellists are separated by partitions and sit at the ports in an odour free chamber. At a signal they open the stopcock and sniff the emerging air at approximately 7 litres/minute. They note their judgements by activating an electrical switch. The advantage of this system is that all 8 panellists experience the same stimulus.

Hemeon olfactometer

In the Hemeon type olfactometer, Hemeon (1968), an odour sample is diluted with odorless air through a series of stop cocks and flowmeters and is presented to three panellists simultaneously from the three ports arranged around the dilution module (Figures 3.8 and 3.9). One concentration is evaluated at a time. Hemeon (1968) recommends that each concentration is judged for its odour intensity using a category scale, as shown in Table 3.3.

Table 3.3. Odour intensity category scale after Hemeon

0 - no odour
1 - very faint
2 - definite
3 - strong
4 - very strong

Figure 3.8. Schematic view of the Hemeon olfactometer

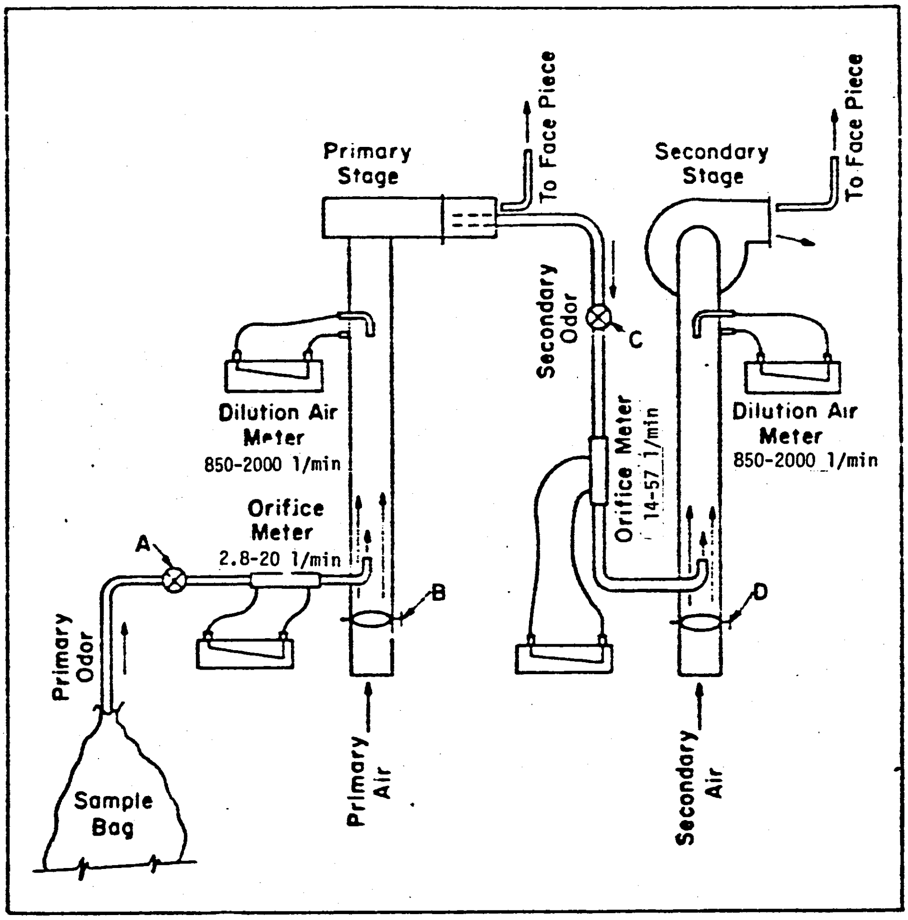
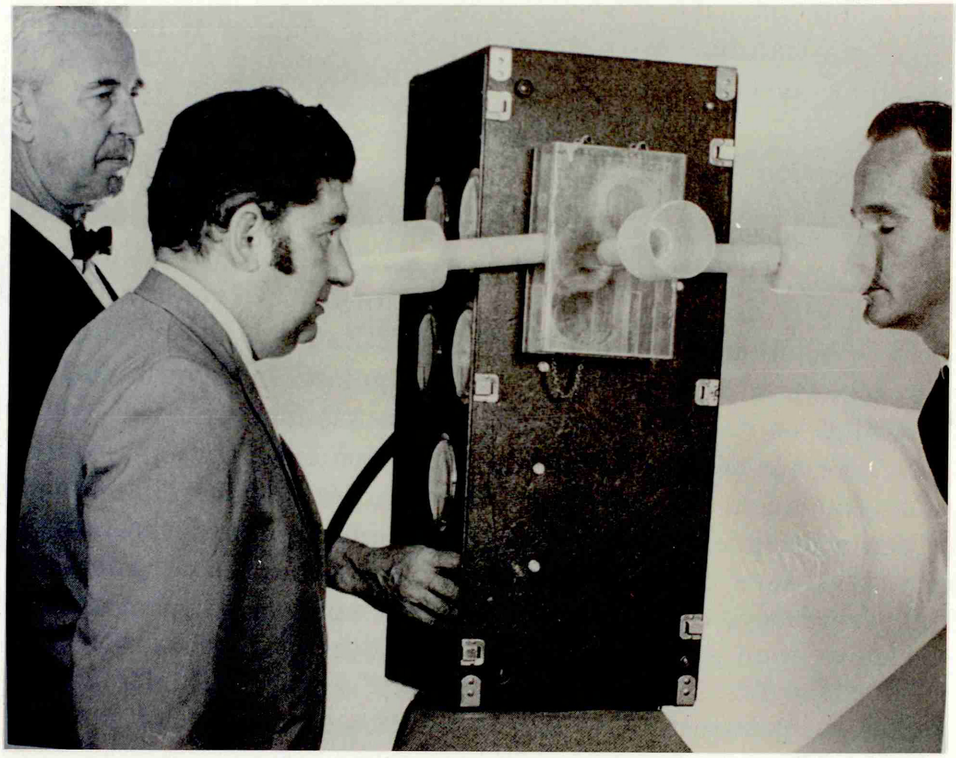


Diagram of apparatus depicted in Figure 3.9. Selected dilution ratios are prepared by adjustment of valves A, B, C, D, referring to corresponding air meters. Streams for odour evaluation pass through a distribution box (not shown) for selection of primary or secondary stream.

Figure 3.9. Hemeon olfactometer in use



A sample (85-140 litres) of the odour bearing stream is collected in a plastic bag visible at right rear, now connected to the odorometer. Dilution streams are delivered through the distribution box to face pieces. (Courtesy of Hemeon Associates)

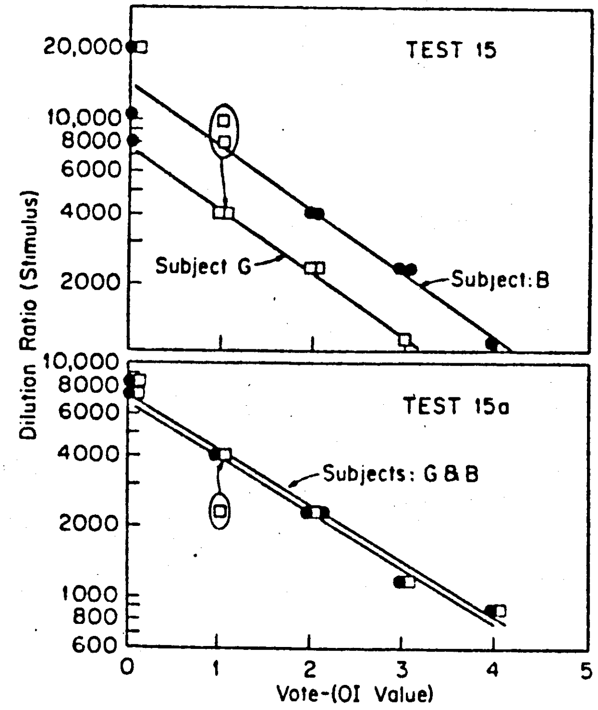
The logarithm of the dilution ratio is then plotted against the odour intensity scale as indicated in Figure 3.10. The best line fit through the points is then extrapolated to zero intensity. The corresponding concentration is taken as the group threshold at which no odour is detected. This is a fundamentally sound and practical procedure dating back to Katz and Talbert (1930) and confirmed by Dravnieks (1974). The reasoning is that the threshold determination does not depend on judgements made solely at the threshold, the concentration of most uncertainty.

Sanders olfactometer

In the Saunders olfactometer (Dravnieks 1974) odour is diluted with deodorised air and delivered to a mask as indicated in Figure 3.2 at a total flow rate of 7 l/min. The panellist gradually increases the concentration of odour by turning an ungraduated dial until detecting an odour. Flow meters are read and the odour dilution at that point is calculated. An important provision is that each panellist's threshold for a known reference odorant be determined at each session. Then to eliminate the effect of day-to-day variation in the sensitivity of the observer, the threshold of the emission is related to the threshold of the reference compound.

Dravnieks does not report the variation in threshold for the observers but tests carried out by Huey et al (1960) indicate that the range could be between -55% and +130% of the mean. One main disadvantage of this system is the anticipation which may occur and which is difficult to detect.

Figure 3.10. Odour intensity (OI) v concentration



Illustrating graphical treatment of data which exposes uncertainties at OI values of 0 and 1, facilitates derivation of threshold value and comparison of individual reactions. Test 15a is a re-check of the same sample and with the same subjects.

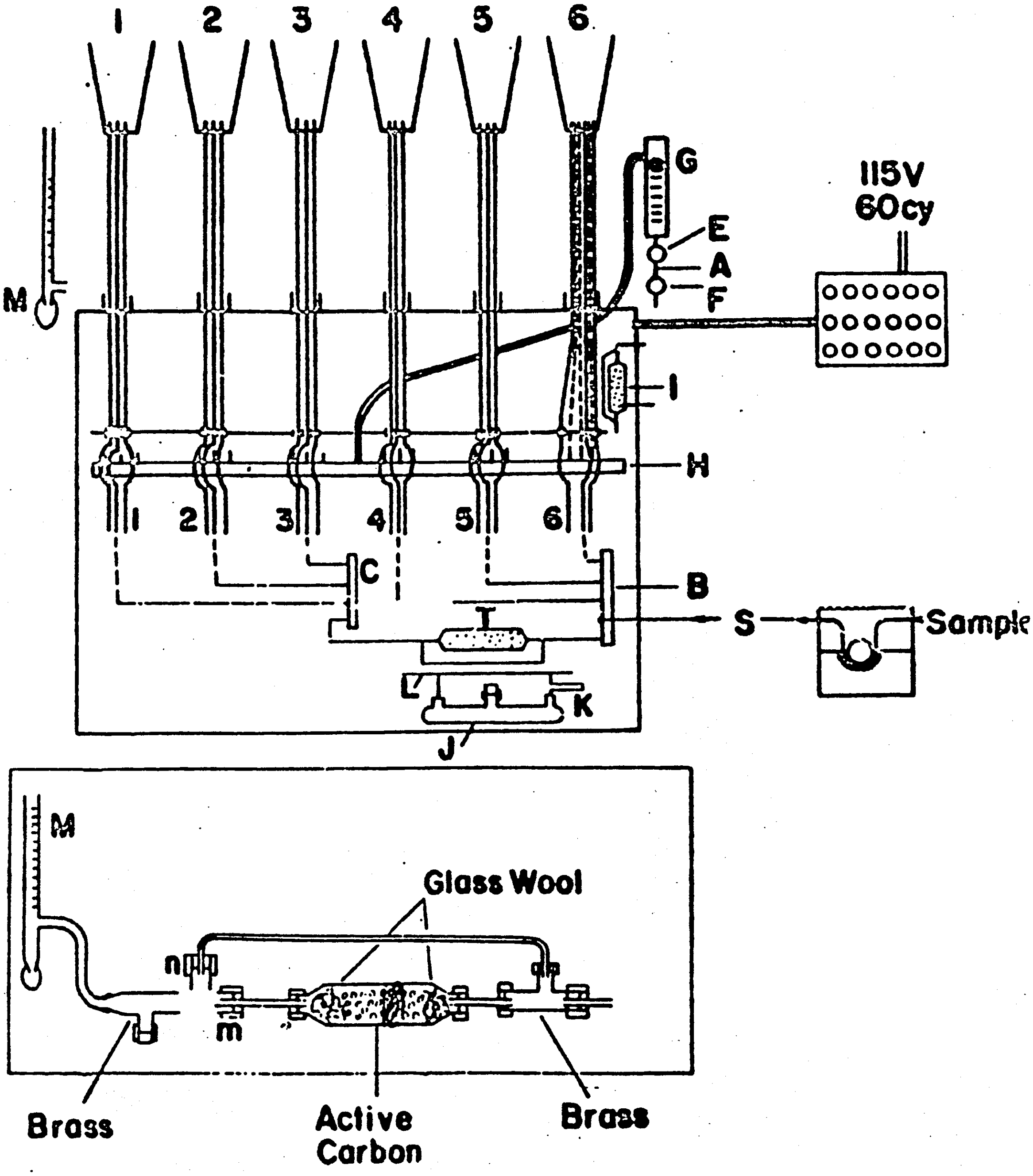
Odour fountain olfactometer

An odour fountain olfactometer has been used by Hellman and Small (1973). In this system three ports provide rapidly flowing jets or fountains of air. The left and right port are blanks while the centre port may contain an added odour. The blanks generate the same sensation of air movement as the centre port. Thus the presence or absence of an odour in the centre port can be judged by mentally discounting the mechanical effect. The rate of flow is of the order of 20-80 l/m from a 25mm diameter opening. After passing upwards through about 350mm of room space the jets enter larger ventilation ports that exhaust the odours, so preventing contamination of the test room. This system requires a very large odour sample.

Forced choice triangle olfactometer

This instrument, which was developed by the Illinois Institute of Technology Research Institute (Dravnieks 1973) is a development of ASTM manifold olfactometer described above. It also relies on the resistance of different lengths of capillary tube to maintain known flow rates and hence dilution rates. However, as Figure 3.11 shows it employs a forced-choice triangle system. A dilute sample is presented with two odorless (room air) samples. The panellists must choose which is the odorous and signals his choice by pressing a button. By guess alone there is a 1:3 chance to signal the correct port. There are six dilution levels typically from 4500x to 15x or from 80,000x to

Figure 3.11. Dynamic triangle olfactometer



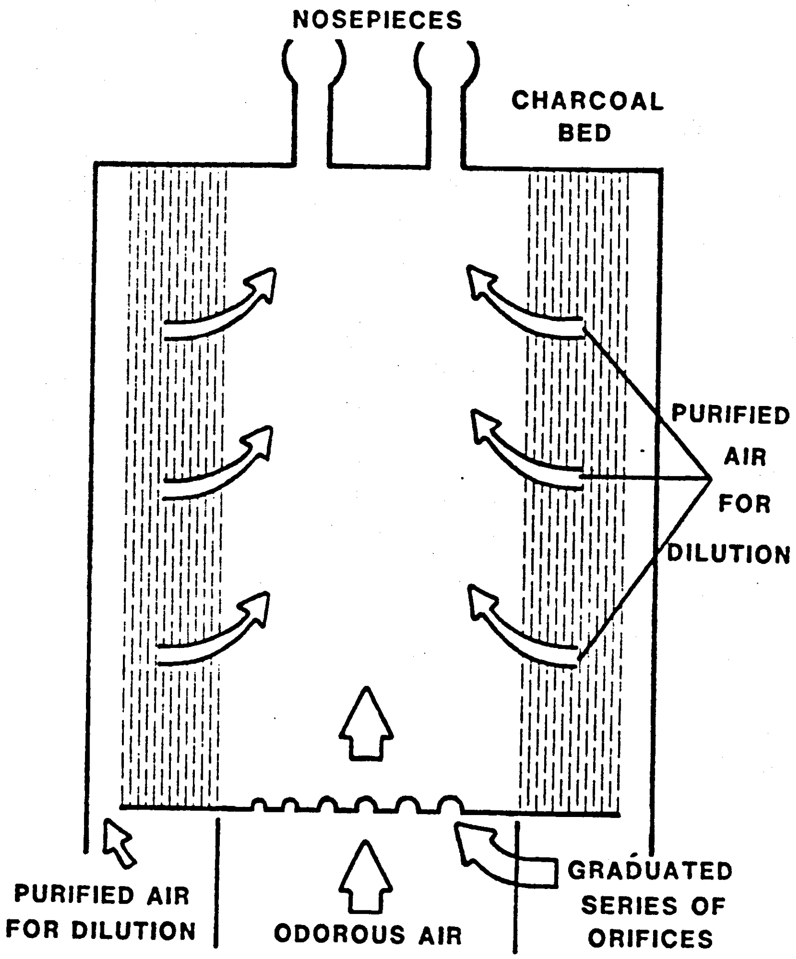
Measuring Attenuator Split Ratio

450x. Successive levels differ in concentration by a factor of 3. All of the required dilutions and blanks continuously emerge from the appropriate sampling port at 500 ml/min. Such flow rates do not produce an odour build-up in a normally ventilated room, nor is a large sample required, but there is some doubt about dilution of the odorous sample before it enters the nostril (Bedborough 1978).

Scentometer

The Scentometer was developed by Huey et al (1960). It is a box-like instrument constructed from perspex (Figure 3.12). It consists of a central chamber between two layers of activated carbon. Two 13mm holes on opposite sides introduce ambient air through both layers of carbon which deodorise it for dilution and mixing with odorous air sample in the centre chamber. At the lower end of the instrument 4 holes of varying diameter (12.7, 6.4, 3.1 and 1.6mm) are provided to control the volume of odorous air sample entering the mixing chamber. These different size holes correspond to dilutions of 2, 8, 32 and 128. At the upper end of the instrument are two glass nosepieces for insertion into the panellists nostrils (Figure 3.13). The panellist inhales through the nosepieces and exhales through the mouth to draw in odorous air samples through one of the four end holes and the dilution air through both side holes.

Figure 3.12. Schematic of scentometer



Odorous air passes through graduated orifices and is mixed with air from the same source, which is purified by passing through charcoal beds. Dilution rates are fixed by the orifice selection.

Figure 3.13. Scentometer in Use

The difficulty with this instrument is that it relies on the response of just one judge and it is limited in dynamic range. (The author has made a scentometer and has found that in ambient air it is difficult to assess odours that fluctuate at a rate of more than about five times per minute. This is because a passing puff of odour can occur while the observer is exhaling or changing dilution).

Warren Spring dynamic dilution apparatus

In this country the Warren Spring Laboratory has developed a dynamic dilution apparatus which is now commercially available from Prosser Scientific Instruments Ltd. (Bedborough 1978).

The apparatus is shown in Figure 3.14 together with four sampling ports for members of an odour panel. The instrument is very simple in design and is shown schematically in Figure 3.15. An odour sample is drawn from a Tedlar bag manufactured from heat welded Dupont Tedlar PVF film (200SG40TR) by negative air pressure. This sample is then mixed with clean air and emitted from sniffing or sampling ports. For greater dilution ratios a second dilution stage can be used. The clean air flow is set by orifice plates and voltage stabilised fans. The dilution rate is adjusted by a valve on the sample inlet line with flows registered by a hot wire anemometer system.

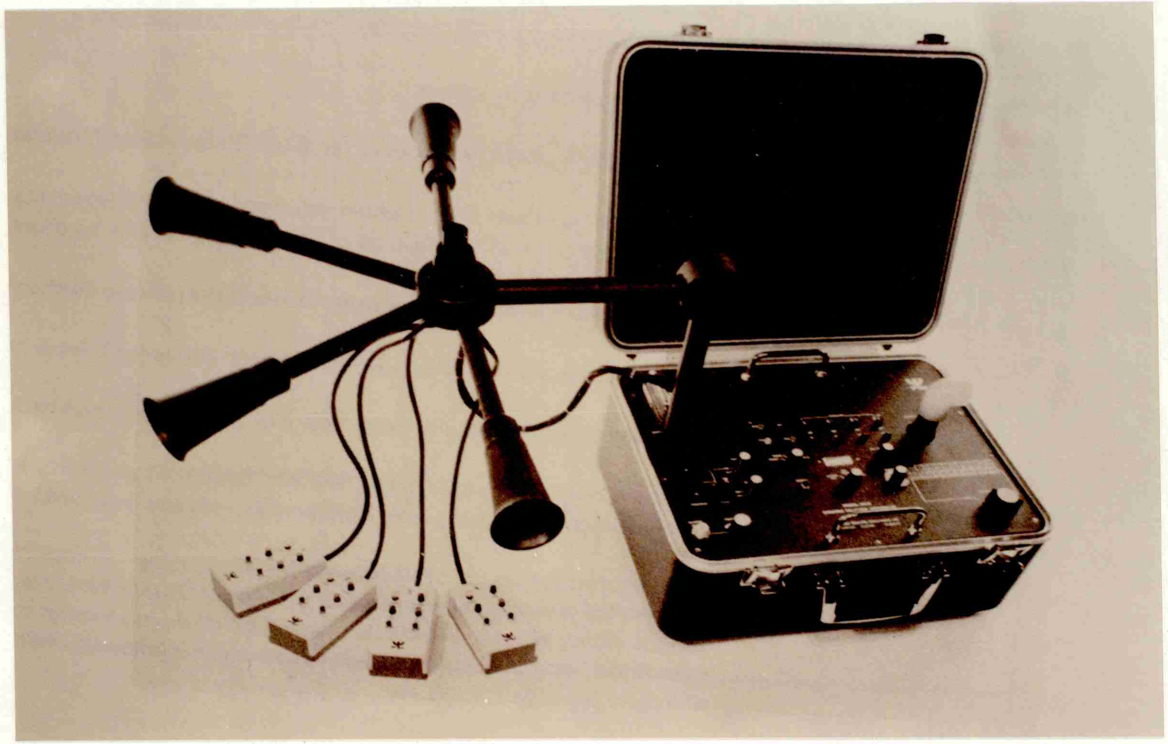
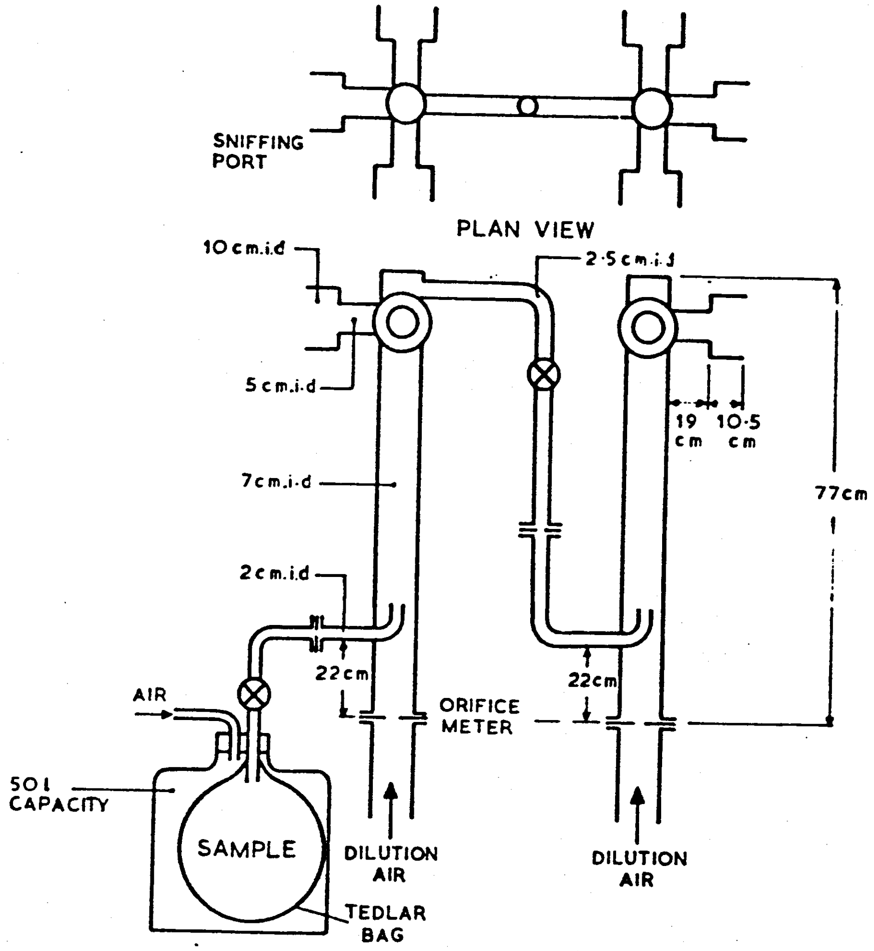


Figure 3.14. Commercially Available Portable Dilution Apparatus

Figure 3.15. Schematic view of commercially available portable dynamic dilution apparatus

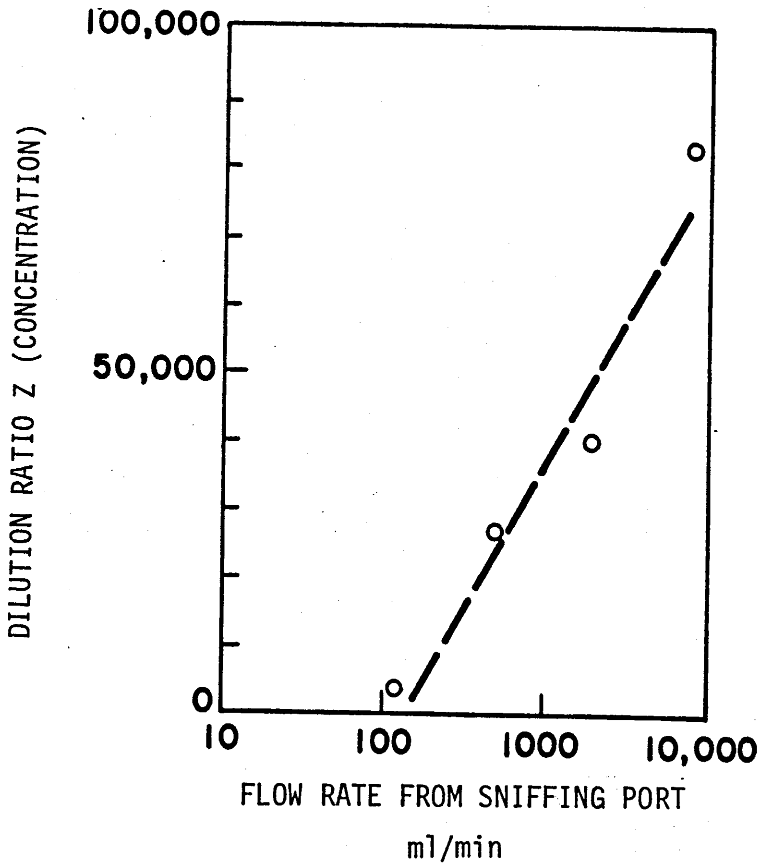


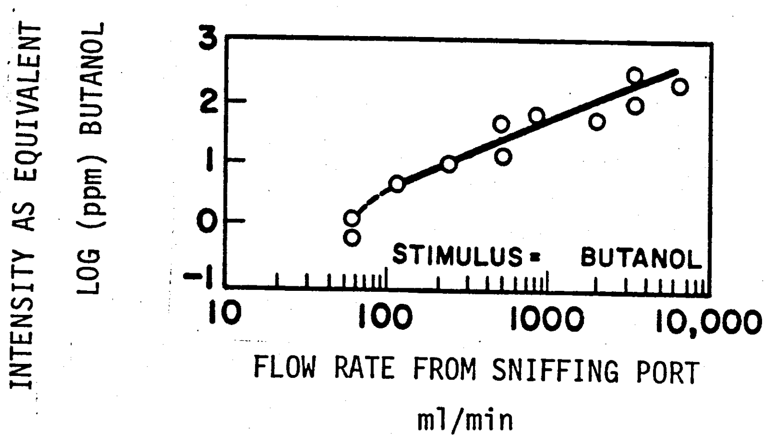
Diluted samples can be supplied to the four sniffing ports at a rate of 240 l/min. The basic design of this instrument is very similar to that constructed by Hemeon.

3.4.3 Comparision between olfactometers

At present there is no standardisation of olfactometers or the taking of olfactory measurements. Jann (1984) in a survey of the design of 15 research and portable dynamic olfactometers showed that different instruments yielded different results. In 1974 TRC Environmental Consultants (Wade et al 1974) were commissioned to compare three commercially available dynamic olfactometers with the ASTM D1391 static syringe method. Five odorants at three dilution levels were compared for detection threshold and operational characteristics. Using the same system with the same panel of 9 on the same day, the ratio between the highest and lowest threshold concentration was 2.5. Keeping all things equal as above and changing the presentation flow rate from 0.5 to 9 litres/minute the range of thresholds increased four times. When all three olfactometer systems were compared using the same odorant, same panel, same day, the range increased 200 times. Duffee and Cha (1980) noted that a 100 fold increase in the presentation flowrate could cause a 1000 fold difference in the threshold concentration. They reported that the change of flowrate was second only to sample deterioration for causing measurement error. Dravnieks and Jarke (1980) reported threshold versus presentation flowrate data for butanol (see Figure 3.16).

Figure 3.16. Influence of stimulus flowrate on the odour dilution threshold and perceived odour intensity of butanol vapour





This figure shows the influence of stimulus flowrate on the measured concentration or odour threshold ratio and the perceived odour intensity of butanol vapour. The measured concentration is proportional to the logarithm of the flowrate and the intensity, expressed in equivalent concentration of butanol vapour is linearly proportional to the flowrate. The intensity in this case has been measured by comparitive scaling (see page 3.4).

Table 3.4 summarises the major characteristics of the olfactometer designs surveyed by Jann. Table 3.5 summarises the spread in threshold determination caused by the instrument and technique variables.

Most olfactometers surveyed have panel interfaces that cover both the nose and mouth, either by a mask, face portal or large diameter funnel (75-100mm). Most interfaces are constructed from non absorbing glass or Teflon and have flow rates ranging from 3-50 l/min. The Illinois Institute of Technology Research Institute forced triangle olfactometer was notably low at 0.5 l/min and the Warren Spring Laboratory very high at 240 l/min.

Engen (1982) recommends that olfactometers should provide the observer with a constant, gentle flow at a rate that closely matches normal breathing. Jann (1984) concluded that the presentation should be standardised to 10-15 l/min (and at low velocity) to ensure adequate volume around the nose. This can

Table 3.4. Olfactometer design summary

			Dilution			Presentation				
Instrument Mfg	Date	Range	Sample Diluent*	Stages	Flow Control	Interface	Flowrate (lpm)	Protocol (Step Conc.)	Stimulus Stations	Perception Principle
Laboratory Research Units										
Ford Research	1979	$2x10^3$	PA	1	Microprocessor	Glass Funnel	12.5	Ramp or Random Step	3	Yes/No
TRC In-House	1971	$1.5x10^6$	CFA	3	Rotameter	Glass Funnel	5.	Ascending	8	Yes/No Paired**
Du Pont MOL	1976	$1x10^6$	CFA	3	Rotameter- Orifice	Teflon® Funnel	8.5	Ascending	3	Intensity Scale 1-5
Louisiana MOL	1983	$1x10^6$	CFA	2	Rotameter- Capillary	Glass Funnel	3.	Ascending	3	Forced Choice Triangle
CSIRO (Australia)	1977		CFA	2	Rotameter	Face Portal	10.	Random or Ascending	7	Yes/No
Warren Spring Lab(GB)	1976	$3x10^6$	CFA	2	Orifice- Turbinmeter	Teflon® Funnel	150.	Geometric Descending	4	Yes/No
Lindvall MOL(Sweden)	1968	$1x10^3$	PA	2	Needle Valve- Capillary	Teflon® Face Portal	100.	Random	2	Yes/No Paired
Wash Univ MOL	1965	$1x10^7$	PA	2	Needle Valve- Rotameter	Face Portal	50.	Ascending	6	Yes/No
Commercial & Field Units										
IITRI	1974	$8x10^4$	RA	2	Rotameter- Capillary	Glass Nose Port	0.5	Ascending	6	Forced Choice Triangle
HEMEON	1968	$7x10^5$	RA	2	Orifice- Manometer	Teflon® Funnel	142.	Ascending	3	Intensity Scale 0-4
MISCO (Sanders)	1974	$3x10^5$	CFA	2	Rotameters	Mask	12.	Ascending	1	Yes/No
TRC Portable	1974	$1x10^3$	CFA	1	Rotameters	Glass Funnel	5.	Ascending	1	Yes/No Paired
Butanol Olfactometers										
1 ASTM E544	1975	16-2000 ppm	RA	2	Rotameter- Capillary	Glass Nose Port	0.16	Ascending	8	Intensity Comparison
2 Shell (Johnson)	1978	0.3-250 ppm	BA	2	Rotameter	Mask	11.	Random	1	Intensity Comparison
3 Texas A&M Field	1982	0-80 ppm	BA	1	Rotameter Metering Valve	Ceramic Mask	15.	Random	1	Intensity Comparison

*Diluent RA = Room Air CFA = Carbon Filtered Air PA = Purified Air Using Several Filtering Media BA = Bottled Air
**Paired = Yes/No Comparison to Blank

Note. Warren Spring olfactometer is an earlier version than the instrument described in the text. The new instrument has a presentation flow rate of 240 l/min.

Table 3.5. Summary of threshold scatter

Variable	R
1. Instrument to instrument (overall)	up to 200X
2. Same Instrument	
a. Presentation (combined)	20X
flowrate	4-20X
interface	(6X)
protocol	(4X)
b. Flow Control (w/calibration)	(.5X)
c. Panel	2X
d. Odorant	(2X)
e. Diluent	2-3X
3. Panel to Panel	10X

*Range of measured threshold values expressed as ratio, R, for lowest to highest in comparative testing.
( ) denotes estimation.

best be accomplished by using a mask or funnel. Accuracy would further be improved if the forced choice triangle technique with its double blank presentation were used.

According to the Assembly of Life Sciences National Research Council (Anon 1974) the order of sample concentration presentation is important, because it can affect the threshold value determined.

- Decreasing concentration series - with this procedure the panellists evaluate more and more dilute samples until no odour is detected. The problem often encountered with this approach is that stronger odours fatigue the sense of smell and make the odour of weaker samples presented later more difficult to detect. There is also the possibility of odorants adsorbed on the inner surfaces of the instrument being desorbed and contaminating the weaker samples.

- Increasing concentration series - very dilute samples are evaluated first and then the concentration is increased until it is detected by all panellists. This avoids the problems of fatigue and contamination of weaker samples associated with a decreasing concentration series procedure. However, there are problems of anticipation. Panellists anticipate that an odorous sample will eventually appear and tend to report detection or recognition prematurely.

- Random concentration series - with this procedure weaker and stronger dilutions are presented in random order in an effort to eliminate anticipation. However, the problems encountered are similar to those associated with a decreasing concentration series. Lindvall (1970) states "randomised order ...... makes it almost impossible adequately to evaluate odour threshold" and advocates an ascending concentration series with blanks.

- Ascending concentration series with blanks and out of order samples - instead of steadily increasing the concentration in regular steps, blanks and repeat samples are inserted in the series in order to reduce the anticipation associated with a simple ascending concentration series. Table 3.4 indicates that most olfactometers are used with one of the ascending concentration series procedures.

Dravnieks and Jarke (1979) concluded that it was evident that without standardisation of olfactometric procedures it is useless to talk of a dynamic olfactometric threshold and base any control regulations on such a threshold. Either all measurements must be conducted by some agreed device and procedure, or the results with one system should be calibrated against the results with other systems so that data can be compared.

3.5. Signal Detection Theory

In using olfactometers odour panels have to make judgements as to the presence of an odour in the sample being tested. Such decisions can be treated by signal detection theory.

Signal detection theory originally evolved to treat radar signal detection in the presence of random electric noise and dealt with the detectability and recognisability of weak signals. It was later introduced into psycho-physics and its application to odorous air pollution was explored by Lindvall (1970).

This theory postulates that when an observer judges the presence of an odour in a sample, the judgement depends upon both the sensitivity of the observer's sense of smell and on the criteria used to decide whether a signal (odour) is perceived on the background of various other spurious signals (noise). It is assumed that fixed sensory thresholds do not exist and that the criteria used by the subjects for detecting the stimulus vary. Sensory perceptions are judged by the observer on a probability basis and the responses make it possible to estimate how interchangeable the sensory signals are with the background signals. The signal detection approach allows the investigator to measure the effect of response bias better than any other technique since both positive and negative false alams can be corrected for.

In making a judgement there are four possible outcomes.

- odour is present and is reported (a hit)
- odour is present but is not reported (a miss)
- odour is absent but is reported (false alarm)
- odour is absent and is not reported (correct rejection)

From the numbers N of responses in each of these categories a statistical detectability index d' is determined. This is a sensitivity measure separated from the decision criteria effect.

Numerically the procedure is as follows:

Two probabilities are calculated, i.e.

$$\text{Probability of hits} = \frac{\text{N of hits}}{\text{N of hits + N of misses}}$$

$$\text{Probability of false alarms} = \frac{\text{N of false alarms}}{\text{N of false alarms + N of correct rejections}}$$

Tables derived from probability distribution equations are then used to find a d' value for the calculated values of P (hits) and P (false alarms)

Signal detection theory has been used to measure ambient odours by Lindwall (1970, 1973) and by Reboux et al (1978). Whilst the technique can provide an objective measure of sensitivity which is independent of the subject's criteria and other factors such as the relative proportions of positive stimuli and blanks in the stimulus presentation sequence it does have certain disadvantages. The main difficulty in calculating the detectability d', is that a large number of observations are required, e.g. 500-1500. However, because of the time consuming nature of this process and the difficulty in terms of presenting odorous and non-odorous samples to the subject without the certainty of inter-sample contamination, this method has not yet found extensive use in routine odour measurements.

3.6. Characterisation of Exposure in Ambient Situations

Until now we have considered the assessment of a constant dose either in terms of concentration or intensity. Olfactometers are ideal for assessing the strength of a stable or static sample, i.e. when measuring the odour source. However, in ambient air much useful information is not collected. This is because the concentration is rarely constant. Turbulent mixing of the atmosphere means that odours' levels fluctuate rapidly. The best that an olfactometer can achieve is a measure of the average concentration of the sample.

The alternative is to use a direct sensory approach by employing sniffing teams. Hogstrom (1974) and more recently Thiele et al (1986) and Harssema (1986) have used such techniques. They placed the teams down wind of odour sources to record the presence and intensity of odours. When the observation time is long enough for a given meteorological situation the odour frequency at each point can be determined. That is the percentage of time that the odour threshold is exceeded.

The use of sniffing teams is attractive but it also poses some problems. It is a direct sensory approach and according to Harssema can be quite objective if standardized methods are applied. In both the Netherlands (Anon 1986) and in Germany, Verein Deutscher Ingenieure (VDI) (Anon 1985) there are initiatives for standardisation of measurement by sniffing teams.

The main disadvantage of this technique is that it can be expensive because of the large number of measurements necessary for the quantification of some problems.

Harssema claimed that sniffing teams can only be used in existing situations where no other sources are present. There are, however, examples in the scientific literature, e.g. Copley (1971) in which the sniffing panel has successfully discriminated between different types of odour.

The other problem with the method is that panellists can adapt to the odour, particularly where there is little variation in concentration. Intensity measurements are variable, unless a simple reference method is available.

Nevertheless, if these limitations are taken into account in the testing protocol then the direct sensory approach can provide useful measures of ambient odour characteristics which cannot be obtained in any other way.

A variation on sniffing teams is the use of population panels. With this system, which is gaining favour in the Netherlands (Maiwald 1986, Punter 1986), members of the public in the study area are encouraged to take part in a monitoring exercise over a period of a year or more. Two or three are selected at random from each postal zone to give a reasonable sampling network.

Routinely every week at a specified time they step outside their homes and make a note of any odours that they experience, giving an estimate of its annoyance on the five point scale given in Table 3.6. The observations are then sent by prepaid post card to the coordinating laboratory for analysis. The aim being to assemble data on the community annoyance to odours.

The individual category responses are placed on a numerical scale; with the value 0 for (no odour and not annoying), 25 (a little annoying), 50 (annoying), 75 (very annoying) and 100 (extremely annoying). All of the responses in the same area are then aggregated. If no-one is annoyed the odour index is 0, if everyone is (extremely annoyed) then the index is 100.

This method of assessment gives a very coarse measure of community odour annoyance. It is averaged over all meteorological conditions and for this reason cannot be used to identify a particular source. Even if it could, it would be too slow to react, to be of any use in odour control. The other major difficulty is panel motivation.

It has been found difficult to maintain the panel's interest in the project and to make the observations regularly. A number of measures, such as the circulation of news sheets and giving small rewards to the best observers, has been necessary to maintain high levels of participation.

Table 3.6. Annoyance scale used with population panels

Scale	Category
1	no odour or not annoying
2	little annoying
3	annoying
4	very annoying
5	extremely annoying

3.7. Summary

Most odour measuring systems use an olfactometer in conjunction with human judgement or the opinions of a panel of judges. These are known as organoleptic methods. The human olfactory system is utilised as part of the measuring system because of its greater sensitivity and selectivity over purely instrumental methods.

A large number of olfactometers have been developed for the measurement of concentration and intensity but there has been no standardisation in approach. Consequently there are wide variations in the results obtained. Without standardisation of instruments and procedures it is difficult to relate the results from one system to another.

Methods of assessment based upon the use of the signal detection theory have been applied to odour measurement but have been found to be too unwieldly for routine measurements.

Currently there is growing interest in using a direct sensory approach for the assessment of ambient odours by using sniffing panels.

4. DISPERSION MODELLING

According to Janni (1982) odour problems are the result of the three step process listed in Table 4.1.

Table 4.1. Processes involved in the formation of odour at a receiver

---

a) Formation of odorous compounds.
b) Emissions to the atmosphere.
c) Transport and dispersion.

Modelling of odour transport and dispersion provides an important insight into the likelihood of a problem and gives an indication of how much control is necessary.

4.1. Gaussian Models

Several approaches have been adopted for modelling the dispersion of odours. The first model used was a Gaussian plume model generally attributed to Sutton (1932) for the atmospheric dispersion of gases. This model assumes that eddy diffusion in the atmosphere causes air pollution to be dispersed in a bi-normal manner downwind of the source. It also assumes that the magnitude of diffusion depends upon the stability of the atmosphere.

Pasquill (1961) categorised atmospheric stability into 7 categories for use with the Gaussian dispersion model, from A (very unstable) through D (neutral) to G (very stable) assigning a dispersion parameter to each stability distance combination.

Category A (very unstable) occurs typically on a warm sunny summer afternoon with light winds and almost cloudless skies when there is strong solar heating of the ground and the air immediately above the surface. Bubbles of warm air rise from the ground in thermals. The lapse rate near the surface is superadiabatic (i.e. it exceeds the dry adiabatic lapse rate).

Category D (neutral) occurs in cloudy conditions or whenever there is a strong surface wind to cause vigorous mechanical mixing of the lower atmosphere. Category D occurs both by day and night. The period immediately after sunrise and immediately before sunset is normally considered neutral. The lapse rate is equal to or less than the dry adiabatic lapse rate.

Category G (very stable) occurs typically on a cold clear calm night when there is strong cooling of the ground and the lowest layers of the atmosphere by long wave radiation to space. There is a strong inversion of temperature. Category G only occurs at night. Categories E and F also only occur at night normally with a slight or moderate inversion of temperature.

The stability categories are estimated from the total cloud amount, wind speed and time of year. During the day an estimate is made of the incident solar radiation and this is combined with wind speed to estimate the stability category. At night the stability is a simple function of cloud cover and wind speed.

Wohlers (1963) used a dispersion model based on a Gaussian plume model developed by Sutton (1947) to compare estimated and actual travel distances by odours from various industrial sources: Nordstedt and Taiganides (1971) used a similar model to study meteorological control of odours during land spreading of livestock waste.

Gaussian plume models have also been used to predict the average concentrations of specific compounds downwind of sources based on the Pasquill Gifford (P.G.) equations (Turner 1970), i.e.

$$c(x,y,z,H) = \frac{Q}{2\pi\sigma_y\sigma_z u} \exp\left(-1\left(\frac{y}{\sigma_y}\right)^2\right) \times$$

$$\left[\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right] \qquad \text{E4.1}$$

where

c(x,y,z,H) = concentration at downwind position xyz for a source of effective height H (grams per cubic metre) (g/m^3)

Q = emission rate (g/s)

u = windspeed at emission height (m/s)

σ_y = standard deviation of plume concentration in the cross wind direction (m)

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

Janni (1982) used such a model to investigate the important factors in the dispersion of odours from agricultural facilities.

These models do not take account of the short term fluctuations in the concentration due to turbulence. According to Murray (1978) such fluctuations are important because people respond to detectable odour levels lasting of the order of a few seconds rather than over 10 minutes to an hour as is assumed in most Gaussian dispersion models. Some investigators make allowances for this difference in averaging time. Anon (1980) op. cit. recommend the use of an empirical mean to peak ratio of 10. Thus, the 3 minute average concentration estimated by the P.G. Gaussian plume dispersion model is multiplied by 10 to give the peak occurring for periods of one to five seconds. Bahmann et al (1983) have also reported an empirical mean to peak ratio of 10.

At this point it should be noted that Turner (1970) gives a correction for averaging time of the form

$$C_S = C_K \times \left[\frac{t_K}{t_S}\right]^p \qquad \text{E4.2}$$

where

C_S = desired concentration for sampling time t_S

C_K = concentration estimate for the shorter sample time t_K.

p is a constant between 0.17 and 0.2

This relationship is tabulated for a few key values in Table 4.2.

Table 4.2. Correction factor for change in sampling time

Sampling Time	Ratio of Caluclated Concentration to 3 Minute Concentration
3 minutes	1.0
15 minutes	0.82
1 hour	0.61
3 hours	0.51
24 hours	0.36

Constant p in equation E4.2 = 0.17

4.2. Puff Models

Finally there are a group of models which consider the odour plume as a series of puffs. These models, which are based on the principles described by Slade et al (1968), usually predict the odour frequencies or number of occurrences that a specified odour concentration is exceeded during a given time period. Included in these models are those described by Hogstrom (1972), Murray (1978), McCarthy (1980). The classic work which established this method of modelling was conducted by Hogstrom (1972) in association with Lindvall (1970). Hogstrom carried out a rigorous mathematical analysis of the problem of dispersion.

Hogstrom (1964) conducted a series of tests in which 30 second puffs of smoke tracer were released and photographically tracked downwind. From these experiments Hogstrom extracted horizontal and vertical diffusion parameters for puff releases.

Using these results he suggested (1972) that over a period of several puffs dispersion is made up of two terms (Figure 4.1). The first is the diffusion of each individual puff itself; the second is meander in the plume of the series of puffs in the large scale turbulence field.

Diffusion of individual puffs can be represented as σ_{yp} (horizontal) and σ_{zp} (vertical). Using these parameters it is possible to rewrite equation E4.1 which describes the standard P.G. Gaussian plume model given by equation E4.1 to represent the odour dilution ratio at a fixed point at any instant of time as

$$N_i = \frac{VoNo}{\pi u \sigma_{yp} \sigma_{zp}} \exp\left[\frac{-1}{2}\left(\frac{yi}{\sigma_{yp}}\right)^2 - \frac{1}{2}\left(\frac{Hi}{\sigma_{zp}}\right)^2 \right] \qquad \text{E4.3}$$

where

N_i = odour dilution ratio at receiver

V_o = source volume emission rate (cubic metres per second) (m^3/s)

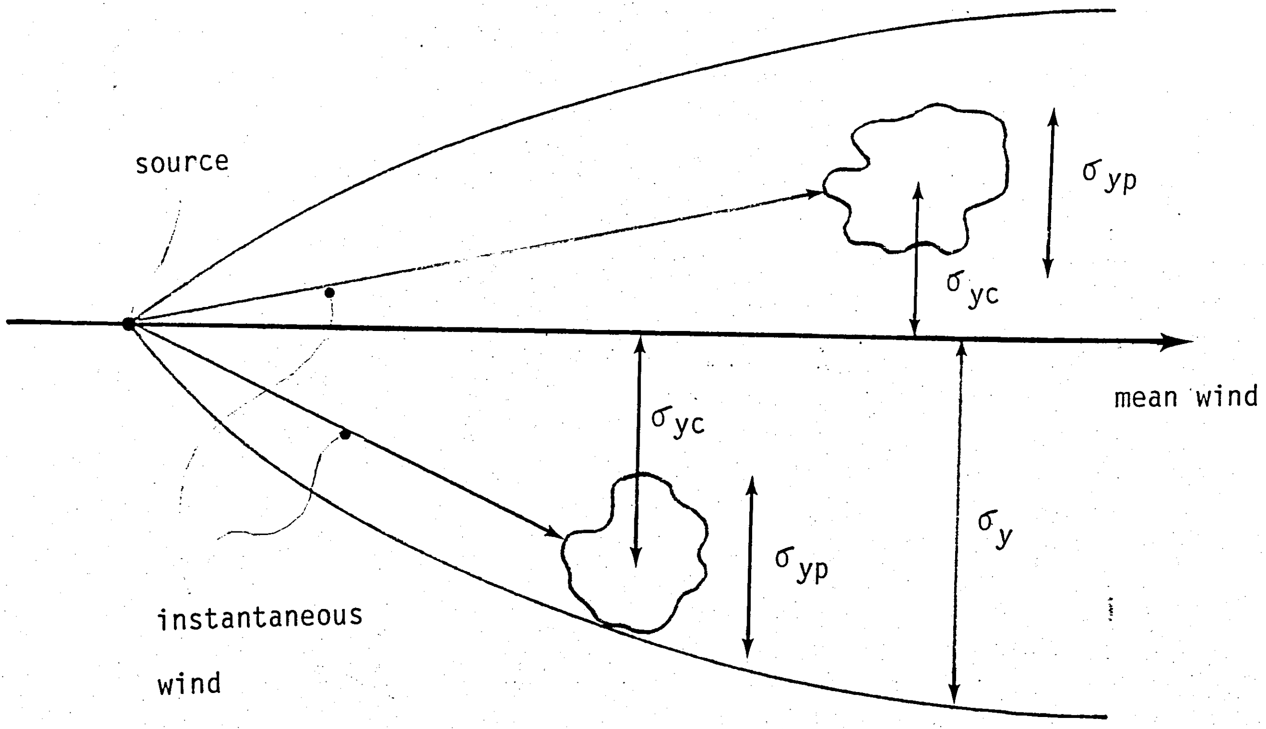
N_o = odour dilution ratio at source.

u = mean wind speed.

y_i = lateral distance of plume centroid from the receptor position at this instant (m)

H_i = vertical distance of plume centroid from the receptor position at this instant (m)

Figure 4.1. Puff dispersion parameters



$$F = \sum_{i=1}^{n} \frac{g_{\phi i}}{g_o} \frac{2\bar{y}\, f_i}{2\pi x} \qquad \text{E4.6}$$

where

f_i = frequency of the ith meteorological situation defined by stability and wind speed.

