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Review of odour character and thresholds

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Steve Killeen Head of Science

Executive summary

The Environment Agency, in its role as Pollution Prevention and Control (PPC) regulator for England and Wales, has produced guidance for measuring and categorising odours. Project 2 of the Environment Agency's Science Odour Cluster was set up to look at ways of improving this guidance. It has already undertaken an Odour Relevance Survey that is referred to in this report and described in more detail in an earlier report (Environment Agency 2005).

This report complements the earlier one and provides a combined literature review and introduction to odour characteristics and thresholds as well as making recommendations. The literature review concentrates on new work published after the draft H4 was issued, i.e. post 2002. The individual chapters of the report discuss different aspects of odour measurement and categorisation and consider ways in which the Environment Agency's guidance (in particular, the draft H4 guidance) could be strengthened. These conclusions are then brought together in the final chapter, which presents key recommendations for amending the H4 guidance.

The report begins by providing an overview of the way people perceive odour, the characteristics of odour (i.e. intensity, quality or character and hedonic tone), and the thresholds at which odours can be detected. It also looks at how odour annoyance occurs and describes one way of showing how an annoyance becomes a complaint: the FIDOL factors (frequency, intensity, duration, character/offensiveness and location). The tools used by the Environment Agency to assess whether or not there is cause for annoyance are also mentioned.

The report goes on to explore the themes of odour intensity and concentration, hedonic tone and odour thresholds in greater detail, including references to recent work done on the unpleasantness of odours. It examines approaches to odour modelling, taking examples from Australia and New Zealand.

The main recommendations for revision of the draft H4 are as follows:

- Give clear guidance that a representative sector-specific dose-response study to provide industry-specific modelling exposure standards is the preferred, best practice approach.
- Make more robust and relevant UK dose-response work a priority.
- Give clear guidance that the use of the Indicative Odour Exposure Standards approach is temporarily acceptable as an interim measure.
- Improve and refine the interim Indicative Odour Exposure Standard approach by (a) establishing a more robust dose-response curve on which the default standard is based, corresponding to a particular level of annoyance (e.g. 10%) and (b) offering clearer guidance on how this standard could then be adjusted for specific conditions and factors.

- Make recommendations for compound-specific odour detection thresholds (ODTs).

The report also notes that a revised H4 would benefit from:

- tighter and bolder definitions of terms to do with odour and more consistency in their use throughout the guidance;
- more precise and prominent explanations of the differences between exposure, annoyance and nuisance;
- description of annoyance impacts in terms of the FIDOL factors;
- use of the term ‘relative unpleasantness’ in place of ‘offensiveness’ to avoid the confusion caused by the two meanings of the latter term;
- a reviewed, and perhaps expanded, odour descriptor list or odour wheel and consistency of this with the Environment Agency’s central system of recording odour complaints;
- clearer and more explicit guidance on use of dynamic dilution olfactometry (DDO) measurements to the standard BS EN 13725;
- review of the sniff test protocol given in Appendix 8 to ensure that all the FIDOL factors are represented and that the impact scale is consistent with those used by other workers;
- encouraging quantitative measurements of total odour concentration by field olfactometry to complement subjective sensory tests;
- explanation and promotion of the use of odour concentration–intensity (OCI) relationships to help strengthen odour impact assessments.

Contents

1. Introduction, aims and scope

1.1 Background

When emissions containing odorants are released to the atmosphere they can have an impact on the environment. Although under some circumstances this could include an impact on the ecosystem or on human health, that would be a factor of the chemical nature (e.g. toxicity) of the release rather than its odorous nature *per se*. By convention, the term 'odour impact' is restricted to the negative appraisal by a human receptor of the odour exposure. This appraisal, occurring over a matter of seconds or minutes, involves many complex psychological and socio-economic factors. Once exposure to odour has occurred, the process can lead to annoyance, nuisance and possibly complaints.

The PPC Regulations include in their definition of pollution 'emissions as a result of human activity which…cause offence to any human senses'. The Environment Agency has given special consideration as to how the endpoint of odour 'offence' may be anticipated, measured and assessed in terms of annoyance. The Environment Agency has published in draft its H4 Technical Guidance Note (Environment Agency 2002a), describing several approaches and techniques for assessing the impact of odours on human receptors. These approaches can be divided broadly into two categories:

i) Measuring directly the odour impact (e.g. annoyance) in the local population using community surveys.

ii) Quantifying some other indicator of odour and inferring or extrapolating to the odour impact (annoyance). This includes:

    (a) Monitoring of complaints.

    (b) Predictions of odour exposure – approaches range from semi-quantitative screening tools (e.g. based on the spreadsheet accompanying Environment Agency Horizontal Guidance Note H1, Environment Agency 2003), through simplified models (e.g. the Radius of Effect Model), to fully quantitative atmospheric dispersion modelling.

    (c) Monitoring of odour exposure in the field – approaches range from fully quantitative sampling and analysis of single compounds to sensory testing (i.e. using the human nose as a detector). These can be subjective (so-called 'sniff tests'), to objective (quantitative) using field olfactometry.

Predictive approaches, such as atmospheric dispersion modelling, are a powerful way of assessing the odour impact of proposed installations. This technique is also useful for comparing different options for odour control and it is useful for both proposed installations and existing installations. The application of this modelling approach for PPC, as described in detail in the draft H4 guidance, forms the background for this literature review.

Atmospheric dispersion modelling typically provides the link between knowledge of the odours emitted at source and the exposure to odour at a community level. From this predicted *odour exposure*, a view must be formed on whether it is likely to cause *odour annoyance* **–** the difference between these two concepts is crucial and is explained in Chapter 4. Making this judgement requires some form of numerical benchmark criterion. Numerical benchmark criteria are the foundation for assessing the impact of any pollutant using predictive modelling, but for odour this is uniquely complex. In contrast to assessing the health impact of pollutants, odour impact can be 'measured' by everyone using his or her nose and sense of smell; no special equipment is needed. However, the perception of the impact involves not just the strength of the odour but also its frequency, intensity, duration, offensiveness (the unpleasantness at a particular intensity) and location of the receptors. These attributes, known collectively as the FIDOL factors, need to be incorporated into (or otherwise accounted for in) the numerical benchmark criterion.

There are two types of numerical benchmark for modelling/monitoring. The first are those that are based on a so-called 'deterministic' theoretical approach that attempts to incorporate from first principles the FIDOL factors. However, earlier Environment Agency research (2002b) concluded that with the current level of understanding such attempts were typically too simplistic to be effective and, as for noise, regulation of odours would be better served by a straightforward, practical approach, even if this did not necessarily involve all the concepts and refinements. The Environment Agency research favoured a second type of numerical benchmark where odour guidelines are derived from the empirical relationship between odour exposure (measured or modelled) and annoyance (measured by a community survey). This led to the Environment Agency developing its numerical benchmarks for odour mixtures that were put forward as 'Indicative Odour Exposure Standards' in the draft H4 guidance.

The Indicative Odour Exposure Standard is, in effect, a modelling guideline standard used by the Environment Agency when determining applications/variations under PPC, to define in numerical terms its 'benchmark' criterion of 'no reasonable cause for annoyance'.[1] Rather than being a fixed concentration over a set averaging period, it defines the allowable odour exposure of a sensitive receptor in terms of the 98th percentile concentration of hourly averages in a year. This requires that the odour concentration at the sensitive receptor remains at, or below, a value of X for 98% of the hours in the year. The Indicative Odour Exposure Standard was developed in earlier Environment Agency research (Environment Agency 2002b) from dose-response data collected in the Netherlands in the late 1980s and early 1990s, using in particular emissions data from livestock (pig production) facilities.

[1] This does not necessarily equate to no complaints. It is designed to be a level of odour exposure that a high proportion of the exposed population, with normal sense of smell, finds 'acceptable' on a long-term basis.

There are two approaches to setting the value of X. For odorous emissions of a single chemical, this concentration X can be the published odour detection threshold (ODT) or World Health Organisation (WHO) guideline value – if one has been assigned – in units of volume per unit volume (e.g. parts per million, ppm, or parts per billion, ppb) or the mass of that compound per unit volume of air (e.g. milligrams per cubic metre, mg m^{-3}, or micrograms per cubic metre, $\mu g\ m^{-3}$). However, most emissions encountered by the Environment Agency in its PPC regulatory role are mixtures and for these a different approach is used: the odour concentration, X, must be expressed in European odour units per cubic metre of air ($ou_E\ m^{-3}$), which is explained in more detail in Chapter 3. It is also necessary to account for the relative unpleasantness of different odour types. In the draft H4 guidance, the Environment Agency has accounted for this by using different odour exposure criteria for odours with different annoyance potential: currently the Indicative Odour Exposure Standard is set at either 1.5, 3.0 or 6.0 $ou_E\ m^{-3}$ for high, medium, or low 'offensiveness' (i.e. unpleasantness) odours,[2] respectively. Thus before the indicative odour exposure standard can be used, an assessment must be made as to which of these unpleasantness/offensiveness bands applies to the industrial odour in question.

The Environment Agency has advised that it may move further towards numerical standards for defining reasonable cause for annoyance.

1.2 Aims and scope of this review

The earlier Environment Agency research (Environment Agency 2002b) made recommendations including confirmation of the dose-effect relationship for the UK situation and comparison of results with existing studies abroad to obtain additional information on relative odour annoyance from different sources, and establishing a rank order for annoyance potential based on UK data, obtained by interviewing environmental professionals with odour experience or by comparative testing in laboratory conditions. These recommendations form the drivers for this research project. The overall objective of this research project is to improve and develop further the robustness of the Environment Agency's odour guidance by further research into the unpleasantness/ offensiveness categorisation of the important odours and chemical species commonly encountered by the Environment Agency in its PPC regulatory role, to allow more confident assignment of an odour to one of the three bands or categories of unpleasantness.

Specific tasks in achieving this objective are:

- an Odour Relevance Survey (Environment Agency 2005), carried out to identify which odours and chemical species were most important to the Environment Agency in its PPC regulatory role;
- this literature review.

[2] Note: the terms unpleasantness and offensiveness are often used interchangeably, although they have subtly different meanings. This is explained in more detail in Section 4.4.

It was necessary to design an approach to be used in this literature review that would maximise the use of the limited time and budget resources available for this work. Accordingly, the review focused on new work published after the draft H4 was issued (i.e. post 2002). A total of 86 papers from three recent national/international conferences on odour have been reviewed. Also, the Environment Agency website has been searched. Additionally, an internet search was carried out with Google® using key words 'hedonic +odour' and 'annoyance potential +odour' and the most promising 64 items found were screened, resulting in detailed reviews of a further 16 items.

Following this introductory chapter, which describes the drivers, aims and scope of this report, the review is presented. This starts with Chapter 2, which gives an overview of how odour is perceived, including how people sense the presence of odours and how they may respond in terms of their emotions, sensitivity tolerance and adaptation. Chapter 3 gives an introduction to the main attributes of an odour: its intensity, quality, character and hedonic tone. The concepts of odour thresholds and odour units are introduced. Chapter 4 gives an overview of how these attributes contribute to the negative human reaction of annoyance and highlights the important differences between odour exposure, odour annoyance and odour nuisance. A summary is given on the tools that are available for practitioners to assess odour annoyance. The main purpose of Chapters 1–4 is to act as a primer on odour. This is both to orient the reader to the underlying technical terms and concepts used in the remainder of the review, and to identify where the understanding of odour has moved on since the publication of the draft H4 guidance.

The remainder of the review goes into more depth, covering new areas and, unavoidably, revisiting some of the areas touched on in the primer. The importance of odour intensity and concentration, and relative unpleasantness, are reviewed in detail in Chapters 5 and 6, respectively. Chapter 7 looks at how the main attributes of odour are incorporated into odour modelling guidelines, reviewing the approach used in arriving at the Indicative Odour Exposure Standard in draft H4, plus some recent refinements to this type of approach used by regulators overseas. Chapters 8 investigates further the unpleasantness of different odours and industrial sectors, focusing on those identified as important to the Environment Agency in its regulatory role in the Odour Relevance Survey (Environment Agency 2005). Chapter 9 provides an up-to-date review of ODTs for single compounds.

At the end of each chapter, a section discusses how the new developments and recent works could be used to strengthen Environment Agency guidance, such as a revised draft H4. Chapter 10 contains a summary of these key improvements.

2 Overview of odour perception

2.1 How we sense odour

Odour is perceived by the brain, being the response to our sensing, through smell, some of the chemicals present in the air we breathe. It forms part of the human ability for chemoreception – the sensing of smell (olfaction) and of taste (gustation). Humans have a sensitive sense of smell and can detect odour even when chemicals are present in very low concentrations. This is an important point – odours in the ambient air can often result from only small traces of these chemicals occurring intermittently.

Most odours are a mixture of many chemicals that interact to produce what we detect as an odour. A distinction needs to be made between odour-free air and fresh air. Odour-free air contains no odorous chemicals at all. Fresh air is usually perceived as being air that contains no chemicals or contaminants that could cause harm, or air that smells 'clean'. Fresh air may contain some odour, but these odours will usually be pleasant in character or below the human detection limit (Ministry for the Environment New Zealand 2003). The likely effect from background odours and existing odours depends primarily on the nature of the odours and the location in which they are occurring. If the nature of the odour is quite different to the background odour, then the background odour will probably not affect the perception of odour from a new odour source. In an area where levels of background odour are high, people can become desensitised to certain odours and the addition of other similar odours may then go unnoticed. In other areas this may not happen and the cumulative effects from additional odour may result in the odour becoming unacceptable.

The human sense of smell is caused by an interaction between molecules in the air and receptor cells located in the sinus cavity. These cells are attached to the olfactory bulb, which lies at the top of the nose, at the base of the brain. This bulb is sometimes viewed as an extension of the brain itself. There are up to a thousand different types of odour receptor compared to four, or at most five, types of taste receptor. Stimulation of an odour receptor leads to the generation of a nerve impulse in the olfactory bulb. Preliminary signal processing in the olfactory bulb is followed by association within the memory centre of the brain, association in the emotional centre of the brain, and identification within the cerebral cortex. This leads to the experienced impression of an odour. The direct connections between the olfactory organ and memory and emotional centres of the brain go some way towards explaining the often emotional response to odours and the way in which they can often be evocative. Comprehensive reviews of the physiology of odour sensation have been given by Leffingwell (2002) and Jacobs (2006).

2.2 How we perceive odour

2.2.1 Odour causes an emotional response

How an odour is perceived and its subsequent effects are not straightforward. An odour can often cause an emotional response, which can be very evocative. The human perception of odour is governed by complex relationships, complicated by the presence of background odours and the mental and physical state of the affected person. The earlier Environment Agency research (Environment Agency 2002b) and the *Good Practice Guide for Assessing and Managing Odour in New Zealand* (Ministry for the Environment New Zealand 2003) describe important factors to consider, which are summarised below.

Odour perception is often related to the source of an odour and whether the activity causing it is considered acceptable in a particular location. An odour associated with a natural source, such as mudflats or geothermal activity, may be accepted whereas a similar odour from an industrial activity may not. Perception and acceptability are also affected by whether people believe an odour contains harmful chemicals. In such cases a person is more likely to consider the odour to be objectionable or offensive – even dangerous – despite the likelihood that the concentrations of the chemicals in the odour are too low to cause direct health effects. This was demonstrated by Dalton (1999) who found that, when exposed to the same odour at the same concentration, a group of subjects who were told that the odour was of industrial origin consistently rated it as higher intensity and irritability than another group who were told the odour was of natural origin. Annoyance can also be influenced by how involved the public is, and how they have been 'sold' the plant or installation. Engaging residents in the odour management process of an installation is known to be an effective means of reducing complaints in some circumstances.

The emotional response (positive or negative) of people to an odour is due, in common with other species, to its evolutionary origins to provide vital information for evaluating the environment. Perception of odours can trigger two basic responses, avoidance or approach, occurring for example with judging food, water or air and in a social and sexual context. As well as this inherited aversion linked to survival (e.g. rotten flesh), some responses are learned through cultural or social norms (e.g. a particular perfume), or learned through personal experience (e.g. good or bad experiences associated with a particular smell). Cultural and social sensitivities about certain sites should also be considered. Perception is an important factor where the activity generating the odour is considered culturally offensive or is offensive in nature (e.g. cremation and sewage treatment). This can cause an adverse reaction in the people who detect odours from such activities regardless of other factors.

In essence, the function of our smell sensor is similar to that of all our senses: to translate environmental information into nerve signals transmitted by neurons firing in our brain. This information is then evaluated in the brain, a process that is termed appraisal. The outcome of this appraisal can modulate the behaviour of the individual.

2.2.2 Sensitivity to odours

The perception of any particular odour is typically the result of the simultaneous stimulation of several different types of receptors. This means that humans can distinguish between thousands of odours. Different life experiences and natural variation in the population can result in different sensations and emotional responses by individuals to the same odorous compounds. Because the response to odour is synthesised in our brains, other senses such as sight and taste, and even our upbringing, can influence our perception of odour and whether or not we find it acceptable or objectionable and offensive.

Odour sensitivity across the population varies widely. Some individuals have little sensitivity to any smells – anosmia is the condition where an individual has no sense of smell at all. Other people may be unable to smell specific odours. Some people will be many times more sensitive than the population average. Various medical conditions (e.g. colds) can suppress the sense of smell and others (pregnancy) can enhance it. The effects from medical conditions may be short-lived or permanent. The variation in odour perception between individuals in a population has been reviewed in detail in earlier Environment Agency research (Environment Agency 2002b).

2.2.3 Perception of the intensity and synergistic effects

The perception of the intensity of odour in relation to the odour concentration is not a linear but a logarithmic relationship (see Section 3.1). The same relationship is known to occur for other human senses such as hearing and sensitivity to light. This means that if the concentration of an odour increases ten-fold, the perceived increase in intensity will be by a much smaller amount, say two-fold.

The perception of odours may be enhanced or suppressed by the presence of other odorous or non-odorous chemicals (e.g. ammonia suppresses the perception of hydrogen sulphide). These interactions between odorous compounds or mixtures of odorous compounds are known as synergistic effects. An example is where one odorous compound disguises or masks the presence of other compounds, an effect that forms the basis of masking agents used to try and mitigate odour impacts by, for example, releasing masking agents into the air around the perimeter of a landfill site to try and reduce odour impact on nearby residents.

The odour intensity experienced by an observer is, in general, *not* equivalent to the sum of the intensities of the odorous compounds: the perceived intensity may be greater, or less than, the components depending on the synergistic effects of the compounds present. Furthermore, as the odour concentration reduces through dilution, different compounds may dominate the perceived effect, changing the nature of the odour (see Section 3.1.1) for more details). For example, mushroom-composting odour has been observed to have a distinctly different odour character at source than when diluted downwind.

2.2.4 Sensitisation and adaptation

Sensitisation of individuals to olfactory stimulants may occur after acute exposure events or as a result of repeated exposure to nuisance levels of odours. Sensitisation changes a person's threshold of acceptability for an odour. This can result in a high level of complaint over the long term and a general distrust within the community of those perceived as responsible for the odour.

Desensitisation can also result from exposure to an odour. A person may become unable to detect the odour, or there is a reduction in the perceived odour intensity and/or effect, even though the odorous chemical is still present in the air. For example, people working in an environment with a persistent odour are often unaware of its presence and may not be aware that the odour is having an impact on the surrounding community. There are various mechanisms for desensitisation: some of these operate over very short time periods (seconds) while others develop over weeks or longer. The term *olfactory fatigue* is sometimes used to describe desensitisation that occurs on a short-term basis.

Adaptation is a long-term process that can occur when communities become increasingly tolerant of a particular source of odour, which is primarily a psychological response to the situation. For example, where odours are associated with a local industry that is considered to be important for the well-being of the local community and the industry maintains a good relationship with community members, then adaptation to the odour effects can occur over time. The normal loss of sensitivity due to adaptation is proportional to the odour concentration and the duration of exposure.

Some adaptation mechanisms may be at least partially overridden by the brain. Adaptation is very specific and a person can temporarily lose sensitivity (become adapted) to one odour while retaining full sensitivity to others. Some activities, for example smoking, can desensitise or mask odour responses in certain situations for relevant individuals.

3 Brief overview of main characteristics of an odour

3.1 The sensory characteristics of an odour

The detectability of an odour (can one smell it or not?) is the primary characteristic. If the odour can be detected, then there are three further dimensions to an odour:

1. Intensity – how strong is it?
2. Quality – what's it like?
3. Hedonic tone – how pleasant is it?

These interlinked sensory characteristics are conventionally used to describe how we perceive an odour (Hobson and Yang 2001; Stuetz and Frechen 2001).

3.1.1 Odour intensity

The magnitude of an odour – the odour strength – can be described in two ways, by its intensity and by its concentration. Odour intensity describes the relative magnitude of an odour sensation as experienced by a person, that is, we perceive odour intensity, not odour concentration. On the other hand, we measure[3] and model odour concentration, not odour intensity. These two descriptions of odour strength therefore complement each other. The distinction between them is explained in more detail below (Jiang 2004).

Concentration

This is the amount of odour present in a given volume of air. For a known, chemical species this can be expressed either as the volume of that compound per unit volume of air (e.g. parts per million, ppm, or parts per billion, ppb) or the mass of that compound per unit volume of air (e.g. milligrams per cubic metre, mg m^{-3}, or micrograms per cubic metre, μg m^{-3}).

However, most odours are complex mixtures of compounds and for these a different measure of concentration is needed. The Comité Europeén de Normalisation (CEN) standard[4] has been adopted by practitioners in most of the world and has become the *de facto* international standard for olfactometry – the measurement of odour concentration using human subjects as the 'sensor'.

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[3] Here we are referring to traditional quantitative measurement. There are some subjective scales for grading odour intensity (see Section 5.2).

[4] BS EN 13725: 2003, Air Quality – Determination of Odour Concentration by Dynamic Olfactometry.

Using laboratory dynamic dilution olfactometry (DDO), odour concentration is measured in European odour units per cubic metre of air (ou_E m^{-3}), which is equivalent to the number of repeated dilutions with a fixed amount of odour-free air or nitrogen that is needed until the odour is just detectable to 50% of a panel of trained observers. DDO is a valuable objective measure of odour concentration. It is limited in application to air samples having odorant concentrations at many times above the detection threshold (usually at least 50 ou_E m^{-3}).

The basis of traceability of this analysis is the linkage with the European Reference Odour Mass (EROM). This, the accepted reference value for 1 ou_E m^{-3}, is equal to 123 µg *n*-butanol evaporated in 1 m^3 neutral gas, which produces a concentration of 0.040 µmol/mol. It means that measured odour concentrations are effectively expressed in terms of '*n*-butanol mass equivalents'. The assumption is made that the precision for olfactometric determination of the reference material, *n*-butanol, is transferable to determinations on non-reference material samples, i.e. source odour samples.

Although DDO has a large uncertainty compared to traditional chemical analyses, this is known and repeatable when carried out strictly in accordance with the standard by a United Kingdom Accreditation Service (UKAS)-accredited laboratory. It is often said that DDO is an expensive measurement. However, typical prices are much the same as they were 15 years ago and so have fallen in relative terms. Prices are also comparable to other laboratory gas analyses and can often be less than analyses by gas chromatography–mass spectrometry (GC–MS).

Intensity

Odour concentration measured in ou_E m^{-3} is a multiple of the detection threshold; it is *not* a measure of intensity. Intensity is how an individual person *perceives* the magnitude (strength) of an odour once it is above its threshold (see Section 3.2 for odour thresholds). It is determined by an odour panel and is described in categories which progress from 'not perceptible', then 'very weak', through to 'extremely strong'. A standard method (VDI 1997a) exists for ranking intensity on a scale from faint to strong by a panel of trained observers. Although intensity increases with concentration, the relationship is not linear but logarithmic (see below) and an increase or decrease in concentration will not produce a corresponding proportional change in odour intensity as perceived by a human subject. For instance, some odours can become intense at relatively low concentrations (such as fishy or putrescent odours), while for other more 'pleasant' odours, such as flowers, concentrations must be quite high before they are deemed intense (Minnesota Pollution Control Agency 2006). This has important implications for control: an odour with a strong intensity at low concentrations may cause odour problems even at low residual levels. For example, increasing the concentration of an odorous chemical or mixture by a factor of ten may only increase its perceived intensity by a factor of two. But, conversely, if a site is causing odour pollution in a community, abatement equipment may have to reduce odour concentrations at the sensitive receptors by 90% in order to halve the intensity of odour they perceive.

The relationship between odour concentration and intensity

The intensity (or sensation) of odour as measured by the human nose is actually related to the logarithm of the odour concentration (see later, in Chapter 5, for more details):

$$\text{Intensity} = f_n \times \log(\text{Concentration})$$

This is referred to as a 'psychometric' property of odour. The relationship is commonly known as Steven's Law, and is also found with other human senses such as noise and light. What it means is that if the concentration of an odour is increased ten-fold, then it will be perceived to increase in intensity by a much smaller amount. This runs against the common belief that the change in odour intensity between consecutive dilutions is nearly equal.

The coefficient f_n may be considerably different for different odorous compounds (see Figure 5.2 in Section 5.3 for an illustration of this) and so, at any given odour concentration, an odorous compound with a high specific intensity will smell stronger than another odorous compound with a low specific intensity. However, an odorous release is usually a mixture rather than a single compound. The mixture will be made up of odorous compounds with differing specific intensities and this has an important influence on how odour is perceived in the environment at different downwind distances and dilutions away from the point of discharge (e.g. a chimney stack). As the plume is dispersed through the atmosphere, odorous compounds in the mixture that may have smelled stronger than others originally (i.e. at the emission concentration) may decrease in intensity at a faster rate than others in the mixture. At some dilution level, a crossover may even occur, such that the initially weaker odour becomes dominant in terms of intensity. Take, for example, the odorous emission resulting from the dehydration of partially decomposed cow manure. Within about 50 m the odour typically has a strong ammonia smell. However, at a distance of 1 km or more the odour is putrid and no ammonia can be detected. Similar effects have been observed downwind of stockpiled treated sewage sludge in New Zealand (Ministry for the Environment New Zealand 2002).

Estimates of odour intensity and concentration tend to have different applications. Estimates of odour intensity can be used for quantifying the magnitude of odour at the receptor itself, by direct field measurement using the subjective sniff test (see appendix to draft H4). In contrast, odour concentration measurements are objective, quantitative determinations. In the UK, their use has to date tended to be restricted to quantifying the source emissions, which are then input to a dispersion model to *predict* the ambient odour concentration. This is because laboratory DDO is generally not suitable for determining odour concentration at ambient levels directly. However, in the USA it is common to find hand-held field olfactometers used to measure the concentration of ambient odours in units dilutions to threshold (D/T). This concentration measurement is in similar units to those obtained from laboratory DDO, but they are not considered interchangeable. It should be remembered that laboratory DDO uses a panel to give an estimate of concentration based on a population ODT, whereas field olfactometry gives an estimate of concentration based on an individual's ODT.

3.1.2 Quality/character

Odour character or quality is basically what the odour smells like. It is the property that identifies an odour and differentiates it from another odour of equal intensity. For example, ammonia gas has a pungent and irritating smell. The character of an odour may change with dilution (Department of Environmental Protection, Western Australia 2002). The odour character is described by a technique known as multidimensional scaling or profiling, in which the odour is characterised by either the degree of its similarity to a set of reference odours or the degree to which it matches a scale of various 'descriptor' terms. The result is an odour profile (Environmental Protection Authority New South Wales 1995). Numerous standard odour descriptor lists have been developed for use as a reference vocabulary by assessors. The first were developed in the perfume and food and drinks industries. The American Society for Testing and Materials (ASTM) published a standard odour descriptor list (ASTM 1985) of 146 terms. An odour descriptor 'wheel', originally developed in the wine and beer industries, was adapted by St Croix Sensory Inc. (2003) for use with environmental odours (Figure 3.1). There are eight general categories (e.g. 'fishy', 'fruity', 'earthy') each of which has specific descriptors that are related to real-life examples. Another odour wheel for urban odours has been developed at the UCLA School of Public Health and is shown in Figure 3.2.

These odour descriptor terms can be useful for pinpointing an odour's source from a complainant's description. They can also be useful in pointing to likely key chemical compounds contained in the odour. A list of descriptors relating them to their underlying odorous compounds was given in draft Technical Guidance Note H4 and other Environment Agency guidance (reproduced here as Tables 3.1 and 3.2). Table 3.1b.shows the descriptors used in Australian odour guidance: looking at the first few rows shows that many (e.g. acetic acid, acrolein, acrylonitrile) are similar to the H4 list (Table 3.1a); however, other descriptors (e.g. acetaldehyde, acetone, benzene, carbon disulphide) are quite different.

3.1.3 Hedonic tone, unpleasantness and relative offensiveness

Hedonic tone is the degree to which an odour is perceived as pleasant or unpleasant. Such perceptions differ widely from person to person, and are strongly influenced by previous experience and emotions at the time of odour perception. Hedonic tone is related to (but not synonymous with) the relative pleasantness or unpleasantness of an odour, as explained later in Section 4.4.

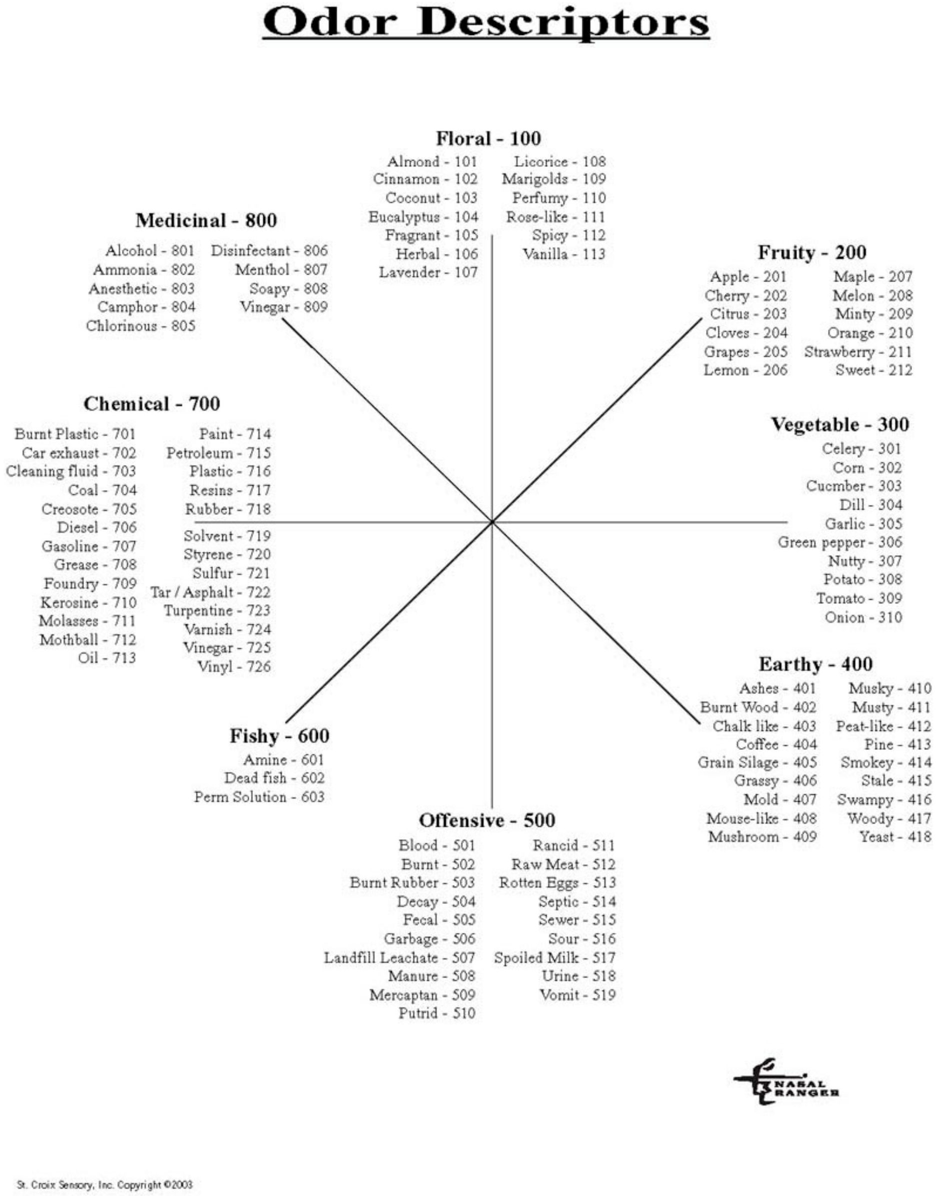

Figure 3.1 St Croix Sensory Inc. (2003) environmental odour descriptor wheel

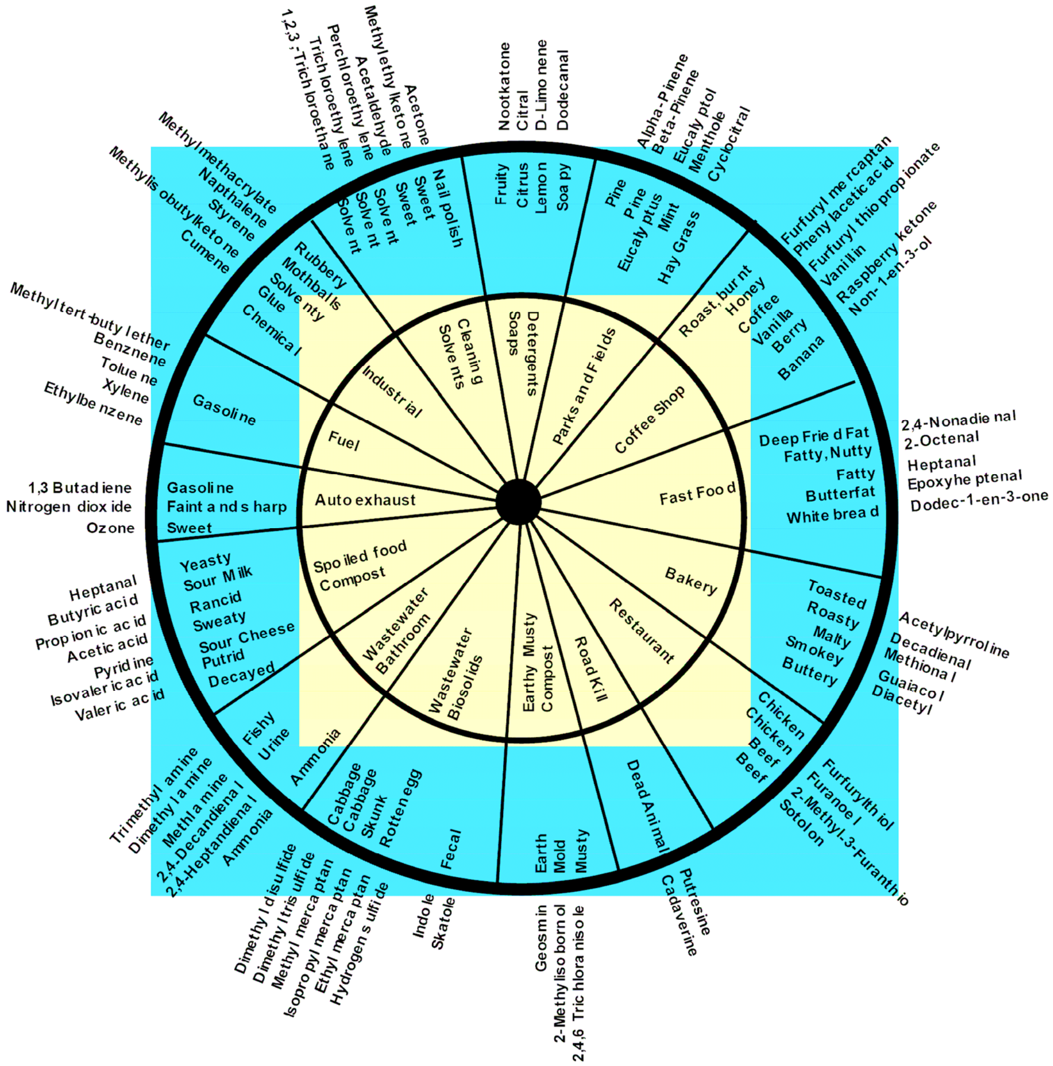

Figure 3.2 UCLA School of Public Health urban odour descriptor wheel (McGinley and McGinley 2004)

Table 3.1a Odour descriptors for commonly encountered compounds[5] (reproduced from Table A10.1 in draft H4)

Substance	Odour	Substance	Odour
Acetaldehyde	Apple, stimulant	Dimethyl sulphide	Rotten vegetable
Acetic acid	Sour vinegar	Diphenylamine	Floral
Acetone	Chemical/sweetish/solvent	Diphenyl sulphide	Burnt rubber
Acetonitrile	Ethereal	Ethanol	Pleasant, sweet
Acrylaldehyde	Burning fat	Ethyl acetate	Fragrant
Acrolein	Burnt sweet, pungent	Ethyl acrylate	Hot plastic, earthy
Acrylonitrile	Onion, garlic, pungent	Ethylbenzene	Aromatic
Aldehydes C9	Floral, waxy	Ethyl mercaptan	Garlic/onion, sewer, decayed cabbage, earthy
Aldehydes C10	Orange peel	Formaldehyde	Disinfectant, hay/straw-like, pungent
Allyl alcohol	Pungent, mustard like	Furfuryl alcohol	Ethereal
Allyl chloride	Garlic onion pungent	n-Hexane	Solvent
Amines	Fishy, pungent	Hydrogen sulphide	Rotten eggs
Ammonia	Sharp, pungent odour	Indole	Excreta
Aniline	Pungent	Iodoform	Antiseptic
Benzene	Solvent	Methanol	Medicinal, sweet
Benzaldehyde	Bitter almonds	Methyl ethyl ketone	Sweet
Benzyl acetate	Floral (jasmine), fruity	Methyl isobutyl ketone	Sweet
Benzyl chloride	Solvent	Methyl mercaptan	Skunk, sewer, rotten cabbage
Bromine	Bleach, pungent	Methyl methacrylate	Pungent, sulphide like
Sec-Butyl acetate	Fruity	Methyl sulphide	Decayed vegetables
Butyric acid	Sweat, body odour	Naphthalene	Moth balls
Camphor	Medicinal	Nitrobenzene	Bitter almonds
Caprylic acid	Animal like	Phenol	Sweet, tarry odour, carbolic acid
Carbon disulphide	Rotten vegetable	Pinenes	Resinous, woody, pine-like
Chlorine	Irritating, bleach, pungent	Propyl mercaptan	Skunk
Chlorobenzene	Moth balls	Putrescine	Decaying flesh
2-Chloroethanol	Faint, ethereal	Pyridine	Nauseating, burnt
Chloroform	Sweet	Skatole	Excreta, faecal odour
Chlorophenol	Medicinal	Styrene	Penetrating, rubbery, plastic
p-Cresol	Tar-like, pungent	Sulphur dioxide	Pungent, irritating odour
Cyclohexane	Sweetish when pure, pungent when contaminated	Thiocresol	Rancid, skunk-like odour
Cyclohexanol	Camphor, methanol	Toluene	Floral, pungent, moth balls
Cyclohexanone	Acetone-like	Trichloroethylene	Solventy
Diamines	Rotten flesh	Triethylamine	Fishy, pungent
1,1-Dichloroethane	Ether-like	Valeric acid	Sweat, body odour, cheese
1,2-Dichloroethylene	Chloroform-like	Vinyl chloride	Faintly sweet
Diethyl ether	Pungent	Xylene	Aromatic, sweet

[5] Royal Society of Chemistry (1988-94); Leonardos *et al.* (1969); Turk (1954) Knowlton, J. and Pearce, S. (1993).

