DEVELOPMENT OF A REGULATORY STRATEGY FOR ODOUR IMPACT ASSESSMENT

By

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Abstract

Based on a critical review of North American odour regulations, it was concluded that current statutory nuisance laws and threshold principles do not meet the requirements of an effective regulatory strategy. An Odour Impact Model (OIM) developed previously helps to solve this deficiency by incorporating the effects of odour hedonics into odour impact assessments. This investigation fit a mathematical expression to the OIM dose-response curves of six pure odorants. A natural extension of this led to the development of the Odour Impact Dispersion Model (OIDM). This model merges the OIM's dose-response profiles with atmospheric dispersion modelling to predict and map a surrounding community's probability of response and degree of annoyance to an odorous emissions. The OIDM is applied to a case-study to investigate the impact of the facility's odorous emissions on surrounding communities. Recommendations for the development of an effective regulatory strategy for measuring and predicting the impact of odorous emissions are presented.

Sommaire

D'après une critique faite sur les règlements nord-américains de l'odeur, les lois de contrariété et les principes actuels du seuil d'intolérance n'atteignent pas les exigences d'une stratégie régulatrice efficace. Le développement antérieur d'un Modèle de l'Impact de l'Odeur (MIO) aide à combattre cette déficience en incorporant les effets du charactère d'odeur avec l'évaluation de l'impact de l'odeur. Cette étude s'est traduit en équation mathématique démontrée par les courbes de six odorants purs à doses réagissantes. Une prolongation naturelle de ceci a mené au développement du MIDO (Modèle d'impact de la Dispersion de l'Odeur). Ce modèle fusionne le graphique des doses réagissantes du MIO avec le modelage de dispersion atmosphérique pour prédire et décrire la probabilité de réaction et le degré de mécontentement d'une communauté environnante à une émission odorante. Le MIDO est appliqué à une étude de cas pour étudier l'impact que l'odeur aura sur les communautés environnantes. De plus, des conseils pour développer des stratégies réglementaires efficaces pour measurer des émissions odorantes sont présentées.

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1.0 Introduction

In today's society, the public has become increasingly aware and concerned for the environment in which they live. Society's desire for a healthy and comfortable living environment drives the public to demand clean water and fresh air, without any offensive odours. In terms of air pollution, odours have been generally ranked as the major contributors of public complaints to regulatory agencies in North American communities. It was estimated in 1979, more than 50% of the complaints related to air pollution dealt with exposure to odours (National Research Council Committee on Odours, 1979). Recently, in a 1994 survey of U.S. regulatory agencies, an analysis of the 25 responses indicated that in excess of 60% of air pollution complaints were related to odours with an estimated total of over 12,000 registered complaints in that year (Leonardos, 1996). For this reason, politicians and administrators who are responsible for the environment are constantly being pressured to find a solution to the odour problem.

In the United States, the Environmental Protection Agency (EPA) maintains that odour problems are local and not of national concern. As a result, there do not exist any federal odour regulations, and the EPA does not become involved in State or regional odour problems or regulations (Duffee, 1996). Similarly in Canada, odour control policies are specific to each province. A variety of odour control regulations and procedures exist across North America, however there does not yet exist a truly objective strategy for assessing the impacts of odorous emissions on residential areas affected by stationary sources. In turn, authorities are limited in establishing fair and effective standards which would eliminate or at least minimise, local odour nuisances.

Of the current odour regulations that do exist, most are based on statutory nuisance laws or the dilution-to-threshold principle. However, they do not meet all the requirements of an effective regulatory strategy, since none provide any insight on the potential degree of annoyance that will be experienced by the neighbourhood. To solve this deficiency, an Odour Impact Model (OIM) has been developed which is based on laboratory measurements of the response of a panel of odour judges to an odour which has been collected from the offending source. The Odour Impact Model provides a population's probability of detection, probability of discrimination, probability of complaint, and degree of annoyance profiles as functions of the number of dilutions of the odour from the source.

The primary objective of this study is to investigate the use of the Odour Impact Model in conjunction with atmospheric dispersion modelling to predict downwind odour dilutions and annoyance levels in the surrounding community. This can then provide regulatory agencies and plant administrators with a strategy for managing industrial odours. The Industrial Source Complex Short Term Dispersion Model Version 3 (ISCST3) developed by the United States Environmental Protection Agency was chosen for this study. The sub-objectives of this investigation include:

(i) a review of the present methods of odour measurement and assessment, and to provide a critical review of existing odour control policies that are used by various regulatory agencies;

(ii) the fit of a mathematical expression to the Odour Impact Model's dose-response curves using data collected in previous OIM investigations of six pure chemical odorants;

(iii) the establishment of a new Odour Impact Dispersion Model (OIDM) that incorporates atmospheric dispersion modelling into the Odour Impact Model to predict the downwind odour dilutions and annoyance levels experienced by

surrounding communities;

(iv) the application of the Odour Impact Dispersion Model to a case study using data collected during a previous year-round study of odorous emissions from a major industry located in Ontario, Canada;

(v) a recommendation of an effective strategy for measuring and predicting odorous emissions from stationary sources that can be used by regulatory agencies and plant administrators as a basis for eliminating or at least minimising local odour nuisances.

2.0 Literature Review

Air pollution has been known to adversely affect human lifestyles since the industrial revolution. Odours are one form of air pollution that stimulate the sense of smell which we all possess. It has been estimated that as many as 50% of all citizen complaints related to air pollution are associated with exposure to odours (Calvert & Englund, 1984). Odorous emissions are generated from a variety of processes and cause a variety of undesirable reactions in people. Consequently, in an attempt to best minimize odour nuisance situations, odour control agencies design odour abatement regulations.

2.1 Perception

The means by which people detect and are affected by odours is relatively complex. Odours are perceived when odorants present in the air interact with the olfactory epithelium, the organ of smell located in the roof of the nasal cavity, which then sends a signal to the brain (Villee, 1989). The olfactory epithelium is highly sensitive, capable of perceiving a broad spectrum of odours. Despite its sensitivity, smell is perhaps the sense that adapts the quickest. Adaptation refers to a diminution of perceived odour intensity over time in response to a constant exposure and is typically responsible for about a 60% attenuation of the perceived intensity over a matter of minutes (Shusterman, 1992). At high exposures this can result in rapid but reversible olfactory fatigue, whereupon the individual is temporarily imperceptive to an odour. On the other hand, there is evidence that repeated exposure to an odorant results in enhancement of odour recognition and detection perception by "training"

an individual's nose to an odour (Shusterman, 1992).

2.2 Emissions

Odorous emissions originate from a variety of municipal, agricultural and industrial operations, as well as from other mobile sources such as transportation. In a recent survey of 38 regulatory agencies, Leonardos (1996) ranked a number of major odour sources in terms of number of emissions as is shown in Table 2.1.

Table 2.1: Ranking of Major Odour Sources (Leonardos, 1996)

Odour Source	No. of times source was ranked as one of the top three odour emitters*
Total Agriculture	17
Sewage Plant	16
Paint	11
Refining	10
Rendering	8
Feedlot	8
Pulp Mills	7
Fibreglass/plastics/styrene	7
Open burning	6
Chemicals	6
Other	5
Landfills	4
Manure	3

* ranked by 38 agencies who responded to a 1995 survey.

In some cases, the source of an odour can be located with little effort, however this is not always the case. For example, complex atmospheric dispersion patterns may make it difficult to accurately pinpoint the location of an offending odour source if a number of

individual sources exist. In addition, odorous compounds are interactive, and tend to combine on a non-additive basis without regard to the nature of the odorants involved or their degree of similarity (Shusterman, 1992). That is, the combination of several odours may cause a synergestic effect whereby an unique odour is created and is more readily perceived because of the presence of another odour (Tchobanoglous, 1991). Alternatively, in certain circumstances, odours may combine in an antagonistic manner, thereby counteracting or neutralizing an odour so that the intensity of the mixture is less than that of its constituents (Wynne, 1996). This is the process by which products known as "masking agents" are used by odour generating facilities to cover up an objectionable odour with a more desirable one.

2.3 Health Effects

The health effects of odours have traditionally been difficult to determine. The obstacle has always been in relating the intensity or duration of the odour to the degree of health effects. Most symptoms reported by individuals who are near environmental odour sources are acute in onset, self-limited in duration, and subjective (Shusterman, 1992). Animal research under controlled conditions has shown that some odours can cause physiological and morphological changes in cardiovascular and respiratory systems, however there is little information available with respect to the toxicity or hazardous effects of odorous substances on humans (Poostchi, 1985). One such study conducted by the California branch of the U.S. Environmental Protection Agency (Cal-EPA), found that the apparent

acute odour-related symptoms in communities that surround hazardous waste, agricultural, and industrial air emission sources frequently defies explanation in classic toxicologic terms (Shusterman, 1992). As was argued by Shusterman (1992), if conventional toxicology is followed, the low levels of exposure that are usually documented would be linked to small increments in probability of developing latent diseases, and not linked with acute symptoms.

Prolonged exposure to odours can cause a general destruction of the sense of well being and enjoyment of food, home and the external environment and can result in emotional stresses such as unease, discomfort, irritation, annoyance, or depression. Physical effects of odours include nausea, vomiting, headaches, respiratory problems, upset of sleep and appetite, and irritation of the eyes, nose and throat (National Research Council Commitee on Odours, 1979). However, because health complaints are typically subjective, regulating agencies have traditionally considered odorous emissions to be nuisance-related rather than health-related. Furthermore, because of the frequently transient timing of exposures, odour sources often elude successful abatement (Shusterman, 1992).

2.4 Measurement

The measurement and assessment of odours is performed using the best known detection device, the nose. Several researchers have attempted to develop an electronic instrument that simulates the sensitivity of the human nose, however because of many complex physical and environmental factors, none have been overly successful (Schmidt & Jacobson, 1995). There are several olfactory techniques used to measure odours, of which some are qualitative while others are quantitative.

2.4.1 Qualitative Measurement

Qualitative measurement requires the panelist (a member of a panel of odour judges) to be introduced to an offending odour in order to describe and characterize what is perceived. Qualitative analysis may be accomplished through characterization, description of hedonic tone, and trained odour detectors.

Characterization is the simplest qualitative method of measurement. It involves defining or describing the perceived odour, using common terms. For example, the odour emanating from a sewage treatment plant might be described as pungent. In 1985, the American Society for Testing and Materials (ASTM) established an odour profiling project to develop odour character information on various odours, ranging from the very pleasant to the very unpleasant. As a result, an Atlas of Odour Character Profiles was compiled for a total of 180 odorant samples. Each sample's odour profile was characterised using a 146-descriptor list, from which panelists (who smell the odorous sample) describe its odour by rating the applicability of each of the descriptors on a scale of 0 (not applicable) to 5 (highly appropriate) (Dravnieks, 1985). Thus, in odour evaluations, this Atlas may help characterise unknown odours by comparison to the listed reference odours with known odour character.

2.4.2 Quantitative Measurement

Quantitative measurements require the collection of an air sample from an odour source in order to determine the amount of odorant present. This may be accomplished by olfactometry, or to some degree, by a scentometer.

The basic principal of olfactometry requires that a sample of odorous gas be diluted

with odour-free air at various dilution levels in order to determine the dilution threshold of a panel (Warren Springs Laboratory, 1980). This dilution threshold is the number of dilutions required for the odour to be perceived by 50% of the members of the panel. A relatively large panel of different age groups is required to be statistically representative of a large population. Samples are analyzed using either a static or dynamic dilution technique.

Static dilution requires that a set volume of diluted air be delivered to a panel of observers for measurement. The following are the two examples of the static dilution techniques.

- *ASTM D1391 Syringe:* This is a basic static dilution technique where diluted samples of an odour are prepared using 100 mL syringes. A sample of the gas whose odour is to be measured is diluted with odourless air until a dilution is achieved in which the odour can be barely perceived. The ratio of the total volume of this diluted mixture (original sample volume plus volume of diluted air) to the volume of the original sample is a measure of the concentration of odour in the original sample (Wark and Warner, 1981). To illustrate, 10 mL of odour are drawn into a syringe followed by 90 mL of odour-free air to obtain a sample of 10 dilutions. The sample is then ejected from the syringe below the nose of the panelist. The panelist then states if he/she can smell the odour. The number of dilutions of a sample of the odorous gas required to render it odourless is then determined, and designated as the threshold level. Due to the fact that it is impossible to avoid inadvertent dilution in the nose, many agencies no longer use or recommend this method (Warren Springs Laboratory, 1980).

- *Odour Room:* Used first in Europe, one example of this application consisted of a test chamber of known volume lined with polished aluminum and supplied with odour-free air via an activated carbon adsorber. A known volume of odorous air is then introduced into the room and mixed by fans for five minutes. The panel enters the chamber and assesses the odour after which the room is then cleansed with odour-free air for twenty minutes (Warren Springs Laboratory, 1980). This is repeated for different dilutions until the gas in the room is rendered odourless, and the threshold level is determined. One drawback is that this is a very slow and costly process.

Unlike static dilution, a dynamic dilution device delivers the sample to the panel in a continuous flow. This technique involves continuously combining a flow of clean air with the odorant. One drawback is that there currently does not exist a standard dynamic olfactometer; therefore different devices may give differing results. All devices dilute the sample odour with clean air and, in some setups, the sample is sniffed through the one port. Others have two or more sniffling ports of which one port contains the sample while the other ports deliver only clean air. In this case, the panelist is required to identify the port emitting the odorous sample. Even if the panelist is unsure of the correct choice, he/she is instructed to make a guess; hence the term "forced choice" is used to describe such a process. Adsorption of the odorant onto the walls of the delivery system must be minimized by using non-adsorbing materials such as Teflon coated bags and tubing. Also, inadvertent dilution during respiration must be eliminated by delivering the diluted odour at a

sufficiently high flowrate; however there is still disagreement on an acceptible flowrate. While there is a high capital cost associated with this method, it is the favoured instrument because of its quickness and accuracy (Warren Springs Laboratory, 1980).

The scentometer is a device used to predict the dilution threshold of an odour present in the ambient air. The user is required to inhale air through two glass nosepieces inserted into the nostrils. These are connected to a plastic box with holes which contains activated carbon. The user receives odour free air by closing all the holes with his fingers, and then obtains increasingly odorous air by opening selected holes (Calvert, 1984). The dilution threshold is reached when the operator first detects the odour. This method has its faults, some of which are:

- the device is not designed to measure odour emissions directly from a stack;
- the instrument relies entirely upon the judgement of the one individual who is operating it, thus results are not reproducible;
- olfactory fatigue (loss of sensitivity) can easily overcome an operator exposed to an intense odour for an extended period of time.

In the case of hedonic tone a rating of the pleasantness or unpleasantness of a particular odour is often specified. For example, panelists may be asked to rate their degree of annoyance on a scale of 1 (tolerable) to 10 (unbearable) (Nicell, 1986). When trained odour sniffers are desired, panelists rate the odour intensity descriptively (e.g. faint, moderate, strong) or on a number scale (i.e. 1 to 10). In this respect, a quantitative description is also applied to the hedonic tone of the odour.

2.5 Odour Control Policies

The regulation of odours is an issue that affects both odour generators and the general public in somewhat differing ways. Odour generators are more often than not motivated by economic factors and may not be as concerned about odorous emissions as an adjacent community might be. Although a standard odour control regulation does not exist across Canada or the United States, all regulations should be designed in an effective, fair and efficient manner for all those involved. In order to be effective, they must:

- eliminate or prevent the occurrence of objectionable odours which threaten public welfare;
- restrict the odorous emissions to levels which are technologically and economically attainable by the offending industry;
- include specific procedures and guidelines for establishing the existence of a community odour problem which take into account community characteristics such as population distribution, socio-economic activity and land-use zoning of the area;
- be implemented on the basis of measured variables including the quality, intensity, frequency and duration of odour episodes which are related to the annoyance experienced by the community; and
- be applied to only those odours which are not directly harmful to health. Hazardous or toxic odorous materials require separate regulations which would require concentrations to be maintained below established physiological danger levels (Nicell, 1994).

The following section describes the current odour control policies used by most regulatory agencies.

2.5.1 Zoning / Separation Distances

In theory, by separating an offending industry and a community by a given distance

there is likely to be less of an odour impact. Some regulatory agencies choose to limit the concentration of the odour in the ambient air beyond the property line of the plant. The selection of an appropriate separation distance creates some problems since:

- odour perception is highly dependant on meteorology, odour intensity and duration, and these are not considered in zoning laws.
- separation distances might be adequate for large open rural environments with low population densities; however, they may be ineffective when there is a pocket of high population density (e.g. a school, hospital or residential area) near the odour source.
- a large facility might have better odour control technologies than a smaller one. In such a case, separation distances based solely on the size of a facility might be meaningless (Schmidt, 1995).

For these reasons, setback distances do not guarantee zero odour impact on a neighbouring community, and are at best only effective in sparsely populated rural environments. This is the case in Augusta County, Virginia, where proposed regulations require that 'intensive agriculture operations' be set back at least 1,000 feet from any property that is not zoned as an 'Agricultural District' (Wynne, 1996). Nonetheless, zoning laws separating industrial areas from residential areas should not be changed at a later date without considering potential odour impacts.

2.5.2 Nuisance Complaints

Some odour control regulations are based on citizen complaints. In this situation, the members of the community affected by the odour are the ones who decide what constitutes an unacceptable ambient odour level. Once a number of complaints are received and verified by the local environmental authority, legal steps can be taken to minimize the odours.

Nuisance laws have several important merits which cannot be ignored. A nuisance suit which is supported by reliable and credible witnesses can be more convincing evidence of a community annoyance than any scientific attempt to prove the same. In addition, court decisions can be made that provide relief which is appropriate to the case and which are not bound by specific guidelines. The leeway available in making such decisions can provide a solution which best fits the needs and interests of all concerned parties (Nicell, 1994)

Consequently, many U.S. states and Canadian provinces rely on nuisance regulations. In these regulations, nuisance odours are included as a particular type of air pollution, but nuisance is not defined other than that it is that which "unreasonably interferes with the enjoyment of life or property" (Duffee, 1996). For example, regulations in Maryland state, "No person shall cause any discharge of gases, vapours, or odours in such a manner that a nuisance or air pollution is created" (Leonardos, 1996).

In Ontario, Canada section 6 of regulation 308 of the Environmental Protection Act states that "No person shall cause or permit to be caused the emission of any air contaminant to such extent or degree as may (a) cause discomfort to persons; (b) cause loss of enjoyment of normal use of property; (c) interfere with normal conduct of business; or (d) cause damage to property" (Government of Ontario, 1990).

In the province of Quebec, section 20 of chapter Q-2 of the Environment Quality Act states that "No one may emit, deposit, issue or discharge or allow the emission, deposit or discharge into the environment of a contaminant (a) in a greater quantity or concentration than that provided for by regulation of the government; (b) the presence of which in the environment is likely to affect the life, health, safety, welfare or comfort of human beings,

or to cause damage to or otherwise impair the quality of the soil, vegetation, wildlife or property" (Government of Quebec, 1995).

Several other agencies attempt to define what constitutes an odour by interpreting an odour nuisance as a specific number of validated complaints or a specified proportion of the residents in the complaint area considering odours objectionable (Duffee, 1996). An example of this is the province of Manitoba's odour nuisance clause, where an odour nuisance is defined as "a continuous or repeated odour, smell or aroma, in an affected area, which is offensive, obnoxious, troublesome, annoying, unpleasant or disagreeable to a person...subject to at least 5 written complaints...within a 90 day period...from 5 different persons who do not live in the same household" (Government of Manitoba, 1996).

This approach eliminates the need to quantify odour levels but raises other questions, such as:

- What constitutes a complaint?
- How many complaints are needed?
- How can these complaints be validated?
- What action must be taken if complaints are validated?

One of the most significant weaknesses in this approach is that complaints cannot be filed until after a facility is built and operating. Thus, this type of regulation is only a basis for reducing odours instead of preventing them.

2.5.3 Threshold Measurements

Regulations that are based on odour perception use odour threshold levels determined by olfactometry or similar instruments. Thresholds may be either of two types,

detection or discrimination. The detection threshold, ED_{50}, is defined as the dilution (or concentration) at which 50% of the panel notices a stimulus as being different from odour free blanks (Cha, 1991). The discrimination threshold, D_{50}, as defined by Nicell (1986) is the dilution at which 50% of the panel states that they are sure, beyond a doubt, about the presence of an odour.

Some fifteen agencies in the U.S. define an odour nuisance in terms of an ambient standard based on the number of dilutions required to render the odour undetectable. Most agencies with this type of regulation such as Colorado, Missouri, Kentucky and Cincinnati, specify that the odorous ambient air in residential and commercial areas must become odourless after mixing with seven parts of odour free air as determined with the aid of a scentometer (Duffee, 1996).

Other regulatory agencies specify limits on the odour concentration directly at the source. An analysis of an odour sample collected directly from the point of emission can be used to assess whether a source is within regulated limits. However, there are some inadequacies to this approach. The most important point is that this approach does not consider the importance of the emission flow rate. Consequently, if two sources within a community were emitting the same odour at the same concentration but at different flowrates, the impact on the neighbourhood would be greater for the source with the higher flowrate (Nicell, 1994).

Another difficulty with threshold regulations is that they only describe the point at which a specified percentage of the panel (usually 50%) notices an odour. The response of the panel to other doses is not provided. Obtaining these values would provide a dose-

response relationship whereby a specific probability of detecting an odour can be related to a specific dose. Furthermore, threshold regulations, in their present form, fail to provide information concerning the impact of an odorous stimulus on a neighbourhood in terms of complaint potentials or degree of annoyance. For example, if two different samples are found to have the same 50% detection thresholds, that does not necessarily imply that they are both annoying at that level. One sample might have a more offensive smell at that level than the other.

The deficiencies of threshold regulations in their present form support the suggestion proposed by Nicell (1994) for retirement of the threshold concept as a means of odour regulation in favour of an odour impact model which accounts for dose-response relationships. This has given rise to a new technique of odour analysis whereby a panel's probability of perceiving an odour, and its degree of annoyance, at various dose levels are described by an Odour Impact Model.

2.6 Odour Impact Model

The Odour Impact Model (OIM), developed by Poostchi (1985) and modified by Nicell (1986), is an extension of the currently used principle of ternary forced choice detection threshold determination with a six-level dynamic olfactometer. Thus, in a forced choice approach, the panelist is forced to declare when odour is detected as well as indicate from which of the three ports the odour is emanating (Nicell, 1986). In addition to identifying the ports at which odours are perceived, panelists are also expected to specify the levels at which they are sure, beyond a doubt, about the presence of an odour.

Furthermore, panel members are asked to indicate at which dilution level they would complain if they were exposed to similar odorous stimuli for an average period of eight hours and to rate the degree of annoyance (0 to 10) at each dilution level. The panelists are advised to rate their annoyance according to the following categories as shown in Figure 2.1:

TOLERABLE	UNPLEASANT	VERY UNPLEASANT	TERRIBLE	UNBEARABLE
0 to 2	2 to 4	4 to 6	6 to 8	8 to 10

Figure 2.1: Annoyance Categories (Nicell, 1986)

With this forced choice technique, the first dilution level beyond which individual panelists make continuous correct choices is taken as the basis for the evaluation of the detection profile, relating percentage probabilities of detection to different odour concentrations as illustrated by the $\mathcal{P}(Dt)$ curve in Figure 2.2.

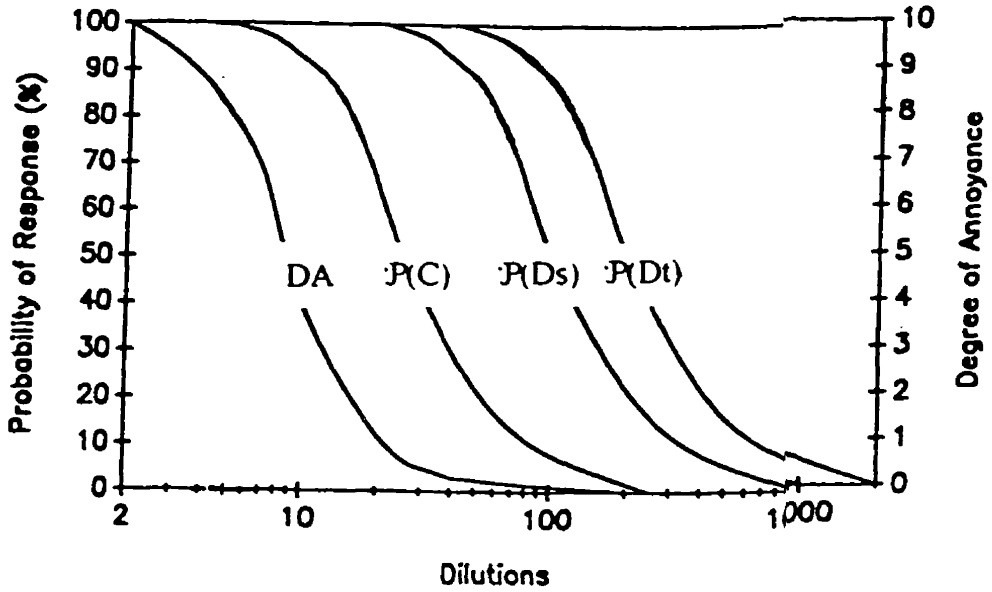


Figure 2.2: Idealized Odour Impact Model

The odour discrimination profile is based on the first dilution level at which the panel members begin to be certain about the presence of the odour. The $\mathcal{P}(Ds)$ curve of Figure 2.2 illustrates the location of a typical discrimination profile with respect to the detection profile. Similarly, the dilution levels at which panelists would complain (i.e. they expressed a degree of annoyance greater than zero), and the magnitudes of annoyance, provide data for the generation of probability of complaint, $\mathcal{P}(C)$, and degree of annoyance, *DA*, profiles as shown in Figure 2.2. Alternatively these profiles can be plotted as a function of odorant concentration when evaluating pure compounds in air (Nicell, 1994).

A mathematical exercise was performed by Nicell et al. (1991) to determine if the effects of chance could be removed from the forced choice technique through the application of probability theory. The following relationship was derived to correct the detection threshold for the random effects of chance (Nicell et al., 1991):

$$X_{50} = ED_{50} \times F^{-\sum_{a=1}^{N} \frac{a}{C^a}} \tag{2.1}$$

where, ED_{50} = the panel detection threshold (dilutions)
X_{50} = the corrected panel detection threshold (dilutions)
N = the total number of dilution stations
C = the number of choices at each station
F = the factor relating the number of dilutions of the original odour between consecutive dilution levels.

The correction factor term, expressed as:

$$K = F^{-\sum_{a=1}^{N} \frac{a}{C^a}} \tag{2.2}$$

is evaluated from characteristics of the olfactometer. If the hypothesis is made that the detection threshold and the discrimination threshold differ only because of the effects of chance, then K can be evaluated experimentally by measuring these two threshold values and determining their ratio according to:

$$K = \frac{D_{50}}{ED_{50}} \tag{2.3}$$

where, ED_{50} = detection threshold
D_{50} = discrimination threshold

when the thresholds are expressed in dilutions. It was also shown by Nicell et al. (1991) that there is an excellent correlation between the predicted and measured values of K, therefore indicating that the detection threshold is the same as the discrimination threshold when it

is corrected for the effects of chance. These results indicate that the detection profile should be eliminated from the OIM because it represents a faulty measurement of the discrimination profile (Nicell, 1994).

The Odour Impact Model does not account for all the variables which are related to the impact of an odour on a community. However, it does represent a significant improvement over current regulations employing threshold measurements because it incorporates the effects of the odour's hedonic character into estimates of the odour impact.

2.7 Atmospheric Dispersion Modelling

Atmospheric dispersion modelling is used to predict the effects of air pollution on surrounding air quality based on factors like weather and topography. The ultimate goal of any atmospheric dispersion model is to accurately predict the concentration downwind of any source (or sources) under any and all atmospheric conditions. Models have been developed to evaluate different source types (point, area, volume), different terrain (simple or complex), different locales (urban, rural), different release rates (plume, puff), and different meteorological conditions (stable, convective). The model that most closely approximates the parameters of the source, or characteristics of the dispersion process under analysis should be selected (Diosey, 1996).

The selection of the appropriate dispersion model for odour impact assessment depends on the source type and release scenario. The relationship that exists between the individual odorous emissions from a given number of sources within an air quality region, and the resulting average concentration of that odour in the ambient air is a complex one.

It must involve a reasonably accurate and complete listing of all the sources (their location, height of stack, rate of emission etc.), known as an "emission inventory", as well as local meteorological data covering the direction and velocity of winds, presence of inversion, etc. (Licht, 1988).

The sources responsible for odour complaints are generally continuous sources, such as from stacks, scrubbers, or basins; although routine but instantaneous or very short-term releases (e.g. from digester release valves) can also pose problems at nearby receptors. Depending on the rate of release relative to odour perception's short time frame, intermittent sources can be classified as either continuous sources (release rate on the odour of minutes or longer), or instantaneous sources (release rate on the order of seconds) (Diosey, 1996). Thus, continuous sources are typically described by plume models, and instantaneous sources are typically described best by puff models. The results obtained from the most appropriate model provide essential information to regulatory decision makers, businesses, and the general public.

2.7.1 Regulatory Need for Modelling

Atmospheric dispersion modelling is an essential tool for providing information that is required by environmental regulatory agencies as well as plant designers. If new facilities need to be built or existing ones need to be expanded, it is desirable to predict the air pollution impact of a facility prior to its construction in order to have a minimum effect on the environment. This helps reduce monitoring and retrofitting costs which may arise once the facility is operational. Dispersion modelling can also predict pollutant concentrations for

comparison to the applicable air quality standards.

2.7.2 Gaussian Theory

The analysis of atmospheric pollution requires an understanding of dispersion theory. Once a pollutant is emitted into the environment, it will be acted upon by a number of environmental forces that will affect its fate over time. A basic assumption of the Gaussian model is steady-state conditions; i.e., both the emissions and the weather conditions in terms of wind speed and direction, air temperature, stability class, mixing height, and precipitation, are assumed constant for a given time interval.

The Gaussian model has been shown in the past to effectively predict the dispersion of plumes in a variety of atmospheric conditions, however some limitations do exist. Beychok (1994) emphasizes that the accuracy of many dispersion models is proportional to the information that is input. Like all models, Gaussian modelling is susceptible to a certain degree of error that can only be minimized with experience.

2.7.3 The EPA's ISC Model

The Industrial Source Complex Dispersion Model (ISC) developed by the United States Environmental Protection Agency can be used to describe either individual episodes lasting a few hours, or for long-term analysis of one year. There are two versions to the program. In the long term version, Industrial Source Complex Long Term (ISCLT), the model computes average concentration values over an area of few hundred square kilometres for a period of a season or a year, depending on the meteorological data provided.

The short term version, Industrial Source Complex Short Term (ISCST), computes mean concentration values for a period of one to a few hours. The ISCST model is usually used to satisfy regulatory requirements and guidelines, and was chosen for this study.

The newest version of the Industrial Source Complex - Short Term Version 3 (ISCST3) dispersion model is a steady-state Gaussian plume model which can incorporate pollutant concentrations from a wide variety of sources associated with an industrial source complex. This model can account for settling and dry deposition of particles, building downwash, area, line and volume sources. The ISCST3 dispersion model was designed to support the EPA's regulatory modelling options. It is written in Fortran but private environmental firms have subsequently developed it into a Microsoft Windows® environment. One of these private firms is Lakes Environmental Inc. which markets a Microsoft Windows® version of the program called ISC3View®. Some of the ISCST3 modelling capabilities are as follows:

- ISCST3 may be used to model primary pollutants and continuous releases of toxic and hazardous waste pollutants.
- ISCST3 can handle multiple sources, including point, volume, area, and open pit source types. Line sources may also be modeled as a string of volume sources or as elongated area sources.
- Source emission rates can be treated as constant or may be varied by month, season, hour-of-day, or other optional periods of variation. These variable emission rate factors may be specified for a single source or for a group of sources.
- The model can account for the effects of aerodynamic downwash due to nearby buildings on point source emissions.
- The model contains algorithms for modelling the effects of settling and removal (through dry deposition) of large particulates and for modelling

the effects of precipitation scavenging for gases or particulates.

- Receptor locations can be specified as gridded and/or discrete receptors in Cartesian or polar coordinates.
- ISCST3 incorporates the COMPLEX1 screening model dispersion algorithms for receptors in complex terrain.
- ISCST3 model uses hourly meteorological data to account for the atmospheric conditions that affects the distribution of air pollution impacts on the modelling area (Lakes Environmental Inc., 1996).

ISCST3 has been specifically developed to simulate air pollution due to an industrial facility, taking into account the effect of high stacks on the behaviour of the pollutant plume. The model adjusts ground-level concentrations for the surrounding terrain elevations below stack height (Friedman & Hill, 1992). It may be applied in urban or rural environment with a moderately complex terrain. Input requirements are divided into five distinct input pathways including control, source, receptor, meteorological, and terrain grid. Each pathway requires the input of numerous environmental and source parameters of the site, some of which are listed in Table 2.2. They can each be modified to describe individual cases. Results can be output in terms of concentration, total deposition flux, dry deposition flux, and/or wet deposition flux. Further information on the specific details of these input parameters can be found in the ISC3 user's guide (USEPA, 1995) and in the ISC3 VIEW® manual (Lakes Environmental Inc., 1996).

Table 2.2: ISC3View Input Pathways and Parameters

Pathway	Input Parameters
Control	• dispersion options (rural or urban) • type of pollutant to be modelled (SO_2, NO_x, CO, PM10, TSP, other) • pollutant exponential decay coefficient • particle size distribution • averaging time (1, 2, 3, 4, 6, 8, 12, or 24 hours) • terrain height (flat or elevated)
Source	• type (point, line, volume, area, or open pit) • the stack location (x, y) • elevation of the source • emission rate • stack gas temperature • gas exit velocity • inner stack diameter
Receptor	• receptor location (Cartesian or polar grid) • flagpole receptors
Meteorological	• anemometer height • wind direction • wind speed • ambient temperature • stability category • vertical temperature gradient
Terrain Grid	• defines terrain elevations (optional)

3.0 Proposed Odour Impact Modelling Strategy

3.1 Odour Impact Dispersion Modelling

The desire to model source characteristics within an ever changing environment has lead to a new approach for the control of odours. The merging of a dose-response model with an atmospheric dispersion model can be used to develop fair and effective regulations, or as a decision making tool to select control options. This proposed strategy links the Odour Impact Model with the USEPA's Industrial Source Complex Short Term Dispersion Model and generates contour lines representing the impact of an odour source on surrounding communities. The impact can thus be represented as a community's probability of detection, probability of discrimination, or degree of annoyance profiles. Analysis of these profiles and surrounding population densities, provides further insight for regulatory agencies and plant management for restricting odorous emissions. The objectives of this Odour Impact Dispersion Model (OIDM) are to include the effects of odour hedonics into impact estimates of odorous emissions from stationary sources on surrounding communities, and to provide a basis for a fair and effective strategy that can provide a basis for eliminating or at least minimising local odour nuisances. A similar approach has been used in the Netherlands and is being considered as a standard odour control policy for the European Community (Harreveld, 1991). However, in the Dutch model, the odour is not characterised by a dose-response curve but instead by an odour threshold.

The incorporation of an odour's dose-response relationships into a dispersion modelling program allows for variables such as odour concentration, gas flowrate, and local

geographical and climatic conditions to be taken into account. This enhances the prediction of the odour levels that might exist beyond a facility's property line, and the community's potential degree of annoyance to an offending odour. Regulations can be developed which specify maximum degree of annoyance limits that cannot be exceeded in the ambient air of the community. An equally important advantage is the ability to predict downwind odour levels before a facility is built or modified. The dispersion model can, in effect, be applied to determine the source parameters that will induce the highest downwind dilutions. Thus, the daily operations of the facility can be optimized to minimize any odour complaints within the community and consequently, minimise any retrofitting or shut-down costs.

3.2 OIDM Methodology

In order to accurately predict the community's degree of annoyance to an odorous emission, it is necessary to develop a strategy that incorporates the odour's hedonics into an atmospheric dispersion model. As was previously discussed, this proposed strategy merges the Odour Impact Model (OIM) with the USEPA's Industrial Source Complex Short Term Dispersion Model (ISCST3) to generate downwind contour lines of a community's probability of response. The resulting union of these two distinct air pollution control systems requires certain procedures to be followed. The following steps summarize the methodology of this strategy:

(1) Collect a representative sample of the odorous gas from the source in a non-adsorbing and properly sealed sampling bag. Immediately, transport the sample to an olfactometry lab for analysis.

(2) Develop the Odour Impact Model for the samples using dynamic olfactometry as described by Nicell (1994), and generate the various dose-response profiles.

(3) Describe the developed dose-response relationships by a mathematical model using regression analysis. The OIM is thus expressed as a series of mathematical equations that defines a population's 'probability of response' and 'degree of annoyance' as a function of 'dilutions' of the original odour sample.

(4) Collect a full range of hourly seasonal meteorological data for the region surrounding the odour source.

(5) Use a dispersion model to predict the downwind dilutions of an odorous emissions in the surrounding community. The model may be run for specific meteorological conditions or can be used to determine those conditions which result in the greatest impact (least dilutions of the original odour) in the community.

(6) Use the dose-response mathematical expressions to transform the dispersion model output file (in dilutions) into downwind community response contours.

The model output may be used to evaluate the impact of the odour on the surrounding community. This impact can be measured in terms of the fraction of people who can discriminate the odour in the neighbourhood or in terms of the potential annoyance which will be generated. Such quantitative information can be used as a basis for the development of regulatory standards for odour, which will account for the number of people influenced by an odour emission and the severity of the influence.

3.3 OIM Considerations

The first step in this method is to obtain the various dose-response relationships for the odour using the Odour Impact Model procedure. The OIM generates four dose-response relationships including: probability of detection, probability of discrimination, probability of complaint, and degree of annoyance. At this point, some considerations for the imperfections of the OIM must be made. First of all, the probability of complaint profile will be excluded from the rest of the study since it can be argued that the definition of complaint in the OIM is too arbitrary. As is illustrated by Nicell (1994), a person is considered to have complained if he/she registers a degree of annoyance greater than zero, regardless of the fact that a low degree of annoyance (i.e. between 0 and 2) is still considered in the 'tolerable' range as is defined by the descriptors in Figure 2.1(Nicell, 1994). This is an arbitrary definition of complaint and, as such, is unlikely to reflect the true complaint potential in the community. As a result, in this study odour hedonics will be evaluated solely using the degree of annoyance profile.

Secondly, a choice must be made between the probability of detection and probability of discrimination profiles. As was previously stated, the detection threshold, ED_{50}, is defined as the dilution (or concentration) at which 50% of the panel notices a stimulus as being different from odour free blanks (Cha, 1991). The discrimination threshold, D_{50}, as defined by Nicell (1986) is the dilution at which 50% of the panel states that they are sure, beyond a doubt, about the presence of an odour. As was shown by Nicell et al. (1991) the detection threshold is in fact the same as the discrimination threshold when it is corrected for the effects of chance. This therefore, indicates that the detection profile

should be eliminated from the OIM because it represents a faulty measurement of the discrimination profile (Nicell et al., 1991). However, at this point the detection profile will not be eliminated from the study, since the debate on the validity of the use of detection or discrimination values still continues.

3.4 Non-Linear Regression

Once the dose-response relationships have been determined, they must be described by a mathematical model in order to be incorporated into the dispersion modelling program. Using non-linear regression, an equation that defines 'probability of response' as a function of 'dilutions' may be fit onto the dose-response profiles. A comprehensive curve fitting computer program, CurveExpert 1.24®, was chosen for this study. The program finds the best-fit values of the variables in the model and plots a graph of the fit curve.

Non-linear regression is an iterative process that starts with an initial estimate value for each variable in the equation, and attempts to find the values that minimize the sum of the squares of the vertical distances of the points from the curve. For regression curve-fits, error is evaluated using the standard error (S_r) and correlation coefficient (r). The standard error, or sum of the squares, of the estimate quantifies the spread of the data points around the regression curve. As the quality of the data model increases, the standard error approaches zero. It is expressed as (Hyams, 1996):

$$S_r = \sqrt{\frac{\sum_{i=1}^{N} (y - y_i)^2}{N - n}} \qquad (3.1)$$

where, y = the value calculated from the regression model
y_i = the data points
N = the number of samples
n = the number of parameters in the particular model (so that the denominator is the number of degrees of freedom).

The correlation coefficient (r) is a measure of goodness of fit and is a fraction between 0.0 and 1.0. As the regression model better describes the data, the correlation coefficient will approach unity. It is defined as:

$$r = \sqrt{\frac{S_t - S_r}{S_t}} \tag{3.2}$$

where, S_t = the standard deviation of the vertical distances of the points from the line (i.e. the standard deviation of the residuals)
S_r = standard error

The standard deviation (i.e., standard error of the mean) operates in exactly the same fashion as the standard error of the estimate defined above; however, it considers the spread around a constant line (the mean) as opposed to the spread around the regression model. This is the uncertainty of the dependent variable prior to regression. Thus, the improvement (or error reduction) due to describing the data in terms of a regression model can be quantified by subtracting the two quantities (Hyams, 1996).

This therefore, makes it possible to express a population's response (detection, discrimination or annoyance) as a function of the dose (dilutions) that they experience. Furthermore, the equation's goodness-of-fit can provide further insight into the confidence of the data. This, as well as the method by which these functions were determined, is further described in the following chapter.

3.5 Dispersion Modelling

Atmospheric dispersion models, like the USEPA's ISCST3 model, can be used to predict the downwind dilution of an odour that is being emitted from an offending source. Within an emission, the various pollutants that are released as a plume from a continuous source, or as a puff from an instantaneous source, are dispersed under the action of atmospheric turbulence (Henry & Heinke, 1989). At the same time pollutants are transported at the speed and direction of the prevailing wind. If it is assumed that odours are integrated and homogeneously mixed within the plume, then dispersion modelling can be used to predict their downwind dilution.

Generally, dispersion modelling software are designed to output downwind ground-level pollutant concentrations. They do not directly output the number of 'dilutions' that a pollutant undergoes as it is dispersed into the atmosphere. For this reason, certain modifications must be made to the output data of the ISCST3 program. For example, traditional pollutant modelling requires an 'emission rate' to be input in terms of grams of pollutant emitted per second from the stack. This is not the case in odour modelling. In this investigation, an 'odour emission rate' ($\dot{\omega}$) will be based on the odour's discrimination threshold and the stack's volumetric flowrate to predict the downwind dilutions. The discrimination threshold is used as a measure of odour concentration instead of the detection threshold for the reasons outlined previously. Other practitioners may choose to use the detection threshold in place of the discrimination threshold. This will not in any way affect the numerical values of dilutions predicted downwind, as will be explained below.

The dispersion of pollutants (or dilution) is dependant on meteorological factors and

source characteristics, and is independent of the amount of odour that is being emitted. In this respect, it can in fact be shown that any emission rate that is input into the program will result in the same downwind dilution pattern output. For example, for a given smokestack, the flowrate (Q) is given by:

$$Q = v \cdot A \qquad [m^3/s] \tag{3.3}$$

where, A = Area of stack exit = $\pi d^2/4$ [m^2]
v = exit velocity [m/s]
d = inner stack diameter [m]

If we express the stack gas concentration in terms of the discrimination threshold, we can say that:

$$C_o = D_{50} \times k \quad [g/m^3] \tag{3.4}$$

where, C_o = stack gas concentration of odour [g/m^3]
D_{50} = discrimination threshold [dilutions]
k = conversion factor to convert odour concentration units [dilutions] to [g/m^3]

While 'k' can be physically interpreted to represent the mass of odorant per unit volume of odorant (i.e. a density), it cannot usually be evaluated in practice since an odorous sample consists of an unknown mixture of odorous materials.

Therefore, the odour emission rate ($\dot{\omega}$) may be expressed as:

$$\begin{aligned} \dot{\omega} &= Q \cdot C_o \\ &= v \cdot A \cdot C_o \\ &= v \cdot A \cdot D_{50} \cdot k \quad [m^3/s] \end{aligned} \tag{3.5}$$

At any point downwind, the odour concentration in the ambient air, C(x,y,z), is subsequently determined by the dispersion model. Thus, the number of dilutions, $\delta(x,y,z)$, by which the original odour concentration is reduced upon dispersion, is equal to the source

concentration divided by the concentration of the diluted mixture. Therefore dilutions may be expressed as:

$$\delta(x,y,z)=\frac{C_o}{C(x,y,z)}=\frac{D_{50}\times k}{C(x,y,z)} \tag{3.6}$$

but, from Equation (3.5), $D_{50} \cdot k = \dot{\omega} / vA$. Therefore, Equation (3.6) becomes:

$$\delta(x,y,z)=\frac{\dot{\omega}}{vAC(x,y,z)} \tag{3.7}$$

which indicates that dilutions are independent of 'k'. Since 'k' can assume any value without any effect on the dilutions calculated using Equation (3.7), in this study 'k' will be assigned an arbitrary value of unity (i.e. k=1.0 g/m^3). It is necessary to assume a specific numerical value for 'k' since ISCST3 specifically requires a mass emission rate ($\dot{\omega}$, g/s) as an input variable.

Running ISCST3 at two different emission rates ($\dot{\omega}$) confirms that the downwind dilutions (δ(x,y,z)) of the odour are indeed independent of the odour emission rate ($\dot{\omega}$) as is shown in Table 3.2. for the arbitrarily chosen source parameters listed in Table 3.1.

Table 3.1: Dilutions Test - ISC3View Model Parameters

Source Specifications	Input
UTM Location (East, km)	0
UTM Location (North, km)	0
Emission Rate (g/s)	10000, 20000, 50000
Vent Height (m)	8
Vent Diameter (m)	4
Vent Gas Velocity (m/s)	5
Vent Gas Temperature (K)	315
Source Base Elevation (m)	0
Height of Building (m)	7
Building Dimensions (m2)	150x250
Building Downwash	Yes
Output Type	Concentration
Dispersion Options	Regulatory Default
Dispersion Coefficient	Urban
Averaging Time	1 hour
Terrain Options	Simple, Flat
Anemometer Height (m)	10
Upper bound of first wind speed category (m/s)	1.54
Upper bound of second wind speed category (m/s)	3.09
Upper bound of third wind speed category (m/s)	5.14
Upper bound of fourth wind speed category (m/s)	8.23
Upper bound of fifth wind speed category (m/s)	10.8
Day (no.)	1
Hour (no.)	1&2
Wind Flow Vector (degrees)	23&52
Wind Speed (m/s)	0.85&1.33
Mixing Height (m)	1200
Temperature (K)	282
Stability Class	5
Source emission rate conversion factor	1
Decay Coefficient	0
Emission Rate Units	(g/s)
Output Units	(g/m3)

Table 3.2: Downwind Dilutions for Varying Odour Emission Rates*

Case	Odour Emission Rate, $\dot{\omega}$ [g/s]	Downwind Odour Concentration, C(x,y,z) [g/m^3]	Odour Dilutions, δ(x,y,z) (dimensionless)
1	10,000	0.0468	3400
2	20,000	0.0935	3400
3	50,000	0.2338	3400

* Running ISCST3 for a given set of data (shown in Table 3.2) with only $\dot{\omega}$ varying, for an arbitrary point (1000m, 800m, 0) downwind.

Therefore, this implies that in the case of a single emission source, the procedure for the calculation of downwind dilutions can be based upon the input of an arbitrary odour emission rate ($\dot{\omega}$) into ISCST3. The downwind dilutions are then calculated based on this arbitrary emission rate using Equation (3.7).

However, when considering situations where multiple sources are emitting odours at different emission rates and at different odour concentrations, arbitrary odour emission rates ($\dot{\omega}$) cannot be used for all the sources. Instead, the odour emission rate from each source must be weighted with respect to all the other sources. The difficulty associated with weighting odour emission rates from different sources may at first appear to be an obstacle to odour modelling. However this can be overcome with the help of the thresholds derived from the Odour Impact Model.

To illustrate, the OIM has the ability to profile the response of a sensory panel to a specific odour at different dilutions. If two sources are emitting the same kind of odour (i.e.

same character of odour), but at different stack concentrations, then the OIM profiles of the two sources will be virtually the same. The only difference between the two OIM's will be in the positioning of the curves along the dilutions axis, as is described in Figure 3.1.

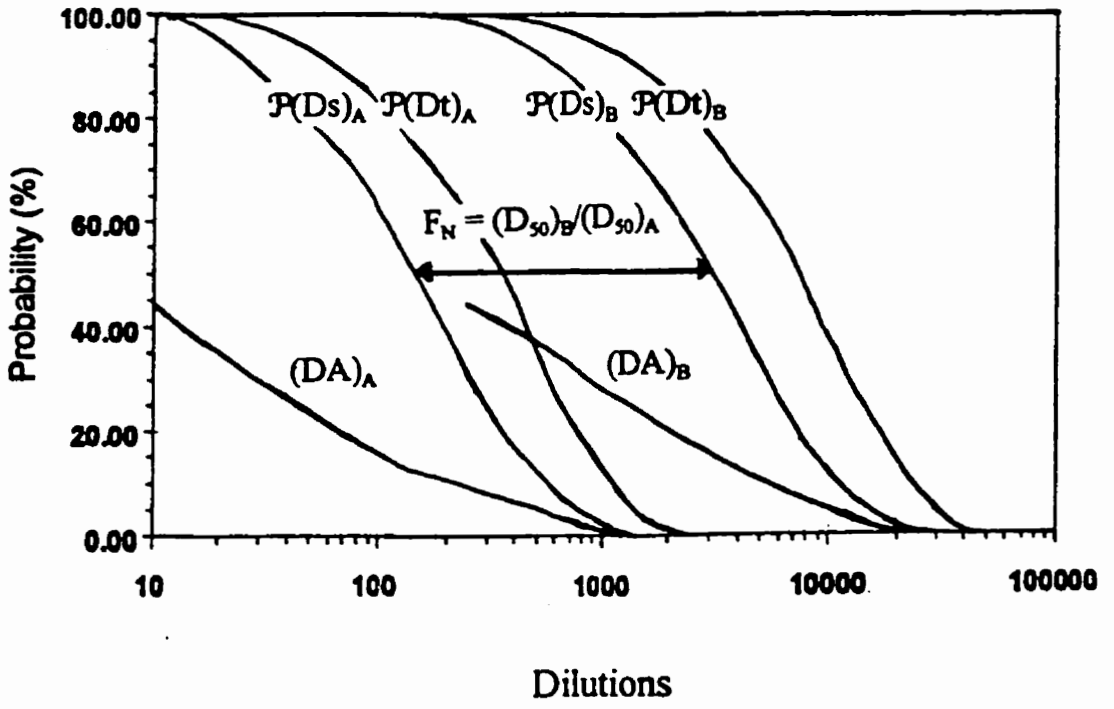


Fig. 3.1 OIM's of Two Identical Odours at Different Sampled Concentrations

In effect, the sample that is less concentrated is represented by $(OIM)_A$, while the sample with the higher initial concentration $(OIM)_B$ will require more dilutions before the panel is no longer able to perceive it. Therefore, applying a normalizing factor (F_N) to the dilutions of $(OIM)_A$ results in a shift of its curves to overlap those of $(OIM)_B$ This normalising factor (F_N) can be determined by dividing the discrimination thresholds (D_{50}) of the two samples:

$$F_N = \frac{(D_{50})_B}{(D_{50})_A} \tag{3.8}$$

where, $(D_{50})_A$ = discrimination threshold of odour from source A
$(D_{50})_B$ = discrimination threshold of odour from source B

In theory, the normalizing factor should be the same regardless of whether any random point along the discrimination, detection, or annoyance curves is chosen as a normalizing reference point. In reality, the detection profile and the degree of annoyance curve both have higher degrees of subjectivity built into them. As was shown by Nicell (1994), since the detection profile is based upon a forced-choice technique, the effects of chance cause the detection threshold to be a faulty representation of the discrimination threshold. This makes it subject to a larger source of error. In contrast, the discrimination threshold evaluation does not involve a forced-choice and therefore, the sources of error are reduced. Similarly, the degree of annoyance profile is dependant on the highly subjective and variable responses of the panelists. Thus, the use of the discrimination threshold in determining the normalizing factor will produce a more reliable estimate.