$\frac{g_{\phi i}}{g_o}$ = non dimensional measure of frequency of winds of direction ϕ +/- $\frac{y_i}{x}$

during those periods when the concentration width is $2y_i$.

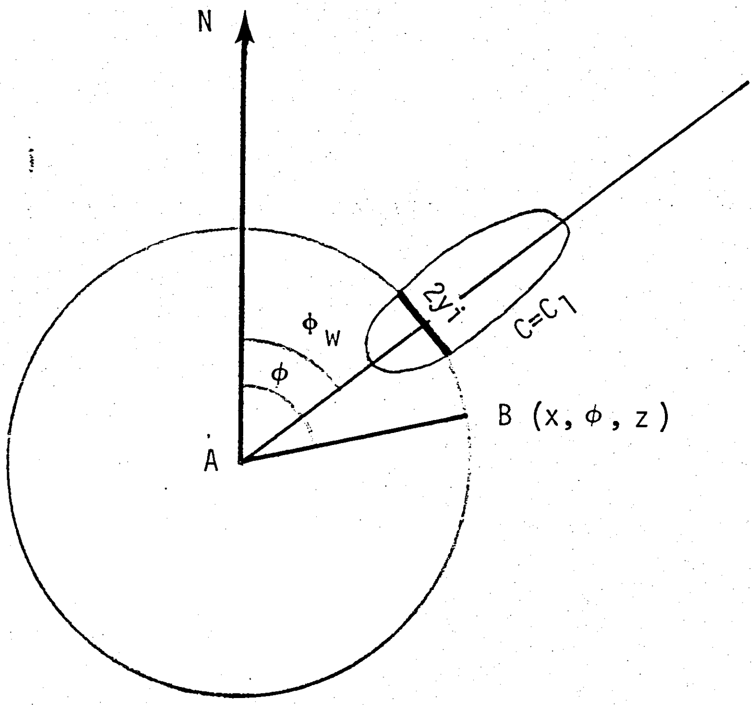
x = distance from source

$2\ y_i$ = width of instantaneous contour

$\bar{y}$ = weighted mean half width of contour.

See Figure 4.2 for an illustration of these terms.

Figure 4.2. Width of instantaneous odour contour



A = the source.

B = fixed measurement point with coordinates $x\ \phi\ z$

ϕ_W = wind direction during particular sampling period.

C = C_1, concentration C_1 contour at height z

$2y_i$ = instantaneous width of contour at fixed measurement point B.

The movement of the whole puff in the large-scale turbulence field may be pictured as the meander of the position of the centroid of mass of each puff as a series of puffs move downwind. This portion of dispersion is σ_{yc} and σ_{zc}. Hogstrom (1964) stated that the total mean dispersions σ_y and σ_z (as used in normal Gaussian dispersion models) are related by equations E4.4 and E4.5

$$\sigma_y{}^2 = \sigma_{yc}{}^2 + \sigma_{yp}{}^2 \qquad \text{E4.4}$$

$$\sigma_z{}^2 = \sigma_{zc}{}^2 + \sigma_{zp}{}^2 \qquad \text{E4.5}$$

Hogstrom (1972) gives the frequency of concentrations greater than a certain value by equation E4.6.

$$F = \sum_{i=1}^{n} \frac{g_{\phi i}}{g_o} \; \frac{2\bar{y}\ f_i}{2\pi x} \qquad \text{E4.6}$$

Equation E4.3 is solved for y_i to obtain the local instantaneous half width of the odorous area at ground level. This is integrated over a range of atmospheric conditions to obtain the weighted mean width for substitution in equation E4.6.

Using this mathematical model Hogstrom estimated the odour frequency distribution downwind of a pulp mill and compared the results with occurrences recorded by trained observers. Whilst the correlations between the predicted and observed Table 4.3 were good at short distances from the plant the method tended to under-estimate at greater distances.

Table 4.3. Comparison of predicted and observed odour frequencies (Hogstrom 1972)

Distance km	2	5	10	20
Total number of observations	6426	7490	5528	6976
No. of positive observations	696	736	470	360
Observed odour frequency (%)	10.8	9.8	8.5	5.1
Predicted odour frequency (%)	9.1	5.7	3.2	1.7
Ratio $\frac{\text{observed}}{\text{predicted}}$	1.2	1.7	2.7	3.0

Hogstrom considered that the discrepancies could arise for several reasons. These included:-

1) there was a chemical and/or physical change in the odorant which could have led to the lowering of the odorous threshold;

2) the model assumed a single source emitting at a constant rate. In reality there were two chimneys on the plant and there was some laboratory evidence to suggest that emissions had varied;

3) inaccuracies in the dispersion parameters which were derived from his earlier work (Hogstrom 1964). Although the model used empirically derived dispersion parameters they were only measured up to a few kilometres from the source and these had been extrapolated in the model up to distances of 20km.

Hogstrom considered that the most important weakness of the model was the assumption about dispersion behaviour in the vertical direction. It was quite possible that σ_z was different for ascending and descending air movements; probably being larger for ascending air. He calculated that for the most frequent meteorological conditions encountered in his field tests, i.e. slightly unstable air with a wind speed of 6m/s, that this factor could account for the discrepancy at 20km.

One point on which he did not comment was the continuity of the atmospheric stability over 20km. Over that distance it is possible that the stability could have been slightly different. If, for example, the atmosphere had been more stable 20km from the source then some stratification of the atmosphere could have reduced vertical mixing. This would mean that his dispersion parameters would have been different.

4) Hogstrom also considered the possibility that the discrepancy could have been caused by the fact that when concentrations are low, as in the case at large distances, observers tend to over-estimate the frequency (Lindvall 1970).

He also went on to argue that the discrepancies could be accounted for by a systematic over-estimation caused by anticipation. He estimated that the error was about 3-4% and that it was independent of distance. However, this appears to be at odds with his previous point that the greatest error occurs at the lowest concentration. Nevertheless his work indicated that it was possible to make quite realistic estimates of odour frequency up to 5km.

Murray (1978) and McCarthy (1980) developed the work of Hogstrom further. They simplified the model and used the atmospheric dispersion parameters published by Bowne (1974) which are reproduced in Figure 4.3, for dispersion rates in rural, suburban and urban areas.

In their model known as the TRC Odour Model (The Research Corporation of New England), the position of the puff centroids is generated from a normally distributed random number generator with a mean value corresponding to the mean wind direction. This permits the consideration of several puffs during the time period and allows the construction of a cumulative frequency distribution of dilution ratios for the chosen period. The

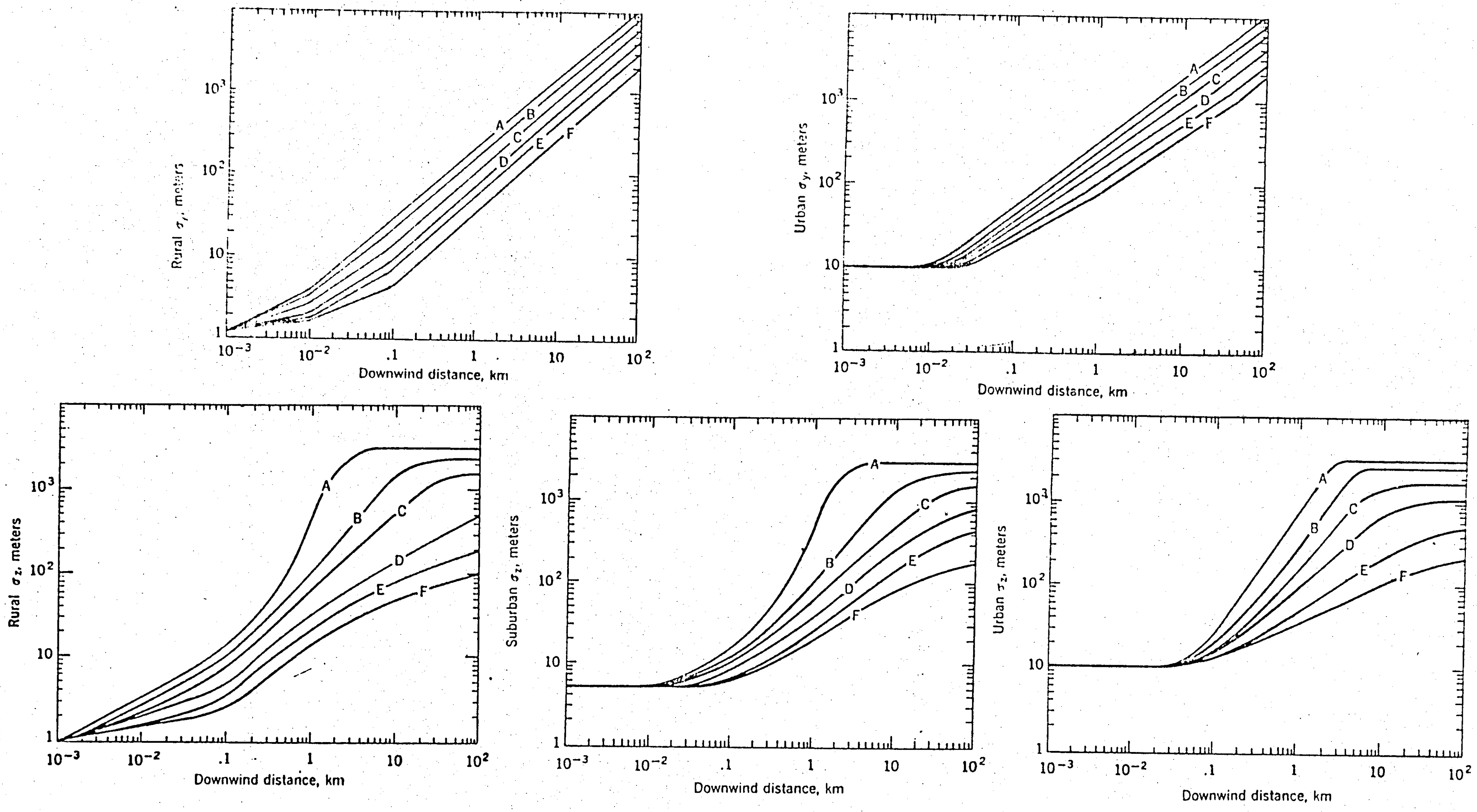


Figure 4.3 Bowne Diffusion Parameters

output from the model is the frequency distribution of specified concentrations. Table 4.4 shows a comparison between the observed and estimated maximum concentrations at ground level downwind of two industrial odour sources.

Other refinements in this model included the entrainment of the plume in the wake of a building and the ability to handle up to twenty simultaneously emitting sources and twenty receptors. Input parameters needed for each source include source strength, stack parameters, building parameters. Meteorological input required include wind speed and direction, ambient air temperature, atmospheric stability and surface characteristics (rural, suburban or urban area).

Table 4.4. Comparison between the estimated and observed maximum odour concentrations

Plant	Distance m	Maximum odour concentration estimated	observed
Spray dryer at	100	50	31
chemical plant (a)	300	2	2
Unspecified (b)	450	75	80
	830	10	<2

(a) McCarthy (1980) meteorological conditions unspecified

(b) Murray (1978) stable atmosphere 2 m/s wind

4.3. Summary

Two types of model have been developed to assess the dispersion of odours.

The first is a rather simplistic model based upon the Gaussian plume model for estimating concentrations of neutral and buoyant gases over periods of about 10 minutes downwind of a steady continuous source of emission. Even with empirical modifications to allow for the short term fluctuations of odour concentrations and the rapid response of the human olfactory system, this group of models can only provide limited information.

The second group of models is also based upon the Gaussian plume model but modified to describe the dispersion of puffs. Although more complicated to use, these models are considered to give more realistic results and better agreement with observations than the simple steady state approach.

5. THE CURRENT SITUATION

5.1. Odour Nuisance, Criteria and Control Regulations

Often, communities must endure exposure to offensive odours for longer than is necessary. The delay in abating the nuisance lies not in the available technology nor always the cost of abatement, but in assessing the need for and degree of abatement necessary.

The main problem is defining the smells and at what concentrations they become a nuisance. Tentative suggestions have been developed in the United Kingdom and in Europe mainly based upon considerable research carried out in the United States.

Before considering the situation in the UK and Europe, let us consider that in the United States.

5.1.1. United States Situation

According to Leonardos (1974) the Federal EPA considers that odours affect welfare but not health, and as a result has left the control of odours to the States and local agencies.

In his review of regulations for the control of odours in the United States he reported that over 200 State and local agencies have subsequently developed odour control regulations. These could be classified into approximately the nine different types listed in Table 5.1. These were essentially based on five technical papers published between the mid 1950s and the late 1960s. (Fox et al 1957, Huey et al 1960, Mills et al 1963, Anon 1966, Leonardos et al 1969.)

It is useful to consider these types of control regulations in greater detail as they provide an illustration of the current situation and a basis for developing new criteria for assessing odour nuisance.

a) No specific regulations

Where there are no specific regulations to odour control, odour problems are generally handled on a public nuisance basis, i.e. in the legal sense.

b) Air pollution/nuisance regulations

This philosophy is based upon the nuisance concept and codifies this concept into air pollution control rules and regulations. The intent is to control odours that are perceived to be nuisances by considerable number of people.

Table 5.1. Types of odour control regulations

---

a) No specific regulations.

b) Air pollution/nuisance regulations.

c) The use of certain criteria to determine objectionability of an odour in the ambient air.

d) Scentometer measurements by control officials in the ambient air by measuring dilutions to threshold (D/T). Violations occur if stated D/Ts are exceeded, usually within specified time periods.

e) The use of the highest and best practicable or reasonable and suitable control system is required at the source.

f) Source emissions standards specifying the concentrations (as dilutions to threshold or odour concentration units) of odour that are not to be exceeded. These are based on the syringe dilution technique.

g) Regulations based on instrumental analysis at the source or in the ambient air.

h) Control regulations that serve as statements of policy for handling odour problems.

i) Both source and ambient standards specified.

j) Ambient odour intensity.

An example of the wording used is given in the following extract from Florida's regulations. "Objectionable odour prohibited: objectionable odour defined as any odour ... that may be harmful or injurious to human health and welfare which unreasonably interferes with the comfortable use and enjoyment of life and property or which creates a nuisance."

c) Objectionability criteria

With this type of criterion an odour is deemed as being objectionable if a specified number of an assessment panel say so, e.g.

Wisconsin - "an odour shall be deemed objectionable when either or both of the following tests are met:

1. Upon the decision resulting from investigation by regulatory authority based upon the nature, intensity, frequency, and duration of the odour as well as the type of area involved and other pertinent factors;

2. Or when 60% of a random sample (consisting of at least 9 persons selected by the regulatory authority) of persons exposed to the odour in their place of residence or employment, other than employment at the odour source, claim it to be objectionable and the nature, intensity, frequency, and observation of the odour are considered."

Objectionability criteria for ambient odours can be traced to a mid-1960 study carried out in the St. Louis, Mo., area by the U.S. Public Health Service (Anon 1966). In that study, it was stated

> "Air quality goals for odours pertain to 'objectionable' odours. An odour is considered 'objectionable' when 15% or more of the people exposed to it believe it to be objectionable in usual places of occupancy. The sample size needed to determine the 'objectionable' quality should be at least 20 people or 75% of the exposed if fewer than 20 are exposed."

d) Scentometer based regulations

The seven agencies that have adopted the Scentometer approach to regulatory control of odour have set standards at the seven dilutions to threshold level, especially for residential-commercial areas (Table 5.2). Huey (1960) stated that "experience has been that odours in the ambient air above 7 D/T (dilutions to threshold) will probably cause complaints while those above 31 D/T can be described as a serious nuisance if they persist for any length of time." The attractiveness of using odour strength (as measured by dilutions to threshold) as the criterion to regulatory agencies appears to be that only one person need make the observation. Enforcement by the determination of a violation is therefore simple and inexpensive. Table 5.2 also indicates specific points in the

Table 5.2. States with regulations based on ambient odour limits

Table 5.2 : STATES WITH REGULATIONS BASED ON AMBIENT ODOUR LIMITS

STATE	TYPE OF STATE	AMBIENT ODOUR LIMITS[a]	FREQUENCY-DURATION CONSTRAINTS[b]	NO OF OBSERVERS	DILUTION DEVICE
		X			
Washington Ø	Residential	2	Yes	n.s.	Scentometer
	Other	32			
Colorado	Residential Commercial	7[c]	Yes	n.s.	Scentometer
	Other	15[c]			
	All Areas	127			
District of Colombia	n.s.	1	(separate complaints of 3 or more person required)		Scentometer
Illinois	Residential-Institutional	8)			
	Industrial	24)	Yes	3[d]	Scentometer
	Other	16)			
Kentucky	n.s.	7	n.s.	n.s.	Scentometer
Minnesota	Residential-Institutional	1 odour unit	n.s.	6-8	Syringe Dilution
	Light Industrial	2 odour units			
	Other	4 odour units			
Missouri	n.s.	7	Yes	-	Scentometer
Nevada[e]	n.s.	8	Yes	n.s.	Scentometer
Wyoming	n.s.	7	Yes	-	Scentometer

[a] Expressed as dilutions (1 part odour: X parts odour free air).

[b] Two observations to be made within 1 hour separated by 15 minutes.

[c] No violation if best practical treatment, maintenance and control currently available is utilized.

[d] Two positive determinations in each series of three determinations required.

[e] Also has objectionability criteria

n.s. Not specified

Ø In parts only

regulations concerning time constraints (how often and within what period of time the observations should be made), and the number of observers required to make the observations.

e) Highest and best practical control

Regulations that require controls on specific industrial sources are usually expressed in terms of an incineration or equivalent control standard. Table 5.3 summarises the states utilising the incineration or equivalent control approach, wholly or in part, the industries covered, and the minimal temperature and residence time required for incineration. Techniques other than incineration may be used to comply if it is shown to the satisfaction of the department that such techniques are equivalent or better than the required incineration in terms of control of odour emissions. These regulations generally prohibit the use of dilution and/or masking as control methods for odour.

f) Source standards based on sensory methods

Examples of the stack or source odour emission limits relying on sensory methods of evaluation are given in Table 5.4. All of these are based in part on the work of Mills (Mills et al 1963).

Table 5.3. States requiring odour control equipment

Table 5.3. STATES REQUIRING ODOUR CONTROL EQUIPMENT

STATES	INDUSTRY(ies)	PRETREATMENT	INCINERATION CONDITIONS	INCINERATION EQUIVALENT
Idaho	Reg. Q rendering	Condensation	$>1200^{o}$F, >0.3 sec	No
	Reg. K other	Techniques approved by the agency		
Maryland	Reduction of offal and veg.	Condensation $<160^{o}$F	$>1400^{o}$F, >0.4 sec	Yes
Minnesota	Rendering	No	$>1500^{o}$F, >0.3 sec	Yes
Montana	Rendering	No	$>1200^{o}$F, >0.3 sec	Yes
	Other	"Control devices as specified by the Director"		
North Carolina	All odours	Must use suitable control measures approved by the board		
Oregon	Rendering	Yes	$>1200^{o}$F, >0.3 sec	Yes
	Hardboard tempering oven		$>1500^{o}$F^{a}, >0.3 sec	No
	Other	Highest and best practicable treatment and control required		
Pennsylvania	16 processes	No	$>1200^{o}$F >0.3 sec	Yes
Vermont	Industrial processes	No	$>1600^{o}$F >0.5 sec	Yes
Wyoming	Rendering	Yes	$>1200^{o}$F >0.3 sec	Yes

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[a] May be lower if odours shown not to be perceived beyond property line.

Table 5.4. Source odour emission standards - by site

State	Standard	Method
Connecticut	<120 D/T	Mills (1963) ASTM
Illinois	<120 D/T[a]	Mills (1963) ASTM
Minnesota	<150 D/T[b]	Sampling and presentation
	<25 D/T[c]	ASTM D 1391-57,
	$<476\ m^3/s$[d]	panel test by Benforado.
		(1969)

a For inedible rendering only.

b For sources 15m (50 ft) or more above grade and adequate dispersion characteristics.

c For sources less than 15m (50 ft) above grade or otherwise failing to create good dispersion conditions.

d Odour emission rate = volumetric flow rate x odour concentration.

D/T Dilutions to threshold.

g) Analytical measurements at the source or in the ambient air

These types of regulations set maximum allowable emissions for odorous substances measured analytically at a well-defined point such as in a stack or vent.

Several state and local agencies have promulgated TRS (total reduced sulphur) source emission rules for the control of odorous emissions from the Kraft pulp mill industry (Table 5.5). Total reduced sulphides include such chemicals as hydrogen sulphide (H_2S), methyl mercaptan (CH_3SH), dimethyl disulphide (CH_3SSCH_3), dimethyl sulphide $(CH_3)_2S$ and any other organic sulphide compounds measured analytically as hydrogen sulphide. These are thought to be the major components associated with Kraft mill odours.

The limiting concentrations were designed to prevent downwind concentrations from exceeding odour threshold values under the most adverse meteorological conditions.

Analytical standards for ambient air have also been promulgated. An objectionable odour is deemed to occur when it can be demonstrated by analysis of the ambient air for any period of time that the recognition odour threshold concentration of any one of 53 listed odorant chemicals is exceeded. However, in the study which originally determined the recognition thresholds, Leonardos (1969), it was stated ...

Table 5.5. Comparison of rules and regulations to control odours from Kraft pulp mills

LOCATION	TOTAL REDUCED SULFUR RULE^{x}	RULE EQUIVALENT IN lb/TON PULP	SOURCE REGULATED	AVERAGING INTERVAL
Humboldt Country APCD	a) 0.012 (Stack height)^{y} lb/day or 60 ppm b) 0.8lb/ton dry wood 0.6lb/ton dry wood (1-1-75)^{z} c) 0.03 ppm-at ground level off premises d) No non-condensible stream over 60 ppm for over 30 min/day	a) 1.7lb/ton pulp (Crown)^{y} 1.4lb/ton pulp (L.P.)^{y} b) 1.6lb/ton pulp 1.2lb/ton pulp (1.1.75)^{z}	a) Any single point b) Total mill c) Total mill	a) One day b) One month c) One hour
Shasta Country APCD	a) 70 ppm 17.5 ppm (1-1-75)^{z} b) 2lb/ton pulp 1lb/ton pulp (1-1-75)^{z}	a) 2.0lb/ton pulp 0.5lb/ton pulp (1-1-75)^{z} b) 2.0lb/ton pulp 1.0lb/ton pulp (1-1-75)^{z}	a) Recovery furnace b) Any other source	a) Undefined b) Undefined
Bay Area APCD	a) 0.2 ppm)Mercaptans only 0.1 ppm) b) 0.1 ppm)Dimethylsulphide 0.05 ppm)only c) 0.06 ppm)hydrogen sulphide 0.03 ppm)at ground level	a) 0.005lb/ton pulp b) 0.003lb/ton pulp	a) Well-defined stack Any other source b) Well-defined stack Any other source c) Total mill	a) 15 mins b) 15 mins c) 3 mins one hour
Oregon (7-1-75)^{z}	a) 10 ppm-or-0.3lb/ton pulp 40 ppm 15 ppm-or-0.45lb/ton pulp b) 40 ppm-or-0.2lb/ton pulp c) Non-condensibles treated equivalent to thermal oxidation d) Lowest practical level	a) 0.3lb/ton pulp) 1.2lb/ton pulp)(7-1-75)^{z} 0.45lb/ton pulp) b) 0.2lb/ton pulp	a) Recovery furnace Recovery furnace Furnace stack b) Lime kiln c) Digester, multiple effect evaporator d) Any other source	a) One day One hour One day b) Undefined
Washington	a) 70 ppm-or-2lb/ton pulp b) 17.5 ppm-or)(7-1-75)^{z} 0.5lb/ton pulp) c) Non-condensibles treated equivalent to thermal oxidation	a) 2.0lb/ton pulp b) 0.5lb/ton pulp (7-1-75)^{x}	a) Recovery furnace b) Recovery furnace	a) One day b) One day
Alabama	a) 1.2lb/ton pulp	a) 1.2lb/ton pulp	a) Recovery furnace lime kiln, digester, multiple effect evaporator	a) Undefined
Florida	a) 17.5 ppm-or-0.5lb/3000lb of black liquor solids (7-1-75)^{z}	a) 0.5lb/ton pulp (7-1-75)^{z}	a) Recovery furnace	a) Undefined
Minnesota	a) 1.0 million odour units/min. b) 150 odour units c) 25 odour units	a) -0.003lb/ton pulp^{y} b) -0.04lb/ton pulp^{y}	a) Any source b) Any stack over 50ft c) Any other source	a) Undefined b) Undefined c) Undefined
Mississippi	a) 70 ppm-or-2lb/ton pulp b) Non-condensibles treated equivalent to therm, oxidation	a) 2.0lb/ton pulp	a) Recovery furnace	a) Undefined
Texas	a) 0.08 ppm-hydrogen sulphide at ground level off premises		a) Total mill	a) 30 mins
Virginia	a) 1.2lb/ton pulp	a) 1 2lb/ton pulp	a) Recovery furnace, lime kiln, digester, multiple effect evaporator	a) One day

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x TRS means hydrogen sulphide, methyl mercaptan, dimethylsulphide, dimethyl disulphide and any other organic sulphide compounds measured at hydrogen sulphide.

y Calculated for recovery furnaces only.

z Effective date of regulation.

> "the recognition odour thresholds reported in this study were developed under ideal laboratory conditions and are not recommended for air quality criteria and standards since no effort was made to define the degree of objectionability of the odorant chemicals."

In spite of this, two agencies; Connecticut and the Bay Area Air Pollution Control District (California) have adopted these data as part of their regulations.

h) <u>Control regulations that serve as statements of policy</u>

An example of regulations that appear to be statements of policy for handling odour problems can be seen in the following extract from Delaware's Regulation on Control of Odorous Air Contaminants.

"Section 1. General Provisions

1.1 The purpose of the Regulations is to control odorous air contaminants which significantly affect the citizens of the State outside the boundaries of the air contaminant source.

1.2 Methods for determining a condition of air pollution due to an odorous air contaminant may include, but are not limited to, Scentometer tests, air quality monitoring, and affidavits from affected citizens and investigators.

Section 2. Requirements

2.1 No person shall cause or allow the emission of an odorous air contaminant such as to cause a condition of air pollution."

i) Both source and ambient standards specified

Although some States have specified both source and ambient limits based on sensory methods, the ambient odour limits are unenforceable. The reason for this is that the specified measuring technique of syringe dilution is not sensitive enough for ambient odours.

At present the methods of measurement at source and in ambient air are different because of the relative concentrations. Thus, in practice, there is no existing regulation covering odorous emissions that can be related by sensory methods or analytically both at source and in the ambient air.

Because there can be both state and local regulations, some areas use a combination of the above nine types of regulations. For example, objectionability criteria are used prior to using the Scentometer, as illustrated in Table 5.6.

Table 5.6. Selected local agency ambient odour control regulations

SELECTED LOCAL AGENCY AMBIENT ODOUR CONTROL REGULATIONS

AGENCY	COMPLAINTS REQUIRED	OBJECTIONABILITY CRITERIA	VAPOR DILUTION METHOD	AMBIENT LIMITS
Polk Country Iowa	n.s.	Odour deemed objectionable by >30% of >30 people	Scentometer	7 D/T
Cedar Rapids Iowa	1	>30% of >30 people or >75% of <30 people	Scentometer or equivalent	Residential - 4 dilutions Industrial -20 dilutions Other areas - 8 dilutions
St. Louis Metropolitan Area Missouri	n.s.	>30% of >20 people or >75% of >20 people	n.s.	Residential - 0 dilutions Industrial -20 dilutions Other areas - 4 dilutions
Omaha, Nebraska	n.s.	Classified source[a] or substantial number of complaints	Scentometer[b] or Mills-ASTM procedure	Residential - 4 dilutions Industrial -20 dilutions Other - 8 dilutions
Chattanooga and Hamilton County, Tennessee	n.s.	>15% of >20 people or 3 people <20 people	n.s.	Residential - 0 dilutions Other - 4 dilutions
Milwaukee County Wisconsin	>3	Investigation or objectionable to >67% of at least 9 people		None

[a] "An odour will be deemed to be objectionable when the source of the odour has been classified as a producer of objectionable odours as designated Appendix B." 45.04.250.

[b] In event of dispute

n.s. - not specified

j) Ambient odour intensity

More recently it has been reported by Duffee (1985) that the state of Louisiana has adopted an odour regulation based upon ambient odour intensity. This regulation states that an ambient odour is a nuisance if it has a perceived intensity equal to or greater than the odour intensity from a number 6 port of the binary butanol olfactometer described in ASTM Method E544-75 (Supra threshold odour intensity measurement). A number 6 port has a butanol vapour concentration of approximately 500 ppm in an airstream flowing at a rate of 160 ml/min through a nasal port of 46 mm^2. According to Dravnieks and O'Neill (1979) this would correspond to an odour intensity of 'strong' (see Table 3.1).

As far as is known, Duffee (1985), this is the only odour nuisance regulation based upon ambient odour intensity. However the south coast Air Quality Management District has a category estimate scale for defining ambient odour nuisance. The "probable odour nuisance" category on this scale has been equated by Duffee to be port 4 on the same binary butanol olfactometer which has a butanol vapour concentration of about 120 ppm or easily noticeable according to Dravnieks and O'Neill (Table 3.1). On other category scales this would be equivalent to just recognisable or slight.

Chamber experiments conducted by W. Cairn (1979) indicated that for indoor odour levels associated with occupancy odour and cigarette smoke an acceptable odour level (for 20% of occupants) was an odour intensity of approximately 60 ppm of butanol vapour (port 3) measured by the binary olfactometer. In Table 3.1 this lies between faint and easily noticeable, i.e. equivalent to very slight to slight on the category scale. However this has been found to be too stringent when applied to external odours.

Duffee considered that odour intensity could be established as a community standard for odour nuisance.

Monitoring

Huey's (1960) work may be described as the Scentometer approach to odour control regulations and emphasised a measurement in terms of dilution to threshold in the ambient air by regulatory officials. Mill's influence, Mills (1963), resulted in the incineration or equivalent rule which has been directed primarily to the rendering industry. The 'highest and best practicable' control, approach (odour must be reduced or eliminated at the source) and to a much lesser extent in regulations for setting odour emission limits at the source.

Both Mills and Huey believed it was difficult to handle the question of quality of odour (as a descriptor or on a like/dislike basis) and relied exclusively on the threshold measurement with the aid of presentation systems to determine compliance. Other control authorities, e.g. Nevada, St. Louis and Omaha decided that it was inappropriate to ignore the objectionability (or like/dislike) aspect of odour and proceeded to incorporate it into their regulations.

Instrumental/analytical approaches for regulatory control of odour have also depended on the availability of threshold measurements of selected chemical compounds thought or known to be present in the odorous emissions of selected industries and the availability of instrumentation and analytical techniques to detect these components at the trace concentrations at which they produce an odour response.

While Leonardos (1974) considered that odour control regulations in the U.S. had had an effect in controlling odorous pollution, there was a lack of evidence in the literature to indicate the extent to which the existing odour regulations of whatever basis had succeeded in reducing complaints. He believed that the problem with existing odour control legislation could be stated in terms of the broader problem of how can odour be measured objectively and reliably.

Enforcement

At the present time in the U.S., virtually all enforcement of existing legislation for the control of odours relies on complaints by the public. However, as by definition nuisance normally involves a sizeable number of persons (the actual number depends on the size of the community affected). Officials often find it difficult to encourage inconvenienced persons to give evidence in court. As a consequence, the enforcement of the legislation is at best difficult. Odour complaints are not only unreliable but also insensitive as an indicator of where a problem may exist. Undoubtedly, the increased publicity given by the media to pollution in general has increased willingness to complain when in the past it may have not been reported.

5.1.2. United Kingdom Situation

In the United Kingdom there are no such regulatory controls or criteria for dealing with odour nuisance. Power to control odours is available to both local authorities and individuals but it is embodied in various acts of Parliament.

With the exception of the offensive trades provisions of the Public Health Act 1936, the public health legislation is concerned with abatement. In the main prevention is the concern of planning legislation. This can be effective in most cases except in situations where planning permission is not required by virtue of the Town and Country Planning (Use Classes) Order 1972.

Prevention

According to Artis (1984) prevention is achieved by the attachment of planning conditions to a planning approval for development or change of use.

"The type of conditions imposed fall into two categories.

a) Those in which the form of words used are based on the definition of "light industrial" use, i.e. Class III use under the Town and Country Planning (Uses Classes) Order 1972. This is generally referred to as a "no nuisance clause" and is imposed to protect the amenity of the locality. An example is that no noise, dust, grit, fumes or odours shall be emitted from the development which in the opinion of the local planning authority create a nuisance in the locality.

b) Those which require equipment to be installed, e.g. carbon filters, odour neutralisation plant, or plans for abatement of the odour to be submitted to the district planning authority for approval and implemented before a particular use may commence."

The advantage of controlling odours by planning conditions is that odours that are detrimental to the amenity of the area can be controlled even if they are not serious enough to amount to a statutory nuisance (see Section 2.1 for definition), which is what they would need to be, before they can be controlled by public health legislation. Enforcement of control is effective when it depends on a certain item of odour abatement being installed before a particular use commences. However, controls which require that there be an absence of nuisance, statutory or otherwise, are difficult to enforce as it may require establishing at law that a nuisance is being caused.

As mentioned earlier, there are no regulations available for controlling odours in the U.K. As a consequence there are no detailed numerical limits or criteria along the lines of those adopted in the U.S.

Generally what happens in the U.K. is that odour problems are dealt with by the local environmental health department (EHD). After having the matter brought to their attention the EHD will generally approach the offender on an informal basis to try to achieve abatement through cooperation often offering advice and assistance as to the methods of abatement. If this does not work then the offender is taken to court but this entails the EHD proving that the odour is a statutory nuisance. This is difficult to achieve in the absence of established criteria. What often happens is that the complainants are called as witnesses in support. However, many are reluctant to undergo this ordeal and sometimes through lack of support the EHD cannot proceed.

Some local authorities call upon the services of Warren Spring Laboratory or consultant air quality engineers initially to advise on the validity of complaints, if remedial action is possible and feasible engineering solutions. They may also be called upon to act as expert witnesses in support of legal action.

The Warren Spring Laboratory (WSL) (run by the Department of Trade and Industry) is this country's leading authority on matters relating to odour problems. After many years of research it has developed its own tentative guidelines on the likelihood of complaints from odour emissions. One such relationship from page 105 Anon (1980) op. cit is given in equation E5.1.

$$d_{max} = (2.2E) \uparrow 0.6 \qquad \text{E5.1}$$

a measure of the uncertainty being given by the range
$0.7E \uparrow 0.6 - 7E \uparrow 0.6$

where d_{max} = the maximum distance at which complaints are expected (m).

E = odour emission rate (m^3/s).

This relationship is based upon a limited amount of emperical data, mainly from emissions effectively at ground level. Some of the data were for chimney emissions but where the reported maximum distances of complaint were at least 40 effective chimney heights from the point of emission. WSL recommend that this relationship should not be used for emission rates in which the concentration is less than 500 dilutions to threshold. They also consider that the maximum distance of complaint is valid only if it exceeds 40 times the effective height of discharge.

It should be noted that this relationship says nothing about nuisance. In a survey of public attitudes to industrial odours carried out by Basarin and Cook (1982) it was found that only 0.5% of those annoyed actually complained.

A guideline (Anon 1980) op. cit. which is used to assess the possibility of annoyance is that of five dilutions to threshold in ambient air. At present this is calculated but Warren Spring have reported that they are currently developing an instrument to measure in this range (Anon 1980) op. cit. The origins of this value of five dilutions to threshold can be traced back to the work of Huey (1960) op. cit. whose work forms the basis of many Scentometer-based regulations in the U.S.

Warren Spring Anon (1980) suggest that ad hoc adjustments to the figure of 5 dilutions to threshold are necessary depending upon the unpleasantness of the odour. They say on page 9 "Expressed in terms of dilutions to reach the threshold value, the nuisance limit can be as low as 2, but a figure of 5 represents a reasonable compromise for offensive smells and about 10 for less offensive ones.". Because of the variation in readings between olfactometers (see Section 3), the WSL guidelines are specific to odour concentrations measured using a dynamic dilution apparatus of their own design.

Thus, although it is possible to relate a situation to past experience of annoyance using the WSL guidelines, the amount of reference material is extremely limited. Either it is a different type of odour, dispersion characteristics are different or the exposure frequency and duration are different. In the end, the Environmental Health Officer on the case is faced with making his own judgement as to whether a nuisance is statutory or not.

The existing situation is not satisfactory even when using the WSL guidelines. This is because ultimately it depends upon the judgement of an individual.

Artis (1984) states that action can also be taken by private individuals to prevent odour nuisance occurring under section 99 of the Public Health Act 1936 but they may not bring proceedings to the High Court.

Such action is rarely undertaken in practice because of the cost involved and the difficulty of proving nuisance. Even if individuals had access to records kept by public bodies, very few authorities keep such records mainly because they do not know how to quantify the problem.

Civil action can also be taken under the common law known as Tort of Nuisance in order to seek an injunction or damages. However, this is normally restricted to public nuisance and action by the local authority in the High Court; again to obtain an injunction.

Indirect legal controls

It is often possible for offensive odours to be controlled indirectly through various statutes other than Public Health Legislation. For example, if an odour is associated with a process that falls within the Alkali Etc. Works Regulations 1906 then there is a possibility of controlling the odour by ensuring that the process is conducted in a safe and effective manner in line with the requirements of the Act.

Likewise it may be possible to control some odours by controlling the emissions of smoke under the Clean Air Acts 1956, 1968. Similarly the Control of Pollution Act 1974 can be used to control odours by enforcing the requirements for controlled disposal of waste. Odours in the workplace can often be controlled by implementing the requirements of the Health and Safety at Work Etc Act 1974 and working within the Health and Safety Executive's guidelines on Occupational Exposure Limits (formerly Threshold Limit Values).

Similarly the Factories Act 1961 and the Offices, Shops and Railway Premises Act 1963 can be used to control certain odours indirectly through controlling ventilation to buildings.

5.1.3. The European Situation

In recent years there has been considerable activity in Europe in moving towards setting air quality standards for odours.

At a recent conference organised by the Verein Deutscher Ingenieure Anon (1986) in Baden - Baden it was reported that several countries are well advanced with implementation.

Netherlands

The responsibility for tackling odour problems in the Netherlands lies with the provincial and municipal authorities under the requirements of the Air Pollution Act and the Nuisance Act.

According to Wijnen (1985) research started in the Netherlands in the early 1980s to define air quality standards and guidelines for odours.

In areas where complaints had been received, community odour exposure was assessed by estimating the odour concentration with an atmospheric dispersion model using measured source odour emission rates.

The model developed by Voerman and Harssema (1984) is similar to that described by Hogstrom (1972) in that it estimates the percentage time that a certain odour concentration is exceeded. It makes use of the well known observation that in multiple source areas, air pollution concentrations are log normally distributed. This means that the frequency distribution is defined by only two parameters - the geometric mean and the geometric standard deviation. The same relationship is assumed for point sources.

In their study, community response was measured using social survey techniques. Population panels were also employed to measure community response, i.e.once a week, at a specified time, 80-100 people in the area made a note of their reactions to airborne odours outside their homes using the annoyance scale given in Table 3.5. Follow up surveys were also conducted after odour control measures had been installed in the offending industries.

After 18 months of investigation by the Ministry of Housing, Physical Planning and Environment, the University of Utrecht and TNO (the Netherlands Organisation for Applied Scientific Research) the estimated exposure was compared with the community response as in Table 5.7 to assess at what level the limit should be set. It can be seen that the reduction of odour emissions reduced the complaint or perception threshold. In other words, after control measures had been implemented complaints were made at a lower concentration than before. It can also be seen that complaints only disappeared completely at an average concentration of about 1 odour unit per cubic metre or at the odour detection threshold. It was concluded that odour complaints in residential areas could only be eliminated when the 99.5 percentile of hourly averaged odour concentrations over a year were reduced to the odour detection threshold.

From this work the investigators were able to derive two standards for inclusion in the Dutch Indicative Multiyear Programme to control air pollution 1985-1989.

Table 5.7. Odour concentration (odour units/m^3) in residential areas near to sources

	No. of companies	Complaints threshold		Perception threshold		Maximum in residential	
		98P	99.5P	98P	99.5P	98P	99.5P
Before control	28	4.7	7.9	1.2	2.4	13	23
After control with complaints	5	1.3	2.5	0.8	1.5	3.6	6.5
After control without complaints	6	-	-	0.25	0.5	0.7	1.1

P Percentile value

- Odour concentration standard

An interim limit value for odour concentration was published in 1984. For new installations this interim limit value in residential areas is 1 odour unit/m^3 (odour threshold) as a 99.5 percentile of the hourly averages over a year. The corresponding limit in non-residential areas is 1 odour unit/m^3 or the odour detection threshold as a 95 percentile of the hourly averages over a year. For existing installations in residential areas the limit is 1 odour unit/m^3 as the 98 percentile. These values were based upon the assumption that nuisance does not depend on the type of odour.

Enforcement and control takes place not by measuring the odour concentration in ambient air, but by calculation directed at the odour source with the aid of a nationally accepted dispersion model described above. Comparison of the maximum permitted odour emission calculated in this way with the actual emission, determines the degree of odour abatement necessary.

The financial consequences of introducing these standards into three branches of industry, considered representative for large, medium and small sources have been examined by Anzion (1974) but the findings were inconclusive. Wijnen (1986) reported that further studies into the financial implications were currently taking place.

- Odour annoyance standard

The study found that 2.5% of the population experiences annoyance in clean areas and that this figure will be used as a target value. However, in the short term, the limit value will be 5% of the population panel suffering annoyance. A draft limit standard was expected to be published in 1987.

The Dutch are taking an integrated approach to controlling odours and as part of the same Indicative Multiyear Programme they are also in the process of setting air quality and/or emission standards for some thirty odorous substances. According to Wijnen (1986) the only air quality limits set to date for specific substances are those for tri- and tetrachloroethene. These limits are reproduced in Table 5.8. Draft emissions standards for those two substances are being prepared in such a way that air quality standards will not be exceeded.

Zoning of odorous industries has also been used as a planning control to reduce the occurrence of odour nuisance.

In practice, the application of the odour concentration standard is encountering a number of problems. The odour emission of sources cannot always be easily sampled and emissions of short duration do not fit into the system.

Table 5.8. Draft air quality standards for tri- and tetrachloroethene

Substance	Annual average ug/m^3	98 percentile ug/m^3	99.5 percentile ug/m^3
Tetrachloroethene			
draft limit value	2000	8300	
draft guide value	1000		8300
target value	25		
Trichloroethene			
draft limit value	50	300	
target value	50		

West Germany

There are similar standards according to Juergens (1985) in West Germany where the odour threshold must not be exceeded for 97% of the time.

The Verein Deutscher Ingenieure (VDI) organisation has recently started publishing guidelines on odorants; covering odour emission control, dispersion, olfactory measurement techniques and control technology. Twenty-seven such guidelines are planned, seven of which deal with measurement techniques.

In the past, VDI standards have been adopted by the EEC, e.g. lead in petrol. If this happens with odours then there is a chance that such practices will be used in the United Kingdom.

A review of odour control legislation worldwide could be undertaken at this point. However, it was considered that this would detract from the theme of the current study.

5.1.4. Summary on Existing Legislation

A wide range of legislative controls have been identified. These include, not allowing certain processes to take place, specifying particular pollution control equipment at source, setting maximum odour emission rates and limiting maximum ambient concentrations or intensities. All of these can be assessed objectively or quantified. Those which relate to the source conditions are generally easiest to monitor, but not always without difficulty, particularly the short term emissions. However, it is open to dispute if the limits set are realistic both for those responsible for the odour and those affected by it.

Other less effective controls are those which specify words to the effect that "it is an offence to cause an odour nuisance". This type of legislation which is the basis of control in the U.K. is difficult to apply. It is difficult to monitor compliance with the legislation and to enforce because there is no criteria upon which to assess nuisance. Legal action taken to force abatement can be both a long and expensive process and as a result the public are generally unwilling to become involved.

5.2. Dose/Response Studies

There now follows a review of recent odour dose/response studies. This was included for two reasons. The first was to illustrate the current situation with regard to the types of investigations being carried out, the difficulties involved and the types of findings that have been reported. The second reason was to introduce field data, for use in testing the odour assessment model in Section 13.

Community annoyance due to odours has been studied primarily in Sweden, the United States and the Federal Republic of Germany. A series of Swedish studies beginning in the early 1960s (Friberg et al (1960), Cederlof et al (1964) and Jonsson (1974) have refined the techniques for the measurement of annoyance and were the first to suggest the use of such measurements to establish legal standards. The results also pointed to the risk of relying on voluntary complaints for enforcement purposes.

In the United States seven major studies of community odour problems have been completed since 1969. Four were in California - two in Eureka, one in Anderson and one in Carson City (Goldsmith 1973). These four studies focused on both annoyance and health aspects and indicated the existence of dose response relationships. The remaining studies of Coply International Inc. (1971) were conducted as a series to determine the social and economic impact of odours and to develop procedures for the identification and assessment of community odour problems. Similar studies have also been undertaken in West Germany and Canada.

It is worth considering these studies in some detail because they illustrate the current state of knowledge and provide useful sources of data against which the new odour assessment model is tested in Section 13.

5.2.1. The Goldsmith Study

The aim of the Goldsmith Study (Goldsmith 1973) was to investigate the health and annoyance impact of odours from pulp mills and refineries with the possibility of establishing air quality criteria for odorous materials.

Eureka is a coastal city in northern California with a population of about 30,000 (1972) located in an area in which the timber industry plays a major part in the economy. Just before the study was carried out in 1969 two paper mills were built on a peninsula to the west of the community. During part of the year, offshore winds carry odours from the pulp mills inland to residential and business areas of the city.

Three residential areas were chosen which had different exposures to the odours based on location with respect to the mills and prevailing winds. Area 1 was 1-2 miles south east of the mills, area 2 was 2-3 miles east of the mills and area 3 was located about 4 miles east of the mills.

Measurements were conducted to determine the odour exposure in each of the areas using a dynamic olfactometer similar to the one shown in Figure 3.7.

In order to sample the ambient air adequately, daily observations were made during three two-week periods in June, July and August. Two observers were exposed to the ambient air at representative sites in each of the three areas at half-hourly intervals during the day. The observers were driven around in a van to each of the monitoring stations in turn. At each location external air was drawn into the van through a dynamic dilution apparatus before being assessed over a period of about 1 minute. On each sampling occasion a record was made of whether the odour was detectable. If it was, then its concentration was measured and recorded.

A regular sampling protocol such as this ignored the wind direction. Consequently many of the observations were taken when the sampling location was upwind of the odour source.

The effects on the population were determined by social surveys. Between 55 and 60 households were chosen in each area by systematic random sampling, representing respectively one fifth of the households in area one, one third in area two and about half of the total households in area three. A member from each household was interviewed and completed an extensive questionnaire. The questions related to:-

1. The subject's background details.
2. Satisfaction with the general conditions in the residential area and the community.

3. Air pollution and noise problems in the residential area.
4. Effects of odours from the pulp mills.
5. The subject's attitude towards pollution and noise problems in general.

The dose/response surveys carried out in 1969 were repeated in 1971.

The most important results of the exposure and community response measurements are summarised in Tables 5.9 and 5.10. Note that the annoyance with odours from the pulp mill are expressed in terms of bother.

The results of 1971 survey (Table 5.9) showed that as in the 1969 survey, area 1 represented the area of greatest exposure to odour in terms of the frequency of occurrence. This pattern is repeated in terms of the 95 percentile of concentrations and average maximum concentrations for the 1969 survey. But in 1971 the gradient is less clear for the other two parameters.

The social survey results in Table 5.10 show a clear gradient of the percentage respondents bothered from area 1 through to area 3.