Table 3.1b Odour descriptors for common odorous compounds, used in Australia (University of New South Wales 2006)

Compounds	Odour description
3-methyl-1H-indole	putrid, fecal
Acetaldehyde	penetrating, pungent, suffocating odour
Acetic acid	vinegar
Acetone	pungent
Acetonitrile	sweet ethereal odour
Acetophenone	sweet pungent odour of orange blossom or jasmine
Acrolein	burnt sweet
Acrylic acid	acrid odour
Acrylonitrile	pungent onion- or garlic-like odour
Allyl alcohol	irritating smell
Allyl chloride	pungent, garlic-onion odour
Ammonia	pungent, irritating
Benzaldehyde	bitter almonds
Benzene	slightly sweet odour
Captan	pungent smell
Carbon disulphide	sweet, pleasant, chloroform-like odour
Chlorine	bleach, pungent
Cresol	sweet tarry odour
Dimethyl disulphide	repulsive
Dimethyl sulphide	decayed cabbage
Ethanol	slight alcohol odour
Ethyl alcohol	sweet-smelling
Ethyl mercaptan	garlic odour
Formaldehyde	pungent, suffocating odour
Hexanoic acid	sharp, sour, rancid odour, goat-like odour
Hydrogen sulphide	rotten egg
Methanol	sweet
Methyl mercaptan	rotten cabbage
Nonyl alcohol	offensive smell
Phenol (carbolic acid)	strong sweet odour
Pyridine	sour, putrid, fishy
Skatole	strong fecal odour
Toluene	sweet pungent
Xylene	sweet odour

Table 3.2 Odour descriptors in alphabetical order without hedonic scores being indicated so as not to influence the use of a particular descriptor (Environment Agency 2001)

Alcoholic	Eggy (fresh eggs)	Oak wood, cognac
Almond	Etherish, anaesthetic	Oily, fatty
Ammonia	Eucalyptus	Orange
Animal	Faecal (like manure)	Paint
Anise (liquorice)	Fermented (rotten) fruit	Peach
Apple	Fishy	Peanut butter
Aromatic	Floral	Pear
Bakery (fresh bread)	Fragrant	Perfumery
Banana	Fresh green vegetables	Pineapple
Bark, birch bark	Fresh tobacco smoke	Popcorn
Beany	Fried chicken	Putrid, foul, decayed
Beery	Fruity, citrus	Raisins
Bitter	Fruity, other than citrus	Rancid
Black pepper	Garlic, onion	Raw cucumber
Blood, raw meat	Gasoline, solvent	Raw potato
Burn, smoky	Geranium leaves	Rope
Burnt candle	Grainy (as grain)	Rose
Burnt milk	Grape juice	Sauerkraut
Burnt paper	Grapefruit	Seasoning (for meat)
Burnt rubber	Green pepper	Seminal, sperm-like
Buttery, fresh butter	Hay	Sewer odour
Cadaverous (dead animal)	Heavy	Sharp, pungent, acid
Camphor	Herbal, green, cut grass	Sickening
Caramel	Honey	Soapy
Caraway	Household gas	Sooty
Cardboard	Incense	Soupy
Cat urine	Kerosene	Sour milk
Cedarwood	Kippery (smoked fish)	Sour, vinegar
Celery	Laurel leaves	Spicy
Chalky	Lavender	Stale
Chemical	Leather	Stale tobacco smoke
Cherry	Lemon	Strawberry
Chocolate	Light	Sulfidic
Cinnamon	Malty	Sweaty
Cleaning fluid	Maple syrup	Sweet
Clove	Meaty (cooked, good)	Tar
Coconut	Medicinal	Tea leaves
Coffee	Melon	Turpentine (pine oil)
Cologne	Metallic	Urine
Cooked vegetables	Minty, peppermint	Vanilla
Cool, cooling	Molasses	Varnish
Cork	Mothballs	Violets
Creosote	Mouse-like	Warm
Crushed grass	Mushroom	Wet paper
Crushed weeds	Musky	Wet wool, wet dog
Dill	Musty, earthy, mouldy	Woody, resinous
Dirty linen	Nail polish remover	Yeasty
Disinfectant, carbolic	New rubber	
Dry, powdery	Nutty	

3.2 Odour thresholds

3.2.1 Odour detection threshold

Because odour concentration is a quantitative measure – and practitioners often prefer to use quantitative measures – it is used in a number of impact assessment tools. It is useful to clarify some additional terms used to describe particular odour concentrations.

The odour detection threshold (ODT) is the lowest concentration of any specific chemical or mixture at which it can be ascertained that an odour is present, i.e. the level that produces the first sensation of odour. This varies not only between different people, but also from day to day for the same individual, depending on factors such as time of day, state of health, whether they are distracted or focused on the odour, whether they are awake or asleep, the presence of interfering odours, the influence of hormones (e.g. ovulation), pregnancy and migraines. Also, the odour sensation threshold usually increases (i.e. the odour sensitivity decreases) with increasing age (Bidlingmaier *et al*. 1997).

A distinction must be made between the ODT for individuals and the ODT for populations. For individuals, the ODT is the concentration where that person can just detect that an odour is present. For populations, the ODT refers to the concentration where 50% of the population can detect an odour is present (under controlled conditions).

Experiments have been carried out to determine values for odour thresholds. Because of the previously mentioned variations, the reported results are statistical values based on the average of when the odour becomes detectable to 50% of a panel of trained assessors working to the European CEN standard for olfactometry. For any chemical compound or mixture, this point – the odour detection threshold – is assigned an odour concentration of 1 ou_E m^{-3}. Odour concentrations are expressed in multiples of this value.

For single odorous chemical compounds this odour detection threshold can *also* be expressed in conventional concentration terms (ppm and mg m^{-3}, or ppb and μg m^{-3}). The ODT values for single compounds reported in the literature can show wide differences. This is because a number of different experimental methods have been used over the years (see Section 3.2.3). Generally, the more recently quoted values are most reliable. Some of the most reliable values are summarised in Environment Agency draft Technical Guidance Note H4, Volume 1, Appendix 10, with a more comprehensive list given in *Odour Measurement and Control – An Update* (Woodfield and Hall 1994). However, it should be borne in mind that many of these were carried out at the Warren Spring Laboratory to its own DDO method and as such the results may not be the same as would be obtained if carried out now strictly in accordance with EN 13725.[6]

[6] For example, the ODT threshold for 1-butanol is given as 30 ppb, whereas EN 13725 uses n-butanol as the reference material, which has a threshold of 40 ppb.

For mixtures, the odour detection threshold is also – by definition – 1 ou_E m^{-3}, but conventional concentration units cannot also be used.

3.2.2 Recognition threshold and typical odour strengths

At some point above the odour detection threshold there will be a concentration at which the odour is recognised as having a characteristic odour quality. This is the recognition threshold. As was explained in Section 3.1, whether an odour is perceived by an observer as faint, distinct, strong, etc. depends on the relationship between odour intensity and odour concentration for the particular odour in question, but the following have been found to apply in many cases (Environment Agency 2002a):

- 1 ou_E m^{-3} is the point of detection of an odour (i.e. 'I can smell something') in the laboratory by a panel of qualified assessors. (However, individuals may develop a tolerance to a medley of normal background odours, such as traffic, grass cutting, plants, etc. This background can be anything from 5 to 40 ou_E m^{-3}.)
- At around[7] 3 ou_E m^{-3} the recognition threshold is reached,[8] i.e. 'I can smell X' (although this can be less for odours with an 'unpleasant' hedonic score, and more if a person is distracted by other stimuli).
- 5 ou_E m^{-3} is a faint odour for many, but not all, industrial odours (although at low concentrations a rapidly fluctuating odour is more noticeable than a steady background).
- 10 ou_E m^{-3} is often a distinct odour.

It is important to recognise that published odour detection thresholds apply to population averages, *not* to individuals. At the odour detection threshold (whether for individual chemical species or mixtures), 50% of the population would be likely to detect the odour while the other 50% would not. Within the half of the population who can detect the odour, some may even find it strong enough to be offensive. Similarly, the recognition threshold is based on a population average, so 50% of the people are likely to be able to identify the odour and 50% are not.

Another important point to bear in mind is that very often an industrial installation will be emitting a range of odours from various sources on site, and these may have widely differing specific intensities (i.e. widely differing concentration:intensity relationships). Both a highly intense odour and an odour with lower intensity will, by definition, have an odour concentration of 1 ou_E m^{-3} at the population-average point of detection. However, at a higher concentration of, say, 3 ou_E m^{-3}, the more intense odour may be perceived as 'distinct', while the less intense odour might not be 'distinct' until a concentration of, say, 15 ou_E m^{-3} is reached.

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[7] This is very much an approximation: most do, however, fall within the range 2 to 10 ou_E m^{-3}.

[8] However, VDI 3940 states that the recognition threshold lies approximately 3 ouE m^{-3} higher than the detection threshold, putting it at 4 ouE m^{-3}.

3.2.3 Caution in using odour thresholds

The EN 13725: 2003 standard replaced the national standards of EU countries, including the Dutch NVN2820: 1990 standard (that formed the basis for the EN standard) and the German standard VDI3881. Australian Standards have also published a method AS/NZ 4323.3 that closely resembles (and is based on) EN 13725. The European standard has become, effectively, the *de facto* international standard for dynamic olfactometry.

As explained earlier, the basis of traceability of the EN 13725 analysis is the linkage with the European Reference Odour Mass (EROM). This, the accepted reference value for 1 ou_E m^{-3}, is equal to a 123 μg *n*-butanol evaporated in 1 m^3 neutral gas, which produces a concentration of 0.040 $\mu mol/mol$ (40 ppb).

However, this move towards international standardisation has been relatively recent: there is much published work and data that have been obtained using older, different methods of dynamic olfactometry, and sometimes using older types of equipment that are less sensitive. Such studies may not give the same results for the odour threshold as EN 13725 carried out using modern performance-based forced-choice dynamic olfactometry having greatly improved sensitivity of odour measurement.

For example, using a popular older style instrument, the three-port IITRI (Illinois Industrial Triangle Research Institute) olfactometer, the measured butanol threshold is reported to range from 80 to 200 ppb, significantly different from the European standard.[9] Similarly, the Regulator for Western Australia (Department of Environmental Protection, Western Australia 2002) noted a factor of two difference between the odour threshold obtained using the Victoria EPA B2 method and the Dutch NVN2820 standard (similar to EN 13725).

If older olfactometers only register 1 ou_E m^{-3} when the *n*-butanol concentration reaches 200 ppb, and the EN 13725 standard registers 1 ou_E m^{-3} at 40 ppb, then modelled odour concentration predictions made using source emissions data obtained using different DDO methods/equipment will not be equivalent. Using the aforementioned example, a predicted ground-level odour concentration of 1 ou m^{-3} would be equivalent to 40 ppb *n*-butanol if the source emission rate were obtained using EN 13725, and equivalent to 200 ppb *n*-butanol if the model input data were obtained using the older DDO technique. Although a nominal concentration of 1 ou m^{-3} is predicted in both cases, the calibration has in effect shifted and the results would mean different things in terms of the odour intensity actually experienced by human receptor.

Similarly, if numerical odour benchmark criteria have been set based on research that used measurements to EN 13725, then their application will only

[9] As well as equipment factors, this difference could also be due to the sensitivity of the assessors used in the measurements: EN 13725 selects assessors with sensitivity to *n*-butanol of between 20 and 80 ppb.

be valid for studies made using the same measurement technique. Their application to studies made using older techniques may result in odour annoyance even when the benchmark concentrations are met. For this reason, the Regulator for Western Australia emphasises (Department of Environmental Protection, Western Australia 2002) the need to thoroughly check the measurement method of any published odour thresholds used, and to apply appropriate adjustment factors prior to their use in odour assessment studies.

3.3 Opportunities identified for strengthening Environment Agency guidance

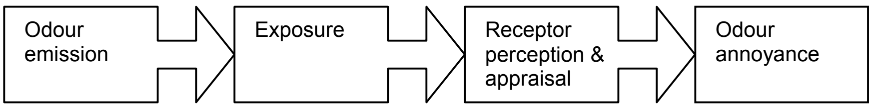
A revised draft of H4 would benefit from the following:

- Tighter and bolder definitions of terms (e.g. odour strength, intensity, concentration, character, quality, offensiveness, relative unpleasantness and hedonic tone) and better consistency in their use through the guidance.
- In describing field odour assessments of ambient odour, the guidance should refer to quantitative measurements of total odour concentration (e.g. by NasalRanger® or Scentometer® instruments) to complement the description of subjective sensory tests ('sniff tests').
- The odour descriptor list needs to be reviewed. It would be helpful to make use of descriptors used by other practitioners, and consider the format for the descriptors, e.g. lists and/or odour wheels.
- Consistency between the revised odour descriptor list/wheels (or a simplified version) and the Environment Agency's central system of recording odour complaints is highly desirable.
- The Environment Agency should make it explicit that the validity of the Indicative Odour Exposure Standards used in the H4 modelling approach are dependent on the dynamic dilution olfactometry measurements being carried out to the full requirements of the standard BS EN 13725. The guidance should make it explicit that assessments that do not use this standard method are unacceptable for regulatory purposes.

4 The annoyance impacts of odours

4.1 Overview of the factors influencing odour annoyance

Winneke *et al.* (2004) caution that a satisfactory embedding of the annoyance concept into a coherent pattern of emotional, cognitive and psychosocial theories is still lacking, making it difficult to give a widely accepted unitary definition of 'annoyance'. Van Harreveld (2001) also draws attention to the lack of generally agreed definitions for terms such as annoyance, nuisance[10] and unpleasantness, often leading to their imprecise and confusing use in the literature. In general, though, odour annoyance can be considered the expression of disturbed well-being induced by adverse olfactory perception in environmental settings. Odour annoyance occurs when a person exposed to an odour perceives the odour as unwanted (University of New South Wales, Sydney, 2006). Odour complaints occur when individuals consider the odour to be unacceptable and are sufficiently annoyed by the odour to take action (Department of Environmental Protection, Western Australia 2002). Van Harreveld (2001) has proposed standard definitions for odour annoyance, odour nuisance and other terms (Table 4.1). The basic elements of the chain that leads from odour emission to odour annoyance are summarised as:



A more detailed conceptual flowchart showing the relationship between exposure to malodour and its effects in a human population is shown in Figure 4.1. The contributing factors and the effects, which may result ultimately in complaints, are far from straightforward, and few of the relationships are completely understood. The following are the main factors:

- The characteristics of the odour that is released, i.e. detectability (odour concentration), intensity, hedonic tone and annoyance potential.
- Variable dilution in the atmosphere through turbulent dispersion (turbulence or stability of boundary layer, wind direction, wind speed, etc.).
- Exposure of the receptors in the population (location of residence, movement of people, time spent outdoors, etc.).
- Context of perception, e.g. other odours, background of odours, activity and state of mind within the perception context.
- Receptor characteristics (exposure history, association with risks, activity during exposure episodes, and psychological factors such as tolerance

[10] Some terms, such as Statutory Nuisance, may have been defined in a legal sense, but not necessarily in a way that allows them to be used easily in a scientific context.

and expectations of the exposed subjects, their coping behaviour, their perceived health and perceived threats to their health).

Once exposure to odour has occurred, the process that leads to annoyance, nuisance and possibly complaints involves many psychological and socio-economic factors. Some of these factors are described below.

Exposure to an odour that causes a negative appraisal is considered an ‘ambient stressor’. Odour detection and appraisal take place in a matter of seconds or minutes, and lead to a decision on the significance of the perception and magnitude of stress. This is followed by a second process of coping, in which the individual adapts to the situation by two types of behaviour (Environment Agency 2002b):

- Problem-focused coping behaviour – attempts to control the problem by removing the cause of stress, e.g. closing windows, making complaints, etc.
- Emotion-focused coping behaviour – no attempt is made to change the unpleasant environment; instead, the subject changes his or her emotional response, e.g. denial, ‘Zen’, seeking distractions, etc.

People’s attitudes towards the source, the inevitability of exposure and the aesthetic expectations regarding the residential environment are other, less tangible, factors that are involved. Once the balance tips, and a particular source of malodour becomes a nuisance to an individual, it is very difficult to reverse the process. What used to be a faint odour can then become a signal for annoyance: an association develops in an individual’s mind between any occurrence of a detectable odour and significant disamenity. Association is because of previous occasions when a faint odour has escalated from detection to beyond the annoyance threshold so that the individual is reacting to the possibility that a faint odour will escalate again in the same way. This is a kind of Pavlovian response resulting from conditioning experiences. Once the first complaint has been made, the problem is much more serious for all those affected than before.

Earlier Environment Agency research (Environment Agency 2002b) has pointed to the work of Cavalini (1992) on characterising annoyance and nuisance. This concluded:

- The association between a particular odour source and annoyance in the mind of an individual with a history of annoyance due to that source is strong and long lasting. This association can persist for years and may cause annoyance at lower exposure levels than would be the case for individuals with no exposure history for that ambient stressor.
- Annoyance in an individual is apparently determined by a cumulative perceptual and appraisal history over long periods of time, or even a lifetime. Memorable episodes or peaks, where appraisal was most negative as a result of high intensity and unfavourable behavioural context appear to determine the interpretation of this history in memory.
- Nuisance is not caused by short-term exposure, and it is not alleviated by relatively short periods (months) of absence of the ambient stressor.

Nuisance appears to be caused by long-term intermittent exposure to odours.

Note that different people exposed to the same ambient loading of odour may show very different annoyance reactions. The standard VDI 3883 method (VDI 1997c) of measuring annoyance is, therefore, not based on the reaction of individual affected persons but on the mean annoyance reaction or the percentage of a community who feel strongly annoyed. This is measured by psychometric questionnaire. A relationship is then established between the odour concentration and the degree of annoyance of the sample of test subjects exposed to that odour loading.

Table 4.1 Proposed technical definitions of annoyance and annoyance potential (Van Harreveld 2001)

Annoyance potential	Annoyance potential is the attribute of a specific odour (or mixture of odorants) to cause a negative appraisal in humans that requires coping behaviour when perceived as an ambient odour in the living environment. It is an attribute of an odour that can cause annoyance or nuisance. Annoyance potential indicates the magnitude of the ability of a specific odorant (mixture), relative to other odorants (mixtures), to cause annoyance in humans when repeatedly exposed in the living environment to odours classified as 'weak' to 'distinct odour' on the scale of perceived intensity (VDI 3882: 1997, part 1). Whether annoyance potential of an odour does, or does not, cause annoyance (see below) depends on location and receptor factors.
Annoyance	Annoyance is the complex of human reactions that occurs as a result of an immediate exposure to an ambient stressor (odour) that, once perceived, causes negative cognitive appraisal that requires a degree of coping. Annoyance may, or may not, lead to nuisance and to complaint action.
Nuisance	Nuisance is the cumulative effect on humans, caused by repeated events of annoyance over an extended period of time, that leads to modified or altered behaviour. This behaviour can be active (e.g. registering complaints, closing windows, keeping 'odour diaries', avoiding use of the garden) or passive (only made visible by different behaviour in test situations, e.g. responding to questionnaires or different responses in interviews). Odour nuisance can have a detrimental effect on our sense of well-being, and hence a negative effect on health. Nuisance occurs when people are affected by an odour they can perceive in their living environment (home, work-environment, recreation environment) and: i) the appraisal of the odour is negative; ii) the perception occurs repeatedly; iii) it is difficult to avoid perception of the odour; and iv) the odour is considered a negative effect on their well-being.
Nuisance potential	Nuisance potential is the characteristic of an exposure situation, which describes the magnitude of the nuisance that can be expected in a human population when exposed to an odour intermittently, but over an extended period of time, in their living environment. Nuisance potential is a function of many factors, such as the attributes of the odorant (mixture) in question, the frequency and dynamics of variation of the exposure (caused both at source and as a result of atmospheric dispersion) and attributes of the specific population that is exposed.
Nuisance sensitivity	Nuisance sensitivity is an attribute of a specific population (or an individual) that indicates the propensity, relative to that of other individuals or populations, to experience nuisance when exposed to an odour intermittently, but over an extended period of time, in their living environment.

Note: these definitions are from a technical perspective to enable a scientific understanding of the odour impact process. They are not legal or regulatory definitions. The regulatory term 'no reasonable cause for annoyance', for example, is defined later, in Section 4.5.1.

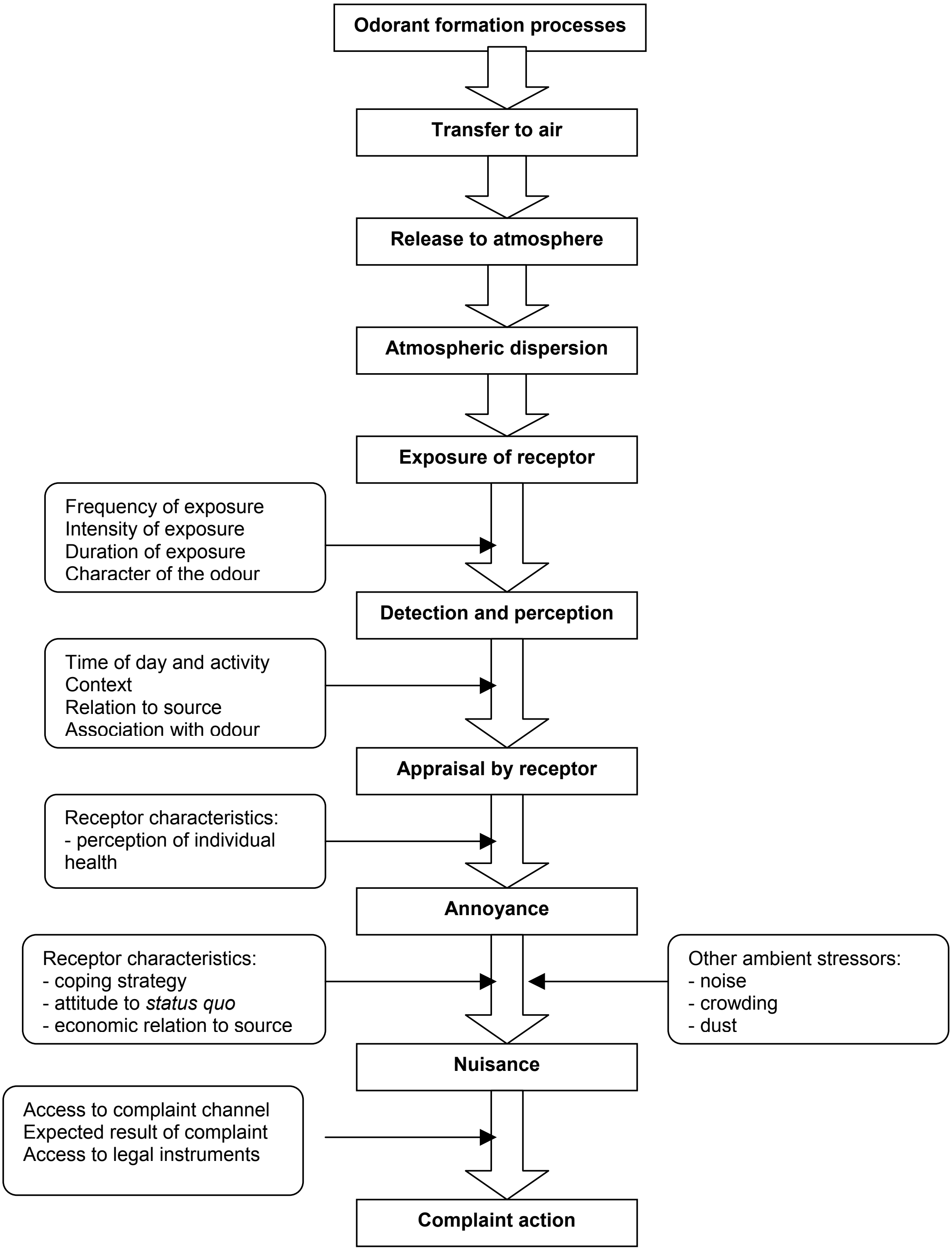


Figure 4.1 From odour formation to complaint (Van Harreveld 2001)

4.2 The FIDOL factors

One conceptual model used to help define what makes an odour episode become a citizen complaint is the pyramid-style hierarchy (Figure 4.2) consisting of four parameters: (1) Character/Offensiveness, (2) Duration, (3) Intensity, and (4) Frequency. This model is sometimes given the acronym FIDO, with the term 'offensiveness' used instead of character. The cumulative effect of these four parameters is said to create the nuisance experience and the citizen complaint (St Croix Sensory Inc. 2003; McGinley and McGinley 2004).

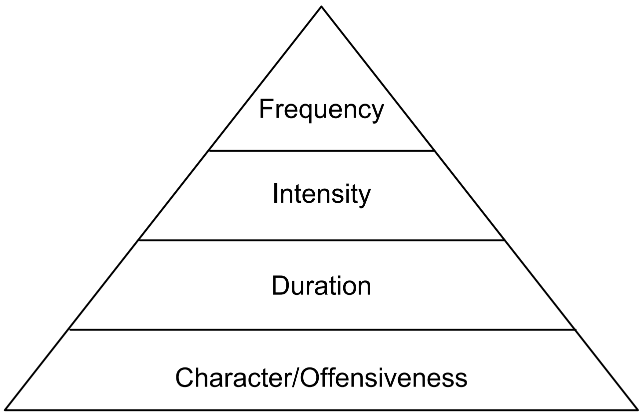


Figure 4.2 The citizen complaint pyramid

Similarly, in Australia (Department of Environmental Protection, Western Australia 2002) and New Zealand (Ministry for the Environment New Zealand 2003) the parameters that determine whether an odour has an objectionable effect are collectively known as the FIDOL factors, the additional parameter being the Location of the odour event. The FIDOL factors are described in Table 4.2. The 'Location' factor can be considered to encompass the receptor characteristics, receptor sensitivity, and socio-economic factors such as those described in Section 4.1 and Figure 4.2.

Table 4.2 Description of the FIDOL factors (Ministry for the Environment New Zealand 2003; University of New South Wales, Sydney 2006)

Frequency	How often an individual is exposed to odour
Intensity	The individual's perception of the strength of the odour
Duration	The length of a particular odour event. Duration of exposure to the odour
Odour unpleasantness (Relative **O**ffensiveness)	*Odour unpleasantness* describes the character of an odour as it relates to the 'hedonic tone' (which may be pleasant, neutral or unpleasant) at a given odour concentration/intensity
Location	The type of land use and nature of human activities in the vicinity of an odour source. Tolerance and expectation of the receptor. The 'Location' factor can be considered to encompass the receptor characteristics, receptor sensitivity, and socio-economic factors

Different combinations of these factors can result in adverse effects. For example, odours may occur frequently in short bursts, or for longer, less frequent periods, and may be defined as having ‘chronic’ or ‘acute’ effects (see Section 4.3.5). Depending on the severity of the odour event, one single occurrence may be sufficient to deem that a significant adverse effect has occurred. In other situations, the duration may be sufficiently short and the intensity sufficiently weak that the frequency of events would need to be higher before an adverse effect would be deemed to have occurred (Ministry for the Environment New Zealand 2003).

It is useful to look at some of the FIDOL parameters in more detail.

4.3 Frequency, intensity and duration

4.3.1 Intensity

The intensity of odour refers to an individual’s perception of its strength. This is different from the odour’s character, or quality. The relationship between the perceived strength (i.e. intensity) of an odour and the overall mass concentration of the combined chemical compounds (mg m^{-3}) was summarised earlier in Section 3.1, and a detailed discussion on odour intensity and concentration is given in Chapter 5.

The odour concentration must have passed the recognition threshold for an odour nuisance to occur (Jiang 2004). Only at this level or above, is it possible that the frequency, duration and offensiveness can have an effect on the receptor.

4.3.2 Frequency

The frequency of the odour occurrence is how often an individual is exposed to odour in the ambient environment. Frequency is influenced by the odour emission source and its characteristics, the prevailing wind conditions, the location of the source in relation to the individual affected and the topography of the area. The frequency of odour exposure is generally greatest in areas that are most often downwind of an odour source, especially under stable conditions with low wind speeds (provided that the odour is not emitted at a significant height above the ground).

4.3.3 Duration

Like the frequency of exposure, the duration of exposure to the odour is related to the type of odour source, the local meteorology and the location of the odour source.

4.3.4 Combined impact of these parameters

There is a risk that descriptions of intensity such as 'faint' odour may be understood to mean that there is limited potential for annoyance, which will be incorrect in many cases. *Frequency, intensity and duration should be considered concurrently*. An objectionable effect can occur either where an odorous compound is present in very low concentrations – usually far less than the concentration that could harm physical health – or when it occurs in high concentrations. Odours may occur in frequent short bursts or for longer less frequent periods. However, all of these odour patterns can cause a significant adverse effect, although an odour of high intensity or concentration occurring for a short period of time is likely to cause a different type of adverse effect to a low-intensity odour occurring almost constantly (Ministry for the Environment New Zealand 2002, 2003).

4.3.5 Classification of odour effects as chronic and acute (Ministry for the Environment New Zealand 2003)

Objectionable and offensive effects from odour can occur from low-intensity, moderately unpleasant odours occurring frequently over a long period, or from high-intensity, highly unpleasant odours occurring infrequently. These effects relate to different combinations of the FIDOL factors and can be termed 'chronic' and 'acute' effects, respectively. It is useful to know what type of effect predominates, although odour effects will often result from a combination of acute and chronic odours. Knowledge of the predominant effect is useful for discussing and selecting the appropriate tools to assess and mitigate odour impacts.