This normalizing factor permits two or more sources to be modelled together in a single ISCST3 run, by relating all sources emitting the same odour to a single normalised OIM. To illustrate, in a simple two stack scenario, if Stack A is emitting a more dilute form of the same odour as Stack B, then by rearranging Equation (3.8) it will have a discrimination threshold that is:

$$(D_{50})_A = \frac{(D_{50})_B}{F_N} \tag{3.9}$$

where, $(D_{50})_A$ = discrimination threshold of source A
$(D_{50})_B$ = discrimination threshold of source B
F_N = normalizing factor

The odour emission rates for each source can thereby be calculated by applying Equation (3.5), to give:

$$(\dot{\omega})_A = Q_A \times (D_{50})_A \times k \qquad (3.10)$$

$$(\dot{\omega})_B = Q_B \times (D_{50})_B \times k \qquad (3.11)$$

where,

$(\dot{\omega})_A$ = odour emission rate for source A [g/s]
$(\dot{\omega})_B$ = odour emission rate for source B [g/s]
Q_A = volumetric flow rate for source A [m^3/s]
Q_B = volumetric flowrate for source B [m^3/s]
$(D_{50})_A$ = discrimination threshold for source A
$(D_{50})_B$ = discrimination threshold for source B
k = conversion factor with assigned value of 1.0 [g/m^3]

Thus, by inputting the two emission rates into ISCST3, along with the individual source characteristics, reliable estimates of the initial source conditions can be implemented into the model. Consequently, since all sources with the same character of odour are normalised to a single OIM, the downwind dilutions in Equation (3.7) are calculated using the odour emission rate of the normalized OIM (i.e. $(D_{50})_B$). This procedure is further illustrated in the case-study which follows in chapter 5. At this point, this approach for modelling multiple odour sources is limited to odorous emissions of the same character since they have the same OIM profiles. As was previously noted, the result of combining two distinctive odours can not be easily predicted due to the complex interactions that they may undergo upon mixing. Therefore, further study is required before two different odours can be modelled together.

Another important consideration that must be made when running the dispersion model deals with the averaging time that is chosen to represent the odour episode. The averaging time, T_A, is defined as the time over which a time-series of concentrations is

averaged (Hanna et al., 1993). Peaks of short-term averages of pollutant concentrations always exceed peaks of long-term averages, for a given time series. The selection of an appropriate averaging time is related to the characteristics of the atmospheric monitoring instruments, the olfactometer, or the health effects that are of interest. The ISCST3 dispersion model assumes that the Gaussian dispersion equation yields a 1-hour average concentration. If the sampling technique in use employs some other time interval, it will be necessary to correct the results predicted by the dispersion model (Wark and Warner, 1981). A commonly accepted method for converting concentrations from one averaging time, T_{A1}, to another averaging time T_{A2}, is:

$$C_2 = C_1\left(\frac{T_{A1}}{T_{A2}}\right)^n \tag{3.12}$$

where,
C_1 = concentration calculated by the dispersion model (for T_{A1})
C_2 = concentration at desired averaging time (T_{A2})
T_{A1} = averaging time used by dispersion model
T_{A2} = desired averaging time
n = exponent based on atmospheric stability (Beychok, 1994)

Rearranging Equation (3.12) to put it in terms of dilutions gives:

$$\delta_2 = \delta_1\left(\frac{T_{A2}}{T_{A1}}\right)^n \tag{3.13}$$

where,
δ_1 = dilutions calculated for averaging time T_{A1}
δ_2 = dilutions for desired averaging time T_{A2}

As described by Beychok (1994), the value of 'n' ranges from 0.2 for stable atmospheric conditions, to 0.52 for moderate-to-strong turbulence, and to 0.7 for highly turbulent conditions. Based on this description, Table 3.3 provides a key to determine the stability exponent, n.

Table 3.3: Stability Exponent Determination By Stability Class

Stability Class	(A)	(B)	(C)	(D)	(E)
Stability Classification	Highly Turbulent	Moderately Turbulent	Slightly Turbulent	Neutral	Stable
"n" Exponent	0.7	0.52	0.52	0.2	0.2

In the case with the Odour Impact Model evaluation procedure, the panel members are subjected to an odour at different dilutions for only a few minutes. Furthermore, other methods of odour assessment use evaluation techniques which are on the order of seconds. This is the case when 'odour judges' are used to survey the ambient air in the neighbourhood of an offending site and rate the degree of annoyance of the odorous emissions. Thus, in order to provide a best representation of the OIM, an averaging time of 1 minute was decided upon for use with the case study. This decision was based on the fact that: (1) an odour impact model was used to assess the odorous emissions from the complex; and (2) odour judges were also used to walk around the neighbourhood of the site and rate the degree of annoyance. In this respect, the choice of averaging time is highly site-specific. Information to date indicates that the effects of sampling time are exceedingly complex and for this reason, more research related to averaging time and odour modelling is required.

Once an acceptable averaging time is decided upon, the source's downwind dilutions can be predicted. As a result, the dose-response expressions derived from the OIM may be mapped onto the predicted output of dilutions. Thus, the community's probability of detection $P(Dt)$, probability of discrimination $P(Ds)$, and degree of annoyance (DA) at each

dilution level can be estimated and plotted as contour lines. Analysis of these patterns can give further insight to regulatory and administrative decision makers attempting to resolve odour nuisance problems, or to help predict future odour annoyances before they arise.

3.6 Limitations to the Strategy

While the proposed odour control strategy does provide a basis for predicting the impact of odorous emissions from stationary sources on surrounding communities, it still has some limitations. The strategy is primarily limited by the two models that are used, namely the Odour Impact Model and the USEPA's Industrial Source Complex Model.

Under most atmospheric conditions, the odour levels at a fixed point are not constant but vary depending on source characteristics, topographic detail and meteorological factors. Only under extreme conditions, such as atmospheric inversions, would odours be detected continually at any location. Continuous exposure to odours may lead to olfactory fatigue which lowers annoyance levels with time, while fluctuating odour levels do not normally result in fatigue and may in fact produce higher complaint potentials (Nicell and St. Pierre, 1996).

The question of the appropriate averaging time has been one of the primary distinctions cited for modifying standard dispersion methods for use in odour assessment. As Diosey (1996) points out, the problem lies in the fact that most standard dispersion models rely on sampling data that are time-averaged, such as the turbulent diffusion parameters. In addition, these models assume a steady-state condition. This makes dispersion models, such as the Industrial Source Complex (ISC3) model, applicable for

averaging times of a few minutes to 1 hour. As a result, if odour emissions are on the order of seconds, then dispersion modelling could conceivably underestimate the odour impact.

Gaussian models, such as the ISCST3 model, are the most widely used models for plume dispersion and are generally used for regulatory modelling. However, there are some potential drawbacks to the model including:

- ISCST3 assumes emission rates to be constant and continuous for a minimum one-hour averaging time period. Modelling for each specific process is representative only when these conditions exist. Thus, odour assessment requires modifying ISCST3 for averaging times on the order of a few minutes.

- no variations occur in wind speed, wind direction and stability category between the odour source and the receptor. This assumption is reasonable within a few kilometres from the source.

- effluent dispersion in the horizontal and vertical directions is assumed to follow a Gaussian distribution.

The accuracy of the Odour Impact Model in modelling a population's probability of response to an odour is dependant on the type of the dynamic olfactometer that is used. Olfactometry involves numerous elements that may influence the result, some of which are:

- the type of sampling bag used for the collection and transport of the odour sample, and the amount of time the sample is stored. Improper storage can cause adsorption or transport of the odour through the film;

- the type of olfactometer/nose interface used provides a unique way of delivering the diluted sample to the nose of the panelist. Until now a standard method that simulates normal 'sniffing behaviour' does not exist;

- the size of the panel and the selection procedure of the panelists critically influences the level of the outcome of odour threshold measurements. Therefore, rigorous panel selection significantly improves the repeatability of the measurements.

The accuracy and precision of this study rely on the USEPA's ISCST3 atmospheric dispersion model and the Odour Impact Model, including the procedures that are followed in working with these models. Other practitioners may choose to use other dispersion models as they see fit.

4.0 OIM Curve Fitting Results

Odour Impact Models (OIM's) were developed in a previous study by Nicell (1986) for the six chemicals listed in Table 4.1. The OIM's for the six chemicals were developed using five panels consisting of ten members each. The overall OIM for each odorant was generated by combining each of the five panels into one large panel consisting of 50 responses. In order to select an appropriate mathematical expression that reliably describes the dose-response relationships of the OIM, the data for each of the profiles was analyzed with a comprehensive curve fitting program, CurveExpert 1.24®.

Table 4.1: Chemical Odorants Investigated

No.	Chemical Name
1	n-Butanol
2	n-Butyl Acetate
3	Isobutanol
4	Methyl Isoamylketone
5	Octane
6	Propylene Glycol Monomethyl Ether

The objectives of this portion of the overall study were to:

(1) select and fit a mathematical expression to the six chemicals' overall OIM profiles of:
   - (i) probability of detection, P(Dt);
   - (ii) probability of discrimination P(Ds);
   - (iii) degree of annoyance (DA);

(2) determine the goodness-of-fit for the mathematical expressions of each profile;

(3) compare the results obtained for a particular chemical's overall OIM to each of the corresponding 10 member panels.

4.1 Detection and Discrimination Thresholds

At the present time there does not exist a regulatory standard for assessing what constitutes an odour problem. Odour control policies are based on zoning laws, nuisance laws, and/or threshold measurements. While all serve a purpose in odour abatement, it has been necessary to focus on the threshold concept as a tool for predicting the impact of odours on a community.

Most odour control regulations rely on a panel evaluation technique to determine the detection thresholds of odorous emissions (Nicell, 1986). This threshold refers to an effective dosage at 50% probability of detection (ED_{50}), and represents the concentration (or dilution) at which 50% of the members of a population perceive the odour. In this investigation, non-linear regression analysis permits the OIM data to be described by a mathematical expression. In this respect, the concentration at which 50% of the panel begin to detect the odour can be interpolated directly from the given curve-fit expression. Another method that has previously been used to determine the ED_{50} involves calculating the geometric mean of the individual panelists thresholds. This however, is only an estimate of the panel detection threshold, while the value which is directly interpolated from the curve-fit expression would be a true representation of the panel's detection threshold. A similar relationship exists for the discrimination threshold D_{50}, which can also be interpolated directly from the curve-fit model. Moreover, the D_{50} may also be estimated as the geometric mean of the individual panelist discrimination thresholds. In this investigation, panel thresholds will refer to the interpolated values from the curve-fit equations.

As was previously explained, at the detection threshold the presence of the odour is

noticed, however its character cannot yet be recognised. The discrimination threshold on the other hand, represents the concentration at which the panelist is sure, beyond a doubt, about the presence of the odour. As a result, it has been suggested that as long as the odour character is unrecognizable, the odour is unlikely to be annoying and so, the discrimination threshold may be a better benchmark for odour control (Nicell, 1986). For this reason, both the ED_{50} and the D_{50} thresholds will be included in this study and are shown in Figure 4.1.

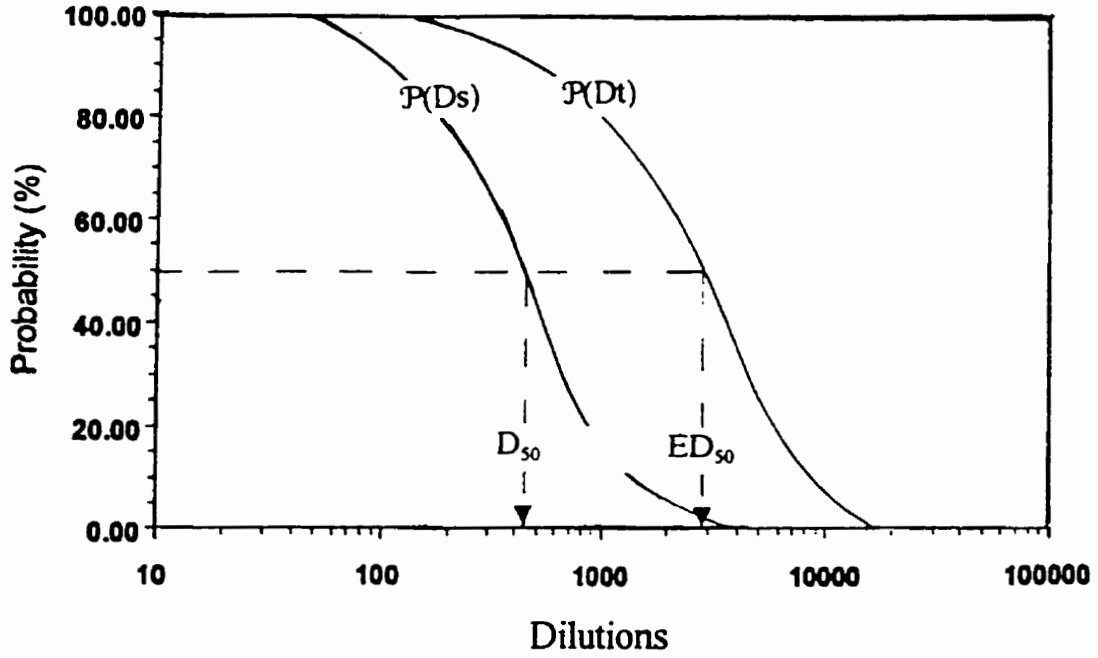


Fig. 4.1: Detection and Discrimination Thresholds (ED_{50} and D_{50}) from OIM

4.2 Probability of Detection and Discrimination Curve-Fitting

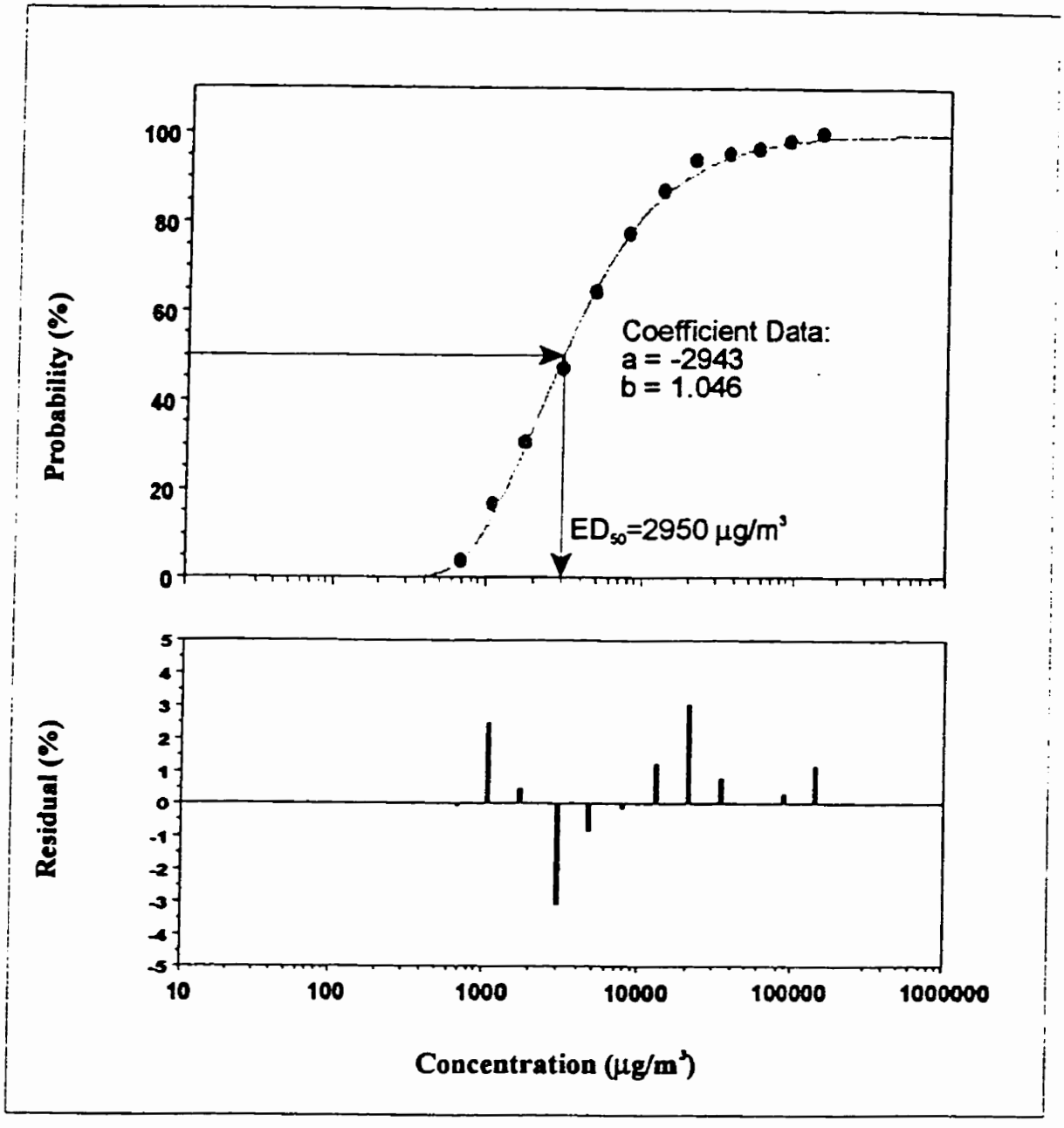
The final Probability of Detection 'P(Dt)'and probability of discrimination 'P(Ds)' profiles for the six chemicals were curve-fit using non-linear regression. The following equation that defines the probability of response (y) as a function of concentration (C) was found to effectively represent the data:

$$y = 100e^{\left(a/C^b\right)} \tag{4.1}$$

where, y = probability of detection $\mathcal{P}(Dt)$ or discrimination, $\mathcal{P}(Ds)$ (%)
C = concentration
a, b = coefficients of curvature

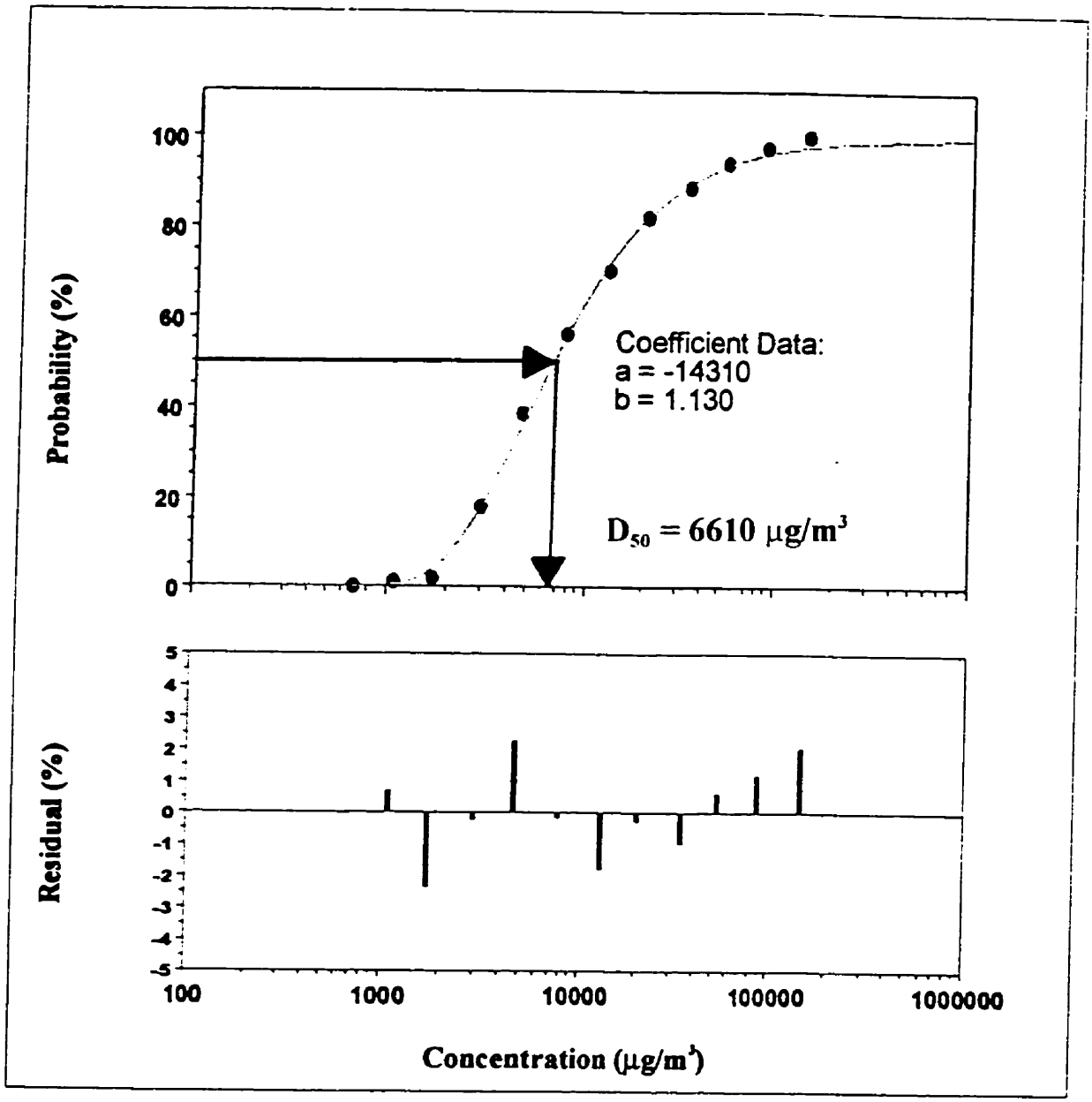
The model is defined by a modified exponential function with 'C' as the dependant variable. This apparently elementary two parameter exponential equation is in fact very flexible and representative of the Odour Impact Model. The two coefficients 'a' and 'b' are responsible for the curvature of the model. Consequently, as long as the value of the coefficient 'a' is negative and 'b' is positive, the expression is restricted to a lower bound of 0 (as $C \rightarrow 0$) and an upper bound of 100 (as $C \rightarrow \infty$). Figures 4.2 and 4.3 illustrate the accuracy of fit for the respective detection and discrimination profiles of n-butanol. Curve-fits for the remaining chemicals are presented in detail in Appendix A, and coefficients of curvature ('a' and 'b') for each chemical's $\mathcal{P}(Dt)$ and $\mathcal{P}(Ds)$ profiles are presented in Tables 4.2 and 4.3.

The standard error (S_y), correlation coefficient (r), and the concentration where 50% of the panel detects and discriminates the odour were also determined using the CurveExpert program and are detailed in Tables 4.2 and 4.3. As can be seen, the residuals and standard errors for all six chemicals are very small. Furthermore, the correlation coefficient values approach unity. These results indicate that the model fits all six chemical OIM's very well.



Standard Error, Sr: 1.731
Correlation Coefficient, r: 0.9989

Fig. 4.2: n-Butanol -Probability of Detection



Standard Error, Sr: 1.467
Correlation Coefficient, r: 0.9994

Fig. 4.3 n-Butanol - Probability of Discrimination

Table 4.2: Probability of Detection Curve-Fitting Parameters

Chemical Name	Coeff. of fit "a"	Coeff. of fit "b"	Standard Error, S_r (%)	Correlation Coefficient (r)	ED_{50}* ($\mu g/m^3$)
n-Butanol	-2.94E+03	1.05E+00	1.73	0.9989	2.95E+03
n-Butyl Acetate	-4.24E+02	9.28E-01	3.73	0.9953	1.01E+03
Isobutanol	-9.80E+01	6.21E-01	3.91	0.9925	2.89E+03
Methyl Isoamylketone	-4.66E+02	1.01E+00	1.48	0.9993	6.31E+02
Octane	-3.13E+05	1.20E+00	5.26	0.9915	5.38E+04
Propylene Glycol Monomethyl Ether	-8.63E+05	1.21E+00	5.30	0.9899	1.05E+05

* at T= 10°C and P= 1 Atm

Table 4.3: Probability of Discrimination Curve-Fitting Parameters

Chemical Name	Coeff. of fit "a"	Coeff. of fit "b"	Standard Error,S_r (%)	Correlation Coefficient (r)	D_{50}* ($\mu g/m^3$)
n-Butanol	-1.43E+04	1.13E+00	1.4675	0.9994	6.61E+03
n-Butyl Acetate	-4.46E+03	1.10E+00	3.8889	0.9957	2.84E+03
Isobutanol	-9.48E+02	8.24E-01	4.0178	0.9942	6.37E+03
Methyl Isoamylketone	-2.42E+03	1.12E+00	2.2796	0.9985	1.37E+03
Octane	-7.62E+07	1.59E+00	4.8008	0.9911	1.14E+05
Propylene Glycol Monomethyl Ether	-1.95E+08	1.60E+00	6.5554	0.9810	1.92E+05

* At T= 10°C and P= 1 Atm

4.3 Degree of Annoyance Curve-Fitting

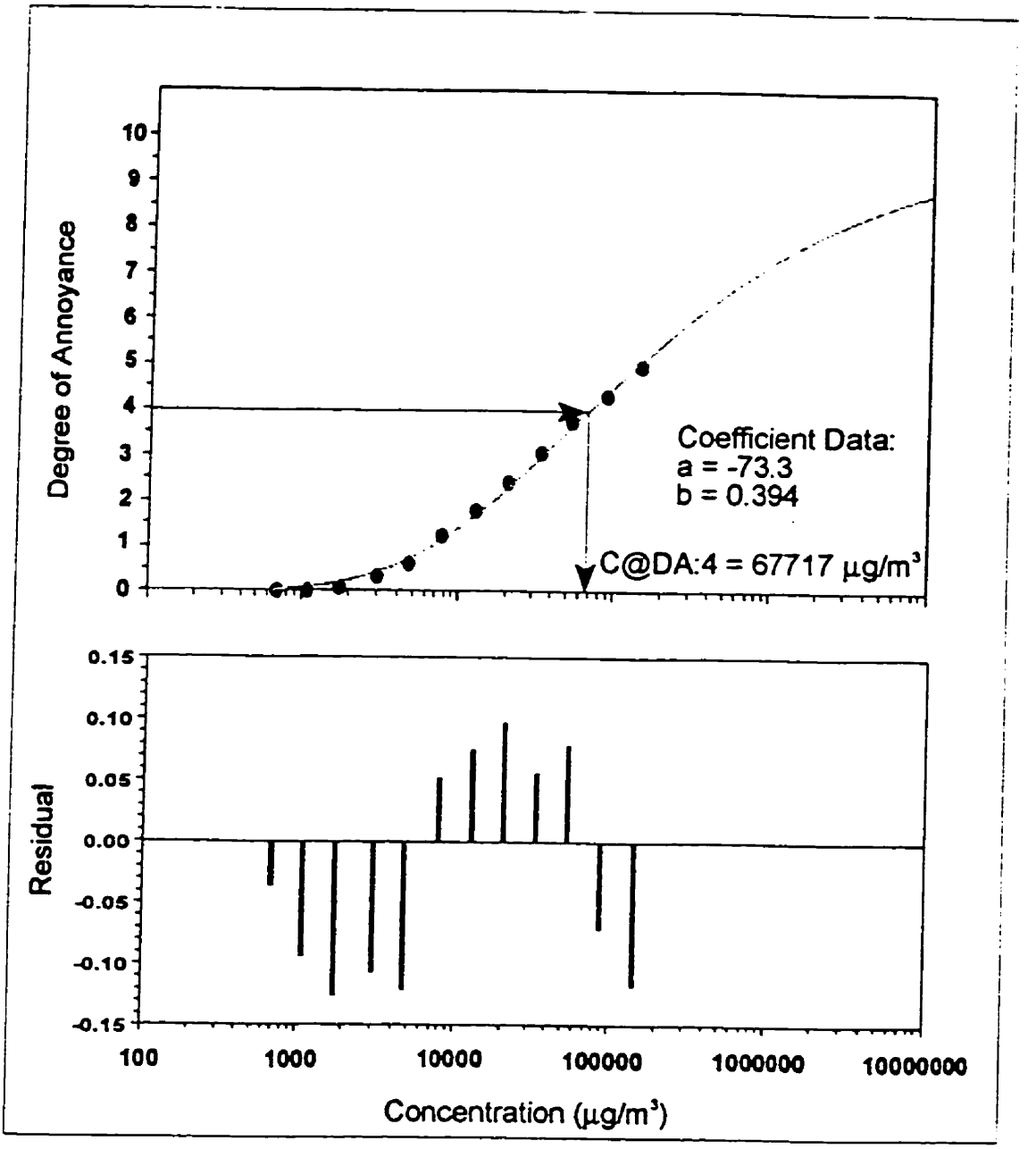
The Degree of Annoyance (DA) data was modelled with an equation similar to the probability of detection and discrimination expressions. This equation which defines the

panel's DA as a function of concentration (X) is represented by a modified exponential function:

$$y = 10e^{\left(a/C^b\right)} \tag{4.2}$$

where, y = Degree of Annoyance, DA
C = concentration ($\mu g/m^3$)
a, b = coefficients of curvature

The two coefficients 'a' and 'b' are responsible for the curvature of the model. Consequently, as long as the value of the coefficient 'a' is negative and 'b' is positive, the expression is restricted to a lower bound of 0 (as $C \rightarrow 0$) and an upper bound of 10 (as $C \rightarrow \infty$). Figure 4.4 illustrates the degree of fit for the Degree of Annoyance profile of n-butanol. Curve-fits for the remaining chemicals are detailed in Appendix A, and coefficients of curvature ('a' and 'b') for each chemical's DA profile are presented in Table 4.4. It should be noted that unlike the P(Dt) and P(Ds) curve-fits, the DA curve-fit was extrapolated beyond the existing data. The predicted degrees of annoyance for large concentrations are from an extended part of the curve that is an estimated plot of the curve-fit function, and so, the information obtained at high concentrations is only an estimate of the panel's true degree of annoyance. This should be taken into account when developing OIM's, as data should be collected to represent a full range of dilutions. It may be the case that another regression model more accurately describes the DA profile at high concentrations however, since the data does not exist, the predicted curve-fit will be used to describe the degree of annoyance profile.



Standard Error, Sr: 0.10
Correlation Coefficient, r: 0.9986

Fig. 4.4: n-Butanol - Degree of Annoyance

It was also decided to obtain from the model the concentration where a degree of annoyance of 4 is experienced by the panel. This value, which by definition represents the point on the curve where the odour begins to be characterised as very unpleasant (see Figure 2.1), was chosen as a reference for further statistical analysis of the panel results. The resultant standard error (S_r), and correlation coefficient (r) were also determined as before and are detailed in Tables 4.4. As was the case with the probability of detection and discrimination profiles, the standard errors for all six chemicals are relatively small and the correlation coefficient values (r) all approach unity.

Table 4.4: Degree of Annoyance Curve-Fitting Parameters*

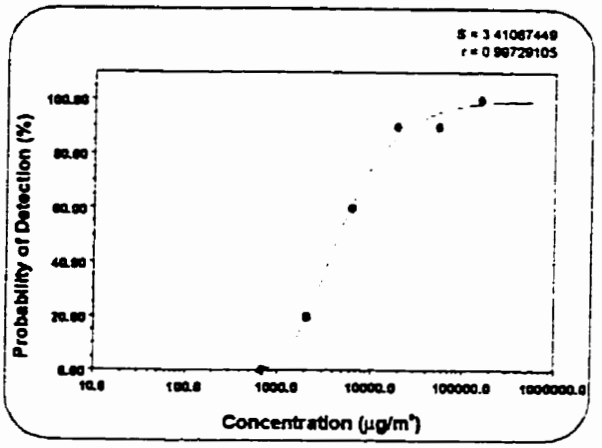
Chemical Name	Coeff. of fit "a"	Coeff. of fit "b"	Standard Error, S_r	Correlation Coefficient (r)	Conc. @ DA=4 ($\mu g/m^3$)
n-Butanol	-7.30E-01	3.94E-01	0.10	0.9986	6.77E-04
n-Butyl Acetate	-1.07E-02	4.53E-01	0.08	0.9979	3.69E-04
Isobutanol	-4.20E-01	3.13E-01	0.04	0.9992	2.05E-05
Methyl Isoamylketone	-5.70E-01	4.11E-01	0.03	0.9998	2.32E-04
Octane	-1.99E-03	5.63E-01	0.04	0.9987	8.49E-05
Propylene Glycol Monomethyl Ether	-3.08E-03	5.79E-01	0.03	0.9987	1.23E-06

* At T= 10°C and P= 1 Atm

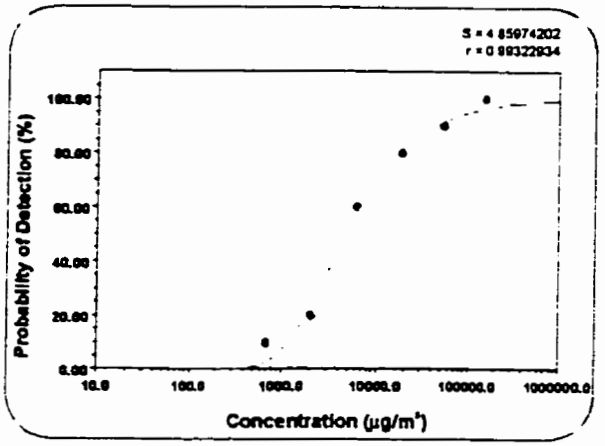
4.4 Panel Curve-Fitting Parameters

The five individual panels were investigated to determine their ability to reproduce the detection and discrimination thresholds of the overall OIM. Similarly, the degree of annoyance of the individual panels were compared to the overall OIM results. As is shown in Figure 4.5 for n-butanol, the data collected from each panel of 10 people were fit to the

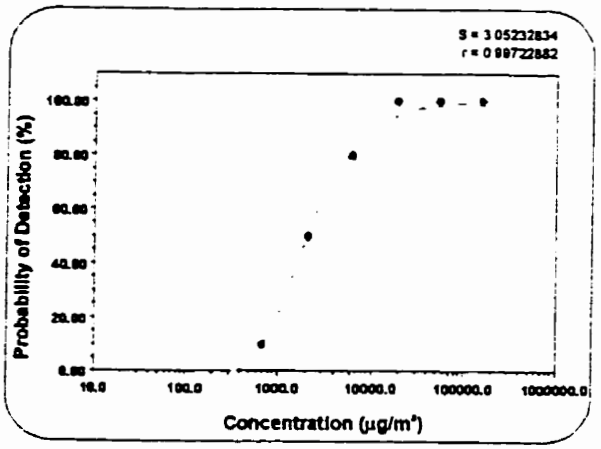
Panel No. 1:



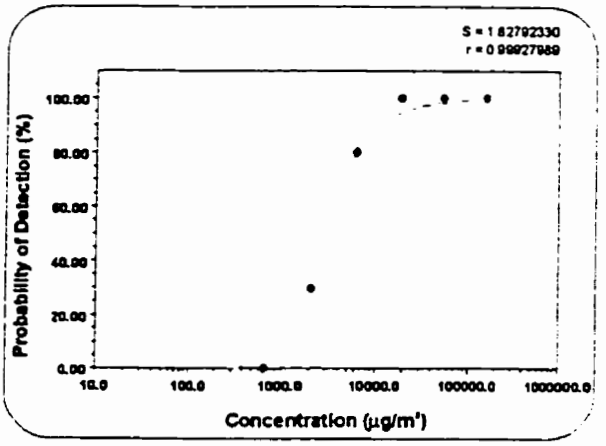
Panel No. 2:



Panel No. 3:



Panel No. 4:



Panel No. 5:

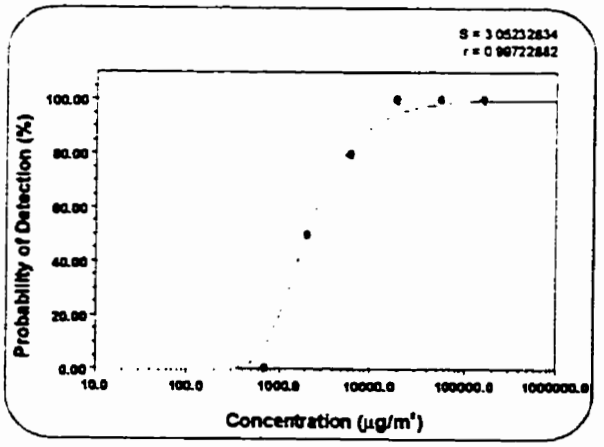


Fig. 4.5: n-Butanol - Panel Probability of Detection

modified exponential function using non-linear regression to obtain a panel curve-fit. In this case however, only six data points were available for each curve-fit. This resulted in a variation in coefficients of curvature 'a' and 'b' for each of the five panels. Consequently, there was some discrepancy in each panel's ED_{50} and D_{50} values. To illustrate, Table 4.5 lists the derived $\mathcal{P}$(Dt), $\mathcal{P}$(Ds), and DA curve-fit coefficients for every panel of the six pure chemicals.

Further comparison of the curve-fit results of each panel to the overall OIM parameters required some statistical analysis. Each panel's 50% probability of detection and discrimination values were extrapolated and their mean, standard deviation, and 95% confidence interval values were determined. These are tabulated in Table 4.6. The geometric mean of the panels was required since the profile thresholds are log-normally distributed (Nicell et al., 1991). This was performed using the following equation:

$$\bar{X} = \left[\prod_{i=1}^{n} X_i \right]^{1/n} \tag{4.3}$$

or,

$$Log\,\bar{X} = \frac{1}{n} \times \sum_{i=1}^{n} LogX_i \tag{4.4}$$

where, $\bar{X}$ = the geometric mean of the panel thresholds (average ED_{50} or D_{50})
n = the number of panels
X_i = the i'th panel's threshold (ED_{50} or D_{50})

Table 4.5: Individual Panels' Coefficients of Curvature and Threshold Values

Chemical Name	Panel Number	Probability of Detection			Probability of Discrimination			Degree of Annoyance		
		Coefficients		ED50	Coefficients		D50	Coefficients		C@(DA=4)
		a	b	(μg/m³)	a	b	(μg/m³)	a	b	(μg/m³)
n-Butanol	1	-6.574E+3	1.089E+0	4.49E+03	-5.201E+5	1.410E+0	1.47E+04	-2.115E+2	4.900E-1	6.65E+04
	2	-9.670E+2	8.554E-1	4.75E+03	-3.936E+3	9.402E-1	9.84E+03	-2.570E+1	2.718E-1	2.11E+05
	3	-4.480E+3	1.152E+0	2.03E+03	-6.550E+4	1.325E+0	5.71E+03	-6.640E+1	3.955E-1	5.05E+04
	4	-2.948E+5	1.625E+0	2.90E+03	-2.279E+5	1.520E+0	4.27E+03	-8.790E+1	4.001E-1	8.99E+04
	5	-2.696E+4	1.376E+0	2.17E+03	-2.829E+5	1.536E+0	4.50E+03	-7.880E+1	4.115E-1	5.02E+04
n-Butyl Acetate	1	-3.232E+2	8.658E-1	1.21E+03	-3.625E+3	1.063E+0	3.16E+03	-1.062E+2	4.474E-1	7.67E+04
	2	-1.072E+2	7.133E-1	1.17E+03	-5.086E+5	1.605E+0	4.50E+03	-3.192E+2	5.542E-1	6.39E+04
	3	-1.142E+4	1.415E+0	9.56E+02	-2.914E+4	1.287E+0	3.91E+03	-1.506E+2	4.931E-1	5.48E+04
	4	-2.030E+3	1.181E+0	8.64E+02	-6.950E+2	9.142E-1	1.92E+03	-4.593E+1	3.639E-1	1.01E+05
	5	-1.557E+3	1.155E+0	7.99E+02	-2.785E+5	1.696E+0	2.01E+03	-8.075E+1	4.222E-1	7.83E+04
Isobutanol	1	-7.602E+1	5.907E-1	2.84E+03	-3.798E+3	9.968E-1	5.63E+03	-4.640E+1	3.422E-1	2.16E+05
	2	-5.044E+1	5.550E-1	2.26E+03	-1.084E+3	8.606E-1	5.14E+03	-3.251E+1	2.715E-1	1.43E+06
	3	-3.009E+3	9.879E-1	4.81E+03	-1.082E+5	1.286E+0	1.10E+04	-3.269E+2	5.158E-1	1.53E+05
	4	-1.859E+2	7.660E-1	1.48E+03	-9.672E+2	8.653E-1	4.31E+03	-4.502E+1	3.241E-1	3.91E+05
	5	-2.562E+2	7.258E-1	3.45E+03	-1.713E+2	6.226E-1	6.97E+03	-2.336E+1	2.440E-1	1.82E+06
	6	-2.185E+2	7.281E-1	2.70E+03	-2.885E+2	6.383E-1	1.27E+04	-3.488E+1	2.603E-1	3.44E+06
	7	-5.602E+3	1.240E+0	1.42E+03	-7.477E+3	1.103E+0	4.54E+03	-6.470E+1	3.898E-1	1.13E+05
Methyl	1	-4.640E+4	1.635E+0	8.95E+02	-6.851E+5	1.810E+0	2.05E+03	-8.002E+1	4.183E-1	8.51E+04
Isoamylketone	2	-3.810E+3	1.357E+0	5.70E+02	-2.978E+4	1.485E+0	1.32E+03	-5.749E+1	4.124E-1	4.49E+04
	3	-8.199E+2	1.136E+0	5.07E+02	-3.338E+5	1.904E+0	9.67E+02	-5.676E+1	4.373E-1	2.37E+04
	4	-1.828E+2	9.122E-1	4.51E+02	-8.280E+2	1.059E+0	8.04E+02	-5.090E+1	3.926E-1	5.65E+04
	5	-3.248E+2	9.052E-1	8.92E+02	-8.428E+3	1.208E+0	2.41E+03	-5.735E+1	3.945E-1	7.27E+04
Octane	1	-7.705E+7	1.641E+0	8.02E+04	-2.264E+6	1.299E+0	1.03E+05	-2.009E+3	5.618E-1	1.46E+06
	2	-7.837E+3	8.628E-1	4.98E+04	-1.678E+7	1.396E+0	1.94E+05	-2.090E+5	9.268E-1	8.16E+05
	3	-1.084E+6	1.283E+0	6.71E+04	-1.222E+7	1.443E+0	1.05E+05	-8.586E+2	4.939E-1	1.83E+06
	4	-5.791E+7	1.725E+0	3.97E+04	-6.087E+6	1.414E+0	8.14E+04	-7.388E+2	4.887E-1	1.57E+06
	5	-1.044E+8	1.746E+0	4.84E+04	-3.204E+7	1.534E+0	9.91E+04	-1.266E+3	5.262E-1	1.58E+06
	6	-4.287E+5	1.238E+0	4.77E+04	-7.080E+6	1.337E+0	1.74E+05	-6.765E+3	6.479E-1	1.44E+06
	7	-4.817E+6	1.437E+0	5.75E+04	-1.858E+7	1.440E+0	1.44E+05	-1.133E+3	5.058E-1	2.25E+06
Propylene Glyco	1	-3.200E+8	1.735E+0	9.83E+04	-3.277E+6	1.264E+0	1.90E+05	-7.794E+1	2.730E-1	1.15E+07
Monomethyl	2	-2.008E+6	1.273E+0	1.19E+05	-7.527E+7	1.514E+0	2.04E+05	-2.279E+4	7.150E-1	2.09E+06
Ether	3	-3.050E+7	1.493E+0	1.31E+05	-4.614E+7	1.451E+0	2.47E+05	-3.618E+3	5.780E-1	1.50E+06
	4	-1.207E+7	1.442E+0	1.05E+05	-9.215E+6	1.378E+0	1.48E+05	-1.607E+3	5.450E-1	1.51E+06
	5	-7.381E+7	1.610E+0	9.70E+04	-2.057E+6	1.232E+0	1.80E+05	-9.908E+3	6.719E-1	1.01E+06

The sample standard deviation, s_x, of the panels' thresholds was calculated using:

$$\mathrm{Log}(s_x) = \sqrt{\frac{1}{(n-1)} \times \sum_{i=1}^{n} \left(\mathrm{Log}\,\bar{X} - \mathrm{Log}X_i \right)^2} \qquad (4.5)$$

The 95% confidence interval for the mean panel ED_{50} and D_{50} values were then determined (see Table 4.6). To illustrate, the lower and upper bounds of a 95% confidence interval for a log-normal distribution are calculated according to:

$$\textit{Lower Bound} = 10^{\left(\frac{\mathrm{Log}\bar{X} - t \cdot Log(s_x)}{\sqrt{n}} \right)} \qquad (4.6)$$

$$\textit{Upper Bound} = 10^{\left(\frac{\mathrm{Log}\bar{X} + t \cdot Log(s_x)}{\sqrt{n}} \right)} \qquad (4.7)$$

where, X = the mean of the panel thresholds (average ED_{50} or D_{50})
s_x = the standard deviation of the panels
n = the number of panels
t = is the 95th percentile of the t-distribution (i.e. for 'n-1' degrees of freedom)

Thus, as is detailed in Table 4.7, the mean concentration threshold obtained from each chemical's panels were comparable to the thresholds extrapolated from the overall OIM curve-fit. Each panel alone provides a good approximation of the detection and discrimination thresholds, as is made evident from the 95% confidence intervals that exist. However, it is clear that a better estimate of the overall ED_{50} and D_{50} values is obtained

Table 4.6: 95% Confidence Intervals for Individual Panel Thresholds

Chemical Name	Detection Threshold ($\mu g/m^3$)					Discrimination Threshold ($\mu g/m^3$)					Degree of Annoyance				
	$Log(ED_{50})$	ED_{50}	$Log(s_t)$	95% Confidence Interval Upper	Lower	$Log(D_{50})$	D_{50}	$Log(s_t)$	95% Confidence Interval Upper	Lower	Log(DA=4)	DA=4	$Log(s_t)$	95% Confidence Interval Upper	Lower
n-Butanol	3.4868	3,100	0.1723	1,870	5,020	3.8398	6,900	0.2326	3,560	13,500	4.9012	79,650	0.2587	38,000	166,900
n-Butyl Acetate	2.9938	1,000	0.0797	790	1,240	3.4662	2,900	0.1674	1,810	4,720	4.8654	73,350	0.1	55,100	97,600
Isobutanol	3.3977	2,500	0.1908	1,660	3,750	3.8198	6,600	0.1857	4,450	9,800	5.7308	538,000	0.5834	155,300	1,864,000
Methyl Isoamylketone	2.8034	650	0.1395	430	950	3.141	1,400	0.205	770	2,490	4.714	51,760	0.2171	27,800	96,300
Octane	4.7356	54,400	0.1026	43,700	67,700	5.09	123,000	0.1401	91,300	165,800	6.1774	1,504,500	0.1353	1,128,000	2,007,000
Propylene Glycol Monomethyl Ether	5.0388	109,300	0.0567	93,000	128,600	5.2812	191,100	0.0808	151,700	240,700	6.348	2,228,400	0.4145	681,000	7,288,000

when the panel thresholds are analyzed together, as mean panel detection and discrimination thresholds. Thus, in order to achieve a high degree of confidence in the thresholds, more than one panel is required when developing an OIM. Similarly, the mean concentration at a Degree of Annoyance rating of '4' is compared to the overall OIM results. As before, each panel alone provides a good approximation of the overall Degree of Annoyance profile. Detailed figures and tables of all six chemicals' individual panel curve-fits are available in Appendix B.

Table 4.7: Overall OIM Thresholds Vs. Geometric Mean Panel Thresholds

Chemical Name	OIM ED_{50}	Panel Mean ED_{50}	OIM D_{50}	Panel Mean D_{50}	OIM DA=4	Panel Mean DA=4
n-Butanol	2.95E+03	3.10E+03	6.61E+03	6.90E+03	6.77E−04	7.97E+04
n-Butyl Acetate	1.01E+03	1.00E+03	2.84E+03	2.90E+03	3.69E−04	7.34E+04
Isobutanol	2.89E+03	2.50E+03	6.37E+03	6.60E+03	2.05E−05	5.38E+05
Methyl Isoamylketone	6.31E+02	6.50E+02	1.37E+03	1.40E+03	2.32E−04	5.18E+04
Octane	5.38E−04	5.44E+04	1.14E+05	1.23E+05	8.49E−05	1.50E+06
Propylene Glycol Monomethyl Ether	1.05E−05	1.09E+05	1.92E+05	1.91E+05	1.23E−06	2.23E+06

The modified exponential function is found to represent the overall and individual panels for the six pure chemicals within acceptable confidence limits. As a result, the function can now be applied to OIM's that have been developed from community odour impact assessments.

