the propagation of noise from petroleum and petrochemical complexes to neighbouring communities

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PART I

A. FOREWORD

In situations where limits are imposed on noise levels in communities near petroleum and petrochemical plant, it is often necessary to calculate environmental noise levels because no direct measurements are possible. Such calculations require knowledge of the sound power levels of the noise sources and of the propagation of sound from the plant to the surroundings.

CONCAWE has already published several reports relating to the determination of sound power levels in the field. The current report gives the results of a more recent study initiated by CONCAWE on the subject of noise propagation.

This latest study was considered necessary since theoretical models have in the past often appeared to be contradictory, and field measurements have been scarce. An outline for the study was defined by a CONCAWE Special Task Force on Noise Propagation, and the work was carried out under contract by Acoustic Technology Ltd., of Southampton, UK, under guidance from the Special Task Force.

The major part of this report briefly describes the various stages of the study and includes a detailed description of the sound propagation model which emerged. More detailed background information may be obtained from two supplementary documents:

- "The Propagation of Noise from Petroleum and Petrochemical Complexes to Neighbouring Communities", AT. 674, Acoustic Technology, November 1977 (Ref. 1) - an interim report on the propagation study which included a literature survey and a review of knowledge on the propagation of sound close to the ground.

- "The Propagation of Noise from Petroleum and Petrochemical Complexes to Neighbouring Communities - Supplementary Data", AT. 931, Acoustic Technology, June 1980 (Ref. 2) - a data report detailing sound power level of all sources considered in the experimental stage of the study, and a summary of the readings of sound pressure levels in the surroundings of the three sites investigated (see Section 3).

The sound propagation models proposed in Sections 5 and 6 are the best interpretation of available data that could be obtained within the study programme. Other interpretations may also be possible.

The report as a whole highlights important factors concerning ground effects, the influence of weather, and the statistical significance of predicted sound levels.

Data with respect to barrier effects, effects of source height, and in-plant screening is more limited, and further work is needed on these aspects.

The report should be regarded as the result of a research study in which CONCAWE has endeavoured to promote a more general understanding of the variability of noise levels. The noise propagation model as such should not be regarded as the final word by CONCAWE on noise propagation. This model is the most comprehensive of its kind and the first in which the supporting data and statistical tests have been made available. It will be subject to improvement as more experience becomes available.

B. SUMMARY OF RESULTS

Literature data, together with new field data were collected over a period of approximately four years. The field data were obtained from points in the neighbourhood of three separate installations operated by companies participating in CONCAWE. The bulk of the current report is devoted to the description of the model on sound propagation which emerged from the study. Separate attenuation curves have been established for six categories of weather conditions, for each of the usual octave bands. This makes it possible to calculate the long term equivalent and percentile levels of community noise due to a particular plant on the basis of the climatic data as normally collected by most meteorological offices (see Section 5).

In addition to the comprehensive model, various simplified models have been derived from the results of the study (see Section 6).

Confidence intervals have been estimated for the predictions of all models through the application of statistical analysis. The new model is statistically more accurate, and it enables predictions for a range of conditions for which no current technique is available.

Finally, two existing sound propagation models in general use, developed by the Oil Company Materials Association (OCMA) and Verein Deutscher Ingenieure (VDI), have been compared with the field data obtained in this study. The results of this comparison indicate that the new procedure described in this report predicts more accurately than the OCMA or VDI models for the specific sites studied (see Section 7).

Some guidance on the application of the noise propagation model is given in Appendix III.

Notes:

(1) Part II of this report, which has been prepared for CONCAWE by Acoustic Technology Ltd., describes the result of research work. Its text may not be suitable for references in contractual documents.

(2) CONCAWE will be interested to learn of readers' experiences in using the propagation model.

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PART II

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1. INTRODUCTION

Acoustic Technology Limited was contracted by CONCAWE to undertake an investigation into the propagation of sound from petroleum and petrochemical complexes to neighbouring communities.

The areas studied comprise the basic concepts of attenuation by the mechanisms of geometrical spreading, atmospheric absorption, ground effects, meteorological conditions, barriers and in-plant screening.

The initial stage (Phase 1) of the study involved a literature survey and review of the current state of theoretical and experimental knowledge on the propagation of sound over long distances, close to the ground (Ref. 1). The validity and relevance of the information obtained in this investigation has been assessed and used to prepare an engineering procedure for the prediction of community noise levels from an industrial complex for a wide range of meteorological conditions. This model is summarised in Section 2.

The next stage (Phase 2) of the investigation consisted of an experimental programme designed to test the accuracy of the prediction technique developed from the initial survey. This comprised measurement of the noise levels under defined meteorological conditions around three typical petrochemical complexes and comparing these with predicted levels, (see Section 3). Investigation of the fit of the prediction model to the experimental data led to improvements and refinement of the model (see Sections 4 and 5). In addition a number of simplified versions of the prediction model were formulated and tested to investigate their relative accuracy compared to the refined prediction model and other prediction techniques currently in use (see Sections 6 and 7).

A mathematical model has thus been developed to predict community noise levels from petrochemical and similar plant for a range of meteorological conditions. This provides a method for establishing the environmental impact of new plant or the expansion of existing plant at the design stage, enabling the most cost effective solution to excessive acoustic emission to be developed.

A full description of the mathematical model, with the derivation and details of the experimental study for its confirmation, together with examples of its uses are given in this report. The various simplified versions of the model investigated are also described, and calculated confidence limits given for all models. Tables of the sound power levels of the major noise sources at each site and tables of the community noise levels measured at the three test sites, together with the predictions, are reported separately (Ref. 2).

A description of the statistical analysis of the models is given in Appendix I.

The symbols used in the report (excluding the notation used in the statistical formulae of Appendix I) are listed below:

A,B,C	Pasquill stability category (see Table on page 20), or one of the sites used in the experimental programme (the difference is clear in the context)
D	Pasquill stability category (see Table on page 20), or directivity index, dB (the difference in clear in the context)
d	source - receiver distance, m
h_s	source height, m
h_r	receiver height, m
K_i	attenuation factor, dB (i = 1-7)
K_1	attenuation factor for geometrical spreading
K_2	attenuation factor for atmospheric absorption
K_3	attenuation factor for ground effects
K_4	attenuation factor for meteorological effects
K_5	attenuation factor for source height effects
K_6	attenuation factor for barrier effects
K_7	attenuation factor for in-plant screening
L_p	sound pressure level re 20 microPascal
L_W	sound power level re 1 picoWatt
L_i	predicted noise level for meteorological category i (i = 1-6 or 1-Ill)
N	Fresnel number (see Section 5.1.6)
S	surface area, m^2
t_i	percentage of occurrence of meteorological catetory i (i = 1-6 or I-III)
v	vector wind speed, m/s (that is the component of the wind blowing from the source to the receiver)
γ	source and receiver height parameter (see Section 5.1.5)
ψ	grazing angle of sound "ray" reflected at the ground

2. DERIVATION OF THE MATHEMATICAL MODEL

2.1 GENERAL

The sound pressure level received at a point remote from the noise source is a function of the acoustic power of the source and the various mechanisms of attenuation. It is possible to separate the dominant factors affecting the attenuation of sound and examine the contribution of each individually.

In the literature survey (Ref. 1) it was concluded that the major attenuation mechanisms could be defined as:-

i) geometrical spreading;
ii) atmospheric absorption;
iii) ground effects;
iv) meteorological effects;
v) barriers;
vi) in-plant screening.

Thus, in a simplified form the sound pressure level at a remote point can be related to the source sound power level by the expression:

$$L_p = L_W + D - \Sigma K \qquad \text{(dB)}$$

where L_p is the sound-pressure level (dB re 20 μPa)
L_W is the sound-power level (dB re 10^{-12}W)
D is the directivity index of the source in dB and
ΣK is the sum of the losses defined above.

2.2 GEOMETRICAL SPREADING (K_1)

It is well established that the attenuation due to geometrical spreading of the sound power from a point source is given by the relationship

$$K_1 = 10 \log 4\pi d^2 \text{ dB}$$

where d is the source-receiver distance in metres.

This equation describes spherical spreading from a source and the effects of a reflective ground surface are allowed for subsequently in the calculated values for Ground Effects (K_3).

2.3 ATMOSPHERIC ABSORPTION (K_2)

The absorption of sound by the atmosphere may be considered to be due to four mechanisms, classical absorption (due to shear viscosity, thermal conductivity, mass diffusion and thermal diffusion within the medium), rotational absorption (caused by relaxation of the rotational energy of the molecules), and the vibrational relaxation of the oxygen and nitrogen molecules in the air. The recommendations of the American National Standard, "Method for the Calculation of the Absorption of Sound by the Atmosphere" (Ref. 3) were adopted in this study.

2.4 GROUND EFFECTS (K_3)

Two basic correction factors for the presence of the ground (K_3) have been adopted. For an acoustically hard surface (e.g. water, concrete) the correction is simply -3 dB for all frequency bands and distances, which provides for hemispherical radiation from the source.

The situation is more complex for a ground with finite acoustic impedance (e.g. grass covered soil) and an empirical relationship between ground attenuation, frequency and distance was adopted. An analysis of experimental data due to Parkin and Scholes (Refs. 4 and 5) provided a series of curves describing the variation of ground attenuation with distance for octave band frequencies in the range 63 Hz - 4 kHz (Ref. 1).

2.5 METEOROLOGICAL EFFECTS (K_4)

The refraction of sound by wind velocity and atmospheric temperature gradients has an important effect on the received sound-pressure level and, because large variations in meteorological conditions will be experienced, it is necessary, when developing an engineering technique, to simplify these effects. In the initial study an analysis of the experimental data of Parkin and Scholes (Refs. 4 and 5) showed that five "meteorological categories" could be defined based on the vector wind velocity and atmospheric temperature gradient. Correction curves to provide a value of K_4 were obtained by subtracting data recorded during neutral meteorological conditions (defined by zero vector wind and temperature gradient) from the data qualified by the other meteorological categories.

For acoustically hard surfaces a simpler relationship was defined, with K_4 =-3 dB for downwind propagation and, for upwind propagation, calculated from the method due to Delany (Ref. 6).

2.6 SOURCE HEIGHT EFFECTS (K_5)

Scholes and Parkin (Ref. 7), and Piercy, Embleton and Donato (Ref. 8) inter alia, have shown that the ground effect as given in Section 2.4 is subsequently modified by a function of the grazing angle of the ground-reflected ray received by an observer, which is, itself, a function of distance and the source and receiver heights. This is important close to a process plant, particularly when major sources, such as airfin coolers are elevated at heights of the order of 10 - 20m.

According to Piercy et al (Ref. 8) the ground effect decreases exponentially with an increase in grazing angle from 0^{o} to become zero at 5^{o}. The procedure in OCMA Specification NWG-1 (Ref. 9) advises a linear reduction in the ground effect to zero at a ratio of source height to source-receiver distance of 3:100, which for most practical purposes approximates to an angle of 2^{o}. In Phase 1 of the study it was decided to adopt, provisionally, the recommendation by Piercy et al., but investigate this factor as part of the experimental phase.

2.7 BARRIERS (K_6)

The calculation of the attenuation due to the presence of significant barriers may be calculated by the method of Maekawa (Ref. 10) modified, as appropriate, to account for wind and temperature gradients using the approach of De Jong and Stusnick (Ref. 11). The presence of a discrete barrier may reduce ground effects and it is proposed that this be covered by recalculating K_5 based on the barrier height and barrier-receiver distance.

2.8 IN-PLANT SCREENING (K_7)

The propagation of noise from a source surrounded by process plant will be influenced by adjacent equipment which can provide not only screening but also reflecting surfaces. The complexity of these localised effects makes a generalised theoretical prediction technique difficult and a paucity of conclusive experimental data did not allow a reliable empirical analysis to be deduced. A tentative method based on the conclusions of Judd and Dryden (Ref. 12) was proposed in the preliminary study, based on distance travelled through the plant and equipment density.