Odour emissions from processing and manufacturing industries will typically have chronic effects. Here, the main odour discharges are usually continuous or semi-continuous emissions, and the main emission sources are often controlled and quantifiable, but there may be a low-level residual odour present for much of the time. Cumulatively, the low-level odour may have an adverse effect even though no single odour event considered in isolation could reasonably be assessed as objectionable or offensive. For chronic odour effects a longer-term assessment of the frequency and character of odour impacts is required.

Acute odour effects are those that can be considered objectionable or offensive on a single occasion or a small number of occasions. Acute effects are often associated with abnormal or upset conditions such as a malfunctioning abatement system, or infrequent activities such as re-opening old areas of fill at a landfill site. Such highly variable and/or uncontrolled discharges are typically very difficult to quantify and, as such, are not amenable to the H4 predictive approach using modelling and an Indicative Odour Exposure Standard. The significance of an effect or a potential effect will often depend on the management practices employed.

4.4 Odour offensiveness and character – the two meanings of 'offensiveness'

A lack of agreed terminology has resulted in there being two meanings in common use of the term *offensiveness* of an odour, which can be confusing (Ministry for the Environment New Zealand 2002). On the one hand offensiveness is sometimes used to describe the character and unpleasantness of an odour, so it is related to the hedonic tone – one of the FIDOL factors. When used in this context, the term *relative offensiveness* is sometimes used. The second meaning of offensiveness is used in the context of overall impact in terms of 'offence to the senses'. Here it has a much broader meaning, encapsulating the combined effect of most or all the FIDOL factors.

These two meanings of offensiveness can sometimes be difficult to distinguish. For example, an odour with quite a pleasant hedonic score could be perceived as offensive! This is particularly so if exposure is frequent and at high concentration. It should be remembered that *all* odours have the potential to be offensive, depending on such factors as concentration, duration and frequency of exposure, the context within which exposure takes place (e.g. at meal times, when feeling unwell) and other factors unique to the individual.

To avoid this confusion of terms, the remainder of this document will, whenever possible, use the term *odour unpleasantness* to describe the character of an odour as it relates to the hedonic tone. The term *offensiveness* will be used solely to describe the combined effect of all the FIDOL factors in terms of 'offence to the senses'.

4.5 The point where odour impact becomes unacceptable

4.5.1 The benchmark criterion of 'no reasonable cause for annoyance'

The PPC Regulations include in their definition of pollution 'emissions as a result of human activity which…cause offence to any human senses'. The Environment Agency has given special consideration as to how this endpoint of odour 'offence' may be anticipated, measured and assessed. For the purposes of the PPC Regulations, the Environment Agency deems the point at which pollution in the form of offence to the sense of smell is occurring to be the point at which there is 'reasonable cause for annoyance'. The aim of odour control is therefore to ensure there is '*no* reasonable cause for annoyance'. This 'benchmark' criterion of 'no reasonable cause for annoyance' does not necessarily equate to no complaints – it is designed to be a level of exposure that a high proportion of the exposed population, with normal sense of smell, finds 'acceptable' on a long-term basis. Conversely, the lack of complaint should not necessarily imply the absence of an odour problem, as there will be an underlying level of annoyance before complaints are made.

4.5.2 Tools available for assessing 'no reasonable cause for annoyance'

In its regulatory role, the Environment Agency is required to assess whether the benchmark criterion of 'no reasonable cause for annoyance' is being met (for existing installations) or is likely to be met (for proposed installations or significant variations). The Environment Agency has at its disposal a variety of odour regulatory and assessment tools for checking compliance with this criterion. These can be grouped into three basic categories:

I) Odour regulation tools that use ambient air quality criteria

a) Quantitative numerical standards for ambient odour concentration, set in multiples of the odour detection threshold (i.e. units of ou m^{-3}). These may be used for mixtures or single compounds and are usually set as a frequency of exceedance of a concentration limit (e.g. the odour concentration at the receptor shall remain at or below a value of X ou m^{-3} for 98% of the hours in the year). Standards set in units of ou m^{-3} imply the use of laboratory DDO, which is of insufficient sensitivity for determinations of ambient odour samples; hence such standards are intended (mainly) for comparison with *predicted* levels of ambient odour from atmospheric dispersion modelling studies. However, direct measurements using portable field olfactometers *are* able to measure total odour concentration in ambient samples (in units of dilutions to threshold, D/T), which is broadly comparable to ou m^{-3}. Ambient standards set as X D/T are common in the USA.
b) Quantitative numerical standards for ambient concentrations of specific odorous compounds. It is possible to measure some of these compounds (e.g. hydrogen sulphide) directly in the ambient air, allowing the standard to apply to both modelled and measured ambient concentrations.
c) Quantitative criteria for odour episode duration and frequency. Measurements can be made using field panels to allow comparison with these criteria. Predictions of the frequency of detection of odours can also be made using atmospheric dispersion modelling.
d) Semi-quantitative, subjective field odour assessments using the 'sniff test' (see Section 4.5.6 for details). Methods vary in the degree of sophistication of the test, some allowing subjective estimates of the ambient odour intensity; estimates may be compared with intensity criteria.

II) Odour regulation tools that use other environmental measures of quality

a) Criteria requiring the absence of annoyance and/or nuisance as judged by officials.

b) Criteria requiring that odours are not detrimental to local amenity.[11]
c) Criteria relating to complaints, e.g. no justified complaints.
d) Community surveys.

III) Standard operational requirements for specific activities

a) Setting quantitative numerical limits on source emissions, such as emission limit values (ELVs). These can be used for controlled releases for which measurement of odour or some surrogate quantity is practicable.
b) Setting requirements to meet certain minimum standards of abatement and control, such as Best Available Techniques (BAT).
c) Defining minimum 'setback' distances for specific industrial or agricultural activities. Standard setback distances for livestock housing units are a popular tool for odour regulation in Australia and New Zealand, Europe and the USA.

Each of these criteria has its own advantages and limitations, but an effective odour regulation strategy should include as many of these tools as possible to allow for effective management of a wide range of situations. None of these approaches are mutually exclusive and many will be most effective when used in combination. It should be remembered that odour criteria are sometimes a function of community consensus on quality of life and expectations of living conditions rather than a true health or environmental-based air quality standard (Minnesota Pollution Control Agency 2006).

Only the first category, 'Odour regulation tools that use ambient air quality criteria', is relevant to the scope of this literature review. Further details of these assessment tools are given in the following sections.

4.5.3 Quantitative numerical standards for ambient odour concentration, set in multiples of the odour detection threshold (i.e. units of ou m^{-3})

It is worth reiterating the different units that can be used for single compounds compared to mixtures of odorous compounds. Where emissions are of a single odorous compound, or where one compound is overwhelmingly responsible for the odour impact, then the modelling or quantitative monitoring of odours can focus on that individual odorous compound. The concentration aspect of the intensity term in the FIDOL factors will be expressed in conventional units for concentration in air (e.g. ppb or μg m^{-3}). However, most emissions encountered by the Environment Agency in its PPC regulatory role

[11] At the time of writing, Defra is proposing as part of its Waste Resources R&D programme to initiate a project 'Impact Assessment: Defining Loss of Amenity through Odour', details at http://www.defra.gov.uk/environment/waste/wip/research/index.htm

are mixtures and for these the odour concentration aspect of any numerical standard needs to be expressed in odour units per volume air (ou_E m^{-3}).

While odour is a subjective experience that varies from person to person, regulation often requires objective and reproducible measurement techniques. In the past 30 years, there has been a trend in Europe to move away from using the judgement of an environmental professional, towards quantitative measurements of odour (Van Harreveld 2003). For some applications, it is appropriate to use computer dispersion modelling (or in some circumstances ambient monitoring) as a tool towards predicting (or estimating, respectively) the offensiveness of the odour. These assessment tools give quantitative results, which need to be compared against some kind of numerical acceptance criterion that encompasses the FIDOL factors. Numerical benchmarks for modelling/monitoring can be derived in two ways:

a) Using a theoretical approach, attempting to incorporate from first principles the FIDOL factors.

b) Empirically deriving a numerical guideline from the relationship between odour exposure (measured or modelled) and annoyance (measured by a community survey). This is how the draft H4 has developed its Indicative Odour Exposure Standard for odour mixtures.

These numerical benchmarks may be used for mixtures or single compounds (see Section 4.5.4), are usually set as a frequency of exceedance of a concentration limit and are intended (mainly) for comparison with predicted levels of ambient odour from atmospheric dispersion modelling studies.

Unlike some other air pollutants, there is no statutory numerical limit in England and Wales for ambient odour levels, whether set for mixtures or for individual odorous compounds. However, the guideline limits that are currently used are summarised below.

Draft H4 Indicative Odour Exposure Standard

As discussed earlier, measurement or modelling of mixtures of odorous compounds needs to be in concentration units of ou_E m^{-3}. There are no mandatory numerical standards set in England and Wales for odour mixtures in ambient air, nor has the WHO set any guidelines. An approach to odour management pioneered in the Netherlands is based on using quantitative measurement (by DDO) of the odour emissions at source, dispersion modelling to estimate exposure, community survey to quantify annoyance, and derivation from the dose-response relationship of a numerical exposure criteria to represent the level where significant annoyance occurs. These criteria may be specific to an industry, depending on the unpleasantness of the odour (Van Harreveld 2003). The Environment Agency has proposed, in the draft H4 guidance, adopting this approach and defines its 'benchmark' criterion of 'no reasonable cause for annoyance' in numerical terms by an 'Indicative Odour Exposure Standard'. This standard was derived from the relationship established between ground-level odour concentration and odour annoyance for a sample of test subjects living around a livestock installation in the Netherlands. The assumption has been made that the results of this study can be applied generically to other applications with certain adjustments and factors applied (see Section 7.2.2 for more details). It leads to the proposed requirement that, at the 98th percentile, a predicted 1-hour average odour concentration at the sensitive receptor (derived from dispersion modelling of source emission strengths) remains at or below 1.5, 3.0, or 6.0 ou_E m^{-3} (depending on the unpleasantness of the source of odour). The Environment Agency's proposed Indicative Odour Exposure Standards for different industries are shown in Table 4.3. This approach addresses the intensity (as concentration), relative offensiveness (unpleasantness), frequency and duration terms of the FIDOL factors. Location is addressed by allowing the indicative exposure standard to be adjusted for local conditions.

For the purposes of PPC regulation, there is 'no reasonable cause for annoyance' if this benchmark air quality criterion is met. As stated earlier, this does not necessarily equate to no complaints. It is designed to be a level of odour exposure that a high proportion of the exposed population, with normal sense of smell, finds 'acceptable' on a long-term basis.

Bespoke odour exposure standards derived from industry-specific dose-response studies

The Environment Agency's draft H4 guidance allows PPC applicants to derive industry-specific dose-response relationships between annoyance and 98th percentile concentrations (1-hour average), as an alternative to using the indicative exposure standards provided (which are effectively 'default values'). At the time of writing, the Environment Agency had not received any applications in England and Wales that used bespoke industry-specific dose-response relationships. It is perhaps worth noting that in the New Zealand guidance (Ministry for the Environment New Zealand 2003) that post-dates the draft H4 a stronger steer is given: industry is expected to derive its own dose-response relationships and it is made clear that the indicative guideline values provided there are temporary and only for use until such studies have been completed (see Section 7.2.3).

Table 4.3 Environment Agency Indicative Odour Exposure Standards for ground-level concentration of mixtures of odorants (reproduced from Table A6.1 in draft H4)

Relative 'offensiveness' of odour

Relative 'offensiveness' of odour	Category	Indicative Criterion
More offensive odours… Activities involving putrescible waste Processes involving animal or fish remains Brickworks Creamery Fat & grease processing Wastewater treatment Oil refining Livestock feed factory	HIGH	**Indicative Criterion** **1.5 ou_E m^{-3} 98th percentile** (existing installations)
Intensive livestock rearing Fat frying (food processing) Sugar beet processing These are odours which do not obviously fall within the HIGH or LOW categories	MEDIUM	**Indicative Criterion** **3.0 ou_E m^{-3} 98th percentile**
Chocolate manufacture Brewery Confectionery Fragrance and flavourings Coffee roasting Bakery Less offensive odours (not <u>in</u>offensive)	LOW	**Indicative Criterion** **6.0 ou_E m^{-3} 98th percentile**

<u>These categorisations are indicative only</u>
Table A1.1 lists a wider range of industrial odours.

The criteria given are based upon: (see Appendix 4)

- 98th percentile;
- 1 hour averaging time

(a). Select most appropriate category – high, medium or low – for the particular odour type (or most offensive odour if there is more than one distinct odour released from the particular installation). The model shows three distinct categories to simplify the process; in reality the gradation is continuous.

(b). Select the corresponding indicative criterion from Table A6.1 and use this as a starting point. See also Table A1.1 which gives a wider range of odour types.

(c) Now make adjustments for any relevant local factors and record the decision.

(d) The end result will be an installation-specific odour exposure criterion in terms of odour ground level concentration at sensitive receptors. This equates to 'no reasonable cause for annoyance'.

Compare this with:

- what the operator is currently achieving
- what is achievable with BAT

to derive Permit conditions.

New installations will be expected to meet indicative BAT standards (as set out in the appropriate Sector Guidance Note) from the outset.

Other 'custom and practice' guidelines used in England and Wales

Work in the UK and Europe led to some 'custom and practice' guidelines being adopted for odour mixtures, set as 98th percentile 1-hour average concentration limits. These have tended to be used in planning applications rather than environmental regulation, in particular within the wastewater treatment industry for predicting the impact of proposed treatment works. Many of these studies relied on the planning decision[12] made in 1993 for a new wastewater treatment plant at Newbiggin-by-the-Sea, where the applicant put forward evidence that there would be no odour nuisance if levels remain below 5–10 ou m^{-3} as 98th percentile of 1-hour means. This was based on Dutch research at 200 sites, although it appears this study has never been published (Bull 2004). Indeed, the draft H4 guidance points out that these 'custom and practice' guidelines have tended to have been adopted largely on the basis of increasingly wide use and convention rather than on any scientific evidence relating them to annoyance.

It is also worth noting that the olfactometry standard being used in the UK at the time of the Newbiggin-by-the-Sea ruling was NVN2820, which preceded EN 13725. There is a factor of 2 (approximately) numerical difference between measurements carried out by these two different methods, i.e. 5 ou m^{-3} measured by NVN2820 is equivalent to 2.5 ou_E m^{-3} measured by EN 13725. Thus the 5–10 ou m^{-3} 'custom and practice' guideline used then would be equivalent to 2.5–5.0 ou_E m^{-3} now following the introduction of EN 13725. This falls within the 1.5 to 6.0 ou_E m^{-3} range now being proposed in H4.

Field olfactometry guidelines

Field olfactometry is popular in the USA. Laboratory DDO is not suitable for ambient samples due to its lower detection limit of about 50 ou_E m^{-3}. However, portable hand-held devices such as the Nasal Ranger® and the Scentometer® allow direct olfactometry measurements to be made in the field without the need for separate sampling and laboratory dilution stages. The more sophisticated Nasal Ranger® has a lower detection limit of 2 dilutions to threshold (2 D/T),[13] but has only been available since 2002 and so has not yet achieved widespread use in England and Wales. Accordingly, no specific numerical guideline standards have been adopted. However, in many parts of the USA these devices are regularly used to make practical quantitative measurements and assessments of legal nuisance. While some of the limitations of 'sniff tests' apply to the use of these dilution devices, they do represent a significant improvement on the 'sniff test'. A review by St Criox

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[12] Appeal by Northumbrian Water: Land Adjacent to Spital Burn, Newbiggin-by-the-Sea, Northumberland, Inspector's Report Ref. APP/F2930/A/92 206240, 15 July 1993.

[13] The dilutions to threshold ratio is a measure of the number of dilutions (with carbon-filtered air) needed to make the odorous ambient air non-detectable. D/T is similar to the units of ou m^{-3} used in DDO, although the two are not interchangeable or directly comparable.

Sensory Inc. (2003) found seven US states using a value of 7 dilutions to threshold (7 D/T) as a nuisance limit.

4.5.4 Quantitative numerical standards for ambient concentrations of specific odorous compounds

With some notable exceptions, odours in ambient air are typically the result of complex trace level mixtures, which do not lend themselves to quantitative analysis in ambient air. However, there may be situations where odours are dominated by releases of a single chemical, or where a single chemical or instrument response can provide a valid surrogate measurement for that odour. Guideline values for limiting odour impacts have been published by the World Health Organisation (WHO). These guidelines have been established for a very limited number of single compounds, rather than compounds in mixtures. They are set as concentrations in air (e.g. in $\mu g\ m^{-3}$) over a particular averaging period. They thus address the concentration aspect of the intensity term in the FIDOL factors and the duration. As the guidelines are compound-specific, it could be argued that they inherently take into account the relative offensiveness (unpleasantness) term. However, the frequency term is not directly taken into account. As it is possible to measure some of these compounds (e.g. hydrogen sulphide) directly in the ambient air, it is possible to compare WHO guidelines with both modelled or measured ambient concentrations.

The most common odour surrogate measurement in ambient air is hydrogen sulphide. As indicated in the WHO air monitoring guidelines for Europe, ambient H_2S levels of greater than 7 $\mu g\ m^{-3}$ (4.6 ppb) averaged over 30 minutes will probably give rise to a significant number of complaints. Monitoring of hydrogen sulphide is commonly carried out around sewage treatment works as a dominant surrogate indicator for odour. It is interesting to note that 4.6 ppb is not that different from the 7 dilutions to threshold used as a nuisance criteria in some US states' nuisance criteria (see below), although the integration times differ. Surrogates for odour may therefore be useful in specific circumstances where measurements can be made. However, this parameter cannot be relied upon to always provide adequate detection of odour annoyance or nuisance (personal communication, Nick Sauer, Environment Agency, 11 January 2005).

4.5.5 Quantitative criteria for odour episode duration and frequency

In Germany, regulation is according to the *Guideline on Odour in Ambient Air* (GOAA[14]), which sets an upper limit on the frequency of recognisable odour (Environment Agency 2002a)[15] in ambient air, with 10% being the frequency

[14] *The Guideline on Odour in Ambient Air* (GOAA), in English, dated May 1998, may be downloaded from http://www.lua.nrw.de/luft/gerueche/GOAA_200303.pdf.

[15] Odour at or above the recognition threshold, i.e. the odour character is definitely identifiable by the observer.

limit set for residential and mixed areas and 15% being the limit set for trade and industrial zones. This frequency can be modelled (VDI 3788), or measured in the field to the VDI 3940 standard *Determination of Odorants in Ambient Air by Field Inspection* (VDI 1993). This unit of measure (% of odour hours) is used as part of the definition of ‘severe detriment’ or ‘significant nuisance’ in the German Federal Immission (exposure) Control Act. The Environment Agency research review (Environment Agency 2002b) quotes work by Steinheider *et al.* (1998) that showed there was a clearly significant relationship between annoyance as measured by community survey, and the percentage of odour hours as determined by the German ‘Field Panel Method’.

This is a ‘go/no-go’ test, taking account only of whether the odour is recognisable – no additional weighting is given to intensity. This is based on German work that showed that odour annoyance of residents is determined mainly by the frequency of recognisable odour. In these investigations it was shown that increasing odour intensities did not necessarily lead to an increasing degree of annoyance. Hedonic tone was not at that time investigated.

No similar episode duration and frequency criteria are in use for England and Wales.

4.5.6 Semi-quantitative, subjective field odour assessments using the ‘sniff test’

For existing installations, the point at which the odour impact becomes unacceptable can also be assessed in the field, using trained assessors to carry out ‘sniff tests’ at the receptors. This tool – also called a direct sensory test, subjective testing or simplified olfactometry – gives a subjective result based on the assessor’s opinion on the FIDOL factors, which are compared with descriptive (or sometimes numerical) guidelines. There is no statutory limit in England and Wales, nor is there any WHO guideline giving acceptance criteria for the results, though some exist in other countries.

‘Sniff tests’ are designed for assessing the odour impact by recording some or all of the FIDOL factors, including odour concentration/intensity, the type of odour/hedonic tone, the daily and seasonal distribution and the temporal pattern of nuisance, and the use of the affected area. Methods vary in the degree of sophistication of the test, some allowing subjective estimates of the ambient odour intensity to be compared with intensity criteria.

This approach should not automatically be considered inferior to quantitative ambient monitoring. When carried out to a rigorous, well-designed methodology, the results of such surveys can be expected to be robust and reproducible. The Protocol for Subjective Testing (‘Sniff-Testing’) in Appendix 8 of the draft H4 guidance shows a method used by Environment Agency field staff for assessing the impact of odours around PPC installations. An odour may be placed in one of three categories of offensiveness (i.e. the combined effect of all the FIDOL factors to give ‘offence to the senses’), after taking into account strength/intensity, nature/character, frequency, extent and sensitivity:

1. Potentially offensive
2. Moderately offensive
3. Very offensive

The *Good Practice Guide for Assessing and Managing Odour in New Zealand* (Ministry for the Environment New Zealand 2003) advises how the overall impact rating of an odour incident on the complainant can be estimated by assessing the FIDOL factors in the field. It recommends that the VDI 3940 standard is followed to log odour observations in the field, which involves recording odour intensity on the VDI scale (see Table 5.1 in Section 5.2) every 10 seconds over minimum 30-minute periods[16] at each location. This provides short-term information on frequency, intensity and duration factors. The odour character of the odour (such as fishy, sewage, bakery, etc.) is logged, using a suggested table of general odour character descriptions (e.g. Table 3.2 in Section 3.1). The investigator then summarises the overall impact of the odour at the receptor using an impact scale, an example of which is shown in Table 4.4. This covers a range of impacts, from chronic through to acute effects.

Another scale used by inspectors in the USA (State of Texas Commission on Environmental Quality) to make an objective determination of nuisance is shown in Table 4.5.

Table 4.4 Example of a scale for rating odour impact from subjective tests (Cudmore and Ryan 2002)

Impact rating	Characteristics
1	The odour can be detected but is not noticeable under normal conditions.
3	The odour can be detected but is not objectionable/offensive, unless it is inside a house and is continuous, in which case it is objectionable/offensive.
5	The odour is moderately strong and is objectionable/offensive if it occurs for periods of more than 5–10 minutes. Short, infrequent occurrences are not objectionable/offensive.
7	The odour is strong and is objectionable/offensive even in periods of short duration. The odour can be nauseating if continuous.

[16] Shorter time periods may result in the observer missing the extent of the effects. An exception to the 'every 10 seconds for 30 minutes' rule is needed when the odour plume is strong and constant, such as in stable, drainage flow conditions. Staying permanently in the plume will result in the observer becoming desensitised to the odour, so it is appropriate in this case to drive or walk through the plume once every 5–10 minutes, then repeat over a period of at least 30 minutes.

Table 4.5 Categories used in Texas for classifying odours in ambient air (Minnesota Pollution Control Agency 2006)

Category	Characteristics
1	No odour detected
2	Odours barely detected Odours very faint Odours very intermittent and faint Odours not strong enough or of sufficient duration to identify or characterise the odour
3	Odours light to moderate, but not objectionable Odours noticeable, but not unpleasant
4	Odours light to moderate, but not unpleasant Odours somewhat objectionable but not sufficient to interfere with the normal use and enjoyment of property Odours strong and objectionable, but very intermittent, and because of lack of duration would not tend to interfere with normal use and enjoyment of property Odours strong but not at all unpleasant and would not create adverse reactions or interference with normal use and enjoyment of property
5	General Odours capable of causing nausea Odours capable of causing headaches Odours overpowering and highly objectionable Odours would create a need to leave the area
	Residential area Odours offensive enough to prevent working or playing in the yard Odours tend to stay in the residence and make it difficult to sleep, eat, etc. Odours tend to interfere with entertaining guests
	Commercial area Odours tend to interfere with normal activities for office workers Odours tend to stay in building and make it difficulty to read, type, concentrate, etc. Odours tend to interfere with normal warehouse work activities Odours tend to interfere with normal outdoor work activities

As was explained in the preceding section, Germany uses the GOAA methodology guideline, which is based solely on the frequency with which odours exceed the recognition threshold (the odour-hour concept). No account is taken of intensity because it is reportedly not a reliable predictor of annoyance. Hedonic tone is also not included in the assessment because at the time the guideline was developed the influence on annoyance had not been quantitatively established. However, recent odour annoyance research (Both and Koch 2004, Both *et al.* 2004) in Germany, presented at the VDI Odour conference in Cologne in 2003, looked again at the GOAA methodology. A new method was used to measure odour intensity and hedonic tone in the field, which concluded the following:

- The annoyance predicting value of frequency measurement, as indicated in the GOAA method, was valid and robust.
- The intensity – and by extension concentration – was *not* a good predictor for annoyance. This is a surprising and counter-intuitive conclusion, but it was unclear what range of odours was being considered in the study.[17] It may be that the study only looked at the effect of concentration at moderate levels.
- There was very little difference between the annoyance impact of unpleasant or neutral odours: odour frequency alone is indeed sufficient to predict the odour annoyance caused by unpleasant and neutral odours and intensity has no additional influence. If odours are recognisable they can cause annoyance.
- Finally, the researchers discovered that for pleasant odours, however, hedonic tone has a clear effect on the dose-response relationship and pleasant odours have a significantly lower annoyance potential (at the same frequency) than unpleasant odours (see Figure 4.3). This recent work may suggest a need to review the Environment Agency's approach under PPC, which applies different benchmark standards for unpleasant and neutral odours.

As a result of this new research, for installations causing 'pleasant' odours German regulators now apply a factor of 0.5 to the odour impact (i.e. frequency of recognisable odour) before it is compared with the frequency limit values. Given the ability to both measure and model odour perception frequencies, it may be that the GOAA methodology, modified to allow for pleasant hedonic tones, holds significant advantages for the monitoring and assessment of odour annoyance.

[17] It seems more likely that annoyance could be caused *either* by frequent low level exposure to odours *or* infrequent exposure to very high levels. Even if annoyance does not result from infrequent exposure to very high levels, there may be little practical difference in the number of situations which are judged to be problematic so long as judgements are not made on the basis of odour concentration alone (personal communication, Nick Sauer, EA, 11 January 2005).

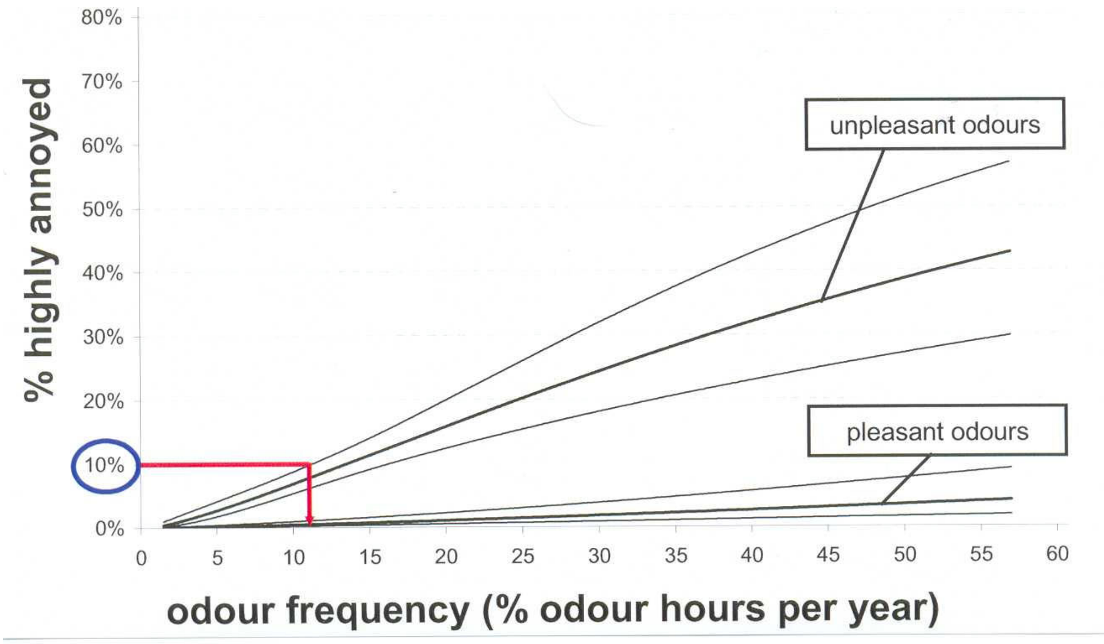


Figure 4.3 The percentage of highly annoyed residents is dependent on the odour frequency and the hedonic tone (Both and Koch 2004)
Note: the ranges shown around the 'unpleasant odours' and 'pleasant odours' lines are not defined in the reference source. It is assumed that they depict some measure of central tendency, for example the 95% confidence limits.

It should also be remembered that there are other tools that can be used for assessing existing installations, including complaints monitoring and measurement of levels of annoyance in the community through community survey investigations (e.g. VDI 3883). However, these do not make use of numerical standards and are therefore outside the scope of this review.

4.6 Opportunities identified for strengthening Environment Agency guidance

A revised draft of H4 would benefit from the following:

- Tighter and bolder definitions of terms, especially the differences between exposure, annoyance and nuisance; the differences between annoyance and annoyance potential; and the two meanings of offensiveness. The revised guidance should use the term relative unpleasantness in place of offensiveness to avoid confusion.
- The annoyance impacts should be described in terms of the FIDOL factors, making the revised guidance consistent with the most up-to-date guidance offered by other regulators.
- The revised guidance should be more explicit in stating that the Indicative Odour Exposure Standards are default values to be used only until such time as UK dose-response studies allow industry-specific exposure

standards to be derived. The guidance should positively encourage relevant industry sectors to become involved in such studies.

- Recent German research on the influence of hedonic tone on annoyance, carried out since the Dutch studies that formed the basis of the draft H4 approach, suggests there is no significant difference between the annoyance potential of unpleasant odours and neutral odours. Pleasant odours do, however, have a significantly lower annoyance potential at the same intensity. This finding throws some doubt on basing the Indicative Odour Exposure Standards on a three-band system for odour unpleasantness; it may be necessary to consider a simplified system, dividing odours into two categories, one for pleasant odours and the other for neutral or unpleasant odours (the latter not distinguishing between moderately unpleasant and highly unpleasant odours). There is in any case probably more consensus on which odours are pleasant than there is in choosing whether an odour falls in the other two bands. Removing the need to decide on assignment to neutral or unpleasant would perhaps remove an area of contention without any loss in robustness of this conceptual model. This would be particularly so if the other Environment Agency research on odour assessment uncertainty shows that the component uncertainty in this band choice is small compared to other component uncertainties in the assessment method.
- The 'sniff test' protocol given in Appendix 8 of draft H4 should be reviewed to ensure all the FIDOL factors are properly represented and that the impact scale is consistent with those used by other workers.
- The technique of field olfactometry should be included in the guidance as a quantitative tool for compliance checking at the site boundary or at sensitive receptors, with the possibility of setting numerical benchmarks.

5 A deeper look at odour intensity and concentration

5.1 Approaches to incorporating odour intensity in impact assessments

Chapter 3 summarised the attributes of an odour and Section 3.1 introduced odour intensity and concentration as two alternative ways of describing the strength of an odour. In this chapter, the approaches to describing and measuring odour intensity are reviewed. The relationship between intensity and concentration is examined in detail, as this is of great importance to how well modelled levels of odour can be said to predict odour annoyance.

The intensity of odours experienced by receptors will be a function of odour concentration, the specific intensity of the odorous mixture and the extent to which they experience adaptation. This parameter is relevant because annoyance will be related to perceived intensity, rather than odour concentration on its own. The intensity of odorant sources can be assessed in the laboratory or directly in the field (see Section 5.2).

Despite intensity being the measure of strength that matters so far as the FIDOL factors and odour impact is concerned, measurement of concentration remains popular because it can be carried out quantitatively. Odour concentration measurements give a more accurate assessment of odour impact in some circumstances when they are combined with the specific intensity relationship for the odour mixture. However, it needs to be remembered that specific intensity determinations (see Section 5.3.1) will be individual to each odour. If there is more than one potential source, or if the source varies in the odours it emits, then the specific intensity may not be a constant. In most cases it will therefore be appropriate to be aware of the effect of specific intensity and either make no correction, or to apply a very approximate[18] correction factor (personal communication, Nick Sauer, Environment Agency, 11 January 2005).

5.2 Measurement of odour intensity

Odour intensity is measured in the laboratory using odour panels and dynamic olfactometry equipment in a similar way to determining odour threshold (i.e. odour concentration using the German standard *Olfactometry Determination of Odour Intensity* VDI 3882 Part 1 (VDI 1997a), which provides qualitative descriptions of odour intensity against a numerical scale (Table 5.1)). Panel

[18] Although any correction factor is likely to be approximate, it will depend on the specific odours in question and its odour concentration–intensity relationship (see Section 5.3.1). It is not possible to give a generic value for this correction.

members are presented with odour at concentrations greater than the odour threshold (by definition 1 ou m^{-3}) and asked to rate the perceived strength, or intensity, of the odour against descriptive terms such as ‘not perceptible’, ‘weak’, ‘strong’, etc.

It is usually accepted that a ‘distinct’ odour may just be able to be recognised (i.e. has a concentration approximately equivalent to its recognition threshold). However, it should be remembered that an odour described as ‘distinct’ under highly controlled laboratory conditions is likely to be harder to detect in the environment (Department of Environmental Protection, Western Australia 2002).

Table 5.1 Odour intensity categories

Odour strength	Intensity level	Comments (Jiang 2004)
No odour/not perceptible	0	No odour when compared to the clean site
The odour detection threshold (ODT) is somewhere between 0 and 1		
Slight/very weak	1	There is probably some doubt as to whether the odour is actually present
Slight/weak	2	The odour is present but cannot be described using precise words or terms
Distinct	3	The odour character is barely recognisable
VDI 3940 says that the recognition threshold intensity is about 3 ou_E m^{-3} higher than the ODT		
Strong	4	The odour character is easily recognisable
Very strong	5	The odour is offensive. Exposure to this level would be considered undesirable
Extremely strong	6	The odour is offensive. An instinctive reaction would be to mitigate against further exposure

An alternative to the subjective measure is used in the USA: an American Society for Testing and Materials (ASTM) method exists for measuring odour intensity using a panellist or technician who compares the sample to a number of standard concentrations of the reference chemical, *n*-butanol. Results are expressed on a numerical scale, each numerical unit corresponding to a particular concentration of *n*-butanol. The test can be applied in the laboratory to collected air samples, or directly in the field to ambient conditions.

Practitioners in Europe, Australia and New Zealand have tended to grade odour intensity during field observations (assessing ambient odours by ‘sniff testing’) by using the same scale as used in laboratory tests (Table 5.1), following method VDI 3881 Sheet 1-4. Experience using this scale has shown that observations have a good degree of consistency between observers (Ministry for the Environment New Zealand 2003). There are other similar (but not identical) intensity scales in use in the USA (Mahin 2003), Korea (Park 2003) and Japan (Yang 2003).