Table 5.9. Summary of Eureka study, odour exposure results, EUREKA 1969

EUREKA 1969

	area 1	2	3
%T	37.4	14.1	5.9
95 percentile of concentration +	6.9	3.9	1.0
Average maximum concentration +	31.6	12.9	3.4
Number of observations	564	846	1128

EUREKA 1971

	1	2	3
%T	19.5	6	13.3
95 percentile of concentration +	9.10	6.9	9.1
Average maximum concentration +	10.95	7.8	14.4
Number of observations	190	285	376

Notes

%T = percentage of observations greater than odour detection threshold
\+ = dilutions to odour detection threshold

The original data gave concentrations in terms of equivalent parts per billion of methyl mercaptan but these have been converted into dilutions to threshold using the recorded odour threshold of the observers to methyl mercaptan.

Table 5.10. Summary of Eureka study, community response results, EUREKA 1969

EUREKA 1969

% of respondents bothered

Amount bothered	area 1	2	3
Very much	28.8	23.6	5.9
Moderately	21.1	7.2	11.8
Little	23.1	23.6	17.6
Not or don't know	26.9	45.5	64.7
Number respondents	52	55	51

EUREKA 1971

Amount bothered	1	2	3
Very much	24.4	17.8	11.9
Moderately	37.7	20.0	16.6
Little	22.3	35.5	21.4
Not or don't know	15.6	26.7	50.0
Number respondents	45	45	42

The study concluded that "It should be possible to formulate a quantitative relationship between measurements of exposure to pulp mill odours and community reactions. Further refinements in methods and a larger number of observations representing a broader span of exposures are needed."

The dose/response study conducted in Carson City in 1972 followed a similar procedure to the Eureka studies, the main difference being that the odour sources in Carson were associated with oil refineries and other components of the petrochemical industry. In addition the study area was exposed to a general background of odour associated with Los Angeles air pollution including automobile exhaust. Questions were also asked concerning health reactions.

A summary of the most important results of the odour exposure and community response for the purposes of this report are given in Tables 5.11 and 5.12. The results of the measurement of exposure failed to differentiate between areas but there is a clear gradient in terms of the community response.

The Carson study (Goldsmith 1973) concluded that the measurement of exposure to odour made by dynamic olfactometry indicated that it was <u>not</u> a very useful method of measuring the exposure to community odours from multiple diffuse sources. Their analysis failed to find a correlation between dose and response.

Table 5.11. Summary of Carson City study, odour exposure results (1972)

	area 1	2	3
%T	100	100	100
95 percentile of concentration +	127	131	143
Average maximum concentration +	204	184	232
Number of observations	917	880	1190

Notes

%T = percentage of observations greater than odour detection threshold
\+ = dilutions to odour detection threshold

The original data gave concentrations in terms of equivalent parts per billion of methyl mercaptan but these have been converted into dilutions to threshold using the recorded odour threshold of the observers to methyl mercaptan.

Table 5.12. Summary of Carson City study, community response results (1972)

	% of respondents bothered		
	area		
Amount bothered	1	2	3
Very much	45	32	10
Moderately	15.5	27	14
Little	27	23	17
Not or don't know	12	17	59
Number respondents	97	95	99

5.2.2. The Copley Study

The Copley study (Copley 1971) was carried out to establish air quality, performance and emission standards that specify what levels of odours are acceptable and how such levels should be determined. The ultimate object of the research was to develop a method to assess the social and economic aspects of community odour problems. To accomplish this, four main test areas were established near a variety of sources to permit a comparison of the effects of odours having widely different qualities.

The test areas were in the Los Angeles Metropolitan area. The first was a community in Hawthorne near a major oil refinery and a chemical plant complex processing by-products from the refinery. The second and third areas were communities near two bakeries, one in Glendale, the other in Beverley Hills. The fourth test area was in Torrance in a community near a paint and varnish factory and a second oil refinery.

For each test area with high odour exposures was selected a control area with similar socio-economic status but with low odour exposure. Technical field exposure surveys and social surveys were carried out in each simultaneously in three two-week campaigns, in December 1970, March and June 1971.

Exposure Surveys

During the exposure surveys systematic measurements were made of the intensity, duration, frequency and temporal variation of odours in the community.

For the study, teams of 13-16 observers were selected by judgement panel tests and trained to recognise a scale of intensities given in Table 5.13 equivalent to the concentrations of tertiary dodecyl marcaptan in mineral oil.

Table 5.13. Intensity scale used in Copley study

Intensity	Equivalent concentration of solvent ml/l	Category value
Very Strong	8	4
Strong	2	3
Moderate	0.5	2
Slight	0.125	1
Very Slight	-	0.5

After training the panellists were assigned to certain locations in the community. Figure 5.1 illustrates the situation in Hawthorne in March 1971. There they recorded the maximum odour intensity in each minute, over a period of about 8 hours, including breaks, regardless of wind direction. Because the panelists' concentration became impaired after working in solitude for about an hour, a sampling schedule was introduced with recalibration periods to help maintain consistent observations.

Tables 5.14, 5.15 and 5.16 reproduce the results of the exposure surveys during the December, March and June campaigns in Hawthorne.

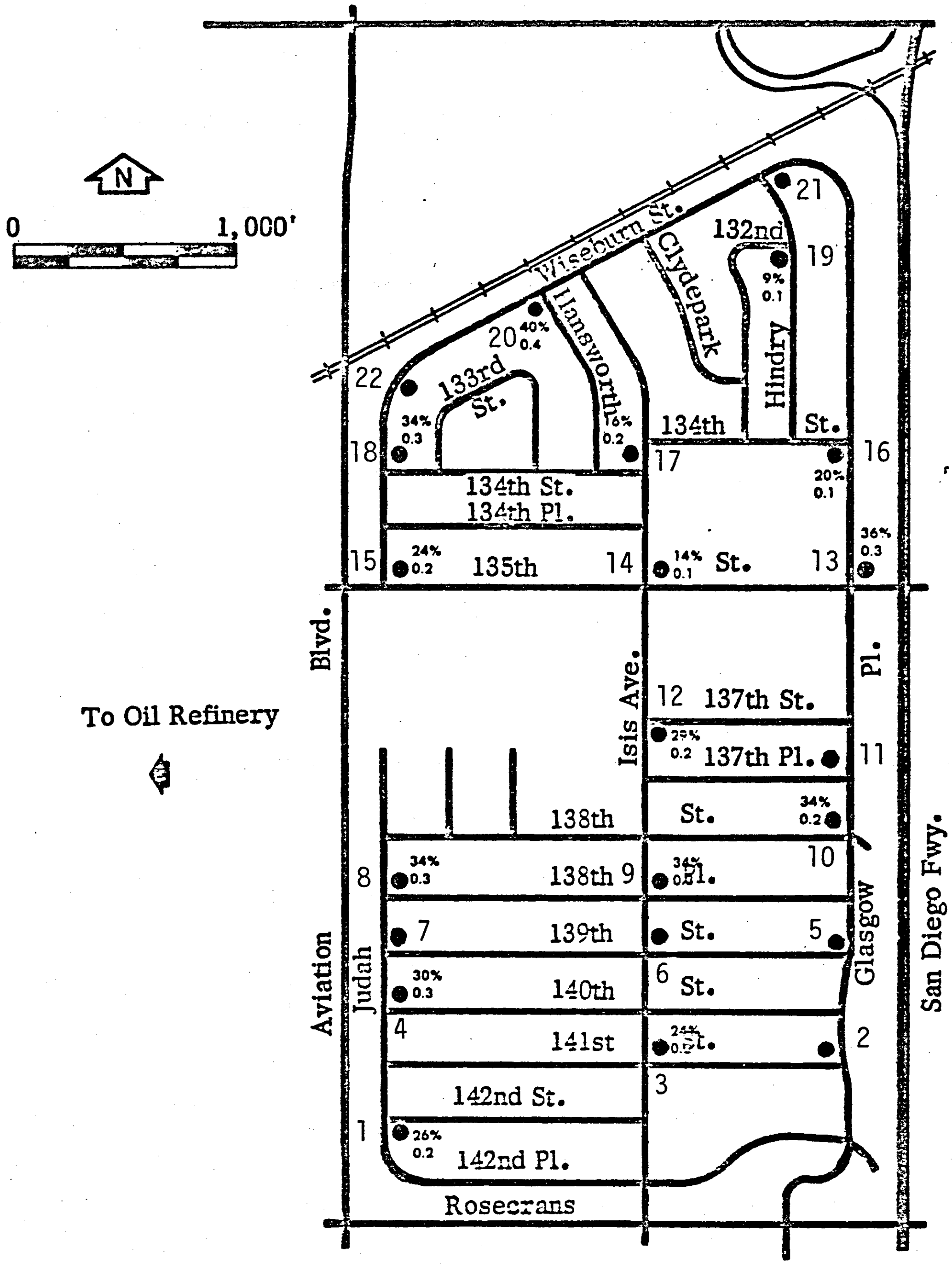
These data give the percentage of observations during which odour was detected and the average maximum intensity. They are used in Section 13 for testing the proposed odour assessment model.

Social Surveys

Social surveys were conducted by telephone rather than by face-to-face interview in order to generate data with greater efficiency and economy. The objectives were -

Figure 5.1. Location of odour monitoring stations in Hawthorne

March 1971



Percentage of time odour was detected and the mean odour intensity at panellist locations in TA(Hawthorne) during March 1971 technical field studies

Table 5.14 Summary of odour intensity obsesrvations, December 1970

Summary of December ratings in TA(Hawthorne).

No.	Panelist Location (Station)	Percent Time Detected and Mean Odor Intensity																			
		Date:11/30/70				Date:12/1/70				Date:12/2/70				Date:12/3/70				Date:12/4/70			
		AM		PM		AM		PM		AM		PM		AM		PM		AM		PM	
		%	M	%	M	%	M	%	M	%	M	%	M	%	M	%	M	%	M	%	M
1	142nd & Judah									36	.4	21	.1			39	.3		PANELISTS USED IN DEVELOPING ODOR PANEL/SCENTOMETER CORRELATIONS		
2	141st & Glasgow									26	.3	9	.1			0	0				
3	141st & Isis		PANELIST SCREENING AND TRAINING, NO FIELD ACTIVITIES				PANELIST SCREENING AND TRAINING, NO FIELD ACTIVITIES			26	.1	44	.5			0	0				
4	140th & Judah															9	.1				
5	139th & Glasgow									30	.3	40	.4			0	0				
6	139th & Isis									13	.1	41	.4			2	0				
7	139th & Judah									15	.2	11	.1								
8	138th & Judah									61	.7	32	.3			20	2				
11	137th & Glasgow									7	.1	46	.5			19	.2				
12	137th & Isis									55	.7	28	.5			20	2				
13	135th & Glasgow									19	.2	54	.6			26	.3				
14	135th & Isis									20	.3	68	1.0			2	0				
15	135th & Judah									100	1.4	45	.9			8	.1				
16	134th & Glasgow									55	.6	79	1.3			56	.6				
17	134th & Isis									47	.7	100	1.5			20	.2				
21	Wiseburn & Hindry									18	.2	23	.2			0	0				
22	Wiseburn & Judah									29	.3	50	.6			14	.1				

Table 5.15 Summary of odour intensity observations, March 1971

Summary of March ratings in TA(Hawthorne).

No.	Panelist Location (Station)	Percent Time Detected and Mean Odor Intensity																			
		Date:3/15/71				Date:3/16/71				Date:3/17/71				Date:3/18/71				Date:3/19/71			
		AM		PM		AM		PM		AM		PM		AM		PM		AM		PM	
		%	M	%	M	%	M	%	M	%	M	%	M	%	M	%	M	%	M	%	M
1	142nd & Judah	PANELIST SCREENING AND TRAINING, NO FIELD ACTIVITIES				20	.1	0	0	5	0	12	.1	60	.8	35	.3	16	.1	61	.5
3	141st & Isis					5	.1	48	.3	54	.3	13	.1	7	0	0	0	40	.3	22	.1
4	140th & Judah					16	.1	27	.3	32	2	0	0	33	.4	23	.2	46	.6	65	.8
8	138th & Judah					32	.2	65	.4	11	.1	9	.1	49	.4	17	.1	19	.1	67	1.1
9	138th & Isis					98	1.1	16	.1	44	.4	0	0	42	.3	30	.4	32	.3	11	.1
10	138th & Glasgow					38	.3			19	.1			87	.5	27	.2	11	.1	42	.3
12	137th & Isis					47	.4	5	0			15	.1	41	.3	0	0	62	.4	63	.4
15	135th & Judah					19	.1	0	0			0	0	21	.1	12	.1	56	.4	60	.3
14	135th & Isis							22	.2			0	0	6	.1	23	.2	10	.1	23	.2
13	135th & Glasgow					60	.8	62	.7	16	.1	23	.2	58	.5	39	.2	28	.2	0	0
18	134th & Judah									7	.1	58	.6	25	.2	11	.1	16	.1	90	.7
17	134th & Isis					3	0	21	.2	0	0	2	0	6	0	94	.95	2	0	4	0
16	134th & Glasgow					27	.2	40	.3	0	0	0	0	13	.1	11	.1	48	.3	23	.1
22	Wiseburn & Judah					100	1.1	57	.6												
20	Wiseburn & Hansworth					28	.1	39	.4	61	.5	28	.1	41	.3	11	.1	86	1.2	23	.2
19	132nd & Hindry					12	.1	25	.2	0	0	0	0	0	0	16	.1	20	.1	0	0

Table 5.16 Summary of odour intensity observations, June 1971

Summary of June ratings in TA(Hawthorne).

No.	Panelist Location (Station)	Percent Time Detected and Mean Odor Intensity																			
		Date:6/14/71				Date:6/15/71				Date:6/16/71				Date: 6/17/71				Date:6/18/71			
		AM		PM		AM		PM		AM		PM		AM		PM		AM		PM	
		%	M	%	M	%	M	%	M	%	M	%	M	%	M	%	M	%	M	%	M
1	142nd & Judah		PANELIST SCREENING AND TRAINING, NO FIELD ACTIVITIES			8	0	11	.1	1	0	0	0	89	.6	0	0	0	0	0	0
3	141st & Isis					16	.1	3	0	10	.1	8	0	0	0	5	0	16	.1	2	0
4	140th & Judah																				
8	138th & Judah																				
9	138th & Isis					38	.2	1	0	1	0	20	.1	0	0	0	0	0	0	0	0
10	138th & Glasgow					36	.3	30	.2	1	0	40	.3	0	0	32	.5	5	.1	0	0
12	137th & Isis					41	.3	27	.1					5	0	12	.1	7	.1	100	1.3
15	135th & Judah					16	.1	33	.3	100	1.5	39	.3	52	.6	49	.5	41	.4	33	.3
14	135th & Isis					51	.6	11	.1	0	0	35	.4	12	.1	33	.3	28	.2	19	.1
13	135th & Glasgow					66	.9	4	0	15	.1	0	0	32	.4	9	.1	5	0	17	.1
18	134th & Judah					56	.4	32	.3	11	.1	92	1.6	37	.3	90	.8	7	.1	10	.1
17	134th & Isis					51	.5	82	1.1	28	.2	46	.6	23	.1	26	.3	10	.1	34	.5
16	134th & Glasgow					60	.5	3	0	48	.6	49	.5	8	0	31	.3	23	.2	12	.9
22	Wiseburn & Judah					22	.3	78	.4	28	.2	15	.2	9	0	100	.6	67	.8	40	.4
20	Wiseburn & Hansworth					100	1.7	10	.1	25	.2	9	.1	1	0	44	.3	12	.1	27	.2
19	132nd & Hindry					84	1.3	52	.5	29	.2	8	0	7	0						

1) to gather data on public attitudes towards noticable odours
2) to obtain an estimate of the existence and severity of community odour problems
3) to define the type and degree of social and economic effects odours have on residents and their property.

A summary of the more interesting results from each of the quarterly surveys in Hawthorne are given in Table 5.17 and Table 5.18. Unfortunately the corresponding results for the other areas were not published.

Generally those bothered by odours indicated that this occurred very often or often. An overwhelming proportion (86%) of respondents bothered by odours said it was the strength of the oil refinery odour that bothered them most. Only 7.1% of respondents considered the length of time to be the most annoying factor followed by the number of times noticed 4.9%.

The study was unable to demonstrate that odours caused an economic effect on the price of homes. However there was some subjective evidence to suggest that odours had caused economic loss for at least three industrial concerns. While these losses could not be quantified they were apparent in terms of increased absenteeism and lower productivity of employees.

Table 5.17 Summary of the degree of bother caused by odours in the Hawthorne area

degree of bother	% of total number of respondents December		March		June	
	test area	control	test area	control	test area	control
Very much	25.2	12.0	34.7	24.0	34.6	14.7
Much	10.7	4.0	9.3	10.0	14.6	4.0
Moderately	21.4	26.0	14.7	16.0	18.7	10.7
Little	1.3	2.0	2.7	2.0	2.7	1.3
Very Little		10.0			4.0	
Not told	41.4	46	38.6	48	25.4	69.3
number of respondents	75	50	75	50	75	75

Table 5.18. Summary of what bothered Hawthorne respondents most about odours

	% of respondents that are bothered December		March		June	
	test area	control	test area	control	test area	control
number of times noticed	11.4	3.7	4.4	3.9	1.8	4.4
strength of odour	77.3	88.9	78.2	92.2	89.3	95.6
duration	6.8	7.4	17.4	3.9	7.1	
don't know	4.5		-		1.8	

The study went on to develop a possible assessment procedure for identifying odour problems by considering odour complaints, area extent, frequency, duration, intensity and temporal variation of odour perception, the influence of meteorological conditions and the results of the community odour exposure and social surveys.

The use of complaint data was rejected in favour of public attitude surveys because it was thought that the complainants did not necessarily represent the typical person in the community. In applying public nuisance law in California the basis for decision rests not solely with the feelings of the population in an odour affected area, but in a comparison of their attitudes with an equivalent social class population in an odour free, control area.

Upon completion of public attitude surveys in matched test and control areas, odour problems are identified by applying "z" statistics. A 95 percent level of confidence ($z. \geqslant 1.65$) that more test area respondents than control area respondents are bothered by odours is required before an odour problem is said to exist.

To simplify the requirements for odour problem identification it was suggested that public attitudes in one odour free area were very similar to those in another with the same socio-economic background. As a result one could eliminate public attitude surveys in control areas as the data already existed from their study.

The study also suggested that a reduction in effort in surveying the test areas could be made through sequential analysis. By this system one of three decisions can be made.

1) that an odour problem exists or
2) that an odour problem does not exist or
3) The results are inconclusive and that an additional interviewer must be completed.

Using this method it was found that an odour problem existed in the Hawthorne test area after reviewing only seven questionnaires in chronological order instead of the 75 questionnaires needed to complete the social survey initially.

An attempt was made to correlate the data obtained from the odour judgement panels with information collected during public attitude surveys in order to establish dose/response relationships. However the way the data was analysed the study failed to find a conclusive relationship. (This point will be discussed in Section 13).

More recent examples of dose response studies undertaken are those by Winneke and Kastka (1977), Winneka and Kastka (1987) and Gnyp et al (1985).

5.2.3. Studies by Winneka and Kastka

Between 1974 and 1977 Winneka and Kastka (1977) were conducting laboratory and field studies designed to develop odour control legislation for the Federal Republic of Germany.

As their starting point they adopted the findings of the Copley Study and recognised that "the only measurable impact associated with a vast majority of odour problems was annoyance, and that a proper means for dealing with such problems must consider the measurement of annoyance as central to success".

As a result Winneka and Kastka felt it necessary to study the psychological structure of odour annoyance; to establish the reliability of annoyance reactions and to validate annoyance scores:

1) by comparing a known problem area with a comparable control area
2) relating degree of annoyance to distance from the source
3) relating annoyance scores to odour concentrations in ambient air as measured by dilutions to threshold.

The first step was to construct a structured questionaire consisting of 40 rating scales dealing with perception of environmental odours. This was tested on 704 subjects drawn at random from three areas. The first was an odour problem area near a detergent and soap works. The other two areas were odour free control areas close to a glass works and a steel mill.

A full statistical analysis of the results showed that there was a clear item structure in the replies to the questions. These could be aggregated under three main factors. The first factor related to those questions about the sensory aspects of perception i.e. its intensity, frequency, quality etc. as well as formal statements of being annoyed or bothered by odours.

The second factor or group of questions dealt mainly with social and emotional effects of perception (e.g. "I feel ashamed of inviting friends to my house"). The third factor contained primarily those items which could be described as somatic reactions to odour perception (e.g. odours cause headaches, nausea, sleeplessness etc.).

These three dimensions of odour annoyance i.e.

Sensory (F_1)

Social-emotional (F_2) and

Somatic F_3

accounted for 50, 23 and 24% of total variance corresponding to the 0.001 level of significance for 702 degrees of freedom.

The stability of these composite annoyance scores over time was tested by conducting follow-up studies on sub-samples of the original samples, i.e. 87 subjects in the polluted areas and 37 subjects in the control areas. It was found that the ratio of polluted to control area annoyance for all three annoyance measures in 1974/75 and 1974/76 agreed, at the 0.05% level of significance.

Further tests were conducted by Winneka and Kastka (1987) near other industrial plants with odour problems. The sources investigated included a coal-tar oil plant, an insulation plant, chocolate factory and a Brewery. The object was to relate the measured annoyance to the distance from the source and to odour exposure data in terms of odour concentration.

Ambient odour concentrations were measured at various distances downwind of the source using a mobile laboratory equiped with an olfactometer serving an odour panel of four. The complete threshold value determination took about 20 minutes ie 10 dilutions each of about two minutes duration.

Direct face to face interviews were also conducted by instructed interviewers and 97 (brewery), 108 (chocolate factory), 108 (insulation plant) and 270 subjects (tar oil refinery) were sampled around the four plants.

A summary of the results obtained can be seen in Table 5.19.

Winneka and Kastka found that the composite annoyance scores related to distance from the source as well as to quantitive odour exposure data and concluded that odour control might eventually progress if these relationships turned out to be related in a meaningful way.

Table 5.19

Summary of odour annoyance and concentrations at various distances from four different industrial odour sources

DISTANCE (m)	TAR OIL PLANT				INSULATION PLANT				CHOCOLATE FACTORY				BREWERY			
	CONCENTRATION	ANNOYANCE			CONCENTRATION	ANNOYANCE			CONCENTRATION	ANNOYANCE			CONCENTRATION	ANNOYANCE		
		1	2	3		1	2	3		1	2	3		1	2	3
		{5.4	3.2	2.4												
10	16	{5.6	3	2.2	16											
25	14	6.3	3.3	3.0					25							
50	14				↑				25	4.7	1.8	1.6	↑			
60					14				↑	4.5	2.1	1.4				
75																
90																
100					12				13	3.3	1.0	0.5	8	5.8	3.4	3.0
115																
125						4.5	2.8	1.2		4.6	1.8	0.8				
130	14				10	6.8	4.2	3.9								
140																
150					↓				↓				↓	5.0	2.3	2.1
190	13	5.8	2.8	3.0		6.6	4.5	4.2								
200									↑							
240	13 ↑				9 ↑	5.3	2.3	1.8								
250														4.7	2.8	2.3
265		6.6	3.5	3.5												
300		6.5	3.5	2.7		5.0	2.3	2.0								
310																
340		6.2	3.6	2.8	7.5				2							
350	16									2.5	0.8	0.5				
400						3.8	2.2	2.0								
410	38				5.6											
425										2.0	0.6	0.4				
450		5.8	3.3	3.0												
470		5.9	3.5	3.0												
500	20 ↓	5.7	2.9	2.6	↓				↓							
600		6.4	2.6	3.3												
700	19															
800		4.5	2.9	2.2		4.1	2	1.2								
1200		5.4	3.0	2.4												
1400	18															
1600						1.6	1	0.2								

It was also demonstrated that the degree of annoyance produced by chocolate factory odours was significantly lower than those produced by other industrial sources of comparable ambient odour concentrations. These differences could not be explained by socio-economic differences between subjects. The data suggested that annoyance was source specific and this was probably due to the hedonic quality of the odorant.

This hypothesis was supported by the finding that intensity rating of ambient odours tended to exhibit a closer association with annoyance data than measured concentration (Winneka and Kastka 1984).

5.2.4. Studies by Gnyp et al

Gnyp, Pierre and Poostchi (1985) have reported on their study to assess the impact of odorous emissions from municipal land fill sites on the surrounding community.

The subject of their study was a land fill site located less than one kilometre from a mobile home park. It had had a long history of causing frequent complaints, although many of these complaints had been validated by independent investigations by members of the Municipal Engineering Department, no regulatory action was taken until the operators of the site sought approval for an extension to within 200 metres of the mobile home park. Legal hearings triggered the need for the study, to obtain an objective assessment of the community odour problem.

The aims of Gynp et al were to:

1) develop procedures for establishing the validity of spontaneous odour complaints
2) obtain on objective measurement of community annoyance
3) find relationships between odour levels and annoyance thresholds

The perception of odours by the community was assessed using public attitude survey techniques, special care being taken to control bias and to avoid creating negative attitudes.

The objective of these surveys was to establish the hedonic tones of twenty six commonly encountered odours on the basis of individual experiences or prejudices of the people in the community and to compare their reactions to odours with those of individuals in other communities, i.e. test the sensitivity of the affected community to odours in general. Other neighbourhoods included in the study, were areas near a fast food restaurant, municipal waste treatment plant, a car paint workshop, a foundry as well as the land fill site. A shopping mall was selected as a control area.

(This is the only survey known to the author, of an assessment of hedonic tones by the community.)

It was found that there was a good agreement between the hedonic ratings given to the 26 odours by the different communities and the control group. This suggested that the residents in the neighbourhood of the land fill site were no different from any other group in their rating of the unpleasantness of odours. As a result it was concluded that their spontaneous complaints could be regarded as honest reactions to offensive odours.

Dose reponse measurements were also assessed. Odour samples were taken from the land fill site and presented to an odour panel via a six level forced triangle dynamic dilution apparatus.

The subjects were asked to identify the ports which were perceived to be emitting odours. Panellists were also required to specify the level at which they were positive about the presence of the odour. In addition the panel members were provided with a preprinted form on which they were asked to indicate at which dilutions (concentrations) they would complain if they were exposed to similar odours for a period of eight hours and to rate the degree of annoyance at each level on a scale ranging from 0 to 10. No annoyance was 0 and maximum annoyance was 10.

Gnyp's results are summarised in Table 5.20.

From these data it was suggested that a possible acceptable standard for a community experiencing odours, which would satisfy 80% of the population in the sense that they would not

Table 5.20. Summary of odour dose and response reactions near four different sources

SOURCE	CONCENTRATION D/T	THRESHOLD RATIO $^{d}/_{d}$	THRESHOLD RATIO $^{d}/_{c}$	MEASURED ANNOYANCE	REACTION	% DETECTING	% COMPLAINING
LAND FILL WELL THRESHOLDS (10000=$^{d}/d$, 2000=$^{d}/c$ for 50% pop)	18000	0.55	0.11	1.0	TOLERABLE	30	24
	10000	1.0	0.22	1.7	TOLERABLE	50	30
	6000	1.7	0.33	2.2	UNPLEASANT	66	37
	2000	5	1	2.9	UNPLEASANT	87	50
	1000	10	2	4.6	VERY UNPLEASANT	92	66
	300	33.3	6.7	7.0	TERRIBLE	100	87
FOUNDRY THRESHOLDS (1000=$^{d}/d$, 800=$^{d}/c$ for 50% pop)	1000	1	0.8	1.5	TOLERABLE	50	34
	500	2	1.6	3.6	UNPLEASANT	86	86
	170	5.9	4.7	6.0	VERY UNPLEASANT	100	100
	60	16.6	13.3	8.0	TERRIBLE	100	100
PAINT WORKSHOP THRESHOLDS (120=$^{d}/d$, 85=$^{d}/c$ for 50% pop	120	1	0.7	2.0	TOLERABLE	50	34
	60	2	1.4	3.6	UNPLEASANT	77	77
	20	6	4.3	6.4	TERRIBLE	88	88
WASTE WATER TREATMENT PLANT THRESHOLDS (300=$^{d}/d$, 240=$^{d}/c$ for 50% pop	300	1	0.8	0.8	TOLERABLE	50	36
	160	1.9	1.5	1.8	TOLERABLE	87	74
	55	5.4	4.4	3.2	UNPLEASANT	100	87
	20	15	12	4.4	VERY UNPLEASANT	100	100

Foot Notes

$^{d}/d$ = dilutions to detection threshold

$^{d}/c$ = dilutions to complaint threshold complain, were upper limits of 34% probability of detection and a degree of odour annoyance of one. In this study the borderline between tolerable and unpleasant was an annoyance of about 2.

Table 5.21 summarises the range of annoyance associated with each level of reaction.

Table 5.21. Range of annoyance associated with different levels of reaction

Reaction Category	Range of annoyance
Tolerable	0.8-2.0
Unpleasant	2.2-3.6
Very unpleasant	4.4-6.0
Terrible	6.4-8.0

The reaction descriptions suggest that tolerable is just acceptable, any higher then is unacceptable or a nuisance.

The upper limit of tolerable and lower limit of unpleasant lies between 2.0 and 2.2.

5.2.5 Summary to Dose/Response Studies

Four major dose/response studies have been reviewed. The aim of each was to establish procedures and criteria for assessing community odour problems.

The first was by Goldsmith in California where extensive surveys were conducted near pulp mills and refineries. Dose/response data was published for two areas, with one area being repeated the following year. The second study was by the Copley organisation which conducted extensive tests near oil refineries, chemical plants, bakeries and near a paint and varnish factory. Unfortunately only complete dose/response data were published for an area near an oil refinery and an equivalent background/reference test area. However, results were given for three separate campaigns spread over a 6 months period. Research undertaken by Winneka and Kastka in West Germany near a tar oil plant, an insulation works, a chocolate factory and a brewery is the third example of dose/response studies. The Gynp study which was primarily concerned with land fill odours is the fourth study reviewed. This latest study also reports observations of annoyance caused by odours from a foundry, a paint workshop and a waste water treatment plant.

These four studies provide an insight into the types of investigations undertaken and the difficulties involved. They also provide basic dose/response data for use later.

6. POSSIBLE WAYS FORWARD

The consensus of opinion of those concerned with basic odour control technology at the Stockholm Symposium on the methods of evaluating odorous air pollutants at the source and in ambient air, (Anon 1970) op. cit. was that a given odour sensation may be generally described by four main "dimensions". These are pervasiveness of the substance, its intensity at suprathreshold levels, the quality or characteristic properties which distinguish one odour from another regardless of intensity or acceptability, and the acceptability or stimulation of annoyance or pleasurable reactions. This opinion was restated in "Odours from Stationary and Mobile Sources" by The Assembly of Life Sciences National Research Council (Anon 1979).

The Stockholm Symposium also concluded that in environmental health, the most important dimensions of an odour was that of acceptability, e.g. what percentage of the population is annoyed by the smell. The acceptability of an odour is probably due in part to the intensity, quality, frequency and duration as well as the conditions under which the exposure occurs.

In addition it was reported that it had not been possible to establish a quantitative objective measure of acceptability or the degree of annoyance by chemical or sensory methods of analysis. It was thought that public reactions of subjective annoyance could probably best be evaluated by sociological inquiry methods. The response could then be related to the degree of exposure to odorous air pollutants to which the population was exposed (the dose).

It was noted that in many cases, classical absolute threshold determinations were used to obtain a measure of the intensity with which an odorous substance was experienced. These undeniably provided valuable information regarding the control of odour, but they do not give any measure of the perceived intensity above threshold levels. It is impossible to establish a general fixed sensory threshold for a particular individual since a real threshold in the usual sense probably does not exist but rather there is a gradual transition from total absence to definitely confirmed odour impression. Some methods of detection are based on the assumption that the momentary threshold varies from time to time and that this variation is normally distributed. The modern detection theories deny even the existence of a momentary sensory limit value and base their indices of detectability on a supposed individual's probability evaluation using the techniques described in Section 3.

Leonardos (1974) also concluded that threshold determinations either at the source, in the ambient air or on specific chemicals were of doubtful significance in measuring the intensity dimension of odour problem.

The Copley study (Copley 1971) recommended that "the measurement of annoyance due to odours ... would serve as a convenient indicator of the existence of undesirable effects and, thus, would provide a basis for deciding whether or not a violation exists. Its adoption would tend to focus technological controls on the annoyance threshold rather than the odour threshold and, thus, would promote more efficient solutions in light of the societal consideration that the added cost of control should equal the added benefit derived from that control."

According to Leonardos (1974) the concern with odour measurement techniques utilised in the field of air pollution and upon which the regulations were based is that they measure only one aspect of the four dimensions that the Stockholm symposium (Anon 1970) had identified as being of critical importance from the standpoint of air quality. He concluded that odour measurement for pollution purposes must include, in addition to "threshold", an assessment of the intensity and the quality of the odorous sensations. He believed that these dimensions would be measured effectively by calibration of the instrument - the human and his nose - by the use of appropriate reference standards both for intensity and quality. With more information on these three dimensions, the acceptability of an odour could then be inferred from a consideration of all three dimensions (concentration, intensity and quality) and from none taken alone.

Preferably, these three dimensions should be correlatable to the acceptability or annoyance dimension of odour and should perhaps be carried out by public attitude surveys as outlined in the Copley study or other acceptable means.

Dravnieks (1979) also suggested that the extent of annoyance caused by odorous air depends on frequency and duration and the odour episodes, odour intensity, odour character and hedonic tone (pleasantness or unpleasantness) of the odour. It is a sensation which is measurable through the subjective responses of individuals. However, as different individuals respond to the same odour quite differently depending upon their sensitivity, expectations and attitudes it is necessary to take the opinions of a panel of observers.

7. RESEARCH PREFACE

At present the assessment of odour nuisance is on an ad hoc basis; usually based on the experience of the assessor. Consequently it can be very subjective and unreliable in as much as consistent results are difficult to obtain.

What is needed is a method of assessment which is based on more realistic objective criteria. There is sufficient empirical data to construct an improved method of assessment. The way forward lies in bringing together the best of empirical knowledge in this field into a unified system.

As far as possible the system should include measures of the four basic dimensions which describe odours, i.e. as recommended by Karolinska Institute (1970), National Research Council (1979), Dravnieks (1979):

1) pervasiveness.
2) intensity.
3) quality.
4) acceptability or pleasantness.

The system may also need to incorporate measures of the frequency of occurrence, duration and the conditions under which exposure occurs.

The pleasantness of the odour, its quality and any previous associations that the receiver has had with the odour will influence his/her reaction. Duration and frequency of exposure both short and long term will also influence the potential for an annoyance reaction.

A particular odour may be perfectly acceptable in one context or at a particular time of the day but on another occasion may be completely unacceptable.

Like all air pollution problems, those caused by odours are not characterised solely by the nature of the odorants and human response to these materials. Numerous other variables need to be considered. For example, the nature of the emission - whether it takes place continuously or in occasional bursts or puffs, or from regular bursts. Discharges can take place from point sources, such as a factory chimney from area sources such as from a waste tip or even from a line source such as a polluted stream.

The dispersion of pollutants will be greatly influenced by weather and topographic conditions. To complicate matters some substances can undergo a physical and/or chemical change between the source and receiver. The fact that the nose responds almost instantaneously to odours is another factor which needs to be considered.

The factors which need to be considered in determining if an emission is likely to cause an odour nuisance are summarised in Table 7.1. To include all of these factors is beyond the scope of this or twenty other such research projects. However, the author believes that the time is right to make a considerable progress using two or possibly three of the basic "dimensions" rather than the single dimension used at present. Apart from being a more accurate predictor of odour nuisance, the method should also be practical and relatively inexpensive of time and equipment. A trained odour panel system would be expensive in terms of manpower but low in capital cost, whereas gas chromagraphic or another instrumental approach could be fairly economical in terms of manpower but high in equipment costs.

For the purposes of this study it has been assumed that the most important "dimensions" associated with odour annoyance are:

1) pervasiveness.
2) intensity.
3) acceptability or hedonic tone (pleasantness or unpleasantness).

Table 7.1. Factors affecting odour nuisance

Process	Factors which need to be considered
Emission	Odour emission rate Exit velocity - plume rise Temperature - plume rise
Dispersion	Wind speed/direction Distance Atmospheric stability Topographical features Atmospheric physical reactions Atmospheric chemical reactions Other chemical compounds present in the atmosphere
Observer Reaction	Odour quality Odour hedonic tone Odour intensity Olfactory acuity or sense of smell of the individual Conditions under which exposure occurs (context) Observer's relationship to source of odours Observer's previous experience of odour Frequency of occurrence Duration

The pervasiveness, the intensity and the acceptability, can be quantified by organoleptic measurement. However, at present there is no known way of quantifying the quality. As described in Section 2.2 there is not even a universally accepted system for classifying odours.

The methods of measurement adopted in this study for each of the three dimensions are described in Section 8. The significance of each of these in predicting annoyance is examined in Section 10.

8. DEVELOPMENT OF EQUIPMENT AND TEST METHODS

The belief that combinations of the parameters listed in the previous section will give a measure of the expected level of community annoyance has led to the need to develop practical cost effective equipment and test methods. To this end the author has adopted what is believed to be the best available and most appropriate techniques for testing the theory.

The scope of these techniques includes determining the characteristics of an odour both at source where it is relatively easy to sample and at the receiver where the annoyance occurs but it is more difficult to take measurements. An effective odour dispersion model may be used to link the two and estimate the likelihood of annoyance given the source parameters.

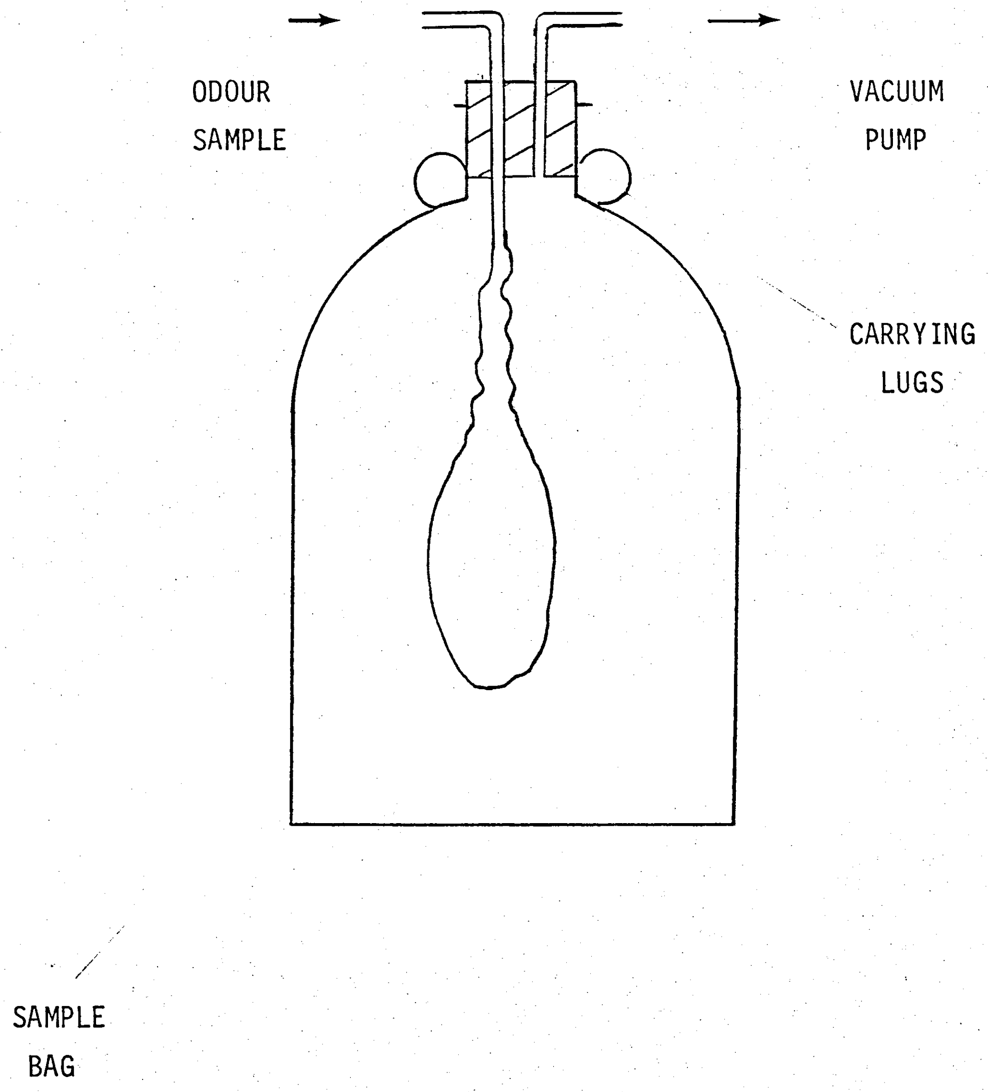
8.1. Equipment

Two items of equipment have been found to be essential. These are an odour sampling system and an olfactometer.

Odour sampling system

Odour samples are collected using the system shown in Figure 8.1. A deflated sampling bag is contained inside a 5 litre glass bottle. A glass demijohn was chosen because of

Figure 8.1. Odour Sampling System

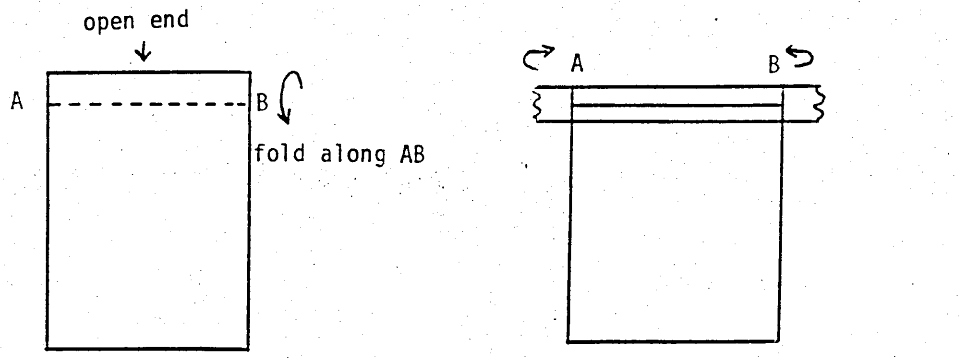


the ease of determining the quantity of sample collected. The carrying lugs also make it a convenient container to handle. Although made of glass, breakages have not been a problem. Five litres is generally sufficient for most tests. If a larger sample is necessary this can be obtained by using another 5 litre sampling unit.

The sample bag is made of food grade PET (polyester terephtalate). It is readily available and sold as a roasting bag in a well known chemist chain store under their own brand name. Considerable care was taken to find an inexpensive bag that was made of a material which neither had an odour of its own nor retains odours on its internal surfaces. As far as is known the material is also impervious to most odours. By using an inexpensive sampling bag it is possible to use one per sample to guard against cross contamination. A simple method of folding, sealing and joining the bag to the sampling line has been developed which uses a non-odorous silicone-based adhesive tape. Figure 8.2 shows the steps necessary to prepare the sample bottle.

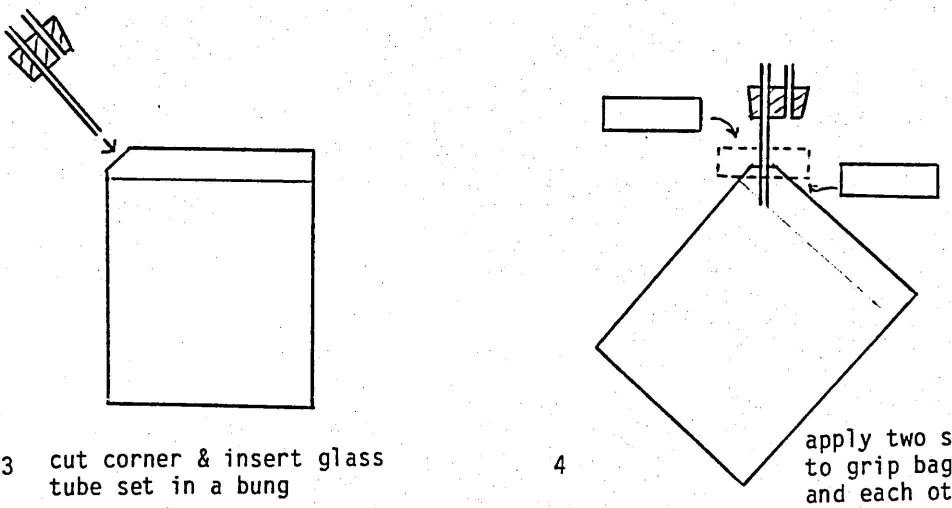
By evacuating the air outside the bag with a simple hand pump, odorous air is drawn into the bag. Sampling is continued until the bag fills the inside of the jar, thereby eliminating any problem of diffusion of odour through the bag. Care is taken during filling to ensure that the bag is not split or ruptured as it unfolds.

Figure 8.2. Preparation of odour sample bag



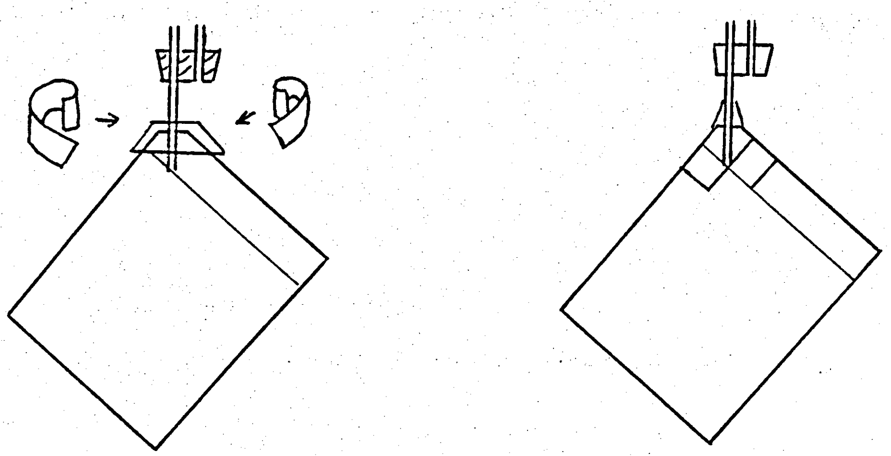
1

2 stick down short flap with tape and turn over ends of tape



3 cut corner & insert glass tube set in a bung

4 apply two sticky tapes to grip bag and glass tube and each other trim surplus



5 apply two more tapes to add strength to joint

6 the finished deflated bag is folded and placed inside the glass jar and held in place by the bung

Particularly strong or wet odorous samples are collected as a prediluted sample, i.e. the odour sample is added to a known volume of dry odourless air in a partially filled bag. The relative volumes are determined by the dilution required and/or the moisture content of the wet sample.

Once sampling is complete the system is sealed with small bungs in the sampling line.

For analysis the sample is displaced from the collector by the introduction of air on the outside of the bag. Normally the sample is analysed by organoleptic methods using the dynamic dilution apparatus described in the next section.

Olfactometer

The review of olfactometers currently in use in Section 3 revealed that the Warren Spring Laboratory olfactometer was probably the only commercially available instrument in the United Kingdom. In 1979 it was available from Prosser Scientific Instruments at £4000. Even if the price had remained unchanged this was beyond the resources available for this project. The alternative was therefore to construct a purpose built instrument.

Prior to this research project the author had designed and constructed several dynamic dilution apparatus for and on behalf of the WS Atkins Group, his employer. Figures 8.3 and 8.4 show the earliest instrument for use in an odorous environment. A known quantity of the sample was deodorised by passing through an activated carbon filter and then added to the remainder of the sample in known proportions. The mixture was then ducted to face masks worn by the odour panel. When the panel member had a positive response a button was pressed to illuminate a lamp on the operator's control panel.

The instrument worked relatively well but was too cumbersome. The panel were also liable to odour fatigue even though they wore activated carbon face masks between tests.

Taking account of the recommendations listed in Section 3 by Engen (1982) and Jann (1984) regarding the sample presentation velocity and flow volume and using the best features of the various instruments examined a new instrument was designed.

This is shown in Figures 8.5 and 8.6. It is compact and is built inside a briefcase. It is simple and therefore easy to maintain and use. Room air is supplied from a diaphragm pump and is deodorised by passing through an activated carbon filter. This is split three ways.

A proportion is metered and passed to the sample bottle on the outside of the bag. The displacing air is adjusted to give the required flow of odorous sample to the mixing chamber. The flow rate of a second clean air stream is adjusted to give the required dilution rate when it meets the odorous air in the mixing chamber.