3. EXPERIMENTAL STUDY

3.1 INTRODUCTION

In order to validate the prediction method developed in Phase 1 of this investigation a series of measurements was undertaken at three European petrochemical process plants. To enable its general application to be studied the sizes of the plants varied from a small process area, through a medium sized oil refinery to a major petroleum and petrochemical complex. The terrain included flat and undulating land in both rural and residential areas. Sound measurements were undertaken in a variety of meteorological conditions during the night and also, where possible, during the day, at a height of 1.2 metres. The results of this survey were then compared with predictions based on the sound-power emission of the plants and relevant meteorological and topographical data.

3.2 SITES INVESTIGATED

3.2.1 Site A

The smallest of the three sites, A, is situated in an inland rural area of flat agricultural land, mainly consisting of grass pasture. The process area is compact and consists of thirteen significant noise sources comprising a single burner floor-fired furnace, six sets of airfin coolers, three pumps and two sources of pipe noise.

A comparison of the site sound-power levels calculated from the perimeter measurements and the sum of the measurements of individual sources indicated a significant error at low frequencies. A detailed investigation of the pipework and other possible sources of low frequency radiation failed to identify its source and a hypothetical low-frequency source was therefore derived, located at the centre of the process area, to equate more closely the sum of the individually measured levels and the perimeter measurements, enabling the individual source power levels to be used for the predictions (Ref. 2).

The highest sources, the airfin coolers, are 3.2 m above grade, all other sources being within 1.5 m of grade. The size and layout of the plant is such that no in-plant screening is in evidence.

The noise emission of the plant restricted measurements to within approximately 800 m of the process area, although measurements in upwind conditions were further restricted to within some 350 m of the plant. However, subject to these limitations, measurements were obtainable in all directions around the plant.

3.2.2 Site B

Site B, a medium sized oil refinery, is situated in an undulating, mainly rural area, near the coast.

Whilst the main process area is compact, there are several "off-sites" noise sources, some of which are run only intermittently.

The process area is located to the north of the site and, although compact, consists of a number of significant sources comprising airfin coolers, furnaces, boilers, compressors, electric motors, control valves and piping. The airfin coolers are above the pump alley, at a height of 10 m, with the furnaces and boilers immediately to the south.

Measurement locations were sited to the north, east and west of the process area at distances of up to 1300 m. At most points the process area was at least partly visible, although at one particular location the undulating ground screened all but the top of the furnace stack. To the south of the process area the ground slopes away to the tank farm before rising again to the extreme south of the site. In this area noise from other industrial plant and, during the day, road traffic, tended to mask the plant noise and it was considered, therefore, unsuitable for measurements.

3.2.3 Site C

The largest of the three sites, site C, is a major petroleum and petrochemical complex. The process plant is extensive, although generally surrounded by tankage areas and other buildings. The number of noise sources is large, but may be conveniently divided into a series of blocks. Source heights vary from grade to 25 m.

The plant is situated in a varied landscape, with the north east side adjacent to a river estuary. Immediately to the north, west and south are mixed residential and industrial areas, whilst at further distances the land becomes more rural, undulating to the south but mainly flat to the north and west. This land is a mixture of pasture and commonland with grass and scrub vegetation. The presence of the river estuary to the north east limited the locations at which measurements could be taken.

The sound power level of this site is such that measurements were possible up to approximately 3.3 km from the process area in some directions.

3.3 SITE SOUND-POWER LEVEL DETERMINATION

In order to predict the noise level from an industrial site at the community it is obviously necessary to determine the sound-power output of the equipment. It was necessary, therefore, to undertake a sound-power level study.

Sound-pressure levels of significant noise sources were measured and sound power levels calculated in accordance with the Oil Companies Materials Association Specification NWG-1 (Ref. 9) and the CONCAWE reports 2/76 and 5/78 (Refs. 13 and 14). The recommendations of CONCAWE for a correction of -3 dB on the near field measurement of large sources, such as airfin cooler banks and furnaces, was applied (Ref. 13).

Some problems were encountered during the survey particularly with high background noise levels from adjacent plant and reverberant sound fields in areas with a high density of equipment. Where necessary, measurements were made close to sources to overcome these problems. Appropriate corrections were also applied to make allowances for the influence of adjacent equipment on measured levels.

Additional measurements were also undertaken to assess the accuracy of the "perimeter" measuring technique for the determination of overall site sound power levels. The two smaller sites were particularly amenable to this method and sound pressure levels were, therefore, recorded at approximately equispaced positions along a perimeter 50 m from the process areas. The overall power level was then calculated using the surface of a "bubble", bounded by the perimeter.

A comparison of these overall sound-power levels with those based on the sum of individual equipment levels (Ref. 2) shows that agreement is generally good. In addition, at site A, the contour method enabled the sound-power level at low frequencies to be calculated where this proved difficult based on individual source measurements.

The size of site C was too large for such a technique to be used for the complex as a whole, but, where levels from individual process blocks were not influenced by adjacent blocks the overall block power level was determined by perimeter measurements and compared with the level based on individual source measurements. A comparison of overall block measurements and individual equipment measurements (Ref. 2) demonstrates that the procedure is, however, limited in its application. This is due partly to high background noise levels and also to the relative locations of major noise sources within the block area.

3.4 COMMUNITY NOISE MEASUREMENT PROCEDURE

In the initial phase of this study it was shown that the sound propagating from industrial plant over long distances is subject to six mechanisms of attenuation. Of these, only geometrical spreading and ground effects may be considered constant, for a given distance, at any site. In-plant screening and barrier attenuation will be unique to a given site and measuring location, whilst the latter, in conjunction with atmospheric attenuation and meteorological effects will vary with weather conditions.

It is obviously necessary, therefore, when attempting to validate a prediction method, to take detailed, concomitant measurements of the meteorological conditions with the sound measurements. The principal factors affecting meteorological attenuation have been shown to be the vector wind speed and the temperature structure of the lower atmosphere. The prediction model for meteorological attenuation was based on the empirical data of Parkin and Scholes (Refs. 4 and 5) and it was decided, therefore, to adopt a similar technique to define these meteorological conditions in this study, particularly the atmospheric temperature gradient. Parkin and Scholes assessed this factor by measuring the temperature at heights of 1 m and 11 m and, whilst this can only indicate the variation in temperature with height close to the ground, it has been shown empirically that, for the distances being considered, it is the first 30 m of the atmosphere which affects noise propagation. For comparative purposes, therefore, temperatures were recorded using screened platinum resistance thermometers mounted at 1 m and 11 m above ground level on a mast.

Wind speed and direction at 11 m were also monitored throughout the measuring period using an anemometer and wind vane mounted adjacent to the upper thermometer.

Wind and temperature measurements were recorded continuously on two battery powered twin-channel chart recorders, designed for this system.

Atmospheric pressure and relative humidity, which vary only slowly with time, were also measured at intervals during the measurement period to enable the atmospheric attenuation to be calculated. Additionally, cloud cover was estimated at intervals to assess the Pasquill Stability Category of the atmosphere (Ref. 15).

The site for the meteorological measurements was chosen so as to be representative of the area being surveyed, whilst far enough from the process equipment so as not to be affected by plant temperature and wind effects.

To facilitate correlation of the measured sound levels with meteorological data and also to allow averaging of short term fluctuations due to instability of the atmosphere, recordings of the plant noise were made over a two minute period at each location. Sound levels were read from the 'A' weighted time history of the recording, which could also be related to the prevailing meteorological conditions and the occurrence of spurious events so that the latter were not included in the analysis. Each recording was then analysed to obtain time-average octave band levels from 63 Hz to 4 kHz using a real-time analyser.

Recordings were only made when the sound level was judged to be dominated by noise from the plant and when transient events, such as traffic movements and overflying aircraft, were not occurring.

To enable the effect of weather conditions on the propagation of sound to be assessed, it is necessary to obtain data for a range of typical meteorological states. However, it should be noted that measurement during periods of rain or winds greater than approximately 7 m/s is impractical and such conditions have been ignored. Measurements were made, therefore, in a range of wind speeds from calm to a limit of approximately 7 m/s and, where possible, for all quadrants. Measurements were also recorded for a range of atmospheric temperature gradients by recording during the day, at night and at dawn and dusk.

3.5 SIZE OF THE EXPERIMENT

In order to give an impression of the amount of experimental work involved in the study, the following table gives details of the numbers of sources, measurement locations and spectral measurements at each site.

	Number of Sources	Number of Measurement Locations	Number of Immission Spectra Obtained
Site A	16	21	685
Site B	81	15	460
Site C	203	23	474
Total	300	59	1619

A "source" may be an individual piece of equipment, several pieces of equipment, or even an entire installation. An "immission spectrum" is the result of one recording over 2 minutes (see Section 3.4).

Most environmental noise measurements were done in the evening and night. Usually 2 to 3 spectra were obtained per night at each location; in such cases there were at least a few hours between the measurements. The experimental work covered a period of one year.

4. ANALYSIS AND IMPROVEMENT OF THE PREDICTION TECHNIQUE

The initial model (Ref. 1) for predicting noise levels was based on a comprehensive literature survey and derived from a combination of theoretical and empirical analyses. Equations were developed to describe the seven major mechanisms of attenuation for each of the octave bands from 63 Hz to 4 kHz and for distances of up to 1100 m.

To enable this method to be checked for accuracy a programme of measurements at three typical petrochemical plants was instigated and noise levels recorded for a variety of distances, weather conditions and ground types.

In order to validate the model it was necessary to assess the contributions to the total measured attenuation for the individual attenuation mechanisms and to separate these it was necessary to make certain assumptions. It is axiomatic that the attenuation due to geometrical spreading can be calculated correctly and it may also be assumed that adoption of the procedures described in the American National Standard, "Method for the Calculation of the Absorption of Sound by the Atmosphere" (Ref. 3) allows the atmospheric attenuation to be computed with confidence.

Separation of the other attenuating mechanisms is, however, more complex. For sites A and B it is possible to assume that, for certain locations, attenuation due to in-plant screening and barriers and the influence of source height on ground effects are negligible and can be ignored. Furthermore, it is possible to select measurements where the effect of meteorological conditions is low (as when the vector wind speed and atmospheric temperature gradient effects are both small and opposite).

Thus, by subtracting the geometrical spreading and atmospheric attenuation factors from the source power level and calculating the difference between this and the measured levels it is possible to obtain an estimate of the ground effect (K_3). The influence of meteorological conditions (K_4) may then be assessed for a given measuring location by calculating the difference between levels measured during "zero meteorological conditions" and those measured for all other categories. For a given location, this difference may be assumed to be a function only of the vector wind and temperature gradient, since all other parameters must remain the same.

Having thus established values of K_3 and K_4 for a series of locations (and, therefore, distances) these were compared graphically with predicted values, as a function of distance. It was generally shown by these plots that the prediction model tended to overestimate the attenuation and the model was, therefore, revised to give an improved fit to the data measured from typical process plants and more realistic ground cover than in Refs. 4 and 5.

After reviewing the meteorological data which would be available at typical sites (Ref. 2) it was decided to modify the meteorological categories of the initial model, and, therefore, the equations for the calculation of K_4 for ground of finite acoustic impedance. The principle of the derivation of this parameter has, however, been retained.

The assessment of atmospheric temperature gradient by measurements of temperatures at 1 m and 11 m has been substituted by use of Pasquill Stability Categories (Ref. 15). Though generally used for calculation of the dispersion of airborne material, these categories define the state of the lower atmosphere in terms of wind, cloud cover and solar radiation and allow an estimation to be made of the temperature gradient without recourse to actual measurement. The definitions of the categories are shown below:

Wind* Speed m/s	Day Time Incoming Solar Radiation mW/cm²				1 hour before Sunset or after Sunrise	Night-Time Cloud Cover (octas)		
	> 60	30–60	< 30	Overcast		0–3	4–7	8
≤ 1.5	A	A–B	B	C	D	F or G**	F	D
2.0–2.5	A–B	B	C	C	D	F	E	D
3.0–4.5	B	B–C	C	C	D	E	D	D
5.0–6.0	C	C–D	D	D	D	D	D	D
> 6.0	D	D	D	D	D	D	D	D

* Wind speed is measured to the nearest 0.5 m/s.