4.6 Curve-Fitting Model - Dilution Modification

The above mentioned OIM dose-response equations (i.e. Equations (4.1) and (4.2))

define the panel's response as a function of concentration (C). In order to use the derived exponential equations to model OIM's as a function of dilutions (δ), some modifications to the P(Dt), P(Ds) and (DA) equations must be made. In this case, dilutions which represent the reduction in concentration that the original odour source has undergone upon mixture with odour-free air, are expressed as:

$$\delta = C_o / C \tag{4.8}$$

where, C_o = initial concentration
C = concentration when diluted with odour-free air
δ = sample dilutions with odour-free air

Therefore, solving Equation (4.8) for 'C' and applying it to Equation (4.1), gives:

$$y = 100e^{(\alpha \delta^{\beta})} \tag{4.9}$$

where, y = Probability of Detection P(Dt) or Discrimination P(Ds) (%)
δ = number of dilutions of sample with odour-free air
α, β = coefficients of curvature

Similarly, Equation (4.2), representing the DA profile as a function of concentration, becomes:

$$y = 10e^{(\alpha \delta^{\beta})} \tag{4.10}$$

where, y = Degree of Annoyance, DA
δ = number of dilutions of sample with odour-free air
α, β = coefficients of curvature

This modification will be applied in the subsequent section which merges the Odour Impact Model with atmospheric dispersion modelling.

5.0 Odour Impact Dispersion Modelling

Based on the ability to reliably fit mathematical expressions to the Odour Impact Model profiles, it appears that a natural extension of the OIM is its incorporation into atmospheric dispersion modelling. This may be accomplished by merging the Odour Impact Model (OIM) with the USEPA's Industrial Source Complex Short Term Dispersion Model (ISCST3). As a result, contour lines representing a surrounding community's probability of detection, probability of discrimination, and degree of annoyance can be mapped. By combining the dose-response relationships from the OIM with dispersion modelling, the strategy allows for variables such as odour concentration, gas flowrate and local geographic and meteorological conditions to be considered in the impact assessment.

For illustrative purposes, an odour impact study conducted in 1991 (Anonymous, 1991) of an industrial facility located in Ontario (summarized in an article by Nicell and St. Pierre (1996)), will be used to investigate the effectiveness of this proposed strategy. Source and meteorological data collected in the odour survey, along with OIM data collected for the same odour source in an earlier study (Anonymous, 1988) provide the required data for the Odour Impact Dispersion Model.

The objectives of this part of the investigation are to:

(1) Use the modified exponential equations introduced in chapter 4.0 to fit the scenario's OIM profiles of: probability of detection, $\mathcal{P}(Dt)$; probability of discrimination, $\mathcal{P}(Ds)$; and degree of annoyance, DA.

(2) Use dispersion modelling to predict the amount of dispersion (dilutions) in the surrounding community that results under specific source and meteorological conditions.

(3) Combine the OIM expressions from (1) with the predicted dilution contours from (2) to generate contour profiles representative of the community's probability of detection, 'P(Dt); probability of discrimination, 'P(Ds); and degree of annoyance, DA.

5.1 OIM Curve-Fitting Results

Of the current odour control regulations that exist, many are based on statutory nuisance laws or the dilution-to-threshold (ED_{50}) principle. Unlike most of the currently available models, the Odour Impact Model provides an overall picture of the impact of an odour problem on a community. This enables a practical procedure for routinely evaluating the plant's odorous emissions in terms of the community's potential of odour detection and discrimination, as well as its degree of annoyance, to be followed.

OIM's can be generated for a variety of plant processes under different operating conditions. Non-linear regression analysis of these OIM's results in mathematical expressions for the Probability of Detection 'P(Dt)', Probability of Discrimination 'P(Ds)', and Degree of Annoyance 'DA' profiles. These functions can therefore be used to transform, the output dilutions from ISCST3 to create a data file that represents the surrounding community's probability of detection, probability of discrimination, and degree of annoyance to an odorous emission. Using a contour plotting computer program such as Surfer Version 2.0® this data file can be mapped-out to display 'P(Dt), 'P(Ds) and DA contours.

5.2 Application of the OIDM - Case Study

5.2.1 Background

A neighbourhood odour survey was conducted for an industrial facility located in Ontario, Canada to identify the extent and nature of the plant's odorous emissions. The goal of the investigation was to define control options that could minimise the community odour problem. To accomplish this, a pool of trained odour observers completed forty-two field odour surveys between October 2, 1990 and August 29, 1991 to detect odours at neighbourhood locations, match the odour characteristics to plant sources, and rate the odours' degree of annoyance. The study focused on five process areas within the plant which each emitted distinct odours. Two process areas making up source No. 1 had indistinguishable odour characteristics in the surrounding neighbourhood. This was also the case with source No. 2. The five distinct odour sources were:

(1) Stacks No. 1A and 1B
(2) Stacks No. 2A and 2B
(3) Stack No. 3
(4) Stack No. 4
(5) Stack No. 5

Among the objectives of that study, a pool of trained 'odour judges' was required to survey the odours around the large complex for a number of days under various meteorological conditions. As a result, the judges were able to map the annoyance levels that they experienced from the various sources around the site. This is shown in Figure 5.1 for a survey that was performed in June of 1991. This study will focus on the process that was identified in the 1991 survey as a major contributor of odour complaint in the neighbourhood, namely stacks No. 2A and 2B (Nicell and St. Pierre, 1996).

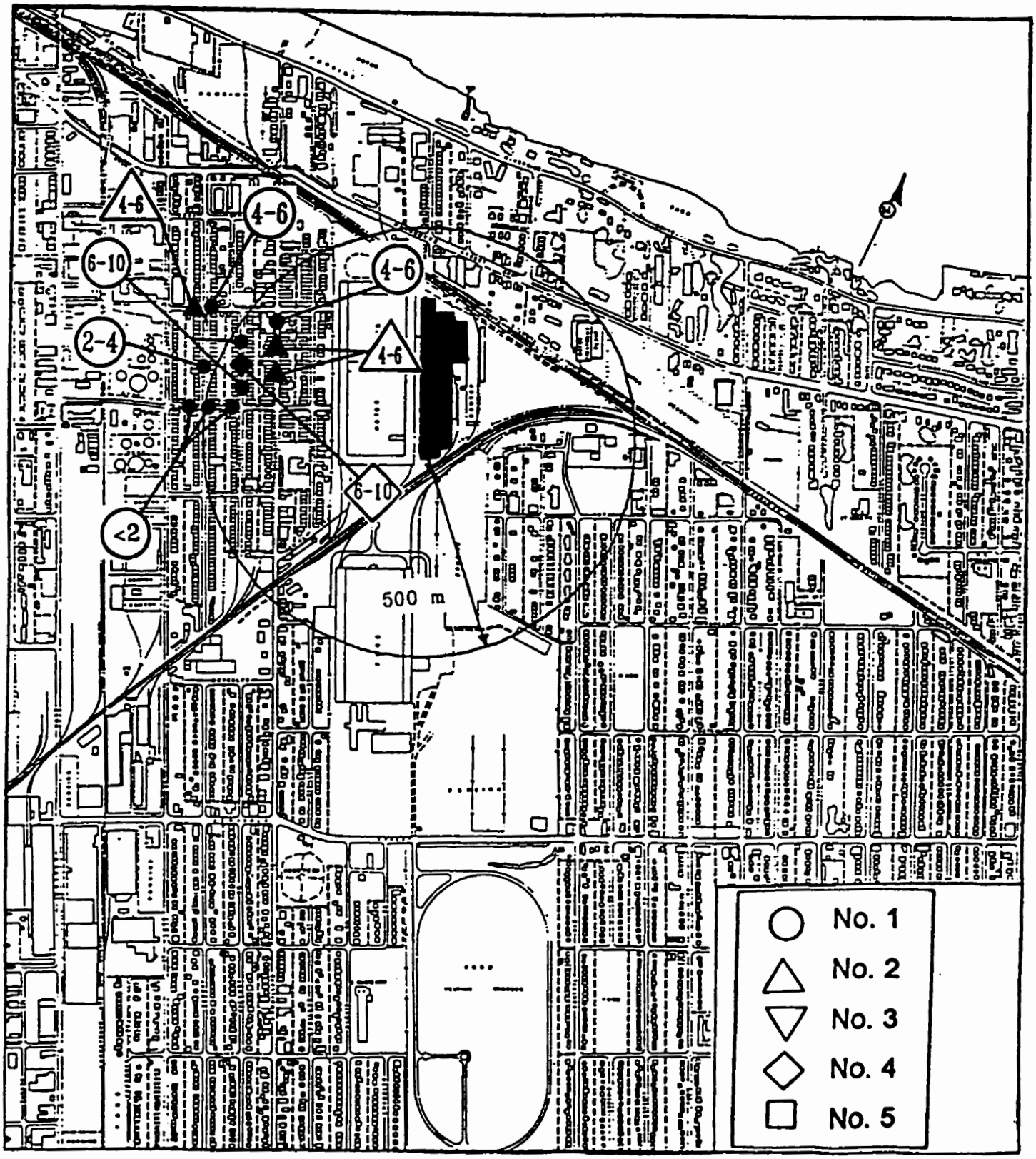


Fig 5.1 Case Study - Field Survey Observations for June 17, 1991

The effectiveness of the Odour Impact Dispersion Model with respect to predicting downwind probabilities of detection or discrimination, as well as its estimating downwind degrees of annoyance experienced by a neighbouring community is investigated here.

5.3 Curve-Fitting Results

In 1988, it was necessary for the administrators of the Ontario complex to quantify the offensiveness of the plant's various odour sources in order to rank their pollution potential. This was accomplished using the Odour Impact Model. OIM's were generated for a variety of plant processes under different operating conditions. This information can now be analyzed using the non-linear regression techniques demonstrated in Chapter 4.

The OIM data from stack No.2A and 2B were used in the fitting of the modified exponential functions (Equations (4.9) and (4.10)) to the probability of detection 'P(Dt)', probability of discrimination 'P(Ds)', and degree of annoyance 'DA' profiles. The modified exponential equation that defines a population's response as a function of dilutions (δ) was used to effectively represent the data. Figures 5.2 through 5.4, illustrate the accuracy of fit for the respective probability of detection, probability of discrimination, and degree of annoyance profiles of the No. 2A and 2B stacks. Table 5.1 presents the curve-fit results for these stacks.

Fig. 5.2: Probability of Detection - Stacks No. 2A and 2B

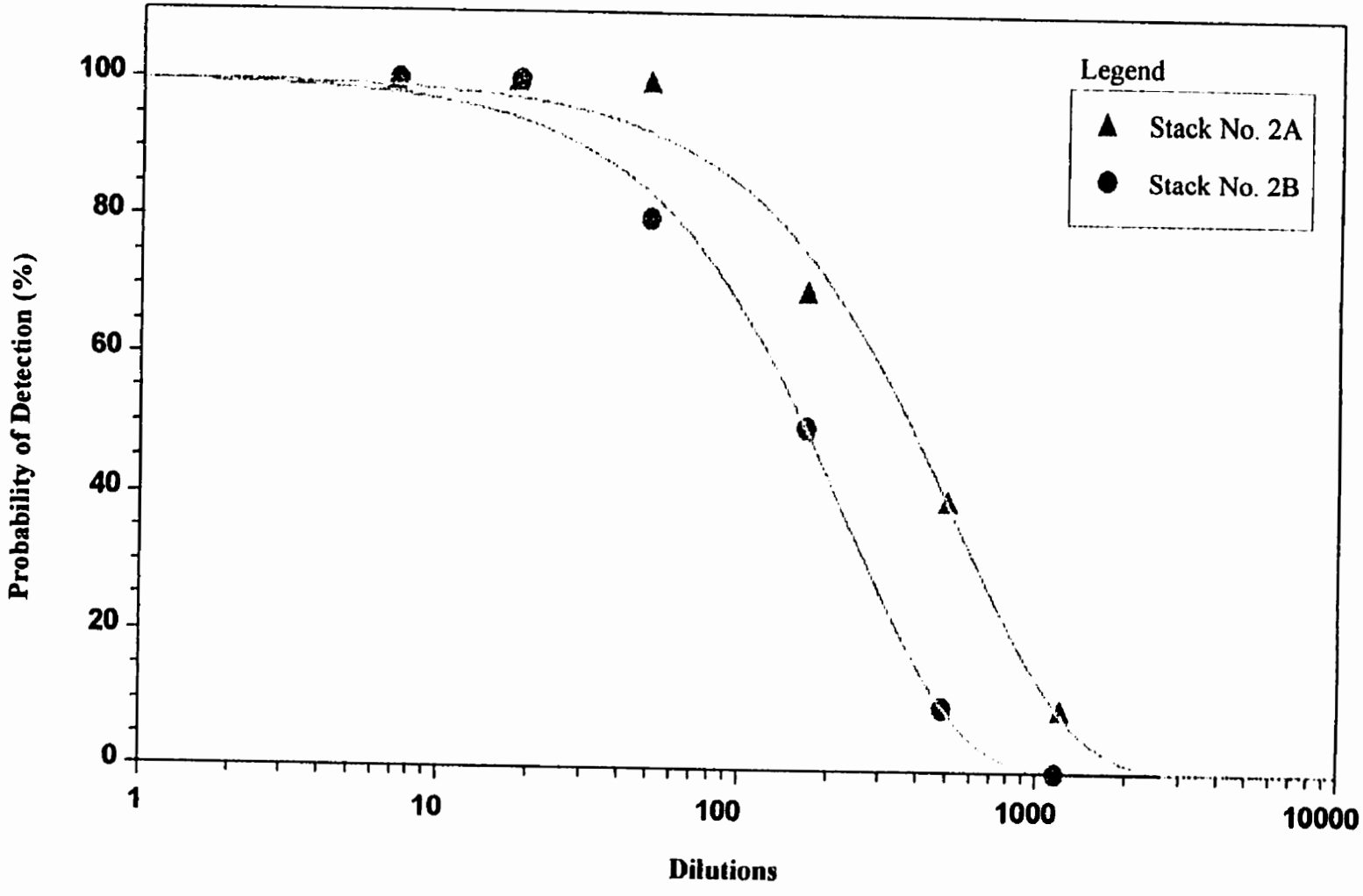


Fig. 5.3: Probability of Discrimination - Stacks No. 2A and 2B

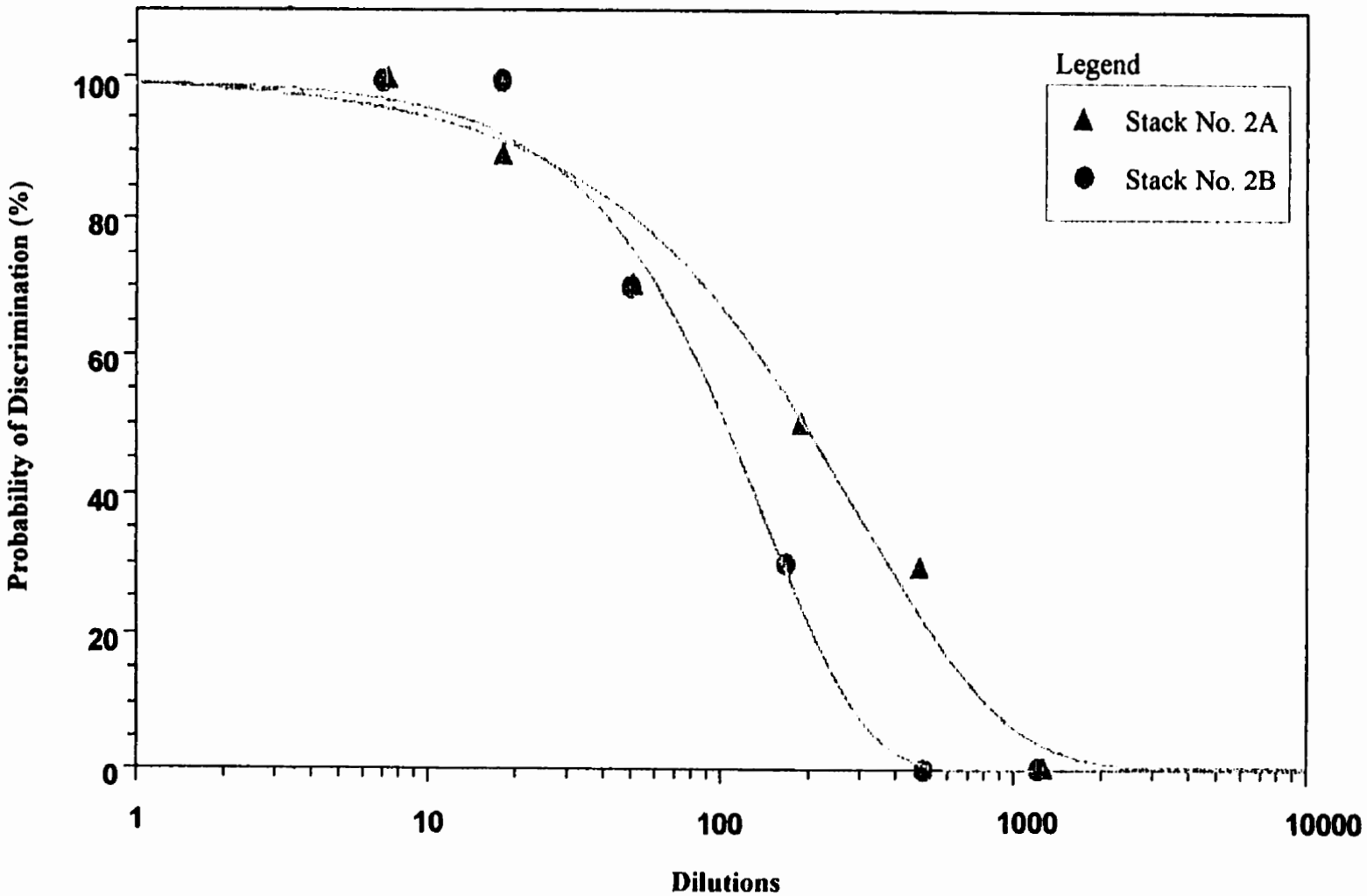


Fig. 5.4: Degree of Annoyance - Stacks No. 2A and 2B

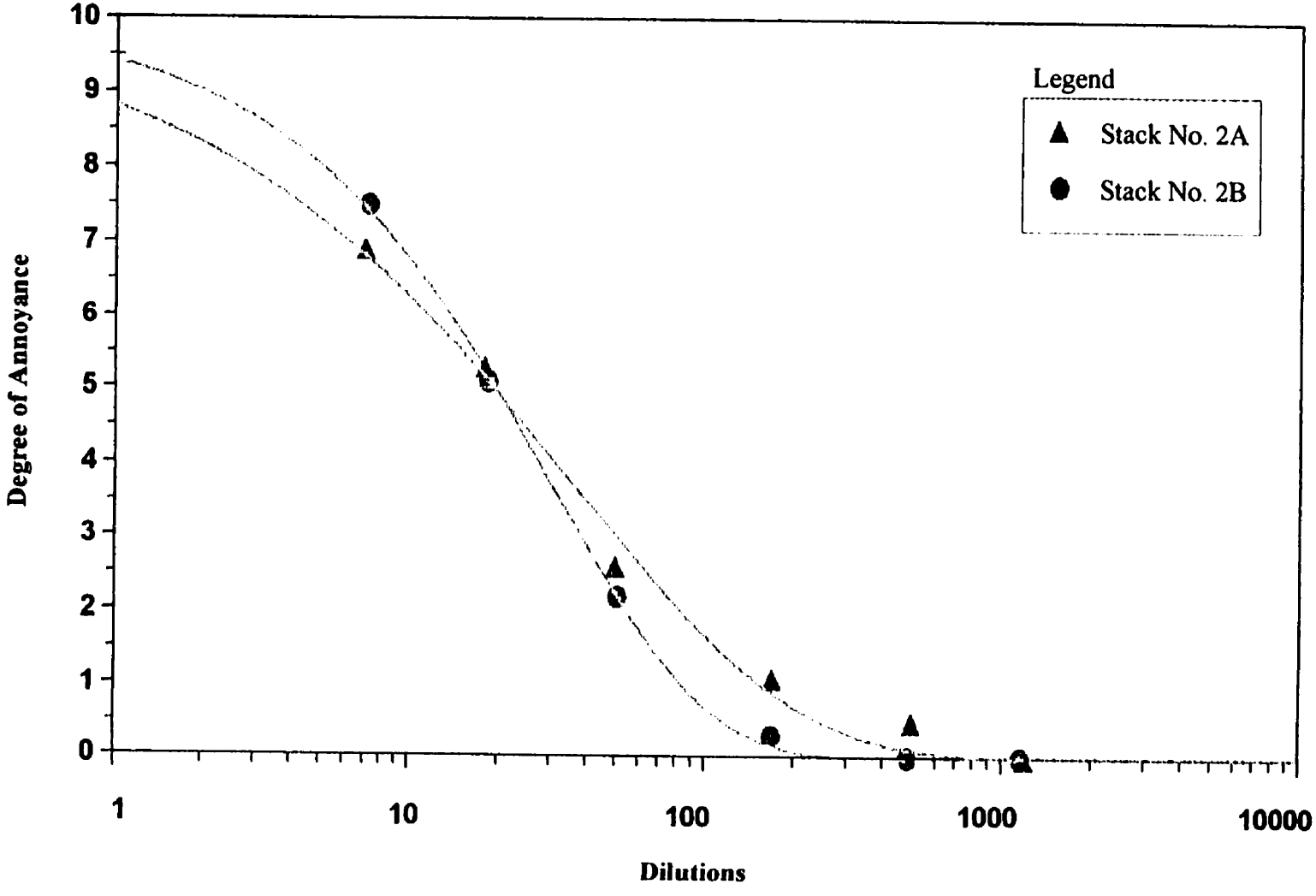


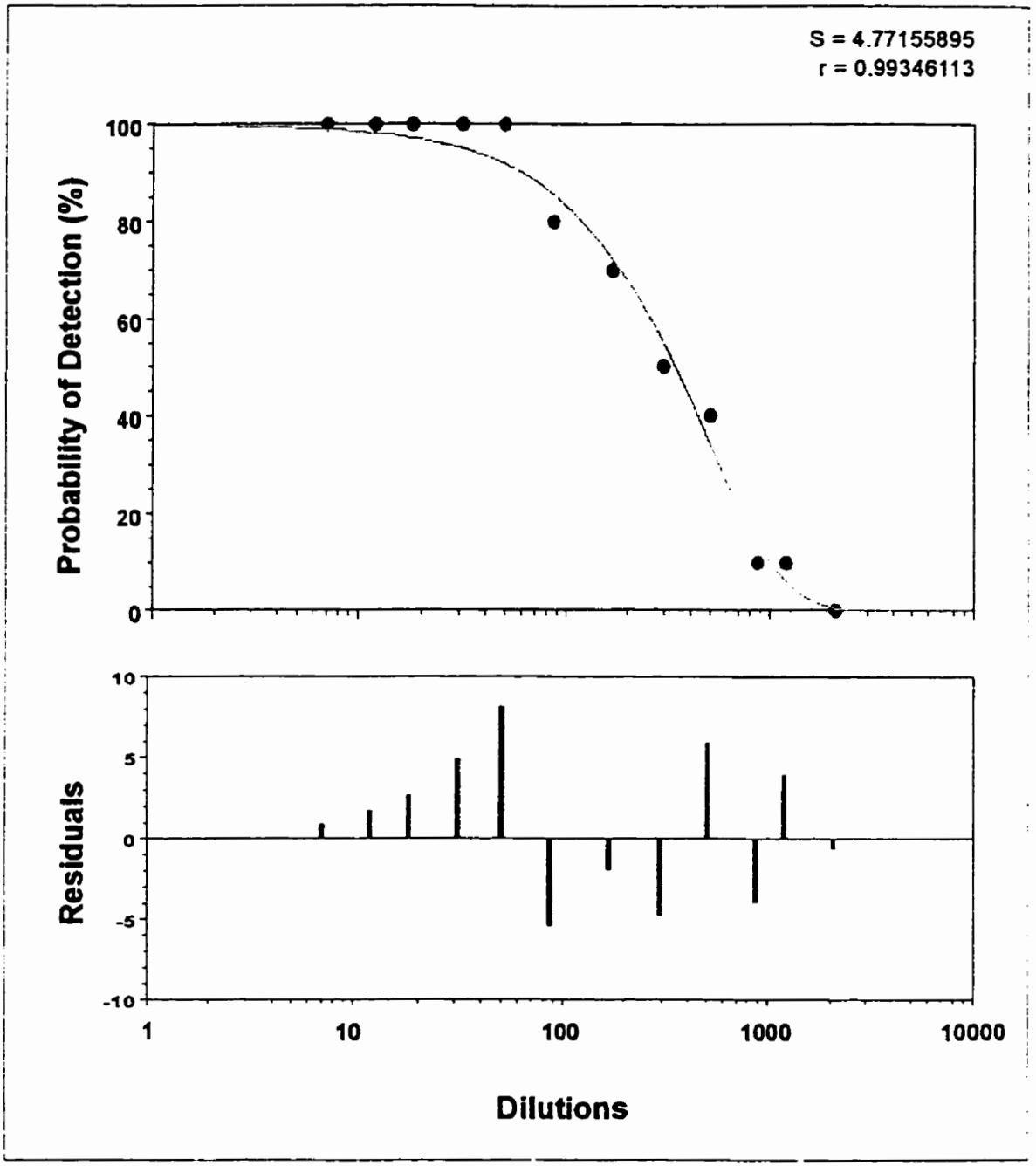
Table 5.1 Stacks No. 2A and 2B Curve-Fit Parameters

	Stack No. 2A			Stack No. 2B		
Curve-Fit Parameters	**P(Dt)**	**P(Ds)**	**DA**	**P(Dt)**	**P(Ds)**	**DA**
α	-1.04E-03	-1.59E-02	-1.21E-01	-2.21E-03	-2.22E-03	-6.10E-02
β	1.094	0.727	0.589	1.121	1.235	0.821
S_r	4.656%	6.512%	0.319	3.471%	5.756%	0.099
r	0.9940	0.988	0.9948	0.9975	0.9936	0.9996
Thresholds (dilutions)	ED_{50}=380	D_{50}=180	–	ED_{50}=168	D_{50}=105	–

In this scenario, stack No. 2A and 2B emitted the same odour but at different concentrations. This is also apparent from the similarity the two stack's OIM profiles shown in Figures 5.2 through 5.4. As can be seen, the OIM profiles for stack No. 2B are virtually identical to stack No. 2B except that they are positioned in a lower range of dilutions. For this reason, a normalizing factor was applied to the profiles of stack No. 2B to merge them to those of stack No.2A. Applying the discrimination thresholds for the two stacks (i.e. $(D_{50})_{2A}$ and $(D_{50})_{2B}$) into Equation (3.8), the normalizing factor, F_N, was found to be:

$$F_N = \frac{(D_{50})_{2A}}{(D_{50})_{2B}} = 1.73$$

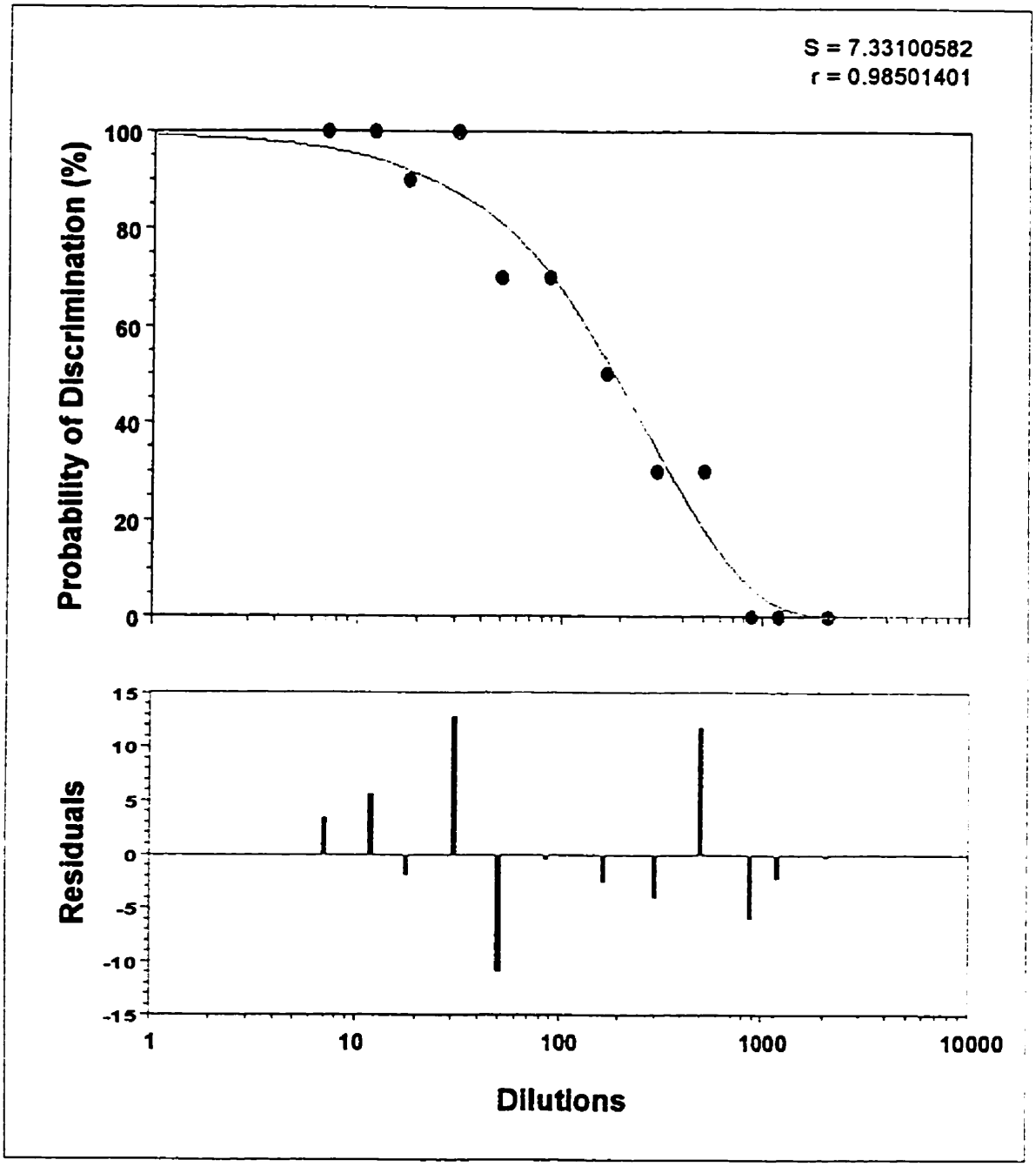
This resulted in a normalized OIM representing both stacks, shown in Figures 5.5 through 5.7. Table 5.2, lists the curve-fit parameters of the normalized OIM.



$y = 100e^{(\alpha x^{\beta})}$

Coefficient Data:
α = -0.0011693643
β = 1.0983776

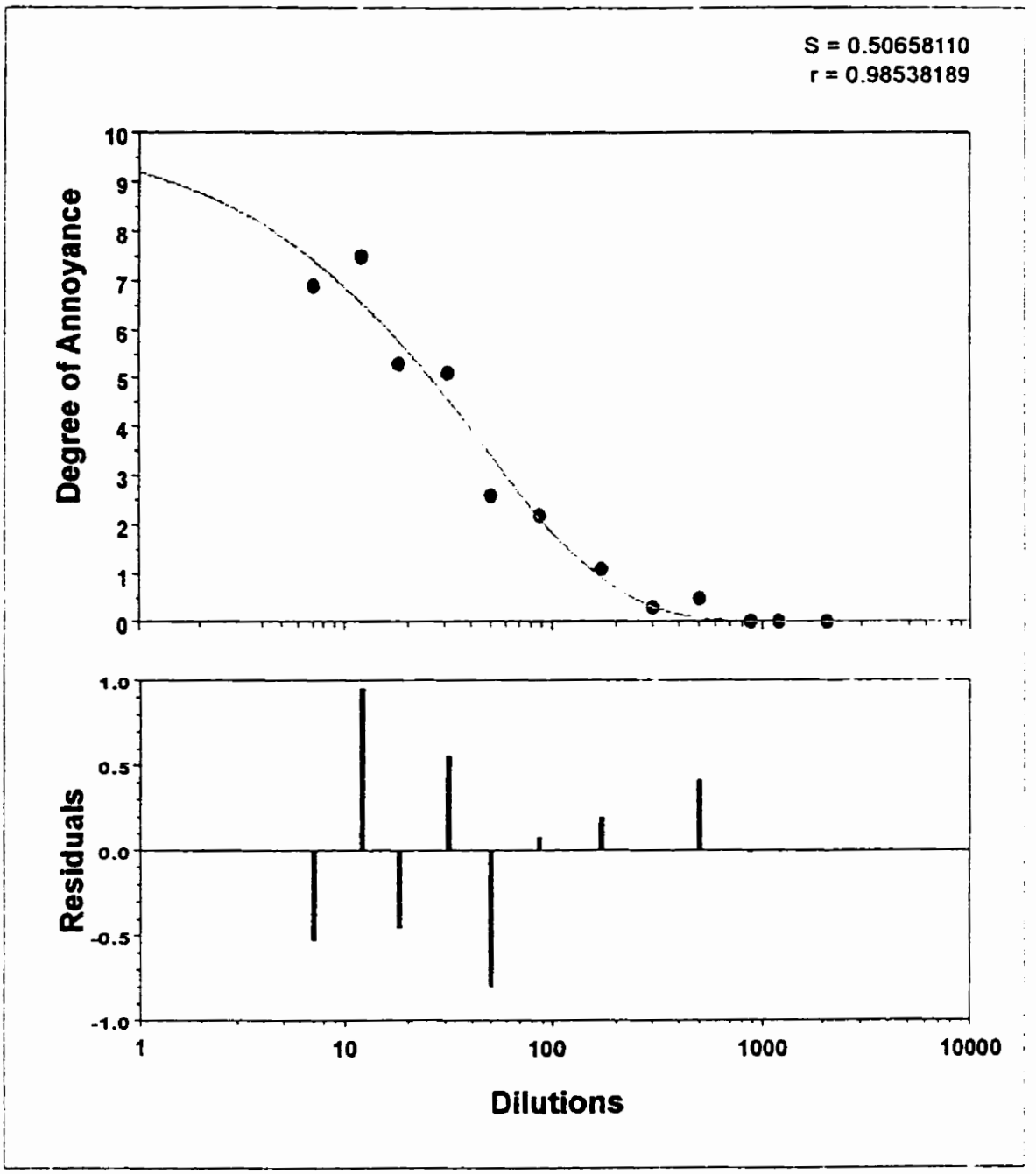
Fig 5.5: Normalised Probability of Detection - Source No. 2



$y = 100e^{(\alpha x^{\beta})}$

Coefficient Data:
α = -0.0061112063
β = 0.90673032

Fig 5.6: Normalised Probability of Discrimination - Source No. 2



$y = 10e^{(\alpha x^{\beta})}$

Coefficient Data:
α = -0.083474631
β = 0.65435733

Fig 5.7: Normalised Degree of Annoyance - Stack No. 2

Table 5.2: Normalised Source No. 2 Curve-Fit Parameters

	Normalized Profiles		
Curve-Fit Parameters	**$\mathcal{P}$(Dt)**	**$\mathcal{P}$(Ds)**	**DA**
α	-1.17E-03	-6.11E-03	-8.35E-02
β	1.098	0.907	0.654
Sr	4.772%	7.331%	0.506
r	0.993	0.985	0.985
Thresholds (dilutions)	$ED_{<0>} = 335$	$D_{<0>} = 185$	–

While these sources were still treated as separate entities in the ISCST3 dispersion model, they were modelled with one OIM to predict their combined impact on the community. Once a normalizing factor is determined, the two stacks' (No. 2A and 2B) odour emission rates ($\dot{\omega}$) can be determined using Equation 3.10 and 3.11. Thus, for this case study, these were set at:

$$\dot{\omega}_{2A} = (v \times A \times D_{50})_{2A} \times k$$
$$= (11.8 \text{ m/s}) \times (19.2 \text{ m}^2) \times (185) \times 1.0 \text{ g/m}^3$$
$$= 42{,}000 \text{ g/s}$$

$$\dot{\omega}_{2B} = (v \times A \times D_{50})_{2B} \times k$$
$$= (15.5 \text{ m/s}) \times (15.6 \text{ m}^2) \times (185 \div 1.73) \times 1.0 \text{ g/m}^3$$
$$= 26{,}000 \text{ g/s}$$

5.4 Dispersion Modelling

The ISC3View dispersion program was run using the source and meteorological data that was collected on June 17, 1991 in an attempt to reproduce the annoyance levels that

were estimated by the field survey on that day. Table 5.3 summarizes the ISCST3 input parameters employed. As a result, using the ISCST3 output file with Equation (3.7) allows the predicted 1-hour downwind dilution contours for the two stacks to be plotted (shown in Figure 5.8). At this point, the mathematical expressions (Equation (4.9) and (4.10)) fit to the normalised OIM profiles were used to transform the model using the predicted downwind dilutions. Thus, contours representing the surrounding community's P(Dt), P(Ds), and DA for a 1-hour averaging time could be mapped using Surfer®. These contours are presented in Figures 5.9 through 5.11.

Comparison of Figure 5.11, which represented the OIDM's predicted degrees of annoyance in the surrounding community for a 1-hour averaging time, with the previously observed degrees of annoyance described in Figure 5.1, indicated that the annoyance levels were being underestimated for specific locations in the surrounding community. In order to provide a better representation of the OIM, an averaging time of 1 minute was decided upon for modelling the No. 2A and 2B stacks. This was considered the most feasible representation of the stacks and the OIM procedures since the sampling time used in the OIM was on the order of a few minutes, and the odour sampling technique used by the "odour surveyors" in the field was on the order of seconds. Therefore, it was necessary to correct the 1-hour output concentration file from ISC3View to describe a 1-minute averaging time.

Table 5.3: ISC3View Input Parameters - Stacks No. 2A and 2B

Source Specifications	Stack No. 2A	Stack No. 2B
UTM Location (East, m)	46	52.5
UTM Location (North, m)	244.8	176.8
Emission Rate (g/s)	42,000	26,000
Stack Height (m)	12.3	16
Stack Diameter (m)	4.94	4.46
Stack Gas Velocity (m/s)	11.8	15.5
Stack Gas Temperature (K)	304	305
Source Base Elevation (m)	0	0
Height of Building (m)	8.5	8.5
Building Dimensions (m2)	335x50	335x50
Building Downwash	Yes	Yes
Output Type	Concentration	Concentration
Dispersion Options	Regulatory Default	Regulatory Default
Dispersion Coefficient	Urban	Urban
Averaging Time	1 hour	1 hour
Terrain Options	Simple, Flat	Simple, Flat
Anemometer Height (m)	10	10
Upper bound of first wind speed category (m/s)	1.54	1.54
Upper bound of second wind speed category (m/s)	3.09	3.09
Upper bound of third wind speed category (m/s)	5.14	5.14
Upper bound of fourth wind speed category (m/s)	8.23	8.23
Upper bound of fifth wind speed category (m/s)	10.8	10.8
Day (no.)	1	1
Hour (no.)	1	1
Wind Flow Vector (degrees)	311	311
Wind Speed (m/s)	3.36	3.36
Mixing Height (m)	1200	1200
Temperature (K)	302	302
Stability Class	B	B
Source emission rate conversion factor	1	1
Decay Coefficient	0	0
Emission Rate Units	(g/s)	(g/s)
Output Units	(g/m3)	(g/m3)

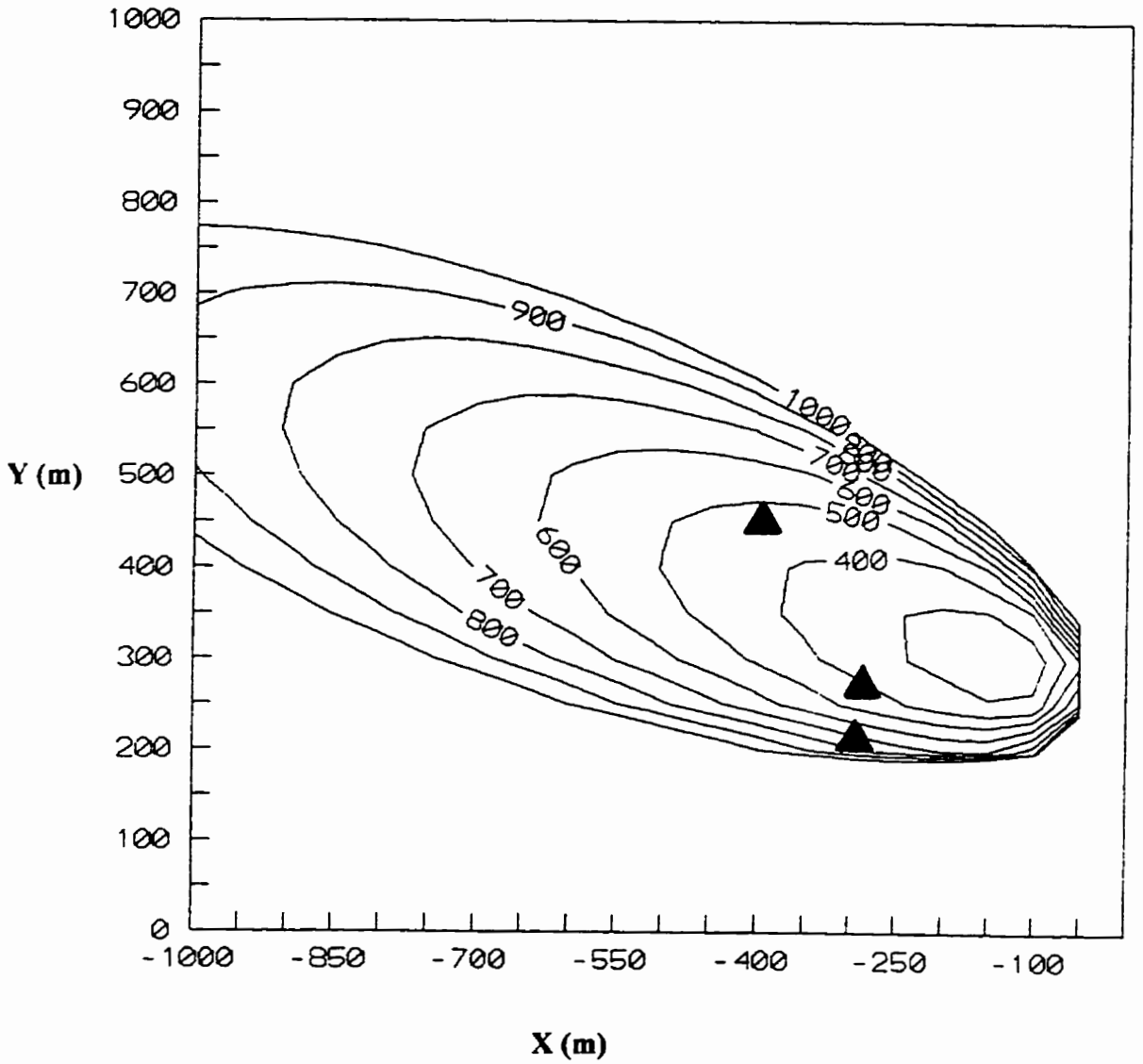


Fig. 5.8: Source No. 2 Predicted Downwind Ground Level Dilutions - T_A = 1-hour
(Note: Origin (0, 0) corresponds to centre of circle on Fig. 5.1)

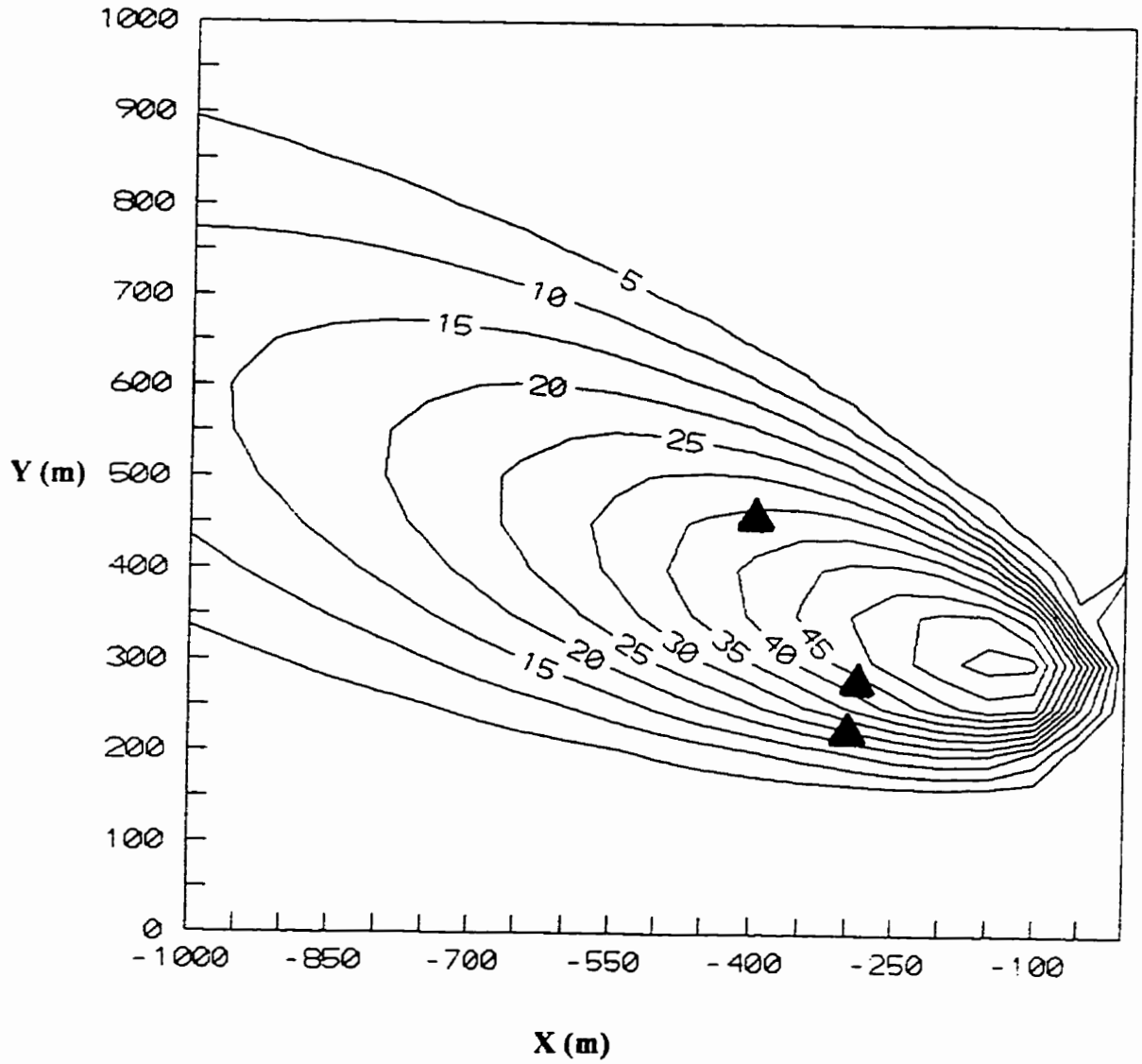


Fig. 5.9: Source No. 2 Probability of Detection - T_A = 1-hour
(Note: Origin (0, 0) corresponds to centre of circle on Fig. 5.1)

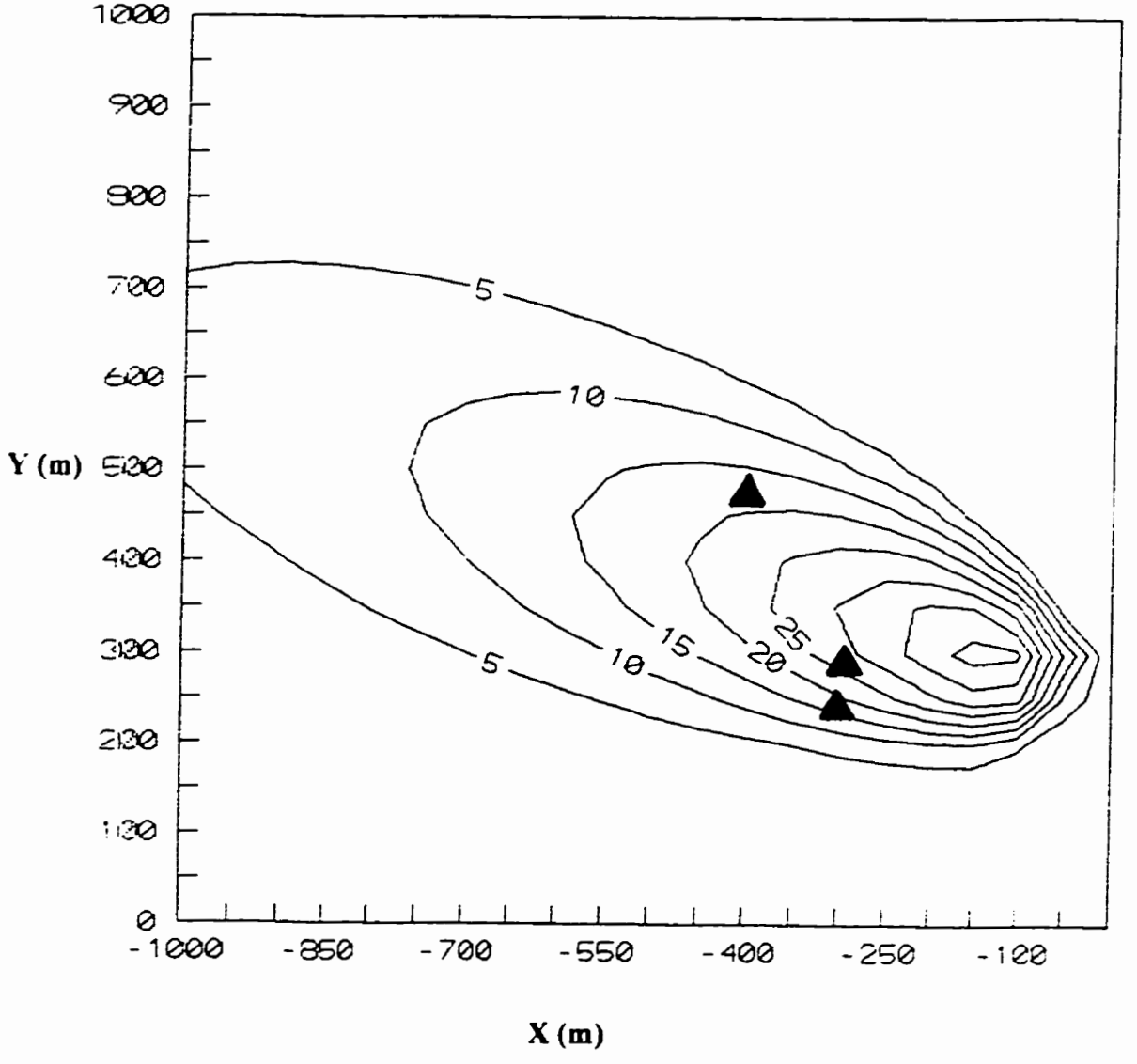


Fig. 5.10: Source No. 2 Probability of Discrimination - T_A = 1-hour
(Note: Origin (0, 0) corresponds to centre of circle on Fig. 5.1)

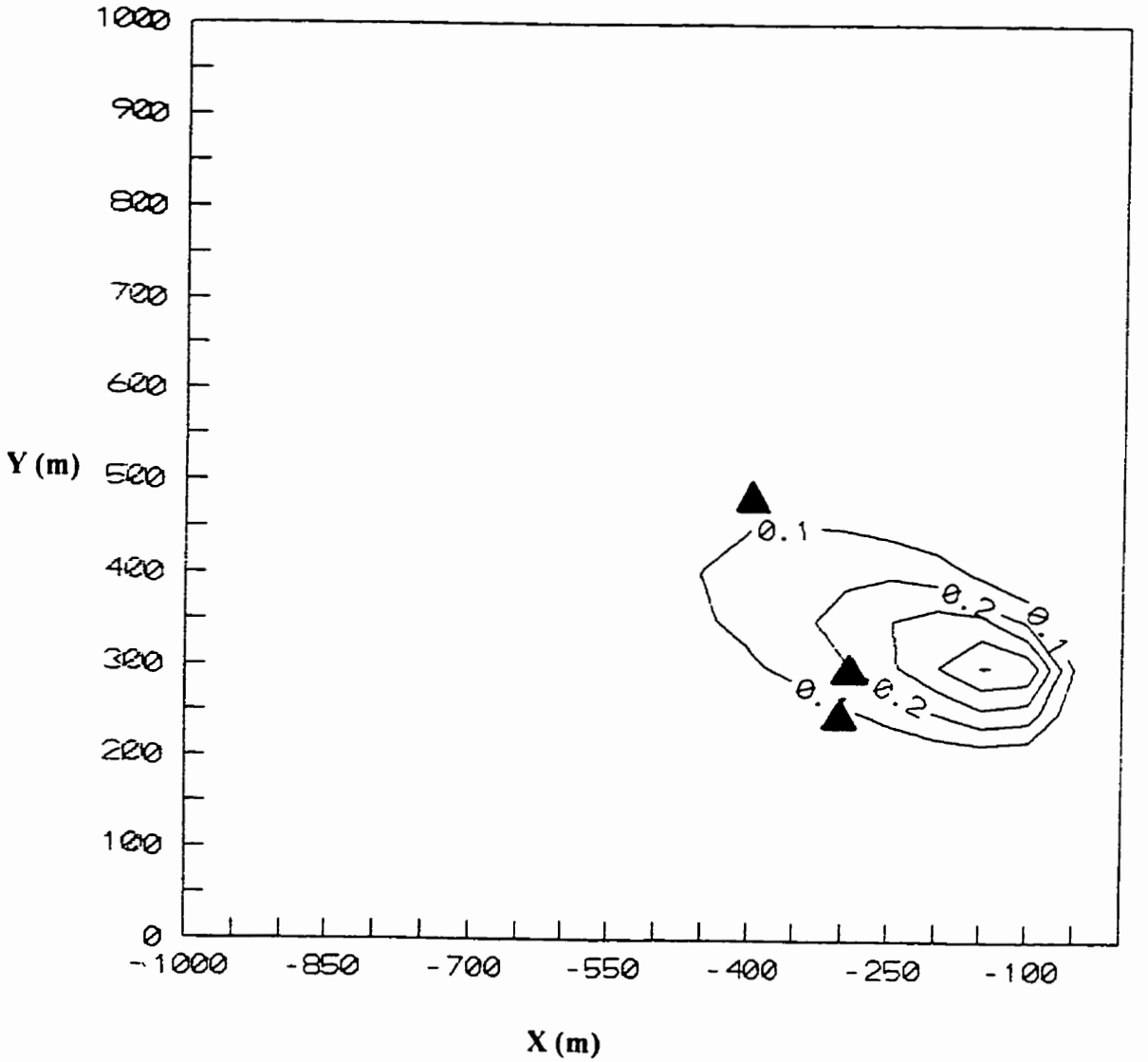


Fig. 5.11: Source No. 2 Degree of Annoyance - T_A = 1-hour
(Note: Origin (0, 0) corresponds to centre of circle on Fig. 5.1)

According to the meteorological data collected during the 1991 study, the atmospheric stability on June 17 was "class B" or moderately unstable". Using Equation (3.13) and the value of 'n' from Table 3.3 (i.e. n = 0.52), a new dilution data file was created representing a 1-minute averaging time. The same procedure as before was repeated and contours representing the surrounding community's $\mathcal{P}$(Dt), $\mathcal{P}$(Ds), and DA and downwind odour dilutions for a 1-minute averaging time were plotted using Surfer®, and are shown in Figures 5.12 through 5.15.