5.3 The relationship between odour concentration and intensity

5.3.1 OCI relationships

Odour *intensity* refers to the perceived strength or magnitude of the odour sensation. Although perceived intensity does increase as a function of concentration, the relationship is not linear. The precise relationship varies from one odour to another: some odours are perceived as being stronger than others. While all odours will, by definition, be just detectable[19] at a concentration of 1 ou m^{-3}, at twice that concentration (2 ou m^{-3}) some odours may be perceived as very weak while others may be perceived as distinct.[20] At ten times the concentration (10 ou m^{-3}), one odour may be perceived as distinct while another odour at 10 ou m^{-3} concentration may be perceived as very strong. This means that defining an odour criterion based on odour concentration – as has historically been done for the purposes of managing odour impact on the community – will result in different perceived odour strengths. The only time this will *not* occur is when the odour criterion is equal to the detection threshold (i.e. at 1 ou m^{-3}), which effectively becomes a 'no impact' criterion (Department of Environmental Protection, Western Australia 2002).

Carrying out repeat odour intensity and concentration measurements to method VDI 3882.1, using dynamic olfactometry, allows the odour concentration–intensity (OCI) relationship to be established for specific odorants (including complex mixtures), enabling different odour types to be compared. An example of the odour intensity measurement from 60 samples is shown in Figure 5.1. The OCI relationship demonstrates the correlation between the inhaled odour concentration and the odour intensity category and gives an indication of the expected odour perception by the receptors to a particular odour concentration. Stevens' Law and the Weber–Fechner Law are examples of formulae that have widespread acceptance for defining the OCI relationship.

[19] This statement is a general one. As explained earlier, the odour detection threshold is different depending on whether it is a population, a panel, or an individual that is being considered. At the population threshold of 1 ou m^{-3}, 50% of people will be able to detect the odour and 50% will not. The threshold of 1 ou m^{-3} for an individual means he/she can detect the odour on 50% of the occasions it is present.

[20] Again, this is a simplification. Because of variations in odour sensitivity in the population, the perception of intensity for the same odour at the same concentration may differ between individuals.

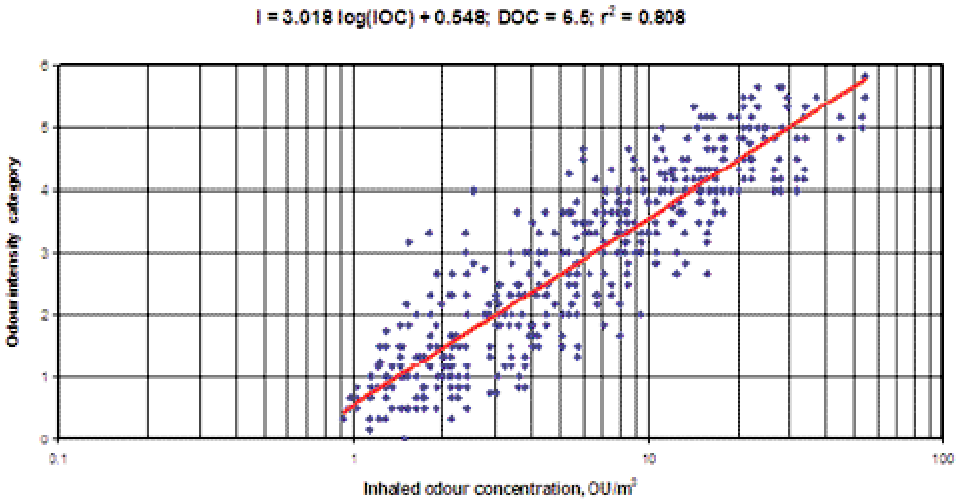


Figure 5.1 Example of odour concentration–intensity (OCI) relationship from 60 samples (Jiang 2004)

5.3.2 Stevens' Law and the Weber–Fechner Law

Earlier reviews (Department of Environmental Protection, Western Australia 2002; Environment Agency 2002b) summarised how the relationship between perceived intensity, *I*, and the magnitude of the stimulus causing the perception stimulus can be described in two ways, either using the Weber–Fechner law (a theoretically derived logarithmic function), or as a power function according to Stevens' Law.

The Weber–Fechner law is expressed as

$$I = k_{w}.\ \log C/C_{o} + const$$

where:

I is the perceived intensity of sensation (theoretically determined), dimensionless;
C is the physical intensity (odour concentration);
C_o is the threshold concentration, i.e. the concentration of odorant at the detection threshold (by definition equals 1 when using odour units);
k_w is the Weber–Fechner coefficient, which depends on the odour substance or odour mixture; and
const = a constant which relates to the use of mean intensity levels. (This constant is calculated from the line of best fit for each odorant.)

So a ten-fold increase in concentration may correspond only to a doubling of the intensity. A logarithmic odour scale – odour decibels – is sometimes used (Bidlingmaier *et al.* 1997 and BS EN 13725), based on the relationship:

$$dB_{OD} = 10 \times \log_{10} [ou\ m^{-3}]$$

It is important to note that, although the Weber–Fechner relationship between intensity, concentration and thresholds applies generally to odorants, the specific value of the coefficient k_w can differ between odorants. This is illustrated in Figure 5.2, which shows the relationship between the perceived intensity and the odour concentration for two compounds, hydrogen sulphide and butanol. Hydrogen sulphide has a higher specific intensity than butanol and so is perceived as a stronger odour at the same concentration. So, if an odour concentration of 10 odour units was chosen as the appropriate modelling guideline, then butanol would be perceived as a weak odour, whereas hydrogen sulphide would be perceived as a distinct odour. To have equivalent protection against different odours would require choosing an *intensity* level for the numerical odour guideline and then working across the graph to determine the appropriate concentration for that odorant. Using Figure 5.2 as an example, if the guideline was set at a 'distinct' perceived odour (in the laboratory) then the appropriate concentrations would be 11 and 33 odour units for hydrogen sulphide and butanol, respectively (Department of Environmental Protection, Western Australia 2002).

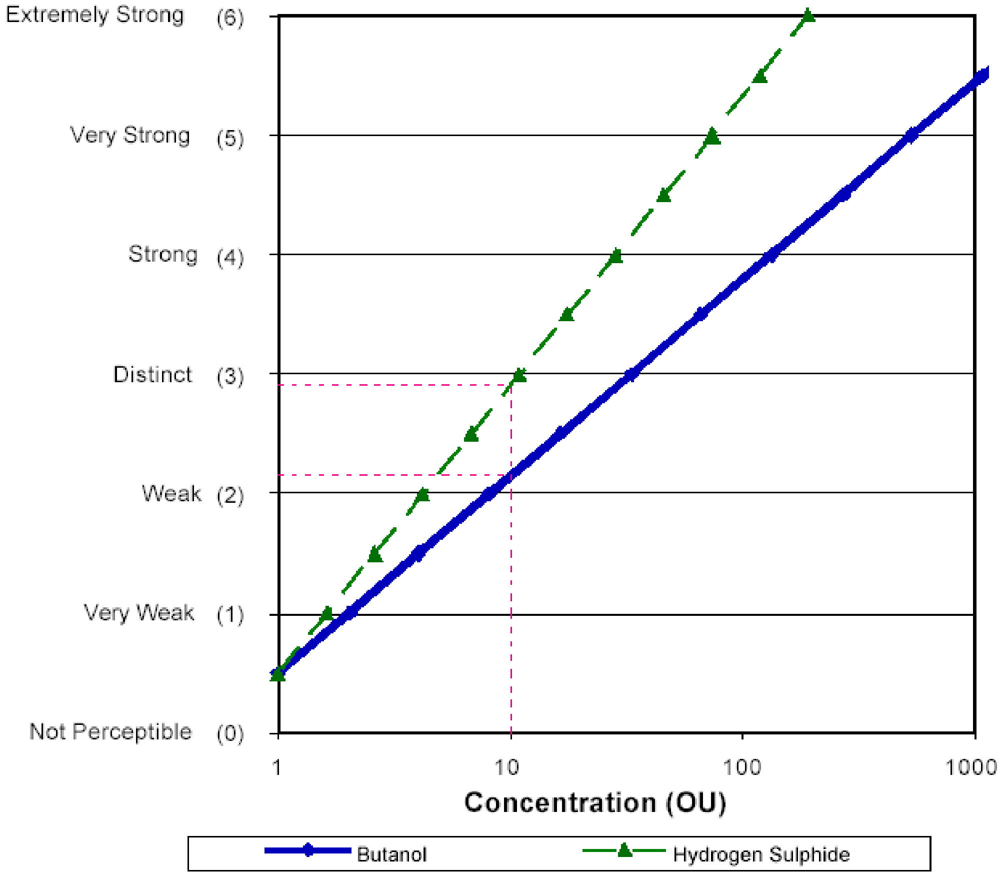


Figure 5.2 Relationship between perceived odour intensity and odour concentration for butanol and hydrogen sulphide (Department of Environmental Protection, Western Australia 2002)

Note a: for an odour concentration of 1 ou (i.e. the 50% odour detection threshold), VDI 3882 effectively defines the corresponding intensity as 0.5. Intuitively then, the odour 'detection' level can be thought of as being higher than 'not perceptible' (which it must be by definition) but lower than 'very weak'.

Note b: Stevens' Law is calculated by taking the logarithm of intensity (I), which for I = 0 is not mathematically possible. By definition, the odour 'detection' level is defined as 1 odour unit, so from a practical consideration the 'not perceptible' level is beyond the range of interest.

In the 1950s and 1960s, through his work at Harvard University, Stevens proposed that apparent odour intensity (strength of the perceived odour sensation) grows as a power function of the stimulus odorant. Stevens showed that this Power Law (Stevens' Law) follows the equation:

$$I = k.\ C^n$$

$$\text{Log } I = \log k + n.\log (C)$$

where:

I is the perceived intensity of sensation (empirically determined);
C is the is the physical intensity (odour concentration);
k is a constant that is different for every specific odorant or mixture of specific odorants; and
n is the Stevens' exponent, ranging from about 0.2 to 0.8, again depending on the odorant.

For an odorant with n = 0.2, a ten-fold reduction in concentration decreases the perceived intensity by a factor of only 1.6; whereas for an odorant with n = 0.8, a ten-fold reduction in concentration lowers the perceived intensity by a factor of 6.3.

Which one of these two descriptions, the Weber–Fechner Law or Stevens' Law, applies depends on the method used. To date no theory has been able to derive the psychophysical relationship from knowledge about the absolute odour threshold of various substances.

5.4 Opportunities identified for strengthening Environment Agency guidance

The concept of OCI relationships could be used in a revised draft of H4 to strengthen guidance on odour impact assessments. If it was a requirement that the OCI relationship for a odour source type be established (by on-site sampling and laboratory odour analysis), this would allow an intensity guidance level (e.g. 'distinct' odour intensity) to be set and then converted to the equivalent concentration units for comparison with the model results.

Though this would strengthen odour impact assessments, it would not provide any advantage to the H4 back-calculation method of setting odour emission limit values based on meeting acceptable numerical benchmarks derived from industry-specific dose-response studies. In a bespoke dose-response study, it is only necessary to get a good correlation with the dose and it does not matter whether that is measured as intensity or concentration. This is perhaps another good reason for emphasising that bespoke odour standards derived from industry-specific dose-response studies carried out in the UK are preferred to the use of Indicative Odour Exposure Standards.

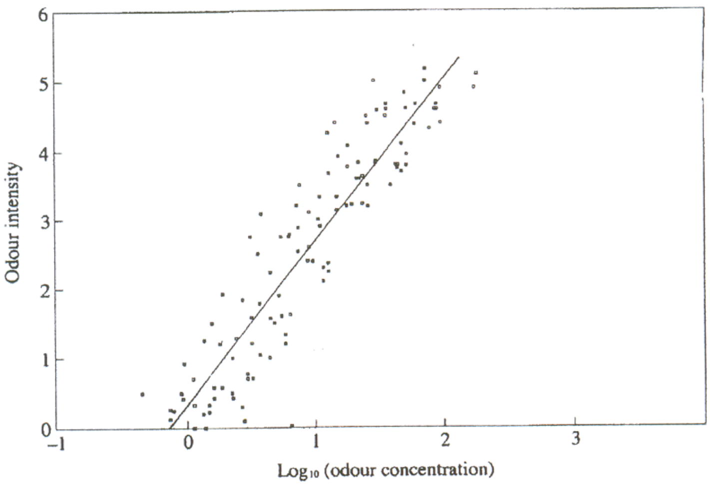
6 More details on odour unpleasantness (hedonic tone)

6.1 The importance of odour unpleasantness

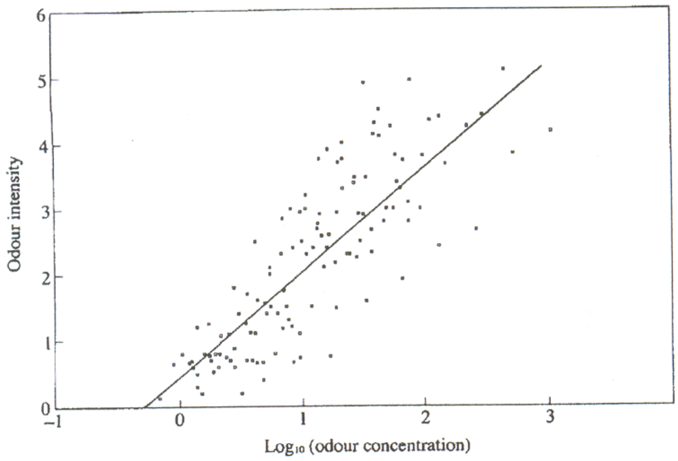
Chapter 3 summarised the attributes of an odour and Section 3.1 introduced the concepts of unpleasantness and hedonic tone. In this chapter, the importance is discussed in practical terms, relating differences in unpleasantness and hedonic tone to different types of odour source. Approaches for ranking odour unpleasantness are described and methods for measuring hedonic tone are listed.

All other things being equal, it would be expected that odours with a steeper rise of intensity with concentration would have a greater impact on receptors than those with a gentler rise: odours with a shallow OCI curve tend to have a small incremental impact as the concentration rises. (Manufacturers of high quality perfumes try to formulate their product in this way so that the intensity of the perfume does not become annoying when an observer gets close to the wearer, where the concentration is highest.) But it is not as simple as this. The illustrative example used in earlier Environment Agency research (Environment Agency 2002b) was for superficially similar odours, pig slurry and poultry manure odours. Figure 6.1 shows the results of experimental work[21] that demonstrates the increase in perceived intensity with concentration is less steep for pig slurry odours than for broiler house odours, which are particularly pungent due to high ammonia content.

[21] The EA research report does not state explicitly how these data were obtained, but it is implicit that concentration and intensity were measured using dynamic olfactometry in the usual way for establishing OCI relationships, as described in Section 5.3.1.



Relationship between intensity and concentration for odour emissions from broiler houses



Relationship between intensity and concentration for odours following application of pig

Figure 6.1 Relationship between odour concentration and perceived intensity, for broiler house odour and the odour of pig slurry after application on farmland

However, the steeper intensity rise characteristic for broiler odour does not translate into a greater impact at receptors. Results of actual impact studies, as shown in Figure 6.2, show pig odour clearly has a greater impact in terms of nuisance,[22] even though it has the less steep intensity curve. This can be accounted for by differences in people's likes and dislikes for different odours, i.e. differences in odour unpleasantness. This illustrates the necessity of considering the unpleasantness of the odour or its hedonic score in any scheme to relate the odour exposure to annoyance or nuisance.

[22] It should be emphasised that the poultry odours were from the broiler house (i.e. a point source) whereas the pig odours were from the slurry spread on the field (i.e. a diffuse area source). Although it is difficult to compare directly the impacts of the two types of source, the general point being made is that when records of odour complaints from agriculture were kept, these were greater for odours from spreading of pig manure than other sources.

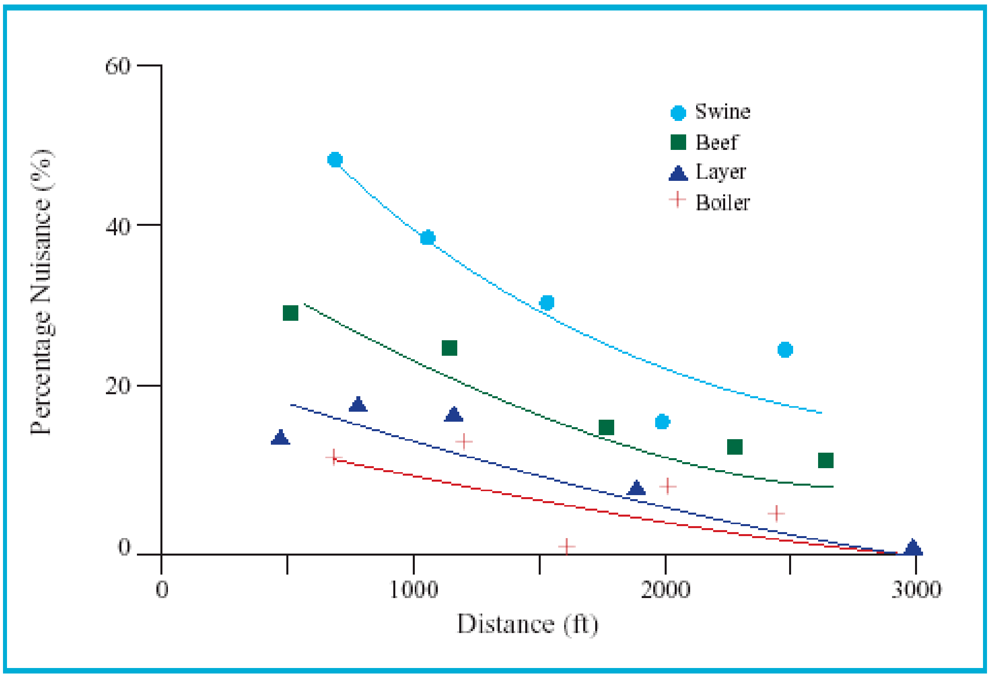


Figure 6.2 Relative nuisance perception for different livestock odours (after Veenhuizen 1996 in Irish Environmental Protection Agency 2001)

People may subjectively rate two different odours as having different degrees of unpleasantness at the same odour concentration. For example, at a standardised concentration of 10 ou m^{-3} (i.e. at a multiple of ten times their respective odour detection thresholds) most people rate odours from a wet feedlot as more unpleasant than those from a dry feedlot. So, although both odours can be considered unpleasant, the wet feedlot odour has greater annoyance potential for annoyance or nuisance. Put another way, the dry feedlot odours would need to be present at greater concentration to elicit the same annoyance response as the wet feedlot (Ministry for the Environment New Zealand 2002).

This chapter examines in further detail *odour unpleasantness* (sometimes termed *relative offensiveness*) as it is used to describe the character and unpleasantness of an odour, related to the hedonic tone – one of the FIDOL factors. As was explained in Section 4.4, the term offensiveness of an odour has a double meaning, which can be confusing. In this chapter we are *not* concerned with offensiveness used in the context of overall impact in terms of ‘offence to the senses’, where it encapsulates the combined effect of all the FIDOL factors. Rather, in this chapter we are concerned more narrowly with the way in which different types of odour elicit different degrees of like or dislike in impacted populations.

In looking at the odour unpleasantness of industrial installations, there are several complicating factors. Firstly, an industrial installation may have several or many different odour sources and these may vary in their relative unpleasantness. For example, on a sewage treatment works sludge odour is generally considered much more unpleasant than odours from many other processes on site. Secondly, the hedonic tone/relative unpleasantness changes with concentration, especially when some emotional responses come into play. Some odours may be pleasant when weak but unpleasant when strong, or when exposure is frequent. So, a cup of coffee may smell pleasant, but the smell of a coffee factory may cause annoyance.

6.2 Comparing the unpleasantness of different odours

6.2.1 The relationship between hedonic tone and odour unpleasantness

Although hedonic tone is closely related to the relative pleasantness or unpleasantness of an odour, the two are not precisely equivalent. The distinction between them is as follows:

- The hedonic tone of an odour is (usually) evaluated in controlled laboratory conditions, where an odour panellist is exposed to a controlled stimulus in terms of intensity and duration. The panellist does not experience the particular spatial and temporal context associated with a particular activity, behaviour or expectation.
- The degree of pleasantness and unpleasantness experienced in the field will be affected by the particular spatial and temporal context associated with a particular activity, behaviour or expectation. In addition, it will be affected by a person's experiences and emotional associations.

To utilise hedonic score data, it must first be assumed that if an odour sample is graded as 'not annoying' in an olfactometric laboratory situation, then it would also be 'not annoying' in the real environment. This is considered a fairly safe assumption because the laboratory situation excludes masking of odours due to background odours (as are always present in ambient air), which means that odours detected in the laboratory are more likely to be rated as unpleasant or annoying than the same odour in the real environment. However, this is countered by the fact that odour panellists do not represent those members of the public with very sensitive nasal responses. Also, it must also be assumed that if an odour sample is graded as 'annoying' or worse in the laboratory situation, then it would also be 'annoying' or worse in the real environment. However, the two arguments given above relating to background odours and public sensitivity tend to cancel each other out or offset each other to some degree (Freeman *et al.* 2000).

There are two approaches for comparing unpleasantness and hedonic tone: the first is simply to rank odours from unpleasant to pleasant (Section 6.2.2); the second is to measure the hedonic score (Section 6.2.3).

6.2.2 Ranking of odours by hedonic tone and odour unpleasantness

One straightforward approach to compare the unpleasantness of different odours is to ask a group of people to rank a list of odour descriptors, according to like and dislike. This approach taps into the 'sensory memory' of the subjects, and their previous exposure, including the influences of context and associations, etc.

As reported in earlier Environment Agency research (Environment Agency 2002b), this approach has been applied more recently in Europe, using two groups of professional odour practitioners to rank 20 industrial and agricultural odours. The ranking order of the list was found to be remarkably consistent between the two groups. Table 6.2 shows the European and UK rankings extended to cover industrial odours. (This table appears as Table A1.1 in Appendix 1 of draft H4.) It should be noted that the latter study simply ranked[23] the different odours in order of their relative unpleasantness, and did not produce actual hedonic scores for individual odours. These European and UK data are strictly on rank order, and do not provide a comparative magnitude. They are not hedonic scores.

Earlier, in the USA, Dravnieks *et al.* (1984) measured the hedonic scores of generic, everyday (i.e. non-industrial) odours. These hedonic scores – also referred to as 'Dravnieks' in the US hedonic scores (Dravnieks) are shown, in order of decreasing level of unpleasantness, in Table 6.1. (This table appears as Table A10.2 in Appendix 10 of draft H4.) The US hedonic scores (Dravnieks) are also given in Table 6.2, where they are shown together with the UK and European ranking data. The ranking in this table, together with some expert opinion, was used in Appendix 6 of draft H4 as the basis for assigning different odours and industry types to the three categories[24] of relative offensiveness (unpleasantness) when using the Indicative Odour Exposure Standard.

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[23] Draft H4 states on page 30 that several hundred responses had been evaluated for the UK and European odour ranking study and that work was currently under way with a much larger group. However, the EA has advised that the study of community response to odours with a large group was never undertaken (private communication, Chris Sidle, EA, 19 May 2005).

[24] Using three unpleasantness bands to categorise the wide range of hedonic tones of different odours is, of course, a simplification. It may be that this is an oversimplification, and the approach needs to be refined, perhaps by using more categories or even hedonic scores. Whether this is worthwhile depends on the significance of this stage in the overall uncertainty of the H4 modelling assessment approach, and this is being considered as part of another project in this R&D Cluster. Alternatively, it may be appropriate to simplify the banding further: German research shows that the annoyance potential of unpleasant and neutral odours are similar, and differ only from pleasant odours (see Section 4.5.5).

Table 6.1 Hedonic scores based on American work (Dravnieks *et al*. 1984) (reproduced from Table A10.2 in draft H4)

Description	Hedonic Score	Description	Hedonic Score	Description	Hedonic Score
Cadaverous (dead animal)	-3.75	Fishy	-1.98	Wet paper	-0.94
Putrid, foul, decayed	-3.74	Musty, earthy, mouldy	-1.94	Medicinal	-0.89
Sewer odour	-3.68	Sooty	-1.69	Chalky	-0.85
Cat urine	-3.64	Cleaning fluid	-1.69	Varnish	-0.85
Faecal (like manure)	-3.36	Kerosene	-1.67	Nail polish remover	-0.81
Sickening (vomit)	-3.34	Blood, raw meat	-1.64	Paint	-0.75
Urine	-3.34	Chemical	-1.64	Turpentine (pine oil)	-0.73
Rancid	-3.15	Tar	-1.63	Kippery-smoked fish	-0.69
Burnt rubber	-3.01	Disinfectant, carbolic	-1.60	Fresh tobacco smoke	-0.66
Sour milk	-2.91	Ether, anaesthetic	-1.54	Sauerkraut	-0.60
Stale tobacco smoke	-2.83	Burn, smoky	-1.53	Camphor	-0.55
Fermented (rotten) fruit)	-2.76	Burnt paper	-1.47	Cardboard	-0.54
Dirty linen	-2.55	Oily, fatty	-1.41	Alcoholic	-0.47
Sweaty	-2.53	Bitter	-1.38	Crushed weeds	-0.21
Ammonia	-2.47	Creosote	-1.35	Garlic, onion	-0.17
Sulphurous	-2.45	Sour, vinegar	-1.26	Rope	-0.16
Sharp, pungent, acid	-2.34	Mothballs	-1.25	Beery	-0.14
Household gas	-2.30	Gasoline, solvent	-1.16	Burnt candle	-0.08
Wet wool, wet dog	-2.28	Animal	-1.13	Yeasty	-0.07
Mouse-like	-2.20	Seminal, sperm-like	-1.04	Dry, powdery	-0.07
Burnt milk	-2.19	New rubber	-0.96		
Stale	-2.04	Metallic	-0.94		
Description	**Hedonic Score**	**Description**	**Hedonic Score**	**Description**	**Hedonic Score**
Cork	0.19	Crushed grass	1.34	Maple syrup	2.26
Black pepper	0.19	Celery	1.36	Pear	2.26
Musky	0.21	Green pepper	1.39	Caramel	2.32
Raw potato	0.26	Tea leaves	1.40	Coffee	2.33
Eggy (fresh eggs)	0.45	Aromatic	1.41	Meaty (cooked, good)	2.34
Mushroom	0.52	Raisins	1.56	Melon	2.41
Beany	0.54	Cooked vegetables	1.58	Popcorn	2.47
Geranium leaves	0.57	Clove	1.67	Minty, peppermint	2.50
Grainy (as grain)	0.63	Nutty	1.92	Lemon	2.50
Dill	0.87	Coconut	1.93	Fragrant	2.52
Woody, resinous	0.94	Grapefruit	1.95	Fried chicken	2.53
Soapy	0.96	Perfumery	1.96	Cinnamon	2.54
Laurel leaves	0.97	Peanut butter	1.99	Cherry	2.55
Eucalyptus	0.99	Spicy	1.99	Vanilla	2.57
Molasses	1.00	Banana	2.00	Pineapple	2.59
Incense	1.01	Almond	2.01	Apple	2.61
Malty	1.05	Sweet	2.03	Peach	2.67
Caraway	1.06	Buttery, fresh butter	2.04	Violets	2.68
Soupy	1.13	Grape juice	2.07	Fruity, citrus	2.72
Bark, birch bark	1.18	Honey	2.08	Chocolate	2.78
Anise (liquorice)	1.21	Cedarwood	2.11	Floral	2.79
Oak wood, cognac	1.23	Herbal, green, cut grass	2.14	Orange	2.86
Seasoning (for meat)	1.27	Cologne	2.16	Strawberry	2.93
Leather	1.30	Fresh green vegetables	2.19	Rose	3.08
Raw cucumber	1.30	Fruity, other than citrus	2.23	Bakery (fresh bread)	3.53
Hay	1.31	Lavender	2.25		

Table 6.2 US, UK and Dutch data ranked according to hedonic score, for generic odours and environmental (industrial) odours (reproduced from Table A1.1 in draft H4)

Generic odours	Hedonic score Dravnieks, 1994	Ranking	Ranking	Ranking	Ranking	Ranking	Ranking	Environmental odours
Descriptor	**USA**	**UK median**	**UK mean**	**NL mean**	**NL mean**	**UK mean**	**UK Median**	**Descriptor**
Roses	3.08	4.0	4.4	3.4	1.7	2.5	1.0	Bread Factory
Coffee	2.33	3.0	4.5	4.6	4.6	3.9	2.0	Coffee Roaster
Cinnamon	2.54	4.0	4.9	6.0	5.1	4.6	3.0	Chocolate Factory
Mowed lawn	2.14	4.0	4.9	6.4	8.1	7.7	6.0	Beer Brewery
Orange	2.86	4.0	5.2	5.8	9.8	8.5	8.0	Fragrance and Flavour Factory
Hay	1.31	7.0	6.9	7.5	9.4	9.2	8.0	Charcoal Production
Soap	0.96	8.0	7.8	7.3	14	10.3	9.0	Green Fraction composting
Brandy		9.0	8.8	7.8	9.8	10.5	9.0	Fish smoking
Raisins	1.56	8.0	8.8	7.9	9.6	11	10.0	Frozen Chips production
Beer	0.14	9.0	9.5	9.3	9.8	11.3	11.0	Sugar Factory
Cork	0.19	10.0	10	10.5	9.8	11.7	12.0	Car Paint Shop
Peanut Butter	1.99	10.0	10.4	11.1	12.8	12.6	12.0	Livestock odours
Vinegar	-1.26	14.0	13.3	14.8	11.2	12.7	13.0	Asphalt
Wet Wool	-2.28	14.0	14	14.1	13.2	14.2	15.0	Livestock Feed Factory
Paint	-0.75	15.0	14	14.4	13.2	14.3	14.0	Oil Refinery
Sauerkraut	-0.6	15.0	14.6	12.8	8.3	14.4	15.0	Car Park Bldg
Cleaning Agent	-1.69	15.0	14.7	12.1	12.9	16.1	17.0	Wastewater Treatment
Sweat	-2.53	18.0	16.6	17.2	15.7	17.3	18.0	Fat and Grease Processing
Sour Milk	-2.91	19.0	18	17.5		17.7	10.0	Creamery/milk products
Cat's Pee	-3.64	19.0	18.8	19.4		17.7	19.0	Pet Food Manufacture
						17.8	18.0	Brickworks (burning rubber (applies to Fletton process)
					17.0	18.3	19.0	Slaughter House
					14.1	18.5	20.0	Landfill

6.2.3 Measurement of hedonic tone

Measurement of hedonic tone of source odour emissions

Section 6.2.2 showed how the descriptors of different odours could be simply ranked for unpleasantness. Laboratory measurements allow more quantitative values to be assigned. The hedonic tone of a source emission sample of odour is measured in the laboratory by a panel of trained assessors in an odour panel following the German method VDI 3882 Part 2 (VDI 1997b). Hedonic tone is scored on a nine-point scale ranging from very pleasant (score of +4, e.g. bakery smell) through neutral to highly unpleasant (score of -4, e.g. rotting flesh). Table 6.3 shows the scale from the German standard

VDI 3882 Part 2. To put these scores in context, Nimmermark (2004) explains that odour panellists should consider ‘extremely unpleasant’ as the most unpleasant odour they had ever experienced; and ‘extremely pleasant’ as the most pleasant odour they had ever experienced. *The Netherlands Emissions Guidelines for Air* (InfoMil 2004) point out that the score for a hedonic assessment is only valid for the odour concentration being presented. Also, because of the differences between the laboratory and ambient conditions of exposure (see Section 6.1), the hedonic tone score is likely to be only an approximation of a subject’s likes/dislikes under field conditions.

Table 6.3 Standard hedonic scale

Hedonic score	Description of relative pleasantness
-4	extremely unpleasant
-3	
-2	
-1	
0	neither unpleasant nor pleasant
1	
2	
3	
4	extremely pleasant

Considerable research (Hangartner and Muller 1989; Paduch *et al.* 1995; Winneke *et al.* 2004) has been carried out in Europe over the last 10 years to quantify the quality of an odour and to compare different odorants according to their hedonic tone. The test population required needs to be large because there are clear differences between test subjects, related to differing odour experiences, upbringing, and socio-economic status (Paduch *et al.* 1995). This contrasts with the smaller variation between people for the perception of odour intensity.

Measurement of hedonic tone of ambient odours

Recent German research (Sucker *et al.* 2004) describes how VDI 3882 Parts 1 and 2 were modified for *field* use for ambient measurements of odour intensity and hedonic tone. Trained assessors made measurements around various industrial installations using the same nine-point scale with values ranging from -4 (extremely unpleasant), through 0 (neither pleasant nor unpleasant, i.e. neutral), to +4 (extremely pleasant). It should be borne in mind, however, that outside of the laboratory, hedonic tone measurement can be subject to substantial variations between individuals. Field assessors need to be screened for normality of olfactory response. It also needs to be remembered that field conditions generally include some background odour and some combinations of odours that do not occur in laboratory testing.

6.3 Opportunities identified for strengthening Environment Agency guidance

A revised draft of H4 would benefit from making clear that the term *offensiveness* has two meanings. The revised guidance should use the term *relative unpleasantness* in place of *offensiveness* to avoid confusion. This would perhaps require the guidance to set a new precedent in describing the acronym for odour impact as the FIDUL factors.

Consideration should be given to measuring the hedonic scores for selected industrial odour types: the European and UK data given in draft H4 are strictly on rank order, and do not provide a comparative magnitude (i.e. they are not hedonic scores); the accompanying US data (Dravnieks) were obtained in the mid-1980s and laboratory odour analysis methodology has since developed a long way. Obtaining hedonic scores for selected industrial odour types would strengthen the basis for assigning different odours and industry types to the three categories of Indicative Odour Exposure Standard.

It would also be possible to try to add some understanding to the comparative magnitude of unpleasantness to the ranked odours described in H4. Samples of the odour or associated odorant would be assessed for hedonic tone to see if they remain in the same order as when the descriptors were ranked. Some candidate odours would be skatole for faecal, ammonia, kerosene, petrol, turpentine, allyl chloride for garlic/onion, eucalyptus, cloves, cologne, and limonene for lemon.

Whether these studies would be good value for the effort involved would depend upon:

- How the effort and expense in refining the banding allocation of the Indicative Odour Exposure Standard approach compares to the effort and expense in carrying out the preferred approach of obtaining UK, sector-specific dose-response relationships. On technical grounds, the latter is the preferred approach.
- How important the choice of unpleasantness band is for the outcome of an H4 modelling exercise compared to the uncertainties in other aspects of the study. For example, the choice of unpleasantness band will determine whether the Indicative Odour Exposure Standard is set at 1.5, 3.0 or 6.0 ou_E m^{-3}. It may be, however, that this choice is much less significant than the uncertainties in quantifying the source odour emission rate or in the atmospheric dispersion modelling. Another Environment Agency project (P4-120/2 Project 3, *Review of Dispersion Modelling for Odour Predictions*) is looking at this issue.