** Category G is resticted to night-time with less thans 1 octa of cloud and a wind speed of less than 0.5 m/s.

Data are recorded in this form by meteorological stations and it is thus a convenient input for prediction. With practice it is also possible to estimate Pasquill Stability Categories in the field from a knowledge of the time, season and visual estimate of cloud cover.

In defining six new meteorological categories, based on a combination of Pasquill Stability Categories (representing the temperature gradient) and vector wind speeds (v m/s), the original philosophy of the theoretical model has been retained with minor modifications. The new categories are shown in the following table with the effect on attenuation.

Decreasing Attenuation ↓

Meteorological Category	Pasquill Stability Category		
	A, B	C, D, E	F, G
1	$v < -3.0$	–	–
2	$-3.0 < v < -0.5$	$v < -3.0$	–
3	$-0.5 < v < +0.5$	$-3.0 < v < -0.5$	$v < -3.0$
4*	$+0.5 < v < +3.0$	$-0.5 < v < +0.5$	$-3.0 < v < -0.5$
5	$v > +3.0$	$+0.5 < v < +3.0$	$-0.5 < v < +0.5$
6	–	$v > +3.0$	$+0.5 < v < +3.0$

* Category with assumed zero meteorological influence

Having thus modified the model, predictions for all locations of Sites A and B were then undertaken. These were then compared with the experimental data and a mathematical analysis of the 'fit' of the prediction to the data, undertaken. This statistical analysis is described in detail in Appendix I.

This analysis led to further refinements in the curves for ground effects (K_3) and meteorological effects (K_4) and these are presented in Figures 1-8. (See pages 63 - 70)

Evaluation of the relationship between source height and ground effects from the site measurements was found to be impractical, since in most cases grazing angles (neglecting the refraction of rays due to meteorological conditions) were less than 2^o. Acoustic Technology, therefore, undertook a series of tests investigating the propagation of octave filtered white noise over flat grassland, at distances of from 100 m to 1000 m, with source heigths of 3 m, 6 m and 9 m. This provided theoretical grazing angles with the range 0^o to 6^o, typical of those encountered at the petrochemical plant. The grazing angles considered were limited by the restricted source height to maintain realistic source-receiver distances such that most of the data related to the range 0^o to 2^o. The results of these tests are presented in Ref. 2.

The tests indicated that the ground effect did not approach zero as the grazing angle tended to 2^o (as would be concluded from the OCMA specification (Ref. 9). There are insufficient data to verify the proposal of Phase 1, however, the indications are that this procedure will not overpredict ground effects for elevated sources and it is recommended, therefore, that this be retained.

An assessment of the recommendations of Phase 1 for the calculation of barrier effects was limited by the sites being clearly visible from most measuring locations. An exception was one location at site B, where the process area was totally obscured by the undulating ground. The predictions obtained without any attenuation due to this screening were all high, but the inclusion of a barrier of representative proportions enabled a marked improvement in the accuracy of the predictions. There were no discrete barriers (fences, walls or buildings) at any of the sites and it was not, therefore, possible to test the philosophy for handling the reduced ground effects in the presence of barriers of this type.

Attenuation due to in-plant screening was not evident at Sites A or B on the basis of comparison of the sum of individual source power levels and the power level based on perimeter measurements. Although this was to be expected at Site A, where the equipment density was low, the possibility of screening by the pump alley and vessels of the furnaces and boilers at Site B was considered. Measurements did not, however, justify this assumption, when compared with calculation using the technique tentatively recommended in Phase 1.

Analysis of Site C, with respect to in-plant screening is more complex. The evidence from the studies at Sites A and B would suggest that, considering each block individually, screening by vessels and other plant would be negligible, but intuitively blocks interposed between the source under investigation and the receiver could provide some attenuation, particularly if they contained substantial acoustically opaque structures (such as box furnaces, tanks and buildings).

An inspection of the data from Site C shows that for categories 5 and 6, predicted levels are higher than those measured.

Statistical analysis of the predictions for Site C assuming $K_7 = 0$ enables the residual attenuation to be attributed to in-plant screening. It was then possible to obtain 'overall' average values for K_7 (at Site C) for each octave band for categories 5 and 6, and these are shown below.

Table of Excess Attenuations (K_7) at Site C, Meteorological Categories 5 and 6

Octave Band Centre Frequency, Hz	63	125	250	500	1k	2k	4k
Excess Attenuation, dB	6	6	4	7	8	9	7

The frequency dependence favoured by Judd and Dryden (Ref. 12) is not evident and it is not possible to resolve these 'total differences' into a factor dependent on distance traversed through the plant and since they include a number of cumulative errors it may be inappropriate to apply them as corrections at other sites.

Data obtained for Categories 2, 3 and 4 showed no significant excess attenuation although these were limited to cases where refinery noise was judged to be above background and as a result were close to the plant such that noise levels were dominated by the nearest (unscreened) process block with noise sources several blocks further away making very little contribution.

It can only be concluded, therefore, that for the two smaller plants in this study, the in-plant screening is insignificant, but that for the large complex with several intervening process blocks in the propagation path, an excess attenuation due to in-plant screening may be observed.

5. FINAL MODEL

5.1 DESCRIPTION

The model takes into account not only significant topographical features, but also the meteorological conditions prevailing at the site. The latter feature allows the prediction of long term equivalent continuous sound levels (L_{eq}) and long term statistical sound levels (L_n), from the site, in addition to probable maxima and minima, on the basis of the statistical distribution of wind velocity and Pasquill Stability for the area.

It is generally possible to obtain records of wind velocity distribution, cloud cover and other atmospheric conditions from meteorological offices and from these the required average meteorological data for the calculation of community levels can be extracted. Predictions may then be made of probable noise levels occurring for the various meteorological conditions expected and these, combined with their frequency of distribution, allow an estimate to be made of the frequency of occurrence of the predicted levels and thus, for example, their annual duration. The combination of predicted noise levels and duration allows the calculation of statistical sound levels on a long term basis.

To summarise the prediction model itself, it has been shown that the sound pressure level at the community may be derived from the equation

$$L_p = L_W + D - \Sigma K$$

The value of the directivity index D depends on both source characteristics and surroundings of the source. In the somewhat reverberant surroundings of a piece of equipment in a processing unit, the value of D=0 is recommended as a first approximation.

The attenuation parameters forming the term ΣK are derived from a combination of theoretically and empirically determined relationships, described below. For convenience in computer calculations the graphs for calculating the attenuation parameters are given as equations and these are quoted in Appendix II.

5.1.1 Geometrical Spreading (K_1)

$$K_1 = 10 \log 4 \pi d^2$$

where d is the source-receiver distance

The formula implies spherical propagation away from the source. Any reflecting areas, including the ground surface, are taken into account in the factors K_3-K_7 (see below).

5.1.2 Atmospheric Absorption (K_2)

Values of the atmospheric attenuation may be obtained from Tables 1-7 of this report for the relevant values of temperature and relative humidity. For octave band width considerations the values corresponding to the lower 1/3rd octave band centre frequency should be chosen. For pure tone considerations values of the atmospheric absorption at the particular frequency should be used, making linear interpolation between tabulated values where necessary.

5.1.3 Ground Attenuation (K_3)

For acoustically 'hard' surfaces, such as concrete or water:

$K_3 = -3$ dB for all frequencies and distances

For all other surfaces K_3 may be determined as a function of frequency and distance from the graphs given in Figure 1.

Where the propagation is partially over an acoustically 'hard' surface and partially over a surface of finite acoustic impedance, values for K_3 may be obtained by using only the distance traversed across the 'soft' ground and obtaining the appropriate value from Figure 1. For example, if a source is surrounded by an area of concrete of 200 metres radius and the receiver is 800 metres from the source, K_3 is obtained by entering 600 metres in Figure 1.

5.1.4 Meteorological Correction (K_4)

The correction due to refractions by wind and temperature gradients is given in the graphs Figures 2 - 8. The attenuation is a function of frequency, distance and meteorological category as defined in Section 4. For meteorological Category 4 the correction is zero in all cases.

5.1.5 Source and/or Receiver Height Correction (K_5)

The decrease in excess attenuation due to source height, where this is greater than 2 m may be obtained from the following relationship:

For $(K_3 + K_4) > -3$ dB

$$K_5 = (K_3 + K_4 + 3)(\gamma - 1) \text{ dB}$$

γ is obtained from the graph Figure 9 as a function of the grazing angle ψ, where

$$\psi = \tan^{-1}\left[\frac{h_s + h_r}{d}\right]$$

and h_s and h_r are the source and receiver heights respectively.

When $(K_3 + K_4) < -3$ dB

$$K_5 = 0$$

The model has been validated for a receiver height of 1.2 m. Sound levels for greater elevations may be calculated using the above formula.

When propagation is to a receiver located on a hillside, or across a valley floor, the value of K_5 should be reduced by up to 3 dB to account for multiple reflections from the hillside, see Section 7 of Ref. 1 and Ref. 17.

5.1.6 Barrier Attenuation (K_6)

The attenuation due to the presence of a discrete barrier should be calculated using Maekawa's method (Ref. 10). This is based on the calculation of a Fresnel number, N, derived from diffraction theory and given by

$$N = \frac{\text{Path Length Difference}}{\frac{1}{2} \times \text{Wavelength}}$$

and the graphs given in Figures 13 and 14. If necessary account should be taken of wind and temperature effects using the approach of De Jong and Stusnick (Ref. 11).

The presence of a discrete barrier may reduce ground effects thus, when the source height is less than that of the barrier the value of K_5 should be recalculated, using the grazing angle, γ, based on the barrier height, receiver height, and barrier-receiver distance. This is not, however, necessary if the barrier is a topographical feature.

5.1.7 In-plant Screening (K_7)

Additional attenuation due to in-plant screening may be observed in practice for a large complex site but this cannot be predicted with certainty.

5.2 STATISTICAL ASSESSMENT

From a comparison of predicted and experimental observed values at Sites A and B confidence limits for the final model have been derived. The data obtained at Site C were not used in the determination of confidence limits because it was feared that plants adjacent to Site C, with similar sound power spectra, could also have contributed to the noise levels measured around this site.

The 95% confidence limits for the final model are given below:

95% Confidence Limits for Final Model								
Meteorological Category	dB(A)	Octave Band Centre Frequency, Hz						
		63	125	250	500	1k	2k	4k
2	6.8	5.4	5.4	9.1	9.4	7.8	9.8	12.4
3	6.9	5.0	6.2	9.4	10.1	8.5	8.5	9.4
4	5.7	4.8	6.5	8.7	9.8	6.6	5.6	6.7
5	4.7	3.9	5.4	8.4	8.1	5.2	5.6	6.7
6	4.5	5.2	6.1	6.7	9.3	4.9	5.5	8.2

The confidence limits in this table should be interpreted as follows: the "true" sound level at a certain location for a specified meteorological category will be, with 95% certainty, between the values:

(predicted level - confidence limits)
and
(predicted level + confidence limits)

The "true" sound level at the location in this respect is to be regarded as the mean of a large number of measured levels within the meteorological category considered. A full explanation of the statistical methods used is given in Appendix I.

The mean differences between the predicted and observed values in each meteorological category were as follows:

Mean Differences (Observed Minus Predicted) for Final Model								
Meteorological Category	dB(A)	Octave Band Centre Frequency, Hz						
		63	125	250	500	1k	2k	4k
2	0.5	0.1	0.1	2.0	2.2	2.2	–0.2	0.4
3	0.6	–0.0	0.5	1.6	0.4	0.8	0.8	0.4
4	0.5	0.3	0.8	–1.2	–0.2	0.1	1.4	0.2
5	0.0	–0.1	–0.0	–2.3	0.4	–0.6	0.9	–0.9
6	0.5	–0.8	–0.3	–1.7	1.2	–0.2	0.1	–0.9

No values for Category 1 have been shown since there were insufficient experimental data to obtain meaningful averages.