Figure 8.3. Schematic view of WSA dynamic dilution apparatus MKI

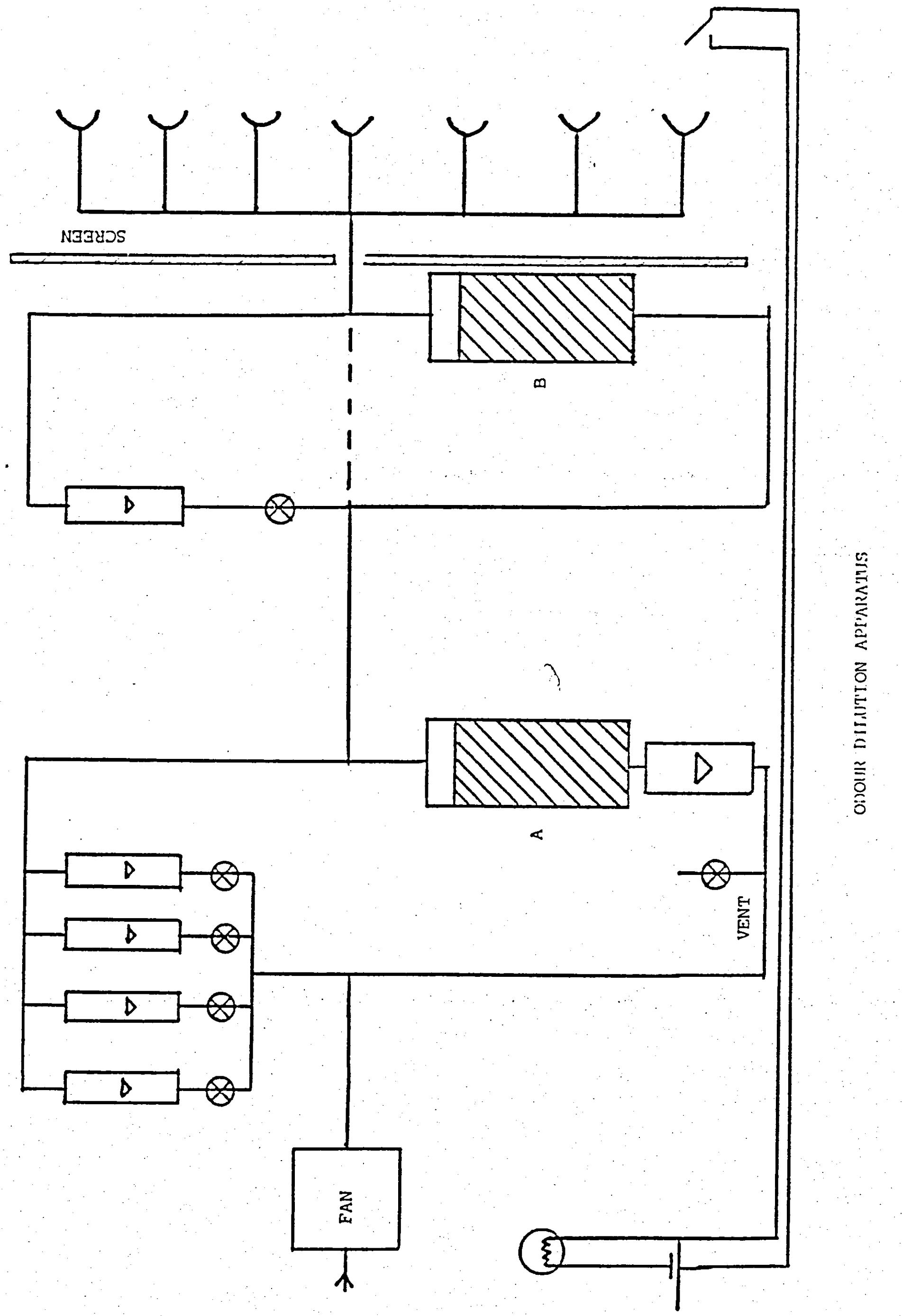


Figure 8.4. WSA dynamic dilution apparatus MKI in use

Figure 8.5. Schematic view of portable dynamic dilution apparatus

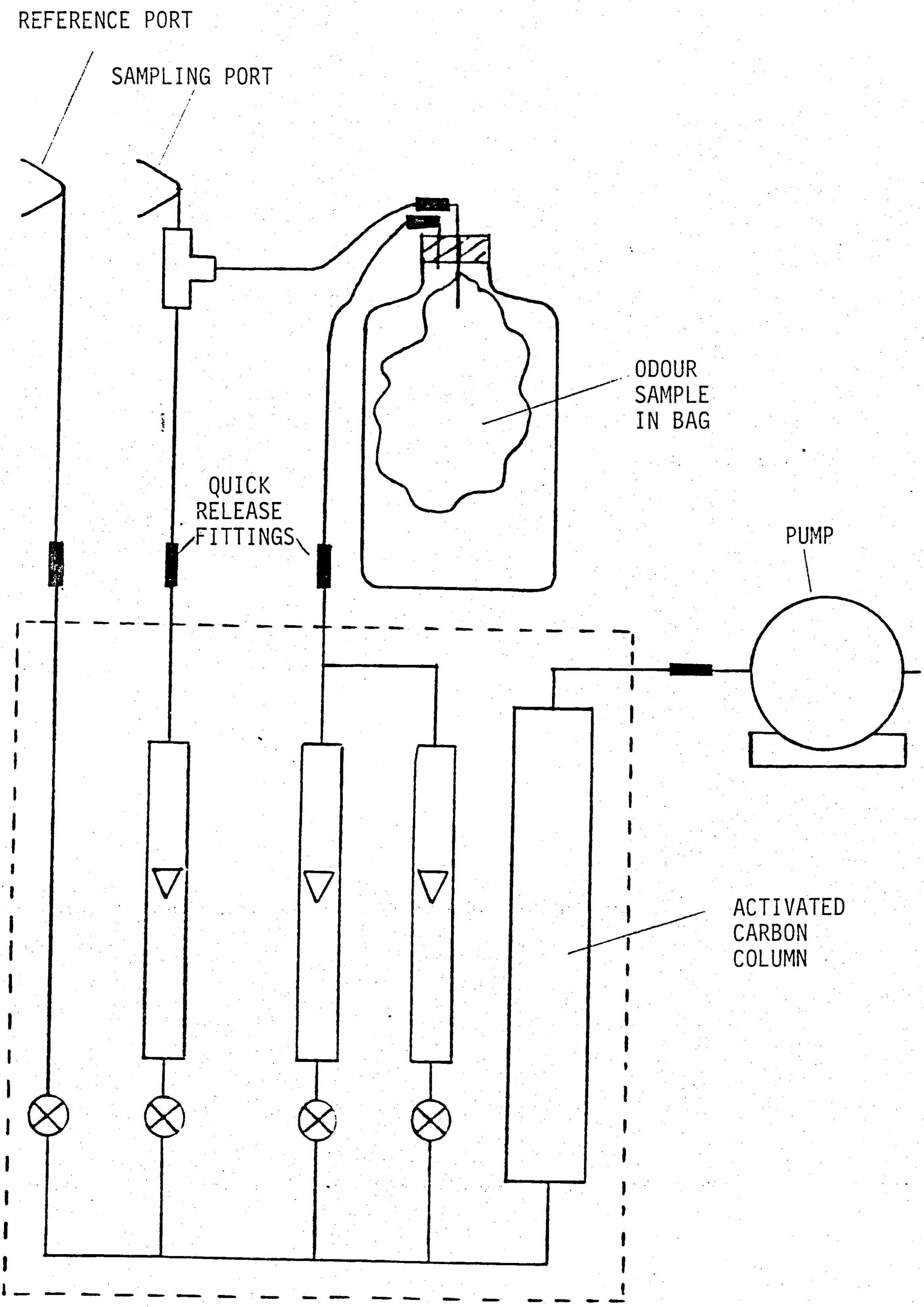
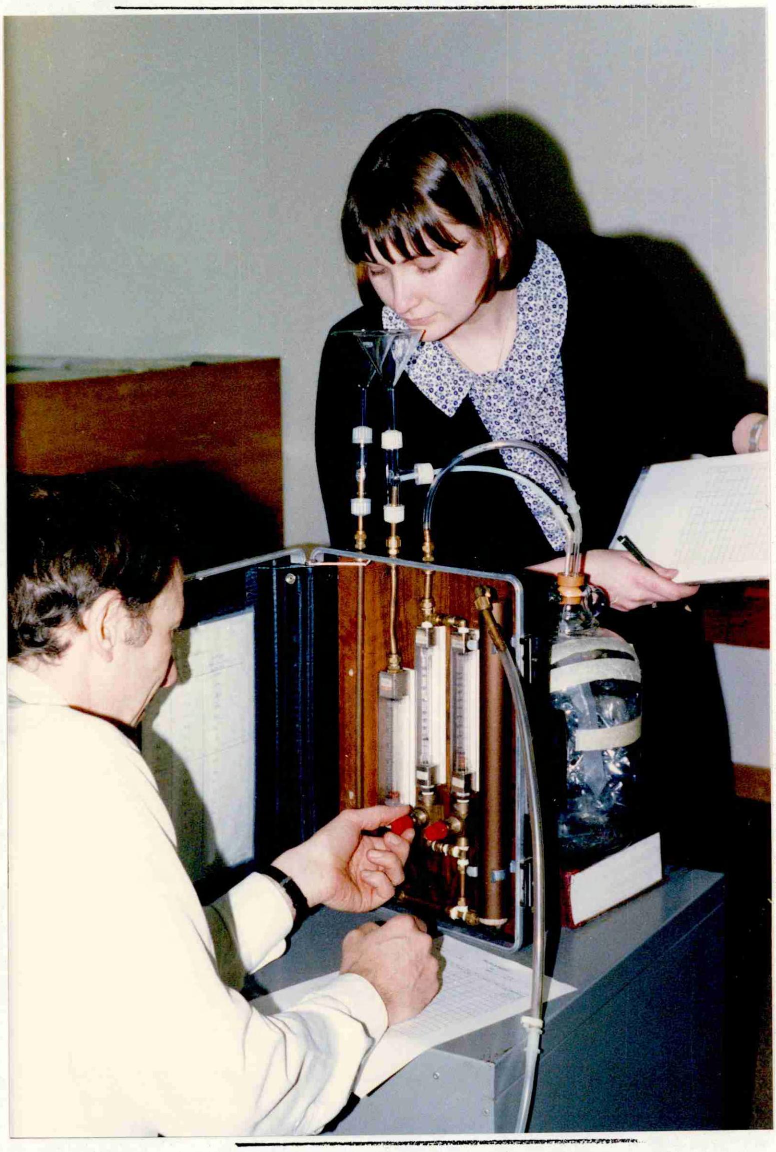


Figure 8.6. Portable dynamic dilution apparatus in use



A third air stream is provided which goes directly to a second sniffing port as a clean air reference.

The pipe connecting the sample bottle to mixing chamber is made of Teflon (a non-stick plastic) and is as short as possible. All other parts that come into contact with odorous samples, including the mixing chamber and sampling port, are made of glass. If contamination does take place then this section can easily be washed and air dried.

In operation the main diluting air flow and reference air flow are typically set to 15 l/min. The displacing air is adjusted to its lowest flow of 5 ml/min, i.e. a dilution of 3000. (When dilutions greater than 3000 are required the sample is prediluted in the dynamic dilution apparatus to produce a working sample.) After sufficient time has elapsed for the sample bag-to-mixing chamber tube to become full of odorous air the first odour panel member samples from the sniffing port.

Each panel member then sniffs in turn for the same dilution setting making a note of his or her response on the questionnaire shown in Figure 8.7. Care is taken to ensure that there is no communication of response between panellists.

Figure 8.7. Odour panel response sheet 2

ODOUR PANEL RESPONSE SHEET 2

Name: ....x Date: x

Clean air .... L/min Sample: x

x x x x x x x x

TEST	SAMPLE SETTING ML/min	DILUTIONS	NIL	POSSIBLE	VERY SLIGHT	SLIGHT	MODERATE	STRONG	VERY STRONG	ANNOYANCE				
										None	Slightly	Fairly	Very	Extremely
1														
2														
3														
4														
5														
6														
7														
8														
9														
10														
11														
12														
13														
14														
15														

8.2. Determination of Intensity, Concentration and Annoyance

The intensity, concentration and annoyance of the collected samples are determined by odour panels using the WSA dynamic dilution apparatus described in Section 8.1.

An ascending concentration series of odour samples are presented to the odour panel, one concentration at a time. Repeat samples are inserted as discussed in Section 3.4, recommended by Lindvall (1971) op. cit. and confirmed by the National Research Council (Anon 1979) op. cit. Each panel member records his/her response on the confidential questionnaire which is reproduced in Figure 8.7.

When the response is positive, i.e. some odour is detected, the panel member is instructed to provide an estimate of the intensity using the category jugements and to record their opinions with regard to potential for annoyance in the context of their community. In making these judgements the panel member makes reference to the clean air issuing from the second sniffing port.

Further increases in concentration are made until it is clear to the operator (by asking individuals in turn) that all panel members are experiencing the highest intensity.

The panel are not informed of the dilution settings, in order to avoid anticipated reactions. During the assessment of a sample several repeat concentrations are given to test for consistency of response.

In theory, the larger the panel size the better. However, as discussed in Section 3, in practice it is difficult and costly to manage large numbers. Best results based upon repeat tests show that with an experienced panel about 6 is the ideal number. This gives a reasonable accuracy without excessive effort.

The data obtained from the odour panel tests are analysed for intensity,concentration and annoyance by the methods described below.

Intensity

A pilot experiment was conducted using a social survey to determine the perceived numerical spacing between each of the intensity categories listed in Table 8.1 in line with those used by Katz and Talbert (1930).

Table 8.1. Intensity category

Intensity category
Nil
Possible
Very slight
Slight
Moderate
Strong
Very strong

Respondents were asked to complete the questionnaire reproduced in Figure 8.8., i.e. if no odour had the value of zero and a very strong odour had the value of 100, where would each of the other categories appear on the scale 0-100? No stimuli were presented with the questionnaire.

The respondents were told that:

Possible corresponded to just detectable.

Very slight corresponded to easily detectable but not recognisable.

Slight corresponded to easily detectable but only just recognisable.

Moderate corresponded to being easily recognisable without effort.

Strong and very strong were self explanatory.

The mean values for each of the categories obtained from 50 questionnaires are given in Table 8.2 together with the corresponding standard deviations.

Table 8.2. Intensity scale

Category	Numerical Scale	
	Mean	SD
Nil	0	0
Possible	9	6.0
Very slight	18	9.8
Slight	29	13.3
Moderate	53	13.1
Strong	80	8.3
Very strong	100	0

Figure 8.8. Intensity scale questionnaire

SUBJECTIVE RESPONSE SCALE TO ODOURS

NAME: (INITIALS)

DATE:

IF YOU CAN DETECT ODOUR AS:	GIVE EQUIVALENT VALUE ON SCALE OF 100
NIL	0
POSSIBLE	
VERY SLIGHT	
SLIGHT	
MODERATE	
STRONG	
VERY STRONG	100

These spacings or weightings were subsequently used to find the numerically weighted average intensity response for the panel. Thus, if the number of responses to each intensity category are as given in Table 8.3, then

Table 8.3. Number of responses at each intensity

Intensity	Number responses	Corresponding weighting
Nil	a	0
Possible	b	9
Very slight	c	18
Slight	d	29
Moderate	e	53
Strong	f	80
Very strong	g	100

the numerically weighted average panel intensity for a specific sample (NWI) =

$$\frac{9 \times b + 18 \times c + 29 \times d + 53 \times e + 80 \times f + 100 \times g}{a + b + c + d + e + f + g} \qquad \text{E8.1}$$

It was found that in almost 100% of cases of organoleptic testing of samples, i.e. using an odour panel that, if the dilution factor was plotted against the overall average panel intensity (NWI) on a log/log scale, then the relationship was a straight line, e.g. Figure 8.9.

A regression analysis between the odour intensity and concentration; in terms of dilutions of the original sample, is summarised in Table 8.4, for the assessment of ten typical odour samples by three different odour panels. (The full data can be found in Appendix 1). Even for relatively small numbers of observations, the correlation coefficient is high with a level of significance corresponding to better than 0.01%.

As this relationship depends upon the intensity weightings given in Table 8.2, the excellent correlation in Table 8.4 implies that the weightings are probably fairly accurate. It would be a study in itself to provide further verification of the intensity weightings.

Using the relationship between log (concentration) and log (NWI) it is possible to determine the detection and recognition threshold concentrations from the suprathreshold assessment of intensity. This so-called indirect approach is similar to that used by Katz and Talbert (1930), Hemeon (1968) and Dravnieks (1974) and described in Section 3 (see also Figure 3.10). The respective thresholds are the concentrations (dilutions to

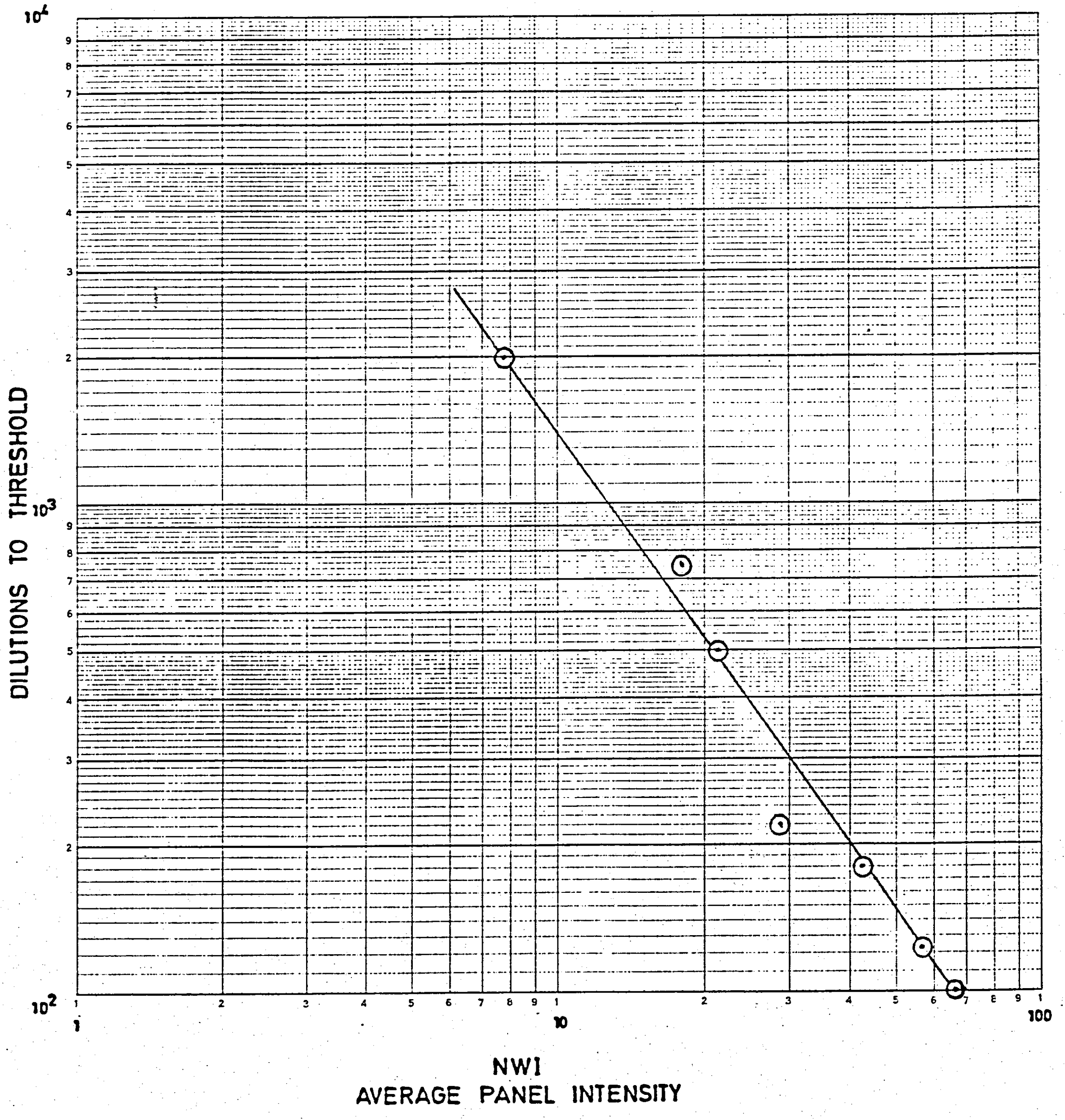
Table 8.4. Linear regression analysis between odour intensity (NWI) and concentration for the typical samples

Odour source	Constant	x coefficient	Correlation coefficient R	Number of observations n	Level of significance P	Size of Odour panel
Hong Kong & China Gas Works						
Gas works cooling tower	3.176	-0.686	-0.987	7	0.0003	6
Naphtha vent during tank filling operation	2.538	-0.427	-0.985	12	0.0000	6
Animal quarantine station foul water interceptor	1.669	-0.247	-0.862	9	0.0032	6
Gas works interceptor	2.960	-0.552	-0.987	8	0.0001	6
Diesel exhaust	2.872	-0.477	-0.938	9	0.0004	6
Watneys Brewery						
Biological tower	6.370	-2.179	-0.970	6	0.0024	6
Sludge vent	4.826	-1.507	-0.972	7	0.0007	6
Final vent	2.785	-0.794	-0.996	12	0.0000	6
Entec (Glass reinforced fibre manufacturer)						
Process air from stack 1	7.682	-2.641	-0.906	10	0.0005	5
Process air from stack 2	2.860	-0.714	-0.885	7	0.0087	5

$x = \log_{10}$ (concentration as dilutions from sample)

$y = \log_{10}$ (numerically weighted intensity NWI averaged for the odour panel

Figure 8.9. Relationship between average panel intensity (NWI) and sample dilution



threshold) at which the average panel intensities are 9 and 29 respectively in accordance with the definitions given in Table 8.1 and the values given in Table 8.2.

Concentration

The concentration of the samples presented to the odour panel was obtained by plotting on log probability paper, the sample dilution factor and the cumulative percentage of panel members indicating their response was at least very slight, e.g. Figure 8.10. Responses given as "Possible" were split, half to category "Nil" and half to category "Very Slight". The dilution at which 50% of the panel gave a positive response to "very slight" was taken as the threshold concentration. The recognition threshold was determined by plotting the cumulative percentage of responses of at least the category "Slight", and the dilution at which 50% of the panel give such responses was taken as the recognition threshold.

The determination of the detection and recognition thresholds from the panel response to certain dilutions will be called the direct approach.

Relationship between direct and indirect methods for assessing thresholds

The results of determination of the detection and recognition thresholds by the direct and indirect methods was found to be remarkably similar. Appendix 2 reproduces the data used to establish the relationship between the two methods. Regression analyses of these data gave the relationship in equation E8.2 for the detection threshold and the relationship in equation E8.3 for the recognition threshold.

$$\text{direct (d/d)} = 1.009 \times \text{indirect (d/d)} + 19.2 \qquad \text{E8.2}$$

$R = 0.942$ $n = 82$ with a level of significance better than 0.0001

and

$$\text{direct (d/r)} = 0.991 \times \text{indirect (d/r)} + 100.5 \qquad \text{E8.3}$$

$R = 0.965$ $n = 66$ with a level of significance better than 0.0001

It was found that there was more scatter in the panel responses around the threshold concentrations using the direct approach as indicated by Dravnieks (1974) op. cit. in Section 3. At times this made it difficult to obtain a best straight line through the data. However, the indirect approach, i.e. extrapolating from suprathreshold intensities, was always able to give an estimate.

Annoyance

In this study annoyance is judged on a category scale as shown in Table 8.5.

Table 8.5. Annoyance categories

nil
slightly annoying
fairly annoying
very annoying
extremely annoying

As with the Intensity Scale, the numeric spacing between these categories was determined by resort to a social survey. From a sample of 50 questionnaires it was found that the spacing was as follows in Table 8.6.

Table 8.6. Annoyance scale

Category	Numerical Scale	
	Mean	SD
Nil	0	0
Slightly annoying	17	8.4
Fairly annoying	42	12.4
Very annoying	77	8.3
Extremely annoying	100	0

By adopting these values as weightings it is possible to find the panel average annoyance in the same way as was achieved for intensity, i.e. in Table 8.7.

Figure 8.10. Typical relationship between positive odour panel response and sample dilution

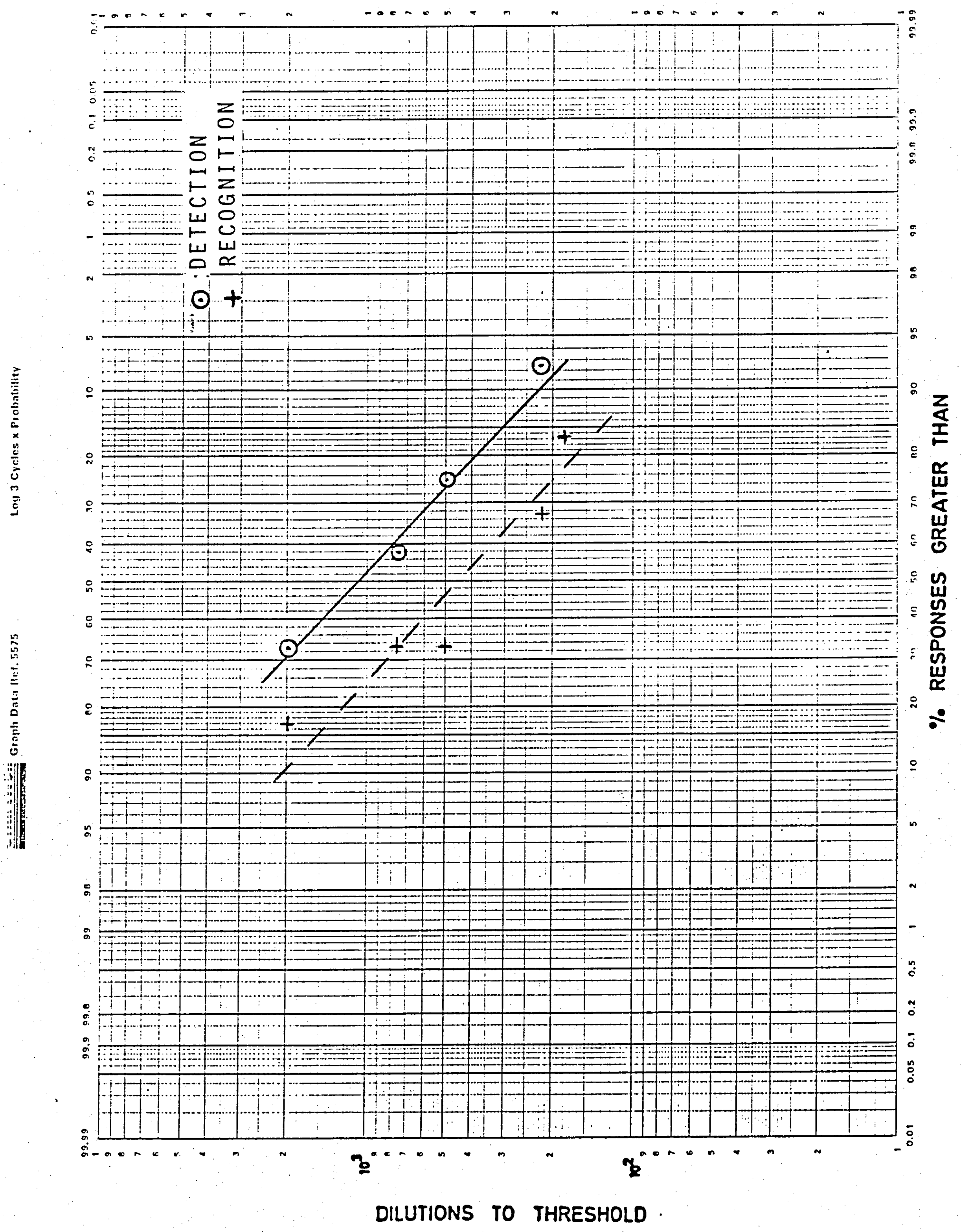


Table 8.7. Number of responses at each annoyance

Annoyance	Number responses	Corresponding weighting
Nil	a	0
Slightly	b	17
Fairly	c	42
Very	d	77
Extremely	e	100

The numerically weighted average annoyance NWA is calculated as follows:

$$A = \frac{17 \times b + 42 \times c + 77 \times d \quad 100 \times e}{a + b + c + d + e} \tag{E8.4}$$

For example in Table 8.8.

Table 8.8. Calculation of average annoyance NWA

Sample	Percentage distribution of annoyance					Average annoyance NWA
	nil (0)	slightly (17)	fairly (42)	very (77)	extremely (100)	
A				100		77
B	10	50	40			25.3

Thus an annoyance value can be obtained for each corresponding intensity and concentration.

8.3. Source Measurements

Emission rate

The emission rate of the source of odour is determined from the product of the volumetric flowrate and the odour concentration. With ducted emissions the volumetric flowrate is obtained in the normal way by measuring the velocity in the duct and the cross-sectional area of the duct, such that flow (m^3/s) = velocity (m/s) x area (m^2). The emission rate is therefore obtained by multiplying by the induct concentration (D/T), i.e.

emission rate = concentration ratio x m^3/s. As concentration is now dimensioned the emission rate will have units of volumetric flowrate.

Emissions from open and fugitive sources are constantly diluted by the movement of clean air across the source. There will also be a concentration gradient vertically above the source. If, as a first approximation it is assumed that the vertical concentration gradient is linear, then the concentration at height x will be mid way between that at the surface and that measured at a height 2x. It follows that the volumetric flowrate for the concentration at height x will be the product of the cross wind width of the source, the height 2x and the wind speed, i.e. the swept volume.

Odour concentration

The odour concentration is determined by first collecting a sample of the odour at source in the sampling system described in Section 8.1. This is then analysed by using an odour panel and dynamic dilution apparatus to find the concentration in the manner described in the previous section.

The techniques are normally applied to a sample taken at source where the concentration is relatively high but it has also been applied to ambient air. However, generally a different approach is used for ambient measurements.

8.4. Ambient Measurements

Intensity

Odour is normally experienced by the general public downwind of the source. In travelling from source to receiver the odours are partially dispersed by fluctuations in air movements. As a result the concentration at the receiver does not remain constant but varies in a manner similar to that suggested by Figure 8.11a.

For this time history of the concentration there will be a corresponding frequency distribution figure 8.11b where TD, TR and TA are the concentrations at which the odour is detectable, recognisable and annoying respectively.

According to Turner (1970) and Hogstrom (1972) the atmospheric dispersion of an odorant downwind from a point source behaves in a binormal manner (see Section 4.1) and therefore the frequency distribution in Figure 8.11b will be normal. Figure 8.11c shows the equivalent cumulative frequency distribution. A more convenient form according to Noll (1977) is the cumulative distribution plotted on a normal probability scale, Figure 8.11d. If the frequency distribution is truly normal then the distribution is represented by a straight line.

Figure 8.11 Downwind Odour Concentration Time History

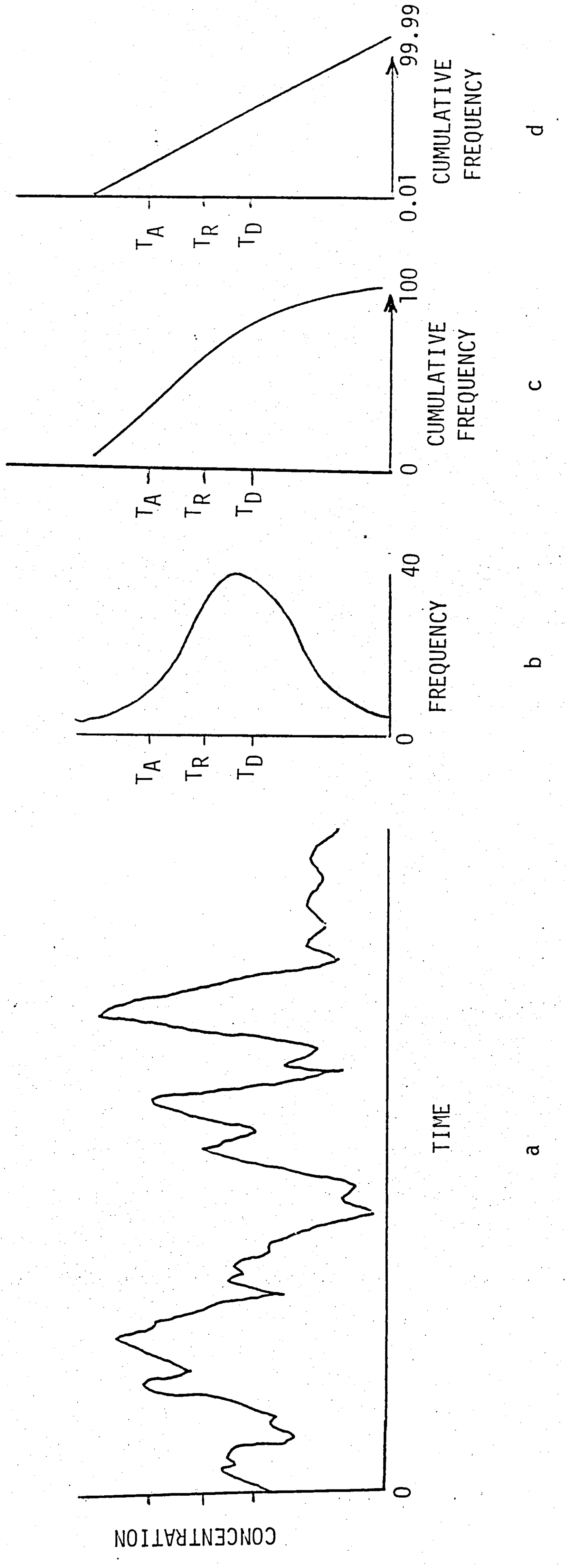


Figure 8.11 - Down Wind Odour Concentration Time History

The main attraction of the data in the form shown in Figure 8.11d is that the frequency of exceeding a certain concentration is expressed as a percentage of the sample time. Thus, if TR is known then it is possible to "read off" the percentage of time that odours were recognisable.

The relationship illustrated in Figure 8.11d provides a very convenient way of assessing the intensity of the receiver in the field situation.

In this study numerous tests have been conducted by small odour panels downwind of a source to determine the reproducibility between individuals making observations of odour intensity. This is merely an extension of laboratory work on specific and controlled odour samples into the field situations where the actual concentration of the odour sample is unknown.

In tests the observer is asked to note the intensity experienced with each breath or sniff using the coding 0 for no odour, 1 for very slight or detectable, 2 for slight or recognisable, 3 for moderate, 4 for strong, 5 for very strong. Thus a set of observations might be recorded as

00132112100121 ....

Observations normally take place over a period of about 10 minutes and are recorded on a data sheet as reproduced in Figure 8.12. Close agreement has been found between individual

Figure 8.12. Odour survey result sheet

ODOUR SURVEY (1)

JOB NO. SHEET NO

DATE TIME

POSITION OF MAP

SOURCE POSITION ON MAP

DISTANCE FROM SOURCE M

SOURCE DESCRIPTION

TEMP °C

WIND SPEED m/s

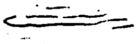
DIRECTION FROM

N nne ne ene E ese se sse S ssw sw wsw W wnw nw nnw N

CLOUD COVER %

CLOUD TYPE (DELETE OTHERS) HIGH MID LOW

(DELETE OTHERS)



PASQUILL STABILITY TYPE

TIME SOURCE IN POSITION

RESPONSE (eg. 10012310)

SNIFF...

....

ODOUR INTENSITY	0 NONE 1 VERY SLIGHT (THRESHOLD) 2 SLIGHT (JUST RECOGNISABLE) 3 MODERATE (EASILY RECOGNISABLE) 4 STRONG 5 VERY STRONG	No.	%	%>

ODOUR DESCRIPTION SMELLS LIKE:-	%T
ANNOYANCE (ONLY TICK TWO CATEGORIES IF JUDGEMENT LIES BETWEEN)	ECI

NIL	SLIGHTLY	FAIRLY	VERY	EXTREMELY	NWA

observers for the percentage of the time that odours were detectable, i.e. category 1 and above. The correlation coefficent between 62 pairs of observers simultaneously exposed to the same odour events was 0.71, corresponding to better than the 0.001 level of significance. (The full data are listed in Appendix 3).

It should be noted that the intensity categories used in ambient conditions differ somewhat from those used when assessing an odour sample with the dynamic dilution apparatus.

Under ambient conditions the intensity is not normally steady but fluctuating rapidly and therefore it is more difficult to use the category of "possible". As a consequence it is not used. By employing only 6 intensity categories rather than 7 as already described, it was necessary to redetermine their values on the scale 0-100.

From a social survey of 33 respondents the scale was determined in Table 8.9.

Table 8.9 Intensity scale for field observations

Category	Numerical scale	
	mean	SD
Nil	0	0
Very slight	9	3.2
Slight	22	7.8
Moderate	43	11.2
Strong	73	10.3
Very strong	100	0

The intensity classes are totalled for each observer by category. For example, an observer may have recorded the totals given in Table 8.10.

Table 8.10. Summary of observed odour intensities

Category	Total number of occurrences
0 Nil	a
1 Very slight	b
2 Slight	c
3 Moderate	d
4 Strong	e
5 Very strong	f

An average or equivalent continuous intensity (ECI) for the observations is calculated from equation 8.5.

$$ECI = \frac{b \times 9 + C \times 22 + d \times 43 + e \times 73 + f \times 100}{a + b + c + d + e + f} \qquad E8.5$$

ECI takes account of the fluctuation of odour intensity with time. It should not be confused with NWI which is the odour panel average intensity for steady odours or the average for maximum odours.

A measure of the spread of values about the ECI is provided by estimating the standard deviation of the ECI from equation E8.6.

$$\text{i.e. standard deviation} = \sqrt{\frac{\sum x^2 f}{\sum f} - \bar{x}^2} \qquad E8.6$$

where x = category weighting 0,9,22,43, etc.

f - frequency totals a,b,c,d, etc.

and

$$\bar{x} = \frac{\sum fx}{\sum f} \qquad E8.7$$

The average ECI for a number of observers is taken as the arithmetic mean.

Annoyance

With fluctuating odour concentrations under ambient conditions it is reasonable to assume that the annoyance will be dependent upon the temporal fluctuations as well as the intensity. The observer will average out the fluctuation and have an overall impression of annoyance for the observation period. As can be seen from Figure 8.12 this assessment of annoyance is categorised by the observer.

Other observations made under ambient conditions are also listed in Figure 8.12.

Measurement of unpleasantness

The hedonic tone is a function of the intensity as well as the type or character of the odour, so that care has to be taken, to make assessments under standard conditions. As with other investigators, e.g. Dravnieks (1979), the author has adopted intensities of slight to moderate for assessment purposes. Source measurements may therefore need to be prediluted before odour profiling takes place. When assessment takes place in the field care was taken to work under conditions of relatively uniform intensity.

The method of measurement adopted was that of odour profiling devised by Dravnieks and described in Section 2.2.

8.5. Summary

A description is given of the design of a simple odour sample collection system and portable olfactometer which was used when odour intensity and concentration were assessed by odour panels. The design incorporates most of the recommendations identified in Section 3.

Descriptions are also given on the measuring techniques which were developed for use in both the laboratory and field situations. These include techniques for odour intensity, concentration and annoyance. Numeric scales were developed for quantifying intensity and annoyance so that observations could be averaged and analysed by statistical methods.

No further development was attempted on the measurement of hedonic tone or the unpleasantness of odours - a standard method was adopted.

9. ODOUR DISPERSION MODEL

9.1. Introduction

In order to be able to predict the effect that an odour source is likely to have on a receiver it is necessary to have a means of estimating the odour dose. This is usually achieved by a mathematical model, several of which were described in Section 4.

The most successful type of these models appears to be the puff model which predicts the short term odour levels corresponding with the response time of the human nose. It was therefore decided to adopt such a model. Although the basic equations and principles had been published there was no computer listing available. A version of the puff model was therefore developed for a personal computer.

9.2. The Model

The program known as ODF was written in GW-Basic, i.e. a version of the BASIC language written by Microsoft Limited which operates in the MSDOS environment. A listing of ODF is given in Appendix 4. It contains some novel features which simplify the calculations and shorten processing time.

As with the puff model developed by Hogstrom and described in Section 4.2, it has been assumed that dispersion is made up of two terms. The first is the diffusion of each individual puff itself; the second is the meander in the plume of a series of puffs in the large scale turbulence field.

It is further assumed that over a period of time the position of the puff centroid will follow a binormal distribution such as illustrated in Figure 9.1. Thus there is a certain probability of finding the puff centroid on a plane downwind from the source depending on its position from the downwind axis.

Not all of these puffs will affect the observer. Some will be too far away. Those that do will be passing the observer within a distance at which the puff has been diluted to the odour threshold. Figure 9.2 illustrates the situation in plan. The edge of the puffs passing the observer are the odour threshold concentrations. Any puff on the source/observer axis affects the observer for a maximum time (x_0/u). Puffs further off axis affect the observer for less time (x_1/u). Puffs passing at a distance $y = +/- b$ from the observer only just brush past the observer. Puffs passing at a greater distance must be diluted below the odour threshold before they reach the observer. Thus there is a critical distance in the y direction beyond which a puff does not affect the observer, because the concentration is below the odour threshold: the effect of simultaneous puffs is ignored.

Figure 9.1. Probability distribution of puff centroid

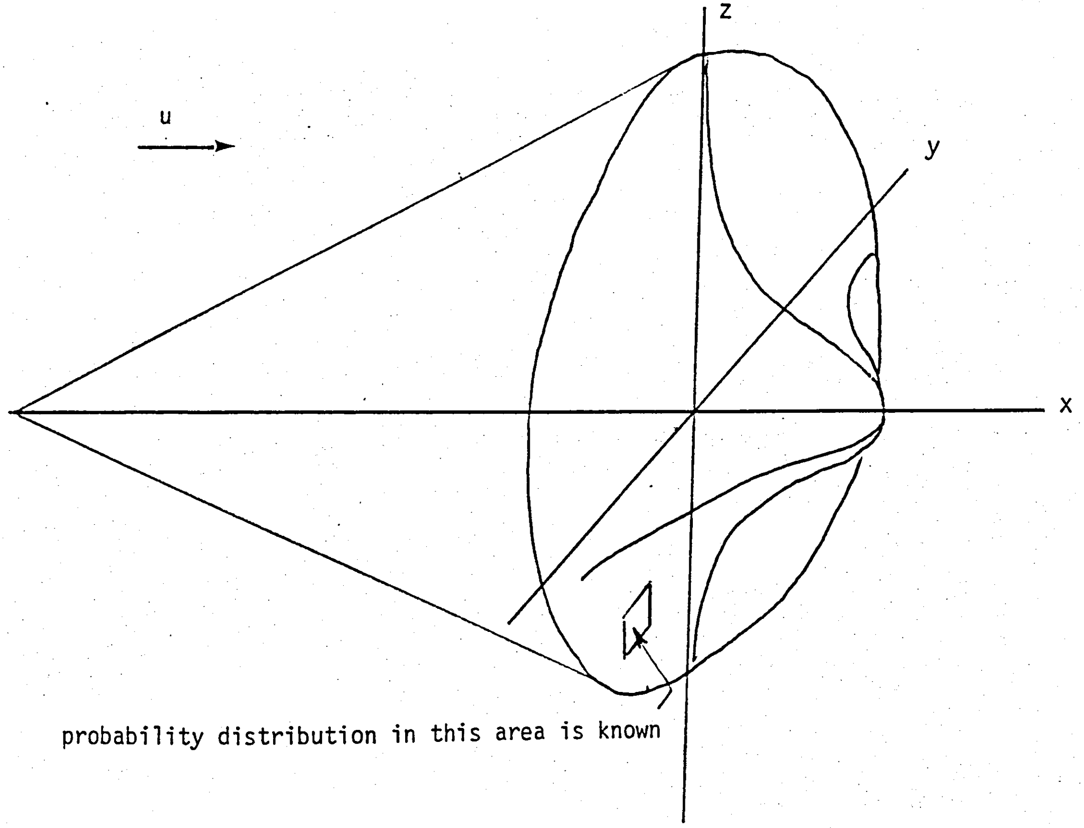
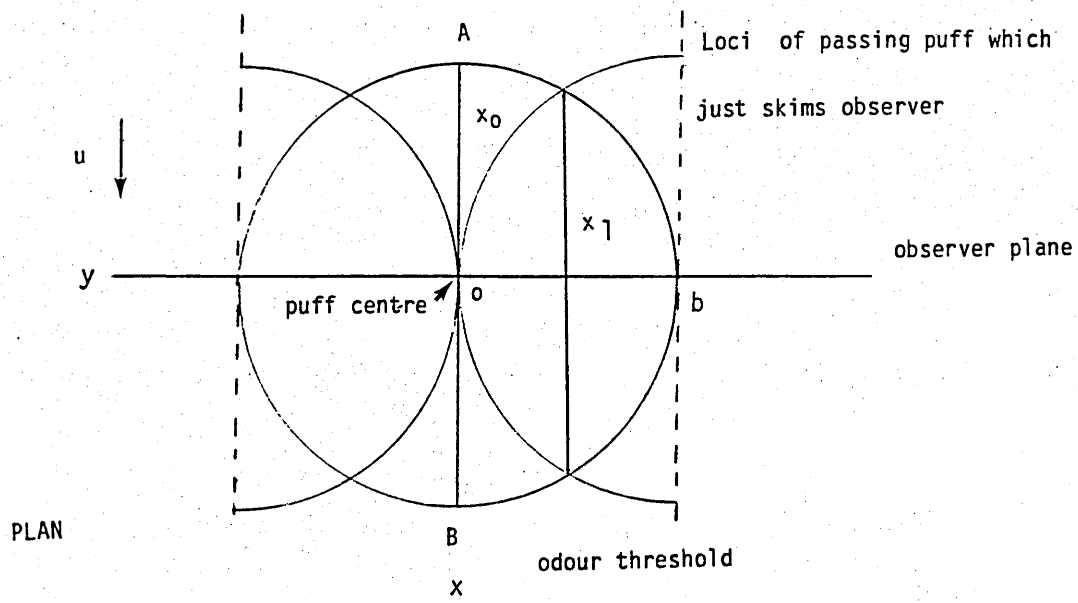


Figure 9.2. Ground level puffs affecting an observer



Similarly there will be a corresponding critical distance c in the Z direction, Figure 9.3.

If the observer is at ground level then the area of influence through which puffs must pass is a semi-ellipse with a height of c and width 2b. The concentration at the observer for a puff at any location in the observer plane is given in equation E4.2 as

$$No = \frac{V_o N_o}{\pi u \sigma_{yp} \sigma_{zp}} \exp\left[\frac{-1}{2}\left(\frac{y}{\sigma_{yp}}\right)^2 - \frac{1}{2}\left(\frac{z}{\sigma_{zp}}\right)^2 \right] \qquad E4.2$$

when z = o y = b

thus

$$b = \sqrt{LOG_e \left(\frac{V_o N_o}{u o_{yp} o_{zp} N_i}\right) 2\, \sigma_{yp}^2} \qquad E9.1$$

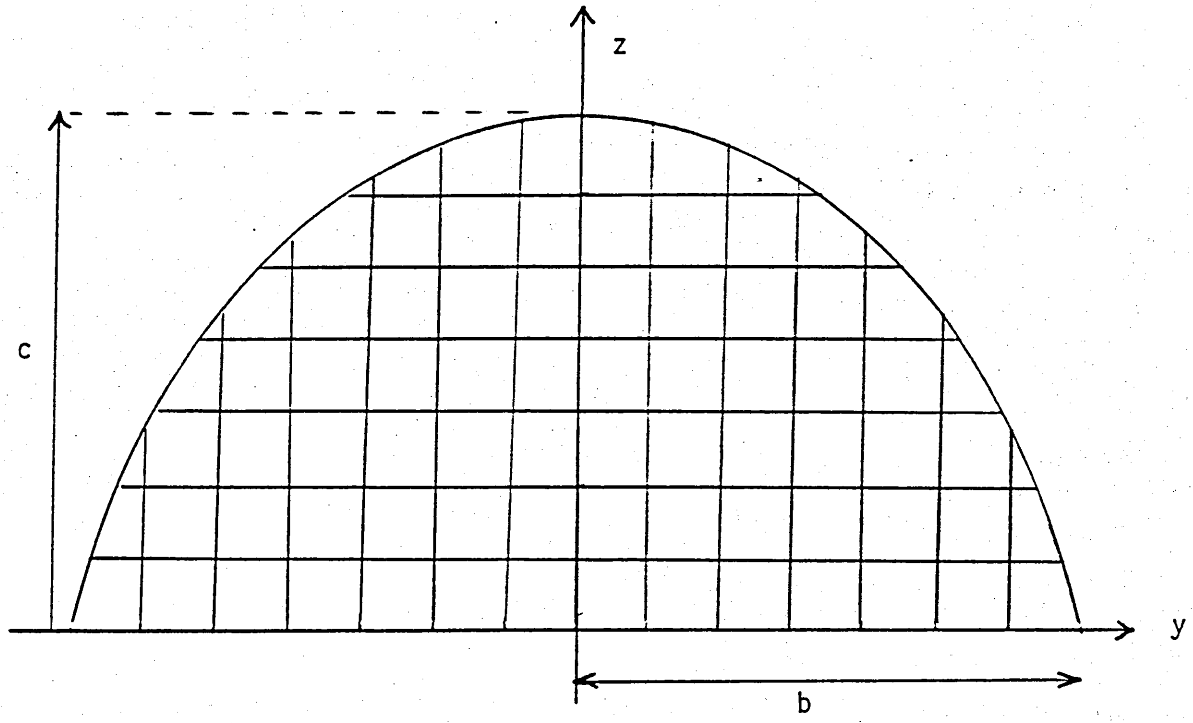
similarly when y = o z = c and

$$c = \sqrt{LOG_e \left(\frac{V_o N_o}{u \sigma_{yp} \sigma_{zp} N_i}\right) 2\, \sigma_{zp}^2} \qquad E9.2$$

The total time that the observer experiences an odour dilution ratio N_i and greater, is therefore the sum of the times that puff centroids pass through the area of influence.