5.5 Discussion

As can be seen, the effect of averaging time on the downwind dilution, $\mathcal{P}$(Dt), $\mathcal{P}$(Ds), and DA contours is considerable. In terms of downwind dilutions, Equation (3.13) indicates that the dilutions for a 1-hour averaging time are approximately 10-fold greater than for a 1-minute averaging time. This is apparent in the two respective downwind dilution contours, Figures 5.8 (T_A = 1-hour) and 5.12 (T_A = 1 min.). With respect to the probability of detection and discrimination profiles, it is clear that a large area (or footprint) of the surrounding community is affected by the odour source, in both cases. In fact, comparison of the 5% footprint for the $\mathcal{P}$(Dt) and $\mathcal{P}$(Ds) plots of the 1-hour averaging time (Figures 5.9 and 5.10), to the 5% footprints of the 1-minute averaging time (Figures 5.13 and 5.14), shows the dependence of predictions made on the averaging time chosen. As the odour concentration in the ambient air increases (i.e. dilutions decrease), the areas covered by the high probabilities of detection and discrimination footprints differ. This leads to the questioning of what fraction of the surrounding community should be protected from an odour.

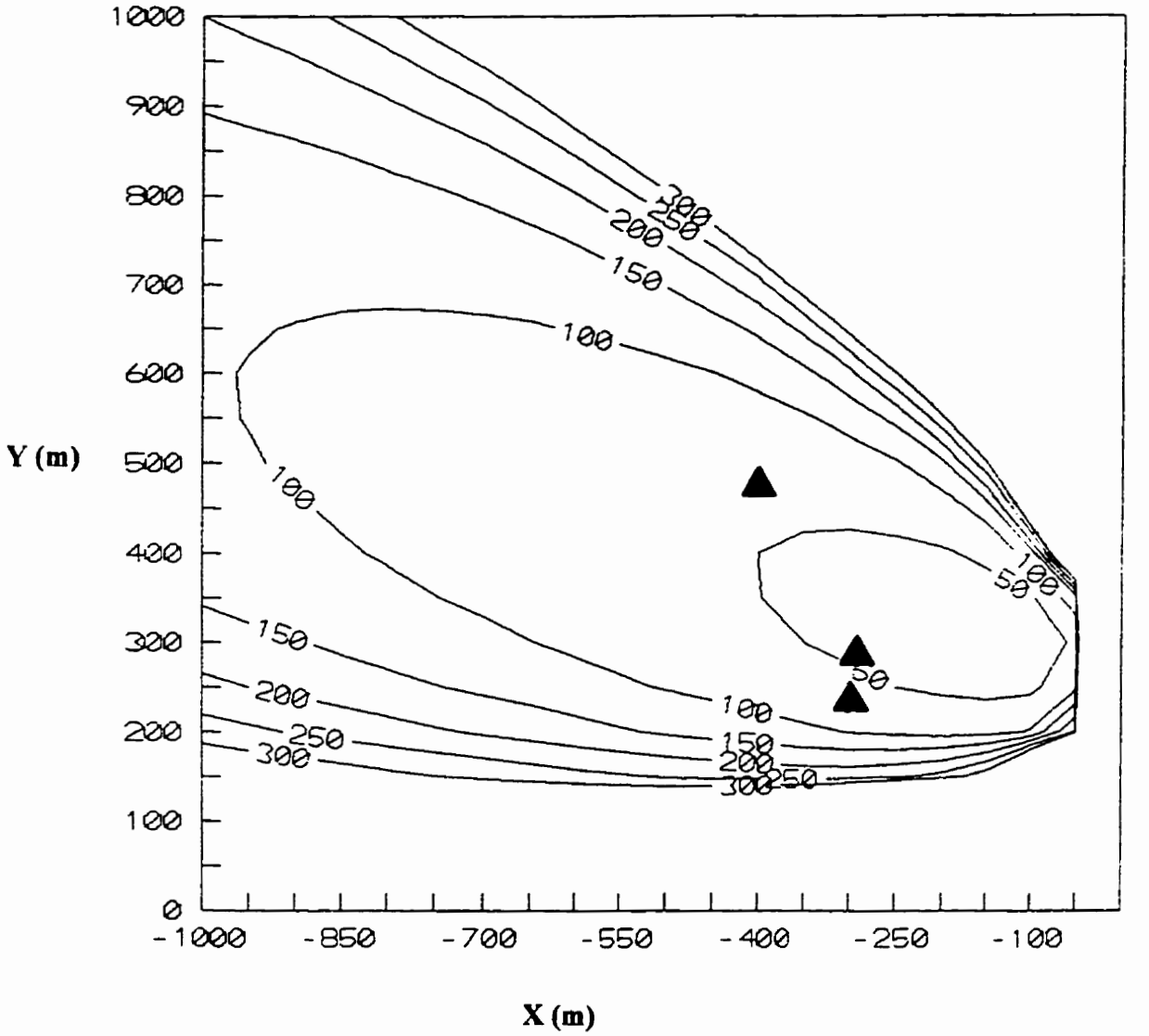


Fig. 5.12: Source No. 2 Predicted Downwind Ground Level Dilutions - T_A = 1-minute
(Note: Origin (0, 0) corresponds to centre of circle on Fig. 5.1)

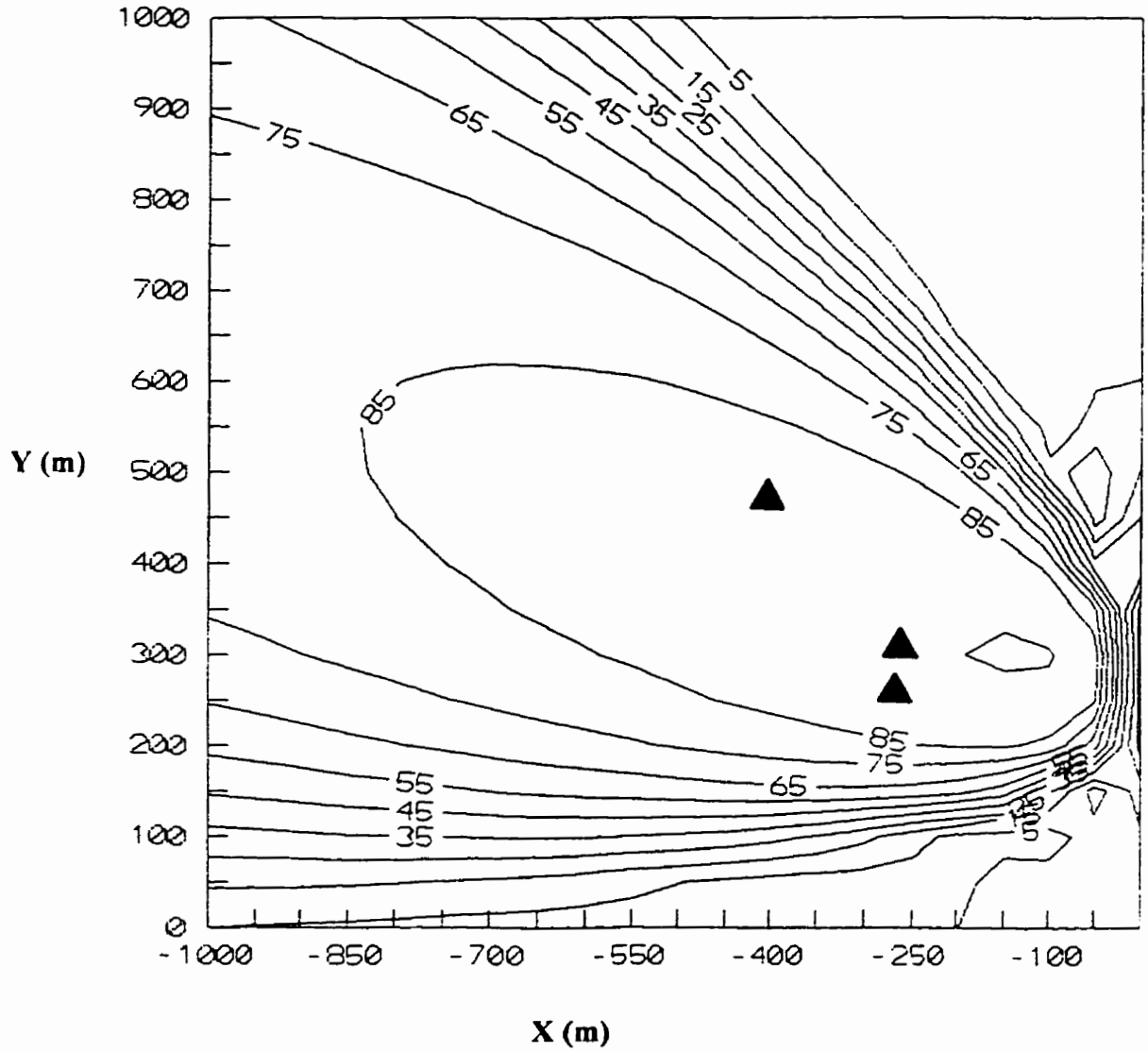


Fig. 5.13: Source No. 2 Probability of Detection - T_A = 1-minute
(Note: Origin (0, 0) corresponds to centre of circle on Fig. 5.1)

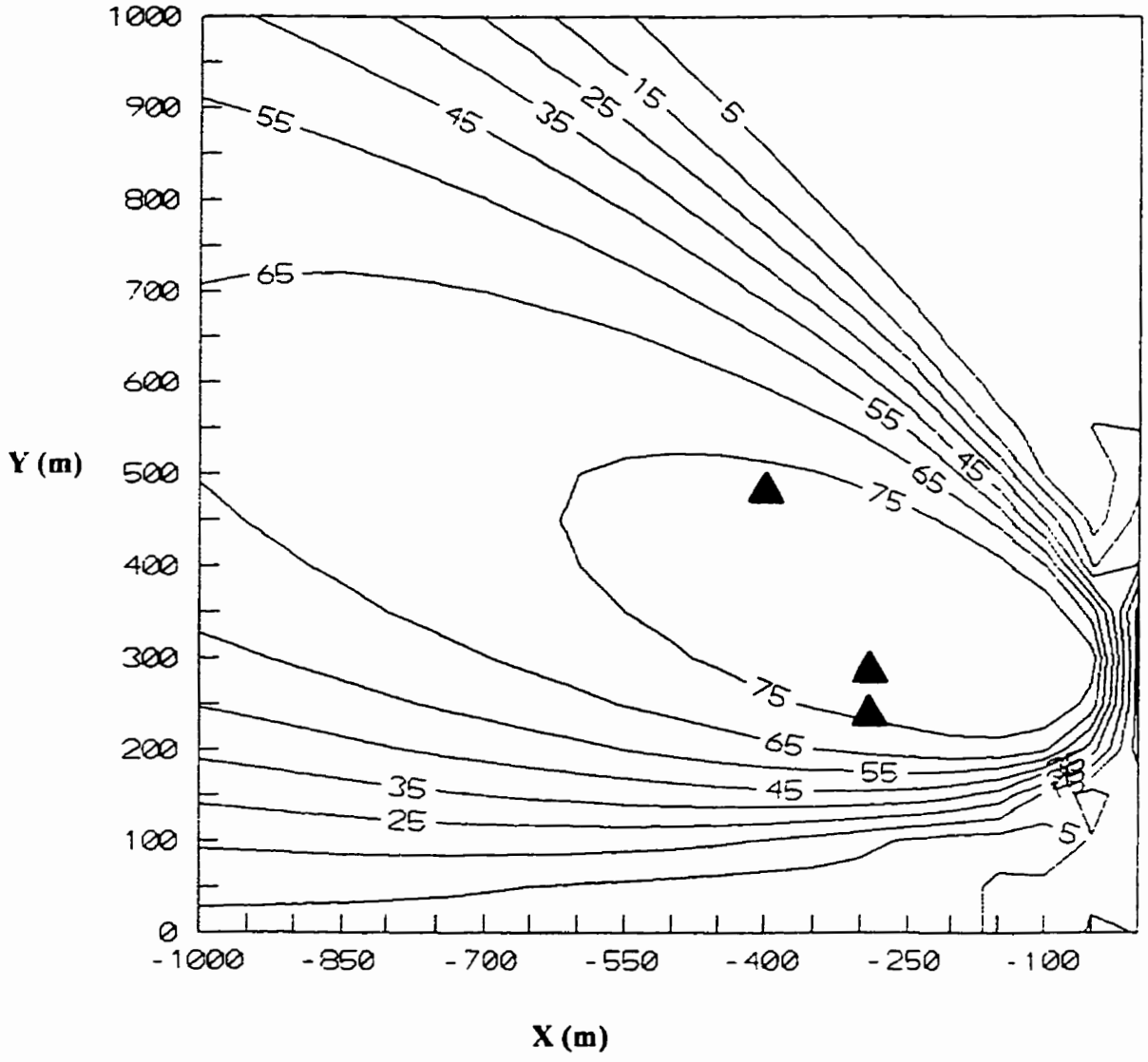


Fig. 5.14: Source No. 2 Probability of Discrimination - T_A = 1-minute
(Note: Origin (0, 0) corresponds to centre of circle on Fig. 5.1)

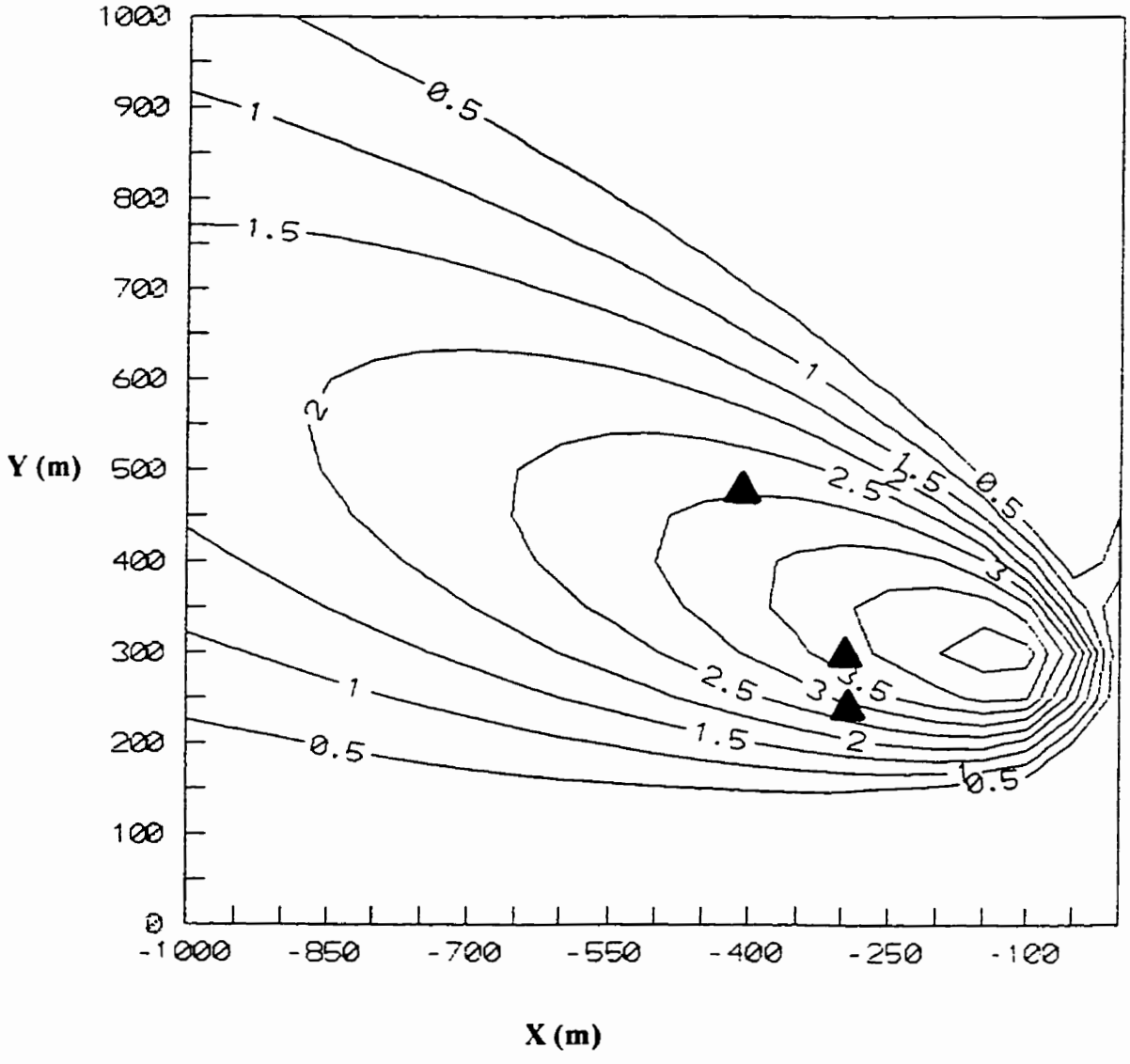


Fig. 5.15: Source No. 2 Degree of Annoyance - T_A = 1-minute
(Note: Origin (0, 0) corresponds to centre of circle on Fig. 5.1)

If it is desired to protect only 50% of the community, then a difference would exist between the size of the $\mathcal{P}(Dt)$ and $\mathcal{P}(Ds)$ footprints. On the other hand, there is a larger difference in area between the 5% footprints of the $\mathcal{P}(Dt)$ and $\mathcal{P}(Ds)$ contours, therefore standards based on the 50% probability of perception footprint (i.e. from $\mathcal{P}(Dt)$ or $\mathcal{P}(Ds)$ contour maps) may provide a more reliable estimate of the population's perception of the odour.

In terms of degree of annoyance, the averaging time had a much more noticeable effect. As is shown in Figure 5.1, the odour surveyors that walked around the industrial complex in 1991 rated the odour emanating from the No. 2A and 2B stacks with a degree of annoyance, DA= 4. When running the model for a 1-hour averaging time, the predicted downwind degrees of annoyance never exceed DA=1, as is shown in Figure 5.11. In contrast, by converting to a 1-minute averaging time (Figure 5.15), the degree of annoyance contour lines increase dramatically. This is due to the fact that in the 1-hour scenario, the range of expected downwind dilutions was on the higher end of the sources' DA profile shown in Figure 5.7, and as such, the predicted degree's of annoyance were extrapolated from a very low range of annoyance levels. Consequently, when a 1-minute averaging time is assumed, lower downwind dilutions are expected and the degree of annoyance is determined from a region of the DA profile (Figure 5.7) that experiences a higher rate of change of annoyance (with respect to dilutions).

To this end, a match was achieved between the annoyance rating assigned by the field survey and the predicted degree of annoyance generated by the OIDM for a 1-minute averaging time, as is shown in Figure 5.15.

5.6 Odour Assessment Strategy

With respect to the Odour Impact Dispersion Model, the output may be used to evaluate the impact of the odour on the surrounding community. This impact can be measured in terms of:

(1) the fraction of people who can detect or discriminate the odour in the neighbourhood, or

(2) the potential degree of annoyance on the community which will be generated by the odour.

5.6.1 Regulatory Applications

Regulatory standards for odours may be based on a number of results obtained by the OIDM. Some suggested options for setting regulatory standards are summarized below:

(1) A standard may be based on the specification of a maximum ceiling limit which would restrict an odour from being perceived beyond the confines of the offending industry to a predetermined upper limit. For example, depending on the level of standards desired, limits may require that a 10% probability of discrimination (or detection) ceiling should never be exceeded in the neighbourhood. Alternatively, if such a limit is found to be too restrictive, regulators may choose to select a ceiling level which allows a higher fraction of the population to perceive the odour (e.g. 50%). Further research should be conducted to determine a ceiling level of $P(Ds)$ or $P(Dt)$ which will provide adequate protection for the community, while respecting the needs of the industry.

(2) Similarly, a maximum allowable degree of annoyance can be set that should not be exceeded beyond the fence-line of the offending facility. Gnyp et al. (1985) suggested a DA=2 as a maximum acceptable annoyance value which must not be exceeded in the neighbourhood as a result of emissions from any odour source. Future studies are required to select an appropriate value.

(3) Standards may be based on the size of an impact area enclosed by a contour that represents a certain fraction of people who will discriminate or detect an odour. This impact area or probability footprint shown in Figure 5.16, may be set at the level of probability which is selected, depending on the level of protection that is required. Figure 5.16 shows impact footprints for regions in which more than 10% or more than 50% of the populations perceive the odours. This allows for a visual interpretation of the area that will be affected by a facility's odorous emissions. Limits could therefore be set on the size of the maximum allowable impact area that can be imposed on a population.

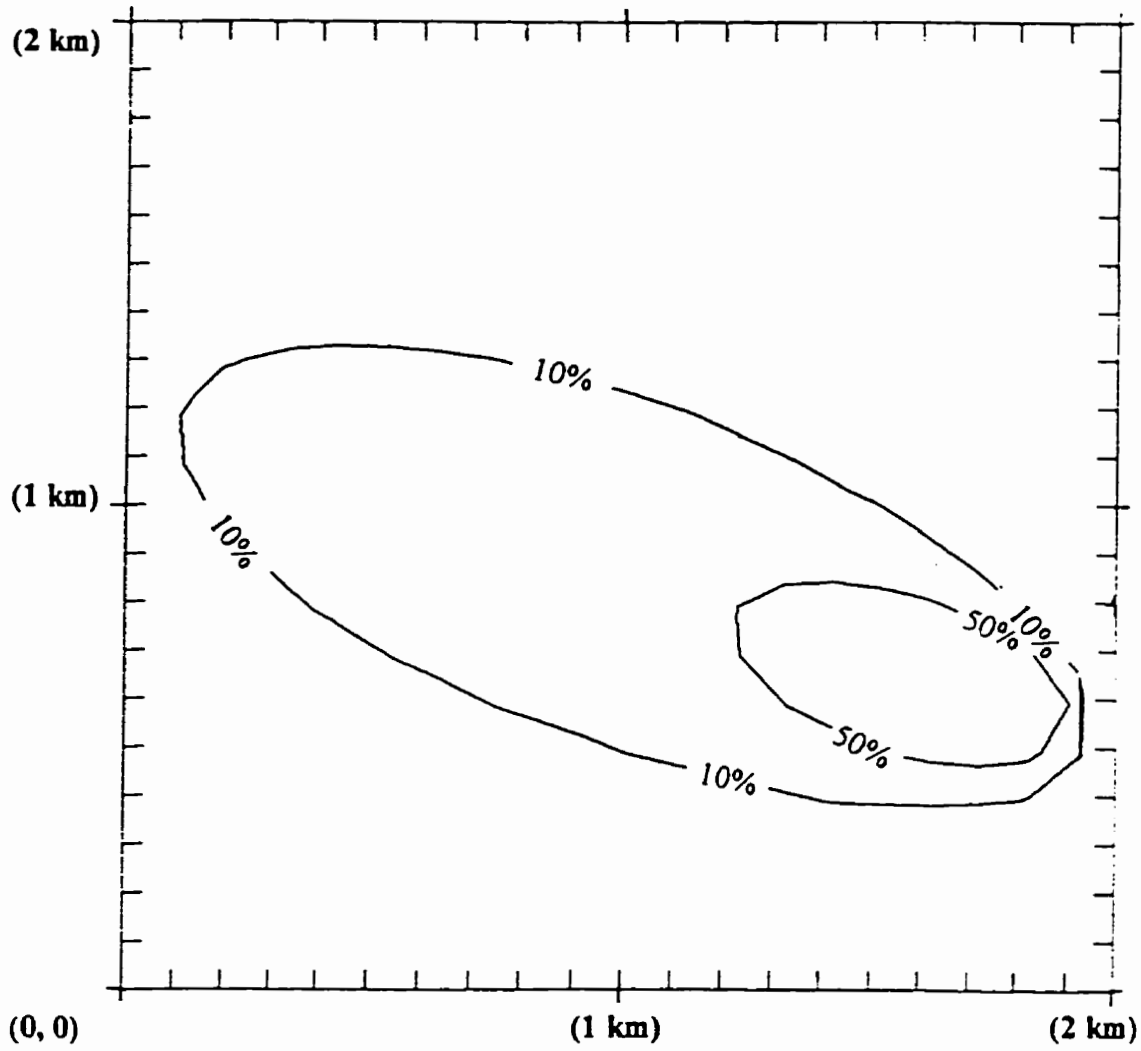


Fig. 5.16: Footprint of an Odour on an Affected Population

(4) Other methods may be based on predicting of the number of people who could perceive the odour. One way of estimating this would be to determine the volume that is enclosed below the probability of discrimination contour profile. Thus, this could be found by integrating below the $\mathcal{P}(Ds)$ contour profile generated by the OIDM from the desired ceiling limit to the maximum probability of discrimination

predicted in the community. The volume enclosed would represent a measure of the community's probability of discrimination $\mathcal{P}(Ds(x,y))$, relative to its position downwind. If the population density within the impact area (i.e. a region, R, defined by a footprint such as in Figure 5.16) is assumed to be constant, the magnitude of the 'Population Impact' (PI) will be evaluated by:

$$PI = \rho \iint_R P(Ds(x,y))dxdy \tag{5.1}$$

where, $\mathcal{P}(Ds(x,y))$ = probability of discrimination over a region R. (i.e. as a function of x and y coordinates)
ρ = population density [persons/m^2]
R = region enclosed by footprint (e.g. 10% or 50%)

If the surrounding population is not distributed uniformly within the enclosed impact area but instead is a function of location, the surrounding community's population density will be represented by $\rho(x,y)$ in Equation (5.1) to give:

$$PI = \iint_R P(Ds(x,y)) \cdot \rho(x,y)dxdy \tag{5.2}$$

This is a better representation of the true PI and would accurately describe the fraction of the population that could perceive the odour.

(5) The hedonic tone of the odour can be incorporated into Equation (5.2) with the addition of the degree of annoyance profile generated by the OIDM. In this respect, the degree of annoyance of a population is dependant on its location within the impact area and is represented by DA(x,y). Thus, Equation (5.2) may be modified to represent a 'Population Annoyance Impact' (PAI):

$$PAI = \iint_R P(Ds(x,y)) \cdot \rho(x,y) \cdot DA(x,y)dxdy \qquad (5.3)$$

Such quantitative information can be used as a basis for the development of regulatory standards for odours which would account for the number of people influenced by an odorous emission and the severity of the influence. Limits could therefore be set on the maximum value of PAI that can be experienced by a population. Defining acceptable values would require further studies to be performed.

The five options for regulatory standards suggested above should be investigated further to assess their abilities to meet the requirements of an effective regulatory strategy.

5.6.2 Industry Applications

The first step in any serious odour control strategy is to reduce or remove an odour directly at the source. This can be accomplished by physically removing the odour from the gas stream by adsorption, absorption, or by chemically converting the odorous product to one less odorous. However, because certain economic or physical constraints may exist on the system this approach is not always effective. As a result, the most commonly employed method of odour control is to discharge the odorous air by means of a stack tall enough to let natural atmospheric dispersion take effect (Wark and Warner, 1981).

Consequently, the standards can also be used by industry to manage their own odorous emissions. Industries can use the results of the OIM to: (1) assess their compliance with a regulatory standard; (2) rank multiple sources within a facility in terms of their potential impact; (3) optimize their allocation of resources to resolve odour problems; (4) predict the potential reduction in impact which can be achieved by implementing control options based on pilot scale investigations of odour control technologies.

6.0 Conclusion and Recommendations

The conclusions of this investigation can be summarized as follows:

(1) A critical review of the various odour control regulations existing in the U.S. and Canada was conducted. As a result, it was concluded that current odour regulations based on statutory nuisance laws or the dilution-to-threshold principle do not meet the requirements of an effective regulatory strategy.

(2) Odour Impact Models (OIM's), obtained from a previous study of six pure chemical odours, were used to select a mathematical expression that best represents the Probability of Detection :P(Dt), Probability of Discrimination :P(Ds) and Degree of Annoyance (DA) profiles. This was achieved using non-linear regression to fit a modified exponential function to the various OIM curves. Statistical tests determined that the function was effective, accurate, and within satisfactory confidence limits to permit its use in odour impact assessments.

(3) Evaluation of the OIM with respect to individual panel size indicated that the accuracy and prediction of the model at representing a population's response to an odour is increased if the number of panelists within a panel is increased or if more panels are used.

(4) An Odour Impact Dispersion Model (OIDM) was developed to include the effects of odour hedonics into odour impact estimates. This model merges the OIM's dose-response profiles with atmospheric dispersion modelling to predict and map the downwind odour dilutions, and the surrounding community's probability of detection, probability of discrimination, and degree of annoyance to an offending odorous emission. Its ability to quantify the impact on

surrounding communities was investigated by applying the OIDM to a case-study using previously collected data of a year-round impact assessment of a major industry located in Ontario, Canada. Analysis of the community's probability of detection, probability of discrimination, and degree of annoyance contours generated by the OIDM indicates that the OIDM is capable of predicting the downwind zone of odour impact.

(5) Based on the OIDM, options were presented for the development of an effective strategy for measuring and regulating the impact of odorous emissions on surrounding communities. Similarly, these options can be used by industry to manage their odorous emissions.

The following recommendations are made:

(1) It is evident that averaging time plays a critical role in atmospheric dispersion modelling. In odour impact assessments, the selection of the appropriate averaging time is dependant on a number of case-specific factors. Future studies are required to help resolve this problem.

(2) ISCST3 assumes a source's emissions are continuous and steady state over a given time interval. Future investigations should examine the abilities of other dispersion models to predict the downwind odour dilution levels for non-steady state emissions.

(3) The OIDM provides a number different options that can be considered as a basis for the development of effective regulatory standards for odours. Future studies should focus on selecting the most appropriate methods that can satisfy the needs of both the residents of a community from odour episodes and the offending industry.

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APPENDIX A:

OIM Data for Six Pure Chemicals

Table A1: Overall OIM Data for Six Pure Chemicals

Chemical Name	Concentration* ($\mu g/m^3$)	Probability of Detection (%)	Probability of Discrimination (%)	Degree of Annoyance
n-Butanol	690	4	0	0.0
	1,090	17	1	0.0
	1,740	30	2	0.1
	2,970	47	18	0.3
	4,730	65	39	0.6
	7,790	78	56	1.2
	12,840	87	70	1.8
	20,420	94	82	2.4
	33,660	96	89	3.0
	53,540	97	94	3.7
	88,250	98	98	4.3
	145,500	100	100	5.0
n-Butyl Acetate	150	0	0	0.0
	230	9	0	0.0
	380	18	0	0.0
	620	34	7	0.4
	990	51	15	9.8
	1,600	63	28	0.2
	2,600	71	43	0.4
	4,230	79	59	0.7
	6,680	90	75	1.4
	10,840	100	91	2.2
	17,600	100	96	2.8
	27,830	100	100	3.4
Isobutanol	310	7	0	0.0
	500	15	1	0.0
	820	23	2	0.0
	1,330	33	9	0.1
	2,150	44	19	0.2
	3,400	53	31	0.4
	5,280	59	46	0.6
	8,740	67	60	0.9
	14,190	75	67	1.2
	23,050	82	72	1.5
	37,420	86	86	2.1
	60,760	100	100	2.6

*at $T = 10°C$, $P = 1$ Atm.

Table A1 (cont.): Overall OIM Data for Six Pure Chemicals

Chemical Name	Concentration* ($\mu g/m^3$)	Probability of Detection (%)	Probability of Discrimination (%)	Degree of Annoyance
Methyl	100	1	0	0.0
Isoamylketone	150	8	1	0.0
	250	16	2	0.0
	400	33	10	0.1
	630	50	20	0.2
	1,040	65	35	0.4
	1,650	76	56	0.7
	2,620	85	73	1.0
	4,020	89	82	1.5
	6,630	95	89	2.2
	10,550	98	94	2.8
	16,780	100	100	3.5
Octanol	1,540	0	0	0.0
	2,500	0	0	0.0
	4,060	0	0	0.0
	6,770	3	0	0.0
	11,000	8	0	0.0
	18,300	15	2	0.0
	29,760	25	5	0.0
	48,330	37	11	0.1
	80,600	62	31	0.4
	130,900	83	50	0.7
	206,900	91	75	1.4
	336,000	100	100	2.1
Propylene Glycol	2,500	0	0	0.0
Monomethyl Ether	4,060	0	0	0.0
	6,410	0	0	0.0
	10,410	2	1	0.0
	16,900	5	2	0.0
	26,700	10	4	0.0
	43,400	19	7	0.1
	68,600	27	10	0.1
	108,400	47	22	0.3
	176,000	67	36	0.5
	285,900	83	66	1.2
	451,800	100	97	2.0

** at T= 10° C, P = 1 Atm.*

Table A2: Probability of Detection CurveFitting Results

Chemical Name	Coefficient Data a	b	ED_{50} ($\mu g/m^3$)	Standard Error, S_r	Correlation Coeff., r
n-Butanol	*-2.94E+03*	*1.05E+00*	*2.95E+03*	*1.73*	*0.9989*
n-Butyl Acetate	*-4.24E+02*	*9.28E-01*	*1.01E+03*	*3.73*	*0.9953*
Isobutanol	*-9.80E+01*	*6.21E-01*	*2.89E+03*	*3.91*	*0.9925*
Methyl Isoamlketone	*-4.66E+02*	*1.01E+00*	*6.31E+02*	*1.48*	*0.9993*
Octanol	*-3.13E+05*	*1.20E+00*	*5.38E+04*	*5.26*	*0.9915*
Propylene Glycol Monomethyl Ether	*-8.63E+05*	*1.21E+00*	*1.05E+05*	*5.30*	*0.9899*

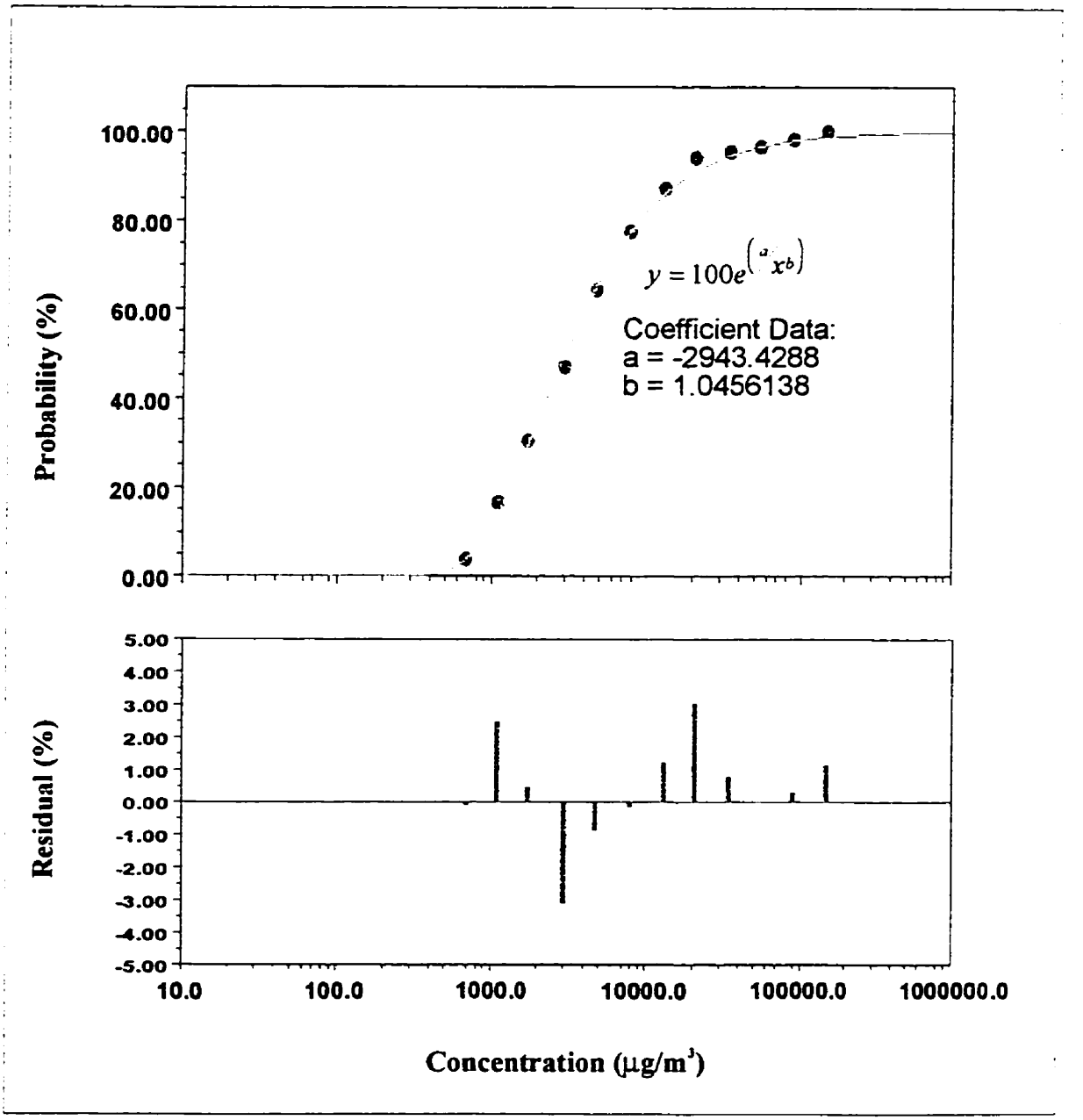
Table A3: Probability of Discrimination CurveFitting Results

Chemical Name	Coefficient Data a	b	D_{50} ($\mu g/m^3$)	Standard Error, S_r	Correlation Coeff., r
n-Butanol	*-1.43E+04*	*1.13E+00*	*6.61E+03*	*1.47*	*0.9994*
n-Butyl Acetate	*-4.46E+03*	*1.10E+00*	*2.84E+03*	*3.89*	*0.9957*
Isobutanol	*-9.48E+02*	*8.24E-01*	*6.37E+03*	*4.02*	*0.9942*
Methyl Isoamlketone	*-2.42E+03*	*1.13E+00*	*1.37E+03*	*2.28*	*0.9985*
Octanol	*-7.62E+07*	*1.59E+00*	*1.14E+05*	*4.80*	*0.9911*
Propylene Glycol Monomethyl Ether	*-1.95E+08*	*1.60E+00*	*1.92E+05*	*6.56*	*0.9810*

Table A4: Degree of Annoyance CurveFitting Results

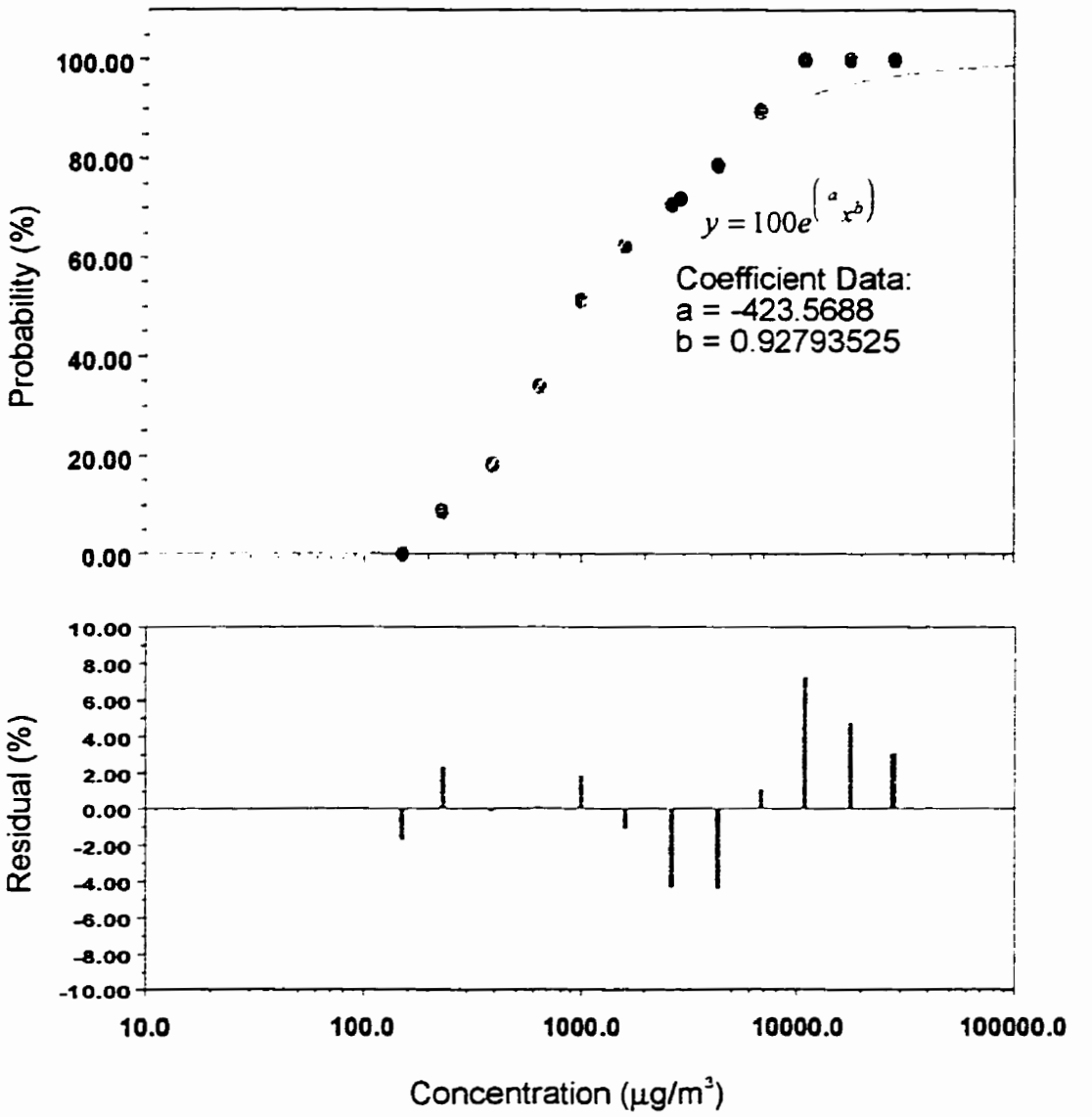
Chemical Name	Coefficient Data a	b	C@(DA=4) ($\mu g/m^3$)	Standard Error, S_r	Correlation Coeff., r
n-Butanol	*-7.30E+01*	*3.94E-01*	*6.77E+04*	*0.10*	*0.9986*
n-Butyl Acetate	*-1.07E+02*	*4.53E-01*	*3.69E+04*	*0.08*	*0.9979*
Isobutanol	*-4.20E+01*	*3.13E-01*	*2.05E+05*	*0.04*	*0.9992*
Methyl Isoamlketone	*-5.70E+01*	*4.11E-01*	*2.32E+04*	*0.03*	*0.9998*
Octanol	*-1.99E+03*	*5.63E-01*	*8.49E+05*	*0.04*	*0.9987*
Propylene Glycol Monomethyl Ether	*-3.08E+03*	*5.79E-01*	*1.23E+06*	*0.03*	*0.9987*

Fig. A1: n-Butanol - Probability of Detection



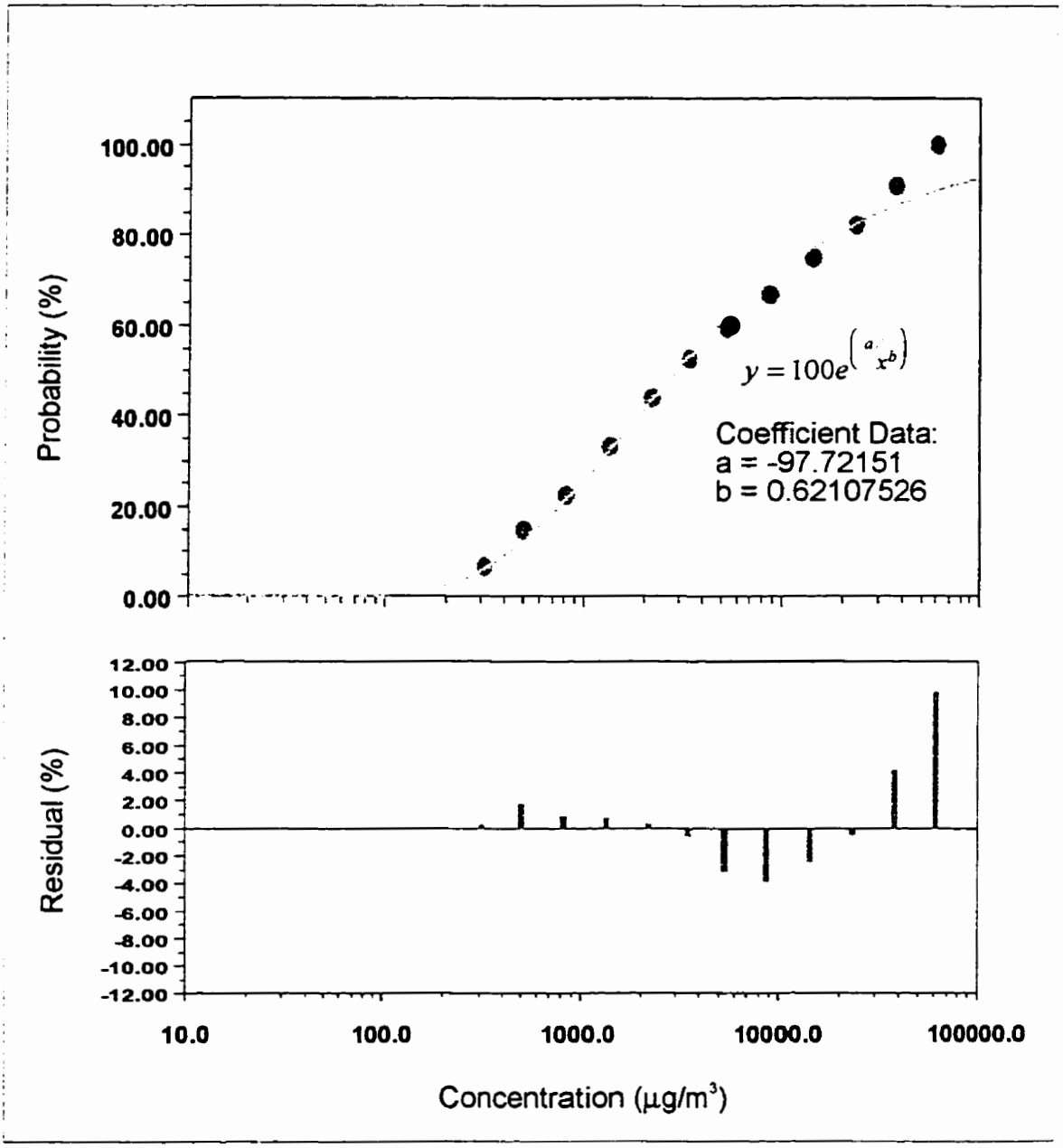
Standard Error, Sr: 1.7305541
Correlation Coefficient, r: 0.9988707