The confidence limits are a measure of the accuracy of the model to predict the sound level at a certain place for each of the defined meteorological categories. Since this sound level is influenced by parameters not contained in the model, the sound level is not fully defined. This is reflected in the considerable standard deviation of measured sound levels (Ref. 2), even for a fixed measuring location (i.e. with variation in ground effects and weather effects kept to a minimum).

The ability of the model to predict the sound level at a certain location is further limited by variation of (presumably) ground effects, due to details of the soil structure and vegetation, not taken into account in the present model.

The above table of confidence limits reflects both effects: for meteorological categories with relatively stable sound propagation the confidence limits are lower due to the small spread in measured sound. For octave bands where ground effects cause differences between locations, the confidence limits are higher.

Note: A partial explanation why confidence intervals increase at high frequencies may be the lack of signal to noise ratio at these frequencies in some measured data. Whilst the overall signal was subjectively judged to be from the petrochemical site under investigation, this may not have been the case at high frequencies where extraneous noises could be controlling (wind noise in vegetation etc.).

5.3 EXAMPLE CALCULATIONS

Some guidance on the application of the noise propagation model is given in Appendix III and in the examples below:

Example 1

An example calculation to illustrate the use of the prediction model for a given meteorological category is given on page 31 for a measurement location 500 m from the source. The source and receiver heights have been taken as 1.5 m with a 3 m high barrier 10 m from the source. Atmospheric temperature, and relative humidity are respectively 10 degrees Centigrade, and 75%. A wind of 2 m/s has been considered to be blowing from the source to the receiver and the Pasquill Stability Category has been taken as D (approximately to a zero temperature gradient), which gives a meteorological Category 5. No source height correction is necessary.

Example 2

As an example of the use of the prediction technique for long term noise levels, consider the following situation:

Meteorological Category	L_i Predicted Noise Level dB(A)	t_i Percentage Distribution by Category
1	38	5
2	40	10
3	43	15
4	47	25
5	49.5	30
6	51	15

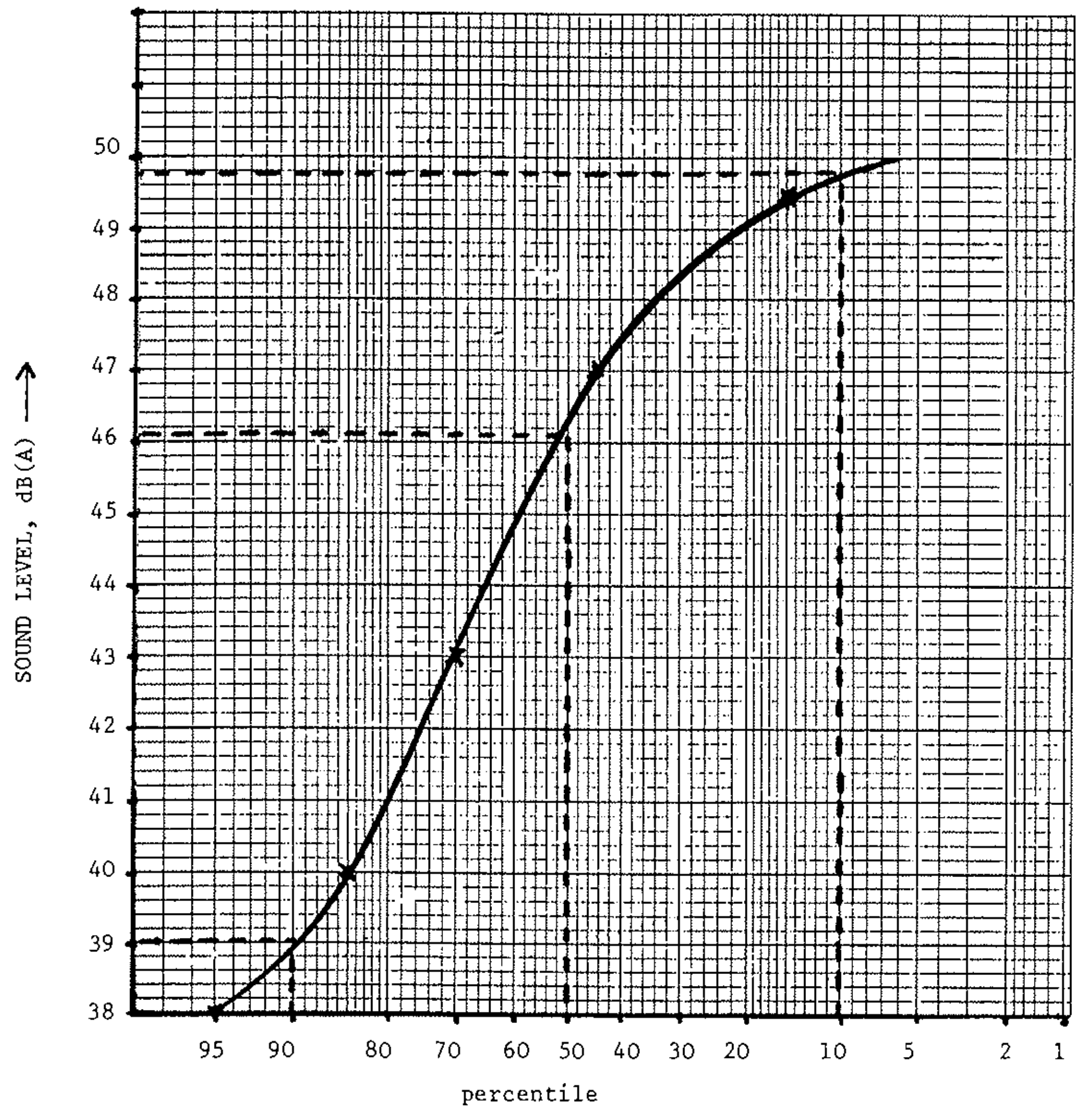
By plotting the above values as a cumulative frequency distribution values of the noise percentiles can readily be obtained, for example: L_{10} = 50 dB(A); L_{50} = 46 dB(A); L_{90} = 39 dB(A). It is interesting to note that although Category 6 occurs for 15% of the time, the level exceeded for 10% of the time is predicted as only 50 dB(A). This is because the prediction is an estimate of a mean value for the range of values contained within a category.

DESCRIPTION			dB(A)	Octave Band Centre Frequency, Hz						
				63	125	250	500	1k	2k	4k
Plant Sound Power Level		L_W	118	127	123	120	113	111	112	108
Directivity	(Omnidirectional source)	D		0	0	0	0	0	0	0
Geometrical Spreading	(d = 500 m)	K_1		65	65	65	65	65	65	65
Atmospheric Attenuation	(Temperature = 10 deg C, Humidity = 75%)	K_2		0	0	0	1	2	3	10
Ground Effects	(Figure 1)	K_3		0	5.5	11	8	4.5	2.5	1.5
Meteorological Correction	(Vector wind speed + 2 m/s Pasquill Stability Factor D, Category 5)	K_4		−1	−2.5	−3.5	−4	−4.5	−3	−4
Source Height Correction	(Source at 1.5m)	K_5		0	0	0	0	0	0	0
Barrier Attenuation	(3m high wall, 10m from source)	K_6		5	6	7	10	11	14	17
		ΣK		69	74	79.5	80	78	81.5	89.5
		L_P	40	58	49	40.5	33	33	30.5	18.5

Worked Example 1 Referred to in Section 5.3

Cumulative Frequency Distribution Used in Worked Example 2. in Section 5.3

L_{90} = 39 dB(A) L_{50} = 46 dB(A) L_{10} = 50 dB(A)



Similarly the long-term equivalent continuous level may be calculated from the following

$$L_{eq}\ dB(A) = 10 \log_{10} \left[\frac{1}{100} \Sigma\, t_i\ 10^{L_i/10} \right]$$

where t_i = percentage time interval for the i^{th} category

L_i = predicted noise level in dB(A) for the i^{th} category

This gives a value of L_{eq} = 48 dB(A) for the above example.

6. SIMPLIFIED MODELS

As a consequence of the data analysis it was decided to try and simplify the Phase 2 prediction model, and examine the associated loss of accuracy. Three main simplifications were considered and these are discussed below:

6.1 MODEL HAVING METEOROLOGICAL CORRECTION K_4 INDEPENDENT OF FREQUENCY WITH METEOROLOGICAL CATEGORIES 5 AND 6 COMBINED (SIMPLIFICATION 1)

This model was derived by taking an average of all the frequency dependent curves for K_4 for meteorological Categories 1, 2, 3, 5 and 6. Meteorological Category 4 remained unchanged because K_4 is, by definition, zero. The revised meteorological attenuation curves are presented in Figure 10.

Predictions were undertaken with this model and the fit to the experimental data at Sites A and B investigated. The 95% confidence limits derived for this model are given in the following table:

95% Confidence Limits for Simplification 1								
Meteorological Category	dB(A)	Octave Band Centre Frequency, Hz						
		63	125	250	500	1k	2k	4k
2	6.3	6.2	6.6	7.9	7.6	9.6	11.5	12.8
3	6.9	5.7	7.6	8.8	10.0	9.2	8.8	9.9
5/6	6.4	5.2	5.8	7.0	10.7	7.0	7.3	8.4

The mean differences between the predicted and observed values in each meteorological Category were as follows:

Mean Differences (Observed Minus Predicted) for Simplification 1								
Meteorological Category	dB(A)	Octave Band Centre Frequency, Hz						
		63	125	250	500	1k	2k	4k
2	−1.1	0.9	1.5	0.5	0.1	−3.7	−2.1	−1.5
3	−0.2	1.3	2.0	0.7	−0.3	−2.0	−0.8	−1.1
5/6	2.0	−1.0	0.3	−0.3	2.5	1.8	2.0	1.5

Comparing these confidence limits with those for the Phase 2 model quoted in 5.2 shows that Categories 2 and 3 are not significantly changed by making this simplification; but the grouping of Categories 5 and 6 does result in an overall loss of accuracy of 1.5 - 2 dB(A). Also comparing the mean differences between predicted and observed values, with those in 5.2 shows that the simplification has caused an increase for Categories 5 and 6.

6.2 MODEL HAVING METEOROLOGICAL CORRECTION K_4 INDEPENDENT OF DISTANCE (SIMPLIFICATION 2)

This model suggested itself as a consequence of the changes in curve shape undertaken during the comparison of predicted and experimental results for Phase 2 of the study. Many of the meteorological attenuation curves were made flatter over the range 200 - 2000 metres as a result of this curve fitting. Single figure values for the meteorological correction K_4 were, therefore, extracted from the Phase 2 curves for each category and octave band as follows:

Attenuation Constants – Simplification 2							
Meteorological Category	Octave Band Frequency, Hz						
	63	125	250	500	1k	2k	4k
1	8.0	5.0	6.0	8.0	10.0	6.0	8.0
2	3.0	2.0	5.0	7.0	11.5	7.5	8.0
3	2.0	1.5	4.0	3.5	6.0	5.0	4.5
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	–1.0	–2.0	–4.0	–4.0	–4.5	–3.0	–4.5
6	–2.0	–4.0	–5.0	–6.0	–5.0	–4.5	–7.0

Predictions were undertaken with this model and the fit to the experimental data at Sites A and B again investigated. The 95% confidence limits derived for this model are given in the following table:

95% Confidence Limits – Simplification 2								
Meteorological Category	dB(A)	Octave Band Centre Frequency, Hz						
		63	125	250	500	1k	2k	4k
2	6.7	6.0	5.3	8.7	9.9	8.0	10.0	12.3
3	6.8	5.4	6.5	9.5	10.0	8.4	9.1	9.5
5	5.2	3.9	5.8	9.8	8.6	5.7	5.3	7.9
6	5.0	5.1	7.0	8.4	9.5	5.2	5.3	9.6

The mean differences between the predicted and observed values in each meteorological category were as follows: -

Mean Differences (Observed Minus Predicted) for Simplification 2								
Meteorological Category	dB(A)	Octave Band Centre Frequency, Hz						
		63	125	250	500	1k	2k	4k
2	0.6	0.3	0.2	1.4	2.2	2.2	0.9	2.1
3	0.9	0.8	1.2	1.7	0.4	0.9	1.4	0.7
5	−0.3	−0.3	−0.1	−2.7	−0.1	−0.6	0.7	−2.0
6	−0.2	−0.4	−1.1	−2.1	0.0	−0.7	0.2	−2.2.