7 Developing odour modelling guideline values

7.1 The component parts of a numerical guideline for modelling odour

7.1.1 Typical form of odour modelling guideline values

There is little value in using atmospheric dispersion modelling to predict the concentrations of odour at various receptor sites unless these can be related to the occurrence of adverse effects, such as annoyance. An *odour modelling guideline* value is needed, against which the dispersion model results can be compared to judge whether significant adverse effects are likely to occur. An odour modelling guideline should ideally encompass all the FIDOL factors. In general, there are two types of numerical benchmark for modelling/monitoring:

Type 1 – Theoretical Odour Modelling Guidelines – these are based on theoretically derived odour annoyance thresholds with adjustments for site-specific factors. This type of guideline attempts to incorporate from first principles the FIDOL factors. In New Zealand and Australia it is called the ‘annoyance threshold approach’.

Type 2 – Empirical Odour Modelling Guidelines – the second type of numerical benchmark uses an odour guideline derived from the empirical dose-response relationship between:

- odour exposure – measured in the field, or (more usually) modelled from measured plant emissions;
- annoyance – measured by a community survey.

This epidemiological approach regards the intermediate processes largely as a ‘black box’, but does relate the dose and effect with sufficiently high correlation to allow an effective guideline value to be derived. This site-specific guideline can be used in other similar circumstances, if necessary by applying adjustment for site-specific factors. In New Zealand and Australia it is called the ‘community-response empirical approach’.

Dose is typically determined as odour exposure. This is arrived at from a measurement of the source odour emission rate, which is used with atmospheric dispersion modelling to predict the exposure at ground-level receptors. This exposure is usually expressed as a concentration that is exceeded with a particular probability for a particular averaging time, producing parameters to characterise dose such as a maximum 1-hour average concentration limit for the 98th percentile ($C_{98,\ 1\text{-hour}}$) as described in Section 7.2.2. So, despite the German fieldwork (Both and Koch 2004) suggesting that frequency is the overwhelming factor in determining annoyance and that intensity is not important, most numerical guidelines for modelling odour have tended to take both frequency and intensity (or more often concentration) into account. It is common for numerical odour guidelines to be set with a concentration component and a percentage compliance component: for example, 'Odour concentration shall not exceed X ou m^{-3} for more than Z% of the meteorological conditions'[25]. Odour modelling guidelines are sometimes worded 'odour concentration shall be less than X ou m^{-3} for more than (1 - Z)% of the meteorological conditions' (e.g. Z may be 0.5%, and (1 - Z) would be 99.5%). These two forms are effectively the same. Some odour modelling guidelines also take account of hedonic tone and location. In the following sections, these components of a modelling guideline are examined in more detail.

7.1.2 General limitations of modelling guidelines for odour

It is important to stress that even though such numerical odour guidelines express the concentration aspect in units of ou m^{-3}, this odour concentration cannot easily be measured directly in the field. It is *not* usually possible to use standard dynamic dilution olfactometry (DDO) to measure ambient concentrations of odours at the receptors themselves[26] and so these guidelines cannot usually be used for checking compliance by monitoring odour concentrations directly at receptors. The usefulness of ambient odour guidelines set in units of ou m^{-3} is limited to assessing the impact of odours *predicted* using computer dispersion modelling. The draft H4 guidance describes how computer dispersion modelling may be used to 'back-calculate' from notionally acceptable ground-level odour concentrations to find what upper limit could be placed on the emission rate of odour at source to prevent odour annoyance. Obviously, the approach of setting emission limit values (ELVs) as a tool for managing releases is suitable only for those releases that can be controlled, i.e. controlled emissions (usually point sources such as stacks and vents), and not for diffuse or fugitive emissions.[27]

It is important that the powerful tool of computer dispersion modelling is not misused. The New Zealand *Good Practice Guide* (Ministry for the

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[25] In practice, Z% of meteorological conditions is taken to mean Z% of 'the time', where the period of time covers a representative range of atmospheric dispersion (i.e. meteorological) conditions.

[26] Laboratory DDO is not suitable for determining odour concentrations in samples having less than about 50 ou m^{-3}, which usually precludes ambient measurements. Field olfactometry, using the 'Scentometer®' or 'Nasal Ranger®' can be used in some ambient situations, but the results are not directly comparable with those from laboratory-based DDO (see Section 4.5.3).

[27] By definition, fugitive releases cannot easily be captured or controlled by engineering methods that would allow regulation by means of setting upper emission limit values. Control of fugitive releases is usually by application of BAT and good management practice, such as an Odour Management Plan. Odour emissions from other diffuse sources (e.g. area sources such as lagoons or landfill surfaces) can be measured and modelled. However, this tends to be for the purpose of environmental impact assessment rather than management of odour emissions by setting ELVs.

Environment New Zealand 2003) considers that odour dispersion modelling *is* suitable for:

- new activities where the predominant odour effect is due to normal process discharges that are continuous or semi-continuous and reliable odour emissions data are available.

It also considers that odour dispersion modelling should *not* be used for:

- investigating potential acute effects of odour discharges; or
- trying to 'prove' the absence of an adverse effect when community data can be collected, or are available to demonstrate the current level of effect. In other words if, say, robust analysis of complaints data shows there is annoyance in a community, then this should be enough. It should not be necessary to prove or validate (or otherwise) the complaints by modelling. In fact, complaints can validate the model – where modelling has been carried out on an installation receiving complaints, the results can be expected to show an annoyance impact consistent with complaints. If they do not, the reasons should be investigated. Modelling can be used, however, in further investigating complaints in terms of directions and distances of the greatest complaints.

7.1.3 The percentage compliance component

The choice of averaging time for modelling of odours is important. Odours are noticeable over periods of a few seconds, whereas models generally simulate averages over longer periods of time such as 1 hour. There is a need to consider treatment of concentration fluctuations in models, i.e. specific realisations of concentrations which are higher or lower than the ensemble-average concentration generated by (most) models. Although this is not within the scope of the literature review here, such considerations are covered in a related Environment Agency report (2007) within this project cluster.

Different values for percentage compliance are in use around the world. There are a number of factors that influence the choice of value to be used. Figure 7.1 shows the example of a site where dispersion modelling has been used to predict the percentage of time (% hours in a representative year of meteorological data) that odours occur at a single receptor, given in the *Review of Odour Management in New Zealand* (Ministry for the Environment New Zealand 2002). For this site, 2 ou m^{-3} at 99.5% compliance was equivalent to 5 ou m^{-3} at 99.9% compliance, and represents the same degree of adverse effect (which could be, for example, annoyance or complaints).

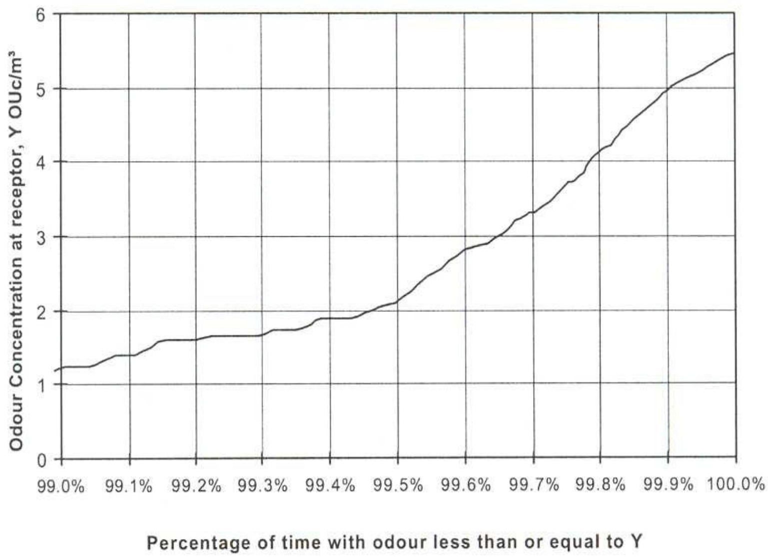

Figure 7.1 Example of percentage occurrence of odours at a single receptor (1-hour averaging time)

However, the New Zealand review points out that Dutch case studies reported by Miedema (1992) indicated that higher percentile concentrations were best correlated to odour annoyance when the emission source is active for less than 50% of the time. Therefore, for highly variable and intermittent sources the 99.9th percentile concentration may be a stronger determinant of odour annoyance than the 99.5th percentile. A 99.5th percentile concentration provides a useful indication of the potential for chronic adverse odour effects, whereas a 99.9th percentile concentration prediction would also provide some indication of the potential for acute (stronger short-term odour) impacts. More discussion on the importance of choice of averaging time for modelling of odours is to be given in another project (Project 3) of this Environment Agency report cluster. Project 3 includes discussion of the fact that odours are noticeable over periods of a few seconds, although models generally simulate averages over long periods of time, and consideration of the treatment of concentration fluctuations in models, i.e. specific realisations of concentrations which are higher or lower than the ensemble-average concentration generated by (most) models. These detailed modelling issues are outside the scope of this literature review of odour unpleasantness.

7.1.4 The concentration/intensity component

Generally, the source emission is quantified using odour concentration measurement. The odour concentration is, therefore, commonly used[28] as an

[28] As an alternative approach, modelling practitioners sometimes assign a value of unity to the release from a chimney stack, giving predicted ground-level concentrations as decimal fractions of the original emission. The inverse of these predicted ground-level concentrations represents the number of dilutions of the original source strength.

input parameter for modelling and the resulting prediction of the ground-level magnitude of odour will be in units of odour concentration (ou m^{-3}).

On the other hand, at the receptor itself, the odour magnitude is perceived in terms of intensity. Subjective measurements at the receptor for the purposes of regulation (e.g. using the ‘sniff test’) are usually made using an intensity scale.

It has been argued recently (Jiang 2004) that it would be better to use the odour intensity value in any numerical odour guideline, instead of concentration. This would allow compatibility of regulating the odour by odour dispersion modelling and direct field measurement. However, this is not commonly done except in Australia (see Section 7.2.3).

Figure 7.2 illustrates why this is an important issue. Consider, for example, the case where an odour source discharges odour at a concentration of 10,000 ou m^{-3}. This source emission concentration is as determined by olfactometry and it is important to remember that the initial concentration is not measured directly: the measurands are the ODT and the number of successive dilutions required to reach that threshold, i.e. the measurement endpoint is the ODT. The initial emission concentration is 10,000 times the ODT, but not 10,000 times the odour intensity at the receptor. If we take as the odour modelling guideline a limit value of 2 ou m^{-3}, the source emission concentration of 10,000 ou m^{-3} needs to be diluted 5000 times to achieve this guideline. Figure 7.2 shows that so long as the model predicts that there is adequate dispersion at the nearest critical receptor (point ‘A’ on Figure 7.2), the way in which the odour intensity reduces between the source and the receptor is irrelevant[29] – because there are no receptors in this portion of the graph. However, if the model predicts there is *not* sufficient dispersion at the nearest critical receptor (say at point ‘B’ on Figure 7.2), then the model’s predicted concentration could be considerably higher than the actual intensity of odour that would result (Freeman *et al.* 2000). This is because of the log-linear relationship.

[29] This assumes, of course, that any masking and synergistic relationships can be ignored.

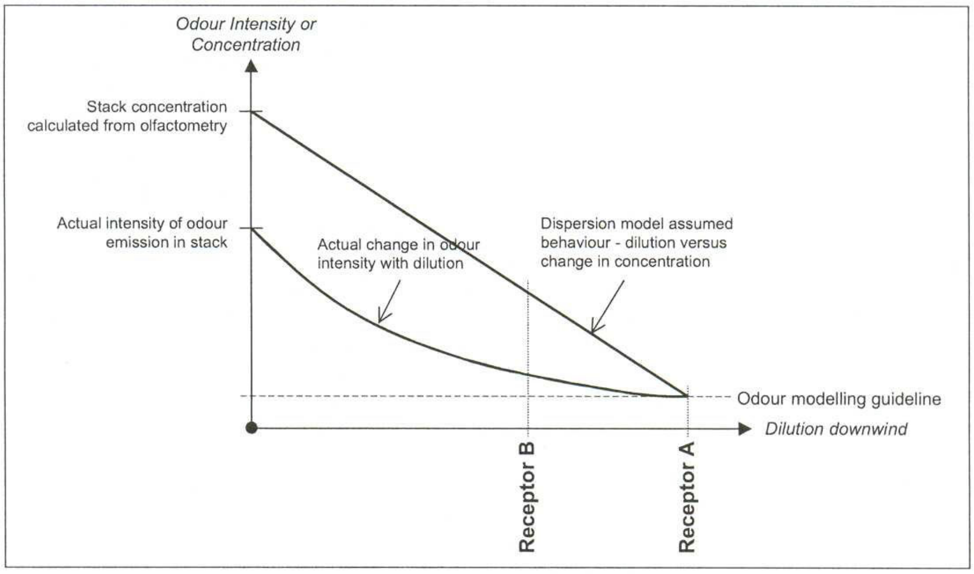

Figure 7.2 How a dispersion model treats odour dilution (Freeman *et al.* 2000)

It is useful to consider the odour concentrations of some typical perceived intensities. The New Zealand review (Ministry for the Environment New Zealand 2002) notes that for many (but not all) industrial odours a concentration of 5 ou m^{-3} would very approximately equate to a weak odour, but sufficient for the underlying character to be recognised. For industrial or agricultural odours to appear strong to people, concentrations of 30 ou m^{-3} or higher would most likely be necessary, and probably much higher in some cases. Within the range of 10–30 ou m^{-3} we can expect the perceived odour intensity to change from faint or weak to moderate, and possibly strong.

7.1.5 Odour perception and percentile concentrations

In an odour modelling guideline, the percentile compliance component indicates the allowable fraction of time above the concentration component. Generally, practitioners have used a 1-hour average value for this concentration component. Recommendations for percentile components in current use in New Zealand and Australia range from 0.1 to 1.0%, with the most common being 0.1 and 0.5%.

There is little convincing evidence to support the use of any particular percentile component. Other authors who cover this issue appear to have selected a certain percentile component and then varied the concentration component to match the odour modelling guideline with their particular model to their case study data. The New Zealand review (Ministry for the Environment New Zealand 2002) recommends that the baseline percentile for all guidelines be 0.5%, although 0.1% should also be used to assist in the evaluation of model results for highly and moderately sensitive receiving environments.

The percentage exceedance calculated by the model does not necessarily mean that odour nuisance would occur for all of those hours, for the following reasons:

- Model results give an hourly average, and the peak odour concentration will only occur for short times within that hour. When the model predicts that the odour annoyance threshold will occur, this means that for a few minutes during that hour a noticeable odour may occur. For the rest of the hour the actual odour concentration will be less than the peak concentration, and will not be noticeable.
- The model assumes that for each 1-hour period the wind direction is constant, with a small amount of deviation around the average direction. It therefore predicts that the same downwind receptor location will be affected for the whole hour. However, the wind direction can fluctuate widely within an hour, so the odour plume will not always be carried towards the same location.
- The dispersion model assumes that the estimated rate of odour emission from each source is constant from hour to hour. In reality this is not the case, as the emission rate can vary over time and, in the case of area sources (where these are modelled for environmental impact assessments), from one place to another over the surface of the odour source. The best way to be confident that the emission rate data for the model are typical for the source is to make a number of emission rate measurements over a period of time. The usual approach to modelling is then to use the mean of all the measurements as the typical emission rate in the model. However, because the rate of odour emission will sometimes be lower than the average, the model prediction tends to overestimate the number of exceedances of the guideline.

From Section 7.1.4 it might be thought that there is very little difference between the perception of an odour at a concentration of 5 ou m^{-3} versus one of 8 ou m^{-3}. However, when these concentrations are described as percentile concentrations, the difference is more significant. This can be appreciated when considering what a 99.5th or 99.9th percentile concentration means.

When specifying guideline concentrations as either 99.5th or 99.9th percentiles, the relevance of 5 ou m^{-3}or 8 ou m^{-3} is not the perceived strength, but the frequency with which stronger odour impacts are likely to occur over the set time implied by these percentile concentrations. For example, a 99.5th percentile concentration of 5 ou m^{-3} indicates that the hourly average of this concentration is reached or exceeded for 0.5% of the time. This implies that there are about 44 hours per year during which the 1-hour average concentration exceeds 5 ou m^{-3}. Although a concentration of 5 ou m^{-3} may be equivalent to only faint or mild in intensity, it must be stressed that there will be many more than 44 hours per year during which there are short-term (e.g. 10-second duration) episodes with concentrations exceeding 5 ou m^{-3}. These episodes are likely to contribute to annoyance and possibly complaints. The upshot of this is that it is not correct to assume that compliance to an annoyance criterion set as a 99.5th percentile will only lead to people being annoyed for 44 hours per year.

Similarly, although a 99.9th percentile concentration standard of 10 ou m^{-3} indicates that odours would exceed 10 ou m^{-3} as a 1-hour average for only 0.1% of the time (about 9 hours per year), there will be many more than 9 hours per year during which there are short-term (e.g. 10-second duration) episodes with concentrations exceeding this. As 10 ou m^{-3} may be equivalent to moderate to strong intensity, there is a good chance these episodes will contribute to annoyance and complaints.

7.1.6 Accounting for odour unpleasantness in modelling guidelines

Earlier Environment Agency research (Environment Agency 2002b) compared odour unpleasantness rankings with odour exposure criteria that had been set for specific industries in the Netherlands. The ranking was, to a reasonable degree, reflected in the agreed air quality criteria. The point was made that these exposure criteria are only partly based on epidemiological data and in fact they are the expression of a consensus between the regulatory agency and industry on the relative odour annoyance potential of these odours. The interpretation put on this was that it is necessary to take into account some measure of the odour's annoyance potential when considering the impact on a residential population.

It was proposed that a method be developed in the future for characterising and measuring odour 'annoyance potential' – the attribute of a specific odour (single compound or mixture of odorants) to cause a negative appraisal in humans that requires coping behaviour when perceived in the living environment. Annoyance potential is likely to be a function of both hedonic tone and odour quality/character in addition to perceived intensity. See also Table 4.1 for a definition of annoyance potential.

Even though the methodology had not yet been developed to allow the annoyance potential of an odour to be expressed in quantitative terms, the authors stated that it could nevertheless be demonstrated from available data that for most odours the differences based on perceived impact were limited to a factor 5 (equating to 7 dB_{od}) in terms of exposure expressed as the 98th percentile 1-hour concentration ($C_{98,\ 1\text{-hour}}$). It was concluded that, given the magnitude of these differences on the impact, a unified air quality criterion for all odours alike could not be justified and some mechanism should be included to account for differences in odour annoyance potential.

The Environment Agency's draft H4 guidance describes how such differences in relative unpleasantness of odours are currently accounted for in the Indicative Odour Exposure Standard. The basis for this is described in Section 7.2.2.

7.2 Approaches to deriving and setting odour guidelines

7.2.1 Development of odour modelling guidelines in Europe

Earlier Environment Agency research (Environment Agency 2002b) reviewed in detail the development of odour policy in other countries, including those European states using advanced forms of numerical odour guidelines such as the Netherlands, Germany, Belgium and Denmark, as well as Australia, New Zealand, Japan and the USA. This is covered here only where it provides further background on how odour unpleasantness has been dealt with.

Van Harreveld (2003) describes how the Netherlands pioneered in Europe the use of quantitative criteria for assessing acceptable exposure to odours, based on DDO measurement of source emissions of odour, dispersion modelling to define exposure, and the derivation from dose-response studies of numerical exposure criteria. The first quantitative odour guideline value for industrial sources was introduced in 1984, based on a percentile value of 1-hour average odour concentrations. This was modified in 1995 to allow for differences in unpleasantness and has been formalised in the Netherlands Emission Guidelines of 2004. The approach in the Netherlands was typical of the trend in other Northern European countries, such as Germany and Denmark. French regulations use a 5 ou_E m^{-3} (1-hour average) limit as a 98th percentile or 99.5th percentile for existing and new sites, respectively (Senate *et al.* 2004). Flemish odour standards are set as 1-hour concentrations at the 98th percentile (Van Elst and Van Broeck 2004). More recently, Belgium has started to develop a framework for managing environmental odours, and the Irish Environmental Protection Agency has moved to define criteria for specific industrial sectors, such as livestock (pig) production and mushroom growing.

A sophisticated new assessment parameter has been proposed in Denmark (Lofstrom 2004) which recognises that short and tall stacks complying with the same 1-hour maximum concentration limit, as a percentile, will probably result in different odour annoyance experienced at receptors. Since different types of sources observing the same limit value could result in different concentration frequencies around the limit values. This is because the critical meteorological conditions occur more often for low stacks than for tall stacks, leading to more short-term fluctuations above the detection threshold concentration. It is proposed that a new single unifying assessment parameter is used that accumulates all odour concentrations above the odour threshold and weights the frequency of the individual odour concentrations with the intensity (which is proportional to the log concentration).

7.2.2 The basis of the Environment Agency's draft H4 Indicative Odour Exposure Criteria for England and Wales

Earlier Environment Agency research (Environment Agency 2002b) concluded that a full deterministic model of all the factors affecting the occurrence of nuisance was not yet within reach and theoretical attempts to incorporate from first principles the FIDOL factors into numerical benchmarks for modelling/monitoring were typically too simplistic to be effective. As is the case for noise, regulatory practice for odours was thought to require a straightforward, practical approach, not necessarily involving all concepts and refinements. The Environment Agency research favoured the second type of numerical benchmark, derived from the empirical relationship between cause and effect, i.e. odour exposure and community annoyance. Accordingly, in its draft Technical Guidance Note H4, the Environment Agency followed the Netherlands approach of setting quantitative criteria for assessing acceptable exposure to odours, based on quantitative measurement (by DDO) of source emissions of odour, dispersion modelling to define exposure, and the derivation from dose-response studies of numerical exposure criteria. The 'default' exposure criteria[30] in draft H4 are termed Indicative Odour Exposure Criteria. These are set as a 98th percentile, 1-hour average concentration ($C_{98,\ 1\text{-hour}}$) of 1.5, 3.0 or 6.0 $ou_E\ m^{-3}$ for high, medium and low categories of odour unpleasantness, respectively. The proper assignment of different industrial odour mixtures to one of the three bands or categories of unpleasantness is the main driver for this research project, so it is helpful to look at them in more detail at the background to the Indicative Odour Exposure Standards. Although this current research project is not focused on the precise $C_{98,\ 1\text{-hour}}$ levels attached to each band, an appreciation of the basis of these bands is nevertheless helpful.

Van Harreveld (2004) describes how the draft H4 odour exposure benchmarks for mixed odorants were determined. The main background work for H4 was carried out in the Environment Agency research review (Environment Agency 2002b) on community impacts of odour, where a large variety of odour benchmark exposure values and regulatory criteria were identified. The review also considered epidemiological data (Miedma *et al.* 2000) obtained using a well-established VDI methodology (VDI 1997c). The dataset that formed the main underpinning for the proposed values was collected in the Netherlands for livestock odours (Bonger *et al.* 2001) as specific data for the UK were not available.[31] (This dataset was also used by the Irish EPA as a starting point to derive odour exposure criteria for livestock odours.) In brief, odour emissions from a piggery were measured at source by olfactometry, then modelled to predict the surrounding ground-level concentrations ($C_{98,\ 1\text{-hour}}$). Zones of distinct odour exposure levels were identified and the percentage of people annoyed in each zone was estimated using questionnaires and a random sample of addresses falling in each zone. The percentage of 'annoyed' respondents in the sample was then plotted against the exposure band to establish a dose-effect relationship for livestock odours. Regression fitting an S-shaped curve showed a strong correlation ($r>0.9$) between modelled exposure and annoyance. A level of 10% annoyed

[30] Draft H4 also invites industry sectors to establish their own, UK-specific, dose-effect curves to enable bespoke odour exposure criteria to be derived.

[31] The EA research noted that, ideally, the dose-effect relationship for UK citizens in UK conditions should be assessed experimentally to confirm the findings obtained abroad, but as of date this has not been carried out.

was chosen as the lowest level that would be statistically significant, based on the 'background noise' for measurement of annoyance using questionnaires plus two times the standard deviation of the annoyance measurement.

For the general public, the level of 10% annoyance to pig odours correlated with an exposure ($C_{98,\ 1\text{-hour}}$) of 1.3 $ou_E\ m^{-3}$ and this was used for the basis of the most stringent draft H4 indicative criteria, for high offensiveness (i.e. unpleasant) odours of 1.5 $ou_E\ m^{-3}$.

The earlier Environment Agency research considered that it would be preferable to use the measurement of annoyance potential to characterise odour emissions, rather than using odour concentration ($ou_E\ m^{-3}$), for input to the dispersion modelling and comparison with the percent annoyed respondents to establish a dose-effect relationship. This would allow the true effect of hedonic tone, unpleasantness and odour character to be included in the relationship for different types of odour. However, a laboratory method for measuring annoyance potential had not then been developed, so it was proposed that existing rank-order data for industrial odours as shown in Table 6.2 should be the basis for assigning different odour types into a simple three-band categorisation:

- High odour annoyance potential (e.g. animal rendering, fat and grease processing).
- Medium odour annoyance potential – all odours not in categories High or Low.
- Low odour annoyance potential (e.g. bakeries, coffee roaster).

The particular numerical guidelines that were assigned in draft H4 to the indicative criteria for odours of medium unpleasantness and odours of low unpleasantness were arrived at as follows:

For residents in areas where pig odours were a common feature, the 10% annoyed level corresponded to an exposure of ($C_{98,\ 1\text{-hour}}$) of 3.2 $ou_E\ m^{-3}$ and this value was used for the basis of the draft H4 Indicative Odour Exposure Standard for mildly unpleasant odours of 3.0 $ou_E\ m^{-3}$. The most lenient draft H4 Indicative Odour Exposure Standard of 6 $ou_E\ m^{-3}$, assigned to 'less offensive' odours, was based on 10% annoyed of respondents who worked in agriculture (corresponding to 13 $ou_E\ m^{-3}$) combined with data from a dozen dose-effect studies for industrial sectors in the Netherlands (Miedma *et al.* 2000) where the 10% annoyed level corresponded with approximately $<5\ ou_E\ m^{-3}$. In addition, inspection of a number of consultancy projects indicated that between 90 and 95% of complaints registered for wastewater treatment and solid waste management occurred in the exposure range of 5–10 $ou_E\ m^{-3}$.

As is obvious from the summary of the Indicative Odour Exposure Standards in Table 7.1, it was necessary to make a number of assumptions on the applicability of the research data to conditions in the UK and to industries other than intensive livestock.

Table 7.1 How the Indicative Odour Exposure Standards relate to the Dutch study results

Results of Dutch livestock dose-response study		**Indicative Odour Exposure Criteria for draft H4 inferred from these results**
1.3 ou_E m^{-3} was equivalent to 10% annoyance of general public to pig odours	→	1.5 ou_E m^{-3} chosen as limit for industry sectors with odours considered 'more offensive'
3.2 ou_E m^{-3} was equivalent to 10% annoyance of residents to pig odours in areas where pig odours were a common feature	→	3 ou_E m^{-3} chosen as limit for industry sectors with odours considered 'mildly offensive'
13 ou_E m^{-3} was equivalent to 10% annoyance to pig odours of respondents who worked in agriculture, combined with data from a dozen dose-effect studies for industrial sectors in the Netherlands	→	6 ou_E m^{-3} chosen as limit for industry sectors with odours considered 'less offensive'

Although the study used piggery odours to establish the benchmark for the most offensive, draft H4 assigns livestock to the 'mildly unpleasant' band. Further discussion on this is contained in Section 8.3.7.

The draft H4 guidance does state that the above benchmarks are indicative standards and that UK dose-effect studies are planned. It also states elsewhere in the document that 'the only realistic way of estimating the actual level of annoyance in a particular community resulting from exposure is by carrying out dose-response studies locally'. However, draft H4 appears much less explicit than the New Zealand guidance in highlighting the 'interim' nature of these generic-type odour guidelines and that they should ideally be superseded by industry-specific guidelines developed from bespoke dose-response studies. It is possible that some dose-response studies will be performed around waste management facilities as part of a study into defining loss of amenity though odour carried out as part of Defra's Waste Research R&D programme.[32] There is also a possibility of UK Water Industry Research (UKWIR) coordinating some studies around wastewater treatment plants to support the water industry in meeting the Defra Code of Practice on Odour Nuisance from Sewage Treatment Works.

Regarding the use of Dutch livestock dose-response studies as a basis for the draft H4 indicative exposure criteria, the level of annoyance measured by the survey in the New Zealand Technical Report (Ministry for the Environment New Zealand 2002) was found to be consistent with the odour dose-community-response curves reported by Miedema (1992). The dose-response curves, although developed for other industries and using a Dutch community response, appeared to be valid for pulp mill odours in New Zealand.

[32] Details at http://www.defra.gov.uk/environment/waste/wip/research/index.htm

7.2.3 Development of odour modelling guidelines in New Zealand and Australia

The two approaches used in New Zealand

Because it is not always possible to conduct empirical case-study-style research to derive bespoke guidelines, a practical and conservative approach was needed. Theoretical odour modelling guidelines based on the odour annoyance threshold approach (refer Section 7.1.1) offered a relatively fast and inexpensive approach to providing odour modelling guideline values. A review of odour management in New Zealand (Ministry for the Environment New Zealand 2002) showed that this theoretically derived odour annoyance thresholds approach had been used by practitioners from the mid-1990s. It was used firstly to develop a design odour modelling criterion for a wastewater treatment plant, then later adopted by the Auckland Regional Council as an interim standard for both new and existing odour assessments within that region (Freeman *et al.* 2000). Very similar criteria were also used in other regions of New Zealand, and this approach was also widely used in Australia. It led to a 'default' concentration component of 2 ou m^{-3}, and provided the basis for the interim criteria that were recommended as New Zealand's first national odour concentration guideline values for all types of odour sources. The default guideline could be adjusted for the sensitivity of the receiving environment and (in some cases) the 'offensiveness' of the odour. (The details of how this was done are given in Chapter 8.)

This odour annoyance threshold resulted from an essentially theory-based analysis of odour definitions from first principles. Examples of published odour detection and recognition data are shown in Table 9.1 (Section 9.4). These show the relationship between the *detection threshold* (the concentration at which the odorant is detected with certainty by an olfactometry panel) and the *recognition threshold* (the concentration at which the character and hedonic tone of the odorant is recognisable). In theory, a single odorant detected in ambient air will not cause nuisance until it is present at a concentration that is at the recognition threshold or higher. For the range of odorants considered (see Table 9.1), the ratio between the two thresholds varies considerably, between 1 (no difference between the thresholds) and 50 (large difference). The typical ratio is in the range of two to ten. However, many odours occurring in ambient air are mixtures of odorants, and the detection and recognition thresholds can change markedly from these levels if several odorants are present in a mixture and act synergistically to produce either a greater or lesser-perceived odour strength than their individual components. Therefore, to allow for those members of the community with greater sensitivity to odours, this approach has made the conservative, pessimistic assumption that the recognition threshold would equate to the annoyance threshold concentration. For the data considered in Table 9.1, then this puts the annoyance threshold as two to ten times the detection threshold. To be conservative and to ensure that most circumstances are covered, a value towards the lower end of this range, 2 ou m^{-3}, should be used as the annoyance threshold (Ministry for the Environment New Zealand 2002).

Despite the advantages of speed and cheapness, there are various limitations with the theoretical annoyance threshold approach, two of which are as follows:

a) It is difficult at present to adequately take account of the odour unpleasantness in a theoretically derived odour annoyance threshold value. While the hedonic tone measurements described in Section 6.2.3 give an indication of the unpleasantness of an odour relative to other odours in a laboratory situation, these values cannot at this stage be readily extrapolated to predict population annoyance to odours. Firstly, the applicability of laboratory-based hedonic tone tests to the real environment has yet to be confirmed. In addition, a person in a panel taking part in a laboratory-based olfactometer test is likely to be more sensitive to odours than in the real environment because they are concentrating on detecting the odours and are isolated from normal, background odours (Ministry for the Environment New Zealand 2002). This factor has the potential to lead to a conservative guideline.

b) The theoretical annoyance threshold approach represents a highly simplified mechanism for how nuisance occurs in many cases. A 1-hour period with an average concentration of 2 ou m^{-3} could have instantaneous concentrations at or below this for 50% of that hour (1800 seconds) and at or above it for the other half of the time. Some of these short-term odour excursions may have the potential to cause adverse effects such as annoyance and complaints. This factor means the guideline is not particularly conservative.

It is perhaps because the above two factors may offset each other to some extent that the theoretical annoyance threshold approach produced modelling guidelines that were at least consistent with the findings of various case studies using the empirical community response survey approach. Odour modelling guidelines obtained by the theoretical annoyance threshold approach have been adopted in New Zealand as interim guideline values, and it is made clear that they should be used only until alternative industry-specific guidelines become available from empirical dose-response research.

The alternative empirical approach, utilising modelling and community survey data to develop a bespoke dose-response relationship and industry-specific guidelines, was expected over time to replace the interim criteria. Empirical dose-response studies were considered more difficult and expensive to implement, but the approach was considered more robust if implemented appropriately (Ministry for the Environment New Zealand 2002).

The empirical dose-response approach was considered to have some important advantages:

a) it takes account of the real effects and interactions of multiple physical and social factors;

b) it tended to produce higher modelling guideline values (i.e. less stringent) than those derived by the annoyance threshold approach, particularly for odour sources that were related to sewage treatment.

However, such community dose-response studies do require a definable odour source and an existing community with sufficient population density to represent a suitable case study. They also require considerable resources to undertake successfully and in New Zealand this is generally expected to require industry sector and/or government support. Nevertheless, the use of population annoyance indicators as a basis for setting assessment standards was considered in New Zealand to represent best practice for managing odours in an effects-based way. Empirical dose-response studies relating modelled exposures to community responses involving real case studies was considered the only robust method for either validating the interim odour modelling guidelines or revising them in the future.

So far, the New Zealand approach is consistent with the Dutch-based approach used to derive the draft H4 Indicative Odour Exposure Criteria (although in New Zealand an annoyance level of 20% is used instead of 10%). However, the New Zealand approach has a further stage that allows for differences in the tolerance of a community to a new compared to an existing odour. In the community response-based studies, an odour modelling guideline is determined for a particular site based on population annoyance data, and therefore is based on the tolerance of an existing community to an existing industrial or trade activity. The tolerance of an *existing* community to a *new* industrial or trade activity, or increased odour emissions from an existing activity, would be expected to be lower. Therefore, a tolerance factor was applied to reduce (i.e. make more stringent) the odour modelling guideline determined by community response-based studies. This tolerance factor represents the lower tolerance of existing communities to new sources of odour. Based on case studies, the tolerance factor was estimated at approximately 2 to 5.