Since the position of the observer is known in relation to the source it is possible to integrate the probability or percentage time that a puff is at each grid point in Figure 9.3 numerically.

Figure 9.3. Range Over Which Puffs Affect Observer



To simplify this a simple algorithm was derived for the frequency of a normal event depending on its position from the mean in standard deviation units.

The probability of a normal distribution event occurring is given by equation E9.3.

$$\text{Probability} = \int_{Z1}^{Z2} \frac{1}{\sqrt{2\pi}} \exp\left(\frac{-z^2}{2}\right) dz \qquad \text{E9.3}$$

(Reference Spiegel 1975)

For 0.1 standard deviation steps E9.3 approximates to E9.4

$$\text{Percent probability} = \frac{4.47 - 1.98\ z}{100} \qquad \text{E9.4}$$

with a correlation coefficient of 0.995.

In carrying out this modelling use was made of the atmospheric dispersion parameters for puff diffusion (Turner 1970) and puff centroid diffusion in rural, suburban and urban areas as published by Bowne (1974) and discussed in Section 4.

9.3. Model Testing

This odour dispersion model has been tested by comparing estimates with observations made on site, at situations where the source emission characteristics were known. Some of the data was obtained from published sources but mostly collected by the author.

Table 9.1 summarises the observed and estimated percentage times greater than odour threshold. These data are plotted in Figure 9.4 which indicates that the model gives a good estimate in rural situations. Agreement is less close in an urban area with tall buildings. The reason for this is that the dispersion will be distorted by buildings and the dispersion parameters used will only be very approximate.

The relationship between estimated and observed values of percentage time greater than the odour threshold is given in equation E9.5.

$$\text{Observed} = 0.876 \times \text{estimated} + 1.48 \qquad \text{E9.5}$$

The correlation coefficient of 0.98 ($p < 0.001$) suggests that a high degree of confidence can be placed upon the estimates. The development of this odour dispersion model has been reported in "Atmospheric Environment". A reprint is contained in Appendix 4.

Table 9.1. Summary of comparison between observed and estimated percentage times greater than the odour threshold

Reference (type of odour)	Source emission rate *(m³ s⁻¹)	Discharge height (m)	Wind speed (m s⁻¹)	Atmospheric stability	Rural/ urban	Source/ receiver distance (m)	Number of observers	Sampling time (min)	Number of samples	Observed %	Predicted %	P/O
Building Board (Process	10,080	5	3	D	R	305	2	5	152	52	60	1.15
Autoclaves) +	10,080	5	3	D	R	500	2	7	208	38	39.7	1.04
Hogstrom (1972) (Kraft	7,133,068	360	6	A	R	2000	6	3600†	6426	10.8	13.7	1.27
Papermill)	7,133,068	360	6	A	R	5000	6	3600†	7490	9.8	10.4	1.06
	7,133,068	360	6	A	R	10,000	6	3600†	5528	8.5	3.3	0.38
Adhesive Coating	682,395	6	8.5	D	R	320	2	5	148	90	100	1.11
Plant +	682,395	6	8.5	D	R	1945	2	5	144	61	69.5	1.14
Lithographic Printing	4127	0	1	D	R	300	2	10	258	83	86.2	1.04
Works +	4127	0	1	D	R	500	2	10	276	38	51.7	1.36
Blood Drying	23,130	14	2	D	U	200	1	15	173	28 #	12.5	0.45
Plant +	23,130	14	2	D	U	240	1	7	101	4 #	12.2	3.05
	23,130	14	2	D	U	360	1	5	75	8 #	11.3	1.41
	23,130	14	2	D	U	480	2	7	172	12 #	9.6	0.8
	23,130	14	2	D	U	560	1	10	147	16 #	10.3	0.64
GRP Factory	8492	6	7	D	R	160	2	5	144	59	49	0.83
	8492	6	4	D	R	120	2	7	176	71	62.3	0.88
	8492	6	5	D	R	180	2	6	162	43	54.4	1.3
McCarthy (1980)	15,675	7.9	1	F	R	300	NA	NA	NA	8.5‡	11.6‡	1.36
Chemical Plant	15,675	7.9	1	F	R	500	NA	NA	NA	7.5‡	13.4‡	1.79

* Emission rate is the product of concentration in terms of the number of dilutions to threshold and the volumetric flow rate ($m^3 s^{-1}$).

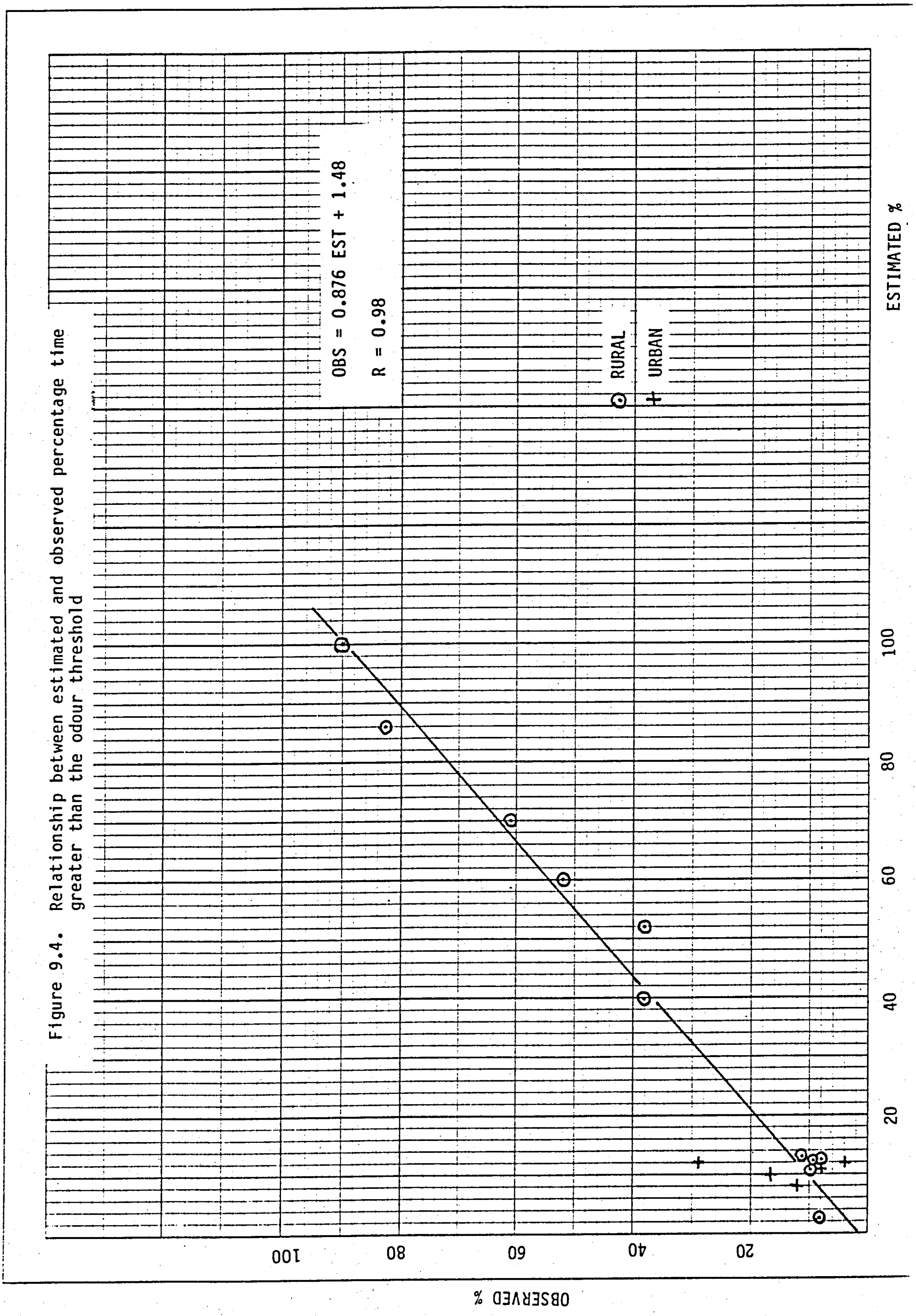
† Sampled every 2 min over period of one month, 8 h/day, 5 days/week.

‡ Eight dilutions to threshold predicted by TRC model.

not all observations downwind observations. In an urban area with very tall buildings inaccuracies expected because of distorted dispersion.

\+ data from this work

Figure 9.4. Relationship between estimated and observed percentage time greater than the odour threshold



9.4. Summary

An odour dispersion model was developed based upon the puff model principle described in Section 4. The model which was written in GW-Basic adopted a slightly different approach to that adopted by earlier modellers in that it conducted a numerical integration of the probability of exceeding a certain concentration in the plane passing through the observer, depending upon the position of the puff on the plane. The model was tested against field data collected both by the author and by other investigators and found to provide a good estimate of the observed values over a range of conditions.

10. DATA COLLECTION AND ANALYSIS

Research for this study was developed in laboratory tests and in the field. Tests conducted under laboratory conditions enabled better control of the variables but at the expense of testing under slightly artificial conditions, i.e. not fully representing real life where odours can fluctuate over a very short time.

The objective of these tests was to collect sufficient data which could be used to identify the important variables for assessing odour nuisance and could be used to develop a predictive model.

In practice the laboratory and fieldwork were conducted in parallel as the opportunity arose. Some of the information was drawn from historical data and the results of measurements taken during work on projects for the author's employer prior to the commencement of and during this study.

Information gained under laboratory conditions was tested on site. Discrepancies, unexpected features and variations observed in the field were then studied further under laboratory conditions. This iterative process was repeated until a greater understanding of the nature of odour nuisance was achieved and a predictive model was developed.

The investigations and tests carried out in the laboratory and on-site are described under separate headings.

10.1. Laboratory Tests

The main thrust of the laboratory tests was the assessment of odour samples; usually taken from the source, by odour panels using the dynamic dilution apparatus and methods described in Section 8.

Types of odours

The types of odours included in this study are listed in Table 10.1. They cover a wide range of unpleasant smells from hedonic tone -0.28 to -2.23.

Table 10.1. Types of odours studied in laboratory tests

Project	Type of odour
Pitsea Land Reclamation	Household Refuse, Chemicals, Oils
Milk Marketing Board	Dried Milk
Gatwick Airport	Aircraft Engine Exhaust
Campbells Chemicals	Pesticides
Cadishead Oil Storage Depot	Petroleum Products
Impact Litho	Lithographic Printing
Atherstone	Solvent Drying Ovens
Cape Boards	Fibre Board Curing Oven Emissions
Petroleum Development Oman	Crude Oil & Petroleum Products
PDO Single Buoy Moorings	Crude Oil Emissions from Tankers
Oman Refinery Company	Crude Oil & Petroleum Products
3M	Solvent Drying Ovens
Mina al Fahal Industrial Complex	Crude Oil & Petroleum Products
Ball & Young	Rubber Carpet Underlay Manufacture Drying Oven Emissions
Reclamation at Corby Steel Works	Toxic Waste Ponds
Entec (Pollution Control) Ltd	Glass Fibre Reinforced Plastic Manufacture Fumes
Watneys Brewery	Effluent
Springfield Proteins	Dried Blood
Blackamoor Lane Land Reclamation	Partially Decayed Waste Chemicals
Hong Kong Gas Works	Emissions Associated with Gas Production
Dover Engineering	Foundry

Data processing and analysis

The empirical data were assembled under the headings given in Table 10.2.

Table 10.2. Empirical data categories

1. Substance
2. *Detection threshold ratio
3. *Recognition threshold ratio
4. Annoyance score
5. Intensity
6. Hedonic tone

* i.e. dilution of sample divided by threshold dilutions.

In all 260 complete data sets were analysed. A full listing of the data is given in Appendix 6.

Table 10.3 indicates the range of the data tested. Data 2-5 (Table 10.2) inclusive were transformed to their logarithm to the base 10 to become data items 7, 8, 9 and 10 respectively. This transformation was undertaken as many of the relationships were expected to be of a logarithmic nature

Table 10.3 Descriptive data collected in laboratory tests

SUBSTANCE	NO. OF OBSERVATIONS	d/d		d/r		$\frac{d/d}{d/r}$	ANNOYANCE		INTENSITY		
		Mean	SD	Mean	SD		Mean	SD	Mean	SD	Tone
1	15	3.87	3.90	1.26	1.22	3.1	27.00	15.50	28.30	21.20	-0.82
2	17	5.95	5.60	1.65	1.56	3.6	29.40	16.30	33.20	19.50	-0.99
3	6	9.95	9.80	3.63	3.56	2.7	25.70	15.50	47.00	20.20	-2.2
4	17	13.65	21.90	0.91	0.97	15	25.60	13.50	22.80	15.80	-1.24
5	34	7.86	9.50	1.60	1.80	4.9	26.40	14.80	23.60	14.90	-1.51
6	46	20.36	31.90	0.95	1.19	21.4	16.90	11.40	21.90	12.70	-0.47
7	20	8.43	11.30	1.44	1.94	5.9	23.10	10.95	21.90	14.70	-0.63
8	8	3.45	3.60	0.73	0.74	4.7	22.50	15.20	19.80	17.60	-1.51
9	9	4.77	5.20	1.81	2.00	2.6	15.39	19.20	24.10	20.70	-0.64
10	8	10.20	16.90	3.14	5.20	3.2	25.13	27.00	28.10	29.90	-0.56
11	9	9.08	10.80	2.90	3.50	3.1	19.90	17.70	28.80	25.10	-1.0
12	10	6.68	8.10	1.84	2.30	3.6	15.81	14.30	29.37	18.90	-0.92
13	8	4.53	4.87	0.49	0.52	9.2	12.00	7.30	23.30	24.60	-1.25
14	8	5.56	6.20	1.44	1.60	3.9	24.90	29.10	34.60	31.20	-0.28
15	9	5.69	8.28	1.49	2.20	3.8	22.11	21.90	24.80	27.00	-0.71
16	10	8.51	12.97	2.23	3.40	3.8	25.92	27.20	28.90	31.30	-0.84
17	7	2.39	3.63	0.11	0.19	21.7	4.91	8.70	11.40	16.50	-0.84
18	9	2.67	3.50	0.68	0.86	3.9	8.73	14.30	15.49	19.60	-0.66
19	10	3.87	5.20	1.35	1.80	2.9	17.10	31.20	19.55	28.10	-0.72
	260					6.5					

Tone mean = -0.94 SD = 0.46 d/d = dilutions to detection threshold d/r = dilutions to recognition threshold

Table 10.3 Descriptive data collected in laboratory tests

Data 2-10 were then taken as variates and analysed for multiple linear regression relationships between annoyance or log annoyance and the other independent or predictor variables. An Apricot microcomputer was used to carry out this analysis running software known as SPP (Statistical Package for Personal Computers written by Royson (1984)).

Secondary variables were also derived from the primary variables, e.g.

- ratio $\dfrac{\text{dilutions to detection}}{\text{dilutions to recognition}}$
- psychophysical constant

and their use as predictors was also investigated.

Table 10.4 summarises the results of the multiple regression analysis of prediction models for annoyance and prediction models for intensity.

Table 10.4 is in four parts; 10.4(a) to 10.4(d). Part (a) lists regression relationships for annoyance, part (b) lists relationships for the logarithm of annoyance, part (c) relationships for intensity and part (d) gives relationships for logarithm of intensity.

In Table 10.4 each model tested is described in three columns of data, the first column and the pair of columns starting 'COEFFICIENT' then 'F TO REMOVE'. For example, the first model tested is described in columns 1, 2 and 3. The next model is described in columns 1, 4 and 5 and so on.

The first column lists the independent or predictor variables tested against annoyance. The value of the coefficient for the predictor variable is given under 'COEFFICIENT'. Under the 'F TO REMOVE' column are the F ratios for each variable, which represent the contribution of each variable to the goodness of fit in the presence of the others. The statistical significance of the constant (intercept) term is also given to indicate whether it may be omitted from the model. At the foot of each model is the amount of variance explained and the residual standard deviation or standard error of the estimate. Consider for example model 3 for annoyance in Table 10.4(a) in columns 1, 4 and 5. In this model, which is reproduced in equation E10.1, the only predictor variable was intensity (NWI). Thus:

$$\text{Annoyance} = 0.754\ \text{NWI} + 2.811 \qquad \text{E10.1}$$

$R^2 = 0.74$ $R = 0.86$ $n = 260$ stardard error of estimate = 8.903

corresponding to the 0.001 level of significance.

This simple equation gives a good estimate of annoyance, explaining 74% of the variance without the need to include a large number of variables. It can also be seen that intensity is far more significant than the intercept constant.

Table 10.4 Multiple linear regression models

ANNOYANCE	CO-EFFICIENT	F TO REMOVE	CO-EFFICIENT	F TO REMOVE	CO-EFFICIENT	F TO REMOVE	CO-EFFICIENT	F TO REMOVE	CO-EFFICIENT	F TO REMOVE	CO-EFFICIENT	F TO REMOVE	CO-EFFICIENT	F TO REMOVE
Detection threshold ratio	- 0.03	0.37	-		-		- 0.033	0.43	0.519	82.75				
Recognition threshold ratio	+ 0.565	1.14	+ 0.379	0.58			+ 0.624	1.31	-				6.283	308.3
Intensity	+ 0.671	101.43	+ 0.681	148.8	0.754	721.56	+ 0.678	98.22	-					
Hedonic tone	- 2.567	2.96	- 2.883	3.88	-		- 2.559	2.93	- 5.972	5.85				
Log (detection threshold ratio)	- 0.665	0.1	-				-1.469	0.30	-					
Log (recognition threshold ratio)	+ 1.114	1.44	+ 1.151	2.1			+ 1.465	1.52			11.39	159.7		
Log intensity	+ 1.221	0.46	-				+ 1.309	0.52						
Psychophysical constant	-		-		-		- 1.552	0.22	+ 18.56	28.02				
Constant	+ 1.21	0.27	+ 1.786	0.89	2.811	10.15	+ 2.636	0.48	- 3.718	1.0	25.03	780.6	12.25	189.3
VARIANCE EXPLAINED %	**74.6**		**74.4**		**73.7**		**74.6**		**27.1**		**38.2**		**54**	
RES S.D.	8.852		8.826		8.903		8.866		14.871		13.635		11.71	

Table 10.4 Continued

LOG (ANNOYANCE)	CO-EFFICIENT	F TO REMOVE	CO-EFFICIENT	F TO REMOVE
Detection threshold ratio	- 0.004	1.56		
Recognition threshold ratio	- 0.055	2.89		
Intensity	+ 0.009	4.96	+ 0.997	268.7
Hedonic tone	- 0.27	8.79	-0.253	7.43
Log (detection threshold ratio)	- 0.329	6.73		
Log (recognition threshold ratio)	+ 0.077	1.86		
Log intensity	+ 0.532	23.51		
Psychophysical constant				
Constant	- 0.142	1	- 0.425	14.4
VARIANCE EXPLAINED %	**57.1**		**52.8**	
RES S.D.	0.541		0.562	

Table 10.4 Continued

INTENSITY	CO-EFFICIENT	F TO REMOVE	CO-EFFICIENT	F TO REMOVE	CO-EFFICIENT	F TO REMOVE	CO-EFFICIENT	F TO REMOVE	CO-EFFICIENT	F TO REMOVE
Detection threshold ratio					+0.705	135.24	+ 0.71	137.4		
Recognition threshold ratio			8.14	615.9					+ 8.192	592.1
Intensity										
Hedonic tone							- 3.973	2.29	+ 0.42	0.06
Log (detection threshold ratio)	+22.89	379.6								
Log (recognition threshold ratio)										
Log intensity										
Psychophysical constant					+23.78	40.92	+ 23.24	38.91	- 1.623	0.43
Constant	+12.76	167.8	+12.8	246.16	-0.869	0.07	-4.139	1.1	+14.401	34.09
VARIANCE EXPLAINED %	**60**		**70**		**35.9**		**36.5**		**70.5**	
RES S.D.	12.564		10.732		15.842		15.802		10.763	

Table 10.4 Continued

LOG (INTENSITY)	CO-EFFICIENT	F TO REMOVE	CO-EFFICIENT	F TO REMOVE	CO-EFFICIENT	F TO REMOVE
Log (Detection threshold ratio) = A					0.671	114.22
Log (Recognition threshold ratio) = B					0.040	0.81
Psychophysical constant = C					0.347	10.56
C x A	0.910	530.7				
C x B			0.699	380.1		
Constant	0.855	1164.6	1.318	3078.3	0.581	22.53
VARIANCE EXPLAINED %	**67.3**		**59.6**		**65.1**	
RES S.D.	0.331		0.368		0.343	

It can be seen that intensity is the best single predictor of annoyance. The relationships given in Table 10.4 also suggest that tone is the next most important parameter after intensity, but only when in combination with intensity. By itself tone is a poor predictor of annoyance. The psychophysical constant was also of little value in determining annoyance.

Contrary to popular belief neither the detection nor the recognition threshold ratios, i.e. concentrations, are particularly good predictors of annoyance. Their relationships to annoyance in equations E10.2 and E10.3 show that only 38 and 54% of the variance can be explained, i.e. correlation coefficients of 0.62 and 0.74 respectively.

$$\text{Annoyance} = 11.39 \log {}^{d}/_{d} + 25.03 \qquad \text{E10.2}$$

$R^2 = 0.38$ $R = 0.62$ $n = 260$ standard error of estimate = 13.635 corresponding to the 0.001 level of significance.

and

$$\text{Annoyance} = 6.28 {}^{d}/_{r} + 12.25 \qquad \text{E10.3}$$

$R^2 = 0.54$ $R = 0.74$ $n = 260$ standard error of estimate = 11.709 corresponding to the 0.001 level of significance.

The relationships between odour detection and recognition threshold ratios and intensity are given in equations E10.4 and E10.5.

$$\text{Intensity} = 22.89 \log {}^{d}/_{d} + 12.76 \qquad \text{E10.4}$$

$R^2 = 0.60$ $R = 0.77$ $n = 260$ standard error of estimate = 12.564 corresponding to the 0.001 level of significance.

$$\text{Intensity} = 8.14\ {}^{d}/_{r} + 12.8 \qquad \text{E10.5}$$

$R^2 = 0.71$ $R = 0.84$ $n = 260$ standard error of estimate = 10.732 corresponding to the 0.001 level of significance.

It was found that the ratio of detection to recognition thresholds for 250 observations was distributed in the manner listed in Table 10.5.

Table 10.5. Ratio of detection to recognition threshold for 250 odorous samples

Ratio Range	Number of Occurrences	Percentage Occurrence
2 - 6	184	73.6
6 - 10	22	8.8
10 - 20	11	4.4
20 - 30	15	6.0
30 - 40	16	6.4
40 - 50	2	0.8
	250	100.0

These results confirm the findings of other investigators. Huey et al obtained a ratio of 7 and Hellman and Small (1974) obtained values in the range 2 to 10.

It should be emphasised that all of these relationships are based upon laboratory assessments of steady odours. We must now turn to observations in the field to consider the complete picture.

10.2. Fieldwork

During the studies listed in Table 10.1 it was possible to make a number of field observations and measurements.

These were essentially collecting data on the observed odour intensity downwind of the source using the techniques described in Section 8.4. Observations were also made of the conditions during the emission and in some cases the subjective effects, either as annoyance rating or as complaints. In only (two) studies was it possible to conduct social surveys to measure annoyance from a general population. In other situations where annoyance was assessed this was done by experienced observers. Table 10.6 indicates the range of data collected from field observations. A full listing of the data is given in Appendix 7.

Table 10.6. Descriptive data collected in field situations

Substance	Number Observations	ECI Mean	ECI SD	ANN Mean	ANN SD	Tone
Styrene	12	19.6	10.5	36.1	29.8	-0.34
Building board manufacture	4	2.6	1.3	4.3	8.5	-1.07
Dried blood	7	3.9	5.2	8.4	16.1	-2.09
Brewery effluent	1	9.3		17.0		-2.23
Land fill gas	7	7.6	3.7	10.9	15.9	-1.59
Farm silage	1	6.2		8.8		-1.68
Foundry emissions	6	24.9	10.4	69.2	22.9	-1.78
Waste disposal site	10	10.9	4.8	24.9	12.8	-1.22
	48					

Tone mean = -1.5 SD = 0.61

These data were analysed using multiple linear regression techniques as described in Section 10.1 "under data processing and analysis". Table 10.7 summarises the results of the analysis of prediction models for annoyance and logarithm (ECI).

The relationship between the intensity (ECI) and annoyance observed at locations downwind of five factories and a waste disposal site is plotted in Figure 10.1 and given in equation E10.6.

Annoyance = 2.61 ECI - 5.28 E10.6

$R^2 = 0.87$ R = 0.93 n = 48 standard error of estimate = 10.274 corresponding to the 0.001 level of significance.

With the inclusion of tone the relationship becomes that in equation E10.7.

Annoyance = 2.759 ECI - 6.51 TON - 15.37 E10.7

$R^2 = 0.872$ R = 0.93 n = 48 standard error of estimate = 9.459 corresponding to the 0.001 level of significance.

The field data were also analysed to find the relationship between the percentage time (%T) that the odour detection threshold was exceeded and the equivalent continuous intensity ECI.

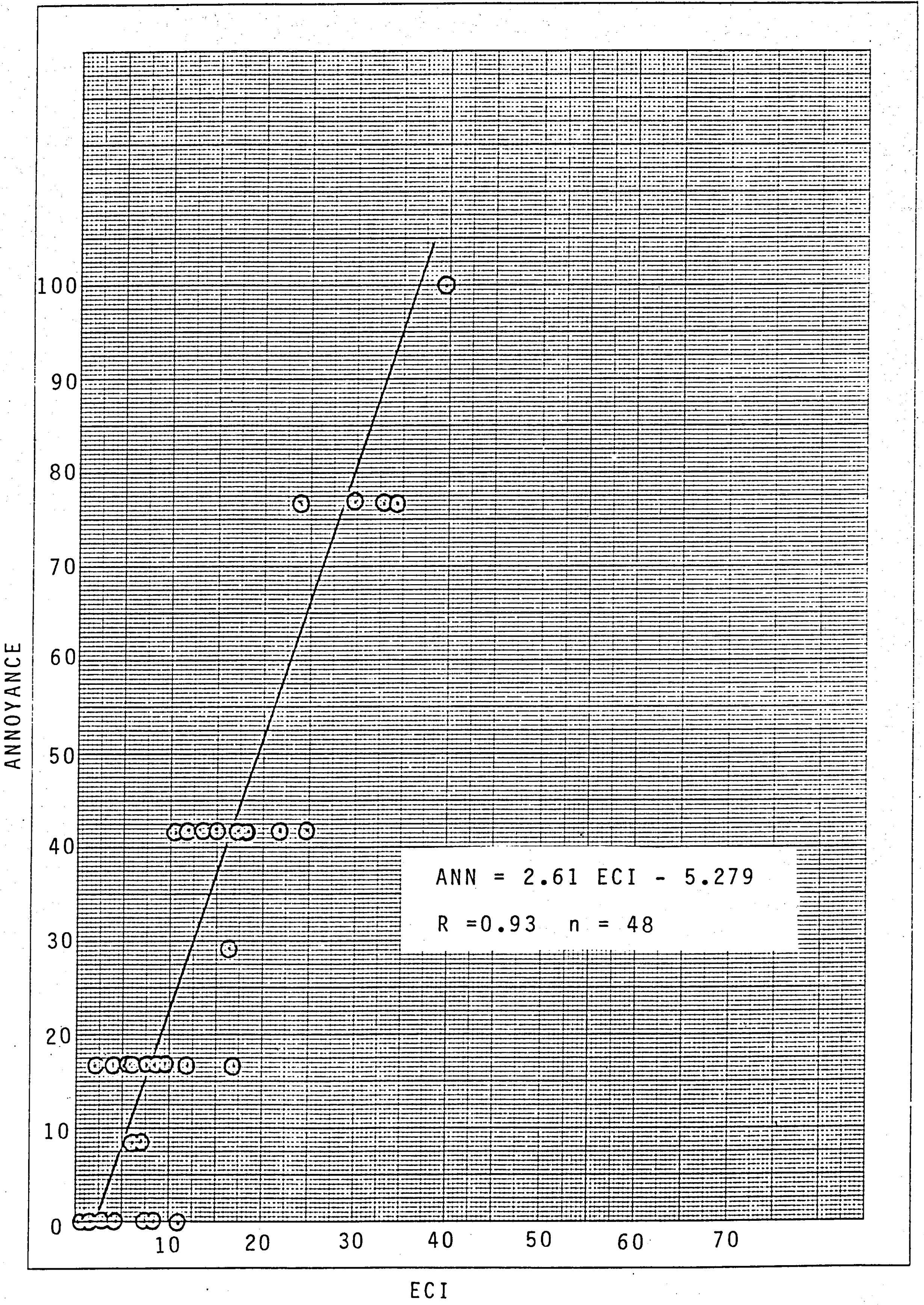
The best "fit" of the results from 158 observations using the Statistical Package for Personal Computers (SPP) was the relationship given in equation E10.8.

Table 10.7. Multiple linear regression models

ANNOYANCE	CO-EFFICIENT	F TO REMOVE	CO-EFFICIENT	F TO REMOVE
ECI	2.61	313.06	2.759	365.52
TON			-6.507	9.27
CONSTANT	-5.279	4.99	-15.368	15.03
VARIANCE EXPLAINED %	87.2		89.4	
RES S.D.	10.274		9.459	

LOG ECI	CO-EFFICIENT	F TO REMOVE
% T	0.015	617.0
CONSTANT	0.119	9.58
VARIANCE EXPLAINED %	79.8	
RES S.D.	0.206	

Figure 10.1 Relationship between observed downwind intensity and annoyance



$$\text{Log ECI} = 0.015\%T + 0.119 \qquad \text{E10.8}$$

$R^2 = 0.80$ $R = 0.893$ standard error of estimate = 0.206 corresponding to the 0.001 level of significance.

10.3. Summary

Data collected from the testing of a wide range of odours both in the laboratory and field situations included odour concentration, intensity, hedonic tone and annoyance. Various combinations of the predictor variables have been tested against annoyance and intensity in turn, using multiple correlation analysis to find relationships for use in a predictive model.

Very significant relationships have been found between annoyance and intensity (equation E10.1). Significant relationships have also been found between annoyance and concentration ratio (equations E10.2 and E10.3), intensity and concentration ratios (equations E10.4 and E10.5). In field tests, annoyance was found to be related to the effective continuous intensity (ECI) (equation E10.6) and the percentage time greater than the odour threshold (equation E10.8).

Each of these relationships are used in Section 12 in the development of the odour nuisance assessment model.

11. DEVELOPMENT OF CRITERIA

Section 5 sets out the current situation with regard to odour nuisance criteria, some of the difficulties experienced in applying the limits and recent developments in this field. In this section an attempt is made to develop these ideas into a simplified approach compatible with the odour annoyance model developed in this study.

The criteria identified in Section 5 which will be considered include the objectionability criteria for community annoyance, ambient concentrations based upon scentometer readings, ambient intensity criteria and the Netherlands odour standards.

11.1. Nuisance Criteria

Objectionability criteria

Community annoyance caused by odours is assessed by six control agencies in the U.S. by the use of objectionability criteria (see Section 5 and Table 5.6).

It can be argued that an odour nuisance exists or is deemed objectionable (U.S. terminology) when a certain level of annoyance is exceeded.

The levels of annoyance used in this study are:

a) none
b) slightly annoying
c) fairly annoying
d) very annoying
e) extremely annoying.

It is possible to interpret the annoyance scale as follows:

Something that is not annoying is acceptable. Probably something that is slightly annoying is tolerable and a nuisance occurs when the situation is no longer tolerable.
Therefore, fairly annoying is equal to the onset of nuisance.

If something is tolerable then it is not objectionable. Conversely we can assume that anything that is not tolerable is objectionable, i.e. **Fairly, very and extremely annoying are all objectionable.**

We can therefore assume that at the level at which something becomes objectionable it also becomes a nuisance, i.e. **Objectionable equals nuisance.**

As the level of annoyance will vary between individuals it is necessary to work with the average or 50% response in respect of the community. This is equivalent to the situation where 50% of the population are at least fairly annoyed, i.e. 50% of annoyance rating of at least 42 (see Section 8.2 on annoyance scaling) is an annoyance of at least 21.

The community odour criteria given in Table 5.6 can be interpreted in terms of community annoyance as indicated in Table 11.1.

Thus the criteria adopted in practice (U.S. legislation) to control odours through objectionability criteria, i.e. at least 17.3 is approximately equivalent to adopting a community annoyance of at least 21 as a nuisance criterion.

Ambient concentrations

Another approach to obtaining a tolerable level of annoyance is to consider the standards based upon maximum scentometer readings. Tables 5.2 and 5.6 are summarised in Table 11.2.

The average ambient limit applied by 12 different control agencies is 5 dilutions to detection threshold, i.e. approximately the threshold of recognition. This is consistent with the general consensus that odours become a nuisance when they are recognisable - Dravnieks (1979), WSL (1980), Keddie (1984) - see Section 2.

Table 11.1. Community annoyance

Agency	Implied not objectionable % (not annoying slightly annoying value $\frac{0 + 17}{2}$ = 8.5)*	Objectionable % (fairly+very+ extremely annoying minimum value 42)*	Average annoyance value (minimum)
Polk Country (Iowa)	70	>30	12.6 $
Cedar Rapids (Iowa)	70	>30	12.6
St. Louis	70	>30 (>20 people)	12.6
Missouri	25	>75 (>20 people)	31.5
Chatanooga + Hamilton County Tennessee	85	>15	6.3
Milwalkee County) Wisconsin)	33	>67	28.1
	Average	41	17.3

* see Section 8.2 on odour annoyance scaling

$ e.g. 30% of 42 = 12.6

Table 11.2. Summary of agencies with ambient odour limit control regulations

Agency	Ambient Limit Dilutions to detection threshold
Polk County (Iowa)	7 residential
Cedar Rapids (Iowa)	4 residential
St. Louis, Missouri	0 residential
Chatanooga + Hamilton County, Tennessee	0 residential
Omaha, Nebraska	4 residential
Colorado	7 residential
Columbia	1 ns
Illinois	8 residential
Kentucky	7 ns
Missouri	7 ns
Nevada	8 ns
Wyoming	7 ns
Average	5

ns = not specified

In Table 8.1 the threshold of recognition was equated to an intensity of "slight". In Table 8.2 this has a numerical value of 29 on the intensity scale. As an observer using a scentometer records the maximum concentration experienced and takes no account of odour fluctuations he is measuring the numerically weighted intensity (NWI).

By applying equation E10.1 an equivalent value of annoyance can be obtained.

Thus

$$\text{Annoyance} = 0.754\ \text{NWI} + 2.811 \qquad \text{E10.1}$$

$$\text{Annoyance} = 24.7 \doteqdot 25$$

Ambient intensity

Section 5.1.1 paragraph j describes the ambient odour intensity approach to assessing odours with the corresponding levels at which nuisance occurs. These data are summarised in Table 11.3.

Table 11.3. Odour intensity and nuisance

Binary butanol olfactometer port number	ppm_V butanol	Intensity category	Response	NWI	Annoyance
6	500	Strong	Nuisance	80	63
4	120	Easily noticeable, just recognisable, i.e. slight	Probable nuisance	29	25
3	60	Faint to easily noticeable, just recognisable, i.e. very slight-slight	Acceptable	23.5	21

ppm_V = parts per million by volume

Also included in Table 11.3 are the numerical intensity values (NWI) for each intensity category. These have been used to derive the corresponding value of annoyance based on the relationship given in equation E10.1.

It would appear from this table that nuisance as assessed by intensity occurs at an annoyance value somewhere between 21 and 25.

Netherlands odour standards

Consider now the odour standards developed in the Netherlands and described in Section 5, i.e. a limit of one odour unit/m^3 as the 99.5 percentile of the hourly averages over a year for new installations and one odour unit/m^3 as the 98 percentile for existing installations.

As described in Section 5 it is possible to estimate the concentration exceeded for any percentile using the log normal relationship, i.e.

$$C_f = M\ (S_g \uparrow Z_f) \qquad \text{E11.1}$$

where

C_f = concentration at percentile

M = geometric mean, i.e. 50 percentile

S_g = standard geometric deviation (S_g is used in order to avoid confusion with σ which has a special meaning, i.e. standard deviation of the plume concentration distribution)

Z_f = number of deviations from mean to equivalent frequency

If in Table 5.7 it is assumed that the 98 percentile and 99.5 percentile for each condition are derived from the same data base then it is possible to calculate the geometric mean and standard geometric deviation for each condition using simultaneous equation E11.1s. The results are given in Table 11.4.

Of primary importance are the geometric standard deviations which when averaged equal 3.28. This lies between that expected for an area source, i.e. 2, Voerman (1984), Luna (1974), Knox (1974), and that for a point source of 5, Knox (1974).

Table 11.4. Geometric mean and standard deviation of the odour concentration (odour units/m^3) in residential areas near to sources

	Number of companies	Complaints thresold		Perception threshold		Maximum in residential areas	
		M	S_g	M	S_g	M	S_g
Before control	28	0.58	2.77	0.07	3.89	1.3	3.06
After control with complaints	5	0.09	3.60	0.06	3.43	0.33	3.19
After control without complaints	6			0.015	3.89	0.11	2.42

Now it is possible to convert the odour standards into more familiar units using this geometric standard deviation of 3.28.

For example, starting with the odour standard.

Now 99.5 percentile = 1 (odour unit/m^3) hourly average, let the corresponding 50 percentile concentration = M

since

$C = M\ (S_g \uparrow Z_f)$

$M = 1/(3.28 \uparrow 2.56)$

$\therefore\ M = 0.0478$

With the geometric mean and standard deviation it is possible to estimate any percentile concentration, e.g. 90 percentile

$C_{90} = 0.0478\ (3.28 \uparrow 1.28)$

$C_{90} = = 0.219$

The concentrations so obtained are however the hourly averages. To be compatible with the system developed here it is necessary to consider the short term peak. Methods of making allowances for averaging time were discussed in Section 4, Table 4.2.

According to Turner (1970) the 3 minute average can be obtained from the 1 hour average by dividing by 0.61. According to WSL (1980) the 1 second average can be obtained by multiplying the 3 minute average by 10. Thus the corresponding 1 second concentrations are 16.4 ou/m^3 (99.5 percentile) 3.5 ou/m^3 (90 percentile) and 0.78 ou/m^3 (50 percentile).

If these and other percentile concentrations are plotted on log normal graph paper as in Figure 11.1, it is possible to obtain the percentile for exceedance of the short term (1-5 second) odour threshold or 1 ou/m^3, i.e. 41%.

If the same process is repeated for the 98 percentile odour standard then we obtain the corresponding 1 second concentrations of 16.4 ou/m^3 (98 percentile), 66 ou/m^3 (90 percentile) and 1.4 ou/m^3 (50 percentile). Again, if these are plotted in Figure 11.1 with other concentration percentiles related to the 98 percentile standard then it is possible to obtain the corresponding percentile for exceedance of the short term odour threshold. In this case a value of 62% is obtained.

We now have two estimates of the percentage time the odour threshold should not be exceeded, i.e. 41 and 62% of the time.

Using equations E10.4 and E10.2 the corresponding values of annoyance are calculated as 8.9 for new and 23.9 for existing premises respectively.

11.2. Discussion

Table 11.5 summarises the findings from the previous assessments of odour standards.

Figure 11.1 Short-term peak concentration percentiles equivalent to the Netherlands Odour Standards

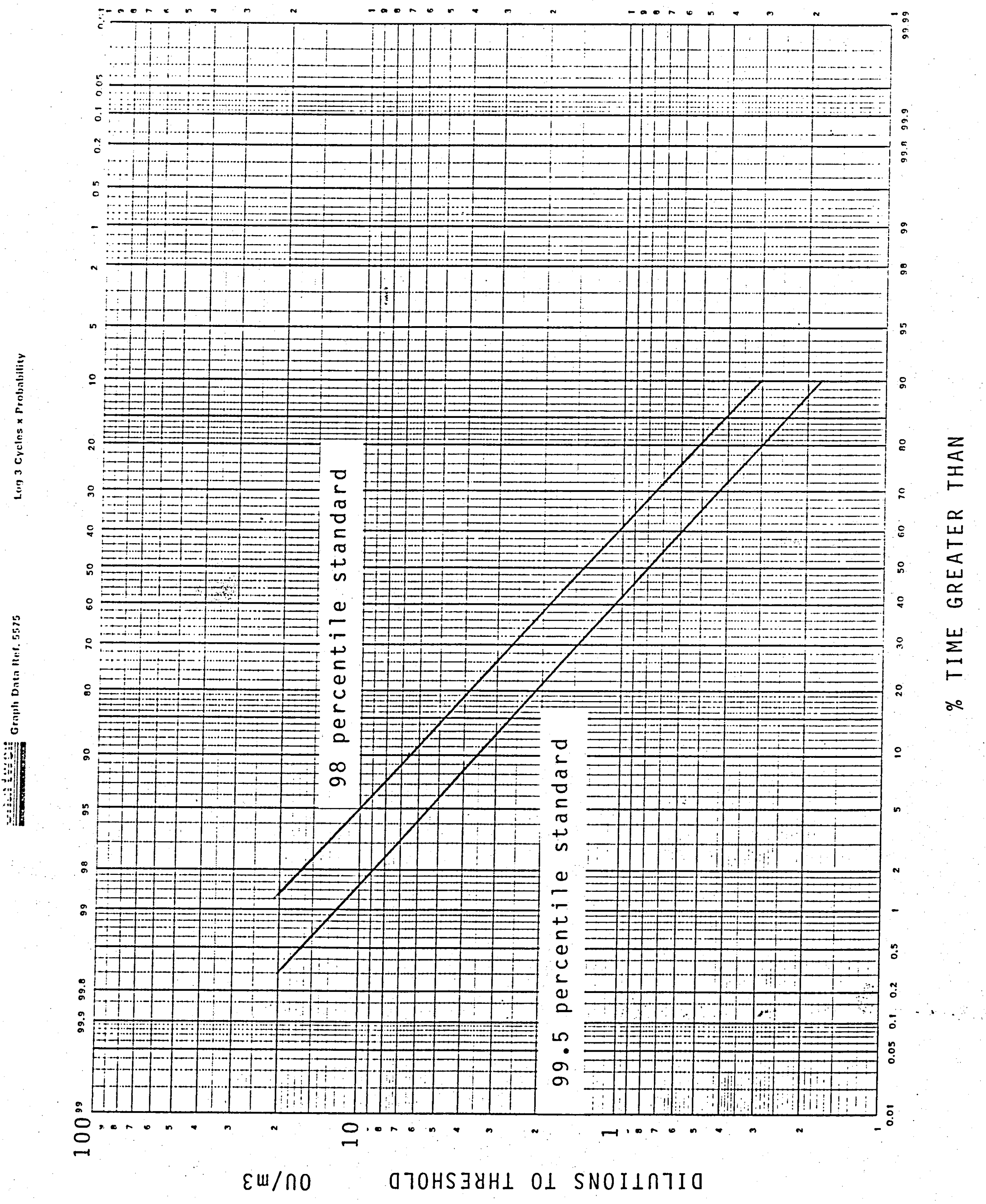


Table 11.5. Summary of odour annoyance criteria

Criterion	Annoyance Value
Objectionability	>21
Scentometer reading	25
Ambient intensity	21-25
Netherlands 99.5 percentile (new premises)	8.9
Netherlands 98.5 percentile (existing premises)	23.9

As far as can be determined all these criteria are based upon independent assumptions and are not different interpretations of the same data. The first criterion uses only the derived annoyance scale. Although the next two criteria rely on the intensity scale and the relationship given in equation E10.1 they are based upon very different observations. The second criterion is based upon observations related to concentration measurements, whilst the third is based on a comparison between a reference odour intensity and subjective response. The Netherlands odour standards were based upon independent empirical data collected from social surveys.

Except for one criterion which is very much stricter than the others, i.e. 8.9 for new premises, the consensus appears to be that conditions are no longer acceptable (a nuisance) at a level of annoyance of about 23. If all criteria are considered equally then nuisance occurs at an annoyance of about 21. This consensus figure is used in Section 12 in the development of the odour nuisance assessment model.

12. ODOUR NUISANCE MODEL

12.1. The Model

The relationships described in the last three sections can be combined to construct an odour annoyance model for assessing the existence of odour nuisance (i.e. unacceptable annoyance).

In Section 10, field data were analysed to find the inter-relationships between annoyance and the readily measurable parameters, i.e.

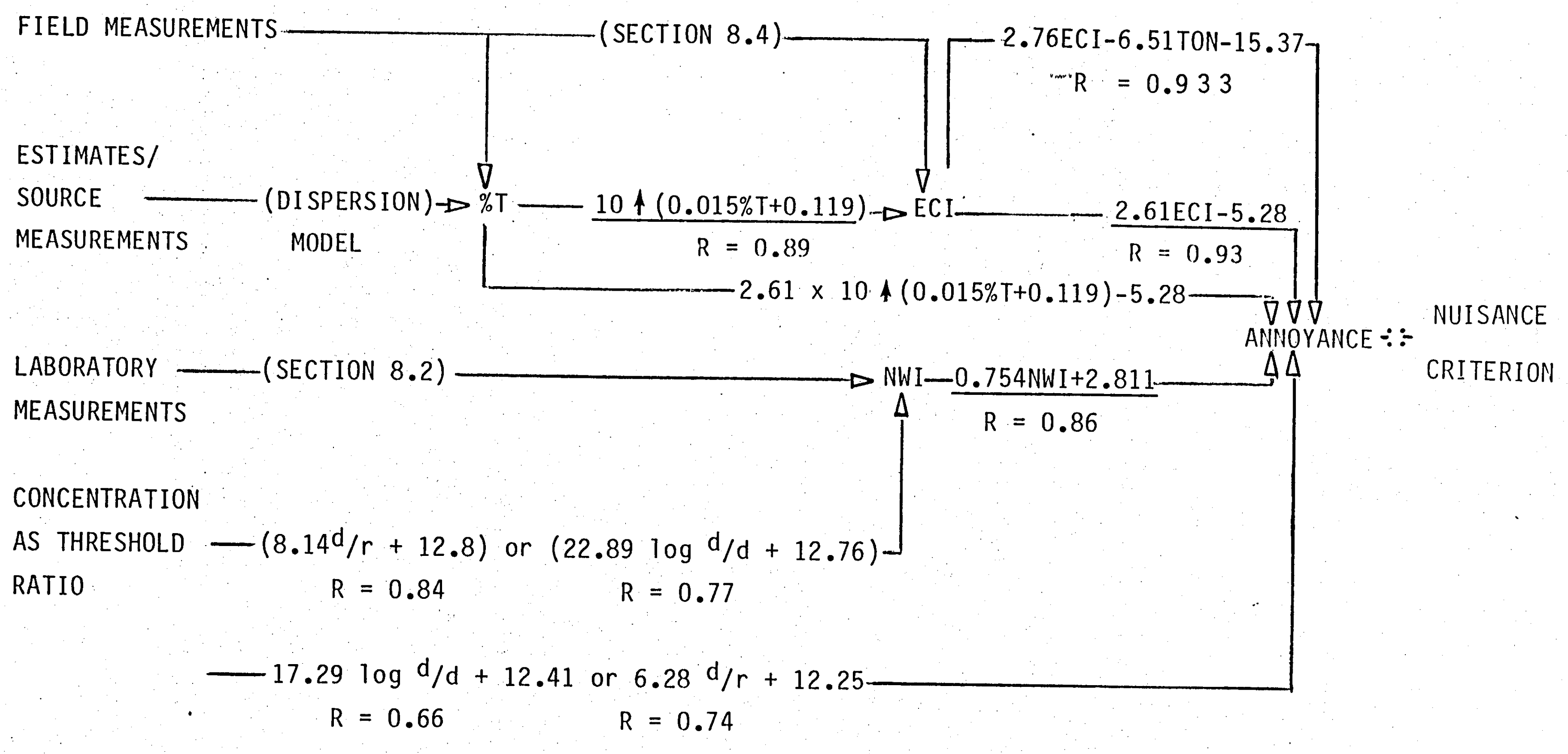
perceived intensity
hedonic tone
percentage time greater than the odour threshold
odour concentration
psychophysical parameter n.

Tables 10.4 and 10.7 summarise some of the relationships and their statistical significance.

Figure 12.1 indicates how these relationships relate to each other and how an odour annoyance "model" can be constructed.

The percentage time, greater than the odour threshold (%T), can be obtained from field observations as described in Section 8 or estimated using the computer model described in Section 9. The

Figure 12.1 The odour annoyance assessment "model"



%T = percentage time greater than detection threshold

Figure 12.1. The odour annoyance assessment "model"

%T can then be used with the relationships given in equation E10.8 to calculate the effective continuous intensity (ECI). Alternatively the ECI can be obtained directly from field observations as described in Section 8.4. The ECI is then used with the relationship given in equation E10.6 to estimate the corresponding value of annoyance.