This model compares very favourably with the Phase 2 model for Categories 2 and 3, and results in a loss of accuracy of only 0.5 dB(A) for meteorological Categories 5 and 6. Mean differences between predicted and observed values remain of the same order as in the full model.

6.3 VECTOR WIND MODEL IGNORING TEMPERATURE STABILITY (SIMPLIFICATION 3)

The meteorological attenuation curves include a combination of wind and temperature gradient effects, and for practical simplicity it was decided to investigate a model which was a function of vector wind only. Such a model was not identified in the Phase 1 study, and it therefore had to be derived from the experimental data gathered at Sites A and B. The experimental data was first sorted into three new categories:

Category I - all negative vector winds ($v<-1m/s$)

Category II - still/light winds ($-1m/s<v<1m/s$)

Category III - all positive vector winds ($v>1m/s$)

Predictions were then undertaken using the Phase 2 model with $K_4 = 0$ (corresponding approximately to the new Category II). Any residual attenuation was then attributed to the vector wind Categories I and III and residual plots as a function of distance were obtained. These showed that Category II was a good fit to the newly sorted experimental data, comparable to the fit obtained for Phase 2 meteorological Category 4.

Curves were drawn from the residual plots such that Category I has positive attenuation at all frequencies as a function of distance, and Category III has negative attenuation. These are presented in Figures 11 and 12.

These curves were then included in the prediction model and new analyses undertaken. This new model showed a degree of fit to the data comparable with the Phase 2 model, and at first appearance little accuracy has been lost as a result of this simplification. This model was, however, derived from the experimental data and any lack of fit is a measure of how well the curves were drawn through the experimental points, there now being no independence data set against which to test the model. The data set used to form the model is known to be biased, particularly in the absence of strong negative vector winds and negative vector winds at large distances (cf.the lack of experimental data for the Phase 2 meteorological Category 1). Higher numerical attenuation values for vector wind Category I would have been expected and this model should, therefore, be used with extreme caution.

Because of the lack of an independent test it is not considered appropriate to quote confidence limits for this model.

7. COMPARISON WITH OTHER MODELS

There are two existing prediction techniques which are used in Europe for the prediction of noise levels around large industrial complexes. These are the methods described in The Oil Companies Materials Association (OCMA), document NWG-1 (Ref. 9), and the VDI draft code 2714, 'Outdoor Sound Propagation'(Ref. 16).

7.1 OCMA PREDICTION

The meteorological conditions for which this method predicts, correspond closely to the Phase 2 Category 5 definition. Predictions using this method were, therefore, undertaken for Sites A and B and compared with the experimental data sets for meteorological Category 5. A parallel analysis to that undertaken on the Phase 2 model was performed and the following 95% confidence limits and mean differences were calculated:

Comparison of OCMA Model and Experimental Data, Category 5								
	dB(A)	Octave Band Centre Frequency, Hz						
		63	125	250	500	1k	2k	4k
Confidence Limits	6.9	4.0	6.1	10.0	10.1	9.5	14.5	14.5
Mean Difference (Observed Minus Predicted)	1.3	−0.2	−0.6	−3.2	0.2	2.8	6.4	5.1

These confidence limits may be directly compared with those quoted in Section 5.2 for the Phase 2 model, meteorological Category 5. The confidence limits of the Phase 2 model are about 2 dB(A) narrower than those of the OCMA model.

For the sites under consideration the OCMA model appears to underpredict the high frequencies (octave band at 1 kHz and above), see Section 7.3.

7.2 VDI PREDICTION

The VDI method has three curves covering meteorological effects which may be described as follows:

Curve 1 - constitutes a measure of the maximum downwind noise level which is 'unlikely to be exceeded'. The Phase 2 experimental data was not acquired with a view to measuring this parameter and it was thus not possible to test the validity of the prediction using this curve;

Curve 2 - this curve corresponds to light downwind conditions and is considered to be comparable to Phase 2 meteorological Category 5;

Curve 3 - this gives a long term noise level which may be compared with an average of all the experimental data since these will approximate to an equal wind distribution and night-time conditions in accordance with the VDI philosophy.

Predictions were, therefore, undertaken using curves 2 and 3 and comparison with experimental data and confidence limits and mean differences obtained as before:

Comparison of VDI Curve 2 and Experimental Data, Category 5

	dB(A)	Octave Band Centre Frequency, Hz						
		63	125	250	500	1k	2k	4k
Confidence Limits	8.4	12.4	8.4	8.7	7.6	13.4	12.9	18.0
Mean Difference (Observed Minus Predicted)	2.7	5.6	2.9	−2.9	−0.2	5.5	5.7	7.9

Comparison of VDI Curve 3 and All Experimental Data

	dB(A)	Octave Band Centre Frequency, Hz						
		63	125	250	500	1k	2k	4k
Confidence Limits	10.1	14.6	11.0	9.4	12.2	14.2	14.8	19.4
Mean Difference (Observed Minus Predicted)	2.7	6.6	4.4	−1.6	−0.3	4.4	5.4	7.8

The confidence limits for the VDI model for meteorological Category 5 conditions are about 1.5 dB(A) wider than the OCMA model and about 3.5 dB(A) wider than the Phase 2 model.

In view of the mean differences between predicted and observed levels for both VDI Curve 2 and Curve 3 it would appear that the Phase 2 model predicts the spectrum shape more accurately than does the VDI model for the specific sites studied.

7.3 DISCUSSION OF COMPARISONS

In comparing the experimental data with the OCMA and VDI models a common trend appears: both models seem to underpredict the high frequency octave bands at 1 kHz, 2 kHz and 4 kHz.

This common trend could be taken as throwing some doubt on the experimental data. In this respect the following possible causes of experimental error were considered:

a. Tape-recorder noise

Noise introduced by tape-recording the signal for later analysis may have affected a few low level recordings, but this should be a negligible effect, averaged over the whole data set.

b. Noise from extraneous sources

During the measurements care was taken that recordings were only made when it was judged by ear that there was no extraneous noise. This ensures that at least the A-weighted level of the extraneous noise is negligible. For some locations however, the possibility cannot be excluded that extraneous noise contributed in octave bands of which the contribution to the A-weighted level was only small.

c. Sound power levels

There is a theoretical possibility that in determining the sound power levels of the various sites, some high frequency sources have been missed. In practice, however, this is very unlikely, since sums of sound power levels of individual equipment items agreed with the sound power levels determined by the "perimeter" method for the group of sources.

It is concluded that there is little evidence for experimental errors causing the difference between measured levels and those predicted by OCMA and VDI. It is difficult therefore to account for these observed trends.

8. CONCLUSIONS

A model has been developed which enables noise levels from petroleum and petrochemical complexes to be predicted over large distances, varying terrain, and for a range of meteorological conditions. Where direct comparison with existing prediction techniques is possible this new model has been shown experimentally to be significantly more accurate. In addition prediction is possible for a range of meteorological conditions for which no current technique is available.

Simplified versions of the prediction model have also been tested and these have been shown to be useful in certain cases.

It is concluded that this model based on current theoretical and experimental knowledge, represents a significant advance in terms of accuracy and flexibility of prediction. There is still scope for refinement particularly in the areas of partial barriers, in-plant screening and source height effects when further experimental data becomes available.

The validity of the prediction model has been tested over the range 100 - 2000 metres and for wind speeds of up to 7 metres/second. Any extrapolation beyond these ranges should be done with caution.

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the propagation of noise from petroleum and petrochemical complexes to neighbouring communities

TABLES: ATMOSPHERIC ABSORPTION VALUES

LIST OF TABLES

Table 1: Atmospheric Absorption Values, dB km^{-1}, at $0^{o}C$.

Frequency Hz	Relative Humidity, %									
	55	60	65	70	75	80	85	90	95	100
50	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
63	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
80	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1
100	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2
125	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3
160	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4
200	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
250	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
320	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
400	1.3	1.3	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
500	1.8	1.7	1.6	1.5	1.5	1.5	1.5	1.5	1.5	1.5
630	2.5	2.3	2.2	2.1	2.0	2.0	1.9	1.9	1.9	1.9
800	3.6	3.3	3.1	2.9	2.8	2.7	2.6	2.5	2.5	2.4
1000	5.3	4.8	4.5	4.2	3.9	3.8	3.6	3.5	3.3	3.2
1250	8.0	7.3	6.7	6.2	5.8	5.4	5.2	4.9	4.7	4.5
1600	12.2	11.0	10.1	9.3	8.6	8.1	7.6	7.2	6.9	6.6
2000	18.6	16.8	15.4	14.2	13.1	12.2	11.5	10.8	10.3	9.8
2500	28.1	25.6	23.5	21.6	20.1	18.7	17.5	16.5	15.6	14.8
3200	42.1	38.7	25.7	33.0	30.7	28.6	26.8	25.2	23.8	22.6
4000	61.7	57.5	53.5	49.8	46.6	43.6	41.0	38.6	36.5	34.6
5000	87.7	83.1	78.5	74.0	69.7	65.7	62.1	58.8	55.7	53.0
6300	119	116	112	107	102	97.2	92.6	88.2	84.1	80.3
8000	156	155	153	149	144	140	135	130	125	120

Table 2: Atmospheric Absorption Values, dB km^{-1}, at $5^{o}C$.

Frequency Hz	Relative Humidity, %									
	55	60	65	70	75	80	85	90	95	100
50	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
63	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
80	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1
100	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2
125	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3
160	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4
200	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6
250	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
320	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
400	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
500	1.8	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.8	1.8
630	2.3	2.2	2.2	2.1	2.1	2.1	2.1	2.1	2.1	2.1
800	3.1	2.9	2.8	2.8	2.7	2.7	2.7	2.6	2.6	2.6
1000	4.3	4.0	3.8	3.7	3.6	3.5	3.4	3.4	3.3	3.3
1250	6.2	5.8	5.4	5.1	4.9	4.7	4.6	4.5	4.4	4.3
1600	9.2	8.5	7.9	7.4	7.0	6.7	6.4	6.2	6.0	5.8
2000	13.9	12.7	11.7	10.9	10.3	9.7	9.2	8.8	8.5	8.2
2500	21.3	19.3	17.8	16.5	15.4	14.5	13.7	13.0	12.4	11.9
3200	32.5	29.6	27.2	25.1	23.4	21.9	20.7	19.5	18.6	17.7
4000	49.4	45.2	41.6	38.5	35.8	33.5	31.6	29.8	28.3	26.9
5000	74.2	68.4	63.3	58.8	54.9	51.4	48.4	45.7	43.4	41.2
6300	109.1	101.8	95.1	89.0	83.5	78.5	74.1	70.1	66.6	63.4
8000	156	148	140	132	125	119	112	107	102	97.0

Table 3: Atmospheric Absorption Values, dB km^{-1}, at 10°C.