The review concluded that if the use of such a tolerance factor was accepted, there was little difference[33] between the interim odour modelling guidelines and those derived from the case studies. Accordingly, the Ministry for the Environment New Zealand recommended (2002) the odour modelling guideline values summarised in Table 7.2, which were based on the two approaches: the annoyance threshold method and the dose-response method. The New Zealand Ministry for the Environment will update the modelling guideline values as necessary when more empirical research of the effects of odours on communities emerges from odour dose-response studies (Ministry for the Environment New Zealand 2003).

[33] The exception remained the question about the interpretation of peak-to-mean ratios for tall stacks, for which further investigation and research was recommended.

Table 7.2 Recommended interim odour modelling guideline values for New Zealand (Ministry for the Environment New Zealand 2003)

Sensitivity of the receiving environment	Concentration (ou m^{-3})	Percentile of 1-hour average concentrations
High (worst-case impacts during unstable to semi-unstable conditions)	1	0.1% and 0.5%
High (worst-case impacts during neutral to stable conditions)	2	0.1% and 0.5%
Moderate (all conditions)	5	0.1% and 0.5%
Low (all conditions)	5–10	0.5%

Note that:

- atmospheric stability has been accounted for in high-sensitivity receiving environments (stability refers to the degree of mixing that occurs);
- the percentile allows for a small level of exceedance of the predictions, to account for worst-case meteorological conditions, at which objectionable odours are unlikely because the conditions occur infrequently;
- the 'baseline' percentile is 0.5%, although 0.1% will also be used to assist in the evaluation of model results depending on the type of source and consistency of emission data; further discussion of percentile selection is given in the Technical Report (Ministry for the Environment 2002c);
- the concentration components in the table already include the peak-to-mean ratio adjustment for all source types, and should be used as design ground-level concentrations for 1-hour modelling averages.

The approach in Australia

In Australia, the frequency, intensity, duration and location are considered quantifiable enough to be built into a regulatory guideline. However, the *Odour Methodology Guideline* (Department of Environmental Protection, Western Australia 2002) considered hedonic tone and odour character to be too subjective and difficult to quantify to be used within a regulatory framework at that time.

The use of odour intensity instead of concentration is an advanced feature of the Australian approach to modelling odour impact. Guidance from Western Australian EPA (Department of Environmental Protection, Western Australia 2002) requires the applicant to undertake both odour threshold and intensity analyses. Once the odour intensity–concentration data are available, the Weber–Fechner Law[34] (see Section 5.3.2) is used to develop the

[34] The Weber–Fechner Law was chosen over Stevens' Law because it is simpler to derive from experimental data and it is also described in the German Standard with a worked example.

mathematical relationship between intensity and concentration. This relationship is then solved for the odorant concentration that corresponds to an appropriate intensity criterion. For example, the Western Australian EPA suggests an intensity of 3 (‘distinct’) for use as the comparative criterion for new proposals. The guidance shows the relationship between odour intensity and concentration for poultry odour, with samples taken from poultry sheds under various conditions. An intensity of 3 (distinct) corresponded to 7.0 ou m^{-3}. The emissions are modelled and the 7.0 ou m^{-3} concentration (3-minute average, 99.5 percentile) contour is used to define the minimum separation distance between poultry farms and sensitive land uses.

7.3 Guidelines for dealing with multiple sources of differing unpleasantness

7.3.1 The limitations of dispersion models in dealing with multiple sources

The situation becomes complex when there are multiple sources on an industrial site. The different sources may have very different character and unpleasantness. The New Zealand Technical Background Report considers two extreme examples of odour sources on a site: a single-stack discharge from a small, fully enclosed factory, and a multitude of discharges from, for example, a wastewater treatment plant, large industrial site, or landfill. The single-stack source would be easy to quantify, and would be of consistent hedonic tone. The detection and recognition thresholds of the odour or its components could be readily measured, and an odour modelling guideline customised for that particular discharge. In the second example, odours would be discharged from a number of different activities carried out on the site, such as those listed in Table 7.3. Each of the individual sources is a mixture of chemical constituents, and the mixture may be different for each source. Therefore, each source can contribute different unpleasantness weightings to the total odour impact, and may even have a totally different character. In a wastewater treatment plant, for example, discharges from earth filters are described as ‘earthy/musty/organic’, discharges from primary effluent as ‘sulphur/sewage/rotten eggs’, and discharges from biogas combustion engines as ‘chemical/gas/smoke’. Another example is a meat rendering works, where the biofilters emit an odour that is much less unpleasant than the meat cooker (Ministry for the Environment New Zealand 2002).

Table 7.3 Examples of multiple odour sources (Ministry for the Environment New Zealand 2002)

Possible sources of odour at a wastewater treatment plant	Possible sources of odour at a landfill	Possible sources of odour at a large industrial site
•inlet works • screening facilities • pre-aeration and grit removal tanks • primary sedimentation tanks • secondary aeration and sedimentation tanks • flow-splitting structures • final discharge structures • screenings and grit dewatering and reception bins • sludge treatment and dewatering • biogas combustion engines/generators • odour treatment (e.g. biofilters/scrubbers)	•waste reception facilities and trucks • landfill gas diffusing through capped refuse, or evolved when covered refuse is opened • open work faces • landfill gas flares • leachate treatment and disposal	•raw material reception • stack discharges from process equipment • discharges of building ventilation air (could be from open doors, roofline ridge vents, or stacks) • fugitive releases from leaks in process equipment, doorways left open, truck loading, etc. • boiler stacks • odour treatment equipment

A further complication comes from the way atmospheric dispersion models generally assume that the mass of pollutants is conserved as dispersion/dilution takes place, i.e. the mass of pollutants is not affected by chemical reaction in the atmosphere. Although some models can allow for some simple chemical reactions (e.g. $NO \rightarrow NO_2$), none can deal fully with the complexities of odour mixtures.

The New Zealand Technical Report (Ministry for the Environment New Zealand 2002) describes the problem. When odour is modelled, it is treated as a single pure substance rather than a cocktail of different odorous chemicals. Where there are two odour sources, each emitting an odorous gas mixture, the model assumes the resulting odour concentration (or intensity) that is modelled is equal to the sum of the odour concentrations (or intensities) of the two mixtures. In other words, if Source A causes a concentration of X_A ou m^{-3} at a certain downwind receptor, and Source B (emitting a mixture made up of a combination of chemical constituents) causes a concentration of X_B ou m^{-3} at the same receptor in the same wind conditions, then the model assumes that the combined downwind odour concentration at that receptor from these two sources will be $X_A + X_B$ ou m^{-3}.

Take, as an example, a person downwind of a wastewater treatment plant who smells an odour mixture from the sludge lagoons. If an additional odour source from primary sedimentation tanks (which is an odour made up of different chemical compounds) is then introduced, the model assumes that the odour intensity noticed by the person downwind would increase by the same amount as if the primary sedimentation tanks were being sniffed on their own. It also assumes that the odorous events due to the two sources occur at exactly the same moments in time, which will probably not be the case.

However, odours are not in reality additive, nor does the intensity vary linearly with concentration. The mathematical functions that describe the relationship between concentration and intensity, and masking and synergistic effects, are complex and vary for each mixture of odorants. It is not possible with current dispersion models to account fully for these factors.

7.3.2 An approach for dealing with multiple sources of odour

Where there are different odour sources, a decision must first be made as to whether one odour will provide significant masking of the other odorants in question, or whether they are more likely to impact during different times and conditions. If two odour sources have impacts that overlap at some locations and some times, it is most likely that only one source will dominate and that the effects will not be additive, unless they are of a very similar nature and character (e.g. two piggeries). If, however, the two different sources impact at a specific location during different wind conditions, then their cumulative effects on the percentile odour concentrations will most likely be additive.

The degree to which this masking or additive behaviour occurs depends on the type and strength of the odours, whether the odorants are similar types of chemical species, the intensity of the odorants, and how the individual chemical species in the odours react together. If one odorant contains the same key chemical species as another odour, then the degree of masking could be quite significant. On the other hand, if the other odorant is of quite different character, then the background odour could have little effect as a masking agent.

The New Zealand Technical Report (Ministry for the Environment New Zealand 2002) considers two options to moderate the effect of a model's over-prediction caused by odour masking:

i) Where the odour discharges on a site can be classified according to their offensiveness as, say, 'very offensive' and 'slightly annoying' categories, the 'very offensive' sources are likely to dominate the 'slightly annoying' sources unless the latter group has a very high predicted downwind concentration relative to the other group. Therefore, the groups of sources can be modelled separately.

ii) Where a small number of sources on a site are of much lower offensiveness than the others (e.g. a biofilter on a rendering plant), then the odour emission rate determined for that source (or those sources) could be corrected downwards by dividing the source's emission rate by suitable factors.

Alternatively, depending on the complexity of the situation, it may be just as appropriate to model all the sources together, and to bear in mind that the model is likely to have over-predicted the downwind odour concentrations (because the diluted odour mixture will be dominated by the more offensive components in the mixture, which mask the less offensive components) when interpreting the model results.
Currently, for cases where there is more than one distinct odour released from an installation, the draft H4 guidance recommends that the highest

unpleasantness category of the odours present should be used to select the Indicative Odour Exposure Standard.

7.4 Opportunities identified for strengthening Environment Agency guidance

The Indicative Odour Exposure Standards in the current draft of H4 were derived from a dose-response study of a Dutch piggery using an older style atmospheric dispersion model. Although this response curve was found by researchers in New Zealand to be valid for a pulp mill there, in order to strengthen a revised H4 guidance more robust and relevant UK dose-response work should be made a priority. It should be noted that this was a key recommendation in the earlier Environment Agency research (Environment Agency 2002b) that formed the backdrop to the draft H4.

The most robust and relevant approach would be for representative sector-specific dose-response studies to be carried out in the UK, to derive bespoke odour modelling standards for those industries. Experiences in other countries have suggested that these usually require industry-sector-wide support and/or government support. As well as promoting and supporting such studies itself, the Environment Agency should forge links with other interested parties: it is possible that some dose-response studies will be performed around waste management facilities as part of Defra's Waste Research R&D programme. There is also a possibility of UK Water Industry Research (UKWIR) coordinating some studies around wastewater treatment plants to support the water industry in meeting the Defra Code of Practice on Odour Nuisance from Sewage Treatment Works. Regulators in other countries (particularly Australia and New Zealand) have issued odour guidance strongly encouraging industries to carry out sector-specific dose-response studies. Forging links with these regulators could allow valuable data to be obtained that have not otherwise been published.

The wording and the prominence of such wording in any revised H4 guidance should make it clear that sector-specific dose-response studies are the best practice approach, but Indicative Odour Exposure Standards based on non-sector specific studies are acceptable in the interim period, until the sector-specific studies have been performed. However, even such interim non-sector specific studies need to be robust, and there are opportunities for improving and refining the interim Indicative Odour Exposure Standard approach:

- It is recommended that one carefully selected study is carried out as soon as possible in the UK, using the EN 13725 olfactometry method and a currently accepted dispersion model. The application of annoyance guidelines from this study to other industry sectors would require consideration of how to deal with sources of differing unpleasantness and multiple sources. One option would be to continue with the existing draft H4 approach of putting different sectors/activities into a number (currently three) of different bands, having Indicative Odour Exposure Standards with different concentration limits to account for the varying unpleasantness. Practical research on hedonic scores for selected industrial odours would help refine this approach.

- The Environment Agency should also investigate what progress has been made on determining odour annoyance potentials.
- Other possible improvements to a revised version of H4 would be to improve on the guidance for dealing with multiple sources, and the New Zealand guidance offers a possible route. A revised version of H4 could also strengthen its guidance on taking account of site-specific factors in setting an Indicative Odour Exposure Standard. The New Zealand guidance offers an interesting approach on applying a tolerance factor for new odours in an area, and on categorising the sensitivity of an area.

It is recognised that there are limits on resources for such studies and careful consideration needs to be given as to how much should be invested in refining the interim Indicative Odour Exposure Standards approach as against investing in the preferred representative sector-specific dose-response studies to be carried out in the UK, to derive bespoke odour modelling standards for those industries.

8 Further investigation of odour unpleasantness of mixtures

8.1 Background to recent work on odour unpleasantness

Consideration of the hedonic tone is important when interpreting dispersion modelling results, particularly when assessing the effectiveness of odour abatement processes such as biofilters and scrubbers. The quality of an odour is changed by most odour abatement procedures, and the resulting odour can be more pleasant, or less pleasant, than the original crude gas. For example, a gas passing through a soil and bark biofilter medium picks up the character of the soil and bark. Not only does this cause a change in the character of the exit gas from the biofilter but it also (usually) causes a change in the relative unpleasantness compared to the upstream (unabated) gas. Although the biofilter reduces the odour concentration – the usual measure of abatement efficiency – it reduces the annoyance potential (see Section 7.1.6) to an even greater extent. For any abatement system, the 'real' abatement efficiency may be under or overestimated (if based on concentration alone), depending on the direction of the shift in hedonic tone (Freeman *et al.* 2000).

Figure 8.1 shows the concentrations of different odorants needed to evoke a response of unpleasantness that can be classified as 'strong', i.e. a ranking of -2 on the VDI 3882 scale. It can be seen, for example, that for exhaust air from a rendering plant a concentration of 6 ou m^{-3} produces a response of strongly unpleasant. If, however, the air has passed through a biofilter, a concentration of 34 ou m^{-3} is needed to stimulate the same degree of unpleasantness. The authors caution that these relationships are directly applicable only to the particular cases and types of activities where these samples were collected; in using the relationships more generally the numbers in this figure should be considered as indicative only (Freeman *et al.* 2000).

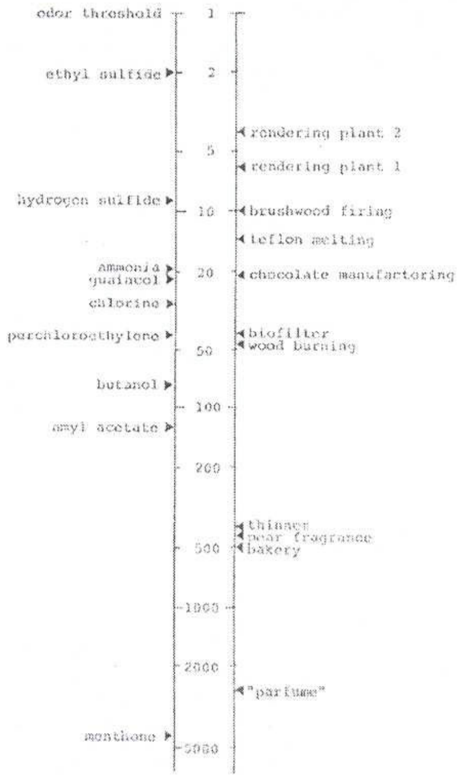

Figure 8.1 Multiples of odour thresholds (ou m^{-3}) that evoke the same degree (strong) of unpleasantness.

8.2 Recent work on tailoring modelling guideline values to odour unpleasantness

As described in Section 7.2.2, the Environment Agency's draft H4 Indicative Odour Exposure Standard ($C_{98,\ 1\text{-hour}}$) of 1.5 ou_E m^{-3} for 'unpleasant' odours was based on an actual dose-response study for livestock (pig odours). However, the Indicative Odour Exposure Standards of 3.0 ou_E m^{-3} for 'mildly unpleasant' odours and 6.0 ou_E m^{-3} for 'least unpleasant' odours are not so robust. These were *not* derived from bespoke dose-response studies of industrial odours of different unpleasantness. Rather, the concentration values chosen were based on dose-response curves for receptors of differing sensitivities to the same livestock odours, as was summarised in Table 7.1. This raises the questions of:

a) Whether the apparently empirical selection of concentration factors to give the exposure benchmarks of ($C_{98,\ 1\text{-hour}}$) 3.0 ou_E m^{-3} for 'mildly unpleasant' and 6.0 ou_E m^{-3} for 'least unpleasant' odours are appropriate. (However, this question is outside the scope of this study/review.)

b) Exactly how the relative unpleasantness of livestock odours should be categorised: in the research work the dose-response curve for livestock (pig odours) was used to define the exposure benchmark of 1.5 ouE m^{-3} for 'unpleasant' odours; in contrast, Table A6.1 in draft H4 (Table 4.3 in this review) categorises intensive livestock rearing odours as falling in the medium category of 'mildly unpleasant'.

Bearing in mind these questions, it is valuable to compare what was done in draft H4 in setting different bands for unpleasantness with what has been done in other countries. In particular it is interesting to see whether the approaches used by regulators in New Zealand when faced with a lack of dose-response data, and the methods used to adjust the concentration factor in the guideline to take account of odour unpleasantness, are of any help in reviewing the categories in the draft H4. Section 7.2.3 explained how regulators in New Zealand used the theoretical 'annoyance threshold approach' to develop percentile concentration values as interim odour modelling guidelines (Table 7.2) that could be used until more robust industry-specific guidelines were obtained from empirical dose-response studies. The interim recommendation of the New Zealand Technical Report (Ministry for the Environment New Zealand 2002) was for the annoyance threshold to be set at 5 ou m^{-3} (1-hour average, 99.5th percentile) for new proposed activities in areas such as a residential zone boundary, that are neither highly sensitive nor of low sensitivity. However, this default, interim annoyance threshold of 5 ou m^{-3} was thought to be too conservative (i.e. the concentration should be higher) for the following circumstances:

i) odours with a low unpleasantness rating, such as those discharged from biofilters;
ii) where the sensitivity of the receiving environment is low, such as a rural zone;
iii) areas where significant background odours are present and therefore cumulative adverse effects may already be occurring.[35]

Some possible options were summarised for adjusting this 5 ou m^{-3} annoyance threshold (both the concentration component and percentile component) to account for offensiveness, receptor sensitivity and background odours (though the report cautions that these adjustment methods may require further research and validation before adoption in national guidelines). The research (Freeman *et al.* 2000) on which the New Zealand Technical Report and policy was based showed examples of how the odour modelling guideline *could* be varied to take account of the hedonic tone of a single source (or multiple sources of the same hedonic tone) – evaluation of multiple sources of different hedonic tone would be more complex (this is discussed in Section 8.3 for individual sectors of concern). However, the Technical Report

[35] Intuitively, one would expect the threshold would be conservative if background odours were adding to the unpleasantness of the odour, but not if they were masking the effect. Perhaps what is being referred to here are 'unpleasant background odours'.

recommends that the benefits of determining an unpleasantness rating, and the sensitivity of the conclusions from the odour evaluation process to the unpleasantness rating, need to be determined before embarking on such a task. Even if the unpleasantness measurement is comprehensive, the result reflects only the laboratory hedonic tone of the odour, not the unpleasantness as may be rated in the environment (i.e. the context of the regulatory modelling assessment), where other factors such as frequency and activity of the affected person come into play (Ministry for the Environment New Zealand 2002). Such an approach is, therefore, no substitute for a representative dose-response study.

These reservations aside, the research concluded that if sufficient data were available relating the unpleasantness of the odour in question to a control odour, then the concentration component of the odour modelling guideline *could* in principle be varied by multiplying the baseline annoyance threshold guideline value by a correction factor. However, the application of this technique would need to be evaluated case by case, depending on the quality of offensiveness data available. If sufficient data were not available (as would usually be the case) then the baseline annoyance threshold should not be corrected and the possible effect of the lower offensiveness should simply be allowed for when interpreting the model results. These two data scenarios are discussed in more detail below.

Scenario I – Correction of odour modelling guidelines for unpleasantness using quantitative hedonic scores

There may be some situations where relative unpleasantness data similar to those in Figure 8.1 (Section 8.1) are available. These data may have been determined experimentally for the site in question, from another (applicable) site, or may have been derived from published literature.

The New Zealand regulators linked their default, interim annoyance threshold guideline to Figure 8.1 by assuming that the default value of 5 ou m^{-3} applies to hydrogen sulphide (which they consider likely). The relative unpleasantness ratings of other odours can then used to determine their corrected annoyance thresholds. This is shown in Table 8.1: the concentration component of the default, interim modelling guideline (5 ou m^{-3}) is varied by multiplying by the correction factor – the ratio of the odorant concentration relative to hydrogen sulphide that evokes the same hedonic response. In gathering this sort of data, it is important to have a control substance, in this case hydrogen sulphide, which is assumed to correspond to the baseline annoyance threshold and against which the odours in question can be rated.

Table 8.1 Examples of annoyance threshold corrections (Freeman *et al*. 2000)

Odour type/source	Value on Hangartner scale (refer Figure 8.1)	Value relative to hydrogen sulphide
Hydrogen sulphide	8	1
Rendering plant	5	0.6
Biofilter	40	5
Bakery	500	62

Taking from Table 8.1 the example of a biofilter, the corrected interim odour modelling guideline would be 25 ou m^{-3} (i.e. the default guideline of 5 ou m^{-3}, multiplied by a correction factor of 5). For comparison it is useful to look at the different example of a bakery, which can be considered one of the least unpleasant odour sources, but where odours can still be found to be offensive or objectionable at sufficiently high concentrations. Here, the corrected odour modelling guideline would be much higher (more lenient) at 310 ou m^{-3} (i.e. the default guideline of 5 ou m^{-3}, multiplied by a correction factor of 62). In contrast, if the nature of the odour was very unpleasant (i.e. likely to cause significant adverse effect at lower concentrations than hydrogen sulphide), such as the rendering plant example, then the corrected annoyance threshold could even be reduced to less than 5 ou m^{-3} by applying a correction factor of less than unity, to give 3 ou m^{-3}.

Scenario II – When only relative scale of offensiveness (hedonic ranking) data are available

There may be other situations when no quantitative hedonic scores are available and the data can only be ranked, such as shown in Table 8.2, in terms of their relative unpleasantness. To utilise these data, it must first be assumed that if an odour sample is graded as 'not annoying' in the olfactometry laboratory situation, then it would also be 'not annoying' in the real environment. This is considered a fairly safe assumption for the reasons already explained in Section 6.2.

Unless such data are given for more than one concentration of the odorants (in which case an analysis similar to that in Scenario I above could be carried out), the magnitude of the correction factor to the concentration component cannot be estimated. The best that can be interpreted from the data in Table 8.2 is to conclude that odours with an unpleasantness ranking of less than, say, 3 are likely to have annoyance thresholds above the default, interim guideline of 5 ou m^{-3}. The lower the unpleasantness rating, the greater the difference will be between the default, interim guideline value and any corrected interim guideline value. In this case it was suggested (Freeman *et al.* 2000) that it would be better to keep the interim guideline at the default value of 5 ou m^{-3}, but to bear in mind when interpreting the results of any dispersion modelling that this may be a little conservative.

Table 8.2 Example of offensiveness data for a wastewater treatment plant and a rendering plant (from Lincoln Environmental methodology 1997)

Source	Relative unpleasantness* at concentration = 5 ou m^{-3}
Wastewater treatment plant example	
Biogas	4.2
Sludge lagoons	3.1
Primary sedimentation tanks	2.3
Oxidation pond	1.9
Biogas combustion engines	1.7
Biofilter	1.4
Rendering plant example	
Raw material reception bin	5.3
Scrubber exhaust	4.5
Building ridge vents	3.0
Drier exhausts	1.9

Based on the following scores:*

0 = not annoying (= not unpleasant)

1 = slightly annoying (= slightly unpleasant)

2 = annoying (= unpleasant)

-----------------------------Threshold for significant adverse effect likely to be somewhere between a rating of 2 and 4 (probably less than 3).

4 = very annoying (= very unpleasant)

8 = extremely annoying (= extremely unpleasant)

*The term used in the source reference was 'offensiveness rating' and this has been changed here to relative unpleasantness to avoid ambiguity. The scores given in the original reference source are for how 'annoying' the odour is. This has been changed here to how 'unpleasant' the odour is. This is because, as explained in Section 7.1.6, annoyance potential has a specific meaning and is likely to be a function of both hedonic tone and odour quality, in addition to perceived intensity. The methodology to determine annoyance potential has not yet been developed fully.

8.3 Further investigation of odours from some sectors of concern

8.3.1 Identifying the sectors of concern

The earlier Environment Agency research (Environment Agency 2000b) made a number of recommendations for future work to strengthen what would become the draft H4 odour modelling approach using Indicative Odour Exposure Standards. These recommendations included confirmation of the dose-effect relationship for the UK situation and comparison of results with existing studies abroad to obtain additional information on relative odour annoyance from different sources; and establishing a rank order for annoyance potential based on UK data, obtained by interviewing environmental professionals with odour experience or by comparative testing in laboratory conditions. As part of the overall project of which this literature review forms a part, an Odour Relevance Survey (Environment Agency 2005) was carried out to identify which odours and chemical species were most important to the Environment Agency in its PPC regulatory role. The Odour Relevance Survey was carried out primarily by means of a concise questionnaire designed to gather the key information from relevant Environment Agency Process Industry Regulation (PIR) staff. In addition to the questionnaire, an attempt was made to obtain the information from records and systems held by the Environment Agency. The odour complaints received for the year 2003 were summarised by industry sector and by odour descriptor (e.g. 'landfill-type' odour, 'sulphide odour', 'chemical odour' and 'ammonia/amine' odour)

The responses from the Odour Relevance Survey questionnaire suggested the most relevant existing activities listed in draft H4 Table A6.1 (shown as Figure 4.3 in this report) are:

- Activities involving putrescible waste, wastewater treatment, and processes involving animal or fish remains. These activities were most often cited by respondents as having led to them receiving complaints. These activities are all currently categorised as 'High' relative unpleasantness in draft H4 Table A6.1. The respondents largely – but not unanimously – agreed with this categorisation.
- There was only one activity where a majority of respondents (60%) disagreed with the current categorisation: livestock feed factory, where no complaints had been received. The respondents disagreeing thought that the odour should be reclassified as 'medium' unpleasantness.

The Odour Relevance Survey respondents thought there were a number of other activities not currently listed in draft H4 Table A6.1 that could have a potentially significant odour impact. The most relevant odours from the Environment Agency's point of view that are not already in draft H4 Table A6.1 are ferrous and non-ferrous metals foundries and paper/pulp mills.

The Project Steering Board asked specifically whether the Odour Relevance Survey suggested there was a need to split down further the draft H4 Table A6.1 categories (e.g. some subsectors within a sector). Although some industrial processes and even sectors can be placed in certain broad categories of odour unpleasantness, there are a number of situations that can complicate or change this:

i. The first situation is when there are multiple sources on an industrial site. The different sources may have very different character and unpleasantness.
ii. The second factor causing complications is that on certain categories of industrial site there may be different ways of carrying out the activity (e.g. automotive paint shops may use solvent-based paints or water-based paints). These have different odour concentration–intensity

relationships, different odour characters and different levels of unpleasantness.

iii. The third situation is the use of odour control technologies that modify the character and unpleasantness of a discharge. An example is abatement of rendering odours using biofilters; the latter generate an earthy/musty odour which is much less unpleasant than the untreated air stream. As was discussed in Section 8.2, in New Zealand it has been argued (Freeman *et al.* 2000) that the default guideline of 5 ou m^{-3} should be corrected to 25 ou m^{-3} for a biofilter. Another example is the use of chemical scrubbers, which can produce an odour of chlorine/chemical character (Ministry for the Environment New Zealand 2002).

The responses from the Odour Relevance Survey questionnaire suggested there is support for subdividing along the following lines:

- Waste-derived fuel storage separate from other activities involving putrescible waste.
- Brickworks where there is potential for release of significant quantities of hydrogen sulphide separate from those where there is not.
- Intensive pig installations separate from intensive poultry installations, under intensive livestock rearing.

Additionally, analysis of Environment Agency complaints records show that odours from PPC waste management processes are very relevant to the Environment Agency from a regulatory point of view.

In the remainder of this chapter, this literature review has investigated further the odour character and unpleasantness from the above sectors and processes of concern.

8.3.2 Activities involving putrescible waste

Arguments for subdividing this category

The Odour Relevance Survey indicated the importance of odour from waste management processes to the Environment Agency's regulatory role. In Table A6.1 of draft H4, waste management processes presently fall under a single category, of 'activities involving putrescible waste', and is currently assigned to the 'High' relative 'offensiveness' (i.e. unpleasantness) band for choosing the Indicative Odour Exposure Standard.

In contrast, the Dutch government (InfoMil 2004) lists separately two waste management sectors – composting of vegetable refuse, and organic waste composting plants – among the 16 industry sectors to which standard sets of odour control measures will be applied.

The Odour Relevance Survey showed there was support among Environment Agency staff dealing with odour, specifically, for subdividing this category to separate waste-derived fuel storage from other activities involving putrescible waste: waste-derived fuel storage would be re-categorised under the 'Medium' unpleasantness band.

However, there is also a wide range of other odour sources at waste management installations, and these have different degrees of unpleasantness (described in more detail below). This would suggest it is more appropriate to subdivide the heading in Table A6.1 of 'activities involving putrescible waste', and/or have a default category as a starting point only, to be modified according to site-specific circumstances (e.g. hedonic tone and consideration of multiple sources). Careful thought needs to be given to how the model is configured (i.e. which sources are modelled together) and what level of unpleasantness is assumed for the particular odour source in question.

Landfill gas

Odours can be discharged from a number of different sources and activities carried out on landfill sites. Possible sources of odour at a landfill are:

- waste reception facilities and trucks;
- open work faces;
- landfill gas diffusing through capped refuse, or evolved when covered refuse is opened;
- landfill gas flares;
- leachate treatment and disposal.

These sources have different degrees of unpleasantness, with odour from fresh waste generally being regarded as being much more unpleasant than odours from landfill gas or from leachate. However, no details of hedonic scores or bespoke dose-response studies were encountered during the literature review. If more robust data were needed to allow a decision on assigning landfill gas or leachate odours to a lower unpleasantness band than the current 'High' category band then further work would be needed. It is possible that some dose-response studies will be performed around waste management facilities as part of Defra's Waste Research R&D programme.

Waste-derived fuel storage

On the basis of their professional involvement with odour investigation and regulation, respondents in the Odour Relevance Survey thought that odours from waste-derived fuel storage should be assigned a lower unpleasantness band than the current 'High' category in draft H4 for activities involving putrescible waste.

No details of hedonic scores or bespoke dose-response studies were encountered during the literature review. If more robust data were needed to allow a decision on re-categorisation, then further work would be needed.

Composting of vegetable waste[36]

Using the presently available information, Dutch regulators (InfoMil 2004) have been unable to establish a dose-response relationship between the odour concentration and the percentage of people experiencing odour nuisance. However, on the grounds of the research results and practical experience, 1.5 ou_E m^{-3} as 98th percentile value of the hourly averaged levels over a year has proved to be a practicable target value for which it may be assumed that the residual nuisance is acceptable. The value of 1.5 ou_E m^{-3} is not taken as a fixed standard but as a target value for defining the area where nuisance can occur.

The draft H4 unpleasantness category aligning most closely to this odour criterion 1.5 ou_E m^{-3} as 98th percentile, is the 'High' unpleasantness band.

However, there are significant uncertainties in the calculations of the emissions. Also, for some composting techniques there are hardly any odour emissions during the actual process of composting, but during the opening up of the heap after the process has finished a very considerable emission can take place which causes considerable nuisance over a very wide area. Such acute odour episodes are not really amenable to the H4 modelling and back-calculation technique.

Organic waste composting plants

Chapter 3 of *The Netherlands Emissions Guidelines for Air* (InfoMil 2004) quotes a hedonic odour investigation carried out by the VAR (1995) that concluded a general framework for assessing installations for producing compost based on a target value in the range of 1.5 to 3 ou_E m^{-3} (as 98th percentile), depending on the characteristics of the surrounding area. This value also corresponded with the pattern of complaints observed by the competent authorities.

The draft H4 unpleasantness category aligning most closely to these odour criteria of 1.5 and 3 ou_E m^{-3} as 98th percentile, are the 'High' and 'Medium' unpleasantness categories, respectively.

[36] Waste of vegetable origin in this context means organic (vegetable) waste produced during planting and maintenance of public greens, forests and nature reserves, and any other waste of a comparable composition such as waste from private gardens and gardening firms, waste from mowing shoulders and ditches, waste of agricultural origin and waste produced in the landscaping and maintenance of grounds belonging to institutions and corporate owners.

8.3.3 Processes involving animal or fish remains

Rendering

A New Zealand case study carried out for Auckland Regional Council (Freeman 2000) describes an odour investigation carried out at a rendering facility. Because of a low population density around the plant a dose-response study could not be carried out to derive an industry and community-specific modelling guideline. It was decided to compare the modelled ground-level odour concentrations to a default guideline of 5 ou m^{-3}, as a 99.5th percentile of 3-minute average concentrations, using AUSPLUME (converted after peak-to-mean ratio correction to 4 ou m^{-3}, 1-hour average). It was decided that no correction to the default odour modelling guideline should be applied, as 'rendering odours are known to be of a highly objectionable nature'.

More recent New Zealand research (Freeman *et al.* 2000) shows how the hedonic score data for very unpleasant odours from a rendering plant can be used to derive a correction factor of 0.6 to give modelling guideline value of 3 ou m^{-3} that takes account of the odour unpleasantness, compared to the default guideline of 5 ou m^{-3} (as a 99.5th percentile of 1-hour average concentrations).

Arguments for subdividing this category

Although this sector was not identified in the Odour Relevance Survey as one that respondents named as needing subdivision, the literature review showed there are good grounds for considering individual sources separately. Odours can be discharged from a number of different activities carried out on the site, each of the individual sources consisting of a mixture of chemical constituents, and the mixture may be different for each source. Therefore, each source can contribute different unpleasantness weightings to the total odour impact, and may even have a totally different character. In a meat rendering works, the biofilters emit an odour that is much less unpleasant than the meat cooker (Ministry for the Environment New Zealand 2002). The data in Table 8.2 (Section 8.2) show that sources on a rendering plant vary significantly in the unpleasantness of the odours:

- raw material reception bin = 5.3 unpleasantness score;
- scrubber exhaust = 4.5 unpleasantness score;
- building ridge vents = 3.0 unpleasantness score;
- drier exhausts = 1.9 unpleasantness score.

There is no doubt that odours from rendering facilities can produce odours that are very unpleasant. Careful thought needs to be given to how the model is configured (i.e. which sources are modelled together) and what level of unpleasantness is assumed for the particular odour source in question. All the evidence seen in this literature review is that draft H4 is justified in assigning rendering facilities to the current 'High' category for activities involving putrescible waste. When considering the relevant site-specific factors, such as multiple sources with different hedonic tones, then this categorisation can be modified. For example, biofilter exit gas should be assigned a lower unpleasantness band than meat cooking odours.