Fig. A2: n-Butyl Acetate - Probability of Detection



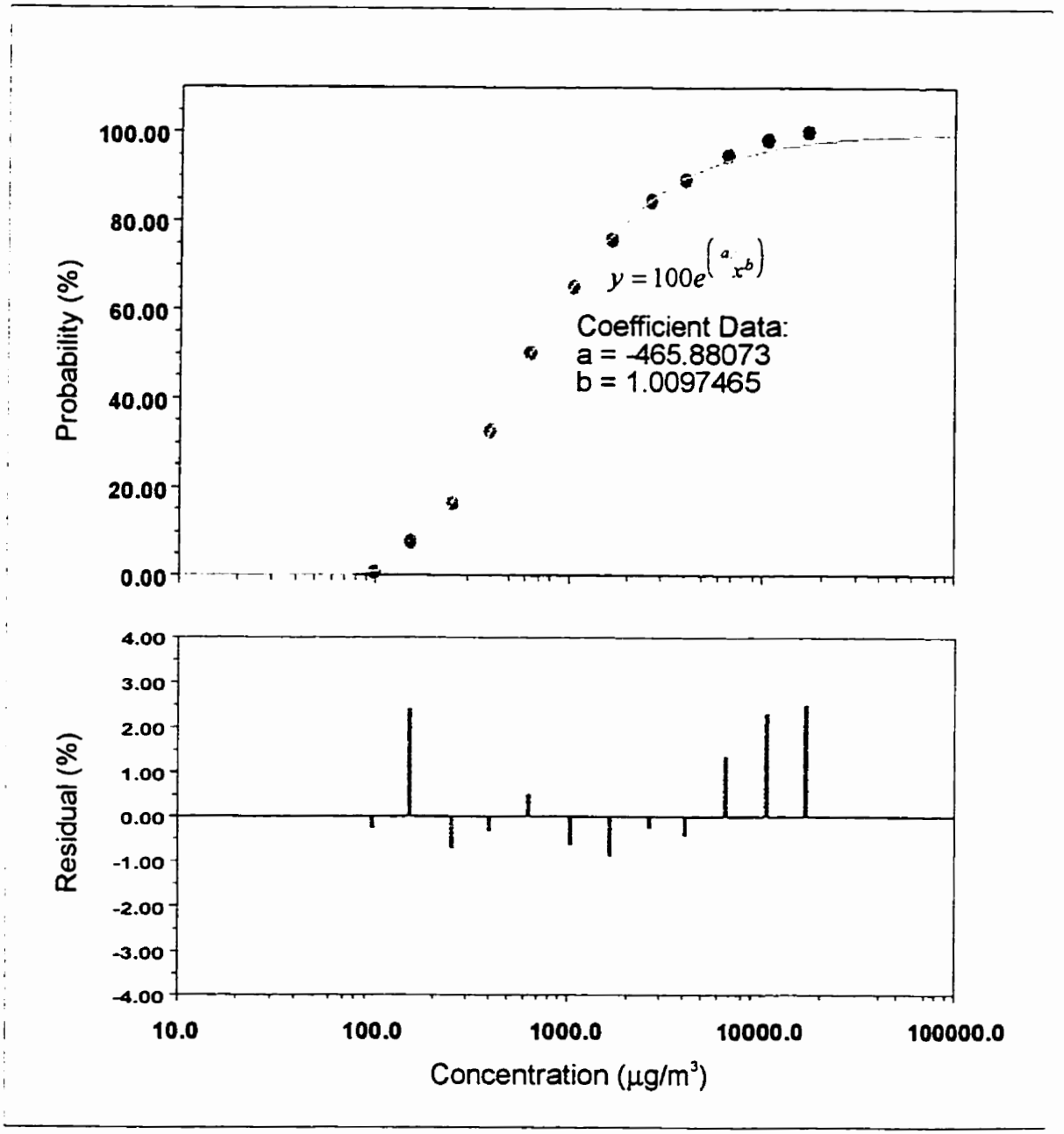
Standard Error, Sr: 3.7292280
Correlation Coefficient, r: 0.9953087

Fig. A3: Isobutanol - Probability of Detection



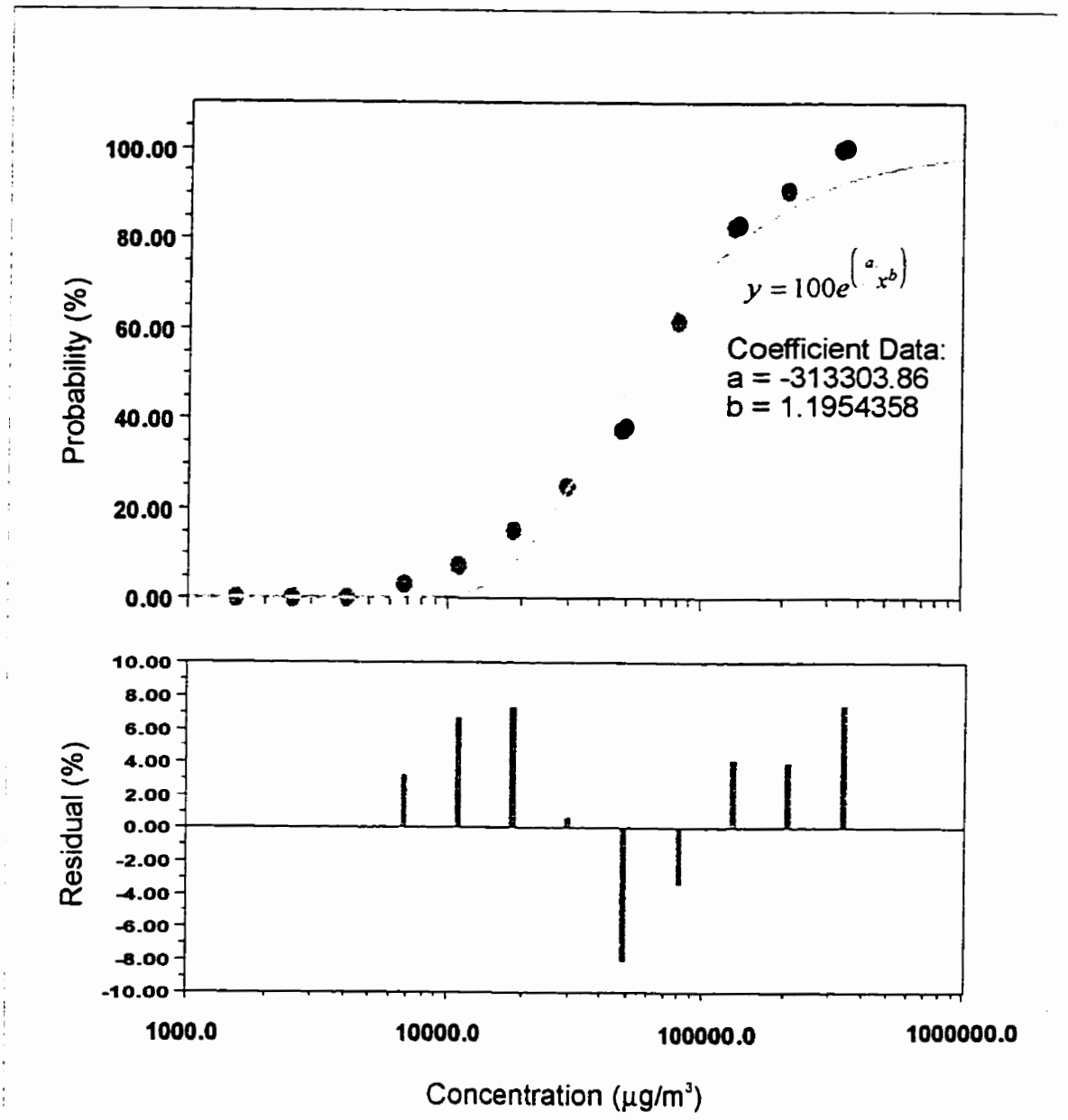
Standard Error, Sr: 3.9090718
Correlation Coefficient, r: 0.9924904

Fig. A4: Methyl Isoamylketone - Probability of Detection



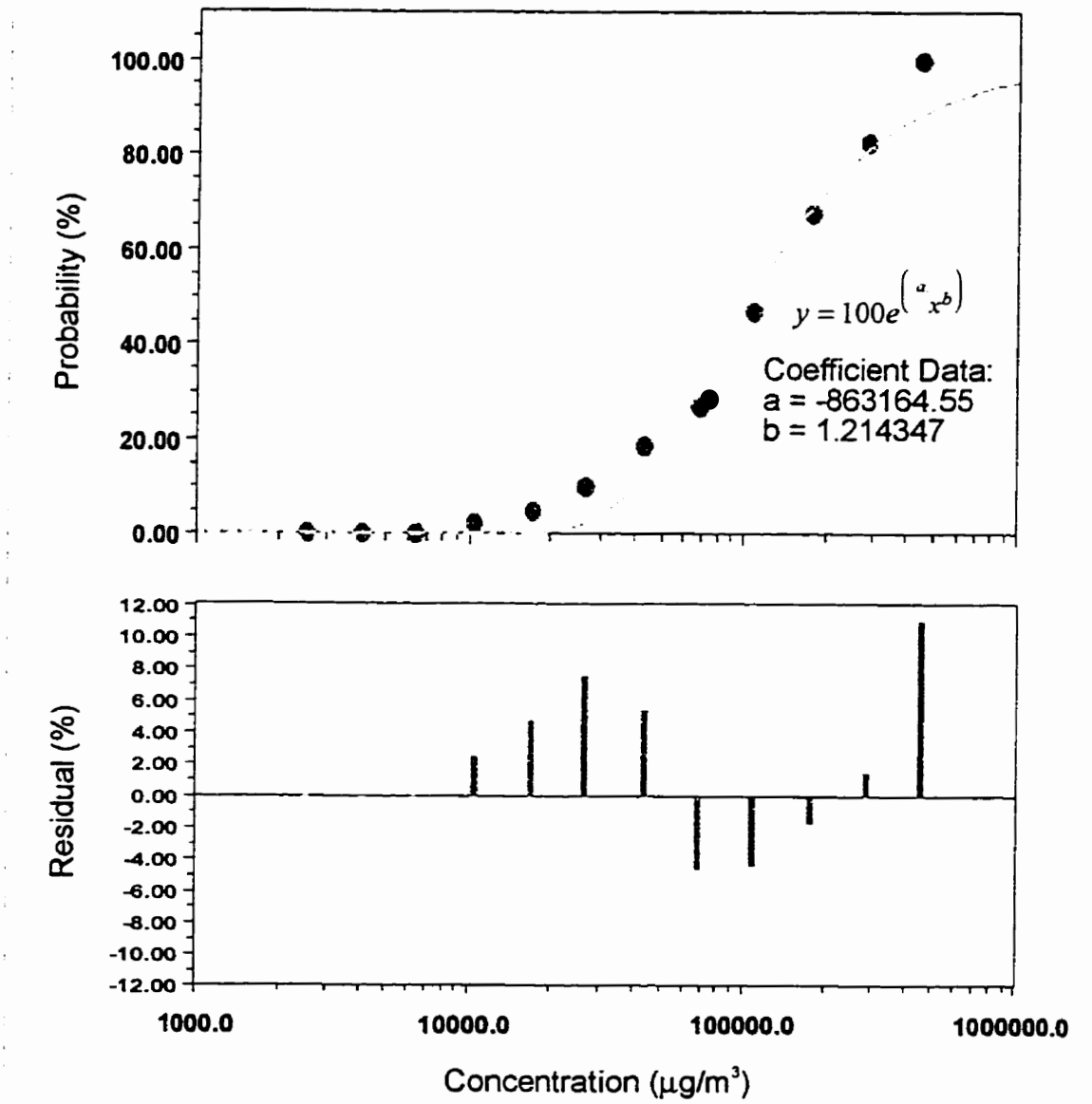
Standard Error, Sr: 1.4777792
Correlation Coefficient, r: 0.9992743

Fig. A5: Octane - Probability of Detection



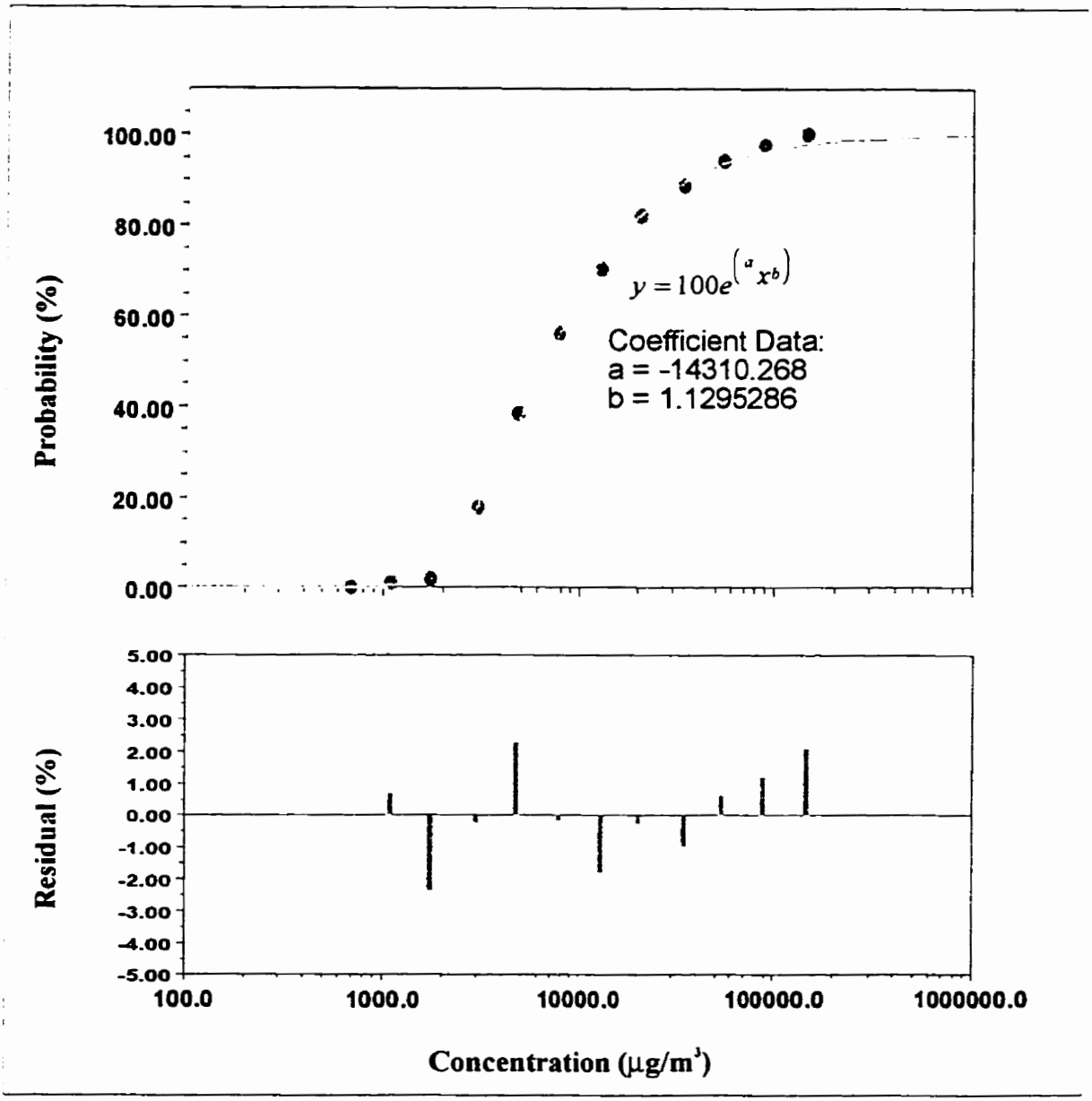
Standard Error, Sr: 5.2641405
Correlation Coefficient, r: 0.9914582

Fig. A6: Propylene Glycol Monomethyl Ether - Probability of Detection



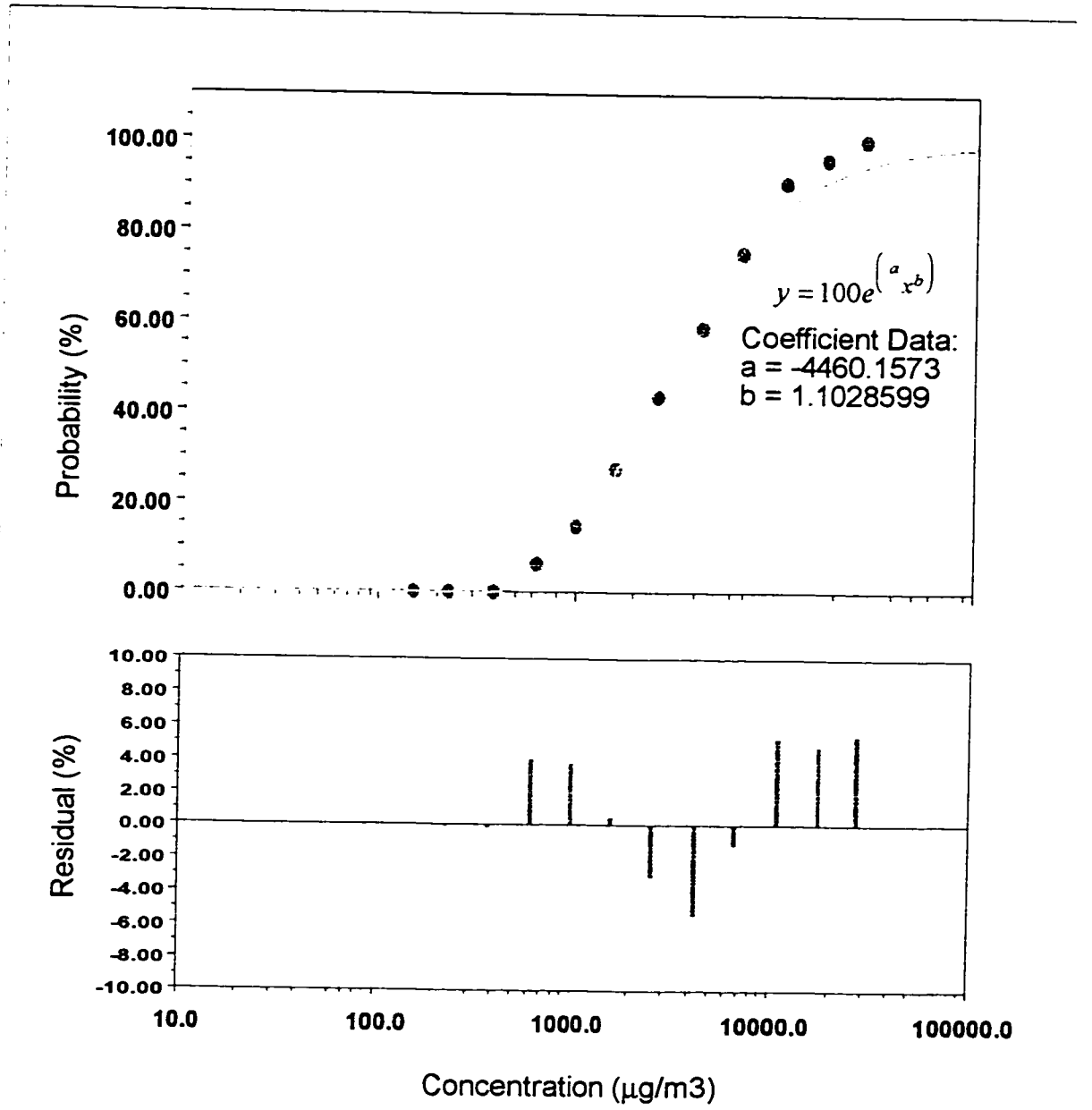
Standard Error, Sr: 5.3046866
Correlation Coefficient, r: 0.9899148

Fig. A7: n-Butanol - Probability of Discrimination



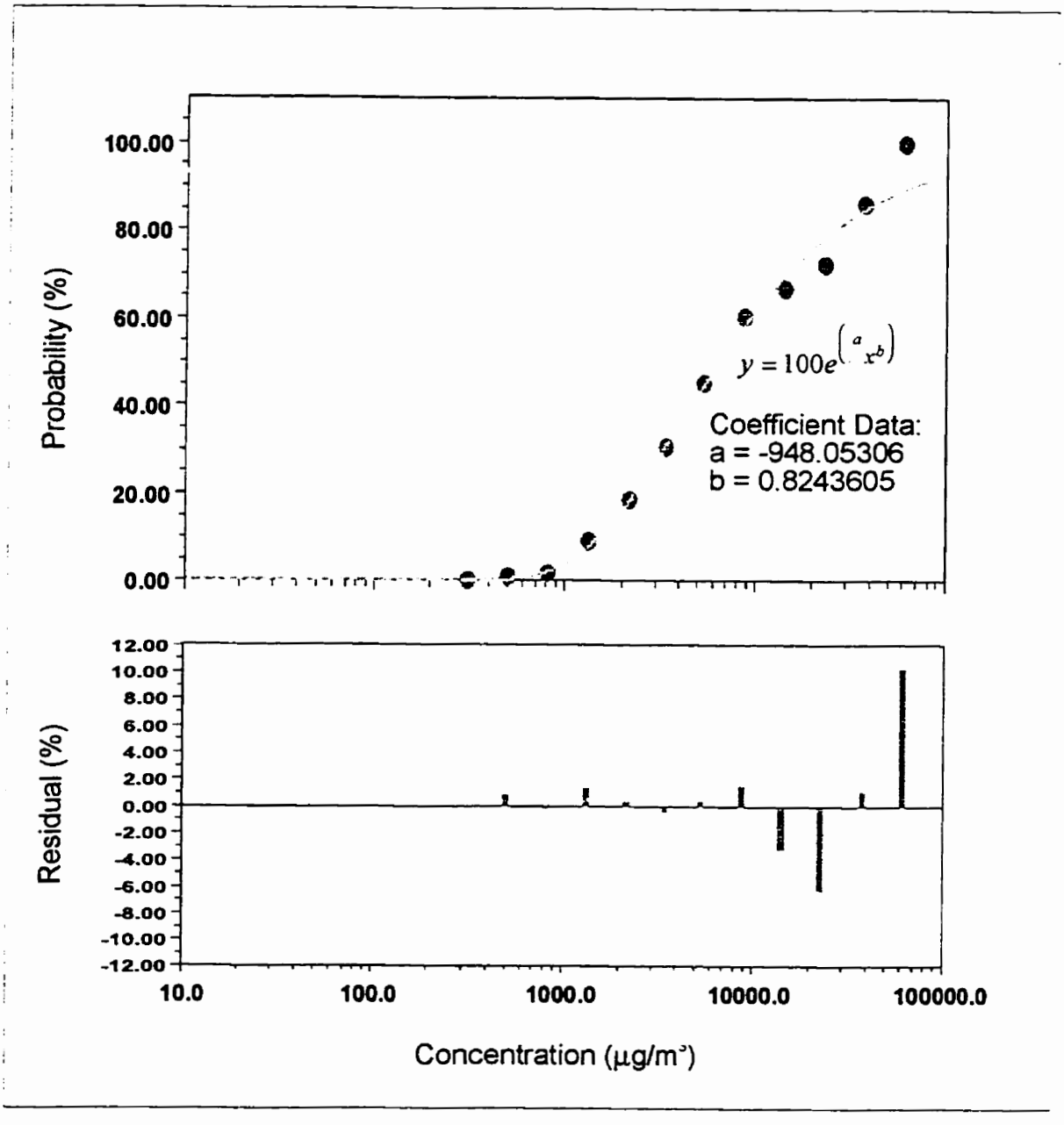
Standard Error, Sr: 1.4674775
Correlation Coefficient, r: 0.9993963

Fig. A8: n-Butyl Acetate - Probability of Discrimination



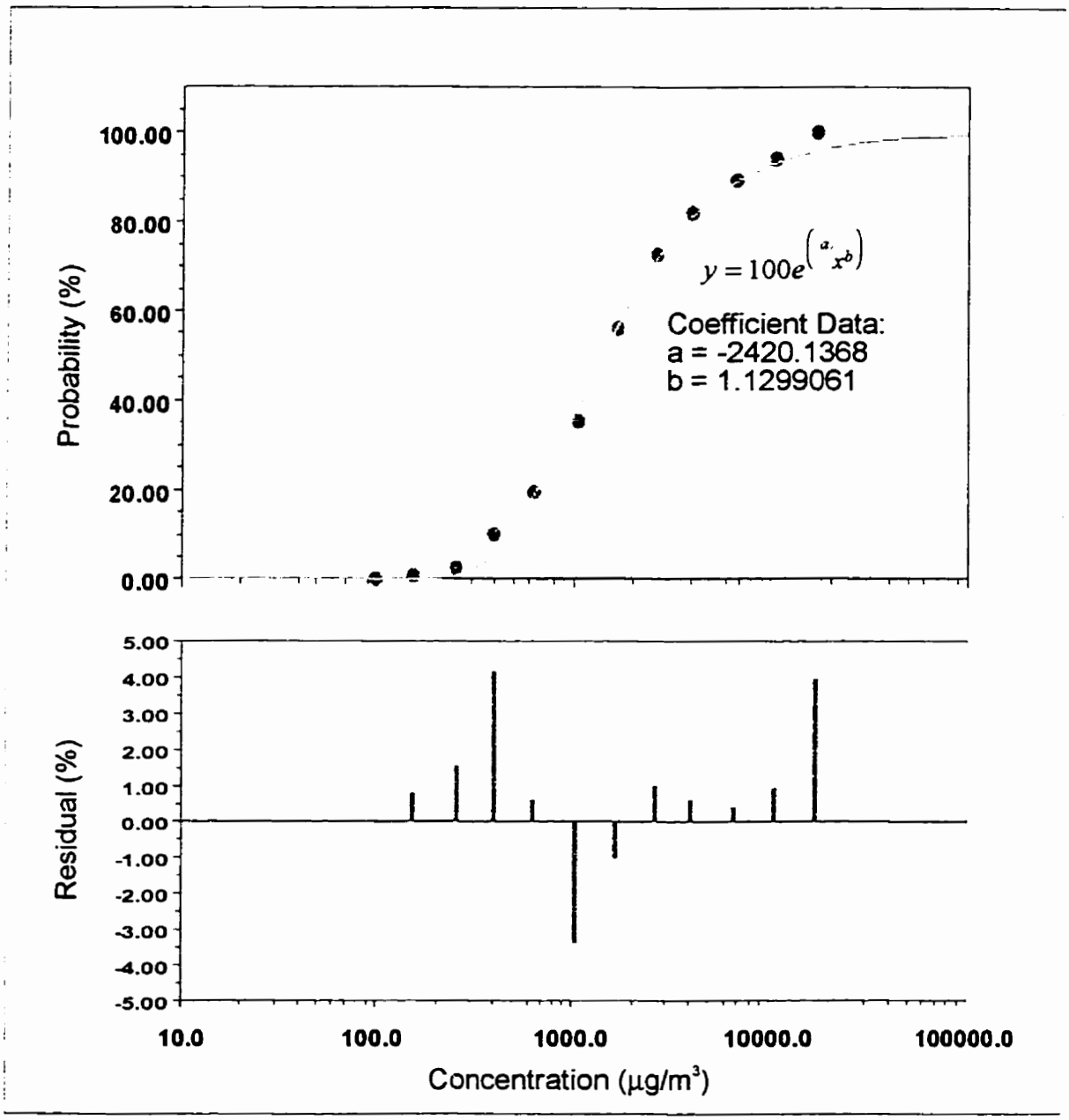
Standard Error, Sr: 3.8888955
Correlation Coefficient, r: 0.9956741

Fig. A9: Isobutanol - Probability of Discrimination



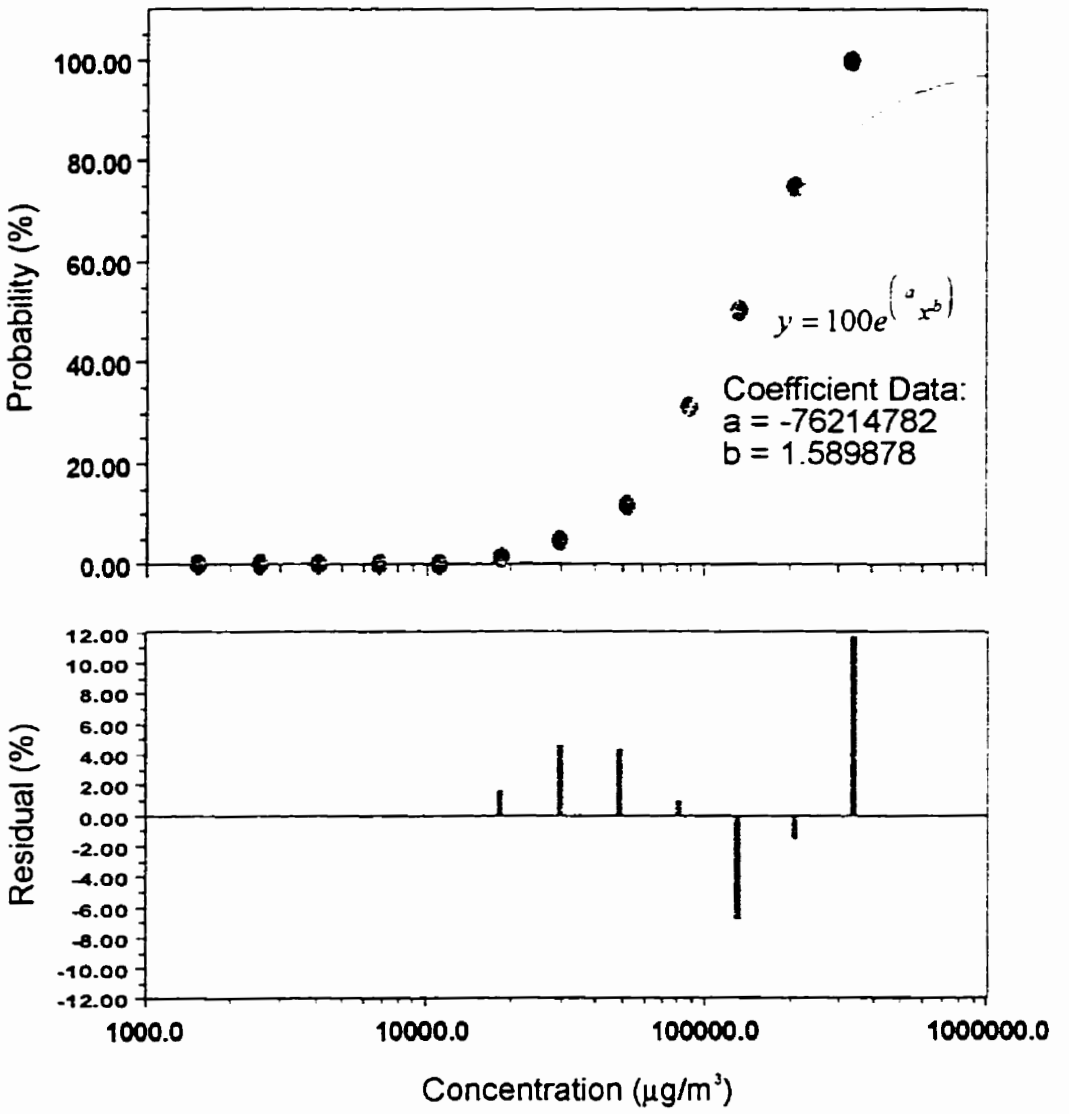
Standard Error, Sr: 4.0178175
Correlation Coefficient, r: 0.9941908

Fig. A10: Methyl Isoamylketone - Probability of Discrimination



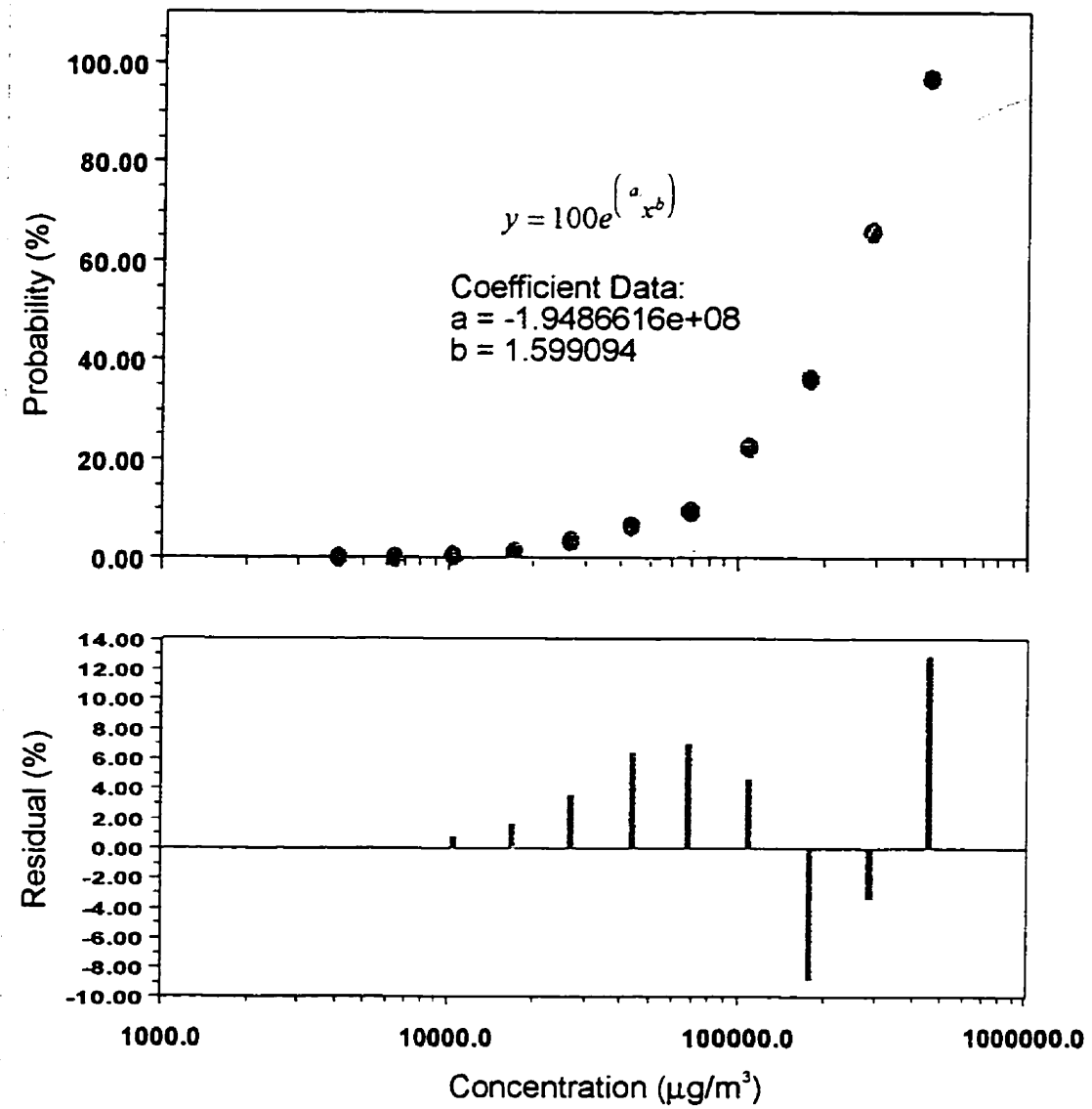
Standard Error, Sr: 2.2795989
Correlation Coefficient, r: 0.9985058

Fig. A11: Octane - Probability of Discrimination



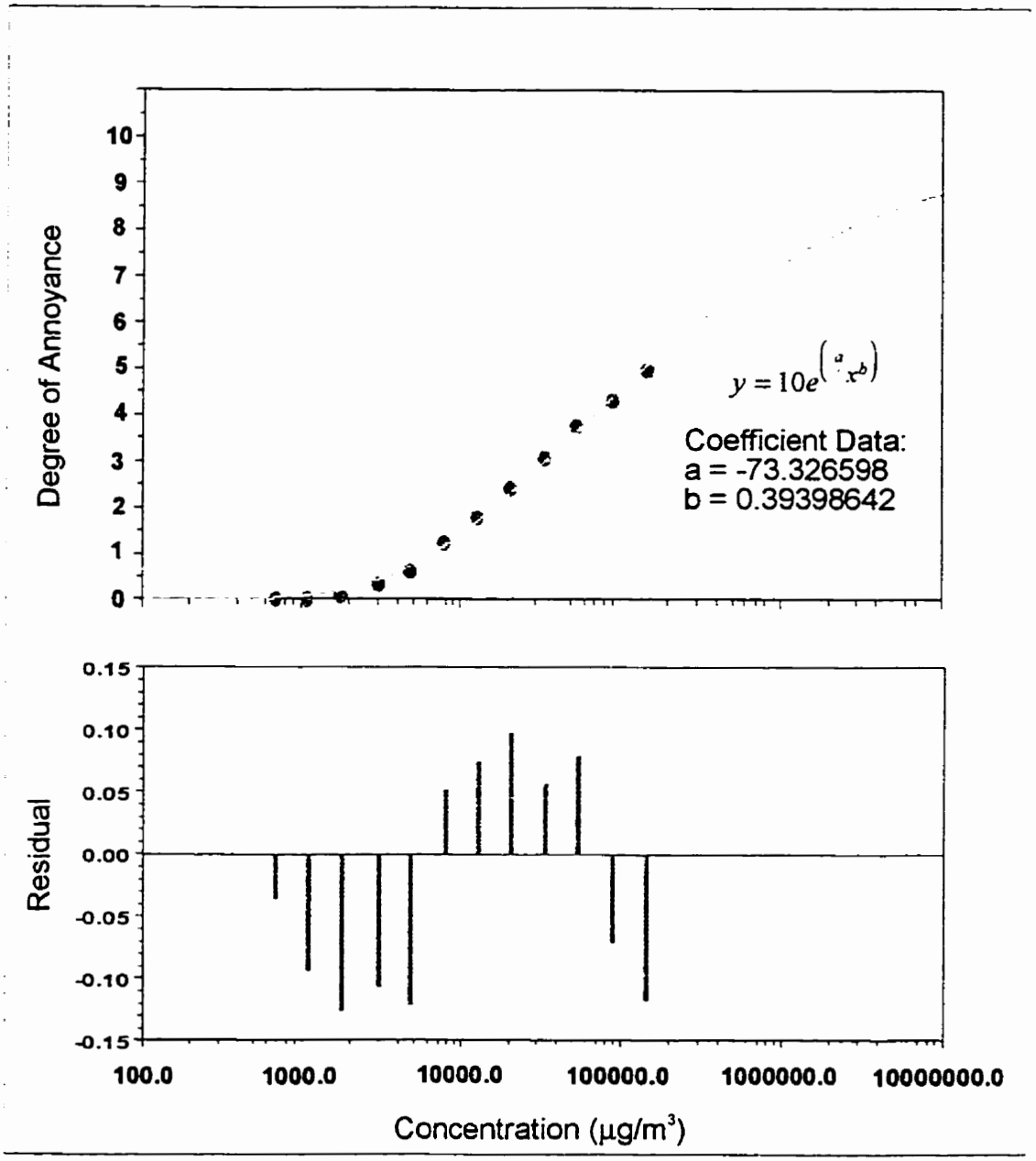
Standard Error: 4.8007854
Correlation Coefficient: 0.9910954

Fig. A12: Propylene Glycol Monomethyl Ether - Probability of Discrimination



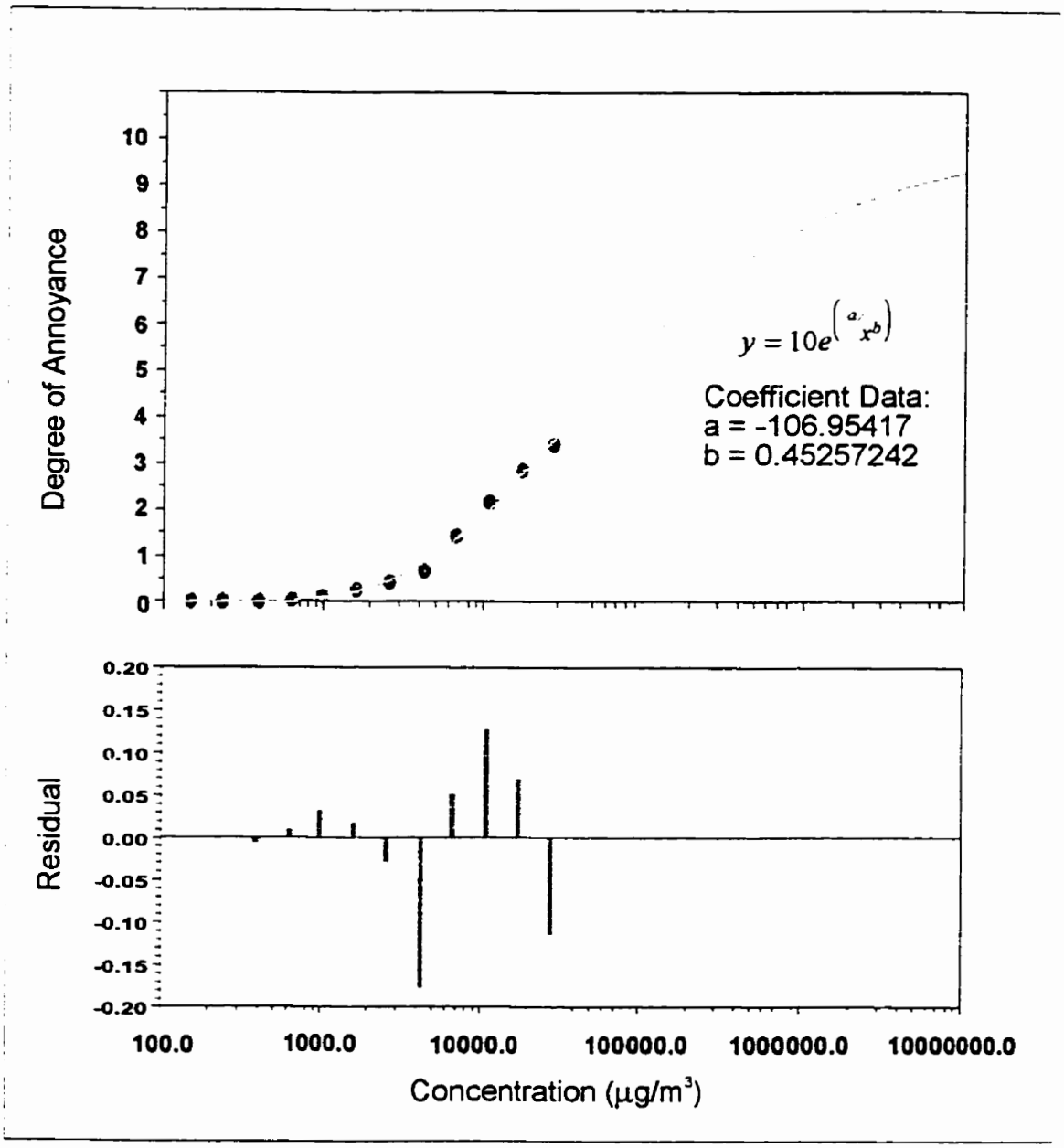
Standard Error, Sr: 6.5554406
Correlation Coefficient, r: 0.9809886

Fig. A13: n-Butanol - Degree of Annoyance



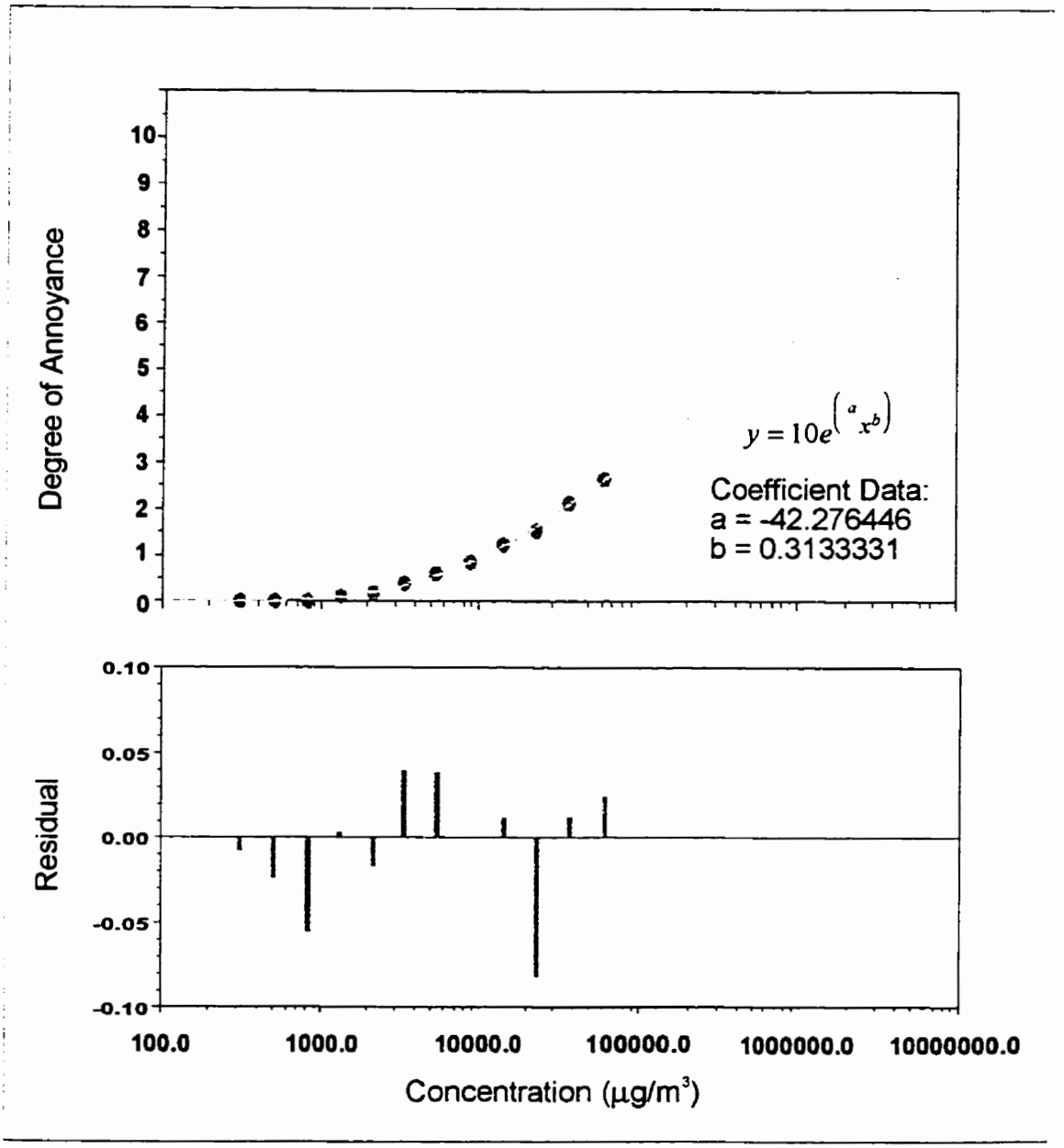
Standard Error, Sr: 0.0993965
Correlation Coefficient, r: 0.9985975

Fig. A14: n-Butyl Acetate - Degree of Annoyance



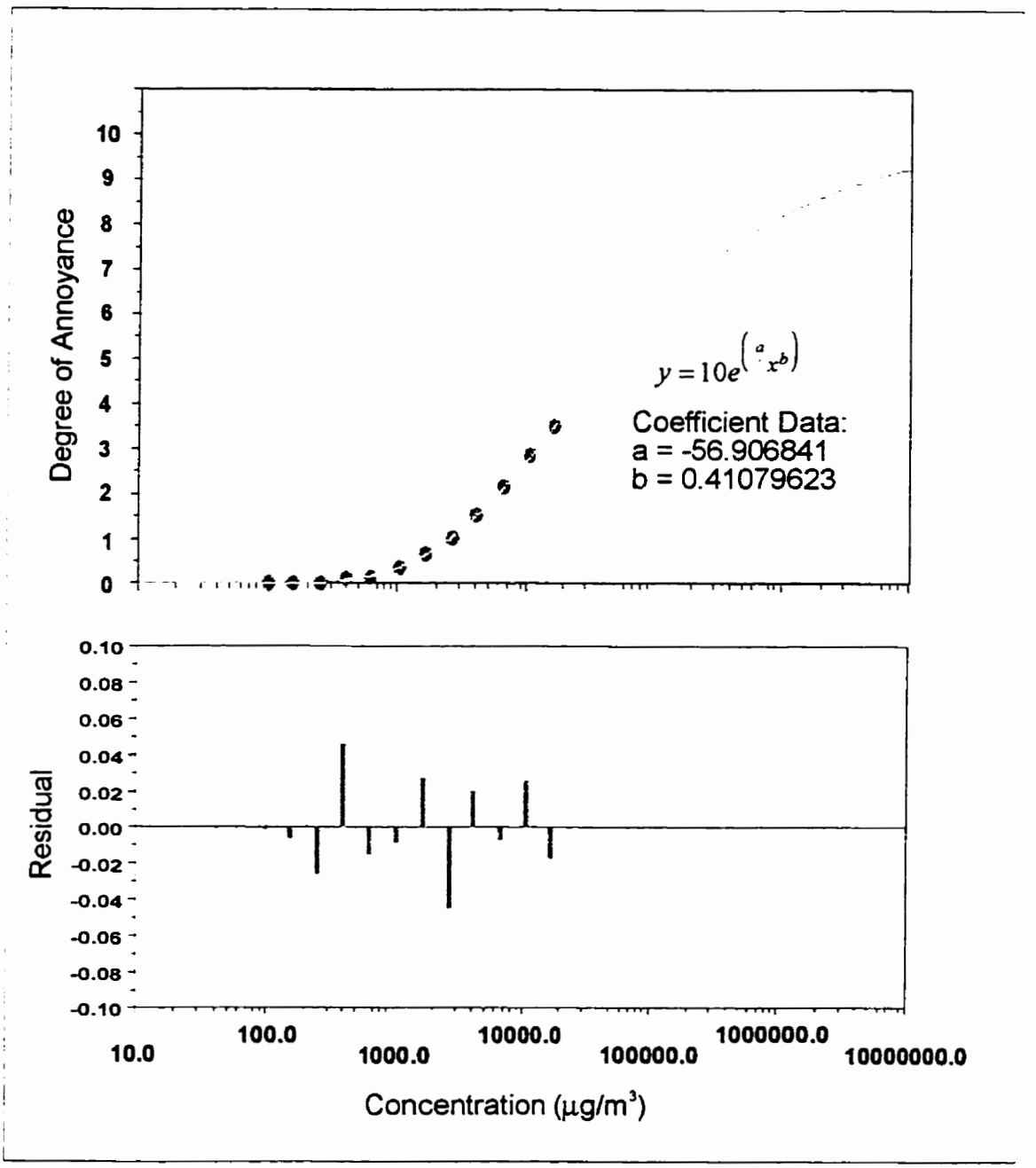
Standard Error, Sr: 0.0838743
Correlation Coefficient, r: 0.9978579