Frequency Hz	Relative Humidity, %									
	55	60	65	70	75	80	85	90	95	100
50	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
63	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
80	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
100	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
125	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3
160	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4
200	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.6	0.6	0.6
250	1.1	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.9
320	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.2
400	1.6	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.6	1.6
500	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.1	2.1	2.1
630	2.5	2.5	2.5	2.5	2.5	2.5	2.6	2.6	2.6	2.6
800	3.1	3.0	3.0	3.0	3.0	3.1	3.1	3.1	3.1	3.2
1000	4.0	3.9	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8
1250	5.4	5.2	5.0	4.9	4.8	4.8	4.7	4.7	4.7	4.7
1600	7.6	7.2	6.9	6.6	6.4	6.2	6.1	6.0	6.0	5.9
2000	11.1	10.4	9.7	9.3	8.9	8.5	8.3	8.1	7.9	7.8
2500	16.6	15.3	14.3	13.4	12.7	12.1	11.7	11.3	10.9	10.7
3200	25.1	23.1	21.4	20.0	18.8	17.8	17.0	16.3	15.7	15.2
4000	38.4	35.1	32.5	30.2	28.3	26.7	25.4	24.2	23.1	22.2
5000	58.7	53.8	49.7	46.2	43.2	40.7	38.5	36.5	34.9	33.4
6300	89.4	82.3	76.1	70.9	66.3	62.4	58.9	55.9	53.2	50.9
8000	134	125	116	108	102	95.7	90.5	85.9	81.8	78.1

Table 4: Atmospheric Absorption Values, dB km^{-1}, at 15^{o}C.

Frequency Hz	Relative Humidity, %									
	55	60	65	70	75	80	85	90	95	100
50	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
63	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
80	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
100	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1
125	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2
160	0.6	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4
200	0.8	0.8	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.5
250	1.1	1.1	1.1	1.0	1.0	1.0	0.9	0.9	0.9	0.8
320	1.5	1.5	1.5	1.4	1.4	1.4	1.3	1.3	1.2	1.2
400	1.9	1.9	1.9	1.9	1.9	1.9	1.8	1.8	1.8	1.7
500	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.3
630	2.9	2.9	3.0	3.0	3.0	3.1	3.1	3.1	3.1	3.1
800	3.5	3.6	3.6	3.6	3.7	3.7	3.8	3.8	3.8	3.8
1000	4.3	4.3	4.3	4.4	4.4	4.5	4.5	4.6	4.6	4.7
1250	5.4	5.4	5.4	5.4	5.4	5.4	5.5	5.5	5.6	5.6
1600	7.2	7.0	6.8	6.8	6.7	6.7	6.7	6.7	6.8	6.8
2000	9.8	9.4	9.1	8.8	8.7	8.6	8.5	8.4	8.4	8.4
2500	14.0	13.2	12.6	12.1	11.7	11.4	11.2	11.0	10.9	10.8
3200	20.5	19.1	18.0	17.1	16.4	15.8	15.4	15.0	14.7	14.4
4000	30.8	28.5	26.6	25.1	23.9	22.8	21.9	21.2	20.6	20.0
5000	46.8	43.1	40.1	37.7	35.6	33.8	32.3	31.0	29.9	28.9
6300	71.6	66.0	61.2	57.3	53.9	51.0	48.5	46.4	44.5	42.9
8000	110	101	94.0	87.8	82.5	78.0	74.0	70.6	67.5	64.8

Table 5: Atmospheric Absorption Values, dB km^{-1}, at $20^{o}C$.

Frequency Hz	Relative Humidity, %									
	55	60	65	70	75	80	85	90	95	100
50	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
63	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
80	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
100	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1
125	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2
160	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3
200	0.8	0.7	0.7	0.7	0.6	0.6	0.6	0.5	0.5	0.5
250	1.1	1.1	1.0	1.0	0.9	0.9	0.9	0.8	0.8	0.8
320	1.6	1.6	1.5	1.4	1.4	1.3	1.3	1.2	1.2	1.1
400	2.2	2.1	2.1	2.0	2.0	1.9	1.9	1.8	1.7	1.7
500	2.8	2.8	2.8	2.7	2.7	2.6	2.6	2.5	2.5	2.4
640	3.5	3.5	3.6	3.6	3.5	3.5	3.5	3.4	3.4	3.4
800	4.3	4.3	4.4	4.4	4.5	4.5	4.5	4.5	4.5	4.4
1000	5.1	5.2	5.3	5.4	5.4	5.5	5.6	5.6	5.6	5.6
1250	6.2	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	6.9
1600	7.6	7.6	7.7	7.7	7.8	7.9	8.0	8.1	8.2	8.3
2000	9.7	9.6	9.5	9.5	9.6	9.6	9.7	9.8	9.9	10.0
2500	13.0	12.6	12.4	12.2	12.1	12.0	12.0	12.1	12.1	12.2
3200	18.2	17.4	16.7	16.3	15.9	15.7	15.5	15.4	15.3	15.3
4000	26.2	24.7	23.6	22.6	21.9	21.3	20.9	20.5	20.2	20.0
5000	38.9	36.4	34.3	32.7	31.3	30.2	29.2	28.5	27.8	27.3
6400	58.8	54.6	51.2	48.4	46.1	44.1	42.4	41.0	39.8	38.7
8000	89.8	83.2	77.7	73.2	69.3	66.0	63.2	60.7	58.6	56.7

Table 6: Atmospheric Absorption Values, dB km^{-1}, at 25^{o}C.

Frequency Hz	Relative Humidity, %									
	55	60	65	70	75	80	85	90	95	100
50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
63	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
80	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
100	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
125	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2
160	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3
200	0.7	0.7	0.6	0.6	0.6	0.5	0.5	0.5	0.4	0.4
250	1.1	1.0	1.0	0.9	0.9	0.8	0.8	0.7	0.7	0.7
320	1.6	1.5	1.4	1.4	1.3	1.2	1.2	1.1	1.1	1.0
400	2.3	2.2	2.1	2.0	1.9	1.8	1.8	1.7	1.6	1.6
500	3.1	3.0	3.0	2.9	2.8	2.7	2.6	2.5	2.4	2.3
640	4.1	4.0	4.0	3.9	3.8	3.8	3.7	3.6	3.5	3.4
800	5.1	5.2	5.2	5.1	5.1	5.1	5.0	4.9	4.8	4.8
1000	6.2	6.3	6.4	6.5	6.5	6.5	6.5	6.5	6.5	6.4
1250	7.4	7.6	7.8	7.9	8.0	8.1	8.1	8.2	8.2	8.2
1600	8.9	9.1	9.2	9.4	9.6	9.7	9.9	10.0	10.1	10.2
2000	10.8	10.9	11.1	11.3	11.4	11.6	11.8	12.0	12.2	12.3
2500	13.6	13.5	13.6	13.7	13.8	14.0	14.2	14.3	14.5	14.7
3200	17.8	17.5	17.3	17.2	17.2	17.2	17.3	17.5	17.6	17.8
4000	24.3	23.5	22.9	22.5	22.2	22.0	21.9	21.9	21.9	22.0
5000	34.5	32.9	31.7	30.7	30.0	29.4	29.0	28.7	28.4	28.3
6400	50.6	47.8	45.5	43.6	42.1	40.9	39.9	39.1	38.5	38.0
8000	75.9	71.1	67.2	64.0	61.3	59.0	57.2	55.6	54.2	53.1

Table 7: Atmospheric Absorption Values, dB km^{-1}, at $30^{o}C$.

Frequency Hz	Relative Humidity, %									
	55	60	65	70	75	80	85	90	95	100
50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
63	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
80	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
100	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
125	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1
160	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.2	0.2
200	0.6	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4
250	1.0	0.9	0.9	0.8	0.8	0.7	0.7	0.6	0.6	0.6
320	1.5	1.4	1.3	1.2	1.2	1.1	1.1	1.0	1.0	0.9
400	2.2	2.1	2.0	1.9	1.8	1.7	1.6	1.5	1.5	1.4
500	3.2	3.1	2.9	2.8	2.7	2.6	2.5	2.4	2.3	2.2
640	4.4	4.3	4.2	4.0	3.9	3.8	3.6	3.5	3.4	3.3
800	5.9	5.8	5.7	5.6	5.5	5.3	5.2	5.0	4.9	4.8
1000	7.4	7.5	7.5	7.4	7.3	7.2	7.1	7.0	6.9	6.8
1250	9.1	9.3	9.4	9.4	9.4	9.4	9.4	9.3	9.3	9.2
1600	10.9	11.1	11.4	11.5	11.7	11.8	11.9	11.9	12.0	12.0
2000	12.9	13.2	13.5	13.8	14.1	14.3	14.5	14.7	14.8	14.9
2500	15.5	15.8	16.1	16.4	16.7	17.1	17.4	17.6	17.9	18.1
3200	19.2	19.3	19.5	19.8	20.1	20.4	20.7	21.0	21.4	21.7
4000	24.7	24.5	24.4	24.5	24.6	24.8	25.1	25.4	25.7	26.0
5000	33.2	32.4	31.9	31.6	31.4	31.3	31.4	31.5	31.7	31.9
6400	46.5	44.8	43.4	42.5	41.7	41.2	40.9	40.6	40.5	40.5
8000	67.5	64.2	61.6	59.5	57.9	56.6	55.5	54.7	54.1	53.6

the propagation of noise from petroleum and petrochemical complexes to neighbouring communities

FIGURES: ATTENUATION CURVES

LIST OF FIGURES

Figure 1: Ground Attenuation Curves - (Category 4)

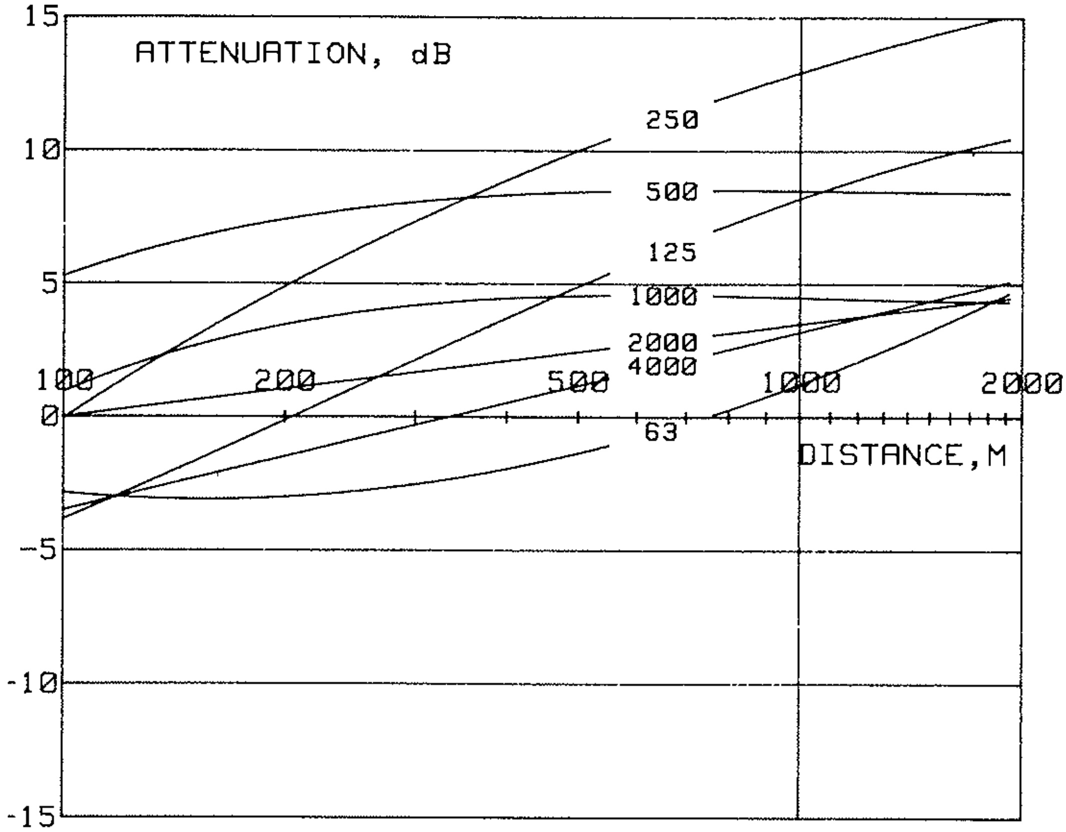

Figure 2: Meteorological Attenuation Curves - 63 Hz
(Experimental Data not available for Category 1)