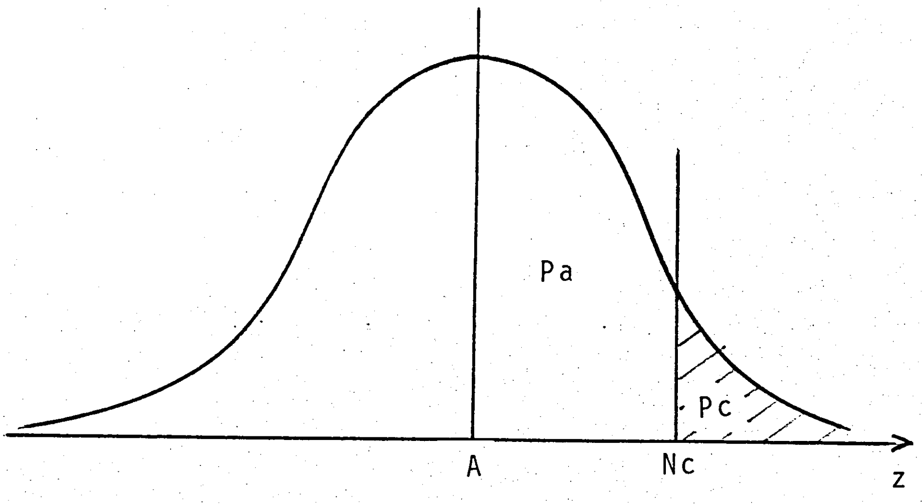
Alternatively annoyance can be calculated from various parameters measured on a sample of the odour in the laboratory. These include the measurement of the numerically weighted intensity as described in Section 8.2 or the concentration as described also in Section 8.2.

Neither the psychophysical constant n nor the hedonic tone appears to be an important factor compared to intensity. The reason why the tone as such is not significant is that it has probably already been taken into account subconsciously when assessing intensity. The intensity and hedonic tone are so inter-related (see Section 2.2) that it is almost impossible for the average observer to separate them.

Whether the annoyance is unacceptable, i.e. a nuisance (in the non legal sense) depends on whether its value exceeds the nuisance criterion developed in the previous section, i.e. an annoyance of 21.

Because the relationships for estimating annoyance are not precise the estimated annoyance is only the mean value within a possible range of values. In accordance with standard statistical procedures it is possible to fit confidence limits. However, if we consider the estimated annoyance as the mean of a normal distribution, then part of the distribution could exceed the nuisance criterion, as illustrated in Figure 12.2. The part of the distribution exceeding the criterion represents the probability of a nuisance occurring.

Figure 12.2. Estimated annoyance and the nuisance criterion



For simplicity it has been assumed that the nuisance criterion is a precise value - in practice the criterion will also be a distribution.

The probability can be estimated from the residual standard deviation (RES.SD) or standard error (SE) of estimate associated with the relationships used to obtain annoyance. (Not to be confused with S_g which is the geometric standard deviation and σ the standard deviation of the plume concentration distribution).

For example the probability of exceeding the nuisance criterion (P_c) is the percentage of the normal distribution greater than Nc or 21, i.e. the shaded area under the curve in Figure 12.2.

$$\text{Now } P_c = 50 - Pa \qquad \text{E12.1}$$

where Pa = percentage less than criterion but greater than the mean.

Pa can be obtained by calculating the number of standard deviation units z between the annoyance A and the criterion, 21 and then finding the corresponding probability from normal distribution tables of the function given in E9.4.

$$\text{Probability} = \int_{z1}^{z2} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{z^2}{2}\right) dz \qquad \text{E9.3}$$

$$\text{where } z = \frac{21 - A}{\text{RES.SD}} \qquad \text{E12.2}$$

In order to simplify odour nuisance analysis using the assessment model a computer programme has been prepared in GW-Basic. A full listing of ONAM (Odour Nuisance Assessment Model) is given in Appendix 2.

This programme utilises the relationships given in Figure 12.1 and the concept of the probability of nuisance occurring based upon the discussion above. The relationship described in equation E9.4 is used for estimating Pa; the percentage between the mean and the criterion.

For 0.1 standard deviation steps the probability within each step (dpa) is given by equation E9.4

$$dpa = \frac{4.47 - 1.98z}{100} \qquad \text{E9.4}$$

where z is in standard deviation units from the mean.

The total probability Pa is given by equation E12.3

$$Pa = \sum_{z = A}^{z = 21-A} dpa \qquad \text{E12.3}$$

or

$$Pa = \frac{1}{100}\sum_{z=A}^{z=21-A}\left(4.47 - 1.98\left(\frac{21-z}{10\ \text{RES.SD}}\right)\right) \qquad \text{E12.4}$$

in $z = 0.1$ standard deviation unit steps and where A is the estimated annoyance.

Residual standard deviations (RES.SD) for each annoyance prediction relationship were taken from Tables 10.4.

12.2. Summary

The relationships found between the variables measured during the data collecting stage of this project have been brought together to construct the odour nuisance assessment model given in Figure 12.1.

The standard error of estimate associated with each relationship was used to provide a probability of a nuisance occurring when the derived annoyance was compared with the nuisance criterion.

13. ODOUR NUISANCE ASSESSMENT MODEL TESTING

13.1. The Approach

There are two ways to test the validity of the odour assessment model described in Section 12.

The first method is to study a real situation and compare observed annoyance with predicted annoyance. This would involve firstly finding a suitable situation, where all the parameters could be measured and conducting a social survey to obtain the observed community annoyance. At the same time access would be necessary to the source of the odour to determine its emission characteristics.

Odour panels would be needed to determine the source odour concentration and intensity. The panel would also be needed to determine the effective continuous intensity in the community.

Alternatively one can test the elements of the model using historical data collected from previous studies.

The author hoped to be able to adopt the first approach using data from a study carried out as part of his employment duties. However, the opportunity did not arise. Rather than attempt to undertake a survey which would be beyond the resources of an individual, the author decided to use the second method of verification, i.e. using published data.

This has the attraction of using independent data which, if it can be applied, adds extra weight to the validation. However, since no other investigator is using an identical approach as the author there is no one source of data for testing the model fully. Several cases need to be examined.

13.2. Data Sources

In testing the odour annoyance model use has been made of the data collected by the investigators, described in Section 5.

The first data set originates from Goldsmith (1973) collected in the study described in Section 5.3.1 and summarised in Tables 5.8, 5.9, 5.10 and 5.11.

In order to be able to use these data it is necessary to express them in a compatible form. Annoyance which is given in degrees of bother needs to be converted into a numerical scale between 0-100.

If the highest degree of bother used in the Eureka and Carson studies, i.e. "very much bothered" is taken as 100 and "not bothered" taken as zero, then the question is what values should be given to "moderately bothered" and "little bothered"?

Table 13.1 sets out the scale of annoyance used in the California Study and that adopted for this work on the assumption that bother is another way of describing annoyance.

Table 13.1. Comparison of scales of annoyance - California study

California Study (Bothered)		This work (Annoyed)	
Very much	(100)	Extremely	100
Moderately	(60)	Very	77
		Fairly	44
Little	(17)	Slightly	17
Not	(0)	Nil	0

"Moderate" (on California scale) would appear to fall between very and "fairly" (on this work's scale).

"Little" (on California scale) seems to equate to "slightly". The equivalent numerical values in brackets were derived for the California scale. The average numerical values for "very" and "fairly annoyed" was used for "moderately bothered". "Little bothered" was given the same value as "slightly annoyed". The reader will recall that the numerical values for the annoyance scale used in this work were derived in Section 8.

Once the Eureka and Carson annoyance data can be equated to numerical values it is possible to derive an overall numerically weighted annoyance value using the procedure described in Section 8 (equation E8.2). The complete translated data for the Californian study is given in Table 13.2.

Table 13.2. Summary of odour exposure and translated community annoyance results for the California study

EUREKA 1969

	Area 1	 2	 3
%T	37.4	14.1	5.9
95 percentile concentration +	6.9	3.9	1.0
maximum concentration +	31.6	12.9	3.4
NWA	45.3	34.8	16.0
Number of respondents	52	55	51

EUREKA 1971

	Area 1	 2	 3
%T	19.5	6.0	13.3
95 percentile concentration +	9.0	6.9	9.1
maximum concentration +	10.95	7.8	14.4
NWA	50.8	35.8	25.5
Number of respondents	45	45	42

CARSON 1972

	Area 1	 2	 3
%T	100	100	100
95 percentile concentration +	127	131	143
maximum concentration +	204	184	232
NWA	59	52	21
Number of respondents	97	95	99

Footnotes

%T = percentage of observations greater than odour detection threshold

\+ = dilutions to odour detection threshold

NWA = numerically weighted annoyance

As the percentage time observations in the Californian data include all wind directions the reported percentages will be lower than the downwind, % times greater than the odour threshold, i.e. short-term frequency or STF, the parameter used to develop the model. The recorded values represent the long-term frequency LTF of % T.

The 95 percentile concentrations also contain the effects of wind variation but the maximum concentrations will be more representative of the downwind conditions.

The second data set originates from the work carried out by Copley International Inc. (1971) and described in Section 5.3.2 and summarised in Tables 5.12 to 5.17.

Again, as with the first data sets, these need to be put into a compatible form for use in this study.

Annoyance

Annoyance in the Copley study is again expressed as degrees of bother but unlike the Goldsmith data these are on a six point scale. The corresponding annoyance scales for the Copley study and this study are set out in Table 13.3 together with the intensity scale used in this study.

A numerical scale in brackets has been assumed for the Copley study scale of bother corresponding to the numerical values of intensity used in this work. This was adopted because of the same number of points on each scale and the similarity between descriptors. The corresponding numerical values on this study annoyance scale are also very similar.

Table 13.3. Comparison of scales of annoyance - Copley study

Copley Study		This work			
Degree of Bother		Annoyed		Intensity	
Very much	(100)	Extremely	100	Very strong	100
Much	(73)	Very	77	Strong	73
Moderate	(43)	Fairly	42	Moderate	43
Little	(22)	Slightly	17	Slight	22
Very little	(9)			Very slight	9
Don't know	(0)	Nil	0	Nil	0

( ) assumed scale

As with the Goldsmith data, once the annoyance results are equated to numerical values it is possible to derive an overall numerically weighted annoyance value for the data given in Table 5.16 using the procedure described in Section 8.

The corresponding values of annoyance for the Hawthorne area in 1970/71 are given in Table 13.4.

Table 13.4. Summary of odour exposure and translated community annoyance results for the Copley study

	December	March	June
%T	50	67.7	72.7
Average peak I(ECI)	15.9	17.0	22.5
NWA	42.5	48.4	54.3
Number of respondents	75	75	75

%T = average of the maximum percentage time detected

peakI = average of the maximum peak intensity detected

Intensity

In the Copley study the scale used for the intensity was 0-4. This is compared with the intensity scale used in this study in Table 13.5.

Very approximately the Copley study values are numerically one twentyfifth of the values used in this study, across all categories. A factor of 25 has therefore been applied to the observed intensities reported in Tables 5.13, 5.14 and 5.15 (reproduced as tables 13.6, 13.7 and 13.8).

As the intensity observations in the Copley study include all wind directions, an average figure will tend to be on the low side. A more realistic value for the downwind situation has been taken as the average maximum recorded. A single intensity value for each quarter was obtained by taking the average peak intensity over the study area. For example, in Table 5.15 the peak recorded at Location No. 1, i.e. the junction of 142nd and Judah Streets in June was an intensity of 0.6. The average peak intensity over all monitoring locations was 0.9 which when multiplied by a factor of 25 equates to an intensity of 22.5. This and the corresponding intensity values for the other testing campaigns are listed in Table 13.4.

Table 13.5. Comparison of intensity scales used in the Copley study and this work

Copley Category	Scale	This work Category	Scale
Very strong	4	Very strong	100
Strong	3	Strong	73
Moderate	2	Moderate	43
Slight	1	Slight	22
Very slight	0.5	Very slight	9
Nil	0	Nil	0

Table 13.6. Translated summary of odour intensity observations

December 1970

Summary of December ratings in TA(Hawthorne).

PEAK I	No	Panelist Location (Station)	Percent Time Detected and Mean Odor Intensity																PEAK %T
			Date:11/30/70				Date:12/1/70				Date:12/2/70				Date:12/3/70				
			AM		PM		AM		PM		AM		PM		AM		PM		
			%	M	%	M	%	M	%	M	%	M	%	M	%	M	%	M	
0.4	1	142nd & Judah		PANELIST SCREENING AND TRAINING, NO FIELD ACTIVITIES				PANELIST SCREENING AND TRAINING, NO FIELD ACTIVITIES			36	.4	21	.1			39	.3	39
0.3	2	141st & Glasgow									26	.3	9	.1			0	0	26
0.5	3	141st & Isis									26	.1	44	.5			0	0	44
0.1	4	140th & Judah															9	.1	9
0.4	5	139th & Glasgow									30	.3	40	.4			0	0	40
0.4	6	139th & Isis									13	.1	41	.4			2	0	41
0.2	7	139th & Judah									15	.2	11	.1					15
0.7	8	138th & Judah									61	.7	32	.3			20	.2	61
0.5	11	137th & Glasgow									7	.1	46	.5			19	.2	46
0.7	12	137th & Isis									55	.7	28	.5			20	.2	55
0.6	13	135th & Glasgow									19	.2	54	.6			26	.3	54
1.0	14	135th & Isis									20	.3	68	1.0			2	0	68
1.4	15	135th & Judah									100	1.4	45	.9			8	.1	100
1.3	16	134th & Glasgow									55	.6	79	1.3			56	.6	79
1.5	17	134th & Isis									47	.7	100	1.5			20	.2	100
0.2	21	Wiseburn & Hindry									18	.2	23	.2			0	0	23
0.6	22	Wiseburn & Judah									29	.3	50	.6			14	.1	50
Av 0.64																			Av50

	Date:12/4/70			
	AM		PM	
No	%	M	%	M
1		PANELISTS USED IN DEVELOPING ODOR PANEL/SCENTOMETER CORRELATIONS		
2				
3				
4				
5				
6				
7				
8				
11				
12				
13				
14				
15				
16				
17				
21				
22				

Table 13.7. Translated summary of odour intensity observations

March 1971

Summary of March ratings in TA(Hawthorne).

PEAK I	No	Panelist Location (Station)	Percent Time Detected and Mean Odor Intensity																				PEAK %T
			Date:3/15/71				Date:3/16/7				Date:3/17/7				Date:3/18/7				Date:3/19/7				
			AM		PM		AM		PM		AM		PM		AM		PM		AM		PM		
			%	M	%	M	%	M	%	M	%	M	%	M	%	M	%	M	%	M	%	M	
0.8	1	142nd & Judah					20	.1	0	0	5	0	12	.1	60	.8	35	.3	16	.1	61	.5	61
0.3	3	141st & Isis		PANELIST SCREENING AND TRAINING, NO FIELD ACTIVITIES			5	.1	48	.3	54	.3	13	.1	7	0	0	0	40	.3	22	.1	54
0.8	4	140th & Judah					16	.1	27	.3	32	2	0	0	33	.4	23	.2	46	.6	65	.8	65
1.1	8	138th & Judah					32	.2	65	.4	11	.1	9	.1	49	.4	17	.1	19	.1	67	1.1	67
1.1	9	138th & Isis					98	1.1	16	.1	44	.4	0	0	42	.3	30	.4	32	.3	11	.1	98
0.5	10	138th & Glasgow					38	.3			19	.1			87	.5	27	.2	11	.1	42	.3	87
0.4	12	137th & Isis					47	.4	5	0			15	.1	41	.3	0	0	62	.4	63	.4	63
0.4	15	135th & Judah					19	.1	0	0			0	0	21	.1	12	.1	56	.4	60	.3	60
0.2	14	135th & Isis							22	.2			0	0	6	.1	23	.2	10	.1	23	.2	23
0.8	13	135th & Glasgow					60	.8	62	.7	16	.1	23	.2	58	.5	39	.2	28	.2	0	0	62
0.7	18	134th & Judah									7	.1	58	.6	25	.2	11	.1	16	.1	90	.7	90
0.95	17	134th & Isis					3	0	21	.2	0	0	2	0	6	0	94	.95	2	0	4	0	94
0.3	16	134th & Glasgow					27	.2	40	.3	0	0	0	0	13	.1	11	.1	48	.3	23	.1	48
1.1	22	Wiseburn & Judah					100	1.1	57	.6													100
1.2	20	Wiseburn & Hansworth					28	.1	39	.4	61	.5	28	.1	41	.3	11	.1	86	1.2	23	.2	86
0.2	19	132nd & Hindry					12	.1	25	.2	0	0	0	0	0	0	16	.1	20	.1	0	0	25
Av 0.68																							Av 67.7

Table 13.8. Translated summary of odour intensity observations

June 1971

Summary of June ratings in TA(Hawthorne).

PEAK I	No	Panelist Location (Station)	Percent Time Detected and Mean Odor Intensity																				PEAK %T
			Date:6/14/71				Date:6/15/71				Date:6/16/71				Date: 6/17/71				Date:6/18/7				
			AM		PM		AM		PM		AM		PM		AM		PM		AM		PM		
			%	M	%	M	%	M	%	M	%	M	%	M	%	M	%	M	%	M	%	M	
0.6	1	142nd & Judah					8	0	11	.1	1	0	0	0	89	.6	0	0	0	0	0	0	89
0.1	3	141st & Isis		PANELIST SCREENING AND TRAINING, NO FIELD ACTIVITIES			16	.1	3	0	10	.1	8	0	0	0	5	0	16	.1	2	0	16
	4	140th & Judah																					
	8	138th & Judah																					
0.2	9	138th & Isis					38	.2	1	0	1	0	20	.1	0	0	0	0	0	0	0	0	38
0.5	10	138th & Glasgow					36	.3	30	.2	1	0	40	.3	0	0	32	.5	5	.1	0	0	40
1.3	12	137th & Isis					41	.3	27	.1					5	0	12	.1	7	.1	100	1.3	100
1.5	15	135th & Judah					16	.1	33	.3	100	1.5	39	.3	52	.6	49	.5	41	.4	33	.3	100
0.6	14	135th & Isis					51	.6	11	.1	0	0	35	.4	12	.1	33	.3	28	.2	19	.1	57
0.9	13	135th & Glasgow					66	.9	4	0	15	.1	0	0	32	.4	9	.1	5	0	17	.1	66
1.6	18	134th & Judah					56	.4	32	.3	11	.1	92	1.6	37	.3	90	.8	7	.1	10	.1	92
1.1	17	134th & Isis					51	.5	82	1.1	28	.2	46	.6	23	.1	26	.3	10	.1	34	.5	82
0.6	16	134th & Glasgow					60	.5	3	0	48	.6	49	.5	8	0	31	.3	23	.2	12	.9	60
0.6	22	Wiseburn & Judah					22	.3	78	.4	28	.2	15	.2	9	0	100	.6	67	.3	40	.4	100
1.7	20	Wiseburn & Hansworth					100	1.7	10	.1	25	.2	9	.1	1	0	44	.3	12	.1	27	.2	100
1.3	19	132nd & Hindry					84	1.3	52	.5	29	.2	8	0	7	0							84
Av 0.9																							Av 72.7

It will be recalled that the average peak intensity given in Table 13.4 was obtained by the following steps:

1) A category assessment was made on site of the maximum intensity detected in each one minute period (Section 5.3.2).
2) These were averaged over four hours (Tables 5.13, 5.14 and 5.15) to obtain a statistical measure of intensity very similar to ECI.
3) As observations were made regardless of wind direction this study has adopted the average maximum as being representative of the downwind value.

Temporal Variation

Because observations were made regardless of wind direction, a similar argument applies for taking the mean peak percentage time that odours were detected. The resultant averages are included in Table 13.4.

The third data set is that collected by Winneke and Kastka (1977) and described in Section 5.3.3. This was summarised in Table 5.18 and is reproduced as Table 13.9 with some modifications. As the odour annoyance dimensions F1, F2 and F3 accounted for 50, 23 and 24% of the variance respectively, it was assumed that the best measure of total annoyance was the sum of all three. This figure is listed in the appropriate columns of Table 13.9 multiplied by 10/3 to convert the scale from 0-30 to 0-100 for comparison with this work.

Table 13.9 Summary of total odour annoyance and concentrations at various distances from four different industrial odour sources

DISTANCE (m)	TAR OIL PLANT CONCENTRATION d/d	TAR OIL PLANT ANNOYANCE 1	2	3	TOTAL	INSULATION PLANT CONCENTRATION d/d	INSULATION PLANT ANNOYANCE 1	2	3	TOTAL	CHOCOLATE FACTORY CONCENTRATION d/d	CHOCOLATE FACTORY ANNOYANCE 1	2	3	TOTAL	BREWERY CONCENTRATION d/d	BREWERY ANNOYANCE 1	2	3	TOTAL
		5.4	3.2	2.4	36.7															
10	16	5.6	3	2.2	36	16														
25	14	6.3	3.3	3.0	42						25									
50	14										25	4.7	1.8	1.6	27					
60						14						4.5	2.1	1.4	26.7					
75																				
90																				
100						12					13	3.3	1.0	0.5	16.0	8	5.8	3.4	3.0	40.7
115																				
125							4.5	2.8	1.2	28.3		4.6	1.8	0.8	24.0					
130	14					10	6.8	4.2	3.9	50.0										
140																				
150																	5.0	2.3	2.1	31.3
190	13	5.8	2.8	3.0	36		6.6	4.5	4.2	51.0										
200																				
240	13					9	5.3	2.3	1.8	31.1										
250																	4.7	2.8	2.3	32.6
265		6.6	3.5	3.5	45.3															
300		6.5	3.5	2.7	42.3		5.0	2.3	2.0	31										
310																				
340		6.2	3.6	2.8	42.0	7.5					2									
350	16											2.5	0.8	0.5	12.6					
400							3.8	2.2	2.0	26.7										
410	38					5.6														
425												2.0	0.6	0.4	10.0					
450		5.8	3.3	3.0	40.3															
470		5.9	3.5	3.0	41.4															
500	20	5.7	2.9	2.6	35.3															
600		6.4	2.6	3.3	41.0															
700	19																			
800		4.5	2.9	2.2	32.0		4.1	2	1.2	24.3										
1200		5.4	3.0	2.4	36.0															
1400	18																			
1600							1.6	1	0.2	9.3										

The fourth data set is that collected by Gynp et al (1985) and previously described in Section 5.3.4. Very little translation of the data is necessary for use in this study. The measured annoyance was on a scale 0-10 and therefore values given in Table 5.19 need to be multiplied by 10.

For the reasons set out in Section 2 it has also been assumed that the threshold of complaint as measured by Gynp is synonymous with the threshold of recognition and therefore dilutions to complaint threshold in Table 5.19 can be read as dilutions to recognition threshold. These data are reproduced in Table 13.10.

13.3. Model Testing

The component relationships making up the model set out in Figure 12.1 were tested as follows.

13.3.1. Source Parameters to % Time Greater Than The Odour Threshold

The dispersion model was tested by comparing the expected % time (as given by the dispersion model) with observed % times greater than the odour threshold. These comparisons have already been described in Section 9 and in particular in Table 9.1. The correlation coefficient relating the observed and estimated values is 0.98 (Figure 9.4).

Table 13.10. Summary of odour dose and response reactions near four different sources

SOURCE	CONCENTRATION D/T	THRESHOLD RATIO d/d	THRESHOLD RATIO d/c	MEASURED ANNOYANCE*	REACTION	% DETECTING	% COMPLAINING
LAND FILL WELL THRESHOLDS (10000=d/d, 2000=d/c for 50% pop)	18000	0.55		10	TOLERABLE	30	24
			0.11				
	10000	1.0		17	TOLERABLE	50	30
			0.22				
	6000	1.7		22	UNPLEASANT	66	37
			0.33				
	2000	5		29	UNPLEASANT	87	50
			1				
	1000	10		46	VERY UNPLEASANT	92	66
			2				
	300	33.3		70	TERRIBLE	100	87
			6.7				
FOUNDRY THRESHOLDS (1000=d/d, 800=d/c for 50% pop)	1000	1		15	TOLERABLE	50	34
			0.8				
	500	2		36	UNPLEASANT	86	86
			1.6				
	170	5.9		60	VERY UNPLEASANT	100	100
			4.7				
	60	16.6	13.3	80	TERRIBLE	100	100
PAINT WORKSHOP THRESHOLDS (120=d/d, 85=d/c for 50% pop	120	1		20	TOLERABLE	50	34
			0.71				
	60	2		36	UNPLEASANT	77	77
			1.4				
	20	6		64	TERRIBLE	88	88
			4.3				
WASTE WATER TREATMENT PLANT THRESHOLDS (300=d/d, 240=d/c for 50% pop	300	1		8	TOLERABLE	50	36
			0.8				
	160	1.9		18	TOLERABLE	87	74
			1.5				
	55	5.4		32	UNPLEASANT	100	87
			4.4				
	20	15		44	VERY UNPLEASANT	100	100
			12				

Foot Notes

d/d = dilutions to detection threshold

d/c = dilutions to complaint threshold (assumed to be equivalent to recognition threshold)

* = translated

13.3.2. Percentage Time Greater Than Odour Threshold and Effective Continuous Intensity (ECI) To Annoyance

These relationships are given by equations E10.8 and E10.6, i.e.

$$\log ECI = 0.015\%T + 0.119 \qquad E10.8$$

and

$$\text{Annoyance} = 2.61\ ECI - 5.28 \qquad E10.6$$

When combined these equations give the further relationship E13.1.

$$\text{Annoyance} = 2.61 \times 10\ (0.015\%T + 0.119) - 5.28 \qquad E13.1$$

The data used for testing these relationships are taken from Table 13.4. These are reproduced in Table 13.11 together with the annoyance estimated from equations E10.6 and E10.8. There is a better agreement between the observed and estimated annoyance from relationship E10.6, i.e. 0.88, using intensity observations, than there is from both relationships combined (E13.1), i.e. 0.55, starting from observations of the percentage times that odours are detected.

One reason for this has already been identified as being the fact that the observations were made regardless of wind direction.

Table 13.11. Testing of relationship E10.6 and E10.8 using the Copley data

	December 1979	March 1971	June 1971	Average
% T	50	67.7	72.7	
Average peak I (ECI)	15.9	17.0	22.5	
NWA	42.5	48.4	54.3	
Estimated ECI from equation E10.8	7.4	13.6	16.2	
$\frac{\text{Estimated ECI}}{\text{Observed ECI}}$	0.47	0.8	0.72	0.66
Estimated annoyance from equation E10.6	36.2	39.1	53.4	
$\frac{\text{Estimated annoyance}}{\text{Observed annoyance}}$	0.85	0.81	0.98	0.88
Estimated annoyance from equation E13.1	14.0	30.3	37.0	
$\frac{\text{Estimated annoyance}}{\text{Observed annoyance}}$	0.33	0.63	0.68	0.55

If only downwind observations had been made then the % time and intensity values recorded would have been higher. These would have raised the estimated annoyance values and there would have been closer agreement between the predicted and observed annoyance.

There are of course shortcomings in relationships E10.6 and E10.8 as their correlation coefficients are 0.93 and 0.89 respectively and there is probably more error introduced in using a two stage relationship than estimating annoyance direct from observed intensity.

13.3.4. Odour Concentration to Annoyance

There are two relationships between the odour concentration in terms of odour threshold ratios and annoyance depending upon which theshold is used.

These were given in equations E10.2 and E10.3 as

$$\text{Annoyance} = 11.39 \log {}^{d}/d + 25.03 \qquad \text{E10.2}$$

and

$$\text{Annoyance} = 6.28 \, {}^{d}/r + 12.25 \qquad \text{E10.3}$$

The data used for testing these relationships are taken from Tables 13.2, 13.9 and 13.10.

These data are reproduced in Tables 13.12, 13.13 and 13.14 together with annoyance estimated using these two equations.

A summary of the findings is given in Table 13.15.

Table 13.12. Comparison of observed and estimated annoyance using data from Table 13.2

Observed concentration ($^{d}/d$)	annoyance	Estimated annoyance	Estimated annoyance / Observed annoyance
31.6	45.3	42.1	0.93
12.9	34.8	37.7	1.08
3.4	16.0	31.1	1.94
10.95	50.8	36.9	0.73
7.8	35.8	35.2	0.98
14.4	25.5	38.2	1.50
204	59	51.3	0.87
184	52	50.8	0.98
232	21	52.0	2.47
			1.27+/-0.2SE

Table 13.13. Comparison of observed and estimated annoyance using data from Table 13.8

Observed		Estimated	Estimated annoyance
concentration $(^d/d)$	annoyance	annoyance	Observed annoyance
16	36.7	38.7	1.06
14	36	38.1	1.06
14	42	38.1	0.91
13	36	37.7	1.05
13	45.3	37.7	0.83
13	42.3	37.7	0.89
16	42	38.7	0.92
30	40.3	41.9	1.04
26	41.3	41.1	1.00
20	35.3	39.8	1.13
19	41	39.6	0.97
18.5	32	39.5	1.23
18	36	39.3	1.09
12	28.3	37.3	1.32
12	50	37.3	0.75
12	51	37,3	0.75
9	31.3	35.9	1.15
9	31	35.9	1.16
7.5	26.7	35.0	1.31
25	27	41.0	1.52
25	26.7	41.0	1.54
13	16	37.7	2.36
13	24	37.7	1.56
2	12.6	28.5	2.26
2	10	28.5	2.85
8	40.7	35.3	0.87
8	31.3	35.3	1.13
			1.25 +/- 0.1

Table 13.14. Comparison of observed and estimated annoyance using data from Table 13.10

Observed			Estimated		Estimated observed	
$^d/d$	$^d/r$	Annoyance	Annoyance from $^d/d$	Annoyance from d/r	from $^d/d$	from $^d/r$
0.55	0.11	10	22.1	12.9	2.21	1.29
1.00	0.22	17	25.0	13.6	1.45	0.8
1.7	0.33	22	27.7	14.3	1.25	0.65
5	1	29	33.0	18.53	1.14	0.64
10	2	46	36.4	24.8	0.79	0.54
33.3	6.7	70	42.4	54.3	0.61	0.78
1	0.8	13	25.0	17.3	1.92	1.15
2	1.6	36	28.5	22.3	0.79	0.62
5.9	4.7	60	33.8	41.8	0.56	0.70
16.6	13.3	80	52.8	95.8	0.66	1.2
1	0.71	20	25.0	16.7	1.25	0.84
2	1.4	36	28.5	21.0	0.79	0.58
6	4.3	64	33.9	39.3	0.53	0.61
1	0.8	8	25.0	17.3	3.13	2.2
1.9	1.5	18	28.2	21.7	1.57	1.21
5.4	4.4	32	33.4	39.9	1.04	1.25
15	12	44	38.4	87.6	0.87	2.0
					1.21 +/- 0.17SE	
						0.71 +/- 0.07SE

Table 13.15. Summary of comparison between observed and estimated annoyance using equations E10.2 and E10.3

Data	Ratio estimated annoyance / observed annoyance Equation E10.2	Equation E10.3
Goldsmith (1973) Table 13.2	1.27+/-0.2SE n = 9	-
Winneke + Kastka (1977,1987) Table 13.8	1.25+/-0.1SE n = 27	-
Gynp (1985) Table 13.9	1.21+/-0.17SE n = 17	0.71+/-0.07SE n = 17

It can be seen that the two relationships between annoyance and odour concentration (E10.2 and E10.3) are applied to the three independent data sets and that the estimated annoyance approximates to that observed.

13.3.5. Nuisance Criterion

Table 5.20 indicates that the limit to tolerable annoyance is about 2.1 on the Gynp rating or 21 on the scale of annoyance used in this study. These independent data confirm the findings in Section 11 which derived the level of unacceptable annoyance as about 21.

13.4. Summary

Published data have been used for testing the odour nuisance assessment model described in Section 12. However, before these data could be used they had to be converted into a form that was compatible with the model.

Apart from the odour dispersion model, which was tested in Section 9, each component of assessment model was tested individually. Estimates of annoyance using the concentration in terms of the detection threshold ratio, were about 20% higher than observed. The recognition threshold ratios gave values about 30% less than the observed levels of annoyance. Estimates of annoyance based upon the effective continous intensity were about 10% lower than observed. The percentage time greater than the detection threshold under-estimated effective continuous intensity (ECI) by about 30%. The nuisance criterion extracted from the Gynp study was identical to that developed in Section 11 as part of the model.

Considering the original form of the published data which were of unknown accuracy there was generally a good overall agreement between the estimated and corresponding observed values. The assessment model appears to give realistic estimates and can therefore be assumed to be valid.

14. CONCLUSIONS

The assessment method which was tested in Section 13.2 and is set out in Figure 14.1 was found to successfully predict annoyance with +/-20% of the value obtained by independent observers.

Estimates of annoyance based upon intensity and the percentage time greater than the odour detection threshold tend to give values less than the observed value while estimates based on concentrations tend to be slightly in excess of the observed value.

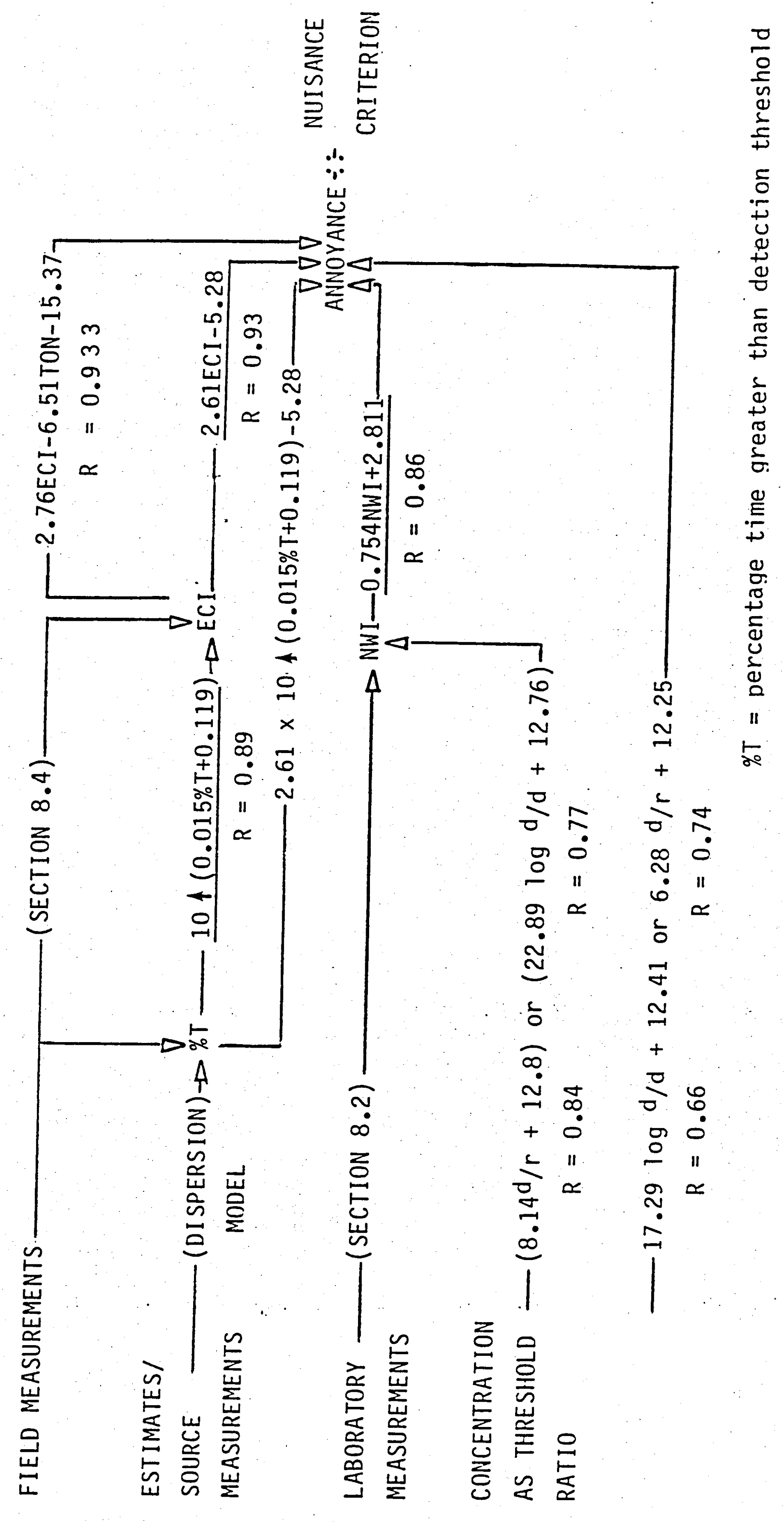
For the first time, a complete odour nuisance assessment method has been assembled which enables the user to assess odour exposure for nuisance by many different routes.

Because it has been tested against independent observations, established odour nuisance standards and guidelines it has been demonstrated that it can be applied to different types of data. Unlike the existing situation it is not dependent upon one particular item of equipment, e.g. Warren Spring dynamic dilution apparatus or the Scentometer. It also eliminates the need to rely heavily on the judgement of the assessor.

The belief is that this method will now bring a unified approach to the assessment of odour nuisance, a greater willingness for both the person responsible for the odour and the control authorities to investigate, speedier resolution of odour problems and a significant improvement in our environment.

Figure 14.1 Odour nuisance assessment model

Figure 12.1 The odour annoyance assessment "model"



%T = percentage time greater than detection threshold

15. RECOMMENDATIONS FOR ASSESSING ODOUR NUISANCE

The way the model is used depends upon the situation being investigated. For example, consider the following scenarios.

15.1. Existing Source-Access Available at the Point of Interest Downwind of the Source

In this situation observations would be made at the point of interest of the odour intensity distribution as described in Section 8.4. This would be used to derive the ECI from which annoyance can be estimated.

Alternatively, annoyance can be assessed directly using an experienced odour panel at the point of interest and applying the techniques described in Section 8.

15.2. A Proposed Source for Which the Source Design Emission Parameters are Known or an Existing Source with Known Emission Parameters Where There is No Access to the Point of Interest or the Point of Interest is Not Downwind During the Assessment Period

In this situation it would be necessary to estimate the downwind annoyance using the odour dispersion model and the relationship between %T and annoyance.

15.3. A Steady Odour in a Confined Space

In this situation it is best to use an odour panel to assess the odour intensity and derive the NWI according to the steps described in Section 8.2 from which the annoyance can be estimated.

If an odour panel is not available then the concentration can be measured using a suitable instrument and making reference to published data on the odour threshold. The annoyance would then be estimated from the concentration using the appropriate relationship, i.e. detection or recognition.

The accuracy of organoleptic measurements can be improved if odour panels are used. As described in Section 3 the bigger the better. However, results with an acceptable degree of accuracy can be obtained by small panels which have been pre-screened and trained.

In estimating the annoyance preference should be made of the approach available with the least number of steps necessary to reach the estimate.

Whatever route is taken to estimate the annoyance, the value should be compared with the nuisance criterion described in Section 11, i.e. a value of 21.

The probability of a nuisance occurring can be determined by using the procedure described in Section 12 to find the percentage of the normal distribution about the estimated annoyance that is greater than the odour nuisance criterion of 21.

The use of the computer model ONAM is recommended for rapid assessment of odour situations.

16. FURTHER WORK

The aim of this work was to develop improved techniques for the assessment of odour nuisance. Table 7.1 listed the more important factors which needed to be considered but in order to make advances, research was concentrated on those areas where most progress could be made most easily.

What is needed now is for the proposed techniques to be tried and tested independently in order to answer the question "how easy do others find them to use?".

Further testing of the relationship between annoyance and the effective continuous intensity would also be valuable particularly if it were linked to social surveys. The recommended techniques relate to relative short term exposure, no account has been taken (except possibly during the testing) of acclimatisation, long term frequency of exposure and the duration of exposure. The relationship between the source of the odour and the recipient and past experiences of the odour are factors which are probably best tackled by social survey techniques.

With regards to modelling the dispersion of odorous gases, further work needs to be carried out on the estimation of odours downwind of fugitive sources, such as a pond, waste tip or field where sewage sludge may have been spread.

The author intends to continue his research beyond this thesis in order to answer these questions.

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REFERENCES

Amoore J.E., Johnston J.W., Rubin M. (1964). The Stereochemical Theory of Odour. Sci Amer. Feb. 1964.

Amoore J.E. (1970). Molecular Basis of Odour. Springfield Ill Charles C. Thomas.

Anon (1957). Attorney General v P.Y.A. Quarries Ltd. 2 QB 169.

Anon (1966). Interstate Air Pollution Study Phase II Project Report Vol. VIII. Proposal for Air Resource Management Program. Vol. IV Odours - Results of surveys. U.S. Public Health Service, May 1960.

Anon (1970). Methods for Measuring and Evaluating Odorous Air Pollutants at the Source and in Ambient Air. (Report of an International Symposium in Stockholm June 1-5 1970.) Nordisk Hygienisk Tidskrift (1970) and Ll nr. 2.

Anon (1979). Odors from Stationary and Mobile Sources. Assembly of Life Sciences National Research Council. Nat Acad Sci, Washington DC, 1979.

Anon (1980). Odour Control - A Concise Guide (editors Valentin F.H.H. & North A.A.). Report for the Department of the Environment by Warren Spring Laboratory.

Anon (1985). Vorentwurf Richtlinie Bestimmung der Geruchsimmission durch Begehungen VDI 3940, Dusseldorf.

Anon (1986). Onderzoek naar de bruikbaarheid van snuffelploegmetingen bij stankonderzoek. DHV Raadgevend Ingenieursbureau BV Amersfoort.

Anzion C.J.M., Boer B. de, Dragt A.J. (1984). Financiele gevolgen van een stankconcentratienorm. (Financial consequences of an odour concentration standard). Publikatiereeks Lucht nr. 27, Staatsuitgeverij, 's-Gravenhage.

Artis D. (1984). Odour Nuisances and Their Control. Shaw, London.

ASTM D22 (1977). (Sensory Evaluation Committee) Task Force D22-02.09. Proposed Revision of D1391-57 Standard Method for Measurement of Odour in Atmospheres (dilution method). April 1977.

ASTM D1391-57 (1972). Standard Method for Odor in Atmospheres (dilution method) ASTM 1391-57 (reapproved 1967). Annual Book of ASTM Standards Part 23. ASTM Philadelphia P.A.

Bahmann W., Kropp L. (1983). Comparison of Odor Diffusion Calculations With Field Experiments and Bulk Adaptations of a Plume Model. Proc. 6th World Congr. Air. Qual 1983 Vol. 4. Union Ass. Prev. Poll. Atmos. 1983 pp 409-415.

Basarin V. and Cook P.E. (1982). A Survey of Public Attitudes to Industrial Odours. Clean Air (Melbourne) May 1982, 28-30.

Beck L.H. (1950). Osmics:Olfaction Medical Physics Vol. 2 pp 685-664. O. Glasser ed Chic. Year Book Publishers.

Benforado D.M., Rotella W.J., Horton D.L. (1969). Development of an Odour Panel for Evaluation of Odour Control Equipment. J.A.P.C.A. 19: pp101-

Bowne N. (1974). Diffusion rates. J.A.P.C.A. Vol 24(9) pp 832-835.

Cain W.S. (1969). Odour Intensity Differences in the Exponent of the Psychophysical Functions. Percept Psychophys 9.

Cain W.S. and Moskowitz H.R. (1974). Psychophysical Scaling of Odor. Human Responses to Environmental Odors. Ed. A. Turk, J.W. Johnston, D.G. Moulton. Acad. Press, New York.

Cederlof R., Friberg L., Jonsson E., Kaij L., Lindvall T. (1964). Studies of Annoyance Connected with Offensive Smell From a Sulphate Cellulose Factory. NORD HYG TIDSKR 45:39-48.

Cheremisinoff P. ed (1975). Industrial Odor Technology Assessment. Ann Arbor.

Copley International Inc (1971). A Study of the Social and Economic Impact of Odours - Phase II Final Report Prepared for the Environmental Protection Agency. Nov. 1971.

Crocker E.C., Henderston L.F. (1927). Analysis and Classification of Odours. Amer. Perf. and Essent Oil Rev (22) pp 325-327,356.

Davies J.T. and Taylor F.H. (1959). The Role of Adsorption and Molecular Morphology in Olfaction. The Calculation of Olfactory Thresholds. Biol. Bull (117) pp 222-238.

Department of the Environment (1974). Odours Report of the Working Party on the Suppression of Odours from Offensive Trades and Selected Other Trades Part 1. Assessment of the Problem in Great Britain. Warren Spring Laboratory 1974.

DeVries H., Stuiver M. (1961). The Absolute Sensitivity of the Human Sense of Smell Ch. 9 pp 159-167. In Rosenblith W.A (ed). Sensory Communication New York J. Wiley & Sons.

Dovek E. (1974). The Sense of Smell and its Abnormalities. Edinburgh Churchill Livingstone 1974.

Dravnieks A., Prokop W.H. (1973). Source Emission Odor Measurement by a Dynamic Forced Choice Triangle Olfactometer. Proc. 66 Ann Meeting A.P.C.A. Chicago 1973 Paper 73-276.

Dravnieks A. (1974). Measuring Industrial Odours. Chemical Engineering, 1974. Oct 21, 91-95.

Dravnieks A., Bock F.C., Powers J.J., Tebbetts M, Ford M. (1978). Comparison of Odours Directly and Through Profiling. Chemical Senses and Flavour. Vol 3. No. 2 1978.

Dravnieks A., Jarke F.H. (1979). Odor Threshold Measurement by Dynamic Olfactometry - Significant Operational Variables. Proc. 72nd Ann Meeting. A.P.C.A. June 1979, paper 79-53.1.

Dravnieks A., O'Neill J. (1979). Annoyance Potentials of Air Pollution Odours. J.Am Indus. Hyg. Assoc. 1979. 40, 85-95.

Dravnieks A., Masurat, T, Lamm R.A. (1982). Odor Character Profiling and Hedonic Tones of Odors and Odor Descriptors. Paper 82-28.3 presented at 75th Ann Meeting A.P.C.A. June 1982.

Duffee R.A., CHA.S (1980). Consideration of Physical Factors in Dynamic Olfactometry J.A.P.C.A Vol 30 pp 1294-1295.

Duffee R.A. (1985). Community Odour Nuisance Standards - a Possibility? Preprint to VDI Conference on Odorants. Baden-Baden, October 1985.

Findley A.E. (1924). Further Studies of Henning's System of Olfactory Qualities. Am J. Ps 35. pp 436-445.

Flesh R.D., Turk A. (1975). Social and Economic Effects of Odors in Industrial Odor Technology Assessment. Ann Arbor 1975.

Fox E.A., Gex V.E. (1957). Procedure for Measuring Odour Concentration in Air and Gases. J. Air Poll. Cont. Assoc, 1957, 7;60-

Friberg L., Jonsson E., Cederlof R. (1960). Studies on Sanitary Nuisance of Smoke from a Sulphate Cellulose Factory. An Interview Study. Nord Hyg. Tidskr 41:41-43, 45-50.

Gynp A., Pierre C.C.S.T., Poostchi E.M. (1985). Assessing the Impact of Odorous Emissions from Municipal Landfill Sites on the Surrounding Community. Paper 85-79.2 at 78th Annual Meeting of Air Pollution Control Association. June 1985.

Goldsmith J.R. (1973). Health and Annoyance Impact of Odour Pollution. A Report Prepared for U.S.E.P.A Contract 68-02-0083. EPA 650/1-75-001 Research Triangle Park N.C. U.S.E.P.A. Human Studies Laboratory National Environmental Research Centre.

Harssema H. (1986). Characterisation of Exposure in Odour Annoyance Situations. Proc. Conf. Environmental Annoyance. Rijksuniversiteit Utrecht Psychologisch Laboratorium. Elsievier 1987.

Haycraft J.B. (1889). The Objective Cause of Sensation Part III. The Sense of Smell. Brain 11, pp 166-178.

Hazzard F.W. (1930). A Descriptive Account of Odors. J. Exp Ps. 13 pp 297-331.

Health and Safety Executive (1985). Occupational Exposure Limits 1985 - Guidance Note EH40/85. Health and Safety Executive HMSO London.

Hellman T.M., Small F.H. (1973). Characterisation of Petrochemical Odors. Chemical Engg Progr Vol 69, No. 9. Sept 1973, pp 75-77.

Hellman T.M., Small F.H. (1974). Characterisation of the Odour Properties of 101 Petrochemicals Using Sensory Methods. J.A.P.C.A. 1974, 24,297-

Hemeon, W.C.L. (1968). Technique and Apparatus for Quantitative Measurement of Odour Emissions. J.Air Poll Control Assoc. 1968, 18 166.

Henning H. (1924). Der Geruch Leip. Barth.

Herrmann J. (1926). Gesamterlebnisse bei Geruchen. Neue ps. st 1, pp 473-506.

Hayninx A. (1919). Essai d'olfactique physiologique These. Bruxelles.

Hogstrom U. (1964). An Experimental Study on Atmospheric Diffusion. Tellus Vol. SVI No. 2 pp 205-247.

Hogstrom U. (1972). A Method of Predicting Odor Frequencies from a Point Source. Atm. Env. Vol. 6, pp 103-121.

Hogstrom U. (1974). Transport and Dispersal of Odours. In: Turk A., Johnston J.W., Moulton D.G. (eds). Human Responses to Environmental Odours, New York.

Huey N.A., Broering L.C., Jutze G.A., Gruber L.W. (1960). Objective Odour Pollution Control Investigations. J. Air Poll. Cont. Assoc 10:441-446.

Institution of Environmental Health Officers (1982). Survey of Agricultural Odour - England Wales and Northern Ireland. April 1980 to March 1981. Env. Health. June 1982 pp 149-151.