Fig. A15: Isobutanol - Degree of Annoyance



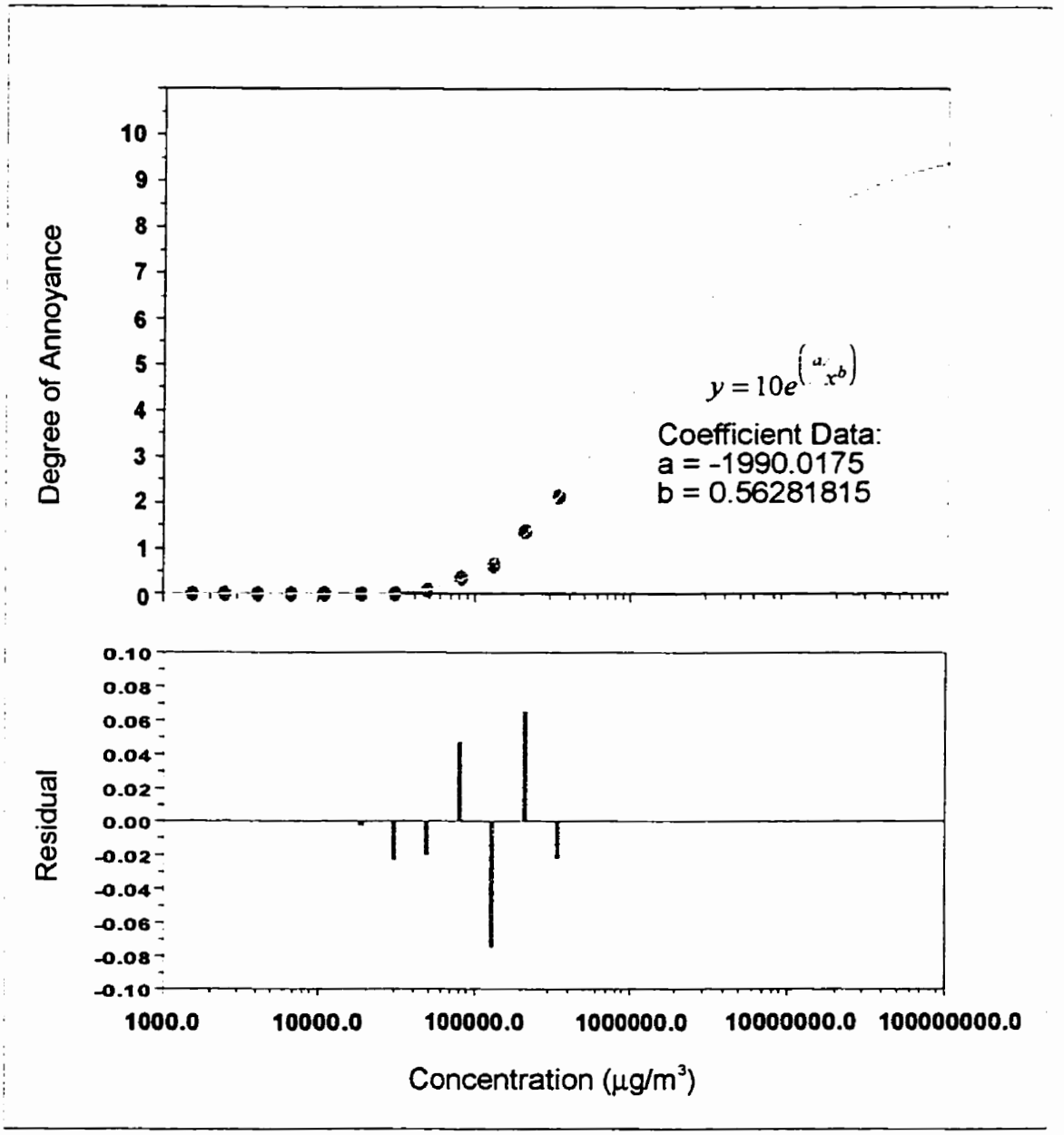
Standard Error, Sr: 0.0385261
Correlation Coefficient, r: 0.9991583

Fig. A16: Methyl Isoamylketone - Degree of Annoyance



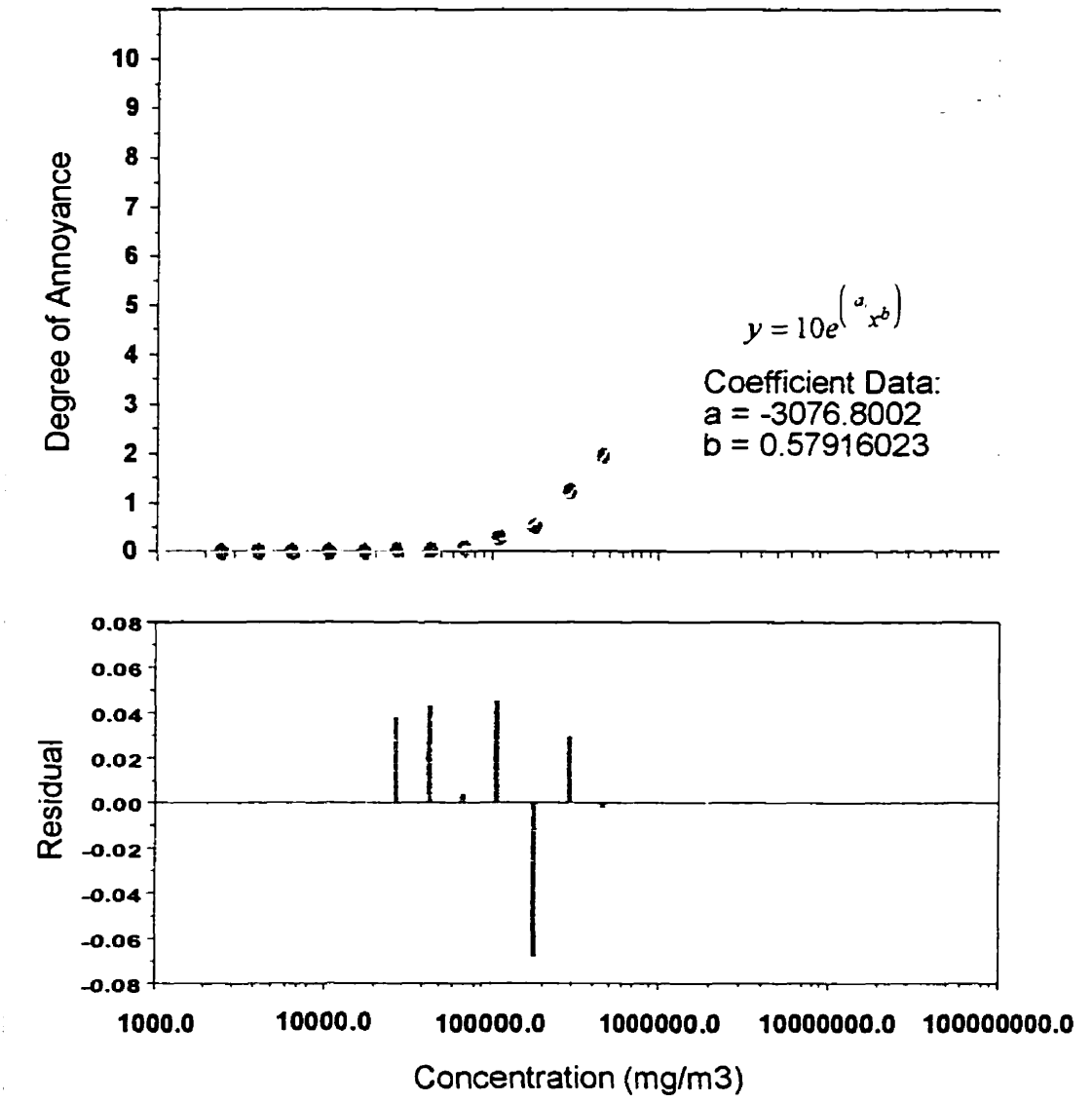
Standard Error, Sr: 0.0271549
Correlation Coefficient, r: 0.9997726

Fig. A17: Octane - Degree of Annoyance



Standard Error, Sr: 0.0368990
Correlation Coefficient, r: 0.9986871

Fig. A18: Propylene Glycol Monomethyl Ether - Degree of Annoyance



Standard Error, Sr: 0.0330999
Correlation Coefficient, r: 0.9986999

APPENDIX B:

Panel OIM Data

Table B1: n-Butanol - Panel OIM Data

Panel	Concentration ($\mu g/m^3$)	Probability of Detection (%)	Probability of Discrimination (%)	Degree of Annoyance
1	680	0	0	0.00
	2,060	20	10	0.30
	6,120	60	10	0.40
	18,650	90	60	1.80
	53,560	90	90	3.70
	154,800	100	100	5.40
2	680	10	0	0.00
	2,060	20	0	0.00
	6,120	60	40	1.10
	18,650	80	60	1.80
	53,560	90	90	2.80
	154,800	100	100	3.50
3	680	10	0	0.00
	2,060	50	0	0.00
	6,120	80	60	1.40
	18,650	100	80	2.60
	53,560	100	90	4.20
	154,800	100	100	5.40
4	680	0	0	0.00
	2,060	30	0	0.00
	6,120	80	60	0.60
	18,650	100	100	1.90
	53,560	100	100	3.30
	154,800	100	100	4.70
5	680	0	0	0.00
	2,060	50	0	0.00
	6,120	80	70	0.90
	18,650	100	100	3.00
	53,560	100	100	4.10
	154,800	100	100	5.40

Table B2: n-butyl Acetate - Panel OIM Data

Panel	Concentration ($\mu g/m^3$)	Probability of Detection (%)	Probability of Discrimination (%)	Degree of Annoyance
1	140	0	0	0.00
	420	20	0	0.00
	1,210	50	20	0.20
	4,160	70	50	0.50
	10,860	100	90	2.20
	28,920	100	100	3.30
2	140	0	0	0.00
	420	30	0	0.00
	1,210	50	10	0.00
	4,160	60	40	0.40
	10,860	100	90	1.60
	28,920	100	100	3.40
3	140	0	0	0.00
	410	10	0	0.00
	1,180	60	0	0.00
	4,040	90	50	0.60
	10,560	100	90	2.50
	28,110	100	100	3.70
4	140	0	0	0.00
	410	20	0	0.00
	1,180	60	40	0.60
	4,040	90	70	0.90
	10,560	100	80	2.10
	28,110	100	100	3.40
5	140	0	0	0.00
	410	20	0	0.00
	1,180	70	20	0.15
	4,040	80	80	0.80
	10,560	100	100	2.20
	28,110	100	100	3.40

Table B3: Isobutanol - Panel OIM Data

Panel	Concentration [µg/m³]	Probability of Detection [%]	Probability of Discrimination [%]	Degree of Annoyance
1	300	10	0	0.00
	900	30	0	0.00
	2,580	40	20	0.40
	8,830	70	70	1.30
	23,100	80	80	2.30
	61,490	100	90	3.40
2	300	10	0	0.00
	900	30	0	0.00
	2,580	60	30	0.25
	8,830	70	70	0.70
	23,100	70	70	1.10
	61,490	100	100	2.00
3	290	0	0	0.00
	860	0	0	0.00
	2,480	30	0	0.00
	8,490	60	40	0.40
	22,180	90	70	1.60
	59,050	100	100	3.20
4	290	0	0	0.00
	860	40	10	0.10
	2,480	70	30	0.30
	8,490	70	70	0.90
	22,180	80	80	1.70
	59,050	100	100	2.80
5	290	0	0	0.00
	860	20	0	0.00
	2,480	40	30	0.40
	8,490	60	50	0.90
	22,180	90	60	1.10
	59,050	100	100	2.10
6	310	10	0	0.00
	920	20	0	0.00
	2,660	50	30	0.10
	9,090	70	30	0.40
	23,760	90	50	0.80
	63,240	100	100	1.40
7	310	10	0	0.00
	920	30	0	0.00
	2,660	70	30	0.60
	9,090	100	70	1.40
	23,760	100	90	3.00
	63,240	100	100	4.10

Table B4: Methyl Isoamylketone - Panel OIM Data

Panel	Concentration ($\mu g/m^3$)	Probability of Detection (%)	Probability of Discrimination (%)	Degree of Annoyance
1	80	0	0	0.00
	240	0	0	0.00
	760	40	0	0.00
	2,400	90	60	0.40
	6,530	90	90	1.40
	19,040	100	100	2.70
2	80	0	0	0.00
	230	10	0	0.00
	730	60	20	0.25
	2,300	90	70	1.00
	6,240	100	100	2.00
	18,220	100	100	3.70
3	80	0	0	0.00
	230	20	0	0.00
	730	60	30	0.50
	2,300	90	90	1.40
	6,240	100	90	2.90
	18,220	100	100	4.60
4	100	0	0	0.00
	290	40	10	0.10
	920	70	60	0.40
	2,920	80	80	1.00
	7,930	100	90	2.25
	23,150	100	100	3.75
5	100	0	0	0.00
	290	10	0	0.00
	920	60	10	0.00
	2,920	70	60	0.90
	7,930	90	80	2.00
	23,150	100	100	3.30

Table B5: Octane - Panel OIM Data

Panel	Concentration ($\mu g/m^3$)	Probability of Detection (%)	Probability of Discrimination (%)	Degree of Annoyance
1	1,550	0	0	0.00
	4,740	0	0	0.00
	14,930	10	0	0.00
	47,150	20	20	0.00
	128,170	70	50	0.70
	373,970	100	100	2.25
2	1,480	0	0	0.00
	4,550	0	0	0.00
	14,320	20	0	0.00
	45,250	40	0	0.00
	123,000	70	10	0.00
	358,900	100	100	2.30
3	1,480	0	0	0.00
	4,550	0	0	0.00
	14,320	10	0	0.00
	45,250	20	0	0.00
	123,000	80	60	0.80
	358,900	100	100	2.10
4	1,400	0	0	0.00
	4,300	0	0	0.00
	13,560	10	0	0.00
	42,830	50	20	0.10
	116,430	100	60	0.90
	339,720	100	100	2.30
5	1,400	0	0	0.00
	4,300	0	0	0.00
	13,560	0	0	0.00
	42,830	40	0	0.00
	116,430	90	60	0.70
	339,720	100	100	2.10
6	1,760	0	0	0.00
	5,200	0	0	0.00
	14,930	0	0	0.00
	51,070	50	0	0.00
	133,500	70	30	0.40
	355,400	100	90	1.80
7	1,760	0	0	0.00
	5,200	0	0	0.00
	14,930	0	0	0.00
	51,070	30	0	0.00
	133,500	80	40	0.60
	355,400	100	100	1.70

Table B6: Propylene Glycol Monomethyl Ether - Panel OIM Data

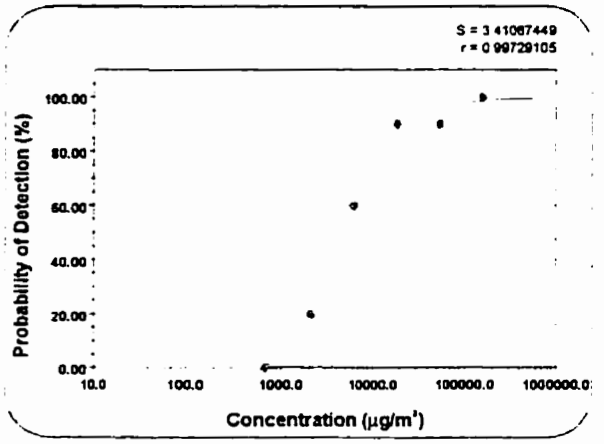
Panel	Concentration ($\mu g/m^3$)	Probability of Detection (%)	Probability of Discrimination (%)	Degree of Annoyance
1	2,480	0	0	0.00
	7,350	0	0	0.00
	21,110	0	0	0.00
	72,230	30	10	0.15
	188,830	80	40	0.75
	502,700	100	100	1.10
2	2,480	0	0	0.00
	7,350	0	0	0.00
	21,110	0	0	0.00
	72,230	30	0	0.00
	188,830	60	40	0.10
	502,700	100	100	1.50
3	2,430	0	0	0.00
	7,190	0	0	0.00
	20,660	10	10	0.15
	70,680	20	10	0.15
	184,770	60	20	0.30
	491,890	100	100	1.60
4	2,430	0	0	0.00
	7,190	0	0	0.00
	20,660	0	0	0.00
	70,680	30	20	0.30
	184,770	70	50	1.10
	491,890	100	100	2.80
5	2,260	0	0	0.00
	6,680	0	0	0.00
	19,180	19	0	0.00
	65,630	28	10	0.00
	171,570	73	37	0.50
	456,760	100	100	2.10

Table B7: Individual Panels' Coefficients of Curvature and Threshold Values

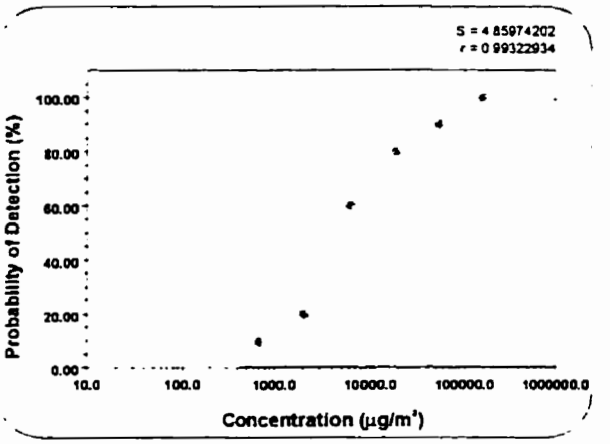
Chemical Name	Panel Number	Probability of Detection			Probability of Discrimination			Degree of Annoyance		
		Coefficients		ED_{50}	Coefficients		D_{50}	Coefficients		C_a(DA=4)
		a	b	($\mu g/m^3$)	a	b	($\mu g/m^3$)	a	b	($\mu g/m^3$)
n-Butanol	1	-6.574E+3	1.089E+0	4.49E+03	-5.201E+5	1.410E+0	1.47E+04	-2.115E+2	4.900E-1	6.65E+04
	2	-9.670E+2	8.554E-1	4.75E+03	-3.936E+3	9.402E-1	9.84E+03	-2.570E+1	2.718E-1	2.11E+05
	3	-4.480E+3	1.152E+0	2.03E+03	-6.550E+4	1.325E+0	5.71E+03	-6.640E+1	3.955E-1	5.05E+04
	4	-2.948E+5	1.625E+0	2.90E+03	-2.279E+5	1.520E+0	4.27E+03	-8.790E+1	4.001E-1	8.99E+04
	5	-2.696E+4	1.376E+0	2.17E+03	-2.829E+5	1.536E+0	4.50E+03	-7.880E+1	4.115E-1	5.02E+04
n-Butyl Acetate	1	-3.232E+2	8.658E-1	1.21E+03	-3.625E+3	1.063E+0	3.16E+03	-1.062E+2	4.474E-1	7.67E+04
	2	-1.072E+2	7.133E-1	1.17E+03	-5.086E+5	1.605E+0	4.50E+03	-3.192E+2	5.542E-1	6.39E+04
	3	-1.142E+4	1.415E+0	9.56E+02	-2.914E+4	1.287E+0	3.91E+03	-1.506E+2	4.931E-1	5.48E+04
	4	-2.030E+3	1.181E+0	8.64E+02	-6.950E+2	9.142E-1	1.92E+03	-4.593E+1	3.639E-1	1.01E+05
	5	-1.557E+3	1.155E+0	7.99E+02	-2.785E+5	1.696E+0	2.01E+03	-8.075E+1	4.222E-1	7.83E+04
Isobutanol	1	-7.602E+1	5.907E-1	2.84E+03	-3.798E+3	9.968E-1	5.63E+03	-4.640E+1	3.422E-1	2.16E+05
	2	-5.044E+1	5.550E-1	2.26E+03	-1.084E+3	8.606E-1	5.14E+03	-3.251E+1	2.715E-1	1.43E+06
	3	-3.009E+3	9.879E-1	4.81E+03	-1.082E+5	1.286E+0	1.10E+04	-3.269E+2	5.158E-1	1.53E+05
	4	-1.859E+2	7.660E-1	1.48E+03	-9.672E+2	8.653E-1	4.31E+03	-4.502E+1	3.241E-1	3.91E+05
	5	-2.562E+2	7.258E-1	3.45E+03	-1.713E+2	6.226E-1	6.97E+03	-2.336E+1	2.440E-1	1.82E+06
	6	-2.185E+2	7.281E-1	2.70E+03	-2.885E+2	6.383E-1	1.27E+04	-3.488E+1	2.603E-1	3.44E+06
	7	-5.602E+3	1.240E+0	1.42E+03	-7.477E+3	1.103E+0	4.54E+03	-6.470E+1	3.898E-1	1.13E+05
Methyl	1	-4.640E+4	1.635E+0	8.95E+02	-6.851E+5	1.810E+0	2.05E+03	-8.002E+1	4.183E-1	8.51E+04
Isoamylketone	2	-3.810E+3	1.357E+0	5.70E+02	-2.978E+4	1.485E+0	1.32E+03	-5.749E+1	4.124E-1	4.49E+04
	3	-8.199E+2	1.136E+0	5.07E+02	-3.338E+5	1.904E+0	9.67E+02	-5.676E+1	4.373E-1	2.37E+04
	4	-1.828E+2	9.122E-1	4.51E+02	-8.280E+2	1.059E+0	8.04E+02	-5.090E+1	3.926E-1	5.65E+04
	5	-3.248E+2	9.052E-1	8.92E+02	-8.428E+3	1.208E+0	2.41E+03	-5.735E+1	3.945E-1	7.27E+04
Octane	1	-7.705E+7	1.641E+0	8.02E+04	-2.264E+6	1.299E+0	1.03E+05	-2.009E+3	5.618E-1	1.46E+06
	2	-7.837E+3	8.628E-1	4.98E+04	-1.678E+7	1.396E+0	1.94E+05	-2.090E+5	9.268E-1	8.16E+05
	3	-1.084E+6	1.283E+0	6.71E+04	-1.222E+7	1.443E+0	1.05E+05	-8.586E+2	4.939E-1	1.83E+06
	4	-5.791E+7	1.725E+0	3.97E+04	-6.087E+6	1.414E+0	8.14E+04	-7.388E+2	4.887E-1	1.57E+06
	5	-1.044E+8	1.746E+0	4.84E+04	-3.204E+7	1.534E+0	9.91E+04	-1.266E+3	5.262E-1	1.58E+06
	6	-4.287E+5	1.238E+0	4.77E+04	-7.080E+6	1.337E+0	1.74E+05	-6.765E+3	6.479E-1	1.44E+06
	7	-4.817E+6	1.437E+0	5.75E+04	-1.858E+7	1.440E+0	1.44E+05	-1.133E+3	5.058E-1	2.25E+06
Propylene Glyco	1	-3.200E+8	1.735E+0	9.83E+04	-3.277E+6	1.264E+0	1.90E+05	-7.794E+1	2.730E-1	1.15E+07
Monomethyl	2	-2.008E+6	1.273E+0	1.19E+05	-7.527E+7	1.514E+0	2.04E+05	-2.279E+4	7.150E-1	2.09E+06
Ether	3	-3.050E+7	1.493E+0	1.31E+05	-4.614E+7	1.451E+0	2.47E+05	-3.618E+3	5.780E-1	1.50E+06
	4	-1.207E+7	1.442E+0	1.05E+05	-9.215E+6	1.378E+0	1.48E+05	-1.607E+3	5.450E-1	1.51E+06
	5	-7.381E+7	1.610E+0	9.70E+04	-2.057E+6	1.232E+0	1.80E+05	-9.908E+3	6.719E-1	1.01E+06

Fig. B1: n-Butanol - Panel Probability of Detection

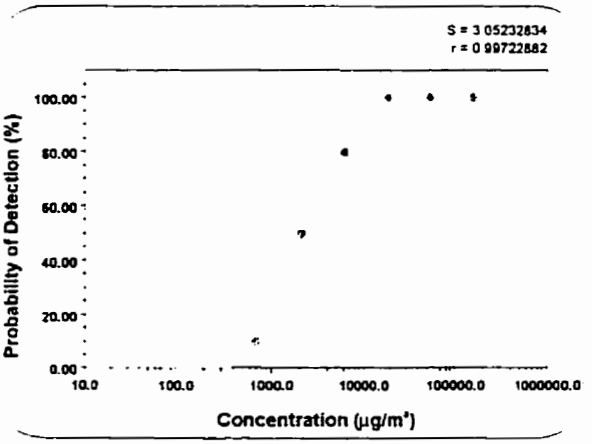
Panel No. 1:



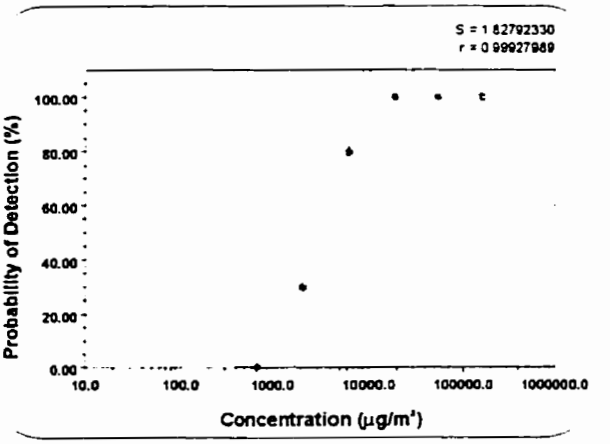
Panel No. 2:



Panel No. 3:



Panel No. 4:



Panel No. 5:

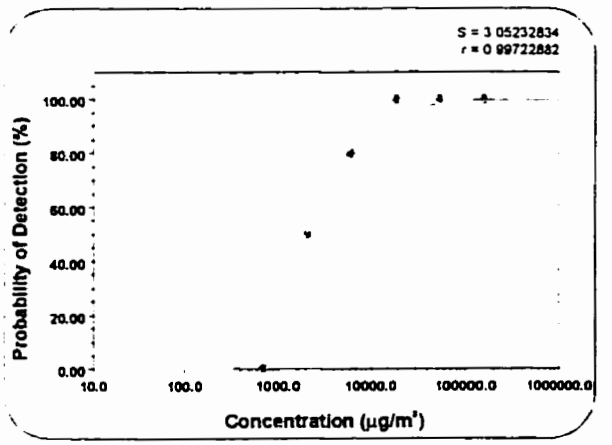
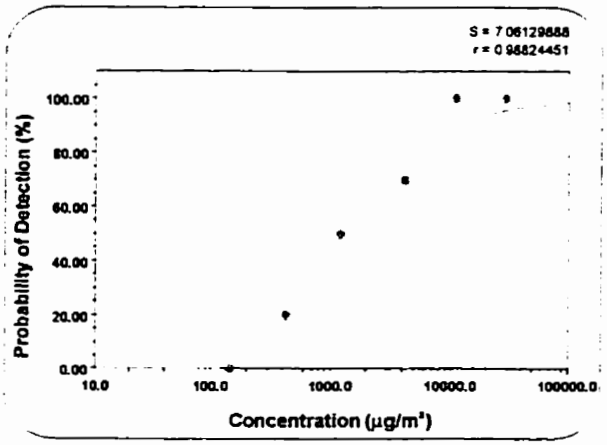
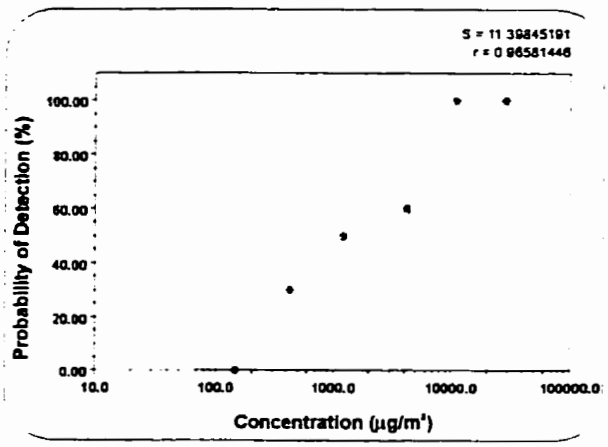


Fig. B2: n-Butyl Acetate - Panel Probability of Detection

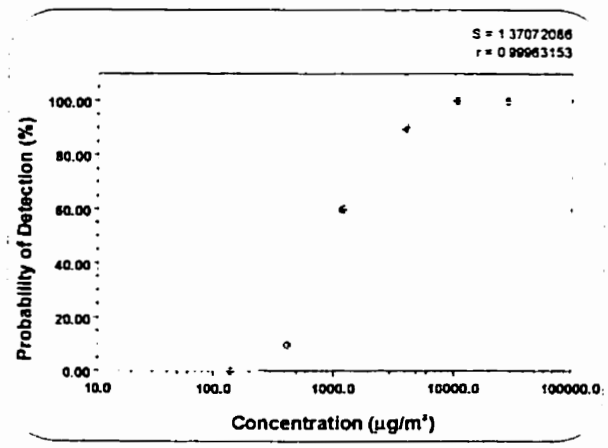
Panel No. 1:



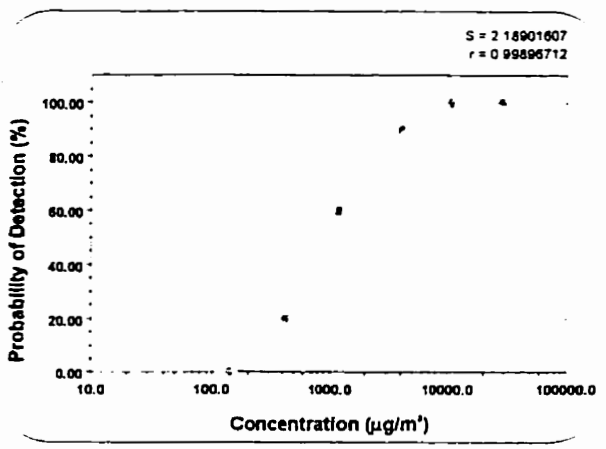
Panel No. 2:



Panel No. 3:



Panel No. 4:



Panel No. 5:

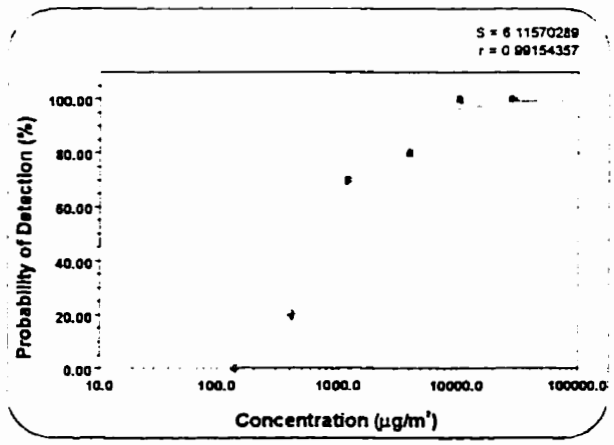
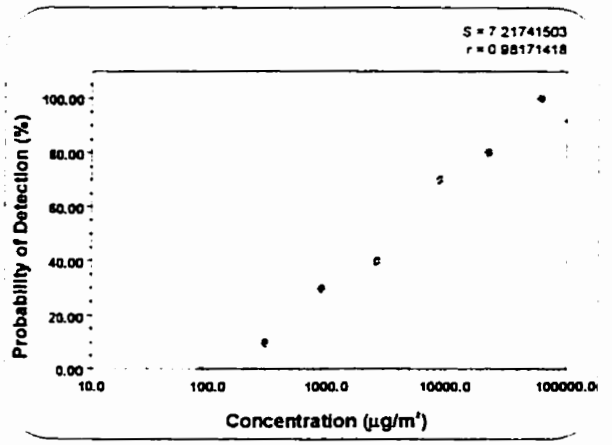
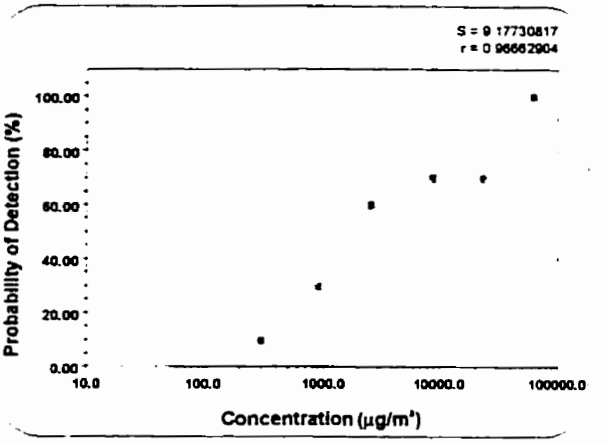


Fig. B3: Isobutanol - Panel Probability of Detection

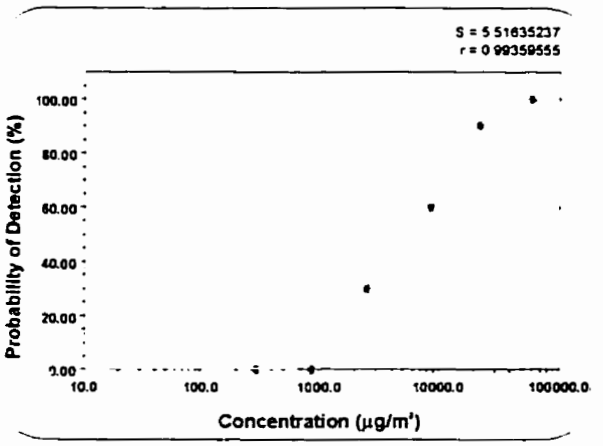
Panel No. 1:



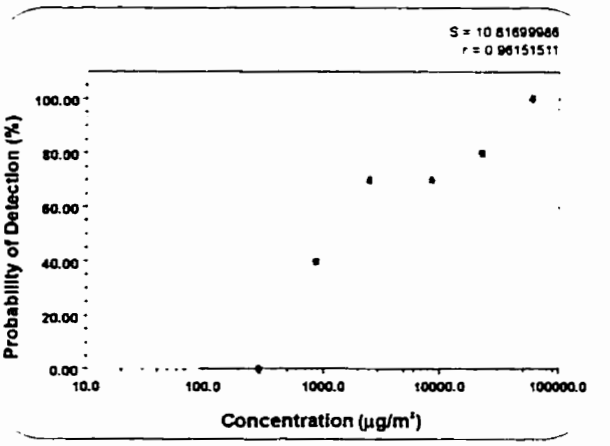
Panel No. 2:



Panel No. 3:



Panel No. 4:



Panel No. 5:

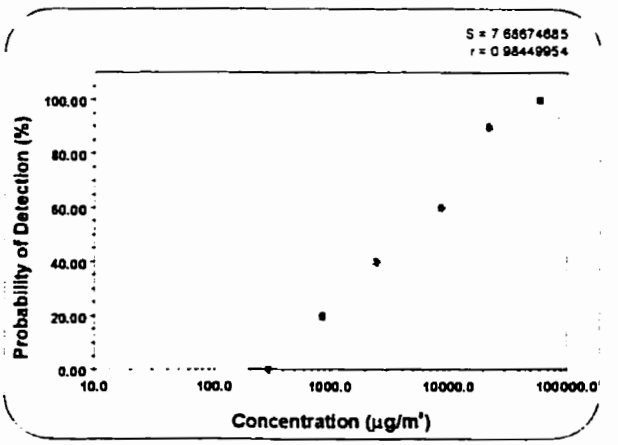
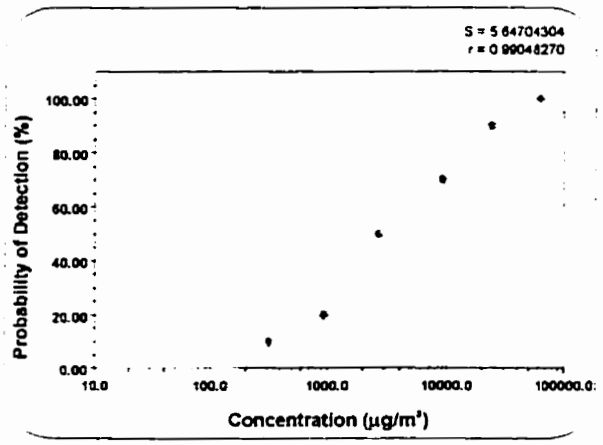


Fig. B3 (cont.): Isobutanol - Panel Probability of Detection

Panel No. 6:



Panel No. 7:

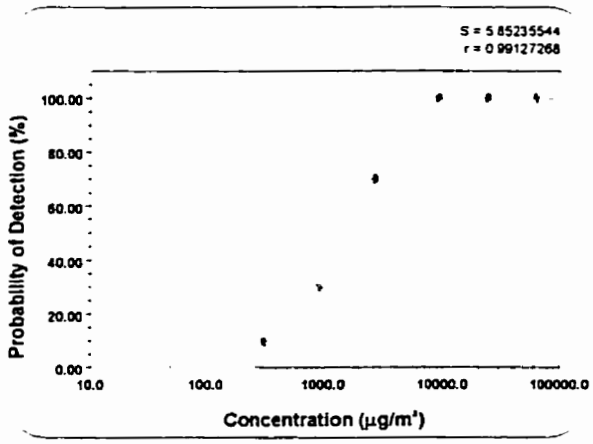
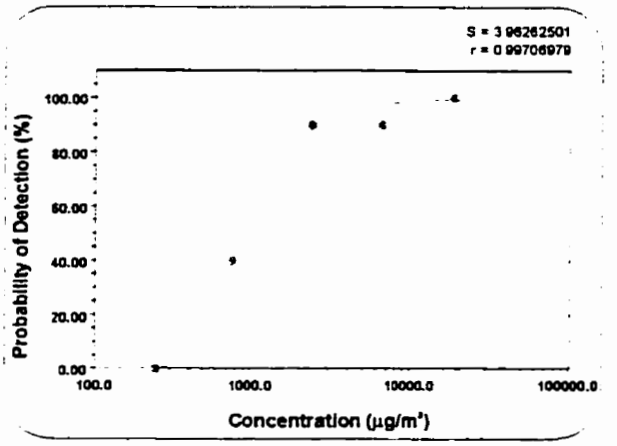
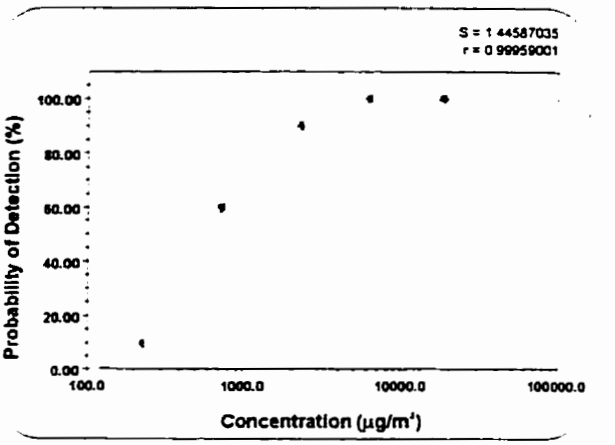


Fig. B4: Methyl Isoamylketone - Panel Probability of Detection

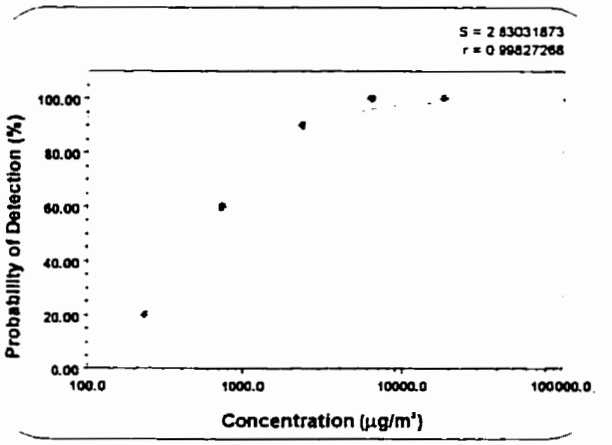
Panel No. 1:



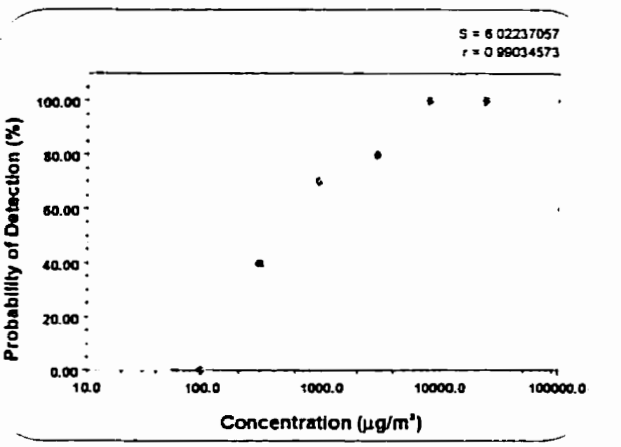
Panel No. 2:



Panel No. 3:



Panel No. 4:



Panel No. 5:

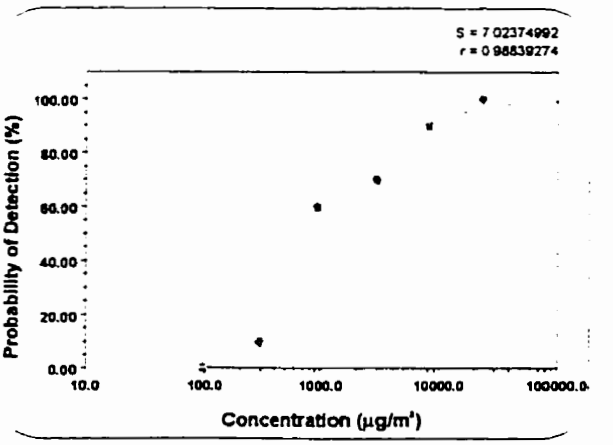
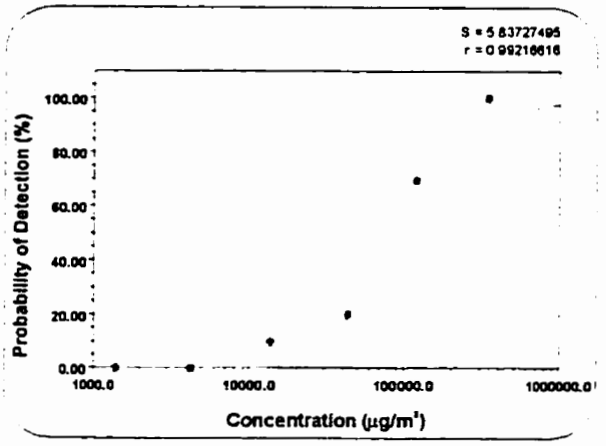
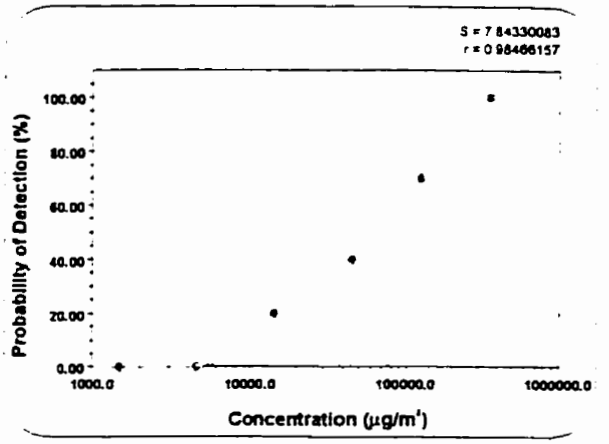


Fig. B5: Octane - Panel Probability of Detection

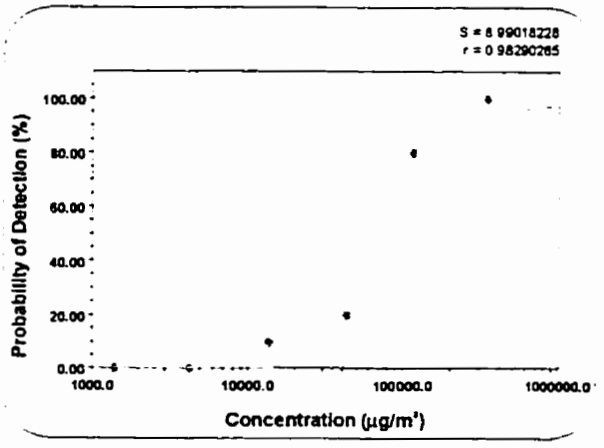
Panel No. 1:



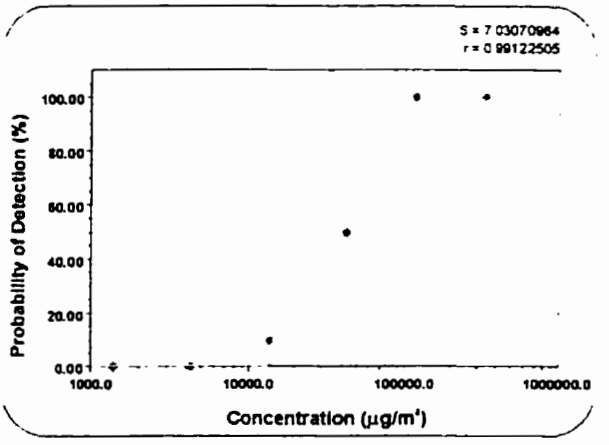
Panel No. 2:



Panel No. 3:



Panel No. 4:



Panel No. 5:

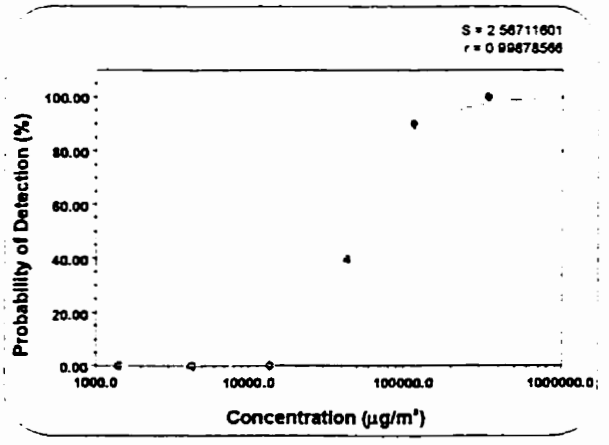
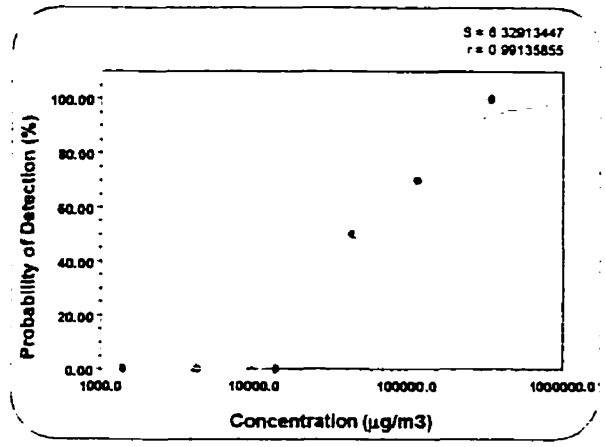


Fig. B5 (cont.): Octane - Panel Probability of Detection

Panel No. 6:



Panel No. 7:

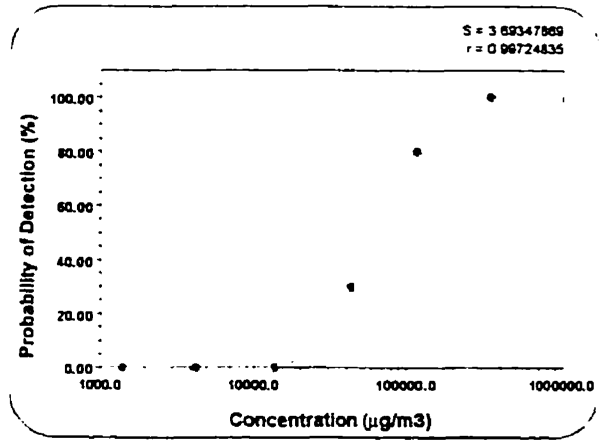
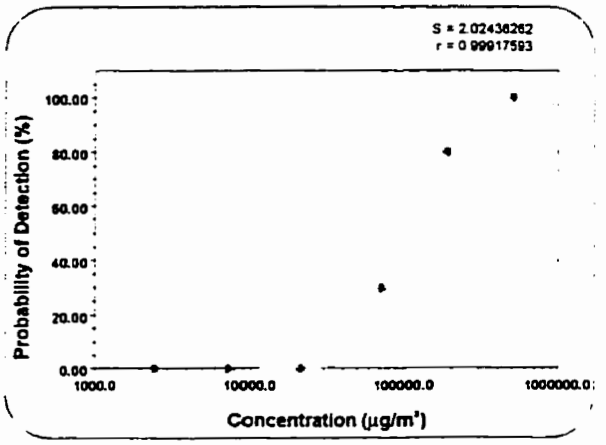
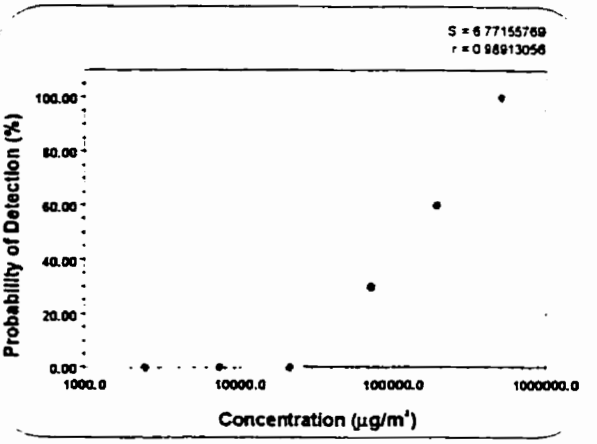