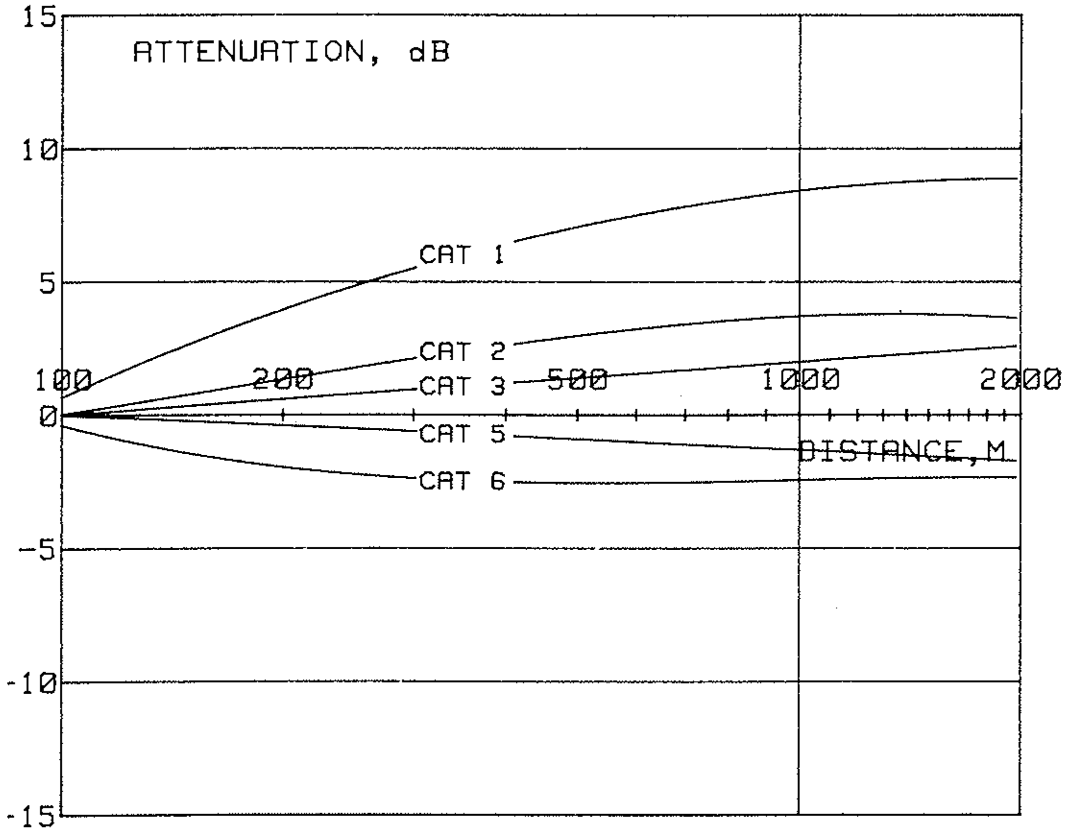

Figure 3: Meteorological Attenuation Curves - 125 Hz
(Experimental Data not available for Category 1)

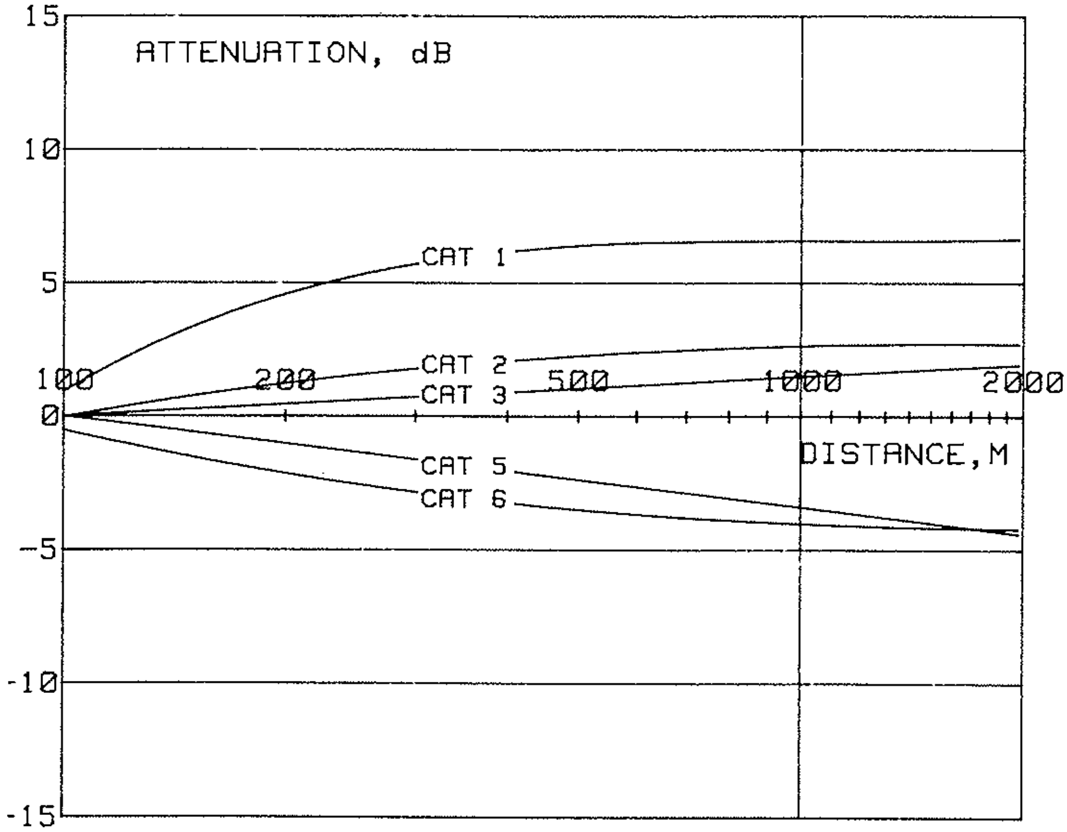

Figure 4: Meteorological Attenuation Curves - 250 Hz
(Experimental Data not available for Category 1)

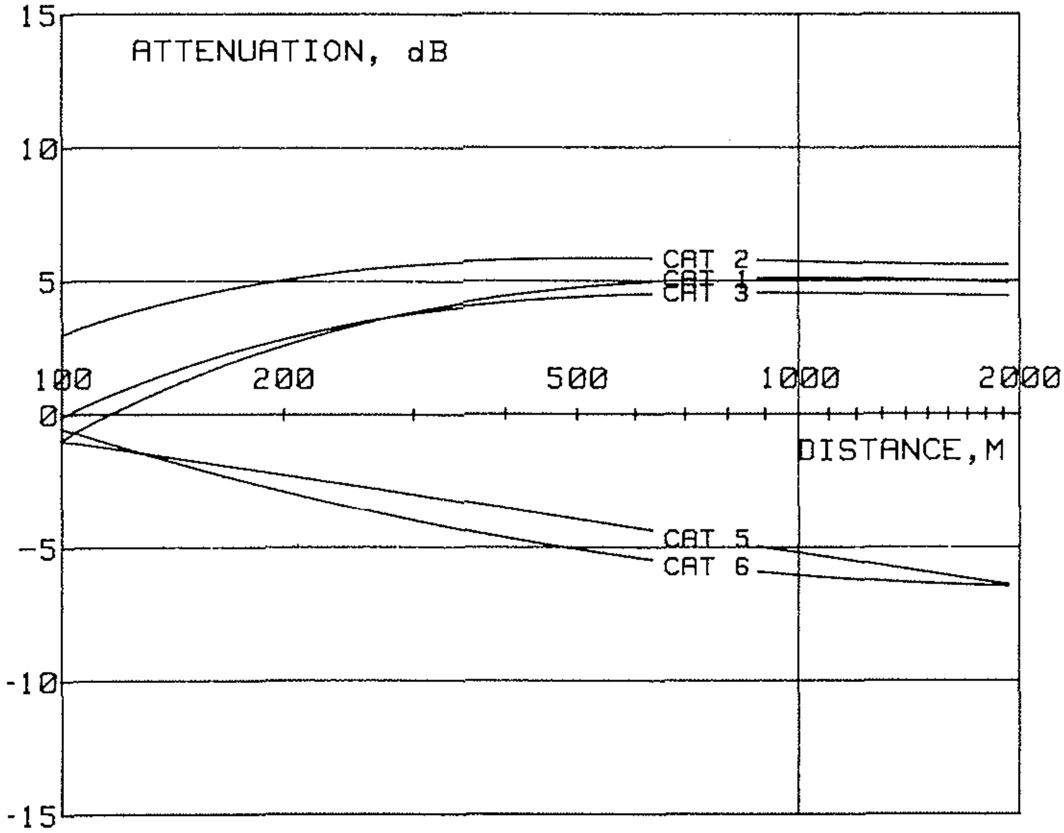

Figure 5: Meteorological Attenuation Curves - 500 Hz
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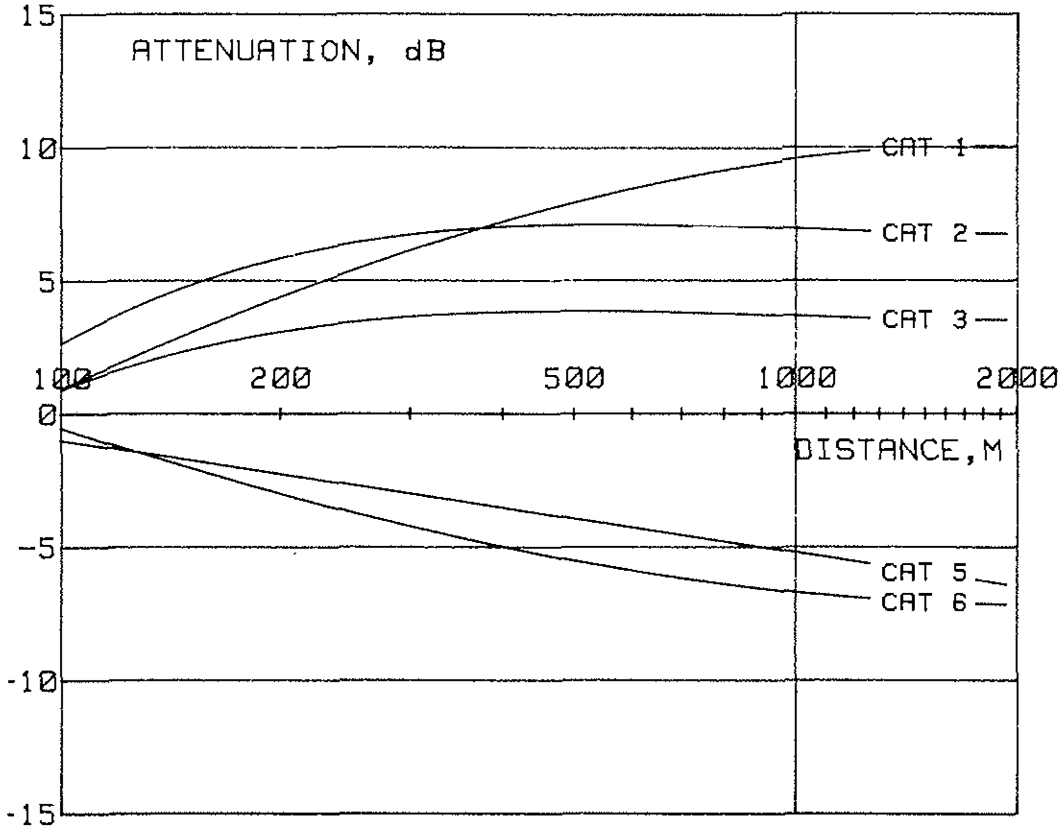