8.3.4 Brickworks

Arguments for subdividing this category

On the basis of their professional involvement with odour investigation and regulation, respondents in the Odour Relevance Survey thought that this category in draft H4 Table A6.1 should be subdivided as follows:

- 'High' unpleasantness band – brickworks where there is potential for release of significant quantities of hydrogen sulphide.
- 'Medium' unpleasantness band – brickworks where there no potential for release of significant quantities of hydrogen sulphide.

No details of hedonic scores or bespoke dose-response studies around brickworks were encountered during the literature review.

8.3.5 Wastewater treatment

There appear to have been no formal odour-dose versus community annoyance investigations completed in New Zealand or Australia. However, there have been some useful case studies.

The case study of a sewage treatment facility in Sydney reviewed in the New Zealand Technical Report (Ministry for the Environment New Zealand 2002) compared modelling results to areas of varying levels of complaint[37] (as have most other similar investigations in Australasia). The study established the link between observed levels of complaint and percentile odour concentrations. The odour concentrations of the plant emissions were also measured using European methods, and ambient concentrations were modelled using AUSPLUME and also using a wind tunnel. The community was alerted to the study by means of regular advertising, and so the community response may have been enhanced. Nevertheless, the study found that for sewage plant emissions, 99.5th percentile concentrations below 46 ou m^{-3} were unlikely to lead to complaint. The equivalent certainty threshold concentration for this study was 5 ou m^{-3}. The application of the 2 to 5 tolerance factor to convert this to a guideline for assessing a proposed new activity indicates a modelling guideline for new sewage plants near sensitive areas in the range of 1 to 3 ou m^{-3} (1-hour average, 99.5%) odour modelling guideline.

[37] Community complaint-based studies are conducted as for community annoyance dose-response studies. The difference between the two is the response parameter used, and therefore the collection method and interpretation of data is different. Both are empirical relationships of a community response compared to modelled concentration data.

Arguments for subdividing this category

Although this sector was not identified in the Odour Relevance Survey as one that respondents named as needing subdivision, the literature review showed there are good grounds for considering individual sources separately.

As shown earlier in Table 7.3, odours can be discharged from a number of different activities carried out on a wastewater treatment plant, such as:

- inlet works
- screening facilities
- pre-aeration and grit removal tanks
- primary sedimentation tanks
- secondary aeration and sedimentation tanks
- flow-splitting structures
- final discharge structures
- screenings and grit dewatering and reception bins
- sludge treatment and dewatering
- biogas combustion engines/generators
- odour treatment (e.g. biofilters/scrubbers)

Each of the individual sources is a mixture of chemical constituents, and the mixture may be different for each source. Therefore, each source can contribute different unpleasantness weightings to the total odour impact, and may even have a totally different character. In a wastewater treatment plant, for example, discharges from earth filters are described as 'earthy/musty/organic', discharges from primary effluent as 'sulphur/sewage/rotten eggs', and discharges from biogas combustion engines as 'chemical/gas/smoke' (Ministry for the Environment New Zealand 2002).

Auckland Regional Council (Freeman *et al.* 2000) reports the case study of odour investigations carried out at Christchurch (NZ) sewage treatment works in 1997, which showed that the oxidation ponds could be a significant source of odour. As well of carrying out area-source sampling and olfactometry to the draft CEN standard, qualitative offensiveness testing was also carried out by Lincoln Environmental on the odour samples from the oxidation ponds. The results indicated that the odours from the inlets were moderately more offensive than the remaining pond areas, which were rated as 'slightly annoying' with the predominant odour description typically not associated with sewage at all (e.g. 'seaweed', 'stagnant water', 'musty'). During the modelling and impact assessment, it was considered that because the '...odour emitted from the oxidation ponds has a low offensiveness rating' (plus considerable background odours) the odour modelling guideline of 2 ou m^{-3} (99.5th percentile, 1-hour average concentrations), was probably too stringent. The model was run again after taking the decision to arbitrarily halve the odour emission rates to account for the low unpleasantness of the oxidation ponds.

The data from Table 8.2 (Section 8.2) show how other specific sources on a wastewater treatment plant vary significantly in the unpleasantness of their odours:

- biogas = 4.2 unpleasantness score;
- sludge lagoons = 3.1 unpleasantness score;

- primary sedimentation tanks = 2.3 unpleasantness score;
- oxidation pond = 1.9 unpleasantness score;
- biogas combustion engines = 1.7 unpleasantness score;
- biofilter = 1.4 unpleasantness score.

Careful thought needs to be given to how the model is configured (i.e. which sources are modelled together) and what level of unpleasantness is assumed for the odour. When considering the relevant site-specific factors such as multiple sources with different hedonic tones, then the existing 'High' categorisation in draft H4 can be modified. For example, biofilter exit gas and oxidation ponds should be assigned a lower unpleasantness band than sludge lagoons.

There is a possibility that the UK Water Industry Research (UKWIR) may coordinate some dose-response studies around wastewater treatment plants to support the water industry in meeting the Defra Code of Practice on Odour Nuisance from Sewage Treatment Works.

8.3.6 Livestock feed factory

This sector already features in draft H4 Table A6.1, but the Odour Relevance Survey shows there is some disagreement about its relative unpleasantness category. None of the respondents had received complaints from this type of process and those survey respondents disagreeing with its existing categorisation thought that the odour should be reclassified as 'Medium' unpleasantness.

On the basis of research into nuisance in the vicinity of livestock feed compounding plants, Dutch regulators (InfoMil 2004) were not able to find a generally applicable dose-response relationship which was valid for the industry as a whole between odour concentrations and the percentage of people complaining of odour nuisance. However, on the basis of the information yielded by the industry-wide investigation and the technical and financial options available, Chapter 3 of *The Netherlands Emissions Guidelines for Air* (InfoMil 2004) sets an odour criterion of 1 ou_E m^{-3} (98th percentile) as constituting the maximum allowable level for densely populated residential areas. (A certain relaxation of this level is permissible for scattered dwellings, as long as a maximum concentration of 1 ou_E m^{-3} as 95th percentile is not exceeded.)

The draft H4 unpleasantness category aligning most closely to this odour criterion 1 ou_E m^{-3} as 98th percentile is the 'High' unpleasantness category. This suggests there should be no change to the current unpleasantness banding in draft H4 Table A6.1.

8.3.7 Intensive livestock rearing

Intensive livestock rearing is currently classified as ‘Medium’ unpleasantness in Table A6.1 of draft H4. However, this literature review found that odour from animal production facilities consists largely of odorants volatilised from manure and urine and the hedonic tone of these may be almost as low (i.e. tending towards the most unpleasant, lower end, of the scale -4 to +4) as for odour from dead animals (Nimmermark 2004). This suggests that such odours should be promoted to the ‘High’ band of odour unpleasantness.

It is interesting to look at why livestock odours appear in the ‘Medium’ unpleasantness band in the current draft of H4. In the original Dutch work the 10% annoyance of the general public to pig odours corresponded to 1.3 ou_E m^{-3} as 98th percentile, which was used as the basis to set the Indicative Odour Exposure Standard of 1.5 ou_E m^{-3} for the ‘High’ unpleasantness band (see Table 7.1). The Indicative Odour Exposure Standard of 3 ou_E m^{-3} for ‘Medium’ unpleasantness was derived from the dose-response curve that showed 3.2 ou_E m^{-3} was equivalent to 10% annoyance to pig odours of residents in areas where such odours were a common feature. The argument for assigning livestock odours as ‘Medium’ seems to be that any sensitive human receptor would be living close to a pig farm, therefore such odours will be a ‘common feature’. This is to some extent a circular argument, in that if a higher standard of control were applied they would cease to be such a common feature.

Arguments for subdividing this category

On the basis of their professional involvement with odour investigation and regulation, respondents in the Odour Relevance Survey thought that this category in draft H4 Table A6.1 should be subdivided to separate intensive pig installations separate from intensive poultry installations. This view would appear to be supported by the results of actual impact studies described earlier in Section 6.1 (shown in Figure 6.2): pig odour clearly has a greater impact in terms of nuisance, even though it has the less steep intensity curve, which is accounted for by its greater odour unpleasantness.

However, the results of other research suggest this is less clear-cut. Nimmermark (2004) studied the hedonic tone of odours from fattening pigs, pig manure culvert, laying hens and dairy cows. In the laboratory, odour panellists rated the hedonic tones of these samples on the standard nine-point scales. The linear regression plots demonstrate the change in perceived hedonic tone with changes in concentration. However, at an odour concentration of 5 ou_E m^{-3} (generally considered to be the strength of a faint odour) the hedonic tones (and their 95% confidence limits) can be estimated to be:

-0.5 ($\pm$1.2) for fattening pigs;
-0.4 ($\pm$1.4) for pig farm manure culvert;
-0.5 ($\pm$1.5) for laying hens;
-0.4 ($\pm$2.0) for cows.

The results tend to suggest the differences in hedonic score between the different types of livestock are not statistically significant.

Intensive pig installations

Another case study carried out for Auckland Regional Council (Freeman *et al.* 2000) into a piggery in New Zealand criticises the original use of a guideline of 15 ou m^{-3} (certainty thresholds, 95 percentile, 1-hour AUSPLUME average concentrations). A more appropriate guideline would be to use the later New Zealand guidance of 2–5 ou m^{-3} (99.5 percentile, 1-hour AUSPLUME average concentration) for a medium-low sensitivity receiving environment and a '...highly offensive odour type'.

It would not be valid to compare the concentration aspect of the New Zealand odour criterion with the Indicative Odour Exposure Standard bands in draft H4 because of the different percentiles involved. However, Dincer *et al.* (2004) cite Sheridan *et al.* as mentioning a new odour annoyance criterion applicable around piggeries of 6 ou_E m^{-3} 98th percentile for modelling minimum allowable distance to sensitive receptors. This *does* use the same percentile value as H4. The draft H4 unpleasantness category aligning most closely to this odour criterion 6 ou_E m^{-3} as 98th percentile is the 'Low' unpleasantness category.

In field tests around pig farms in Germany (Gallmann *et al.* 2004), the intensity and frequency of hedonic tone of perceived pig odours was most frequently (about 40–50% of the assessments) evaluated as very weak or weak and '...slightly unpleasant to unpleasant'.

In an American quality of life study into hog operations in Alberta (Alberta Department of Agriculture Food and Rural Development 1998) interviewees ranked odour quality by hedonic score of -9.37 on a scale -10 to +10, versus an acceptable level of 4.5. The scoring was carried out at an intensity rated 2.33 on a scale of 0 to 3, where 0 = none, 1 = detectable, 2 = moderate and 3 = extreme. However, these results did not appear to have been obtained using quantitative techniques such as the VDI methods. The odour character was described by interviewees as '...nauseating, rank, obnoxious, and foul'.

Intensive poultry installations

No details of hedonic scores or bespoke dose-response studies were encountered during the literature review.

8.3.8 Paper and pulp

This sector/processes is not currently listed in draft H4 Table A6.1, but respondents to the Odour Relevance Survey thought that it could potentially be important to the Environment Agency in its PPC regulatory role.

The case study of the Tasman Pulp and Paper Company Ltd in the Bay of Plenty, New Zealand (reviewed in the New Zealand Technical Report

(Ministry for the Environment New Zealand 2002)) is said to be possibly the only example in Australasia where robust odour modelling results (obtained using AUSPLUME) were compared to annoyance survey results (as opposed to comparing modelling results to areas with varying levels of complaint).

The study indicated that for this ‘moderately offensive’ industrial odour within a relatively low-sensitivity rural area, an odour exposure of around 10 ou m^{-3} appeared to be acceptable to an existing community. Using a tolerance factor of 2 to 5 to convert this to a guideline for assessing the potential effects of a proposed activity gave a modelling guideline value of 2 to 5 ou m^{-3} (99.5 percentile, 1-hour average). This is essentially the same as the interim default odour guideline used in New Zealand based on the theoretical annoyance threshold approach, if the peak-to-mean ratio is accepted as about 2.5.

It follows, then, that if the paper and pulp sector is added to Table A6.1 of draft H4, it should be provisionally assigned to the ‘Medium’ unpleasantness band on the basis (cited in draft H4) that these are odours that do not obviously fall within the ‘High’ or ‘Low’ categories. If more robust data were needed to allow a decision on categorisation, then further work would be needed (e.g. remodelling of the data from the Bay of Plenty study to allow a correlation of response (annoyance) with dose (exposure) as a 95 percentile 1-hour average odour concentration).

8.3.9 Foundries (ferrous) and foundries (non-ferrous)

This sector/processes is not currently listed in draft H4 Table A6.1, but the Odour Relevance Survey shows that it could potentially be important to the Environment Agency in its PPC regulatory role.

No details of hedonic scores or bespoke dose-response studies were encountered during the literature review.

8.4 Opportunities identified for strengthening Environment Agency guidance

The Odour Relevance Survey identified odour sources, sectors and activities that were of greatest importance to Environment Agency regulatory staff and the views of those staff on the categorisation of unpleasantness of those odours. This section takes those views and reviews of other research to address a key recommendation in previous Environment Agency research on this subject: to obtain a revised categorisation of unpleasantness that includes the expert opinion of environmental regulators and practitioners.

While for many odour sources, sectors and activities there is consensus on their relative unpleasantness categorisation, for others there is some disagreement on the category, or there is some argument for subdividing sectors between different categories. This is complicated by the fact that some installations may have multiple odour sources, each with different degrees of unpleasantness. A further complicating factor is that the character and unpleasantness of an odour source can change significantly when certain types of end-of-pipe abatement are used to treat the exhaust gas. The current conceptual model in draft H4 for a three-banded categorisation of industry sectors to give Indicative Odour Exposure Standards has difficulty dealing with these complicating factors.

It is recommended that future revision of the H4 guidance addresses this as follows:

1. By giving clear guidance that a representative sector-specific dose-response study to provide industry-specific modelling exposure standards is the preferred, best practice approach.
2. That the use of the Indicative Odour Exposure Standards approach is temporarily acceptable as an interim measure. The revised guidance could improve this interim approach by:
    a. Establishing a more robust default dose-response curve on which a default Indicative Odour Exposure Standards is based, corresponding to a particular level of annoyance (e.g. 10%). (This may or may not be the same value as the 1.5 ou m^{-3} concentration derived from the Dutch livestock study.)
    b. Rather than a simple three-band classification, the revised guidance could offer clearer guidance to users (perhaps by means of an annotated flowchart) on how, starting from a single default value, the Indicative Odour Exposure Standard value could then be adjusted for specific conditions and factors, i.e. the Indicative Odour Exposure Standard would just be the starting point. These specific conditions and factors would include:
        i. Relative unpleasantness of the odour – guidance would need to consider whether to use an unpleasantness band approach (and how many bands, what concentration values to assign to them, which industries/activities to each band); a correction factor approach, as used in New Zealand, to give a revise exposure standard; or whether to leave the default exposure standard uncorrected and then to bear in mind in the interpretation that the predictions may be either optimistic or pessimistic.
        ii. How multiple sources will be dealt with – the guidance will need to address the hedonic tone of a single source (as in i, above) and also multiple sources of the same hedonic tone and multiple sources of different hedonic tone. It is possible that this approach will not be able to deal with the latter in anything other than a qualitative way.
        iii. The sensitivity of the receiving environment. This could also be expanded to include tolerance to more of an existing odour that is a common feature of the area, or conversely a new odour.

Regarding b(i) above, it is recommended that if the unpleasantness band approach is retained, a revised version of Table A6.1 from draft H1 is drawn up taking into account the findings of this chapter on a revised categorisation of unpleasantness for the odour sources, sectors and activities that were of greatest importance to Environment Agency regulatory staff.

9 Further investigation of odour thresholds for individual species

9.1 The basis of using individual odour thresholds as guideline values

Quantification of the odour impact on local sensitive receptors is uniquely challenging due to:

i) the nature of odour exposure – it is perceived over very short time periods (as short as a few seconds), which makes monitoring using most conventional sampling periods (hours to weeks) inappropriate;

ii) the difficulty of measuring odour at ambient levels – no analytical techniques used in the field odours can currently come anywhere near the sensitivity and speed of response of the human nose for detecting odours.

Odour can be measured in two ways: directly as odour strength using sensory analysis (olfactometry) and indirectly by measuring specific chemical species that are thought to contribute to all or most of the odour.

Sensory analysis – this uses the human nose as the sensor in the measurement process, a technique termed olfactometry. The concentration measurement from dynamic dilution olfactometry is expressed as a value in odour concentration units (ou m^{-3}), which is usually[38] a multiple of the odour detection threshold (ODT), as was explained in Section 3.2.1. Generally, for complex odours, the detection, response and performance of the human nose is superior to any presently known instrument. Nor can any instrument measure the degree of unpleasantness of an odour.

Unfortunately, dynamic dilution olfactometry is only suitable for measuring odour strength of industrial/source emission samples; usually it cannot be used to measure odour strength in samples of ambient air. Therefore, for quantitative monitoring at receptors, it is only possible to measure the odour indirectly as specific chemical species.

Chemical analysis – a variety of instruments can be used as sensors to measure the concentration of one or more odorous chemical compounds. The compound concentration can then be compared to the odour threshold to see if an odour is likely to be detected (odour detection threshold) or recognised (odour recognition threshold). The mass concentration of the compound can

[38] However, some dynamic olfactometry methods use the *recognition* threshold rather than the odour detection threshold.

be converted approximately into odour concentration units (ou m^{-3}) by expressing it in multiples of the compound's ODT.

It was shown in Section 4.5.4 how chemical analysis could be used for comparing with the small number of WHO odour guideline levels set for a limited selection of single compounds. Chemical analysis can also be used for:

i) assessing the odour impact of other single compounds not covered by WHO guidelines, by comparing measured compound concentration with the published ODT for that compound;

ii) assessing the odour impact of a mixture of compounds, by comparison with their ODTs provided that there are no masking or synergistic effects between individual species in the odour mixture.

There are some major limitations of comparing chemical analysis results with individual odour thresholds, which sensory methods of odour measurement avoid by using the human nose. Nevertheless, it is a valuable tool in some applications. The disadvantages and advantages are discussed below, then – in Section 9.4 – details of published odour thresholds are given.

9.2 Limitations of using chemical analysis and individual odour thresholds

Whether this approach will be suitable in a given case will depend on:

- whether the specific compound(s) are responsible for the vast majority of the odour in the emissions, or at least can be considered as an empirical surrogate for the odour. (A list of emission species from different odorous industrial operations and methods of odour control is given in the New South Wales, *Authorised Officers' Manual* (Environmental Protection Authority New South Wales 1995);
- whether there is a monitoring technique available that has sufficient sensitivity (ambient concentrations will be very low) and fast enough response time (odours may be perceived over a few seconds).[39]

Even if the criteria above can be satisfied, monitoring of individual compounds is still an imperfect way of assessing odour impact due to the following:

1. The relationship between gas concentration and odour concentration is assumed to be linear, which is not always the case.
2. An odorous gas can comprise a cocktail of many odorous compounds. The method does not work well for mixtures. Firstly, it is difficult to identify all the odorous compounds. Secondly, the overall odour concentration of a mixture cannot be estimated by simply adding the values of the chemical constituents. This may give an overestimate or an underestimate because there may be non-linear additive or

[39] This restricts the monitoring technique to either a direct-reading continuous analyser, or a grab sample of air followed by later analysis. (Clearly, the latter provides only a snapshot of the ongoing air quality situation.) Monitoring over averaging times of several days or weeks using, for example, diffusion tube samplers can be ruled out.

synergistic effects between the various compounds and due to the way that odour stimuli are processed by the human brain.

3. The annoyance impact of an odorous compound is often perceived at extremely low concentrations (in the parts per billion range), making instrumental analysis difficult.
4. Finally, published odour threshold data may be contradictory and of varying quality. This is due to differences in sensory techniques used by laboratories in the past (although this became more standardised in the late 1990s), and also to different definitions of the odour threshold, such as detection and recognition levels (Ministry for the Environment New Zealand 2002). Most studies have been carried out using the odour detection thresholds, but some practitioners, for example in New Zealand, have begun to use a more sophisticated approach involving the *recognition* threshold.

9.3 Applications and benefits of using chemical analysis and individual odour thresholds

Due to the time, costs and practical difficulties, chemical concentration measurements may be carried out in place of odour unit measurements by olfactometry. Indeed, as mentioned previously, dynamic dilution olfactometry can generally only be used on samples of source emissions and cannot be used to measure odour at ambient air levels. It may also be possible to calculate chemical compound emissions from an industrial installation by mass balance. In some situations the expense of olfactometry may not be justified, and using odour threshold data for individual compounds may be the only option. However, due to the limitations of the approach discussed in the previous section, the use of chemical analysis and odour threshold data is mainly restricted to assessing odour in situations where one compound is known to predominate the odour impact (i.e. there are no synergistic effects with other compounds (Ministry for the Environment New Zealand 2002)). Two main applications of using chemical analysis and individual odour thresholds are given below. New information (post-draft H4) on the values of individual ODTs is given in Section 9.4.

Using a compound as an indicator of odour

A particular application of this is when a specific chemical compound is monitored as a surrogate *indicator* of odour. This approach assumes that by measuring for the presence of a certain chemical compound, such as hydrogen sulphide, one can estimate the amount of odour present. The assumption is valid for odour discharges where the odour is predominantly caused by one component, such as sulphide discharged from a fellmongery. The odour indicator technique can, in appropriate applications, be used for modelling and monitoring ambient concentrations, for determining the efficiency/effectiveness of odour control equipment, and to monitor the activity's compliance with source emissions limit values (ELVs) set in PPC permit conditions

The main limitation of this approach is that the ability of one chemical component to represent the overall odour effect of a mixture of compounds is variable. For example, odour monitoring studies at some sewage treatment works have shown hydrogen sulphide to be a poorer indicator of sewage treatment odours than is commonly assumed. Similarly, other studies have found that hydrogen sulphide and methane concentrations in samples of landfill gas did not correlate well with odour concentration, suggesting that other compounds in the landfill gas were also contributing to the odour nuisance (Freeman *et al.* 2000).

The Western Australian EPA (Department of Environmental Protection, Western Australia 2002) allows the geometric mean air odour threshold to be used for modelling odour impacts when only a single odorant in an air stream is present and there are appropriately reviewed odour thresholds for the odorant available, giving as an example those from the US EPA (1992).

Estimating the total odour of a mixture by summing the individual concentrations

In some circumstances it is said to be possible to estimate the total odour of a mixture by summing the concentrations (in multiples of their individual odour thresholds) of each chemical compound. The chemical analysis is usually carried out using a gas chromatograph/mass spectrometer (GC–MS) to identify and quantify as many of the odorous constituents as possible. The New Zealand *Review of Odour Management* (Ministry for the Environment New Zealand 2002) cites research reported by Stone (1997) that indicates that this can be a reliable method of odour measurement for any source where sufficient chemical compounds to representatively describe the odour can be analysed in a reproducible way. The paper concluded that a correlation between olfactometric and chemical measures of odour does exist in samples where a small number of relatively strong odorants are responsible for the majority of the odour. An example was a starch factory, where the odour source was found to readily provide a clear odour fingerprint dominated by sulphurous and aldehydic compounds, and a good correlation between olfactometry and analytical chemistry was obtained by linear regression analysis. However, the paper also noted that in several cases of very complicated odours with data obtained over an extended period no correlation could be found. In reality, most cases of odour discharge will fall into this category, particularly when one considers the effects of mixtures of different odours combining in ambient air downwind of a site containing multiple odour sources (Freeman *et al.* 2000; Ministry for the Environment New Zealand 2002).

9.4 Odour threshold data

Odour threshold data should be used with caution because many different methods have been used to obtain them and there is a wide variation in values reported in the literature, often by four orders of magnitude. As an example, when using dynamic dilution olfactometry methods the odour threshold is usually taken as the value at which 50% of the panel are able to detect or recognise the odour, but some historical data are based on a range of different percentages.

Furthermore, most of the available odour threshold reference data available appear to have been developed before dynamic dilution olfactometry was standardised, so the data may not be directly applicable to assessments where odour modelling guidelines have been developed based on the standard olfactometry method. It should be noted that before the European Standard for olfactometry, EN 13725, was promulgated, the Dutch standard method NVN280 was widely used (and was probably the most robust method at that time). However, there is a factor of two difference between results obtained using the Dutch method and those obtained by EN 13725, due to differences in how the odour panel report they have detected an odour. Because the other main requirements of EN 13725 are met by the Dutch standard it is possible to divide the results by two to obtain the value in EN 13725 equivalent units. However, many ODTs published in the literature were obtained by olfactometry methods (many not standard methods) that pre-dated both these methods by some time and the quality is very variable.

Van Harreveld (2003) has mainly attributed the wide range of thresholds quoted (typically several orders of magnitude) to no reference odours having been defined and no ‘agreed reference values’ agreed for these odours that could be used to ‘calibrate’ the panels by selecting assessors with ‘normal’ olfactory acuity. These problems have been largely addressed by the EN 13725: 2003 standard, which defines the EROM, or mass that is just detectable when evaporated into 1 m^3 of neutral gas, as equivalent to 123 μg *n*-butanol. In other words, 1 ou_E m^{-3} $\equiv$ 40 μmol/mol $\equiv$ 40 ppb/v, or a $\log_{10}$ value of 1.6.

Both detection and certainty or recognition odour thresholds for compounds are reported in the literature. The detection threshold is the lowest concentration of a compound that can just be detected by a certain percentage of the population, while the certainty or recognition threshold is the lowest concentration of a compound that can be recognised with certainty as having a characteristic odour quality. Typically, recognition thresholds are approximately two to ten times the detection threshold (although some sources quote three to five times). The New Zealand Technical Report (Ministry for the Environment New Zealand 2002) reported threshold data obtained in the USA in the mid-1990s for single, pure compounds (WEF 1995, Table 9.1). This showed the relationship between the *detection threshold* (the concentration at which the odorant is detected with certainty by an olfactometry panel) and the *recognition threshold* (the concentration at which the character and hedonic tone of the odorant is recognisable). In theory, a single odorant detected in ambient air will not cause nuisance until it is present at a concentration that is at the recognition threshold or higher. For the range of odorants in the table, the ratio between the two thresholds varies considerably, between 1 (no difference in the thresholds) and 50 (large difference). The typical ratio is in the range of 2 to 10. When using odour threshold data it is important to be clear about which type of threshold is being reported.

Table 9.1 Detection and recognition thresholds for some odorous compounds (WEF 1995)

Compound name	Odour threshold (ppm v/v)		Odour description	Recognition: detection ratio
	Detection	Recognition		
Acetaldehyde	0.067	0.21	Pungent, fruity	3.1
Allyl mercaptan	0.0001	0.0015	Disagreeable, garlic	15
Ammonia	17	37	Pungent, irritating	2.2
Benzyl mercaptan	0.0002	0.0026	Unpleasant, strong	13
n-Butyl amine	0.080	1.8	Sour, ammonia	22.5
Chlorine	0.080	0.31	Pungent, suffocating	3.9
Di-isopropyl amine	0.13	0.38	Fishy	2.9
Dimethyl sulphide	0.001	0.001	Decayed cabbage	1
Diphenyl sulphide	0.0001	0.0021	Unpleasant	21
Ethyl amine	0.27	1.7	Ammonia-like	6.3
Ethyl mercaptan	0.0003	0.001	Decayed cabbage	3.3
Hydrogen sulphide	0.0005	0.0047	Rotten eggs	9.4
Methyl mercaptan	0.0005	0.0010	Rotten cabbage	2
Phenyl mercaptan	0.0003	0.0015	Putrid, garlic	5
Propyl mercaptan	0.0005	0.020	Unpleasant	40
Pyridine	0.66	0.74	Pungent, irritating	1.1
Skatole	0.001	0.050	Faecal, nauseating	50
Sulphur dioxide	2.7	4.4	Pungent, irritating	1.6

The New Zealand Technical Report (Ministry for the Environment New Zealand 2002) summarises some other useful references for odour threshold data:

- Nagy (1991) undertook work sponsored by the Air Resources Board of the Ontario Ministry for the Environment. Forced-choice dynamic olfactometry was used to determine the 50% detection levels for 86 pure compounds as µg m^{-3} using a nine-member panel.
- The American Industrial Hygiene Association (AIHA) published odour thresholds for 102 compounds in 1989. The AHIA (1989) reference does not incorporate any odour threshold data that are more recent than the 1980s, even though it was last published in 1997, and many of the data they rely on are much older. This was a critical review, and of 191 primary

sources 155 references were excluded as unacceptable. This publication remains one of the preferred sources of odour threshold data.

- Van Gemert (1999) is a compilation reference based on literature values of odour threshold concentrations incorporating studies since 1977. (The most recent study incorporated prior to this review was Devos *et al.* in 1990). No attempt is made to critically evaluate the data, but data are given chronologically for each compound with the original data source identified. More than 1100 compounds with one or more odour threshold references are reported.

All of the above references were available when the draft H4 guidance was written. An updated and revised version of the Van Gemert compilation was published in 2003. A copy has been requested but it has not been possible to obtain this in time for this literature review.

However, recent work on odour thresholds carried out in Japan may add to the knowledge in the draft H4 guidance. In Japan, 22 chemical compounds, known as ‘specified odour offensive substances’ are regulated by local government (Kamigawara 2003; Fujita 2004). Regulation is not just by olfactometry, but also by chemical analysis (by GC) of these compounds and comparison with limit values. Similarly, in Korea the same 22 designated odour compounds (Kim 2004) are regulated, the limit values being shown in Table 9.2

Table 9.2 Permissible atmospheric concentrations (ppm) of single offensive odorous substances in Korea (Kim 2004)

Offensive odorous substance	*Limit (ppm), industrial area*		Limit (ppm), other land-use areas
	Permissible level	**Strict permissible level**	
Ammonia	2	1–2	1
Methyl mercaptan	0.004	0.002–0.004	0.002
Hydrogen sulphide	0.06	0.02–0.06	0.02
Methyl disulphide	0.05	0.01–0.05	0.01
Methyl sulphide	0.03	0.009–0.03	0.009
Trimethylamine	0.02	0.005–0.002	0.005
Acetaldehyde	0.1	0.05–0.1	0.05
Styrene	0.8	0.4–0.8	0.4
Propylaldehyde	0.1	0.05–0.1	0.05
Butyraldehyde	0.1	0.029–0.1	0.029
n-Valeraldehyde	0.02	0.009–0.02	0.009
i-Valeraldehyde	0.006	0.003–0.006	0.003
Toluene	30	10–30	10
Xylene	2	1–2	1
Methyl ethyl ketone	35	13–35	13
Ethyl iso-butyl ketone	3	1–3	1
Butyl acetate	4	1–4	1
Propionic acid	0.07	0.03–0.07	0.03
n-Butyral acid	0.002	0.001–0.002	0.001
n-iValeric acid	0.002	0.0009–0.002	0.0009
i-Valeric acid	0.004	0.001–0.004	0.001
i-Butyl alcohol	4	0.9–4	0.9

Japanese regulation of individual odour species originally made use of odour thresholds published by Leanardos *et al.* (1969) and Hellman and Small (1974), but recently work has been carried out by Nagata (2003) to measure in the laboratory the odour thresholds of 223 substances detected in various odour sources. The triangle bag method of olfactometry was used; this is a very different technical approach to dynamic dilution olfactometry, but it does go to great lengths to address the panel selection issue. Van Harreveld (2003) suggests that this may explain why results obtained by the Japanese triangle bag method appear very close to those obtained using the Dutch method NVN2820 (comparable with EN 13725) for the limited number of compounds that could be found in available papers. This can be seen in Table 9.3.

Table 9.3 Comparison of Dutch and Japanese odour detection thresholds (Van Harreveld 2003)

Compound	Odour quality	Odour detection threshold (ppm)		
		NL	Japan	Factor Japan/NL
Acetone	Sweet/fruity	28.0		
Benzene	Aromatic/sweet	1.7		
n-Butylacetate	Sweet/banana	0.076		
n-Butanol	Sweet/alcohol	0.040	0.038	0.95
Ethyl alcohol	Sweet/alcohol	0.370		
Hydrogen sulphide	Rotten eggs	0.0005	0.000495	0.99
Isobutyl alcohol	Sweet/musty		0.012	
Methyl ethyl ketone	Sweet/sharp	3.1		
Methyl mercaptan	Rotten cabbage		0.000102	
Styrene	Sharp/sweet	0.025	0.033	1.32
Toluene	Sour/burnt	1.6	0.9	0.58

The odour thresholds of 223 substances measured by Nagata in the laboratory using the triangle odour bag method are listed in Table 9.4.