Jann P.R. (1984) A Survey of Dynamic Olfactometer Design. Proc. 77 Ann Meeting of A.P.C.A, June 1984. Paper 84-93.4.

Janni K.A. (1982) Modelling of Odorous Gases from Agricultural Sources. Transactions of Am. Soc. of Agricult. Eng. pp 1721-1723.

Johnson R.A. (1984). The Terminology of Odour Technology in Air Pollution Applications. Proc. 77th Ann Meeting of A.P.C.A. June 1984, Paper 84-93.1.

Johsson E. (1974). Annoyance Reactions to Environmental Odours. pp 329-333. In Turk, A., Johnston J.W., Moulton D.G. Eds Human Responses to Environmental Odours. NY Academic Press.

Jurgens C. (1985). Darstellung von Geruchsimmissionsprognosen unter Berucksichtig ung geltender Techtsvorschriften in Nordrehein-Westfalen. Paper Presented to VDI Conference on Odorants. Baden-Baden, October 1985.

Katz S.H., Talbert E.J. (1930). Intensities of Odors and Irritating Effects of Warning Agents for Inflammable and Poisonous Gases. U.S. Dept of Commerce Bureau of Mines Tech Paper 480.

Keddie A.W.C. (1984) Prediction of Odour Nuisance. Chemistry and Industry. May 1984 pp 323-326.

Knox J.B., Lange R. (1974). Surface Air Pollutant Concentration Frequency Distributions: Implications for Urban Modelling. J.A.P.C.A. Vol 24, No. 1. Jan 1974, pp 48-53.

Komuro K. (1921). Le Minimum Perceptible de l'Odorat dans une Enceinte Absolument Inodore. Arch Neerl Phys. 6, pp 20-24.

Laing D.G., Panhuber H., Baxter R.I. (1978). Olfactory Properties of Amines and n-butanol Chemical Senses and Flavour. Vol 3. N:2 pp 149-167.

Leonardos, G., Kendall D.A., Barnard N.J. (1969). Odour Threshold Determinations of 53 Odorant Chemicals J. Air Poll. Cont. Assoc. 1969, 19:91-

Leonardos G. (1974). A Critical Review of Regulations for the Control of Odors. J.A.P.C.A. Vol 24, No 5, pp 456-468.

Lindvall, T (1970). On the Sensory Evaluation of Odorous Air Pollution Intensities. Nord. Hyg. Tidskr. Suppl. 2 Stockholm Karolinska Institute and National Institute of Public Health.

Lindvall T. (1971) Swedish Experience on Sensory Evaluation of Odorous Air Pollutant Intensities. Proc. 2nd Int Clean Air Conf. H.M. Englund, W.T. Beery eds Acad Press NY pp 52-61.

Linnaeus C. (1756) Odores Medicamentorium. Amoenitates Academicae 3, pp 183-201.

Little A.D. (1969). Odor Determinations of 53 Odorant Chemicals. J.A.P.C.A. Feb 1969. Vol. 19, No. 2, pp 91-95.

Ludel J. (1979). Introduction to Sensory Processes. W. H. Freeman and Co. San Francisco 1979.

Luna R.E., Church H.W. (1974). Estimation of Long-term Concentrations Using a Universal Wind Speed Distribution. J.Appld Meteorology. Vol. 13, Dec 1974. pp 910-916.

MacDonald M.K. (1922). An Experimental Study of Henning's System of Olfactory Qualities. Am.J. Ps. 33. pp 535-553.

Maiwald K.D. (1986). Design of Networks for Monitoring Odour Annoyance by Population Panels. Proc.Conf.Envtl.Annoyance. Rijksuniversiteit Utrecht Psychologisch Laboratorium. Elsevier 1987.

McCarthy E.F., Duffee R.A. (1980). An Interruptible Odor Control System for a Chemical Plant. Proc. 73 Ann Meeting of A.P.C.A. (1980). Paper 80-10.4

Miedema, H.M.E., Ham J.M., de Jong R.G., Don J.A. (1986). Odour Annoyance in the Living Environment in: Geruchsstoffe VDI Berichte 561 Dusseldorf.

Mills J.L., Walsh T., Lvedtke K.D., Smith L.K. (1963). Quantitative Odour Measurements. J. Air Poll Cont Assoc. 13, 467-

Molton P.M., Cash D. (1978). Novel Combination Method Assesses Sewage Odors. Wat & Waste Eng. Feb 1978, pp 47-52.

Moncrieff (1944). The Chemical Senses, N.Y. Wiley.

Moskowitz H.R., Dravnieks A., Gerbers C (1974). Intensity and Pleasantness of Butanol. J.Exptl.Psychol. 103, pp216-223.

Moskowitz H.R., Gerbers C.L. (1974). Dimensional Saliences of Odours. Ann N.Y. Acad. Sci. 237, 1-16.

Moskowitz H.R., Dravieks A., Klarman L.A. (1976). Odour Intensity and Pleasantness for a Diverse Set of Odorants. Percept. Psychophys 19. pp122-128.

Munsell A.H. (1915). Atlas of the Munsell Colour System. Maldin, Mass. Wadsworth, Howland.

Murray D.R., Samual S.C., Bowne N.E (1978). Use of a Fluctuating Plume Puff Model for Prediction of the Impact of Odorous Emissions. Proc. 71 Ann Meeting of APCA. June 1978 Paper 78 68.6.

National Society for Clean Air (1978). Reference Book, Brighton.

Noll K.E., Miller T.L. (1977). Air Monitoring Survey Design. Ann Arbour Science, Mich. U.S.

Nordstedt R.A., Taiganides E.P. (1971). Meteorological Control of Malodors from Landspreading of Livestock Wastes. In Livestock Waste Management and Pollution Abatement. Am. Soc. of Agricult. Eng. Pub PROC-271 pp 107-109,116.

North A.A. (1980). Odours and the Public. Chapter 2 in Odour Control. A Concise Guide. Report for the Department of the Environment.

Ohma S. (1921) La Classification des Odeurs, Aromatiques en Sous-classes. Arch Neerl Phys. 6 pp 567-590.

Pasquill F. (1961). The Estimation of the Dispersion of Wind-borne Material. Meteorological Mag. 90, 1063, 33-49.

Passy J. (1892). Note sur les minimum perceptibles des quelques odeurs. C.R. Soc. Biol. 44pp 84-88.

Pattie F., Etcheto M., Laffort P. (1975). Selected and Standardised Values of Supra Threshold Odour Intensities for 110 Substances. Chem. Sens. Flav 1. p283.

Punter P.H., Maiwald K.D., Blaauwbroek J., Schaefer J., Koster E.P. (1985). Geurnormering in de Woonomgeving Fase 1 Publicatiereeks Lucht VROM 50.

Punter P.H. (1986). Set Up and Use of Population Panels for Measuring and Monitoring Annoyance. Proc. Conf. Envtl. Annoyance. Rijksuniversiteit Utrecht. Psychologisch Laboratorium, Elsevier 1987.

Ross S., Harriman A.E. (1949). A Preliminary Study of the Crocker-Henderson Odour Classification System. Amer. J. Psychol. (62) pp 399-404.

Royston P. (1984). SPP - A Statistical Package for Personal Computers. Version 4.3. 22 Jan 1984.

Skramlik E. von. (1925). Uber die Lokalisation der Empfindungen bei den niederen Sinnen Z. Sinnes Phys. 56 pp69-140.

Slade D.H. ed (1968). Meteorology and Atomic Energy. U.S. Atomic Energy Comm. Div. Tech. Inf. Washington.

Spiegel M.R. (1975). Schaum's Outline of Theory and Problems of Statistics in SI Units. McGraw Hill, London.

Stuiver M. (1958). Biophysics of the Sense of Smell. PhD Thesis, Groningen.

Sutton O.G. (1932). A Theory of Eddy Diffusion in the Atmosphere. Proc. Roy. Soc. London, A (135) pp 143-165.

Sutton O.G. (1947). The Problem of Diffusion in the Lower Atmosphere. Quart. J. Roy. Met. Soc. (73) pp 257-281.

Thiele V., Koch E., Prinz B. (1986). Bestimmung von Geruchsstoffimmissionen mit Probanden. VDI Berichte. 561, pp 313-328.

Turner D.B. (1970). Workbook of Atmospheric Dispersion Estimates. E.P.A Report AP26.

U.N.E.P. (1979). Guidelines for Assessing Industrial Environmental Impact and Environmental Criteria for the Siting of Industry. United Nations Environment Programme.

VDI (1986). Odorants - Report of Conference held at Baden-Baden, October 1985.

Verein Deutscher Ingenieure, Berichte 561.

Voerman J.W.T., Harssema H. (1984). Development of a Dispersion Model for Odours. Proceedings Int. Symp. on Characterisation and Control of Odiferous Pollutants in Process Industry. P231-244.

Wade W.A., Tower and Cha S. (1974). The Evaluation of Four Odor Measurement Systems. Technical Report to the Illinois EPA. TRC. The Research Corp of New England Project 32390.

Wagenaar W.A. (1975). Stevens vs Fechner: A Plea for Dismissal of the Case. Acta Psychol 39, p 225.

Wijnen H. (1986). Air Quality Standards on Odours in the Netherlands. VDI Berichte 561 VDI Kommission Reinhaltung der Luft Geruchsstoffe/ Odorants, pp 365-385. Dusseldorf.

Winneke G., Kastka J. (1977). Odour Pollution and Odour Annoyance Reactions in Industrial Areas of the Rhine-Ruhr Region. Olfaction and Taste VI pp 471-479.

Winneke G., Kastka J. (1984). In: Ges.z.Forderung der Lufthygiene und Silikoseforschung (eds) Umwelthygiene Suppl. 1, pp 103-114.

Winneke G., Kastka J. (1987). Comparison of Odour Annoyance Data From Different Industrial Sources: Problems and Implications. Proc. Conf. Environmental Annoyance. Rijksuniversiteit Utrecht. Psychologischt Laboratorium Elsevier 1987.

Wohlers H.C. (1963). Odor Intensity and Odor Travel from Industrial Sources. Int.J.Air. Wat Poll. Vol 7 pp 77-78.

Woodworth R.S., Schlosberg H. (1954). Experimental Psychology. Methuen & Co., London revised 1954.

Young C.W., Fletcher D.F. Wright N. (1948). On Olfaction and Infra-red Radiation Theories. Science 108, pp 411-412.

Zwaardmaker H. (1922). Odeur et chimisme. Arch neel Phys 6, pp 336-354.

Appendix 1

Data used for the regression analysis between the odour concentration and odour panel's average intensity assessment (NWI)

KEY TO DATA

Data no.	Source description
A	Gas works naphtha loading
B	Animal quarantine centre interceptor
C	Glass fibre reinforced plastic manufacture
D	Glass fibre reinforced plastic manufacture
E	Brewery effluent treatment plant
F	Gas works cooling tower
G	Brewery effluent treatment plant
H	Brewery effluent treatment plant
I	Gas works interceptor
J	Gas works diesel exhausts

A

No.	var 1 conc	var 2 nwi	var 3 logconc	var 4 lognwi
1	2000.000	13.500	3.301	1.130
2	1250.000	18.000	3.097	1.255
3	769.000	20.500	2.886	1.312
4	769.000	20.500	2.886	1.312
5	769.000	19.000	2.886	1.279
6	500.000	24.200	2.699	1.384
7	289.000	27.500	2.461	1.439
8	182.000	32.300	2.260	1.509
9	125.000	45.500	2.097	1.658
10	100.000	61.800	2.000	1.791
11	50.000	65.800	1.699	1.818
12	25.000	82.200	1.398	1.915

B

No.	var 1 conc	var 2 nwi	var 3 logconc	var 4 lognwi
1	731.000	7.200	2.864	0.857
2	588.000	12.600	2.769	1.100
3	333.000	10.800	2.522	1.033
4	250.000	13.000	2.398	1.114
5	182.000	10.800	2.260	1.033
6	125.000	17.000	2.097	1.230
7	100.000	15.200	2.000	1.182
8	50.000	16.600	1.699	1.220
9	25.000	21.000	1.398	1.322

C

No.	var 1 conc	var 2 nwi	var 3 logconc	var 4 lognwi
1	1111.000	5.400	3.046	0.732
2	833.000	3.600	2.921	0.556
3	667.000	11.200	2.824	1.049
4	500.000	9.000	2.699	0.954
5	263.000	12.400	2.420	1.093
6	182.000	14.800	2.260	1.170
7	132.000	25.800	2.121	1.412

D

No.	var 1 conc	var 2 nwi	var 3 logconc	var 4 lognwi
1	500.000	1.800	2.699	0.255
2	333.000	5.400	2.522	0.732
3	200.000	59.000	2.301	1.771
4	250.000	18.200	2.398	1.260
5	400.000	17.000	2.602	1.230
6	222.000	36.000	2.346	1.556
7	200.000	60.000	2.301	1.778
8	182.000	77.000	2.260	1.886
9	143.000	87.000	2.155	1.940
10	118.000	87.000	2.072	1.940

E

No.	var 1 conc	var 2 nwi	var 3 logconc	var 4 lognwi
1	769.000	1.300	2.886	0.114
2	500.000	3.900	2.699	0.591
3	286.000	5.100	2.456	0.708
4	200.000	25.400	2.301	1.405
5	161.000	52.000	2.207	1.716
6	125.000	60.300	2.097	1.780

F

No.	var 1 conc	var 2 nwi	var 3 logconc	var 4 lognwi
1	2000.000	7.800	3.301	0.892
2	769.000	18.200	2.886	1.260
3	500.000	21.200	2.699	1.326
4	222.000	29.200	2.346	1.465
5	182.000	43.700	2.260	1.640
6	125.000	58.000	2.097	1.763
7	100.000	67.000	2.000	1.826

G

No.	var 1 conc	var 2 nwi	var 3 logconc	var 4 lognwi
1	769.000	3.900	2.886	0.591
2	500.000	5.400	2.699	0.732
3	333.000	6.700	2.522	0.826
4	200.000	23.100	2.301	1.364
5	200.000	23.600	2.301	1.373
6	143.000	48.900	2.155	1.689
7	125.000	44.400	2.097	1.647

H

No.	var 1 conc	var 2 nwi	var 3 logconc	var 4 lognwi
1	769.000	3.000	2.886	0.477
2	154.000	10.500	2.188	1.021
3	125.000	15.300	2.097	1.185
4	100.000	16.800	2.000	1.225
5	75.000	18.300	1.875	1.262
6	50.000	24.500	1.699	1.389
7	25.000	46.300	1.398	1.666
8	33.000	39.700	1.519	1.599
9	25.000	48.200	1.398	1.683
10	20.000	59.500	1.301	1.775
11	17.000	68.500	1.230	1.836
12	12.500	73.700	1.097	1.867

I

No.	var 1 conc	var 2 nwi	var 3 logconc	var 4 lognwi
1	3000.000	9.400	3.477	0.973
2	4000.000	9.000	3.602	0.954
3	3000.000	12.600	3.477	1.100
4	1875.000	14.400	3.273	1.158
5	2000.000	16.200	3.301	1.210
6	769.000	20.600	2.886	1.314
7	175.000	49.600	2.243	1.695
8	125.000	69.200	2.097	1.840

J

No.	var 1 conc	var 2 nwi	var 3 logconc	var 4 lognwi
1	3000.000	16.800	3.477	1.225
2	3000.000	14.000	3.477	1.146
3	1875.000	26.800	3.273	1.428
4	1154.000	26.300	3.062	1.420
5	1250.000	26.300	3.097	1.420
6	769.000	29.500	2.886	1.470
7	500.000	29.000	2.699	1.462
8	286.000	47.000	2.456	1.672
9	200.000	73.300	2.301	1.865

Appendix 2

Data used to establish the relationship between the direct and indirect methods of determining odour thresholds

KEY TO DATA (d/d)

Data no.	Source description
1-11	Lithographic printing works
12-26	Solvent drying oven
27-40	Oil refinery emissions
41-43	Solvent drying oven
44-49	Toxic waste ponds
50-53	Building board manufacture
54-59	Toxic waste ponds
60-61	Glass fibre reinforced plastic manufacture
62-65	Brewery effluent treatment
66-67	Land fill gas
68-82	Gas works emissions

d/d

No.	var 1 direct	var 2 indirect
1	720.000	720.000
2	1600.000	1400.000
3	160.000	136.000
4	700.000	600.000
5	74.000	74.000
6	8000.000	8200.000
7	4800.000	4200.000
8	860.000	780.000
9	1400.000	1230.000
10	8500.000	11000.000
11	6400.000	8500.000
12	12000.000	8000.000
13	1500.000	1500.000
14	12000.000	8000.000
15	1800.000	1800.000
16	2900.000	3000.000
17	2300.000	2700.000
18	1350.000	1000.000
19	2000.000	1700.000
20	1000.000	900.000
21	920.000	660.000
22	510.000	400.000
23	500.000	450.000
24	200.000	150.000
25	205.000	140.000
26	195.000	75.000
27	14000.000	14000.000
28	620.000	580.000
29	14000.000	10000.000
30	370.000	330.000
31	3000.000	5000.000
32	3800.000	2500.000
33	1100.000	560.000
34	1200.000	1000.000
35	300.000	500.000
36	480.000	312.000
37	2500.000	2200.000
38	3400.000	2600.000
39	1800.000	1500.000
40	1800.000	2200.000
41	2100.000	2400.000
42	550.000	500.000
43	700.000	500.000
44	780.000	800.000
45	125.000	150.000
46	240.000	180.000
47	170.000	165.000
48	250.000	280.000
49	400.000	390.000
50	800.000	950.000
51	800.000	700.000
52	740.000	780.000
53	880.000	1200.000
54	550.000	550.000
55	620.000	520.000
56	1250.000	1450.000
57	950.000	800.000
58	540.000	560.000
59	780.000	1100.000
60	270.000	320.000
61	500.000	530.000
62	200.000	200.000
63	320.000	380.000
64	230.000	250.000
65	370.000	320.000
66	410.000	400.000
67	740.000	550.000
68	2500.000	2700.000
69	1100.000	1600.000
70	3200.000	2432.000
71	1850.000	1500.000
72	1300.000	1200.000
73	640.000	860.000
74	6000.000	9000.000
75	2300.000	2300.000
76	3500.000	5400.000
77	3500.000	4400.000
78	270.000	230.000
79	460.000	840.000
80	1500.000	1500.000
81	255.000	332.000
82	2000.000	2700.000

KEY TO DATA (d/r)

Data no.	Source description
1-6	Lithographic printing works
7-19	Solvent drying oven
20-34	Oil refinery emissions
35-37	Solvent drying oven
38-40	Toxic waste ponds
41	Building board manufacture
42-46	Toxic waste ponds
47	Glass fibre reinforced plastic manufacture
48-50	Brewery effluent treatment
51	Land fill gas
52-66	Gas works emissions

d/r

No.	var 1 direct	var 2 indirect
1	180.000	220.000
2	500.000	370.000
3	4900.000	3400.000
4	1900.000	2000.000
5	6400.000	7200.000
6	3700.000	3300.000
7	230.000	300.000
8	900.000	600.000
9	950.000	400.000
10	650.000	400.000
11	140.000	75.000
12	760.000	360.000
13	300.000	210.000
14	240.000	200.000
15	135.000	75.000
16	125.000	105.000
17	9.000	26.000
18	50.000	40.000
19	70.000	32.000
20	900.000	830.000
21	220.000	120.000
22	1700.000	700.000
23	150.000	140.000
24	130.000	80.000
25	790.000	780.000
26	130.000	50.000
27	45.000	25.000
28	170.000	120.000
29	130.000	60.000
30	80.000	85.000
31	560.000	540.000
32	230.000	110.000
33	360.000	340.000
34	660.000	380.000

d/r

No.	var 1 direct	var 2 indirect
35	440.000	380.000
36	270.000	525.000
37	125.000	68.000
38	10.000	10.000
39	60.000	50.000
40	155.000	135.000
41	580.000	580.000
42	150.000	135.000
43	350.000	230.000
44	900.000	1040.000
45	220.000	230.000
46	460.000	560.000
47	140.000	110.000
48	50.000	45.000
49	210.000	180.000
50	95.000	80.000
51	290.000	220.000
52	300.000	300.000
53	440.000	320.000
54	250.000	190.000
55	150.000	100.000
56	140.000	100.000
57	70.000	68.000
58	1000.000	540.000
59	420.000	440.000
60	540.000	170.000
61	500.000	550.000
62	6.800	6.500
63	40.000	10.000
64	230.000	170.000
65	60.000	44.000
66	1000.000	430.000

Appendix 3

Data used to determine the agreement between pairs of observers to fluctuating odour intensities in the field

KEY TO DATA

Data no.	Source description
1-5	Land fill gas
6-7	Building board manufacture
8-13	Glass fibre reinforced plastic manufacture
14-54	Toxic waste ponds
55-58	Oil refinery emissions
59-60	Lithographic printing works
61-62	Solvent drying oven

Percentage time greater than the detection threshold

No.	var 1 obs1	var 2 obs2
1	52.000	100.000
2	55.000	100.000
3	47.000	64.000
4	79.000	80.000
5	53.000	45.000
6	14.000	16.000
7	34.000	29.000
8	89.000	94.500
9	68.000	90.600
10	57.000	94.200
11	47.000	71.400
12	68.000	73.100
13	35.000	50.000
14	84.000	29.000
15	36.000	8.000
16	75.000	42.000
17	19.000	18.000
18	69.000	40.000
19	81.000	88.000
20	70.000	53.000
21	27.000	12.000
22	43.000	78.000
23	3.000	0.000
24	35.000	36.000
25	66.000	66.000
26	43.000	26.000
27	98.000	94.000
28	92.000	93.000
29	65.000	60.000
30	54.000	51.000
31	38.000	24.000
32	100.000	100.000
33	79.000	59.000
34	78.000	71.000
35	79.000	59.000
36	67.000	64.000
37	40.000	27.000
38	38.000	20.000
39	38.000	22.000
40	100.000	100.000
41	98.000	84.000
42	88.000	87.000
43	71.000	63.000
44	73.000	45.000
45	31.000	36.000
46	68.000	98.000
47	52.000	90.000
48	92.000	93.000
49	72.000	100.000
50	54.000	74.000
51	62.000	69.000
52	84.000	100.000
53	68.000	94.000
54	100.000	80.000
55	32.000	18.000
56	64.000	43.000
57	71.000	87.000
58	71.000	59.000
59	38.000	38.000
60	90.000	83.000
61	95.000	85.000
62	14.000	61.000

Appendix 4

Computer listing of odour dispersion model in GW-Basic

```
1 REM  odf -odour frequency :ALB 2/88
5 CLEAR
20 DIM T(16),C(2),R(2)
60 INPUT"effective height";H
70 INPUT"wind speed ";U
80 INPUT"vol flow rate";V
90 INPUT"odour source conc";N
100 INPUT "odour conc contour";Q
105 REM
110 FOR I=1 TO 16
120 T(I)=0
125 NEXT I
135 GOTO 760
170 REM
200 C(1)=SQR(P*P-R(1)*R(1))
210 C(2)=SQR(L*L-R(2)*R(2))
220 A=V*N/(3.1416*U*R(1)*R(2))
230 B=C(1)/10:M=C(2)/10
238 J=0
240 I=0
242 T(1)=SQR(2*R(1)*R(1)*LOG(V*N/(Q*3.1416*U*R(1)*R(2))))
244 T(2)=SQR(2*R(2)*R(2)*LOG(V*N/(Q*3.1416*U*R(1)*R(2))))
250 REM
254 IF M*J>T(2) THEN GOTO 500
260 E=(B*I/R(1))*(B*I/R(1))
270 F=((M*J)/R(2))^2
290 GOSUB 650
296 IF J=0 THEN LET   T(10)=T(10)+G:GOTO 300
297 T(11)=T(11)+G
300 REM
305 I=I+1
307 IF ((B*I/T(1))^2+(M*J/T(2))^2)>1 THEN GOTO 320
310 GOTO 250
320 J=J+1:I=0
330 GOTO 250
400 REM
500 REM
605 B=T(10)+2*T(11)
610 PRINT B;" %T> ";Q;" DT"
620 GOTO 5
650 REM
660 G=4.47-1.98*(H-M*J)/C(2)
665 IF G<0 THEN LET G=0
670 W=(4.47-1.98*(B*I/C(1)))
675 IF W<0 THEN LET W=0
680 G=G*W/100
690 RETURN
760 INPUT "sigma yb";P
770 INPUT" sigma zb";L
780 INPUT "sigma yr";R(1)
790 INPUT "sigma zr";R(2)
800 GOTO 170
900 END
```

Appendix 5

Reprint of

"A novel approach to estimating the odour concentration distribution in the community"

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A NOVEL APPROACH TO ESTIMATING THE ODOUR CONCENTRATION DISTRIBUTION IN THE COMMUNITY

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Abstract—A new mathematical model is described for estimating the percentage time that the odour threshold is exceeded in the community. Estimates obtained by using the model are compared with experimental data to demonstrate the effectiveness over a range of conditions.

Key word index: Odour, dispersion, modelling, frequency, distribution.

INTRODUCTION

Odours have always been an indication of air pollution. For most people the presence of an odour is the only indication that air quality is not what it should be.

In investigating the likelihood of community annoyance by odours it is necessary to be able to relate the characteristics of an odour source with the dose received by the community. This is normally achieved by mathematical modelling.

Modelling of odour transport and dispersion also provides an indication of how much control is necessary.

THE HISTORICAL APPROACH

Several approaches have been adopted for modelling the dispersion of odours. Wohlers (1963) used a dispersion model based on atmospheric dispersion theory developed by Sutton (1947) to compare estimated and actual travel distances from various industrial sources. A lack of agreement was found between the estimated and observed concentrations downwind using this model. He suggested that this was due to odours being transported as discrete eddies. Nordstedt and Taiganides (1971) used a similar model to study meteorological control of odours during land spreading of livestock waste; again without much success.

Gaussian plume models have also been used to predict the average concentrations of specific compounds downwind of sources based on the Pasquill–Gifford equations, Turner (1970), i.e.

$$c(x, y, z, H) = \frac{Q}{2\pi\sigma_y\sigma_z u}\exp\left(-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right) \times \left[\exp\left(-\frac{1}{2}\frac{(z-H)^2}{\sigma_z^2}\right) + \exp\left(-\frac{1}{2}\frac{(z+H)^2}{\sigma_z^2}\right)\right] \quad (1)$$

where

$c(x, y, z, H)$ = concentration at downwind position xyz for a source of effective height H ($\mathrm{g\,m^{-3}}$),
Q = emission rate ($\mathrm{g\,s^{-1}}$),
U = wind speed at emission height ($\mathrm{m\,s^{-1}}$),
σ_y = standard deviation of plume concentration in the cross wind direction (m),
σ_z = standard deviation of plume concentration in the vertical (m).

Janni (1982) used such a model to investigate the important factors in the dispersion of odours from agricultural facilities. He considered that it was regular detection of objectionable odours which produced complaints.

These models do not take account of the short-term fluctuations in the concentration due to turbulence. According to Murray (1978) such fluctuations are important because people respond to detectable odour levels lasting of the order of a few seconds rather than over 10 min to 1 h as is assumed in most Gaussian dispersion models. Some investigators make allowances for this difference in averaging time. Warren Spring Laboratories (1980) recommend the use of an empirical mean to peak ratio of 10. Thus, the 3-min average concentration estimated by the P. G. (Pasquill–Gifford) Gaussian plume dispersion model is multiplied by 10 to give the peak occurring for periods of 1–5 s. Bahmann and Kropp (1983) have also reported an empirical means to peak ratio of 10.

Finally there are a group of models which consider the odour plume as a series of puffs. These models, which are based on the principles described by Slade *et al.* (1968), usually predict the odour frequencies or number of occurrences that a specified odour concentration is exceeded during a given time period, i.e. Hogstrom (1972), Murray *et al.* (1978), McCarthy and Duffee (1980). The classic work which established this method of modelling was conducted by Hogstrom

(1972) in association with Lindvall (1970). Hogstrom carried out a rigorous mathematical analysis of the problem of dispersion.

In 1964 Hogstrom conducted a series of tests in which 30 s puffs of smoke tracer were released and photographically tracked downwind. From these experiments he extracted horizontal and vertical diffusion parameters for puff releases. Using the results he suggested (1972) that over a period of several puffs dispersion is made up of two terms (Fig. 1). The first is the diffusion of each individual puff itself; the second is meander in the plume of the series of puffs in the large scale turbulence field.

Diffusion of individual puffs can be represented as σ_{yp} (horizontal) and σ_{zp} (vertical). Using these parameters it is possible to rewrite the standard Gaussian plume model to represent the odour dilution ratio at a fixed point at any instant of time as

$$N_i = \frac{V_0 N_0}{\pi u \sigma_{yp} \sigma_{zp}} \exp\left[-\frac{y_i^2}{2\sigma_{yp}^2} - \frac{H_i^2}{2\sigma_{zp}^2} \right] \tag{2}$$

where

N_i = odour dilution ratio at receiver,
V_0 = source volume emission rate ($m^3 s^{-1}$),
N_0 = odour dilution ratio at source,
u = mean wind speed ($m s^{-1}$),
y_i = lateral distance of plume centroid from the receptor position at this instant (m),
H_i = vertical distance of plume centroid from the receptor position at this instant (m).

The movement of the whole puff in the large-scale turbulence field may be pictured as the meander of the position of the centroid of each puff as a series of puffs move downwind. This portion of dispersion is σ_{yc} and σ_{zc}. Hogstrom (1964) stated that the total mean dispersions σ_y and σ_z (as used in normal Gaussian dispersion models) are related by Equations (3) and (4).

$$\sigma_{y^2} = \sigma_{yc^2} + \sigma_{yp^2} \tag{3}$$

$$\sigma_{z^2} = \sigma_{zc^2} + \sigma_{zp^2}. \tag{4}$$

Hogstrom (1972) gives the frequency of concentrations greater than a certain value by Equation (5).

$$F = \sum_{i=i}^{n} \frac{(g\phi i)}{g_0} \frac{2\bar{y} f_i}{2\pi x} \tag{5}$$

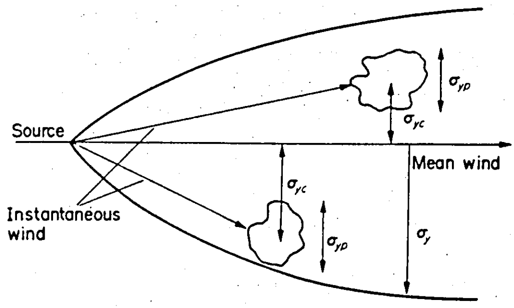

Fig. 1. Puff dispersion parameters.

where

f_i = frequency of the ith meteorological situation by stability and wind speed,
$g\phi i/g_0$ = non-dimensional measure of frequency of winds of direction $\phi \pm \frac{y_i}{x}$ during those periods when the concentration width is $2y_i$,
x = distance from source,
$2y_i$ = width of instantaneous contour,
$\bar{y}$ = weighted mean width of contour.

See Fig. 2 for an illustration of these terms.

Equation (2) is solved for y_i to obtain the local instantaneous half width of the odorous area at ground level. This is integrated over a range of atmospheric conditions to obtain the weighted mean width for substitution in Equation (5).

Using this mathematical model Hogstrom estimated the odour frequency distribution downwind of a pulp mill and compared the results with occurrences recorded by trained observers. Whilst the correlations between the predicted and observed (Table 1) were

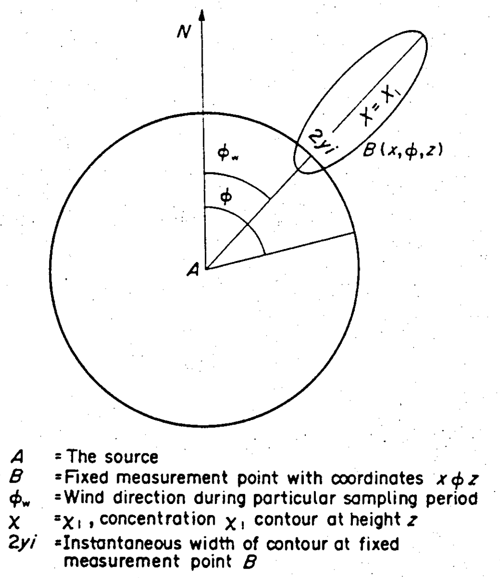

Fig. 2. Odorous half width.

Table 1. Comparison of predicted and observed odour frequencies

Distance (km)	2	5	10	20
Total number of observations	6426	7490	5528	6976
No. of positive observations	696	736	470	360
Observed odour frequency (%)	10.8	9.8	8.5	5.1
Predicted odour frequency (%)	9.1	5.7	3.2	1.7
Ratio *observed* predicted	1.2	1.7	2.7	3.0

good at short distances from the plant, the method tended to underestimate at greater distances.

Hogstrom considered that the discrepancies could be due to several reasons. These included:

(1) there was a chemical and/or physical change in the odorant which could have led to the lowering of the odorous threshold,

(2) the model assumed a single source emitting at a constant rate. In reality there were two chimneys on the plant and there was some laboratory evidence to suggest that emissions had varied,

(3) inaccuracies in dispersion parameters.

Murray (1978) and McCarthy (1980) developed the work of Hogstrom. They simplified and systemized the atmospheric dispersion parameters using more recent experimental data published by Bowne (1974) for dispersion rates in rural, suburban and urban areas.

In their model, known as the TRC (The Research Corporation of New England, CT) odour model, the position of the puff centroids is generated from a normally distributed random number generator with a mean value corresponding to the mean wind direction. This permits the consideration of several puffs during the time period and allows the building of a cumulative frequency distribution of dilution ratios for the chosen period. Other refinements in this model included the entrainment of the plume in the wake of a building and the ability to handle up to 20 simultaneously emitting sources and 20 receptors.

Very good agreement has been reported between estimates made using the TRC model and measured ambient odour concentrations as indicated in Table 2.

THE NEW MODEL

The most successful type of these models appears to be the puff model which predicts the short term odour levels corresponding with the response time of the human nose. It was therefore decided to adopt such a model for the author's work.

A version of the puff model was developed within the restrictions of the computer hardware available, i.e. Sharp PC 1245 pocket computer and the author's ability at writing software.

The program was written in Basic and is listed in Appendix 1. It contains some novel features which simplify the calculations and shorten processing time.

As with other puff models described, it has been assumed that dispersion is made up of two terms. The first is the diffusion of each individual puff itself; the second is the meander in the plume of a series of puffs in the large scale turbulence field.

It was further assumed that over a period of time the position of the puff centroid will follow a binormal distribution such as illustrated in Fig. 3. Thus there is a certain probability of finding the puff centroid on a plane downwind from the source depending on its position from the downwind axis.

Not all of these puffs will affect the observer. Some will be too far away. Those that do will be passing the observer within a distance at which the puff has been diluted to the odour threshold. Figure 4 illustrates the situation in plan. The edge of the puffs passing the observer are the odour threshold concentrations. Any puff on the source/observer axis affects the observer for a maximum time (x_0/u). Puffs further off axis affect the observer for less time (x_1/u). Puffs passing at a distance b from the observer only just brush past the observer. Puffs passing at a greater distance must be diluted below the odour threshold before they reach the observer. Thus there is a critical distance in the y direction beyond which a puff does not affect the observer, because the concentration is below the odour threshold; the effect of simultaneous puffs being ignored.

Similarly there will be a corresponding critical distance c in the z direction (Fig. 5).

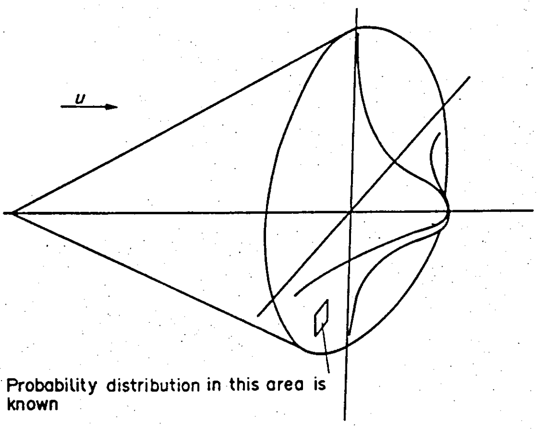

Fig. 3. Probability distribution of puff centroid.

Table 2. Comparison between odour concentrations estimated by the TRC model and ambient measurements

	Plant 1		Plant 2	
Distance (m)	100	200	460	840
Estimated odour concentration	50	2	13	2
Observed concentration	31	2	20	2
Source	McCarthy (1980)		Murray (1978)	

TRC—The Research Corporation of New England, CT.

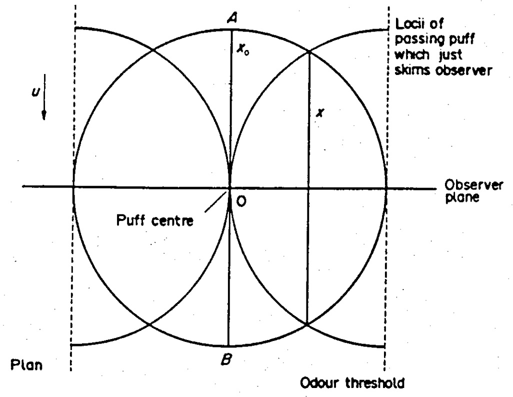

Fig. 4. Ground level puffs affecting an observer.

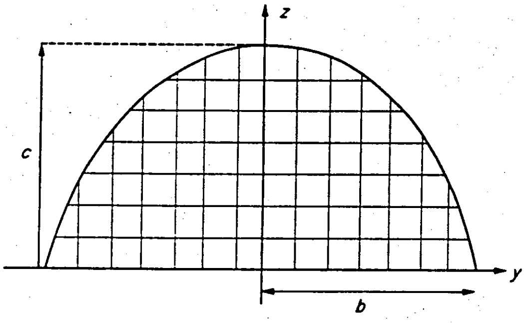

Fig. 5. Range over which puffs affect observer.

If the observer is at ground level then the area of influence through which puffs must pass is a semi-ellipse with a height of c and width $2b$. The concentration at the observer for a puff at any location in the observer plane is given in Equation (2) as

$$N_i = \frac{V_o N_o}{\pi u \sigma_{yp} \sigma_{zp}} \exp\left(-\frac{y^2}{2\sigma_{yp}^2} - \frac{z^2}{2\sigma_{zp}^2}\right) \qquad (2)$$

when $z = o$ $y = b$

thus

$$b = \left(\log_e \frac{(V_o N_o)}{(\pi u \sigma_{yp} \sigma_{zp} N_i)} 2\sigma_{yp}^2\right)^{0.5} \qquad (6)$$

similarly when $y = o$ $z = c$ and

$$c = \left(\log_e \frac{(V_o N_o)}{(\pi u \sigma_{yp} \sigma_{zp} N_i)} 2\sigma_{zp}^2\right)^{0.5} \qquad (7)$$

The total time that the observer experiences an odour dilution ratio N_i and greater is therefore the sum of the times that puff centroids pass through the area of influence.

Since the position of the observer is known in relation to the source, it is possible to numerically integrate the probability or percentage time that a puff is at each grid point in Fig. 5.

To simplify this a simple algorithm was derived for the frequency of a normal event depending on its position from the mean in standard deviation units.

The probability of a normal distribution event occurring is given by Equation (8)

$$\text{Probability} = \int_{z_1}^{z_2} \frac{1}{\sqrt{2\pi}} \exp\left(\frac{-z^2}{2}\right) dz. \qquad (8)$$

For 0.1 standard deviation steps (8) approximates to (9)

$$\text{Percentage probability} = \frac{4.47 - 1.98\,z}{100} \qquad (9)$$

with a correlation coefficient of 0.995.

In carrying out this modelling, use was made of the atmospheric dispersion parameters for puff and puff centroid in rural, suburban and urban areas as published by Bowne (1974).

MODEL VERIFICATION

Data collection

In order to be able to test the model, it was necessary to obtain data which included both source emission parameters and downwind observations for comparison with the model output.

Two main sources of data were employed, i.e. Hogstrom (1974) and McCarthy (1980). Hogstrom's data were observations taken downwind of a Kraft paperworks whereas McCarthy's data were the outputs of the TRC dispersion model for a chemical plant. The TRC model had already been verified by comparisons with field observations. Further supportive data was collected by the author. The means by which this was achieved are described in Appendix 2. A summary of the data used to test the model is given in Appendix 3.

Model testing

The odour dispersion model described above was tested by comparing the observed frequency distribution with the on axis downwind frequency distribution derived from the emission characteristics and the meteorological conditions at the time of the field observations.

Figure 6, in which the observed and estimated frequencies are plotted, indicates that the model gives a good estimate in rural situations. Agreement is less close in an urban area with tall buildings. The reason for this is that the dispersion will be distorted by buildings and the dispersion parameters used will only be very approximate. Other reasons for greater variability in the urban area data is the fact that there was only one observer. Furthermore because the plume was not visible it was not possible to confirm that the observation point was always directly downwind.

The relationship between estimated and observed values of percentage time greater than the odour

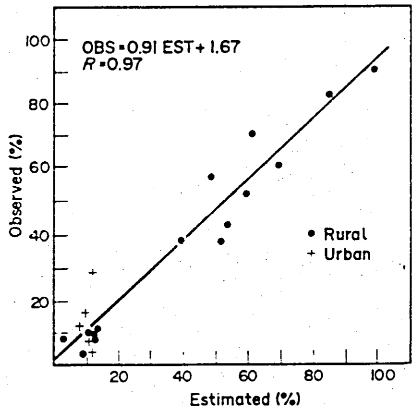

Fig. 6. Relationship between estimated and observed percentage time.

threshold is given in Equation (10).

$$\text{Observed} = 0.91 \times \text{estimated} + 1.67. \qquad (10)$$

The correlation coefficient of 0.97 suggests that a high degree of confidence can be placed upon the estimates.

CONCLUSIONS

The model described above is seen as a useful tool in investigating the likelihood of odour complaints and for the specification of odour control requirements. However, this is just the first step. Further field tests are required to examine the accuracy of the model over a wider range of conditions. Compatible odour nuisance criteria also need to be developed. The author intends to report on his work in these areas in due course.

REFERENCES

Bahmann W. and Kropp L. (1983) Comparison of odor diffusion calculations with field experiments and bulk adaptations of a plume model. *Proc. 6th World Congr. Air Qual*, 1983, Vol. 4. Union Ass. Prev. Pollut. Atmos., pp. 409–415.

Bowne N. (1974) Diffusion rates. *J. Air Pollut. Control Ass.* **24,** 832–835.

Hogstrom U. (1964) An experimental study on atmospheric diffusion. *Tellus* **SVI,** 205–247.

Hogstrom U. (1972) A method of predicting odor frequencies from a point source. *Atmospheric Environment* **6,** 103–121.

Janni K. A. (1982) Modelling of odorous gases from agricultural sources. *Trans. Am. Soc. Agricult. Eng.* 1721–1723.

Lindvall T. (1970) On the sensory evaluation of odorous air pollution intensities. Nord. Hyg. Tidskr. Suppl. 2, Stockholm Karolinska Institute and National Institute of Public Health.

McCarthy E. F. and Duffee R. A. (1980) An interruptible odor control system for a chemical plant. *Proc. 73rd Ann. Meeting of Air Pollut. Control Ass.* Paper 80-10.4.

Murray D. R., Samual S. C. and Bowne N. E. (1978) Use of a fluctuating plume puff model for prediction of the impact of odorous emissions. *Proc. 71st Ann. Meeting of Air Pollut. Control Ass.* Paper 78-68.6.

Nordstedt R. A. and Taiganides E. P. (1971) Meteorological control of malodors from landspreading of livestock wastes. In *Livestock Waste Management and Pollution Abatement*. Am. Soc. of Agricult. Eng. Pub. PROC-271. pp. 107–109, 116.

Slade D. H., ed. (1968) *Meteorology and Atomic Energy*. U.S. Atomic Energy Comm. Div. Tech. Inf., Washington.

Sutton O. G. (1947) The problem of diffusion in the lower atmosphere. *Q. Jl R. met. Soc.* 73, 257–281.

Turner D. B. (1970) Workbook of atmospheric dispersion estimates. E.P.A Report AP26.

Warren Spring Laboratory (1980) Odour control—a concise guide (edited by Valentin F.H.H. and North A.A.). Report for the Department of the Environment.

Wohlers H. C. (1963) Odor intensity and odor travel from industrial sources. *Int. J. Air Water Pollut.* **7,** 77–78.

APPENDIX 1. COMPUTER MODEL LISTING IN BASIC

```
  1 REM odf2- odour frequency
  5 CLEAR
 20 DIM T(16), C(2), R(2)
 60 INPUT “effective height”: H
 70 INPUT “wind speed”; U
 80 INPUT “vol flow rate”; V
 90 INPUT “odour source conc”: N
100 INPUT “odour conc contour”; Q
105 REM
110 FOR I = 1 TO 16
120 T(I) = 0
125 NEXT I
135 GOTO 760
170 REM
200 C(1) = SQR (P*P-R(1)*R(1))
210 C(2) = SQR (L*L-R(2)*R(2))
220 A = V*N/(3.1416*U*R(1)*R(2))
230 B = C(1)/10: M = C(2)/10
238 J = 0
240 I = 0
242 T(1) = SQR(2*R(1)*R(1)*LOG (V*N/
              (Q*3.1416*U*R(1)*R(2))))
244 T (2) = SQR (2*R(2)*R(2)*LOG (V*N/
              (Q*3.146*U*R(1)*R(2))))
250 REM
254 IF M*J > T(1) THEN GOTO 500
260 E = (B*I/R(1))*(B*I/R(1))
270 F = ((M*J)/R(2))^2
290 GOSUB 650
296 IF J = 0 THEN LET T(10) = T(10)+G: GOTO 300
297 T(11) = T(11)+G
300 REM
305 I = I+1
307 IF ((B*I/T(1))^2+(M*J/T(2))^2) > 1 THEN
    GOTO 320
310 GOTO 250
320 J = J+1: I = 0
330 GOTO 250
400 REM
500 REM
605 B = T(10)+2*T(11)
610 PRINT B; “%T >  ”; Q; “DT”
620 GOTO 5
650 REM
660 G = 4.47-1.99*(H-M*J)/C(2)
665 IF G < 0 THEN LET G = 0
670 W = (4.47-1.99*(B*I/C(1)))
675 IF W < 0 THEN LET W = 0
680 G = G*W/100
690 RETURN
760 INPUT “sigma yb”; P
```

```
770 INPUT "sigma zb"; L
780 INPUT "sigma yr"; R(1)
790 INPUT "sigma zr"; R(2)
800 GOTO 170
900 END
```

APPENDIX 2. DATA COLLECTION METHOD

Hogstrom (1974) and more recently Thiele *et al.* (1986) and Harssema (1986) have used direct sensory methods to estimate the percentage of time that odour thresholds have been exceeded downwind of a source. Teams of observers were required to record the presence and intensity of odours at regular time intervals, the percentage of the total observations with detectable odours being determined from the recorded observations. The same basic approach was adopted by the author but with certain refinements.

The observers were required to estimate the intensity of the odour experienced with each breath or sniff and to classify the intensity on the scale given in Table A1.

Table A1

Intensity	Category
Nil	0
Very slight	1
Slight	2
Moderate	3
Strong	4
Very strong	5

Very slight corresponds to just detectable but not recognizable.

Slight corresponds to just recognizable.

Moderate corresponds to easily recognizable.

Nil and *Very strong* are self-explanatory.

Strong is midway between moderate and very strong.

A set of observations might be recorded as 00132112100121 . . . .

Observations are normally carried out by two observers over periods of about 10 min, i.e. about 150 sniff samples.

Close agreement has been found between individual observers for the percentage of the time that odours were at least recognizable, i.e. category 2 and above. The correlation between 61 pairs of independent observers was 0.79.

During each observation a record was also made of the meteorological conditions and any other factors which would influence the result.

APPENDIX 3. SUMMARY OF DATA USED TO TEST THE MODEL

Reference (type of odour)	Source emission rate *(m^3 s^{-1})	Discharge height (m)	Wind speed (m s^{-1})	Atmospheric stability	Rural/ urban	Source/ receiver distance (m)	Number of observers	Sampling time (min)	Number of samples	Observed %	Predicted %	P/O
Building Board (Process Autoclaves)	10,080	5	3	D	R	305	2	5	152	52	60	1.15
	10,080	5	3	D	R	500	2	7	208	38	39.7	1.04
Hogstrom (1972) (Kraft Papermill)	7,133,068	360	6	A	R	2000	6	3600†	6426	10.8	13.7	1.27
	7,133,068	360	6	A	R	5000	6	3600†	7490	9.8	10.4	1.06
	7,133,068	360	6	A	R	10,000	6	3600†	5528	8.5	3.3	0.38
Adhesive Coating Plant	682,395	6	8.5	D	R	320	2	5	148	90	100	1.11
	682,395	6	8.5	D	R	1945	2	5	144	61	69.5	1.14
Lithographic Printing Works	4127	0	1	D	R	300	2	10	258	83	86.2	1.04
	4127	0	1	D	R	500	2	10	276	38	51.7	1.36
Blood Drying Plant	23,130	14	2	D	U	200	1	15	173	28	12.5	0.45
	23,130	14	2	D	U	240	1	7	101	4	12.2	3.05
	23,130	14	2	D	U	360	1	5	75	8	11.3	1.41
	23,130	14	2	D	U	480	2	7	172	12	9.6	0.8
	23,130	14	2	D	U	560	1	10	147	16	10.3	0.64
GRP Factory	8492	6	7	D	R	160	2	5	144	59	49	0.83
	8492	6	4	D	R	120	2	7	176	71	62.3	0.88
	8492	6	5	D	R	180	2	6	162	43	54.4	1.3
McCarthy (1980)	15,675	7.9	1	F	R	300	NA	NA	NA	8.5‡	11.6‡	1.36
Chemical Plant	15,675	7.9	1	F	R	500	NA	NA	NA	7.5‡	13.4‡	1.79

* Emission rate is the product of concentration in terms of the number of dilutions to threshold and the volumetric flow rate (m^3 s^{-1}).