Fig. B6: Propylene Glycol Monomethyl Ether - Panel Probability of Detection

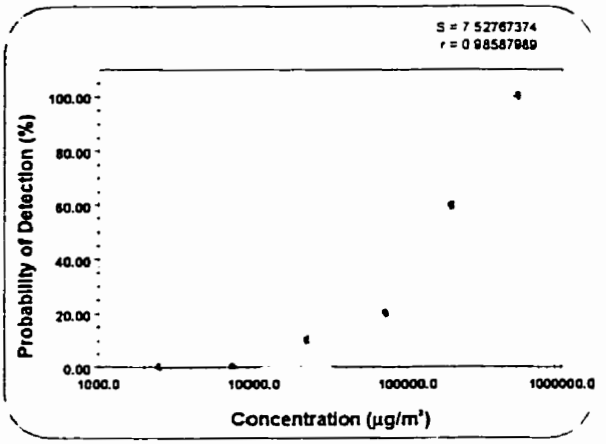
Panel No. 1:



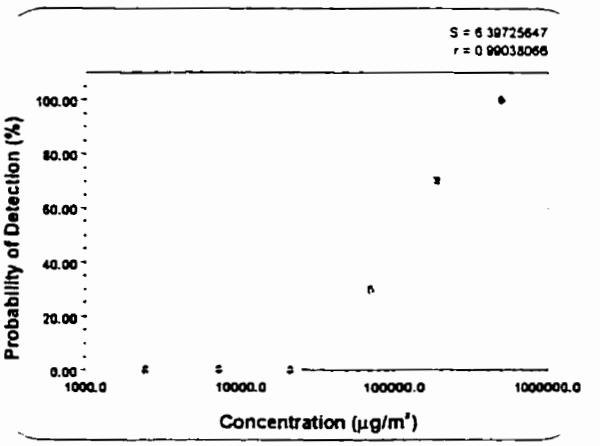
Panel No. 2:



Panel No. 3:



Panel No. 4:



Panel No. 5:

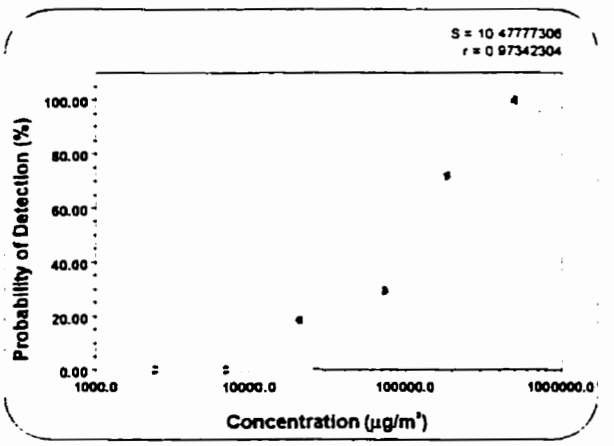
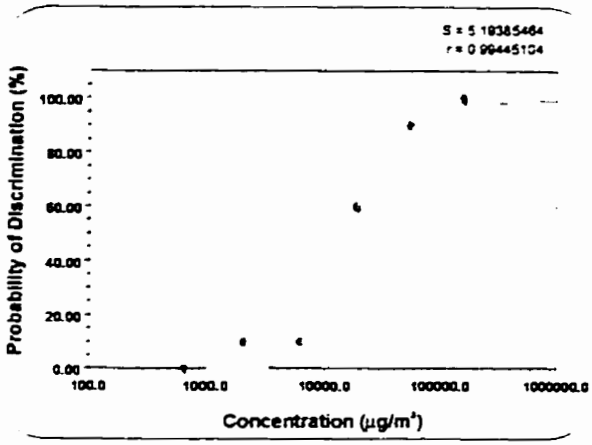
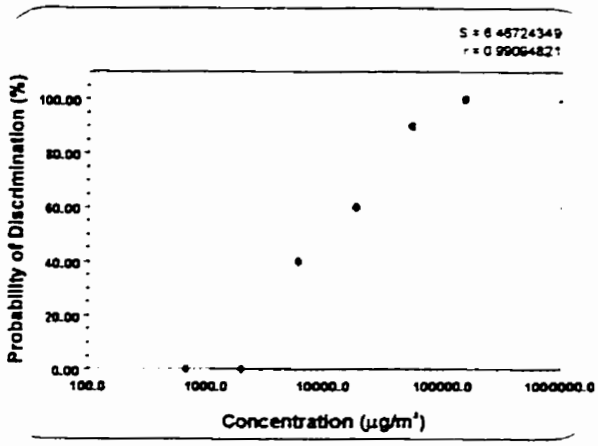


Fig. B7: n-Butanol - Panel Probability of Discrimination

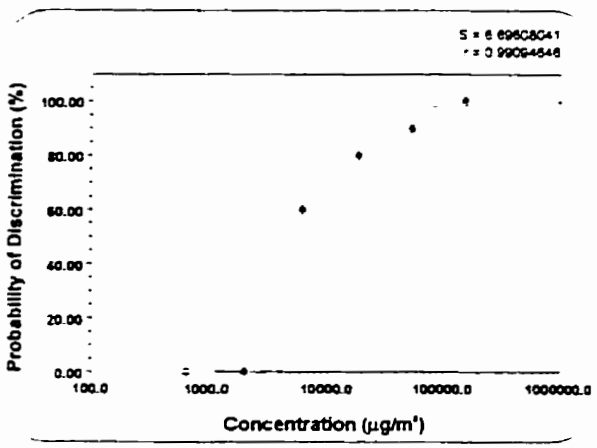
Panel No. 1:



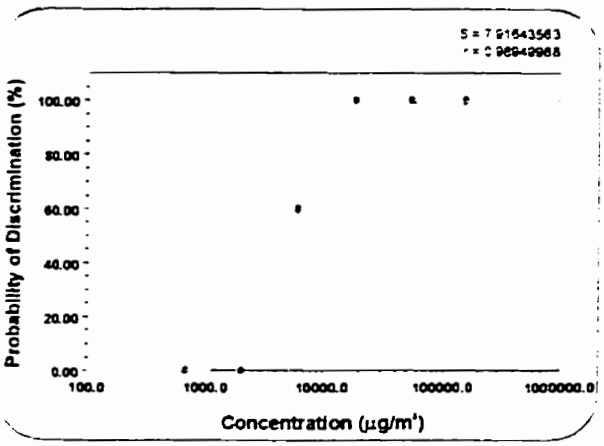
Panel No. 2:



Panel No. 3:



Panel No. 4:



Panel No. 5:

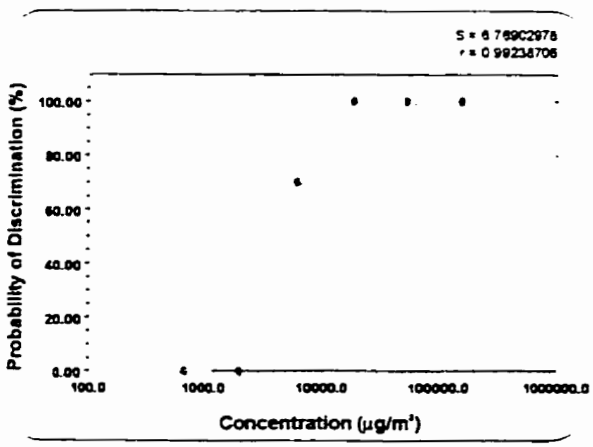
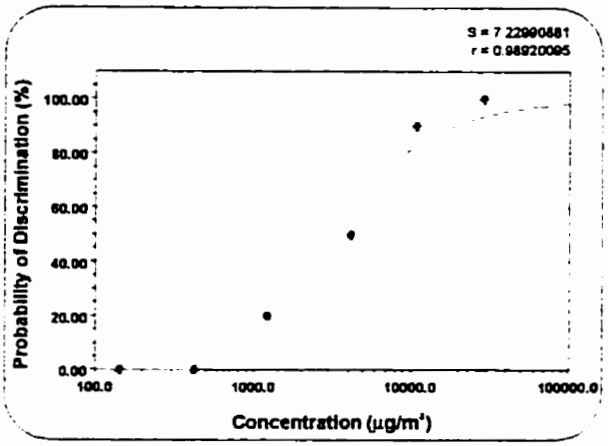
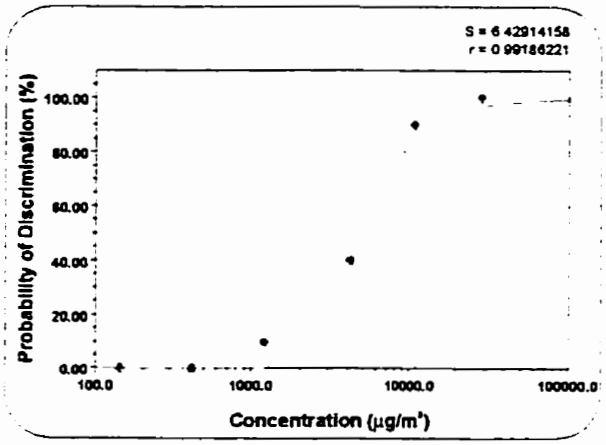


Fig. B8: n-Butyl Acetate - Panel Probability of Discrimination

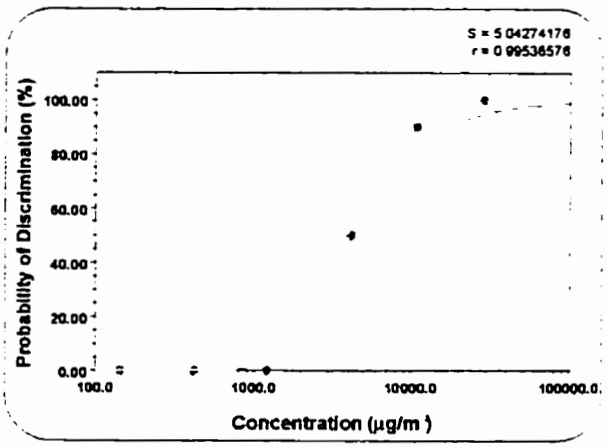
Panel No. 1:



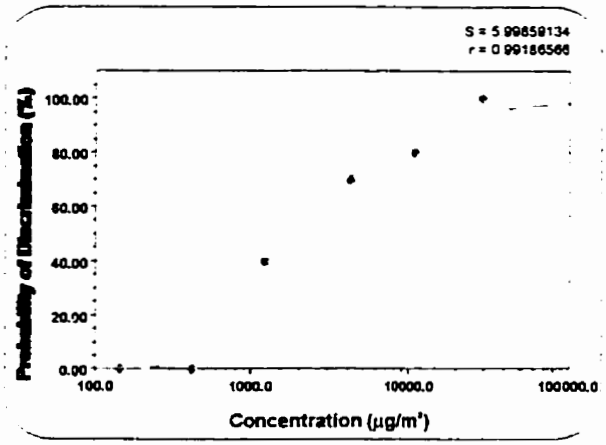
Panel No. 2:



Panel No. 3:



Panel No. 4:



Panel No. 5:

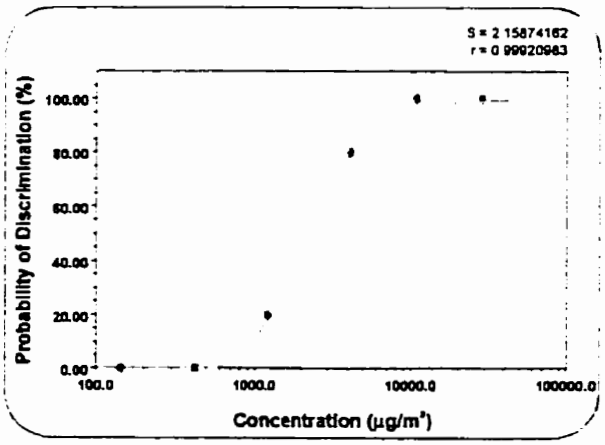
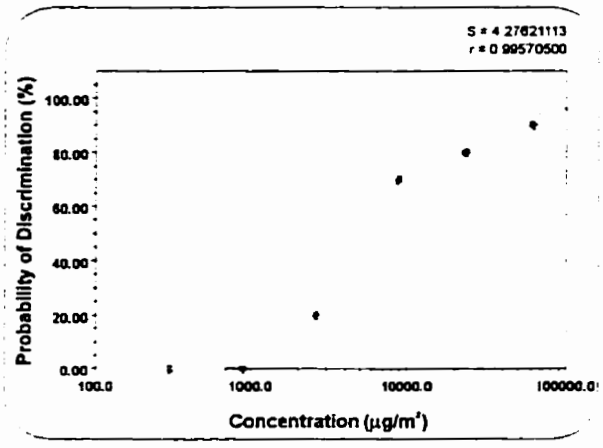
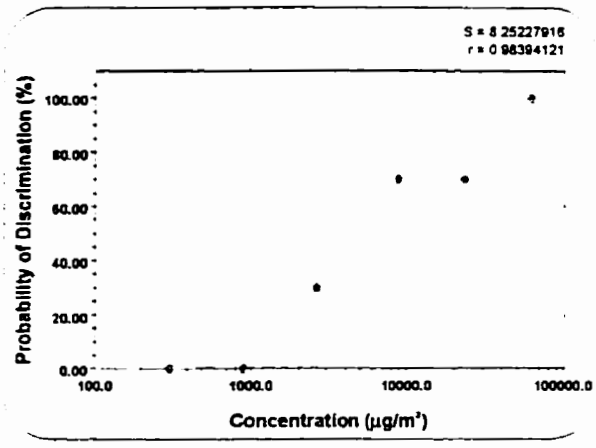


Fig. B9: Isobutanol - Panel Probability of Discrimination

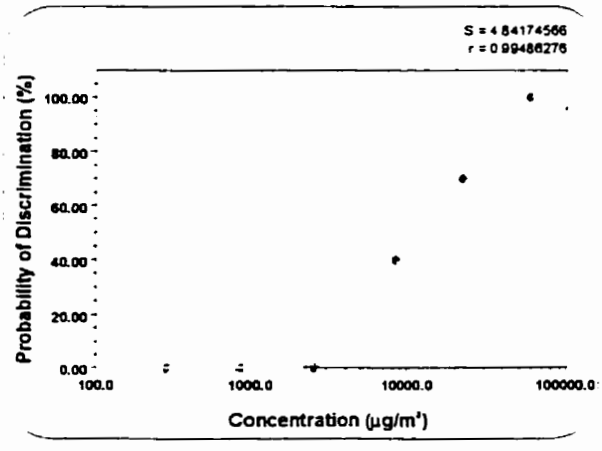
Panel No. 1:



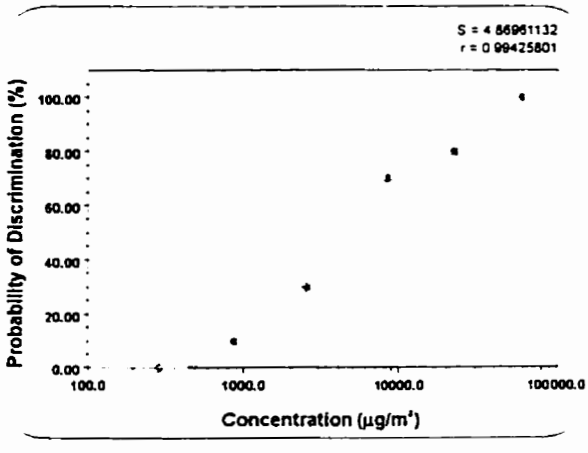
Panel No. 2:



Panel No. 3:



Panel No. 4:



Panel No. 5:

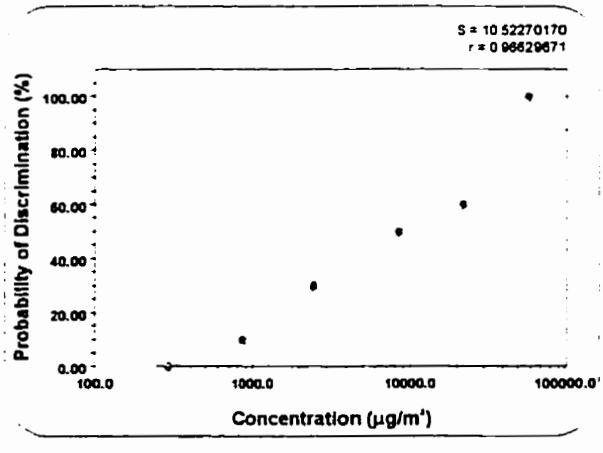
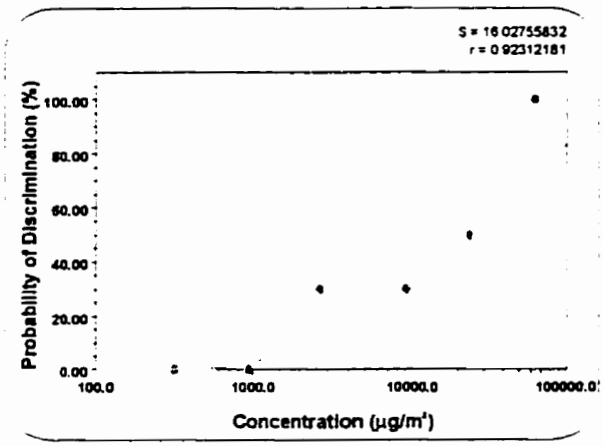


Fig. B9 (cont.): Isobutanol - Panel Probability of Discrimination

Panel No. 6:



Panel No. 7:

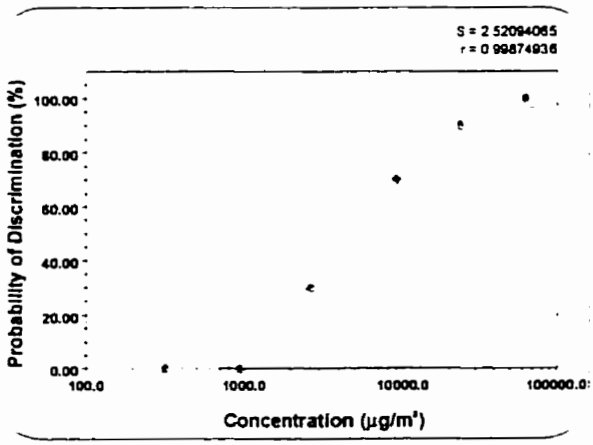
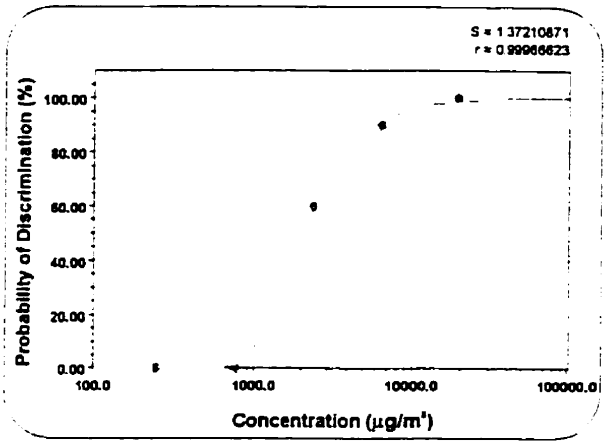
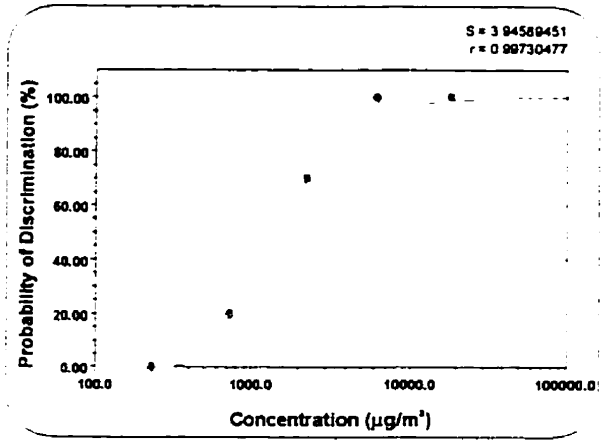


Fig. B10: Methyl Isoamylketone - Panel Probability of Discrimination

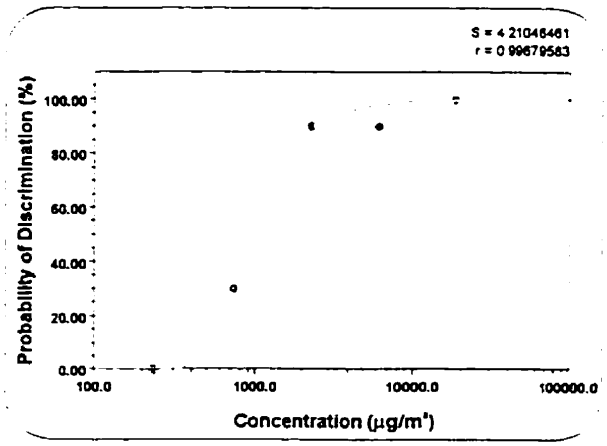
Panel No. 1:



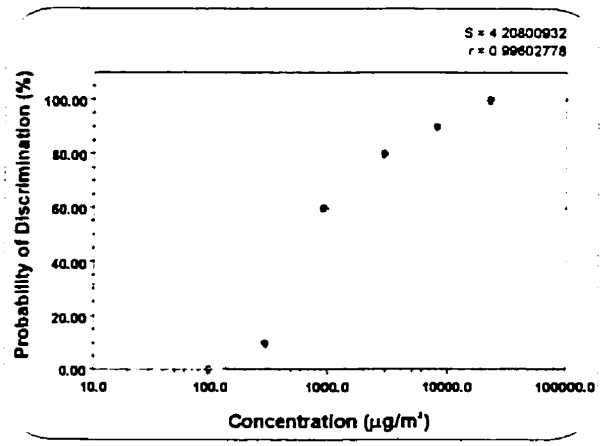
Panel No. 2:



Panel No. 3:



Panel No. 4:



Panel No. 5:

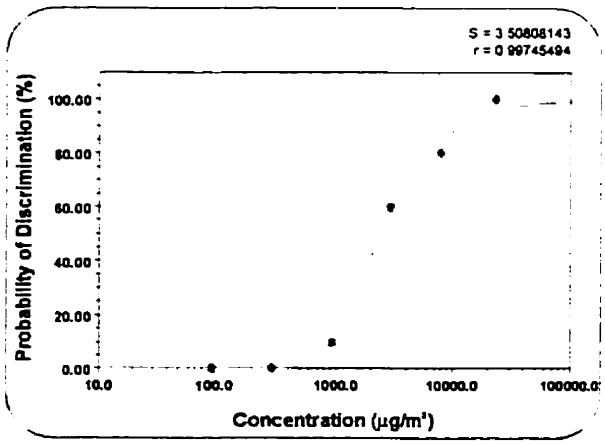
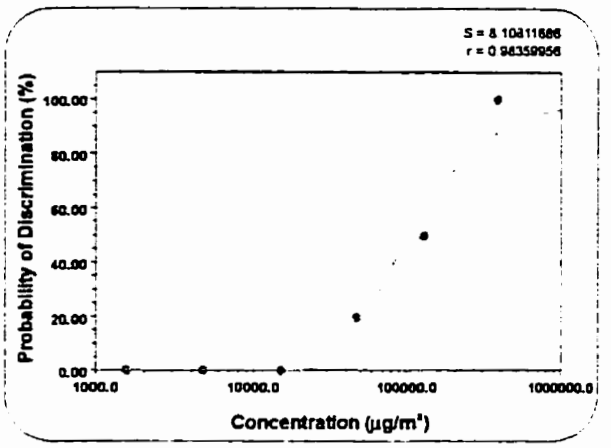
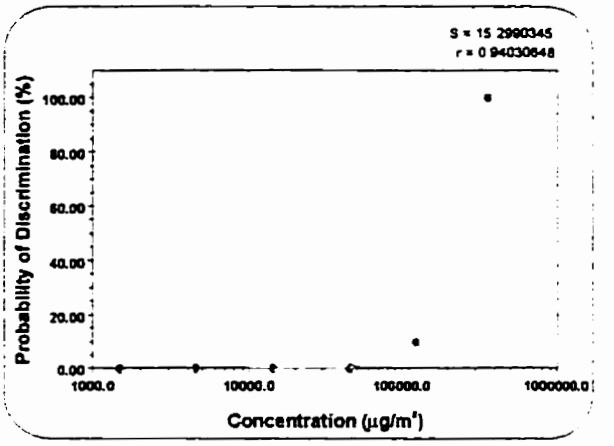


Fig. B11: Octane - Panel Probability of Discrimination

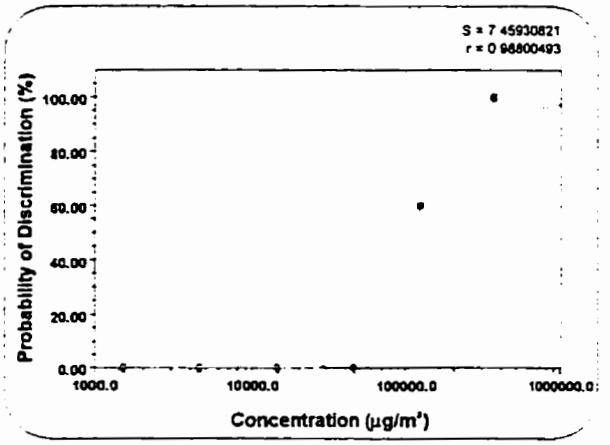
Panel No. 1:



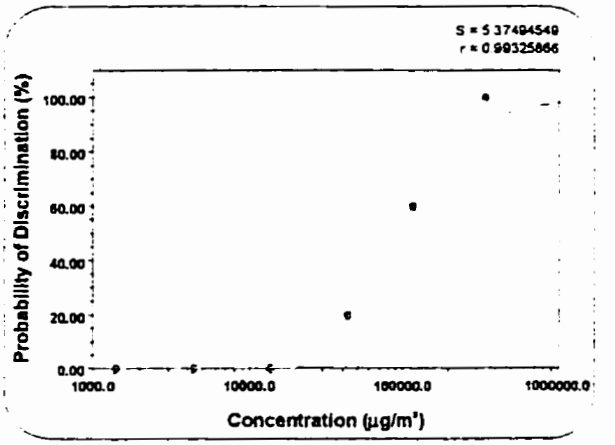
Panel No. 2:



Panel No. 3:



Panel No. 4:



Panel No. 5:

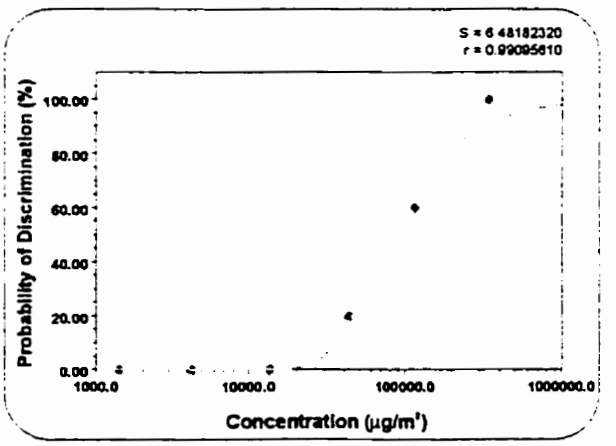
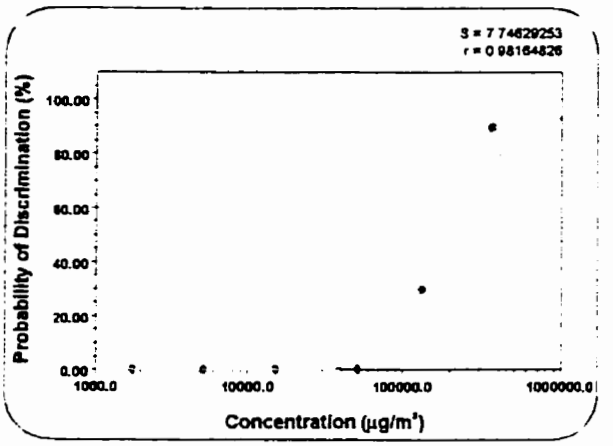


Fig. B11 (cont.): Octane - Panel Probability of Discrimination

Panel No. 6:



Panel No. 7:

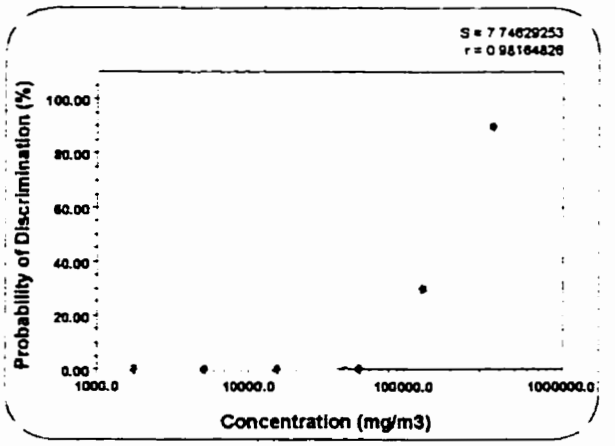
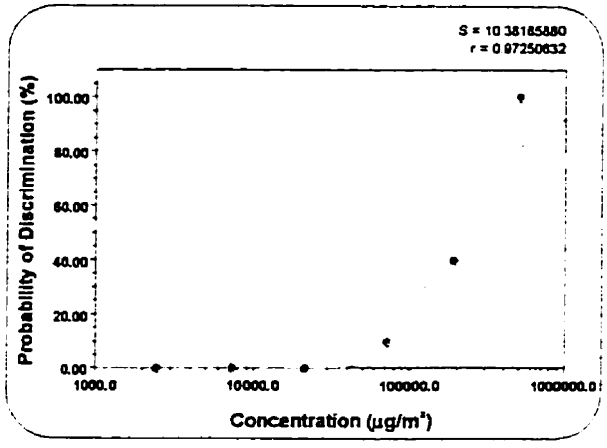
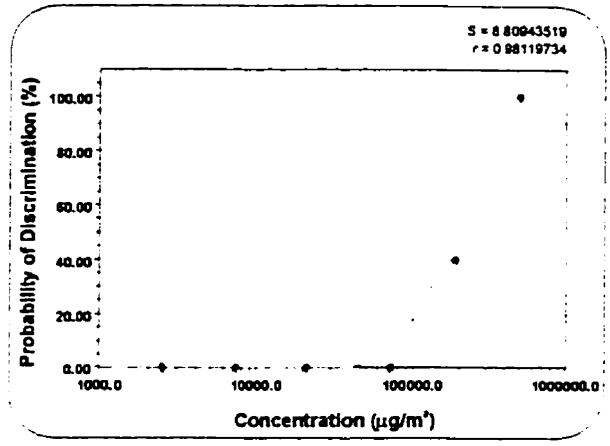


Fig. B12: Propylene Glycol Monomethyl Ether - Panel Probability of Discrimination

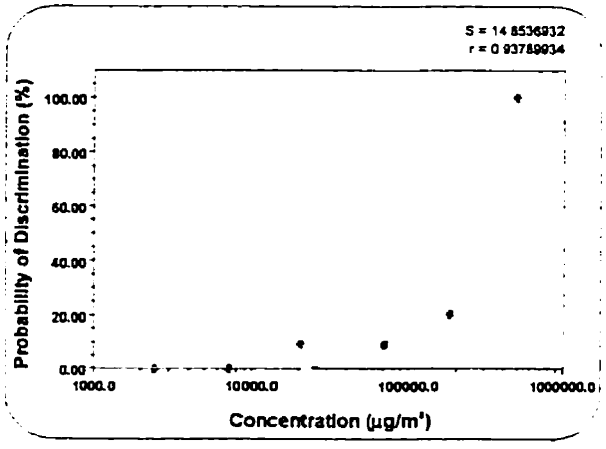
Panel No. 1:



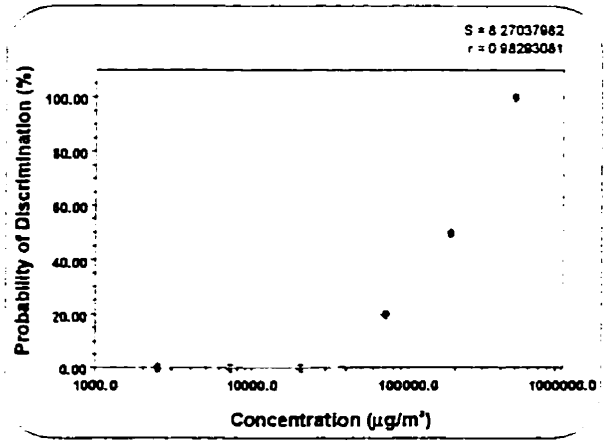
Panel No. 2:



Panel No. 3:



Panel No. 4:



Panel No. 5:

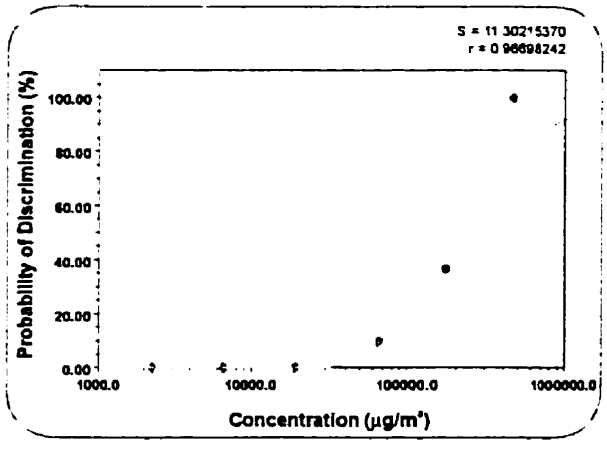
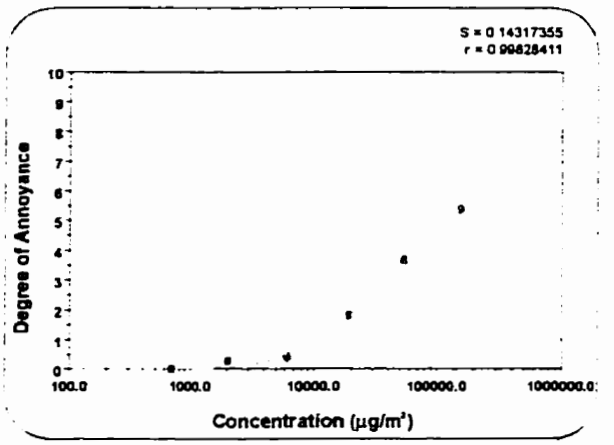
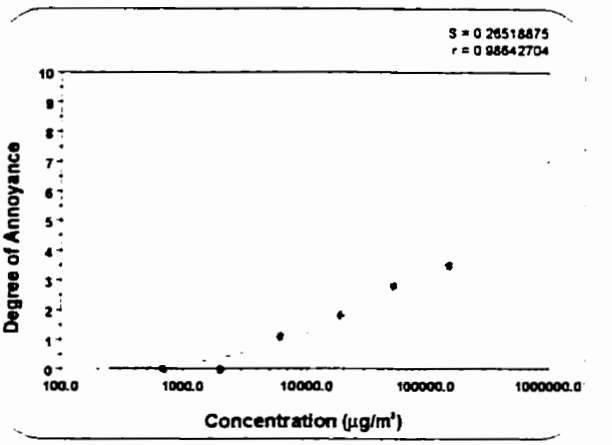


Fig. B13: n-Butanol - Panel Degree of Annoyance

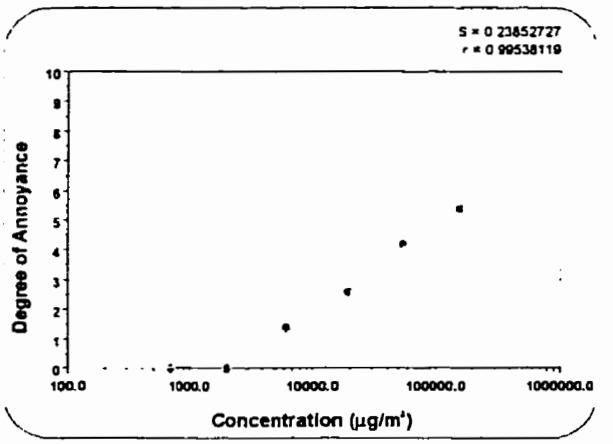
Panel No. 1:



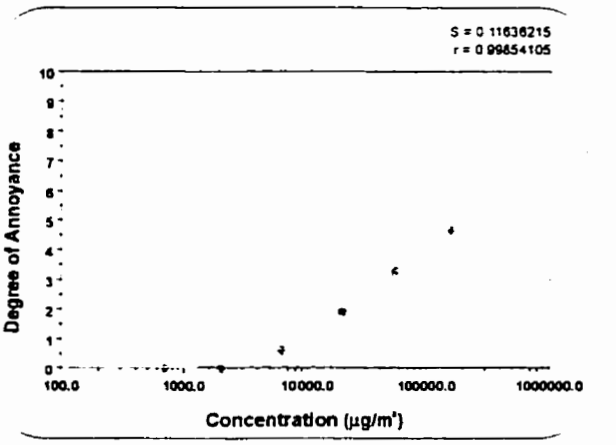
Panel No. 2:



Panel No. 3:



Panel No. 4:



Panel No. 5:

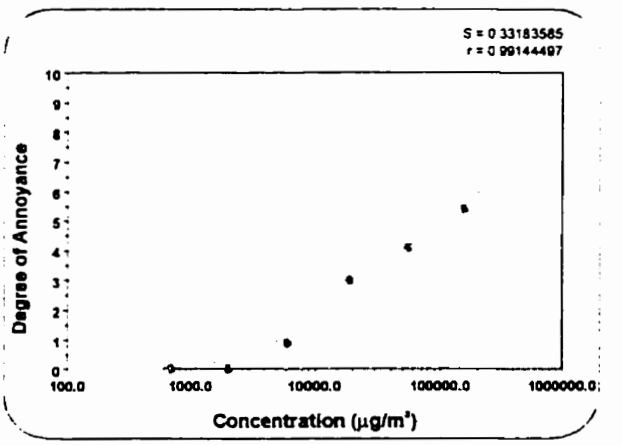
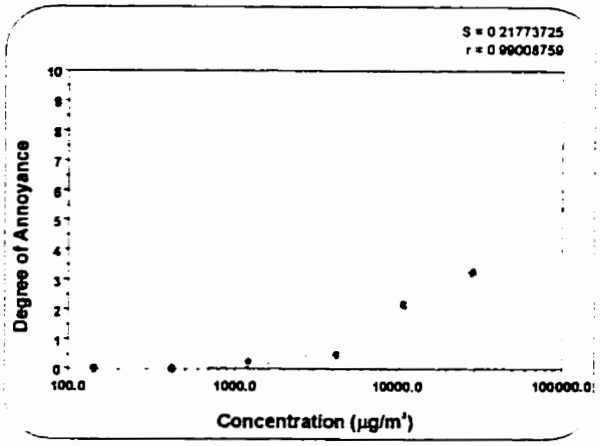
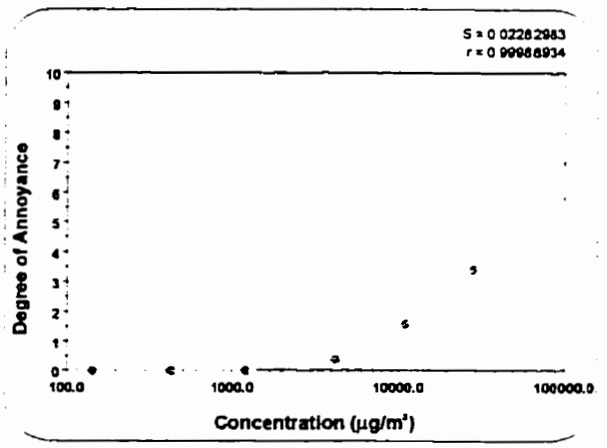


Fig. B14: n-Butyl Acetate - Panel Degree of Annoyance

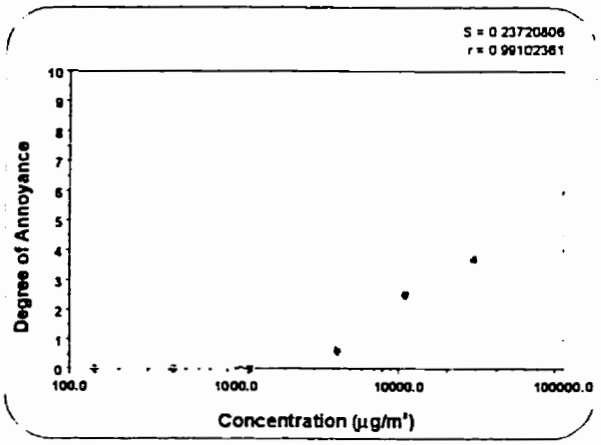
Panel No. 1:



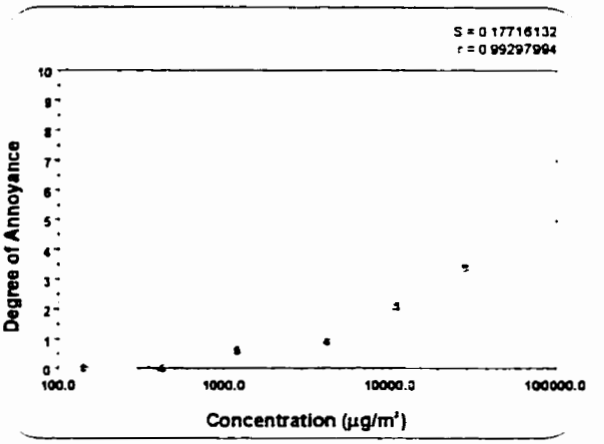
Panel No. 2:



Panel No. 3:



Panel No. 4:



Panel No. 5:

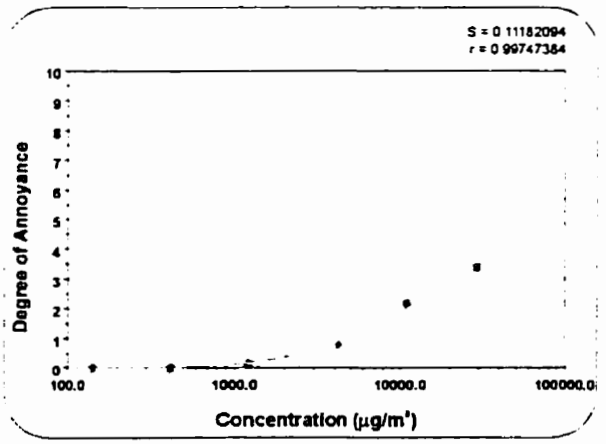
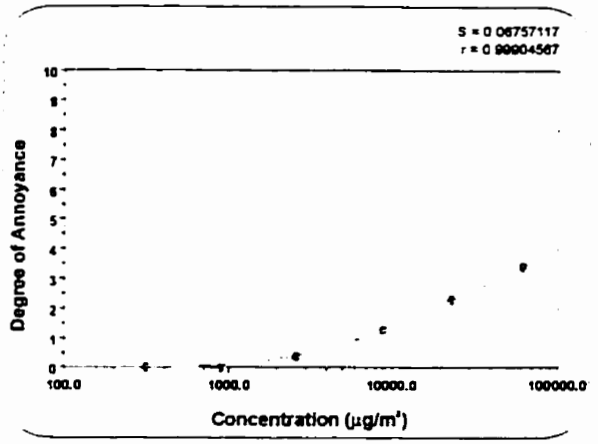
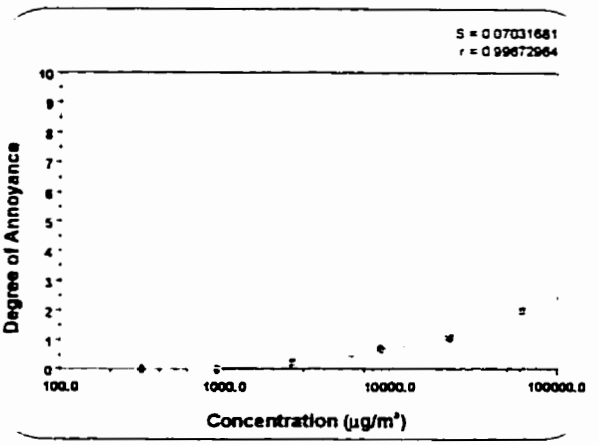


Fig. B15: Isobutanol - Panel Degree of Annoyance

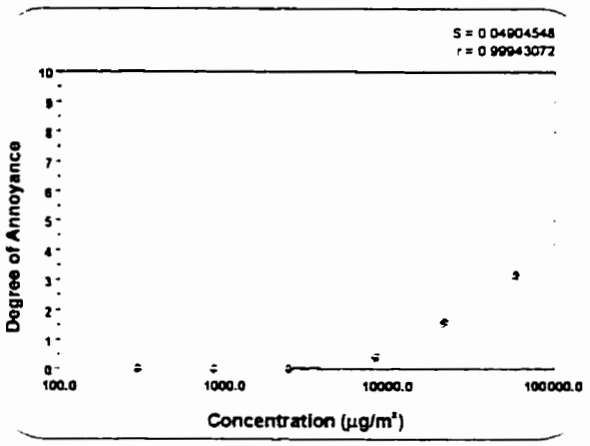
Panel No. 1:



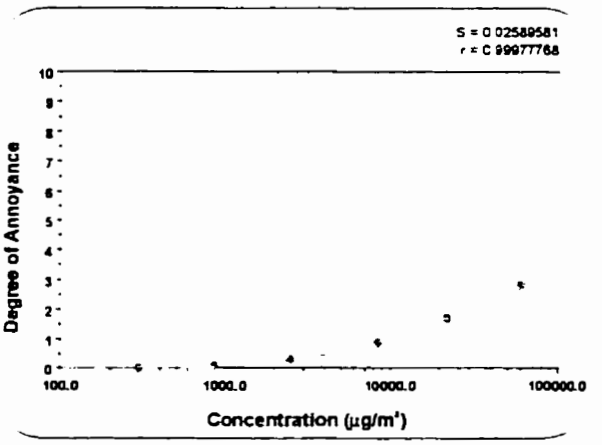
Panel No. 2:



Panel No. 3:



Panel No. 4:



Panel No. 5:

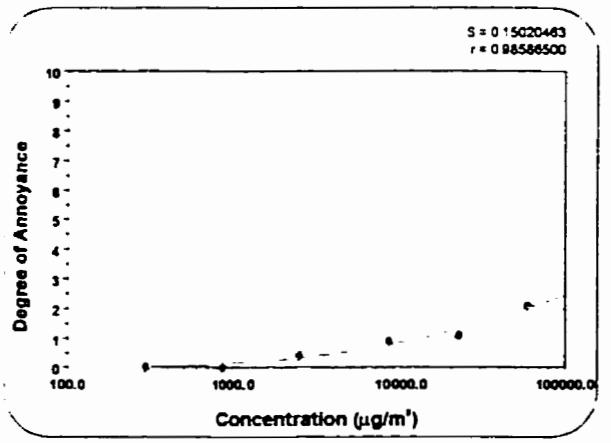
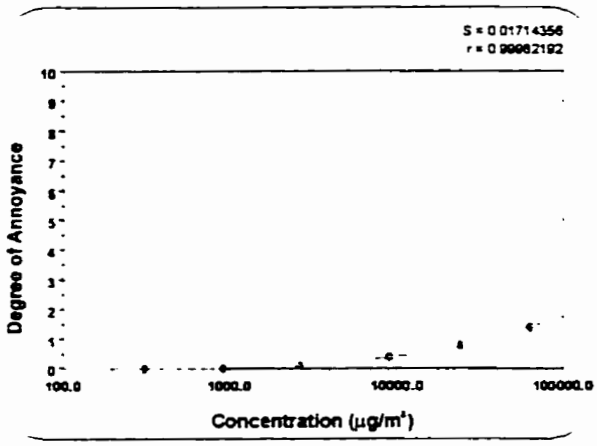


Fig. B15 (cont.): Isobutanol - Panel Degree of Annoyance

Panel No. 6:



Panel No. 7:

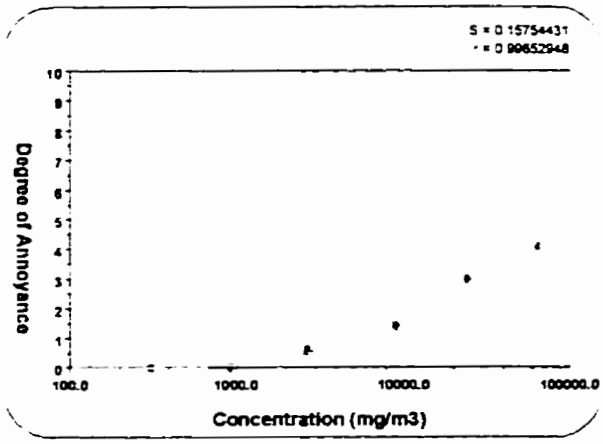
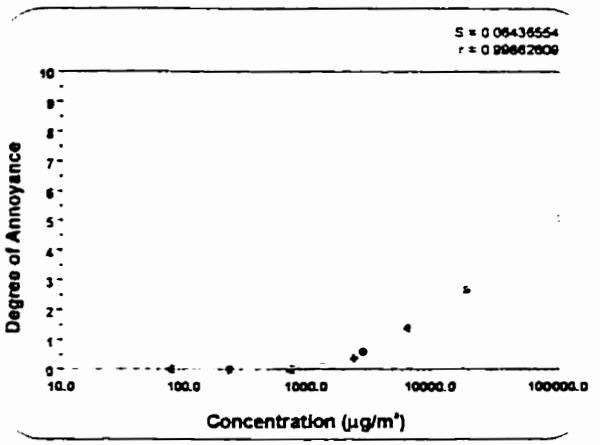
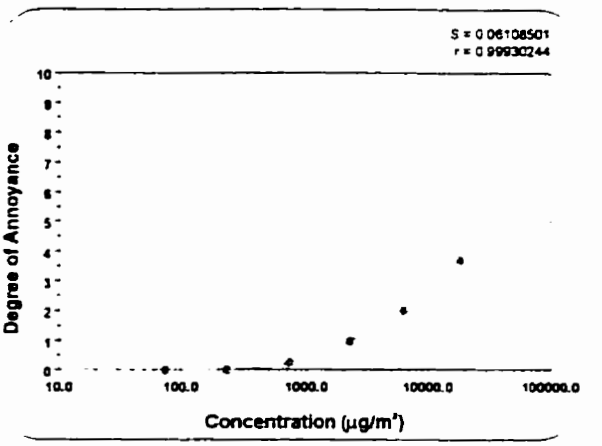