Table 9.4 Odour thresholds (ppm, v/v) measured by the triangle odour bag method (Nagata 2003)

Compound	Odour threshold (ppm/v/v)
Acetaldehyde □	0.0015
Acetic acid	0.0060
Acetone	42
Acetonitrile	13
Acrolein	0.0036
Acrylonitrile	8.8
Allyl sulphide	0.00022
Ammonia	1.5
iso Amyl mercaptane	0.00000077
n-Amyl mercaptane	0.00000078
Benzene	2.7
1,3-Butadiene	0.23
n-Butane	1200
iso Butanol	0.011
n-Butanol	0.038
sec.Butanol	0.22
tert.Butanol	4.5
iso Butene	10
1-Butene	0.36
2-n-Buthoxyethanol	0.043
1-Butoxy-2-propanol	0.16
iso Butyl acetate	0.0080
n-Butyl acetate	0.016
tert.Butyl acetate	0.071
sec.Butyl acetate	0.0024
iso Butyl acryrate	0.00090
n-Butyl acryrate	0.00055
iso Butylaldehyde	0.00035
n-Butylaldehyde	0.00067
Butylamine	0.17
iso Butylamine	0.0015
n-Butylamine	0.17
tert. Butylamine	0.17
n-Butylbenzene	0.0085
n-Butyl n-butyrate	0.00480.0048
n-Butyl iso butyrate	0.022
iso Butyl n-butyrate	0.0016
iso Butyl iso butyrate	0.075
n-Butyl formate	0.087
iso Butyl formate	0.49
Butyl mercaptane	0.000030
iso Butyl mercaptane	0.0000068
n-Butyl mercaptane	0.0000028
tert. Butyl mercaptane	0.000029
iso Butyl propionate	0.020
n-Butyl propionate	0.036
iso Butyl isovalerate	0.0052
n-Butyl isovalerate	0.012
iso Butyric acid	0.0015
n-Butyric acid	0.00019
Carbon disulphide	0.21
Carbonyl sulphide	0.055
Carbon tetrachloride	4.6
Chlorine	0.049
Chloroform	3.8
m-Cresol	0.00010
o-Cresol	0.00028
p-Cresol	0.000054
Crotonaldehyde	0.023
Cyclohexane	2.5
n-Decane	0.62
n-Decanol	0.00077
n-Decylaldehyde	0.00040
Diacetyl	0.000050
Diallyl disulphide	0.00022
Dichloromethane	160
o-Diethylbenzene	0.0094
m-Diethylbenzene	0.070
p-Diethylbenzene	0.00039
Diethyl disulphide	0.0020
Diethyl sulphide	0.000033
Diethylamine	0.048
2,5-Dihydrofurane	0.093
Dimethylamine	0.033
2,2-Dimethylbutane	20
2,3-Dimethylbutane	0.42
Dimethyl disulphide	0.0022
2,2-Dimethylpentane	38
2,3-Dimethylpentane	4.5
2,4-Dimethylpentane	0.94
Dimethyl sulphide	0.0030
n-Dodecane	0.11
Ethanol	0.52
2-Ethoxyethanol	0.58
2-Ethoxyethyl acetate	0.049
Ethyl acetate	0.87
Ethyl acryrate	0.00026
Ethylamine	0.046
Ethylbenzene	0.17
Ethyl n-butyrate	0.000040
Ethyl formate	2.7
Ethyl isobutyrate	0.000022
Ethyl mercaptane	0.0000087
3-Ethylpentane	0.37
Ethyl propionate	0.0070
o-Ethyltoluene	0.074
m-Ethyltoluene	0.018

p-Ethyltoluene	0.0083
Ethyl-o-toluidine	0.026
Ethyl n-valerate	0.00011
Ethyl isovalerate	0.000013
Formaldehyde	0.50
Furane	9.9
Geosmin	0.0000065
n-Heptane	0.67
1-Heptene	0.37
n-Heptanol	0.0048
n-Heptylaldehyde	0.00018
n -Hexane	1.5
n-Hexanoic acid	0.00060
iso Hexanoic acid	0.00040
n-Hexanol	0.0060
1-Hexene	0.14
n-Hexyl acetate	0.0018
n-Hexylaldehyde	0.00028
n-Hexyl mercaptane	0.000015
Hydrogen sulphide	0.00041
Indole	0.00030
Isoprene	0.048
Limonene	0.038
Methacrolein	0.0085
Methacrylonitrile	3.0
Methanol	33 sec
Methyl acetate	1.7
Methyl acryrate	0.0035
Methyl allyl sulphide	0.00014
Methylamine	0.035
Methyl iso amyl ketone	0.0021
Methyl n-amyl ketone	0.0068
1,2,3,4-tetra Methylbenzen	0.011
Methyl n-butyrate	0.0071
Methyl iso Butyrate	0.0019
Methyl n-butyl ketone	0.024
Methyl iso butyl ketone	0.17
Methyl tert.butyl ketone	0.043
Methyl sec.butyl ketone	0.024
Methylcyclohexane	0.15
Methylcyclopentane	1.7
Methyl ethyl ketone	0.44
Methyl formate	130
4-Methylheptane	
2-Methylhexane	0.42
3-Methylhexane	0.84
Methyl mercaptane	0.000070
Methyl methacryrate	0.21
2-Methy3-Methylheptane	1.5
3-Methylpentane	8.9

2-Methylpentane	7.0
Methyl n-propyl ketone	0.028
Methyl isopropyl ketone	0.50
Methyl propionate	0.098
Methyl n-valerate	0.0022
Methyl isovalerate	0.0022
Nitrogen dioxide	0.12
n-Nonane	2.2
n-Nonanol	0.00090
1-Nonene	0.00054
n-Nonylaldehyde	0.00034
n-Octane	1.7
1-Octene	0.0010
n-Octanol	0.0027
iso Octanol sec.	0.0093
Ozone	0.0032
n-Octylaldehyde	0.000010
n-Pentane	1.4
iso Pentane	1.3
n-Pentanol	0.10
iso Pentanol	0.0017
sec.Pentanol	0.29
tert. Pentanol	0.088
1-Pentene	0.10
Phenol	0.0056
á -Pinene	0.018
â -Pinene	0.033
Propane	1500
n-Propanol	0.094
iso Propanol	26
Propionaldehyde	0.0010
Propionic acid	0.0057
n-Propyl acetate	0.24
Propylamine	0.061
iso Propylamine	0.025
iso Propylbenzene	0.0084
n-Propyl n-butyrate	0.011
iso Propyl n-butyrate	0.0062
n-Propyl isobutyrate	0.0020
iso Propyl isobutyrate	0.035
n-Propylbenzene	0.0038
Propylene	13
n-Propyl formate	0.96
iso Propyl formate	0.29
n-Propyl mercaptane	0.000013
iso Propyl mercaptane	0.0000060
n-Propyl propionate	0.058
iso Propyl propionate	0.0041
n-Propyl n-valerate	0.0033
n-Propyl isovalerate	0.000056
Pyridine	0.063

Styrene	0.035
Skatole	0.0000056
Sulfur dioxide	0.87
Tetrachloroethylene	0.77
1,2,3,4-Tetrahydronaphthalene	0.0093
Tetrahydrothiophene	0.00062
Thiophene	0.00056
Toluene	0.33
Trichloroethylene	3.9
Trimethylamine	0.000032
Triethylamine	0.0054

1,2,4-Trimethylbenzen	0.12
1,3,5-Trimethylbenzen	0.17
2,2,5-Trimethylhexane	0.90
2,2,4-Trimethylpentane	0.67
n-Undecane	0.87
n-Valeraldehyde	0.00041
iso Valeraldehyde	0.00010
n-Valeric acid	0.000037
iso Valeric acid	0.000078
o-Xylene	0.38
m-Xylene	0.041
p-Xylene	0.058

9.5 Opportunities identified for strengthening Environment Agency guidance

The ODTs listed in the current draft of H4 were those of the most reliable provenance and quality that were available at the time of publication. However, none of the data were obtained using the olfactometry standard EN 13725 and are therefore of limited use for regulatory purposes. This review did not come across any published ODT lists obtained using EN 13725. Where such data are needed for regulatory purposes it is recommended that new ODT are measured using a UKAS-accredited olfactometry laboratory working strictly in accordance with method EN 13725. The Odour Relevance Survey did not, however, indicate that compound-specific ODTs were of great importance in the regulatory duties of Environment Agency staff and it may therefore be more appropriate to commission (or require operators to commission) any such measurements on a case-by-case basis as and when the need arises, rather than embark on a comprehensive programme.

Such EN 13725-based ODTs can be published in a regularly updated format, either within a revised version of H4 or independent of it. As an interim measure, the next version of H4 could include the odour thresholds of the 223 substances measured by Nagata using the triangle odour bag method, which has been shown to compare reasonably well with the European olfactometric approach.

10 Key findings of the review for improving the draft H4 guide

The Environment Agency's draft H4 guidance allows PPC applicants to derive industry-specific dose-response relationships between annoyance and 98th percentile concentrations (1-hour average), as an alternative to using the indicative exposure standards provided (which are effectively 'default values'). At the time of writing, the Environment Agency had not received any applications in England and Wales that used bespoke industry-specific dose-response relationships. It is perhaps worth noting that in the New Zealand guidance that post-dates the draft H4 a stronger steer is given: industry is expected to derive their own dose-response relationships and it is made clear that the indicative guideline values provided there are temporary and only for use until such studies have been completed.

The Odour Relevance Survey identified odour sources, sectors and activities that were of greatest importance to Environment Agency regulatory staff and obtained the views of those staff on the categorisation of unpleasantness of those odours. This report takes those views, together with reviews of other relevant research, to address a key recommendation in previous Environment Agency research on this subject: namely, to obtain a revised categorisation of unpleasantness that includes the expert opinion of environmental regulators and practitioners.

While for many odour sources, sectors and activities there is consensus on their relative unpleasantness categorisation, for others there is some disagreement on the category, or there is some argument for subdividing sectors between different categories. This is complicated by the fact that some installations may have multiple odour sources, each with different degrees of unpleasantness. A further complicating factor is that the character and unpleasantness of an odour source can change significantly when certain types of end-of-pipe abatement are used to treat the exhaust gas. The current conceptual model in draft H4 for a three-banded categorisation of industry sectors to give Indicative Odour Exposure Standards has difficulty dealing with these complicating factors.

It is recommended that future revision of the H4 guidance addresses this as follows:

1. By giving clear guidance that a representative sector-specific dose-response study to provide industry-specific modelling exposure standards is the preferred, best practice approach

The revised guidance should be more explicit in stating that the Indicative Odour Exposure Standards are default values to be used only until such time as UK dose-response studies allow industry-specific exposure standards to be derived.

The guidance should positively encourage (by appropriate mechanisms) the relevant industry sectors to become involved in such studies.

2. Make more robust and relevant UK dose-response work a priority

The Indicative Odour Exposure Standards in the current draft of H4 were derived from a dose-response study of a Dutch piggery using an older style atmospheric dispersion model. Although this response curve was found by researchers in New Zealand to be valid for a pulp mill there, a priority for strengthening any revised H4 guidance would be to obtain more robust and relevant UK dose-response data. It should be noted that this was a key recommendation in the earlier Environment Agency research (Environment Agency 2002b) that formed the backdrop to the draft H4.

The most robust and relevant approach would be for representative sector-specific dose-response studies to be carried out in the UK, to derive bespoke odour modelling standards for those industries. Experiences in other countries have suggested that these usually require industry-sector-wide support and/or government support. As well as promoting and supporting such studies itself, the Environment Agency should forge links with other interested parties: it is possible that some dose-response studies will be performed around waste management facilities as part of Defra's Waste Research R&D programme. There is also a possibility of UK Water Industry Research (UKWIR) coordinating some studies around wastewater treatment plants to support the water industry in meeting the Defra Code of Practice on Odour Nuisance from Sewage Treatment Works. Regulators in other countries (particularly Australia and New Zealand) have issued odour guidance strongly encouraging industries to carry out sector-specific dose-response studies. Forging links with these regulators could allow valuable data to be obtained that has not otherwise been published.

3. By giving clear guidance that the use of the Indicative Odour Exposure Standards approach is temporarily acceptable as an interim measure

The wording and the prominence of such wording in any revised H4 guidance should make it clear that sector-specific dose-response studies are the best practice approach, but Indicative Odour Exposure Standards based on non-sector-specific studies are acceptable in the interim period, until the sector-specific studies have been performed. However, even such interim non-sector-specific studies need to be robust, and there are opportunities for improving and refining the interim Indicative Odour Exposure Standard approach.

4. Improving and refining the interim Indicative Odour Exposure Standard approach

The revised guidance could improve this interim approach by:

A. Establishing a more robust default dose-response curve on which a default Indicative Odour Exposure Standard is based, corresponding to a particular level of annoyance (e.g. 10%). (This may or may not be the same value as the 1.5 ou m^{-3} concentration derived from the Dutch livestock study.) It is recommended that one carefully selected study is carried out as soon as possible in the UK, using the EN 13725 olfactometry method and a currently accepted dispersion model. The application of annoyance guidelines from this study to other industry sectors would require consideration of how to deal with sources of differing unpleasantness and multiple sources. One option would be to continue with the existing draft H4 approach of putting different sectors/activities into a number (currently three) of different bands, having Indicative Odour Exposure Standards with different concentration limits to account for the varying unpleasantness. Practical research on hedonic scores for selected industrial odours would help refine this approach.

B. Offer clearer guidance on how a default value Indicative Odour Exposure Standard could then be adjusted for specific conditions and factors.

Rather than a simple three-band classification, the revised guidance could offer clearer guidance to users (perhaps by means of an annotated flowchart) on how, starting from a single default value, the Indicative Odour Exposure Standard value could then be adjusted for specific conditions and factors, i.e. the Indicative Odour Exposure Standard would just be the starting point. These specific conditions and factors would include:

i. Relative unpleasantness of the odour – guidance would need to consider whether to use an unpleasantness band approach (and how many bands, what concentration values to assign to them, which industries/activities to each band); a correction factor approach, as used in New Zealand, to give a revise exposure standard; or whether to leave the default exposure standard uncorrected and then to bear in mind in the interpretation that the predictions may be either optimistic or pessimistic. Consideration should be given to measuring the hedonic scores for selected industrial odour types: the European and UK data given in draft H4 are strictly on rank order, and do not provide a comparative magnitude (i.e. they are not hedonic scores); the accompanying US data (Dravnieks) were obtained in the mid-1980s and laboratory odour analysis methodology has since developed a long way. Obtaining hedonic scores for selected industrial odour types would strengthen the basis for assigning different odours and industry types to the three categories of Indicative Odour Exposure Standard. It would also be possible to try to add some understanding to the comparative magnitude of unpleasantness to the ranked odours described in H4. Samples of the odour or associated odorant would be assessed for hedonic tone to see if they remain in the same order as when the descriptors were ranked. Some candidate odours would be skatole for faecal, ammonia, kerosene, petrol, turpentine, allyl chloride for garlic/onion, eucalyptus, cloves, cologne, and limonene for lemon. The Environment Agency should also investigate what progress has been made on determining odour annoyance potentials.

ii. How multiple sources will be dealt with – the guidance will need to address the hedonic tone of a single source (as in i, above) and also multiple sources of the same hedonic tone and multiple sources of different hedonic tone. It is possible that this approach will not be able to deal with the latter in anything other than a qualitative way.

iii. The sensitivity of the receiving environment. This could also be expanded to include tolerance to more of an existing odour that is a common feature of the area, or conversely a new odour.

Regarding B(i) above, it is recommended that if the unpleasantness band approach is retained, a revised version of Table A6.1 from draft H1 is drawn up taking into account the findings of this chapter on a revised categorisation of unpleasantness for the odour sources, sectors and activities that were of greatest importance to Environment Agency regulatory staff.

Recent German research on the influence of hedonic tone on annoyance, carried out since the Dutch studies that formed the basis of the draft H4 approach, suggests there is no significant difference between the annoyance potential of unpleasant odours and neutral odours. Pleasant odours do, however, have a significantly lower annoyance potential at the same intensity. This finding throws some doubt on basing the Indicative Odour Exposure Standards on a three-band system for odour unpleasantness; it may be necessary to consider a simplified system, dividing odours into two categories, one for pleasant odours and the other for neutral or unpleasant odours (the latter not distinguishing between moderately unpleasant and highly unpleasant odours). There is in any case probably more consensus on which odours are pleasant than there is in choosing whether an odour falls in the other two bands. Removing the need to decide on assignment to neutral or unpleasant would perhaps remove an area of contention without any loss in robustness of this conceptual model. This would be particularly so if the other Environment Agency research on odour assessment uncertainty shows that the component uncertainty in this band choice is small compared to other component uncertainties in the assessment method.

It is recognised that there are limits on resources for such studies and careful consideration needs to be given to how much should be invested in refining the interim Indicative Odour Exposure Standards approach as against investing in the preferred representative sector-specific dose-response studies to be carried out in the UK, to derive bespoke odour modelling standards for those industries. Whether these studies would be good value for the effort involved would depend up:

- How the effort and expense in refining the banding allocation of the Indicative Odour Exposure Standard approach compares to the effort and expense in carrying out the preferred approach of obtaining UK, sector-specific dose-response relationships. On technical grounds, the latter is the preferred approach.
- How important the choice of unpleasantness band is for the outcome of an H4 modelling exercise compared to the uncertainties in other aspects of the study. For example, the choice of unpleasantness band

will determine whether the Indicative Odour Exposure Standard is set at 1.5, 3.0 or 6.0 $ou_E\ m^{-3}$. It may be, however, that this choice is much less significant than the uncertainties in quantifying the source odour emission rate or in the atmospheric dispersion modelling. Another Environment Agency project (P4-120/2 Project 3, *Review of Dispersion Modelling for Odour Predictions*) is looking at this issue.

5. Recommendations for compound-specific ODTs

The ODTs listed in the current draft of H4 were those of the most reliable provenance and quality that were available at the time of publication. However, none of the data were obtained using the olfactometry standard EN 13725 and are therefore of limited use for regulatory purposes. This review did not come across any published ODT lists obtained using EN 13725. Where such data are needed for regulatory purposes it is recommended that new ODT are measured using a UKAS-accredited olfactometry laboratory working strictly in accordance with method EN 13725. The Odour Relevance Survey did not, however, indicate that compound-specific ODTs were of great importance in the regulatory duties of Environment Agency staff and it may therefore be more appropriate to commission (or require operators to commission) any such measurements on a case-by-case basis as and when the need arises, rather than embark on a comprehensive programme.

Such EN 13725-based ODTs can be published in a regularly updated format, either within a revised version of H4 or independent of it. As an interim measure, the next version of H4 could include the odour thresholds of the 223 substances measured by Nagata using the triangle odour bag method, which has been shown to compare reasonably well with the European olfactometric approach.

6. Other recommendations

A revised draft of H4 would benefit from:

- Tighter and bolder definitions of terms (e.g. odour strength, intensity, concentration, character, quality, offensiveness, relative unpleasantness and hedonic tone) and better consistency in their use through the guidance.
- The differences between exposure, annoyance and nuisance should be explained in more precise terms and be given greater prominence, as should the differences between annoyance and annoyance potential.
- The annoyance impacts should be described in terms of the FIDOL factors, making the revised guidance consistent with the most up-to-date guidance offered by other regulators.
- Making clear that the term offensiveness has two meanings. The revised guidance should use the term relative unpleasantness in place of offensiveness to avoid confusion. This would perhaps require the guidance to set a new precedent in describing the acronym for odour impact as the FIDUL factors.

- The odour descriptor list needs to be reviewed and perhaps expanded. It would be helpful to make use of descriptors used by other practitioners, and consider the format for the descriptors, e.g. lists and/or odour wheels.
- Consistency between the revised odour descriptor list/wheels (or a simplified version) and the Environment Agency's central system of recording odour complaints is highly desirable.
- The Environment Agency should make it explicit that the validity of the Indicative Odour Exposure Standards used in the H4 modelling approach are dependent on the dynamic dilution olfactometry measurements being carried out to the full requirements of the standard BS EN 13725. The guidance should make it explicit that assessments that do not use this standard method are unacceptable for regulatory purposes.
- The sniff test protocol given in Appendix 8 of draft H4 should be reviewed to ensure all the FIDOL factors are properly represented and that the impact scale is consistent with those used by other workers.
- In describing field odour assessments of ambient odour, the guidance should refer to quantitative measurements of total odour concentration by field olfactometry (e.g. using NasalRanger or Scentometer instruments) to complement the description of subjective sensory tests (sniff tests). Field olfactometry is a quantitative tool for compliance checking at the site boundary or at sensitive receptors, which allows the possibility of setting numerical benchmarks.
- The concept of OCI relationships could be used in a revised draft of H4 to strengthen guidance on odour impact assessments. If it was a requirement that the OCI relationship for a odour source type be established (by on-site sampling and laboratory odour analysis), this would allow an intensity guidance level (e.g. 'distinct' odour intensity) to be set and then converted to the equivalent concentration units for comparison with the model results. Though this would strengthen odour impact assessments, it would not provide any advantage to the H4 back-calculation method of setting odour emission limit values based on meeting acceptable numerical benchmarks derived from industry-specific dose-response studies. In a bespoke dose-response study, it is only necessary to get a good correlation with the dose and it does not matter whether that is measured as intensity or concentration. This is perhaps another good reason for emphasising that bespoke odour standards derived from industry-specific dose-response studies carried on in the UK are preferred to the use of Indicative Odour Exposure Standards.

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Glossary

Abatement
An end-of-pipe control measure to reduce odour levels in the exhaust gas of a source, usually a controlled point source.

Adaptation
The long-term process that can occur when communities become increasingly tolerant of a particular source of odour, which is primarily a psychological response to the situation. For example, where odours are associated with a local industry that is considered to be important for the well-being of the local community and the industry maintains a good relationship with community members, then adaptation to the odour effects can occur over time.

Annoyance
Odour annoyance can be considered the expression of disturbed well-being induced by adverse olfactory perception in environmental settings. Odour annoyance occurs when a person exposed to an odour perceives the odour as unwanted. Annoyance is the complex of human reactions that occurs as *a result of an immediate exposure* to an ambient stressor (odour) that, once perceived, causes negative cognitive appraisal that requires a degree of coping. Annoyance may, or may not, lead to nuisance and to complaint action.

Annoyance potential
Annoyance potential is *the attribute of a specific odour* (or mixture of odorants) to cause a negative appraisal in humans that requires coping behaviour when perceived as an ambient odour in the living environment. It is an attribute of an odour that can cause annoyance and may lead to nuisance and complaint. Annoyance potential indicates the magnitude of the ability of a specific odorant (mixture), relative to other odorants (mixtures), to cause annoyance in humans when repeatedly exposed in the living environment to odours classified as 'weak' to 'distinct odour' on the scale of perceived intensity (VDI 3882:1997, part 1). Annoyance potential is likely to be function of both hedonic tone and odour character/quality. Whether annoyance potential of an odour does, or does not, cause annoyance depends on location and receptor factors

Anosmia
The medical condition where an individual has no sense of smell at all.

Character (of an odour)
Odour character or quality is basically what the odour smells like. It is the property that identifies an odour and differentiates it from another odour of equal intensity. For example, ammonia gas has a pungent and irritating smell. The character of an odour may change with dilution.

Chemical analysis
A variety of instruments can be used as sensors to measure the concentration of one or more odorous chemical compounds. The compound concentration can then be compared to the odour threshold to see if an odour is likely to be detected (odour detection threshold) or recognised (odour recognition threshold). The mass concentration of the compound can be converted approximately into odour concentration units (ou m^{-3}) by expressing it in multiples of the compound's ODT.

Community surveys
Measuring directly the odour impact (e.g. annoyance) in the local population by survey methods (e.g. quality of life surveys).

Complaints
Odour complaints occur when individuals consider the odour to be unacceptable and are sufficiently annoyed by the odour to take action.

Concentration (of an odour)
Concentration is the amount of odour present in a given volume of air. We measure and model odour concentration, not odour intensity. For a known, specific chemical species this can be expressed either as the volume of that compound per unit volume of air (e.g. ppm or ppb) or the mass of that compound per unit volume of air (e.g. mg m^{-3} or μg m^{-3}). For odours that are mixtures of compounds, concentration is measured in ou_E m^{-3}.

Descriptor (of an odour)
The odour character is assessed by either the degree of its similarity to a set of reference odours or the degree to which it matches a scale of various 'descriptor' terms. Numerous standard odour descriptors, in list form or as 'odour wheels' (with the general descriptors placed at the centre of the wheel and more specific characters towards the wheel rim) have been developed for use as a reference vocabulary by assessors.

Desensitisation (of individuals to odour)
This can, like sensitisation, result from exposure to an odour. A person may become unable to detect the odour, or there is a reduction in the perceived odour intensity and/or effect, even though the odorous chemical is still present in the air.

Dilutions to threshold ratio
A measure of the number of dilutions (with carbon-filtered air) needed to make the odorous ambient air non-detectable. D/T is similar to the units of ou m^{-3} used in dynamic dilution olfactometry, although the two are not interchangeable or directly comparable.

Dravnieks
The US term for hedonic scores, after Dravnieks A., Masurat, T. and Lamm, R.A. (1984) who measured the hedonic scores of generic, everyday (i.e. non-industrial) odours. These are shown in Table A10.2 in Appendix 10 of draft H4 (reproduced as Table 6.1 here).

Duration
The duration of the odour occurrence is how long an individual is exposed to odour in the ambient environment.

Dynamic dilution olfactometry
The measurement of odour concentration using human subjects as the 'sensor'. The CEN standard has been adopted by practitioners in most of the world and has become the *de facto* international standard for laboratory dynamic dilution olfactometry (DDO). The concentration of the odour sample is measured in $ou_E\ m^{-3}$, which is equivalent to the number of repeated dilutions with a fixed amount of odour-free air or nitrogen that are needed until the odour is just detectable to 50% of a panel of trained observers. DDO is a valuable objective measure of odour concentration. It is limited in application to air samples having odorant concentrations at many times above the detection threshold (usually at least 50 $ou_E\ m^{-3}$).

Empirical dose-response approach
The approach to obtaining an odour modelling guideline value from an empirical dose-response study relating modelled exposures to community responses (e.g. annoyance).

European odour units per cubic metre of air ($ou_E\ m^{-3}$)
Equivalent to the number of repeated dilutions with a fixed amount of odour-free air or nitrogen that are needed until the odour is just detectable to 50% of a panel of trained observers in a DDO determination to the CEN standard BS EN 13725.

Exposure
The result of an exposure chain, consisting of an odour source, a transport mechanism and a receptor. Magnitude of odour exposure is determined by the FIDOL factors. Once exposure to odour has occurred, the process can lead to annoyance, nuisance and possibly complaints.

FIDOL factors
The perception of the impact of odour involves not just the strength of the odour but also its frequency, intensity, duration and offensiveness (the unpleasantness at a particular intensity) and the location of the receptors. These attributes are known collectively as the FIDOL factors.

Field olfactometers
In the USA it is common to find hand-held field olfactometers (examples are the NasalRanger® and Scentometer® instruments) used to measure the concentration of ambient odours in units of D/T. This concentration measurement is in similar units to those obtained from laboratory DDO (i.e. $ou_E\ m^{-3}$), but they are not considered interchangeable. It should be remembered that laboratory DDO uses a panel to give an estimate of concentration based on a population ODT, whereas field olfactometry gives an estimate of concentration based on an individual's ODT.

Frequency
The frequency of the odour occurrence is how often an individual is exposed to odour in the ambient environment.

Fresh air
Air perceived as being air that contains no chemicals or contaminants that could cause harm, or air that smells 'clean'. Fresh air may contain some odour, but these odours will usually be pleasant in character or below the human detection limit.

Hedonic scores
Quantitative values assigned to the unpleasantness of source emission samples, by measurement in the laboratory by a panel of trained assessors in an odour panel following the German method VDI 3882 Part 2. Hedonic tone is scored on a nine-point scale ranging from very pleasant (score of +4, e.g. bakery smell) through neutral to highly unpleasant (score of -4, e.g. rotting flesh).

Hedonic tone (of an odour)
Hedonic tone is the degree to which an odour is perceived as pleasant or unpleasant. Such perceptions differ widely from person to person, and are strongly influenced by previous experience and emotions at the time of odour perception. Hedonic tone is related to (but not synonymous with) the relative pleasantness or unpleasantness of an odour

Impact (of odour)
When emissions containing odorants are released to the atmosphere they can have an impact on the environment. Although under some circumstances this could include an impact on the ecosystem or on human health, that would be a factor of the chemical nature (e.g. toxicity) of the release rather than its odorous nature *per se*. By convention, the term odour impact is restricted to the negative appraisal by a human receptor of the odour exposure. This appraisal, occurring over a matter of seconds or minutes, involves many complex psychological and socio-economic factors. Once exposure to odour has occurred, the process can lead to annoyance, nuisance and possibly complaints.

Indicative Odour Exposure Standards
The Environment Agency's numerical benchmarks for odour mixtures that were put forward in the draft H4 guidance. The Indicative Odour Exposure Standard is, in effect, a modelling guideline standard used by the Environment Agency when determining applications/variations under PPC, to define in numerical terms its 'benchmark' criterion of 'no reasonable cause for annoyance'.

Intensity (of an odour)
How strong an odour is perceived to be. Odour intensity describes the relative magnitude of an odour sensation as experienced by a person, i.e. we perceive odour intensity, not odour concentration.

No reasonable cause for annoyance
For the purposes of the PPC Regulations, the Environment Agency deems the point at which pollution in the form of offence to the sense of smell is occurring to be the point at which there is ‘reasonable cause for annoyance’. The aim of odour control is therefore to ensure there is ‘*no* reasonable cause for annoyance’. This ‘benchmark’ criterion of ‘no reasonable cause for annoyance’ does not necessarily equate to no complaints – it is designed to be a level of exposure that a high proportion of the exposed population, with normal sense of smell, finds ‘acceptable’ on a long-term basis. Conversely, the lack of complaint should not necessarily imply the absence of an odour problem, as there will be an underlying level of annoyance before complaints are made.

Nuisance
Nuisance is *the cumulative effect* on humans, *caused by repeated events of annoyance over an extended period* of time, that leads to modified or altered behaviour. This behaviour can be active (e.g. registering complaints, closing windows, keeping ‘odour diaries’, avoiding use of the garden) or passive (only made visible by different behaviour in test situations, e.g. responding to questionnaires or different responses in interviews). Odour nuisance can have a detrimental effect on our sense of well-being, and hence a negative effect on health. Nuisance occurs when people are affected by an odour they can perceive in their living environment (home, work-environment, recreation environment) and:

i) the appraisal of the odour is negative;
ii) the perception occurs repeatedly;
iii) it is difficult to avoid perception of the odour; and
iv) the odour is considered a negative effect on their well being.

Nuisance is not caused by short-term exposure, and it is not alleviated by relatively short periods (months) of absence of the ambient stressor. Nuisance appears to be caused by long-term intermittent exposure to odours.

Numerical benchmark criteria
The collective term used for odour exposure limits from different sources and agencies, such as WHO guideline values, the Environment Agency’s Indicative Odour Exposure Standards, and custom and practice benchmarks.

OCI relationships
Carrying out repeat odour intensity and concentration measurements allows the odour concentration–intensity (OCI) relationship to be established for specific odorants (including complex mixtures), enabling different odour types to be compared. The OCI relationship demonstrates the correlation between the inhaled odour concentration and the odour intensity category and gives an indication of the expected odour perception by the receptors to a particular odour concentration. Stevens’ Law and the Weber–Fechner Law are examples of formulae which have widespread acceptance for defining the OCI relationship.

Odour annoyance threshold approach
Odour modelling guidelines derived from an essentially theory-based analysis of odour definitions from first principles. This approach was used as the basis for the interim criteria that were recommended as New Zealand's first national odour concentration guideline values for all types of odour sources.

Odour detection threshold
The ODT is the lowest concentration of any specific chemical or mixture at which it can be ascertained that an odour is present, i.e. the level that produces the first sensation of odour.

Odour-free air
Air containing no odorous chemicals at all.

Odour modelling guideline value
A numerical benchmark criteria used specifically for relating the occurrence of adverse effects, such as annoyance, with the concentrations of odour at various receptor sites as predicted by atmospheric dispersion modelling.

Offensiveness (of an odour)
A lack of agreed terminology has resulted in there being two meanings in common use of the term *offensivenes*s of an odour, which can be confusing. On the one hand, offensiveness is sometimes used to describe the character and unpleasantness of an odour at a particular intensity, so it is related to the hedonic tone – one of the FIDOL factors. When used in this context, the term *relative offensiveness* is sometimes used. However, offensiveness is also used in the context of overall impact in terms of 'offence to the senses'. Here it has a much broader meaning, encapsulating the combined effect of most or all the FIDOL factors.

To avoid this confusion of terms, this document has used the term *odour unpleasantness* to describe the character of an odour as it relates to the hedonic tone. The term *offensiveness* has been used solely to describe the combined effect of all the FIDOL factors in terms of 'offence to the senses'

Olfaction
The human ability for the sensing of smell.

Olfactory fatigue
The term sometimes used to describe desensitisation that occurs on a short-term basis.

Quality (of an odour)
What an odour is perceived to be like. See *Character (of an odour)*.

Recognition threshold
The concentration, at some point above the odour detection threshold, at which the odour is recognised as having a characteristic odour quality. The concentration at which the character and hedonic tone of the odorant is recognisable.

Relative unpleasantness (of an odour)
The degree to which one odour is perceived as being more or less pleasant or unpleasant than another odour under similar conditions.

Sensitisation (of individuals to odours)
This may occur after acute exposure events or as a result of repeated exposure to nuisance levels of odours. Sensitisation changes a person's threshold of acceptability for an odour. This can result in a high level of complaint over the long term and a general distrust within the community of those perceived as responsible for the odour.

Sensitivity (of individuals to odours)
Different life experiences and natural variation in the population can result in different sensations and emotional responses by individuals to the same odorous compounds.

Sensitivity (of the receiving environment)
The type of land use and nature of human activities in the vicinity of an odour source and also the tolerance and expectation of the receptor. The 'Location' factor in FIDOL can be considered to encompass the receptor characteristics, receptor sensitivity and socio-economic factors.

Sensory analysis
Using the human nose as the sensor in an analytical measurement, a technique termed olfactometry.

Sensory testing
Using the human nose as a detector in tests for odour. In this context the tests are usually field tests for the assessment of odour impact. These tests can be subjective (so-called 'sniff tests') or objective (quantitative) using field olfactometry.

Setback distances
The use of a *cordon sanitaire* of a particular distance around specific industrial or agricultural activities to avoid causing adverse odour impact locally by removing the receptors from the odour exposure chain. Standard setback distances for livestock housing units are a popular tool for odour regulation in Australia and New Zealand, Europe and the USA.

Sniff test
This tool – also called a direct sensory test, subjective testing or simplified olfactometry – gives a subjective measure of odour impact based on the assessor's opinion on the FIDOL factors at the receptors which are compared with descriptive (or sometimes numerical) guidelines.

Strength (of an odour)
The magnitude of an odour – the odour strength – can be described in two ways, by its intensity and its concentration.

Abbreviations and acronyms

μg m^{-3} – micrograms per cubic metre
ASTM – American Society for Testing and Materials (method)
BAT – Best Available Techniques
CEN – Comité Europeén de Normalisation/European Committee for Standardisation
dB$_{od}$ – decibel (odor decibel equivalent)
DDO – dynamic dilution olfactometry
Defra – Department for Environment, Food and Rural Affairs
D/T – dilutions to threshold
ELV – emission limit value (at source)
EPA – Environmental Protection Agency
EROM – European Reference Odour Mass
FIDOL – frequency, intensity, duration, offensiveness and location
GC-MS – gas chromatography separation stage combined with mass spectrometry detection stage
GOAA *Guideline on Odour in Ambient Air* (German regulation)
mg m^{-3} – milligrams per cubic metre
OCI – odour concentration–intensity (relationship)
ODT – odour detection threshold
ou$_E$ m^{-3} – European odour units per cubic metre of air
PIR – Process Industry Regulation
ppb – parts per billion
PPC – (The) Pollution Prevention and Control (Regulations)
ppm – parts per million
UKAS – United Kingdom Accreditation Service
UKWIR – UK Water Industry Research (limited)
VDI – Verein Deutscher Ingenieure (standards)
WHO – World Health Organisation

We are The Environment Agency. It's our job to look after your environment and make it **a better place** – for you, and for future generations.

Your environment is the air you breathe, the water you drink and the ground you walk on. Working with business, Government and society as a whole, we are making your environment cleaner and healthier.

The Environment Agency. Out there, making your environment a better place.

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