† Sampled every 2 min over period of one month, 8 h/day, 5 days/week.

‡ Eight dilutions to threshold predicted by TRC model.

Appendix 6

Data collected in laboratory testing and analysed for predictive relationships

No.	var 1 subs	var 2 d/d	var 3 d/r	var 4 ann	var 5 int	var 6 ton	var 7 log d/d	var 8 log d/r	var 9 log ann	var 10 log int	var 11 n	var 12 d:r
1	1.000	0.500	0.100	17.000	14.000	-0.820	-0.301	-1.000	1.230	1.146	0.930	5.000
2	1.000	1.300	0.400	0.500	9.000	-0.820	0.114	-0.398	-0.301	0.954	0.930	3.250
3	1.000	1.800	0.500	23.000	16.000	-0.820	0.255	-0.301	1.362	1.204	0.930	3.600
4	1.000	2.900	0.800	29.000	14.000	-0.820	0.462	-0.097	1.462	1.146	0.930	3.625
5	1.000	3.600	1.000	39.000	29.000	-0.820	0.556	0.000	1.591	1.462	0.930	3.600
6	1.000	7.200	2.000	42.000	47.000	-0.820	0.857	0.301	1.623	1.672	0.930	3.600
7	1.000	14.800	4.200	40.000	62.000	-0.820	1.170	0.623	1.602	1.792	0.930	3.524
8	2.000	1.500	0.500	11.000	12.000	-0.990	0.176	-0.301	1.041	1.079	1.010	3.000
9	2.000	3.800	1.200	11.000	35.000	-0.990	0.580	0.079	1.041	1.544	1.010	3.167
10	2.000	5.900	1.800	24.000	47.000	-0.990	0.771	0.255	1.380	1.672	1.010	3.278
11	2.000	0.400	0.100	20.000	14.000	-0.990	-0.398	-1.000	1.301	1.146	0.890	4.000
12	2.000	0.900	0.200	20.000	21.000	-0.990	-0.046	-0.699	1.301	1.322	0.890	4.500
13	2.000	1.700	0.400	25.000	14.000	-0.990	0.230	-0.398	1.398	1.146	0.890	4.250
14	2.000	2.700	0.700	15.000	15.000	-0.990	0.431	-0.155	1.176	1.176	0.890	3.857
15	2.000	3.300	0.900	15.000	25.000	-0.990	0.518	-0.046	1.176	1.398	0.890	3.667
16	2.000	6.700	1.800	45.000	41.000	-0.990	0.826	0.255	1.653	1.613	0.890	3.722
17	2.000	13.300	3.600	45.000	63.000	-0.990	1.124	0.556	1.653	1.799	0.890	3.694
18	2.000	17.100	4.600	48.000	69.000	-0.990	1.233	0.663	1.681	1.839	0.890	3.717
19	3.000	1.800	0.700	7.000	22.000	-2.200	0.255	-0.155	0.845	1.342	1.170	2.571
20	3.000	2.800	1.000	14.000	28.000	-2.200	0.447	0.000	1.146	1.447	1.170	2.800
21	3.000	5.700	2.100	20.000	45.000	-2.200	0.756	0.322	1.301	1.653	1.170	2.714
22	3.000	8.500	3.100	28.000	49.000	-2.200	0.929	0.491	1.447	1.690	1.170	2.742
23	3.000	12.700	4.600	35.000	63.000	-2.200	1.104	0.663	1.544	1.799	1.170	2.761
24	3.000	28.200	10.300	50.000	75.000	-2.200	1.450	1.013	1.699	1.875	1.170	2.738
25	4.000	1.700	0.100	14.000	10.000	-1.240	0.230	-1.000	1.146	1.000	0.330	17.000
26	4.000	2.800	0.100	14.000	17.000	-1.240	0.447	-1.000	1.146	1.230	0.330	28.000
27	4.000	4.300	0.100	6.000	17.000	-1.240	0.633	-1.000	0.778	1.230	0.330	43.000
28	4.000	6.400	0.200	14.000	14.000	-1.240	0.806	-0.699	1.146	1.146	0.330	32.000
29	4.000	13.300	0.400	14.000	16.000	-1.240	1.124	-0.398	1.146	1.204	0.330	33.250
30	4.000	17.700	0.500	21.000	17.000	-1.240	1.248	-0.301	1.322	1.230	0.330	35.400
31	4.000	22.100	0.600	21.000	20.000	-1.240	1.344	-0.222	1.322	1.301	0.330	36.830
32	4.000	44.100	1.200	35.000	44.000	-1.240	1.644	0.079	1.544	1.643	0.330	36.750

No.	var 1 subs	var 2 d/d	var 3 d/r	var 4 ann	var 5 int	var 6 ton	var 7 log d/d	var 8 log d/r	var 9 log ann	var 10 log int	var 11 n	var 12 d:r
33	4.000	87.200	2.400	50.000	59.000	-1.240	1.941	0.380	1.699	1.771	0.330	36.330
34	5.000	2.000	0.400	17.000	16.000	-1.510	0.301	-0.398	1.230	1.204	0.690	5.000
35	5.000	3.200	0.600	17.000	15.000	-1.510	0.505	-0.222	1.230	1.176	0.690	5.333
36	5.000	5.200	0.900	17.000	20.000	-1.510	0.716	-0.046	1.230	1.301	0.690	5.778
37	5.000	7.900	1.400	35.000	28.000	-1.510	0.898	0.146	1.544	1.447	0.690	5.643
38	5.000	15.900	2.900	42.000	35.000	-1.510	1.201	0.462	1.623	1.544	0.690	5.483
39	5.000	20.000	3.600	42.000	36.000	-1.510	1.301	0.556	1.623	1.556	0.690	5.556
40	5.000	31.800	5.800	35.000	54.000	-1.510	1.502	0.763	1.544	1.732	0.690	5.483
41	5.000	39.700	7.200	35.000	41.000	-1.510	1.599	0.857	1.544	1.613	0.690	5.514
42	6.000	3.500	0.100	5.000	17.000	-0.470	0.544	-1.000	0.699	1.230	0.360	35.000
43	6.000	3.500	0.100	15.000	26.000	-0.470	0.544	-1.000	1.176	1.415	0.360	35.000
44	6.000	5.600	0.200	10.000	15.000	-0.470	0.748	-0.699	1.000	1.176	0.360	28.000
45	6.000	9.200	0.400	5.000	14.000	-0.470	0.964	-0.398	0.699	1.146	0.360	23.000
46	6.000	14.100	0.600	15.000	21.000	-0.470	1.149	-0.222	1.176	1.322	0.360	23.500
47	6.000	22.500	0.900	10.000	25.000	-0.470	1.352	-0.046	1.000	1.398	0.360	25.000
48	6.000	38.700	1.500	10.000	24.000	-0.470	1.588	0.176	1.000	1.380	0.360	25.800
49	6.000	56.300	2.200	15.000	49.000	-0.470	1.751	0.342	1.176	1.690	0.360	25.590
50	6.000	70.400	2.800	25.000	51.000	-0.470	1.848	0.447	1.398	1.708	0.360	25.140
51	6.000	0.900	0.300	23.000	16.000	-0.470	-0.046	-0.523	1.362	1.204	0.910	3.000
52	6.000	1.500	0.400	18.000	12.000	-0.470	0.176	-0.398	1.255	1.079	0.910	3.750
53	6.000	2.500	0.700	18.000	15.000	-0.470	0.398	-0.155	1.255	1.176	0.910	3.571
54	6.000	3.800	1.000	29.000	28.000	-0.470	0.580	0.000	1.462	1.447	0.910	3.800
55	6.000	6.600	1.800	35.000	47.000	-0.470	0.820	0.255	1.544	1.672	0.910	3.667
56	6.000	1.900	0.100	7.000	10.000	-0.470	0.279	-1.000	0.845	1.000	0.330	19.000
57	6.000	3.100	0.100	0.100	11.000	-0.470	0.491	-1.000	-1.000	1.041	0.330	31.000
58	6.000	4.700	0.100	7.000	20.000	-0.470	0.672	-1.000	0.845	1.301	0.330	47.000
59	6.000	7.000	0.200	7.000	13.000	-0.470	0.845	-0.699	0.845	1.114	0.330	35.000
60	6.000	11.700	0.300	7.000	20.000	-0.470	1.068	-0.523	0.845	1.301	0.330	39.000
61	6.000	21.100	0.600	14.000	26.000	-0.470	1.324	-0.222	1.146	1.415	0.330	35.170
62	6.000	48.200	1.400	28.000	27.000	-0.470	1.683	0.146	1.447	1.431	0.330	34.430
63	6.000	95.400	2.700	36.000	39.000	-0.470	1.980	0.431	1.556	1.591	0.330	35.330
64	6.000	120.600	3.500	28.000	37.000	-0.470	2.081	0.544	1.447	1.568	0.330	34.460

No.	var 1 subs	var 2 d/d	var 3 d/r	var 4 ann	var 5 int	var 6 ton	var 7 log d/d	var 8 log d/r	var 9 log ann	var 10 log int	var 11 n	var 12 d:r
65	6.000	146.000	4.200	35.000	54.000	-0.470	2.164	0.623	1.544	1.732	0.330	34.760
66	6.000	1.900	0.100	21.000	12.000	-0.470	0.279	-1.000	1.322	1.079	0.370	19.000
67	6.000	2.700	0.100	20.000	15.000	-0.470	0.431	-1.000	1.301	1.176	0.370	27.000
68	6.000	4.300	0.200	21.000	13.000	-0.470	0.633	-0.699	1.322	1.114	0.370	21.500
69	6.000	5.400	0.200	7.000	11.000	-0.470	0.732	-0.699	0.845	1.041	0.370	27.000
70	6.000	10.800	0.400	28.000	16.000	-0.470	1.033	-0.398	1.447	1.204	0.370	27.000
71	6.000	21.600	0.900	28.000	28.000	-0.470	1.334	-0.046	1.447	1.447	0.370	24.000
72	6.000	27.100	1.100	36.000	26.000	-0.470	1.433	0.041	1.556	1.415	0.370	24.640
73	6.000	32.800	1.300	28.000	23.000	-0.470	1.516	0.114	1.447	1.362	0.370	25.230
74	7.000	0.960	0.100	17.000	8.000	-0.630	-0.018	-1.000	1.230	0.903	0.560	9.600
75	7.000	1.500	0.200	17.000	12.000	-0.630	0.176	-0.699	1.230	1.079	0.560	7.500
76	7.000	3.000	0.400	18.000	14.000	-0.630	0.477	-0.398	1.255	1.146	0.560	7.500
77	7.000	4.500	0.500	28.000	19.000	-0.630	0.653	-0.301	1.447	1.279	0.560	9.000
78	7.000	5.900	0.700	7.000	21.000	-0.630	0.771	-0.155	0.845	1.322	0.560	8.429
79	7.000	7.400	0.900	35.000	20.000	-0.630	0.869	-0.046	1.544	1.301	0.560	8.222
80	7.000	14.800	1.800	35.000	36.000	-0.630	1.170	0.255	1.544	1.556	0.560	8.222
81	7.000	29.500	3.600	45.000	54.000	-0.630	1.470	0.556	1.653	1.732	0.560	8.194
82	7.000	38.200	4.700	45.000	58.000	-0.630	1.582	0.672	1.653	1.763	0.560	8.128
83	1.000	0.400	0.200	7.000	5.000	-0.810	-0.398	-0.699	0.845	0.699	1.220	2.000
84	1.000	0.700	0.200	7.000	5.000	-0.810	-0.155	-0.699	0.845	0.699	1.220	3.500
85	1.000	1.100	0.400	14.000	9.000	-0.810	0.041	-0.398	1.146	0.954	1.220	2.750
86	1.000	1.600	0.600	20.000	17.000	-0.810	0.204	-0.222	1.301	1.230	1.220	2.667
87	1.000	2.600	1.000	34.000	30.000	-0.810	0.415	0.000	1.531	1.477	1.220	2.600
88	1.000	4.900	1.900	42.000	53.000	-0.810	0.690	0.279	1.623	1.724	1.220	2.579
89	1.000	6.500	2.500	42.000	53.000	-0.810	0.813	0.398	1.623	1.724	1.220	2.600
90	1.000	8.200	3.100	49.000	61.000	-0.810	0.914	0.491	1.690	1.785	1.220	2.645
91	2.000	1.000	0.400	9.000	9.000	-0.990	0.000	-0.398	0.954	0.954	1.390	2.500
92	2.000	1.700	0.700	26.000	21.000	-0.990	0.230	-0.155	1.415	1.322	1.390	2.429
93	2.000	2.700	1.200	26.000	28.000	-0.990	0.431	0.079	1.415	1.447	1.390	2.250
94	2.000	4.100	1.800	53.000	39.000	-0.990	0.613	0.255	1.724	1.591	1.390	2.278
95	2.000	6.600	2.800	53.000	47.000	-0.990	0.820	0.447	1.724	1.672	1.390	2.357
96	2.000	12.400	5.300	53.000	64.000	-0.990	1.093	0.724	1.724	1.806	1.390	2.340

No.	var 1	var 2	var 3	var 4	var 5	var 6	var 7	var 8	var 9	var 10	var 11	var 12
	subs	d/d	d/r	ann	int	ton	log d/d	log d/r	log ann	log int	n	d:r
97	6.000	0.500	0.100	7.000	4.000	-0.470	-0.301	-1.000	0.845	0.602	0.510	5.000
98	6.000	0.800	0.100	7.000	8.000	-0.470	-0.097	-1.000	0.845	0.903	0.510	8.000
99	6.000	1.200	0.100	7.000	7.000	-0.470	0.079	-1.000	0.845	0.845	0.510	12.000
100	6.000	1.900	0.200	7.000	12.000	-0.470	0.279	-0.699	0.845	1.079	0.510	9.500
101	6.000	3.300	0.300	7.000	14.000	-0.470	0.518	-0.523	0.845	1.146	0.510	11.000
102	6.000	4.800	0.500	7.000	15.000	-0.470	0.681	-0.301	0.845	1.176	0.510	9.600
103	6.000	6.100	0.600	7.000	23.000	-0.470	0.785	-0.222	0.845	1.362	0.510	10.170
104	6.000	12.100	1.200	7.000	21.000	-0.470	1.083	0.079	0.845	1.322	0.510	10.080
105	6.000	19.400	2.000	20.000	28.000	-0.470	1.288	0.301	1.301	1.447	0.510	9.700
106	6.000	30.300	3.100	20.000	38.000	-0.470	1.481	0.491	1.301	1.580	0.510	9.774
107	6.000	47.900	4.900	55.000	46.000	-0.470	1.680	0.690	1.740	1.663	0.510	9.776
108	4.000	0.500	0.200	19.000	3.000	-1.240	-0.301	-0.699	1.279	0.477	0.980	2.500
109	4.000	0.900	0.300	36.000	7.000	-1.240	-0.046	-0.523	1.556	0.845	0.980	3.000
110	4.000	1.400	0.400	30.000	11.000	-1.240	0.146	-0.398	1.477	1.041	0.980	3.500
111	4.000	2.100	0.600	20.000	13.000	-1.240	0.322	-0.222	1.301	1.114	0.980	3.500
112	4.000	3.200	1.000	30.000	22.000	-1.240	0.505	0.000	1.477	1.342	0.980	3.200
113	4.000	5.300	1.600	39.000	29.000	-1.240	0.724	0.204	1.591	1.462	0.980	3.313
114	4.000	8.500	2.600	44.000	41.000	-1.240	0.929	0.415	1.643	1.613	0.980	3.269
115	4.000	10.600	3.200	39.000	47.000	-1.240	1.025	0.505	1.591	1.672	0.980	3.313
116	5.000	1.000	0.200	7.000	9.300	-1.510	0.000	-0.699	0.845	0.969	0.750	5.000
117	5.000	2.600	0.600	20.000	25.000	-1.510	0.415	-0.222	1.301	1.398	0.750	4.333
118	5.000	3.900	0.900	27.000	34.000	-1.510	0.591	-0.046	1.431	1.531	0.750	4.333
119	5.000	6.400	1.500	20.000	35.000	-1.510	0.806	0.176	1.301	1.544	0.750	4.267
120	5.000	10.300	2.400	27.000	53.000	-1.510	1.013	0.380	1.431	1.724	0.750	4.292
121	5.000	0.500	0.100	17.000	5.000	-1.510	-0.301	-1.000	1.230	0.699	0.760	5.000
122	5.000	0.800	0.200	26.000	6.000	-1.510	-0.097	-0.699	1.415	0.778	0.760	4.000
123	5.000	1.300	0.300	35.000	11.000	-1.510	0.114	-0.523	1.544	1.041	0.760	4.333
124	5.000	2.000	0.400	35.000	13.000	-1.510	0.301	-0.398	1.544	1.114	0.760	5.000
125	5.000	3.100	0.700	35.000	21.000	-1.510	0.491	-0.155	1.544	1.322	0.760	4.429
126	5.000	5.200	1.100	44.000	25.000	-1.510	0.716	0.041	1.643	1.398	0.760	4.727
127	5.000	8.300	1.800	44.000	35.000	-1.510	0.919	0.255	1.643	1.544	0.760	4.611
128	5.000	10.400	2.200	44.000	35.000	-1.510	1.017	0.342	1.643	1.544	0.760	4.727

No.	var 1 subs	var 2 d/d	var 3 d/r	var 4 ann	var 5 int	var 6 ton	var 7 log d/d	var 8 log d/r	var 9 log ann	var 10 log int	var 11 n	var 12 d:r
129	5.000	20.900	4.400	53.000	46.000	-1.510	1.320	0.643	1.724	1.663	0.760	4.750
130	5.000	0.200	0.100	0.100	1.000	-1.510	-0.699	-1.000	-1.000	0.000	0.790	2.000
131	5.000	0.300	0.100	0.100	8.000	-1.510	-0.523	-1.000	-1.000	0.903	0.790	3.000
132	5.000	0.500	0.100	9.000	5.000	-1.510	-0.301	-1.000	0.954	0.699	0.790	5.000
133	5.000	0.800	0.200	9.000	8.000	-1.510	-0.097	-0.699	0.954	0.903	0.790	4.000
134	5.000	1.300	0.300	17.000	11.000	-1.510	0.114	-0.523	1.230	1.041	0.790	4.333
135	5.000	2.100	0.500	17.000	14.000	-1.510	0.322	-0.301	1.230	1.146	0.790	4.200
136	5.000	5.200	1.200	27.000	26.000	-1.510	0.716	0.079	1.431	1.415	0.790	4.333
137	5.000	8.100	1.800	18.000	25.000	-1.510	0.909	0.255	1.255	1.398	0.790	4.500
138	5.000	10.700	2.400	35.000	31.000	-1.510	1.029	0.380	1.544	1.491	0.790	4.458
139	5.000	13.500	3.100	50.000	43.000	-1.510	1.130	0.491	1.699	1.633	0.790	4.355
140	5.000	21.900	5.000	42.000	31.000	-1.510	1.340	0.699	1.623	1.491	0.790	4.380
141	8.000	0.300	0.100	7.000	3.000	-1.510	-0.523	-1.000	0.845	0.477	0.750	3.000
142	8.000	0.500	0.100	14.000	6.000	-1.510	-0.301	-1.000	1.146	0.778	0.750	5.000
143	8.000	0.900	0.200	7.000	6.000	-1.510	-0.046	-0.699	0.845	0.778	0.750	4.500
144	8.000	1.500	0.300	14.000	8.000	-1.510	0.176	-0.523	1.146	0.903	0.750	5.000
145	8.000	2.400	0.500	20.000	14.000	-1.510	0.380	-0.301	1.301	1.146	0.750	4.800
146	8.000	4.800	1.000	35.000	37.000	-1.510	0.681	0.000	1.544	1.568	0.750	4.800
147	8.000	7.300	1.500	34.000	37.000	-1.510	0.863	0.176	1.531	1.568	0.750	4.867
148	8.000	9.900	2.100	49.000	47.000	-1.510	0.996	0.322	1.690	1.672	0.750	4.714
149	7.000	0.200	0.100	20.000	6.000	-0.630	-0.699	-1.000	1.301	0.778	0.850	2.000
150	7.000	0.300	0.100	25.000	8.000	-0.630	-0.523	-1.000	1.398	0.903	0.850	3.000
151	7.000	0.500	0.100	25.000	14.000	-0.630	-0.301	-1.000	1.398	1.146	0.850	5.000
152	7.000	0.700	0.200	5.000	9.000	-0.630	-0.155	-0.699	0.699	0.954	0.850	3.500
153	7.000	1.100	0.300	19.000	17.000	-0.630	0.041	-0.523	1.279	1.230	0.850	3.667
154	7.000	2.200	0.600	25.000	20.000	-0.630	0.342	-0.222	1.398	1.301	0.850	3.667
155	7.000	2.900	0.700	15.000	16.000	-0.630	0.462	-0.155	1.176	1.204	0.850	4.143
156	7.000	3.700	0.900	19.000	16.000	-0.630	0.568	-0.046	1.279	1.204	0.850	4.111
157	7.000	7.300	1.800	10.000	17.000	-0.630	0.863	0.255	1.000	1.230	0.850	4.056
158	7.000	14.400	3.600	23.000	33.000	-0.630	1.158	0.556	1.362	1.519	0.850	4.000
159	7.000	29.500	7.400	29.000	39.000	-0.630	1.470	0.869	1.462	1.591	0.850	3.986
160	9.000	0.600	0.200	0.100	5.500	-0.640	-0.222	-0.699	-1.000	0.740	1.220	3.000

No.	var 1 subs	var 2 d/d	var 3 d/r	var 4 ann	var 5 int	var 6 ton	var 7 log d/d	var 8 log d/r	var 9 log ann	var 10 log int	var 11 n	var 12 d:r
161	9.000	0.700	0.300	0.100	6.700	-0.640	-0.155	-0.523	-1.000	0.826	1.220	2.333
162	9.000	1.000	0.400	0.100	8.300	-0.640	0.000	-0.398	-1.000	0.919	1.220	2.500
163	9.000	1.600	0.600	0.100	10.000	-0.640	0.204	-0.222	-1.000	1.000	1.220	2.667
164	9.000	2.600	1.000	0.100	11.500	-0.640	0.415	0.000	-1.000	1.061	1.220	2.600
165	9.000	4.000	1.500	21.000	25.600	-0.640	0.602	0.176	1.322	1.408	1.220	2.667
166	9.000	6.400	2.400	34.000	41.000	-0.640	0.806	0.380	1.531	1.613	1.220	2.667
167	9.000	10.000	3.800	38.000	49.400	-0.640	1.000	0.580	1.580	1.694	1.220	2.632
168	9.000	16.000	6.100	45.000	59.300	-0.640	1.204	0.785	1.653	1.773	1.220	2.623
169	10.000	0.300	0.100	4.000	3.600	-0.560	-0.523	-1.000	0.602	0.556	1.000	3.000
170	10.000	0.500	0.200	4.000	5.000	-0.560	-0.301	-0.699	0.602	0.699	1.000	2.500
171	10.000	1.300	0.400	4.000	9.200	-0.560	0.114	-0.398	0.602	0.964	1.000	3.250
172	10.000	3.100	1.000	22.000	24.200	-0.560	0.491	0.000	1.342	1.384	1.000	3.100
173	10.000	7.800	2.400	35.000	43.800	-0.560	0.892	0.380	1.544	1.641	1.000	3.250
174	10.000	19.500	6.000	54.000	50.300	-0.560	1.290	0.778	1.732	1.702	1.000	3.250
175	10.000	48.800	15.000	74.000	86.100	-0.560	1.688	1.176	1.869	1.935	1.000	3.253
176	11.000	0.900	0.300	0.100	0.300	-1.000	-0.046	-0.523	-1.000	-0.523	1.030	3.000
177	11.000	1.000	0.300	4.000	10.400	-1.000	0.000	-0.523	0.602	1.017	1.030	3.333
178	11.000	1.500	0.500	4.000	16.700	-1.000	0.176	-0.301	0.602	1.223	1.030	3.000
179	11.000	2.400	0.800	15.000	14.100	-1.000	0.380	-0.097	1.176	1.149	1.030	3.000
180	11.000	3.900	1.200	11.000	19.900	-1.000	0.591	0.079	1.041	1.299	1.030	3.250
181	11.000	6.000	1.900	20.000	23.400	-1.000	0.778	0.279	1.301	1.369	1.030	3.158
182	11.000	12.000	3.800	35.000	39.400	-1.000	1.079	0.580	1.544	1.595	1.030	3.158
183	11.000	24.000	7.700	43.000	55.200	-1.000	1.380	0.887	1.633	1.742	1.030	3.117
184	11.000	30.000	9.600	47.000	80.000	-1.000	1.477	0.982	1.672	1.903	1.030	3.125
185	12.000	1.200	0.300	0.100	5.500	-0.920	0.079	-0.523	-1.000	0.740	0.920	4.000
186	12.000	1.200	0.300	3.000	8.800	-0.920	0.079	-0.523	0.477	0.945	0.920	4.000
187	12.000	0.800	0.200	10.000	17.700	-0.920	-0.097	-0.699	1.000	1.248	0.920	4.000
188	12.000	1.200	0.300	3.000	15.900	-0.920	0.079	-0.523	0.477	1.201	0.920	4.000
189	12.000	1.600	0.500	7.000	19.500	-0.920	0.255	-0.301	0.845	1.290	0.920	3.600
190	12.000	3.000	0.800	10.000	27.400	-0.920	0.477	-0.097	1.000	1.438	0.920	3.750
191	12.000	4.700	1.300	24.000	41.500	-0.920	0.672	0.114	1.380	1.618	0.920	3.615
192	12.000	11.500	3.200	31.000	52.500	-0.920	1.061	0.505	1.491	1.720	0.920	3.594

No.	var 1 subs	var 2 d/d	var 3 d/r	var 4 ann	var 5 int	var 6 ton	var 7 log d/d	var 8 log d/r	var 9 log ann	var 10 log int	var 11 n	var 12 d:r
193	12.000	18.400	5.100	28.000	48.000	-0.920	1.265	0.708	1.447	1.681	0.920	3.608
194	12.000	23.000	6.400	42.000	56.900	-0.920	1.362	0.806	1.623	1.755	0.920	3.594
195	13.000	0.700	0.100	4.000	8.200	-1.250	-0.155	-1.000	0.602	0.914	0.530	7.000
196	13.000	1.000	0.100	9.000	7.400	-1.250	0.000	-1.000	0.954	0.869	0.530	10.000
197	13.000	1.700	0.200	13.000	11.000	-1.250	0.230	-0.699	1.114	1.041	0.530	8.500
198	13.000	2.600	0.300	13.000	17.100	-1.250	0.415	-0.523	1.114	1.233	0.530	8.667
199	13.000	6.500	0.700	17.000	17.100	-1.250	0.813	-0.155	1.230	1.233	0.530	9.286
200	13.000	10.400	1.100	18.000	19.000	-1.250	1.017	0.041	1.255	1.279	0.530	9.455
201	13.000	13.000	1.400	22.000	26.900	-1.250	1.114	0.146	1.342	1.430	0.530	9.286
202	14.000	0.300	0.100	0.100	7.200	-0.280	-0.523	-1.000	-1.000	0.857	0.870	3.000
203	14.000	0.500	0.100	0.100	6.700	-0.280	-0.301	-1.000	-1.000	0.826	0.870	5.000
204	14.000	1.200	0.300	0.100	7.600	-0.280	0.079	-0.523	-1.000	0.881	0.870	4.000
205	14.000	3.000	0.800	13.000	21.400	-0.280	0.477	-0.097	1.114	1.330	0.870	3.750
206	14.000	4.200	1.100	13.000	25.900	-0.280	0.623	0.041	1.114	1.413	0.870	3.818
207	14.000	7.400	1.900	39.000	49.100	-0.280	0.869	0.279	1.591	1.691	0.870	3.895
208	14.000	9.300	2.400	61.000	74.000	-0.280	0.969	0.380	1.785	1.869	0.870	3.875
209	14.000	18.600	4.800	73.000	85.000	-0.280	1.270	0.681	1.863	1.929	0.870	3.875
210	15.000	0.100	0.030	4.000	2.900	-0.710	-1.000	-1.523	0.602	0.462	0.870	3.333
211	15.000	0.300	0.100	4.000	2.900	-0.710	-0.523	-1.000	0.602	0.462	0.870	3.000
212	15.000	0.700	0.200	4.000	6.200	-0.710	-0.155	-0.699	0.602	0.792	0.870	3.500
213	15.000	1.700	0.400	13.000	7.700	-0.710	0.230	-0.398	1.114	0.887	0.870	4.250
214	0.000	2.600	0.700	13.000	15.600	-0.710	0.415	-0.155	1.114	1.193	0.870	3.714
215	15.000	4.200	1.100	21.000	21.900	-0.710	0.623	0.041	1.322	1.340	0.870	3.818
216	15.000	5.200	1.400	30.000	32.000	-0.710	0.716	0.146	1.477	1.505	0.870	3.714
217	15.000	10.400	2.700	40.000	50.300	-0.710	1.017	0.431	1.602	1.702	0.870	3.852
218	15.000	26.000	6.800	70.000	83.400	-0.710	1.415	0.832	1.845	1.921	0.870	3.824
219	16.000	0.300	0.100	0.100	3.800	-0.840	-0.523	-1.000	-1.000	0.580	0.880	3.000
220	16.000	0.700	0.200	0.100	5.800	-0.840	-0.155	-0.699	-1.000	0.763	0.880	3.500
221	16.000	1.000	0.300	9.000	7.200	-0.840	0.000	-0.523	0.954	0.857	0.880	3.333
222	16.000	1.000	0.300	9.000	8.200	-0.840	0.000	-0.523	0.954	0.914	0.880	3.333
223	16.000	1.600	0.400	17.000	11.700	-0.840	0.204	-0.398	1.230	1.068	0.880	4.000
224	16.000	2.500	0.700	17.000	18.700	-0.840	0.398	-0.155	1.230	1.272	0.880	3.571

No.	var 1 subs	var 2 d/d	var 3 d/r	var 4 ann	var 5 int	var 6 ton	var 7 log d/d	var 8 log d/r	var 9 log ann	var 10 log int	var 11 n	var 12 d:r
225	16.000	4.500	1.200	22.000	28.300	-0.840	0.653	0.079	1.342	1.452	0.880	3.750
226	16.000	10.000	2.600	40.000	35.600	-0.840	1.000	0.415	1.602	1.551	0.880	3.846
227	16.000	25.000	6.500	67.000	77.800	-0.840	1.398	0.813	1.826	1.891	0.880	3.846
228	16.000	38.500	10.000	78.000	91.700	-0.840	1.585	1.000	1.892	1.962	0.880	3.850
229	17.000	1.600	0.100	5.000	8.100	-0.840	0.204	-1.000	0.699	0.909	0.390	16.000
230	17.000	4.000	0.200	5.000	13.400	-0.840	0.602	-0.699	0.699	1.127	0.390	20.000
231	17.000	10.000	0.500	24.000	47.400	-0.840	1.000	-0.301	1.380	1.676	0.390	20.000
232	18.000	0.100	0.010	0.100	0.010	-0.660	-1.000	-2.000	-1.000	-2.000	0.850	10.000
233	18.000	0.100	0.030	0.100	0.800	-0.660	-1.000	-1.523	-1.000	-0.097	0.850	3.333
234	18.000	0.300	0.100	0.100	1.600	-0.660	-0.523	-1.000	-1.000	0.204	0.850	3.000
235	18.000	0.600	0.200	0.100	5.100	-0.660	-0.222	-0.699	-1.000	0.708	0.850	3.000
236	18.000	1.000	0.300	0.100	7.800	-0.660	0.000	-0.523	-1.000	0.892	0.850	3.333
237	18.000	1.600	0.400	0.100	8.100	-0.660	0.204	-0.398	-1.000	0.909	0.850	4.000
238	18.000	4.000	1.000	15.000	22.400	-0.660	0.602	0.000	1.176	1.350	0.850	4.000
239	18.000	6.300	1.600	24.000	37.000	-0.660	0.799	0.204	1.380	1.568	0.850	3.938
240	18.000	10.000	2.500	39.000	56.600	-0.660	1.000	0.398	1.591	1.753	0.850	4.000
241	19.000	0.100	0.020	0.100	0.010	-0.720	-1.000	-1.699	-1.000	-2.000	1.120	5.000
242	19.000	0.100	0.050	0.100	0.010	-0.720	-1.000	-1.301	-1.000	-2.000	1.120	2.000
243	19.000	0.100	0.030	0.100	0.800	-0.720	-1.000	-1.523	-1.000	-0.097	1.120	3.333
244	19.000	0.300	0.090	0.100	1.600	-0.720	-0.523	-1.046	-1.000	0.204	1.120	3.333
245	19.000	0.600	0.200	0.100	5.100	-0.720	-0.222	-0.699	-1.000	0.708	1.120	3.000
246	19.000	1.800	0.600	5.000	5.400	-0.720	0.255	-0.222	0.699	0.732	1.120	3.000
247	19.000	4.000	1.400	5.000	15.600	-0.720	0.602	0.146	0.699	1.193	1.120	2.857
248	19.000	6.300	2.200	19.000	29.300	-0.720	0.799	0.342	1.279	1.467	1.120	2.864
249	19.000	10.000	3.500	45.000	56.400	-0.720	1.000	0.544	1.653	1.751	1.120	2.857
250	19.000	15.400	5.400	96.000	81.300	-0.720	1.188	0.732	1.982	1.910	1.120	2.852

No.	var 1 subs	var 2 d/d	var 3 d/r	var 4 ann	var 5 int	var 6 ton	var 7 log d/d	var 8 log d/r	var 9 log ann	var 10 log int	var 11 n	var 12 d:r
251	6.000	1.200	0.100	7.000	18.000	-0.470	0.079	-1.000	0.845	1.255	-0.330	12.000
252	6.000	0.700	0.100	14.000	8.000	-0.470	-0.155	-1.000	1.146	0.903	-0.370	7.000
253	6.000	1.100	0.100	14.000	5.000	-0.470	0.041	-1.000	1.146	0.699	-0.370	11.000
254	5.000	0.100	0.100	0.100	1.000	-1.510	-1.000	-1.000	-1.000	0.000	-0.790	1.000
255	10.000	0.300	0.100	4.000	2.900	-0.560	-0.523	-1.000	0.602	0.462	-1.000	3.000
256	13.000	0.400	0.100	0.100	6.200	-1.250	-0.398	-1.000	-1.000	0.792	-0.530	4.000
257	17.000	0.100	0.100	0.100	0.100	-0.840	-1.000	-1.000	-1.000	-1.000	-0.390	1.000
258	17.000	0.100	0.100	0.100	0.800	-0.840	-1.000	-1.000	-1.000	-0.097	-0.390	1.000
259	17.000	0.300	0.100	0.100	3.300	-0.840	-0.523	-1.000	-1.000	0.518	-0.390	3.000
260	17.000	0.600	0.100	0.100	6.800	-0.840	-0.222	-1.000	-1.000	0.832	-0.390	6.000

Appendix 7

Data collected in field testing and analysed for predictive relationships

KEY TO DATA

Data no.	Source description
1-12	Glass fibre reinforced plastic manufacture
13-16	Building board manufacture
17-23	Dried blood processing
24	Brewery effluent
25-31	Land fill gas
32	Silage
33-38	Iron foundry emissions
39-48	Land fill gas

ECI = effective continuous intensity

Sd = standard deviation

ann = annoyance

>1 = percentage time intensity 1 or greater (very slight)

>2 = percentage time intensity 2 or greater (slight)

>3 = percentage time intensity 3 or greater (moderate)

>4 = percentage time intensity 4 or greater (strong)

5 = percentage time intensity 5 or greater (very strong)

ton = hedonic tone

%t = percentage time greater than detection threshold

No.	var 1 eci	var 2 sd	var 3 ann	var 4 >1	var 5 >2	var 6 >3	var 7 >4	var 8 5	var 9 ton	var 10 %t
1	30.400	22.000	77.000	89.000	78.000	40.000	11.000	2.000	-0.340	89.000
2	27.900	21.400	42.000	95.000	61.000	35.000	11.000	0.000	-0.340	95.000
3	17.500	16.100	42.000	68.000	59.000	15.000	2.000	0.000	-0.340	68.000
4	32.800	23.500	77.000	91.000	76.000	43.000	19.000	0.000	-0.340	91.000
5	11.000	11.900	0.000	57.000	37.000	5.000	0.000	0.000	-0.340	57.000
6	34.100	19.200	42.000	94.000	88.000	53.000	11.000	0.000	-0.340	94.000
7	7.700	11.200	0.000	47.000	21.000	2.000	1.000	0.000	-0.340	47.000
8	22.400	21.000	42.000	71.000	51.000	38.000	5.000	0.000	-0.340	71.000
9	12.200	11.400	17.000	68.000	39.000	5.000	0.000	0.000	-0.340	68.000
10	25.100	23.900	42.000	73.000	54.000	39.000	12.000	0.000	-0.340	73.000
11	4.300	6.800	0.000	35.000	9.000	0.000	0.000	0.000	-0.340	35.000
12	9.500	12.800	17.000	50.000	25.000	8.000	0.000	0.000	-0.340	50.000
13	1.500	4.100	0.000	14.000	2.000	0.000	0.000	0.000	-1.070	14.000
14	1.800	4.700	17.000	16.000	3.000	0.000	0.000	0.000	-1.070	16.000
15	4.400	7.000	0.000	34.000	10.000	0.000	0.000	0.000	-1.070	34.000
16	2.600	4.000	0.000	29.000	0.000	0.000	0.000	0.000	-1.070	29.000
17	1.900	5.100	0.000	15.000	5.000	0.000	0.000	0.000	-2.090	14.900
18	5.300	10.400	17.000	28.000	14.000	4.000	0.000	0.000	-2.090	28.000
19	15.000	23.200	42.000	43.000	32.000	21.000	8.000	1.000	-2.090	43.000
20	0.700	2.400	0.000	8.000	0.000	0.000	0.000	0.000	-2.090	8.000
21	2.400	5.900	0.000	16.000	7.000	0.000	0.000	0.000	-2.090	16.000
22	1.400	5.500	0.000	9.000	3.000	1.000	0.000	0.000	-2.090	9.000
23	0.500	2.700	0.000	4.000	1.000	0.000	0.000	0.000	-2.090	4.000
24	9.300	11.000	17.000	55.000	27.000	4.000	0.000	0.000	-2.230	55.000

No.	var 1 eci	var 2 sd	var 3 ann	var 4 >1	var 5 >2	var 6 >3	var 7 >4	var 8 5	var 9 ton	var 10 %t
25	4.900	7.600	0.000	36.000	13.000	0.000	0.000	0.000	-1.590	36.000
26	9.300	9.400	17.000	57.000	32.000	0.000	0.000	0.000	-1.590	57.000
27	14.400	9.700	42.000	80.000	52.000	2.000	0.000	0.000	-1.590	80.000
28	3.700	7.100	0.000	26.000	11.000	0.000	0.000	0.000	-1.590	26.000
29	8.300	7.700	17.000	65.000	19.000	0.000	0.000	0.000	-1.590	65.000
30	4.500	5.600	0.000	44.000	4.000	0.000	0.000	0.000	-1.590	44.000
31	7.800	8.500	0.000	55.000	22.000	0.000	0.000	0.000	-1.590	55.000
32	6.200	10.900	8.500	36.000	15.000	5.000	0.000	0.000	-1.620	36.000
33	24.500	26.500	77.000	67.000	53.000	32.000	13.000	3.000	-1.780	67.000
34	39.000	29.700	100.000	90.000	79.000	49.000	27.000	9.000	-1.780	90.000
35	10.400	17.600	42.000	45.000	20.000	12.000	4.000	0.000	-1.780	45.000
36	32.800	35.500	77.000	73.000	53.000	37.000	26.000	14.000	-1.780	73.000
37	23.500	18.600	77.000	90.000	57.000	31.000	5.000	0.000	-1.780	90.000
38	18.300	18.300	42.000	72.000	45.000	24.000	3.000	0.000	-1.780	72.000
39	7.000	8.800	8.500	0.000	0.000	0.000	0.000	0.000	-1.840	53.000
40	4.000	4.500	17.000	0.000	0.000	0.000	0.000	0.000	-1.840	45.000
41	16.400	15.700	29.500	0.000	0.000	0.000	0.000	0.000	-1.840	79.000
42	12.000	10.600	42.000	0.000	0.000	0.000	0.000	0.000	-1.840	80.000
43	6.600	9.100	17.000	0.000	0.000	0.000	0.000	0.000	-1.300	47.000
44	7.500	6.900	17.000	0.000	0.000	0.000	0.000	0.000	-1.300	64.000
45	8.800	10.000	17.000	0.000	0.000	0.000	0.000	0.000	-0.530	55.000
46	16.900	6.300	17.000	0.000	0.000	0.000	0.000	0.000	-0.530	100.000
47	17.000	22.500	42.000	0.000	0.000	0.000	0.000	0.000	-0.530	52.000
48	13.200	20.200	42.000	0.000	0.000	0.000	0.000	0.000	-0.530	53.000

Appendix 8

Listing of the full odour nuisance assessment model in GW-Basic

```
10 REM ONAM odour assessment model  :ALB 2/88
20 CLS
30 PRINT "Odour Nuisance Assessment Model"
31 PRINT "-------------------------------"
35 PRINT "SELECT STARTING POINT"
38 PRINT
39 PRINT "PREDICTIONS"
40 PRINT "source parameters              = 1"
45 PRINT
49 PRINT "FIELD OBSERVATIONS"
50 PRINT "intensity distribution         = 2"
60 PRINT "eci                            = 3"
65 PRINT
69 PRINT "LABORATORY TESTS"
70 PRINT "concentration ratio            = 4"
80 PRINT "intensity distributions        = 5"
90 PRINT "average odour intensity        = 6"
95 PRINT
96 PRINT
100 INPUT ;C
110 ON C GOSUB 1000,2000,3000,4000,5000,6000
115 CLS
120 PRINT "ANNOYANCE = ";A
130 S=(21-A)/Z
131 IF S>0 GOTO 135
132 P=50:S=-S: GOTO 140
135 P=-50
140 FOR I=.1 TO S STEP .1
145 P=P+4.47-1.98*I
150 NEXT I
151 PRINT
152 PRINT
153 PRINT
155 IF ABS(P)>100 THEN P=100
160 PRINT ;ABS(P);" % probability of a nuisance"
200 END
1000 REM
1001 CLS
1005 CLEAR
1020 DIM T(16),C(2),R(2)
1060 INPUT"effective height";H
1070 INPUT"wind speed ";U
1080 INPUT"vol flow rate";V
1090 INPUT"odour source conc";N
1100 Q=1
1105 REM
1110 FOR I=1 TO 16
1120 T(I)=0
1125 NEXT I
1135 GOTO 1760
1170 REM
1200 C(1)=SQR(P*P-R(1)*R(1))
1210 C(2)=SQR(L*L-R(2)*R(2))
1220 A=V*N/(3.1416*U*R(1)*R(2))
1230 B=C(1)/10:M=C(2)/10
1238 J=0
```

```
1240 I=0
1242 T(1)=SQR(2*R(1)*R(1)*LOG(V*N/(Q*3.1416*U*R(1)*R(2))))
1244 T(2)=SQR(2*R(2)*R(2)*LOG(V*N/(Q*3.1416*U*R(1)*R(2))))
1250 REM
1254 IF M*J>T(2) THEN GOTO 1500
1260 E=(B*I/R(1))*(B*I/R(1))
1270 F=((M*J)/R(2))^2
1290 GOSUB 1650
1296 IF J=0 THEN LET   T(10)=T(10)+G:GOTO 1300
1297 T(11)=T(11)+G
1300 REM
1305 I=I+1
1307 IF ((B*I/T(1))^2+(M*J/T(2))^2)>1 THEN GOTO 1320
1310 GOTO 1250
1320 J=J+1:I=0
1330 GOTO 1250
1400 REM
1500 REM
1605 B=T(10)+2*T(11)
1620 GOTO 1985
1650 REM
1660 G=4.47-1.98*(H-M*J)/C(2)
1665 IF G<0 THEN LET G=0
1670 W=(4.47-1.98*(B*I/C(1)))
1675 IF W<0 THEN LET W=0
1680 G=G*W/100
1690 RETURN
1760 REM
1770 PRINT
1780 INPUT "stability 1-6  ";K
1790 PRINT
1795 INPUT "distance  = ";D
1800 D=LOG(D)*.4343
1805 IF K>1 GOTO 1835
1810 P=10^(.633*D+.04649*D*D+.005436)
1815 L=10^(.18*D+.189*D*D-.08979)
1820 R(1)=10^(.93*D-.845)
1825 R(2)=10^(.733*D-.287)
1830 GOTO 1170
1835 IF K>2 GOTO 1865
1840 P=10^(.528*D+.06225*D*D+.0145)
1845 L=10^(.194*D+.151*D*D+.069491)
1850 R(1)=10^(.905*D-.92)
1855 R(2)=10^(.728*D-.493)
1860 GOTO 1170
1865 IF K>3 GOTO 1895
1870 P=10^(.451*D+.0734*D*D-.01233)
1875 L=10^(.167*D+.143*D*D+.0266)
1880 R(1)=10^(.899*D-1.042)
1885 R(2)=10^(.723*D-.707)
1890 GOTO 1170
1895 IF K>4 GOTO 1925
1900 P=10^(.378*D+.08442*D*D-.02886)
1905 L=10^(.179*D+.103*D*D+.005855)
1910 R(1)=10^(.917*D-1.213)
1915 R(2)=10^(.727*D-.896)
1920 GOTO 1170
1925 IF K>5 GOTO 1955
1930 P=10^(.238*D+1.11*D*D-.01088)
```

```
1935 L=10^(.127*D+9.890999E-02*D*D+.009256)
1940 R(1)=10^(.954*D-1.582)
1945 R(2)=10^(.653*D-1.132)
1950 GOTO 1170
1955 IF K> 6 GOTO 1760
1960 P=10^(.135*D+.124*D*D+.01041)
1965 L=10^(.03359*D+.112*D*D+.02225)
1970 R(1)=10^(.93*D-1.769)
1975 R(2)=10^(.6*D-1.387)
1980 GOTO 1170
1985 A=2.61*10^(.015*B+.119)-5.28
1986 Z=1.96
1988 PRINT
1989 PRINT
1990 GOTO 120
2000 REM
2005 CLS
2010 PRINT "input total numbers in each intensity category"
2012 PRINT
2014 PRINT
2016 PRINT
2018 PRINT
2020 INPUT "category 0 = ";C0
2030 INPUT "category 1 = ";C1
2040 INPUT "category 2 = ";C2
2050 INPUT "category 3 = ";C3
2060 INPUT "category 4 = ";C4
2070 INPUT "category 5 = ";C5
2080 CT=C0+C1+C2+C3+C4+C5
2090 C1=C1*100/CT
2100 C2=C2*100/CT
2110 C3=C3*100/CT
2120 C4=C4*100/CT
2130 C5=C5*100/CT
2140 E=(C1*9+C2*22+C3*43+C4*73+C5*100)/100
2150 GOTO 3020
3000 REM
3005 CLS
3010 INPUT ;"eci = ";E
3020 A= 2.61*E-5.28
3025 Z=10.274
3030 RETURN
4000 REM
4005 CLS
4010 PRINT "input type of concentration"
4020 PRINT "d/d = 1"
4030 PRINT "d/r = 2"
4032 PRINT
4034 PRINT
4036 PRINT
4040 INPUT ;T
4045 PRINT
4050 INPUT ;"concentration ratio    ";R
4060 ON T GOTO 4070,4090
4070 A=17.29*.4343*LOG(R) +12.41
4075 Z=12.077
4080 GOTO 4100
4090 A=6.28*R+12.25
4095 Z=11.71
```

```
4100 RETURN
5000 REM
5005 CLS
5010 PRINT "input total numbers in each intensity category"
5012 PRINT
5014 PRINT
5016 PRINT
5020 INPUT "nil          = ";N1
5030 INPUT "possible     = ";N2
5040 INPUT "very slight  = ";N3
5050 INPUT "slight       = ";N4
5060 INPUT "moderate     = ";N5
5070 INPUT "strong       = ";N6
5080 INPUT "very srtong  = ";N7
5090 NT=N1+N2+N3+N4+N5+N6+N7
5100 N2=N2*100/NT
5110 N3=N3*100/NT
5120 N4=N4*100/NT
5130 N5=N5*100/NT
5140 N6=N6*100/NT
5150 N7=N7*100/NT
5160 N=(N2*9+N3*18+N4*29+N5*53+N6*80+N7*100)/100
5170 GOTO 6020
6000 REM
6005 CLS
6010 INPUT ;"nwi  ";N
6015 Z=8.903
6020 A=.754*N+2.811
6030 RETURN
```