Fig. B16: Methyl Isoamylketone - Panel Degree of Annoyance

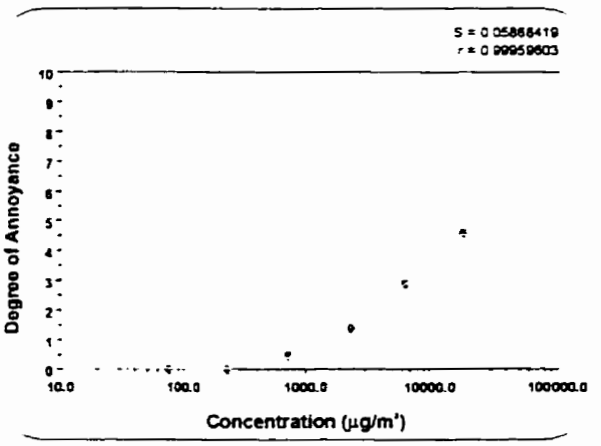
Panel No. 1:



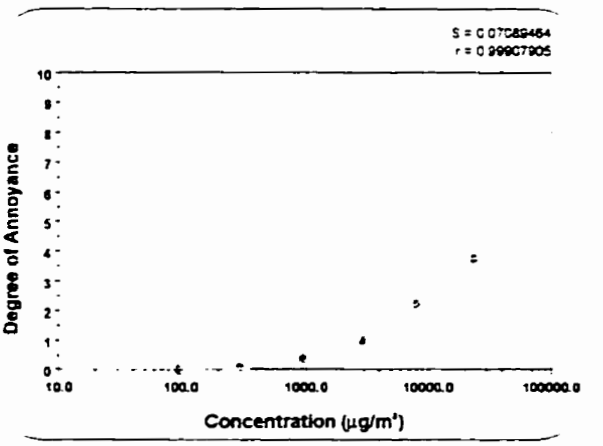
Panel No. 2:



Panel No. 3:



Panel No. 4:



Panel No. 5:

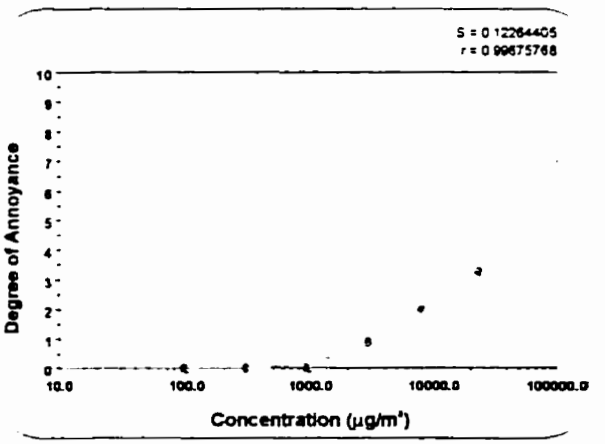
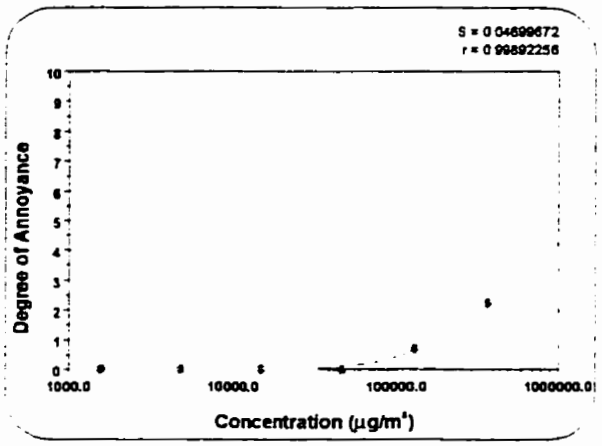
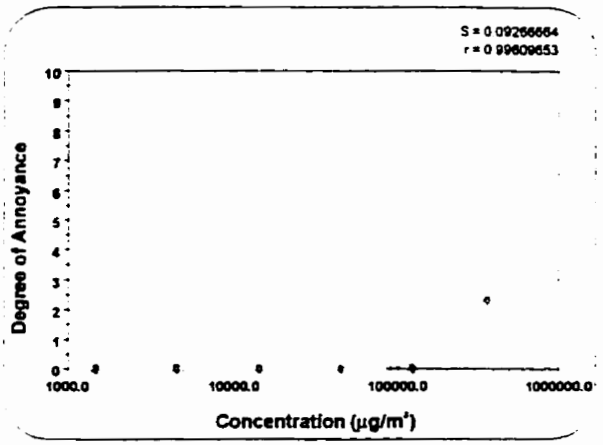


Fig. B17: Octane - Panel Degree of Annoyance

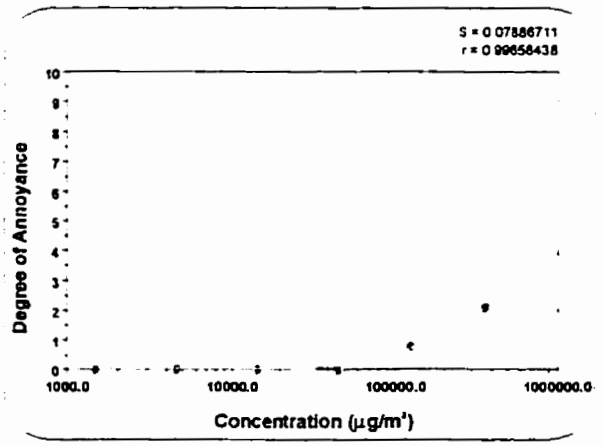
Panel No. 1:



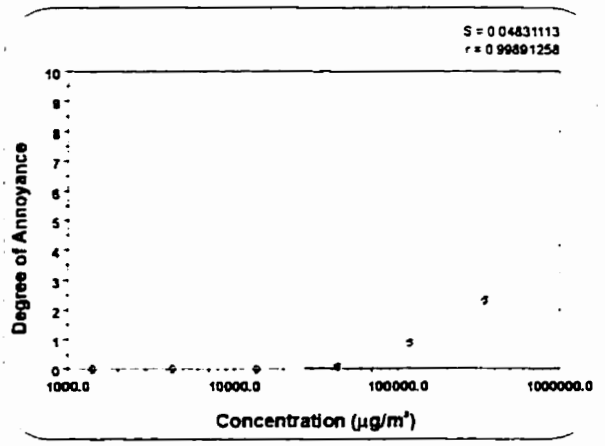
Panel No. 2:



Panel No. 3:



Panel No. 4:



Panel No. 5:

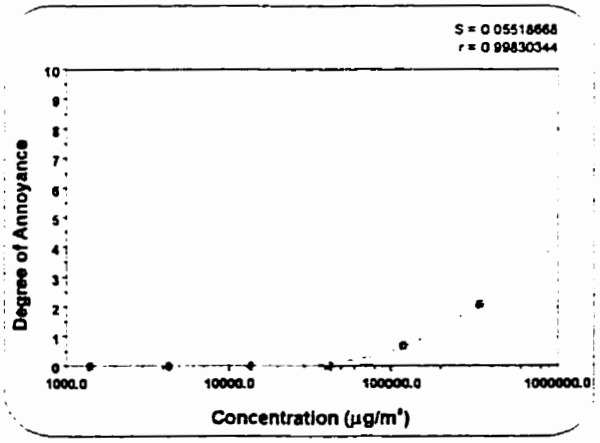
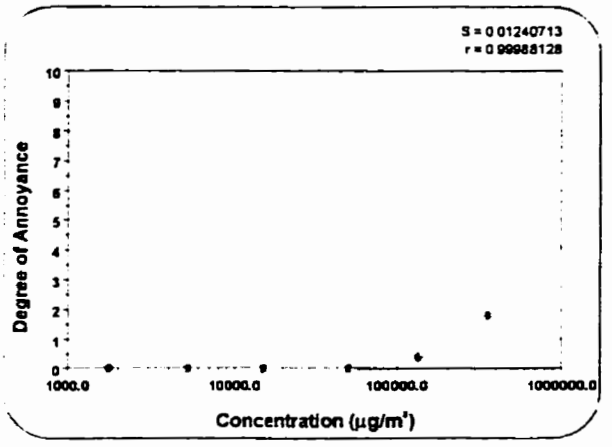


Fig. B17 (cont.): Octane - Panel Degree of Annoyance

Panel No. 6:



Panel No. 7:

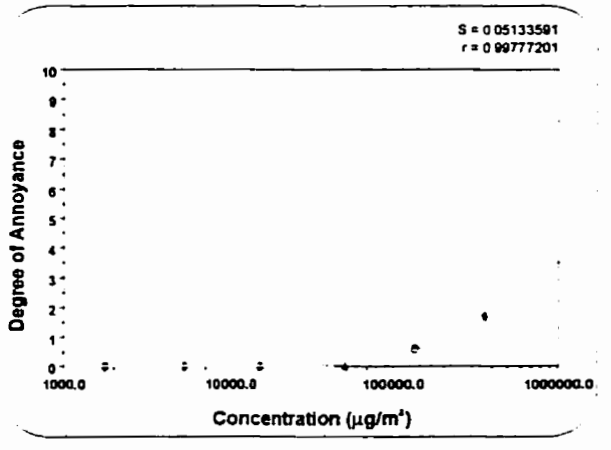
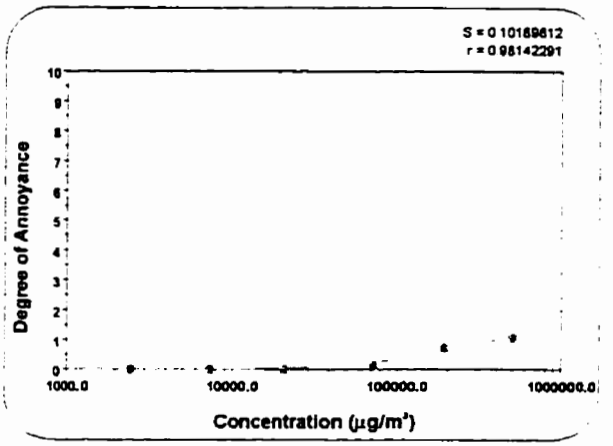
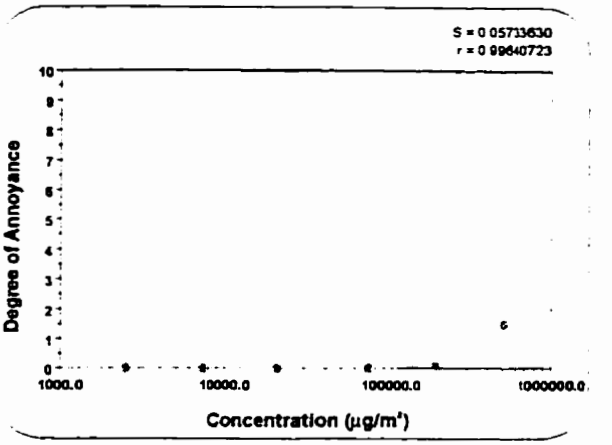


Fig. B18: Propylene Glycol Monomethyl Ether - Panel Degree of Annoyance

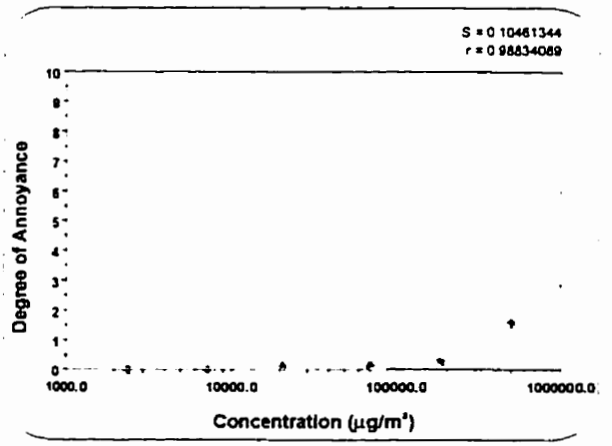
Panel No. 1:



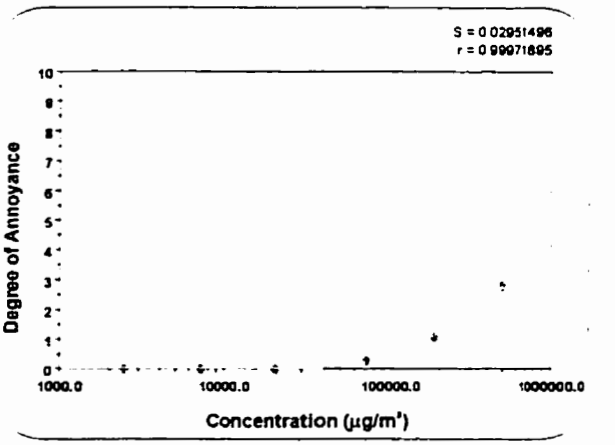
Panel No. 2:



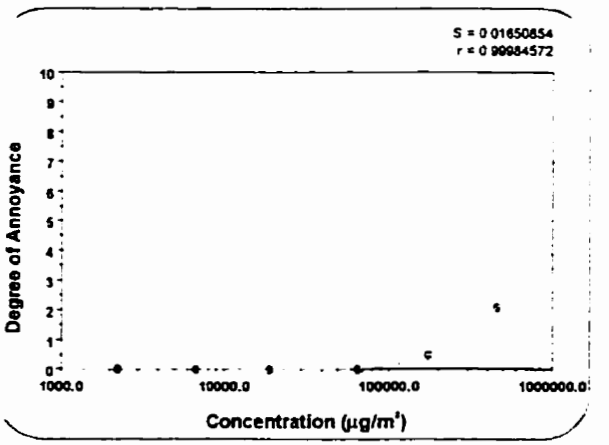
Panel No. 3:



Panel No. 4:



Panel No. 5:



Appendix C:

OIDM Case Study

Table C1: Stacks No. 2A and 2B - OIM Data

Stack Name	Dilution	Probability of Detection (%)	Probability of Discrimination (%)	Degree of Annoyance
Stack No. 2A	7	100	100	6.9
	18	100	90	5.3
	50	100	70	2.6
	170	70	50	1.1
	500	40	30	0.5
	1200	10	0	0
Stack No. 2B	7	100	100	7.5
	18	100	100	5.1
	50	80	70	2.2
	170	50	30	0.3
	500	10	0	0
	1200	0	0	0

Table C2: Normalized Stack No. 2 - OIM Data

Dilution	Probability of Detection (%)	Probability of Discrimination (%)	Degree of Annoyance
7	100	100	6.9
12	100	100	7.5
18	100	90	5.3
30	100	100	5.1
50	100	70	2.6
90	80	70	2.2
170	70	50	1.1
300	50	30	0.3
500	40	30	0.5
870	10	0	0
1200	10	0	0
2100	0	0	0

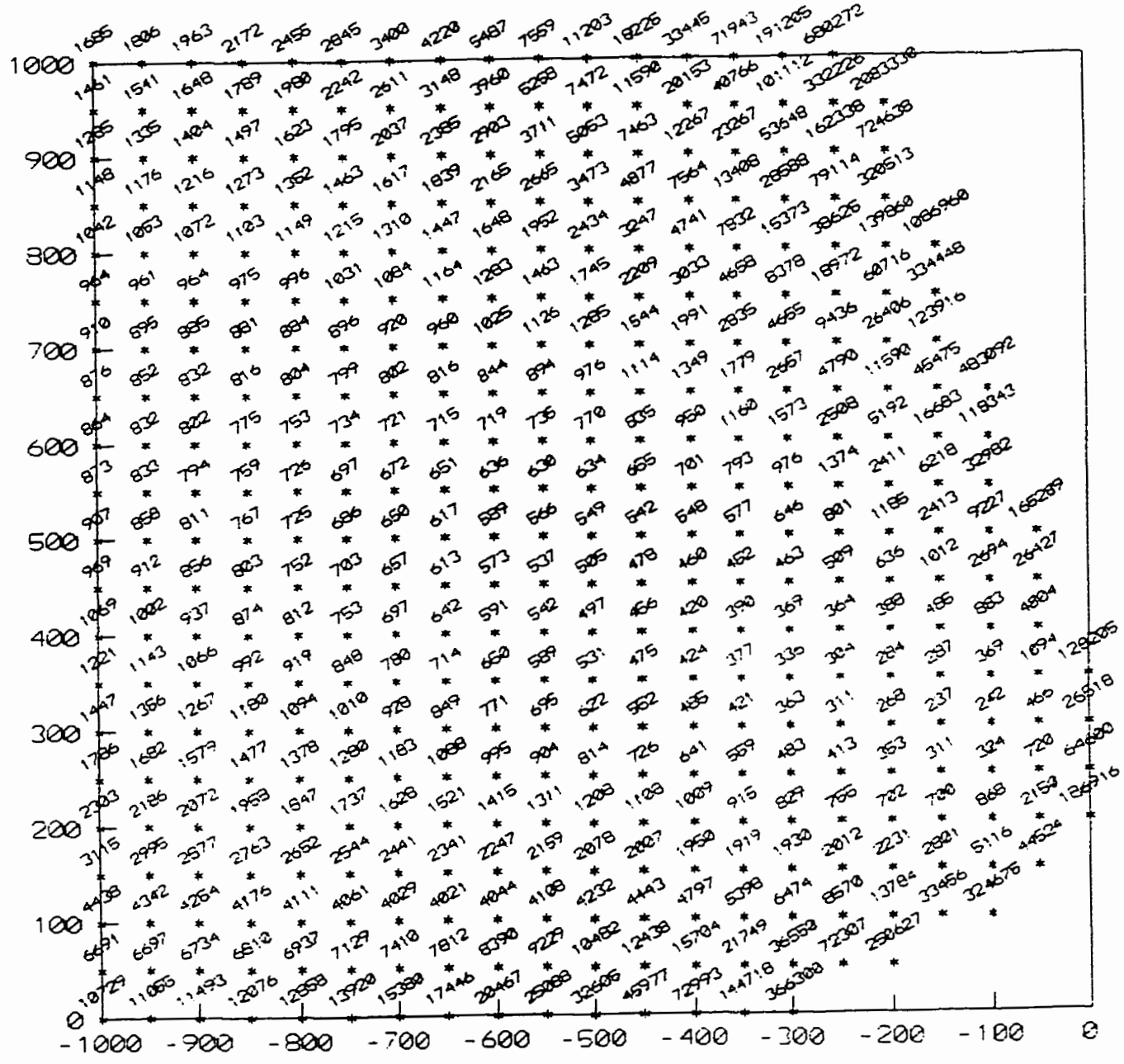


Fig. C1: Source No. 2 Downwind Dilutions Grid - 1 hour

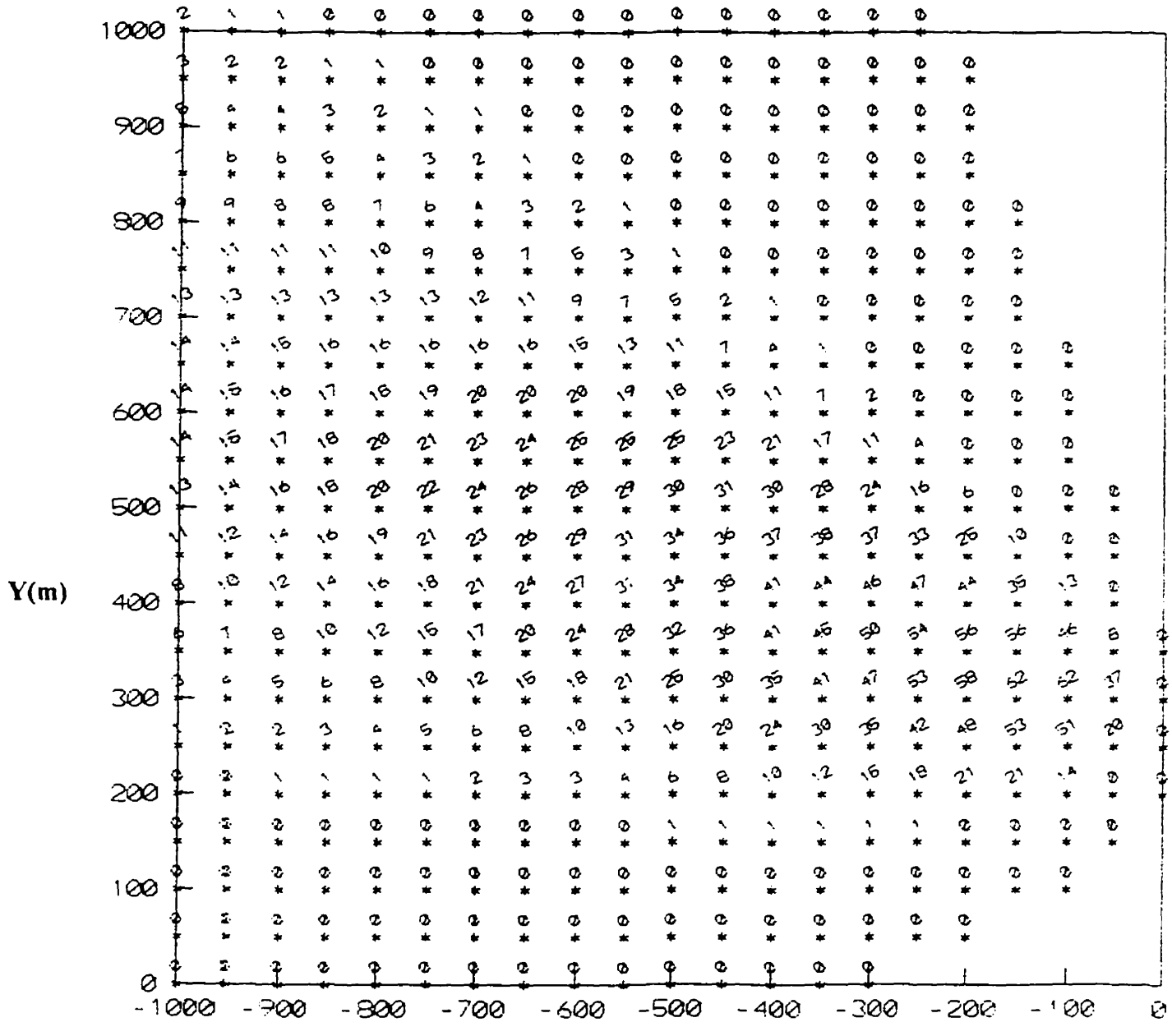


Fig. C2: Source No. 2 Probability of Detection Grid - 1 hour

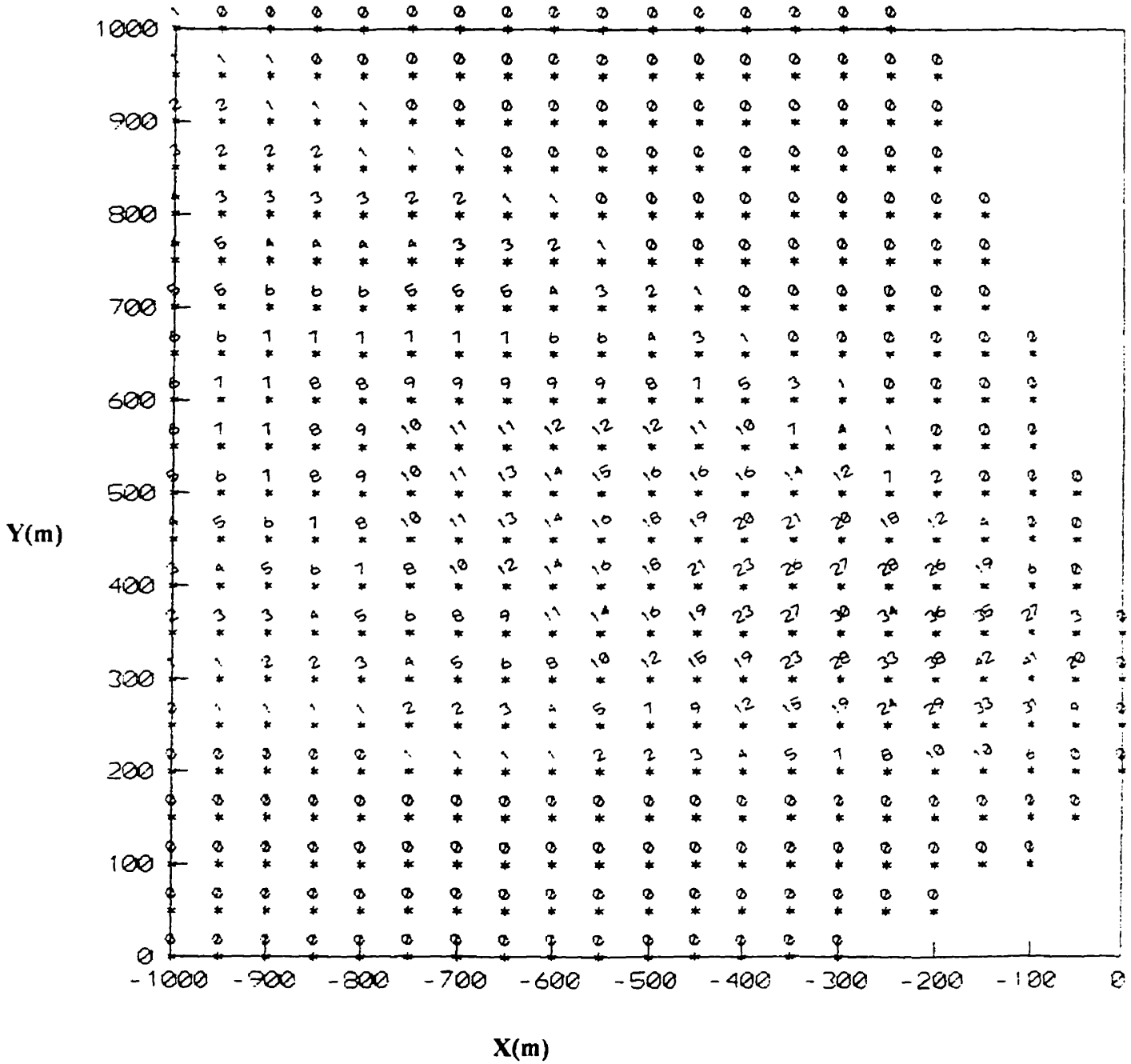


Fig. C3: Source No. 2 Probability of Discrimination Grid - 1 hour

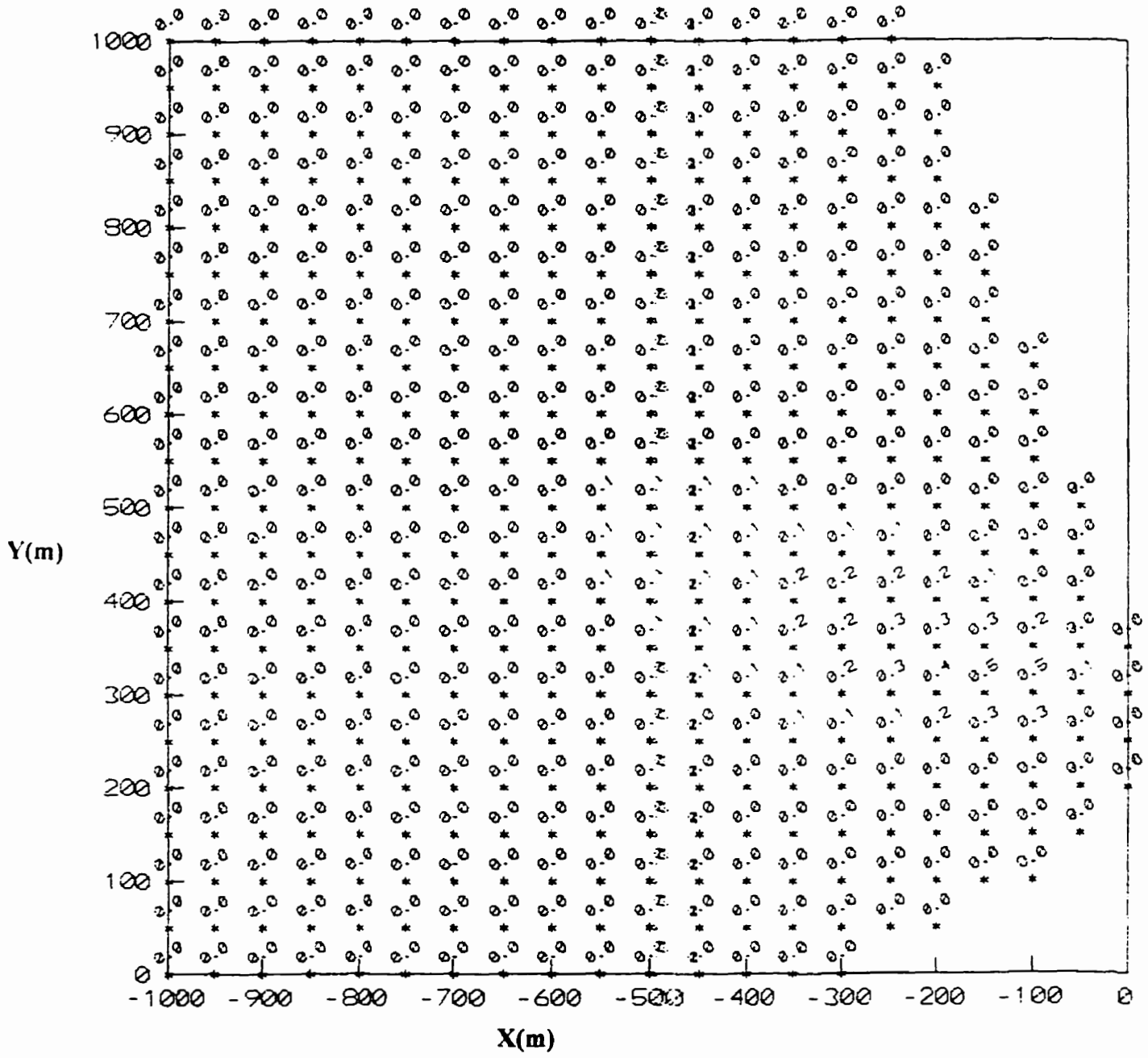


Fig. C4: Source No. 2 Degree of Annoyance Grid - 1 hour

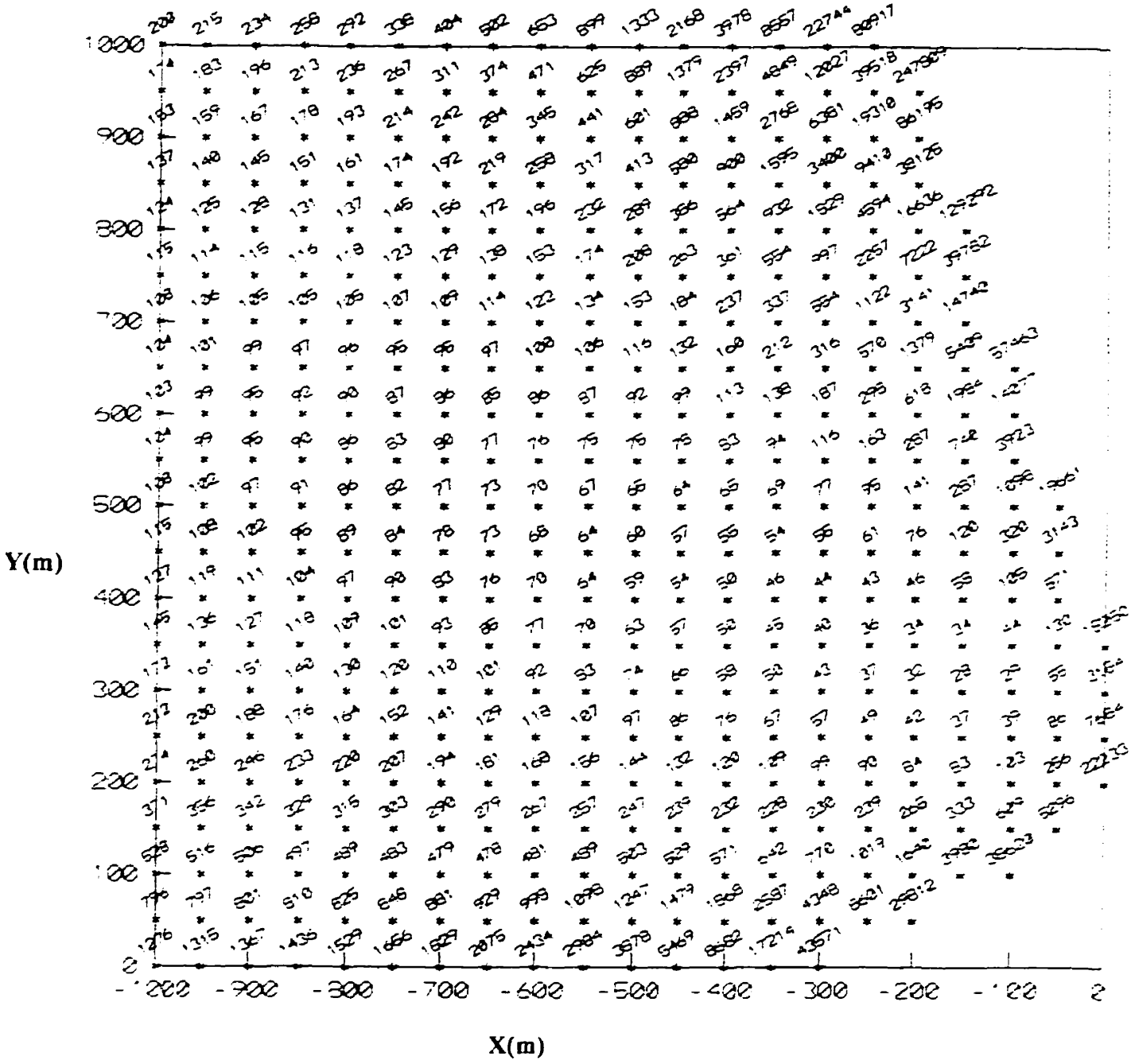


Fig. C5: Source No. 2 Downwind Dilutions Grid - 1 minute

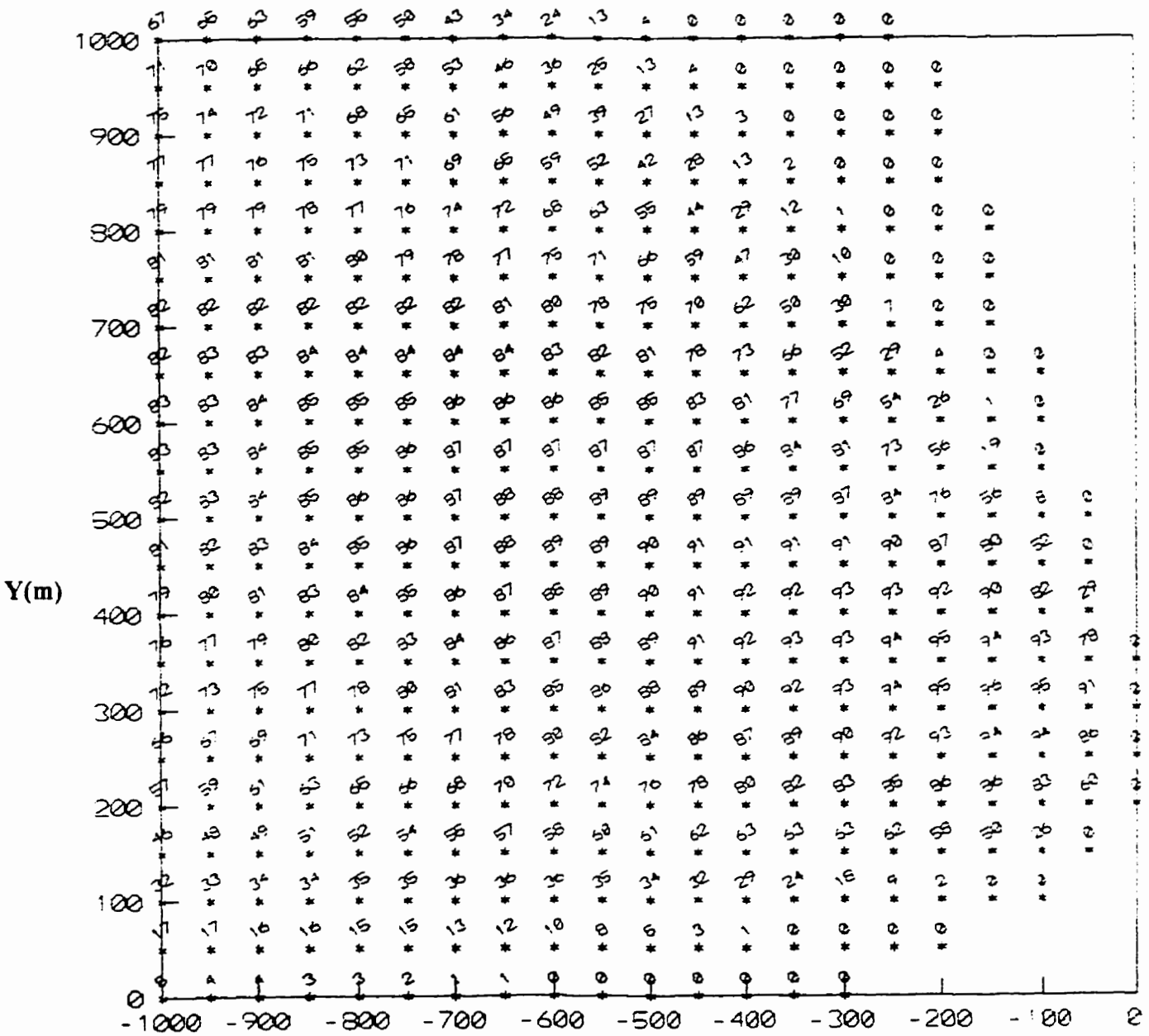


Fig. C6: Source No. 2 Probability of Detection Grid - 1 minute

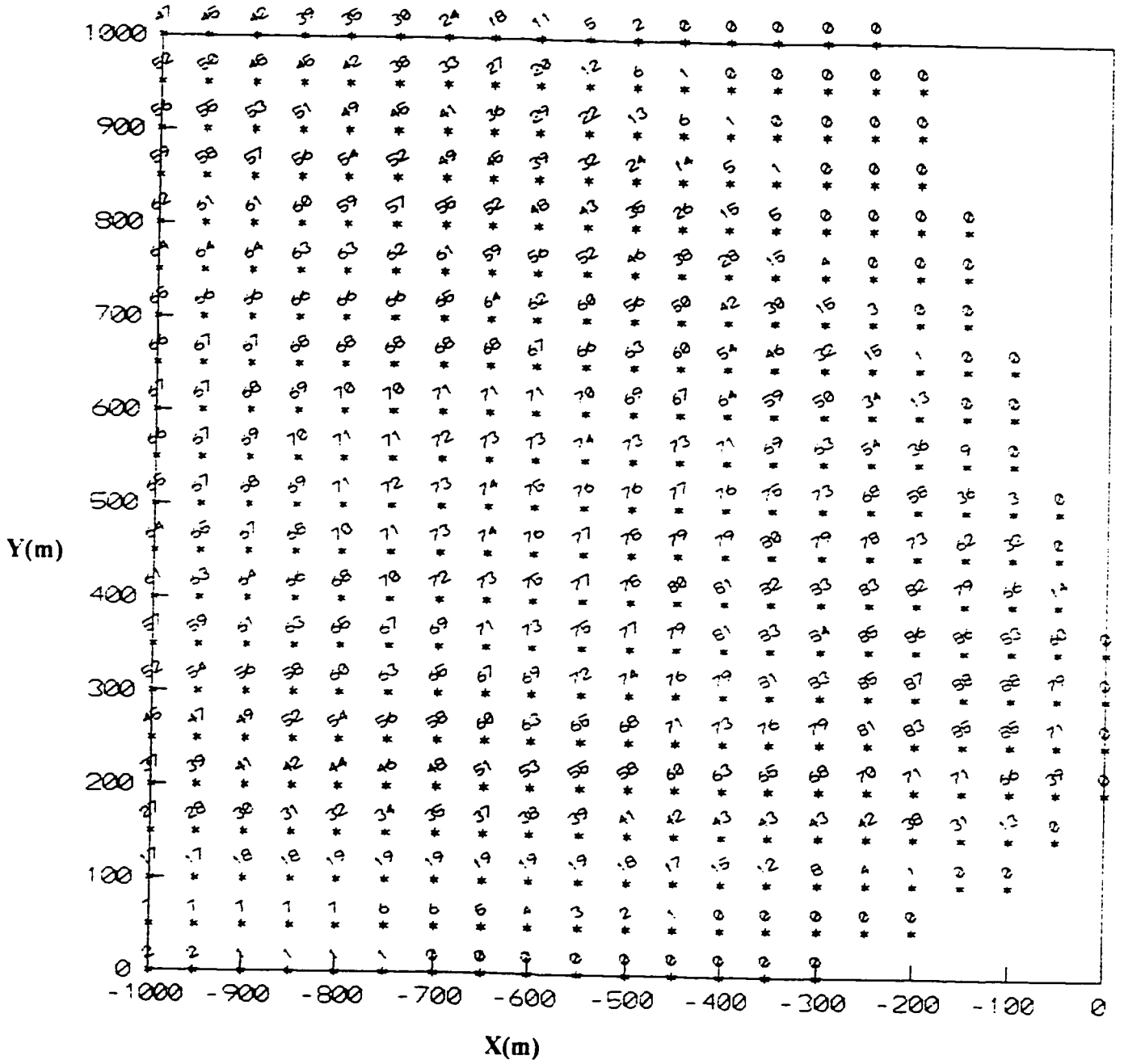


Fig. C7: Source No. 2 Probability of Discrimination Grid - 1 minute

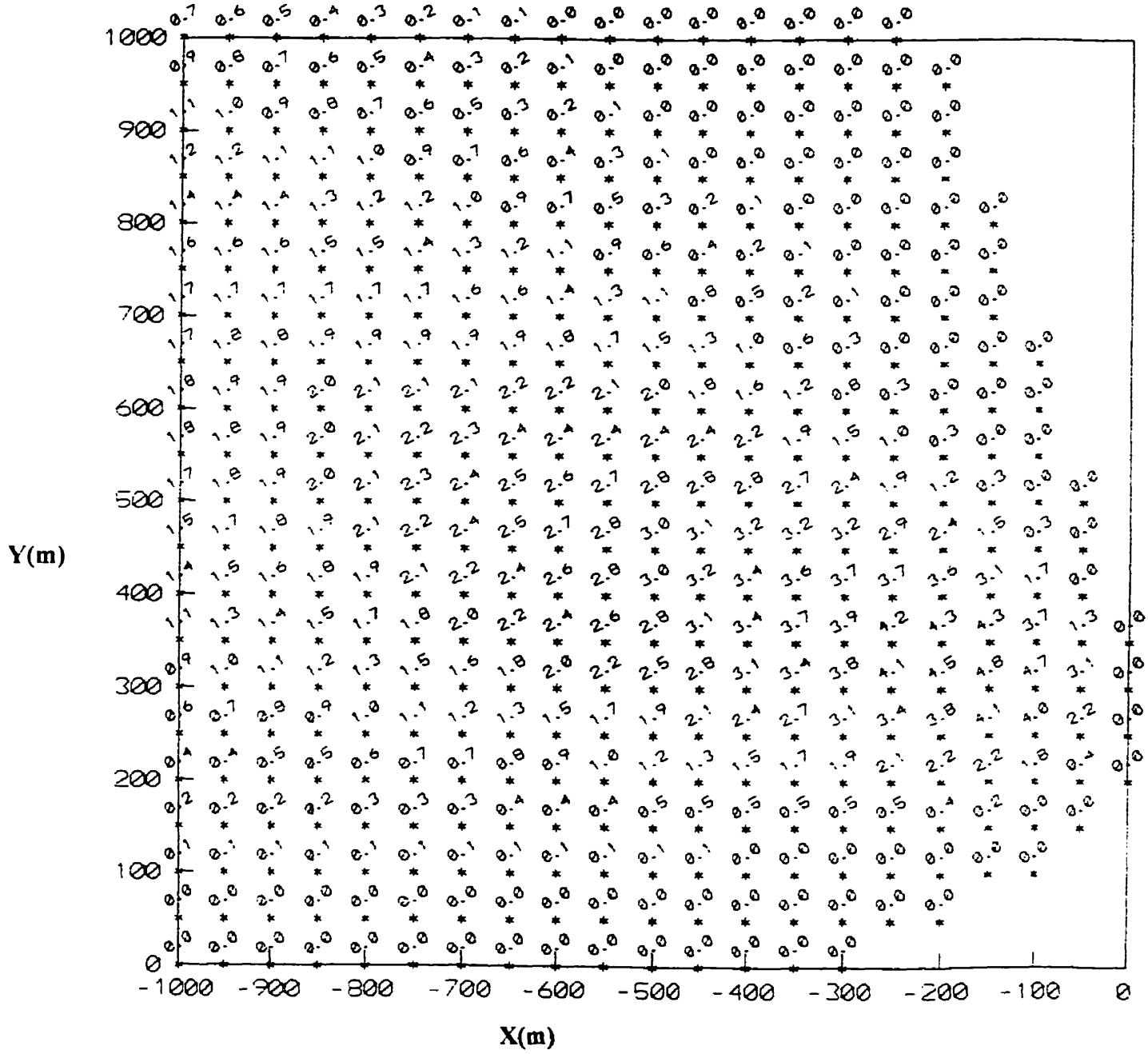
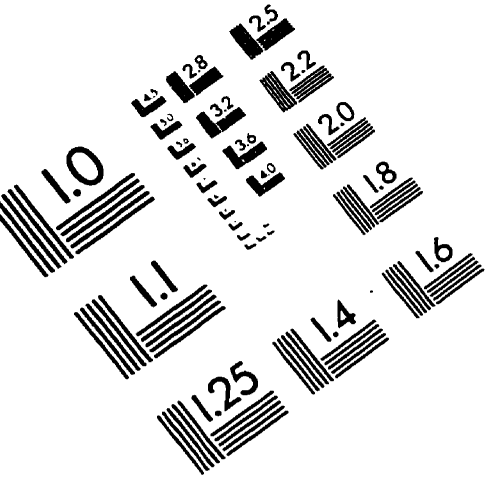
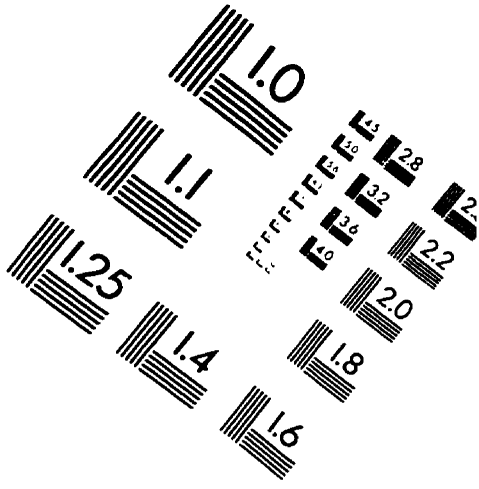
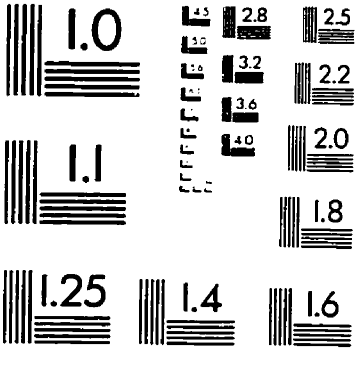


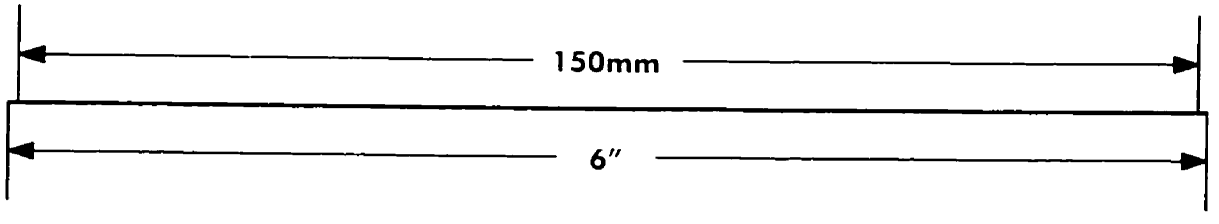
Fig. C8: Source No. 2 Degree of Annoyance Grid - 1 minute

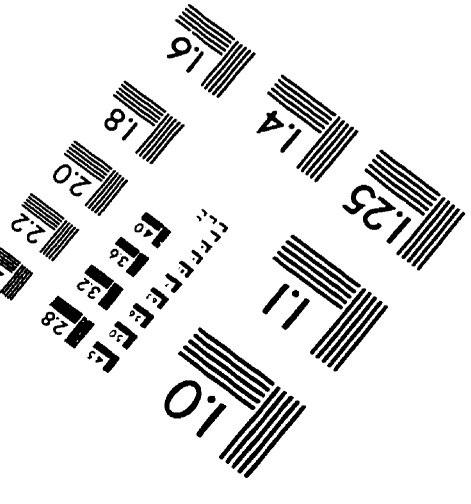
IMAGE EVALUATION TEST TARGET (QA-3)

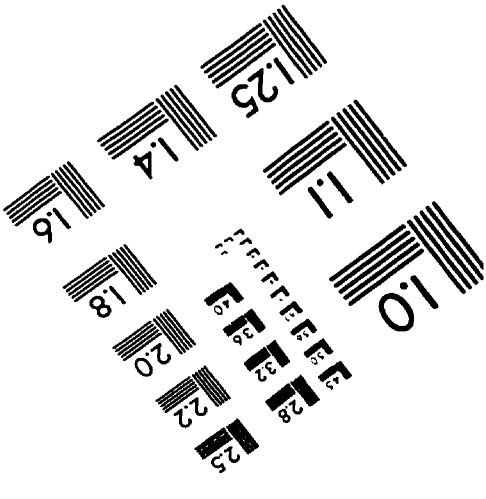












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