Figure 6: Meteorological Attenuation Curves - 1 kHz
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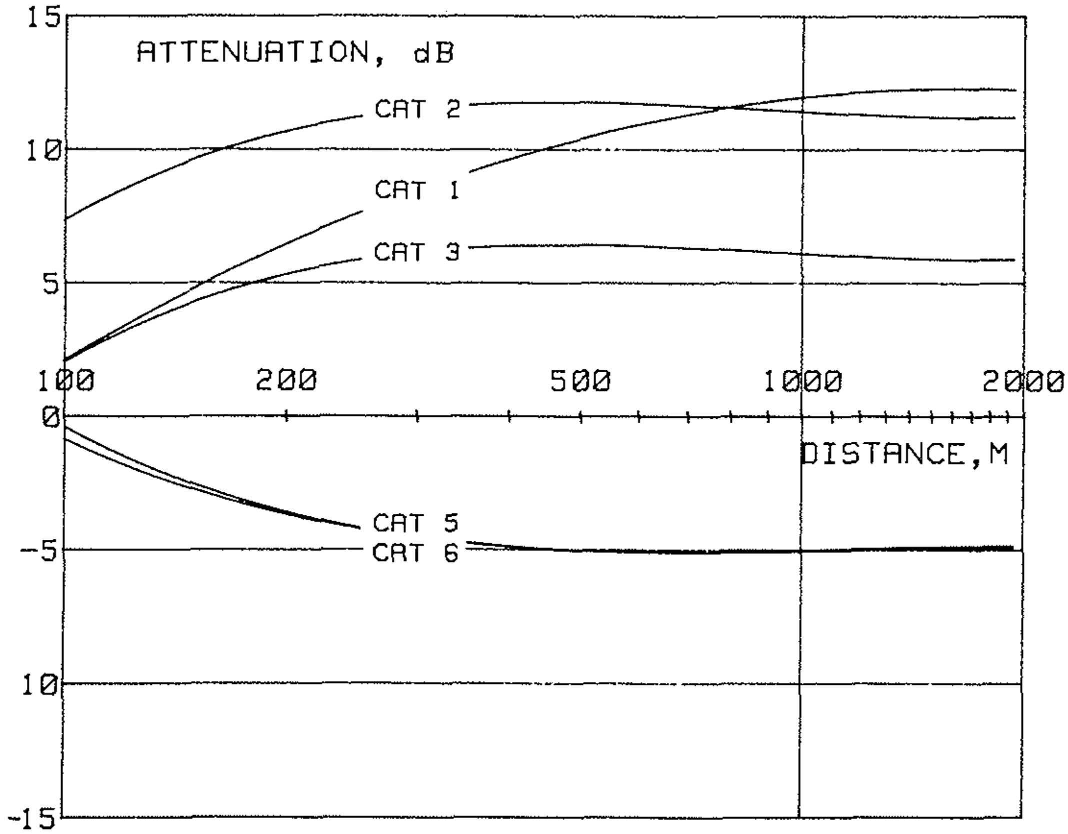


Figure 7: Meteorological Attenuation Curves - 2 kHz
(Experimental Data not available for Category 1)

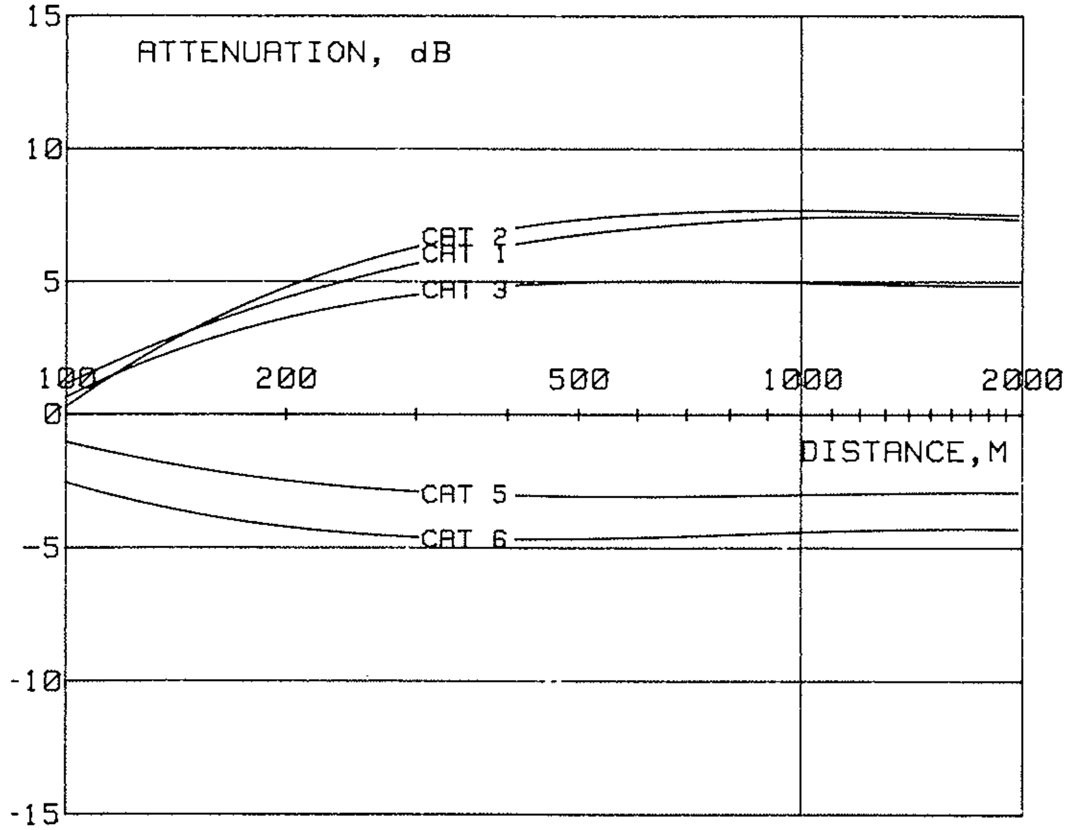


Figure 8: Meteorological Attenuation Curves - 4 kHz
(Experimental Data not available for Category 1)

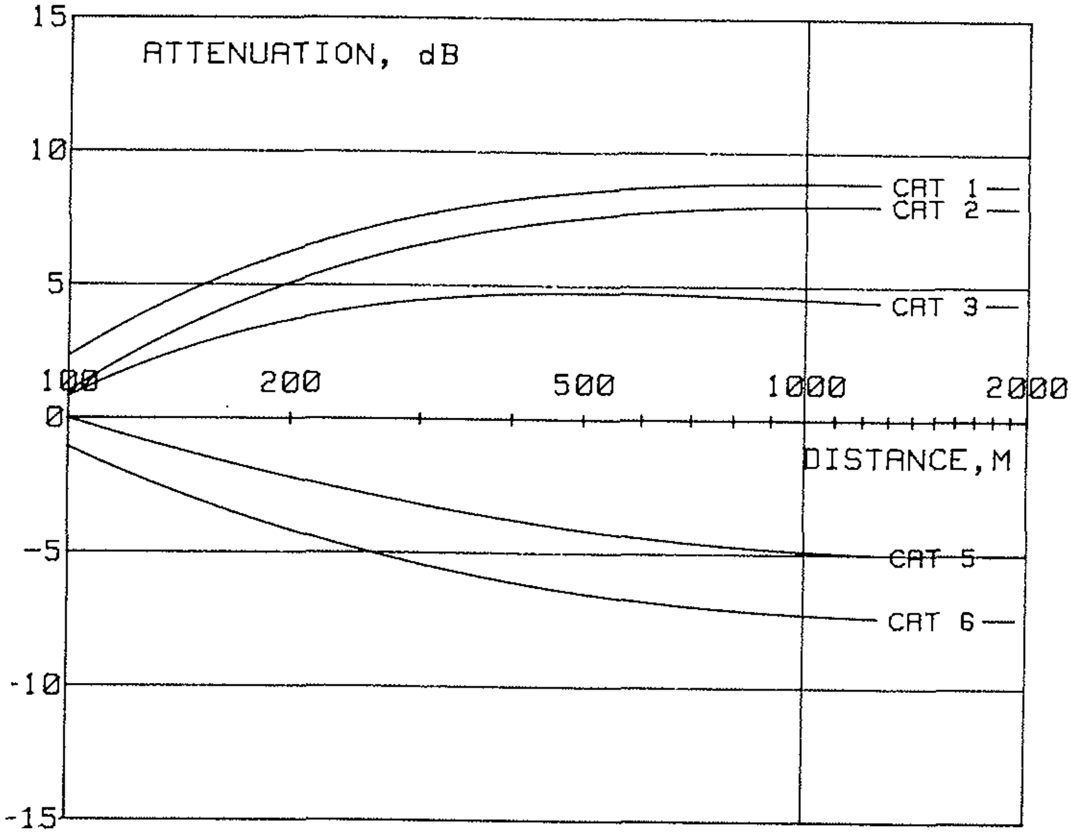
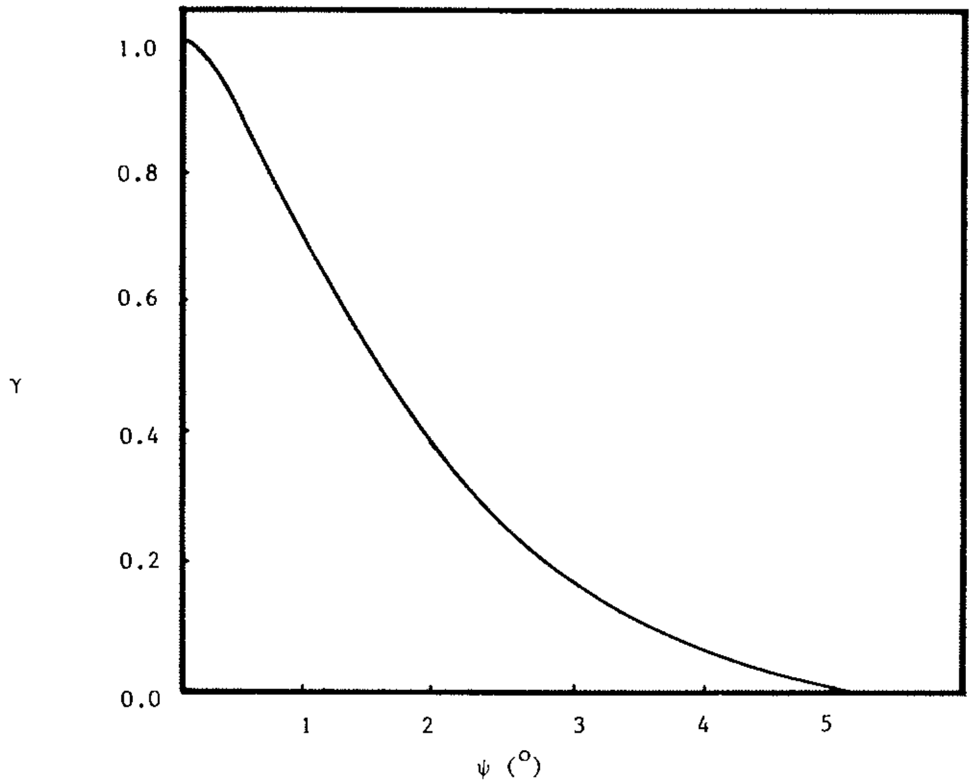


Figure 9: Function γ for Values of Grazing Angle ψ, used in Determining the Reduction in Excess Attenuation due to Source Height



$h_s \leq 2m$: $\gamma = 1$

$h_s > 2m$: $\gamma = 1 - 0.478\psi + 0.068\psi^2 - 0.0029\psi^3$

$$\psi = \tan^{-1} \frac{h_s + h_r}{d}$$

Figure 10: Attenuation for Model having k_4 Independent of Frequency

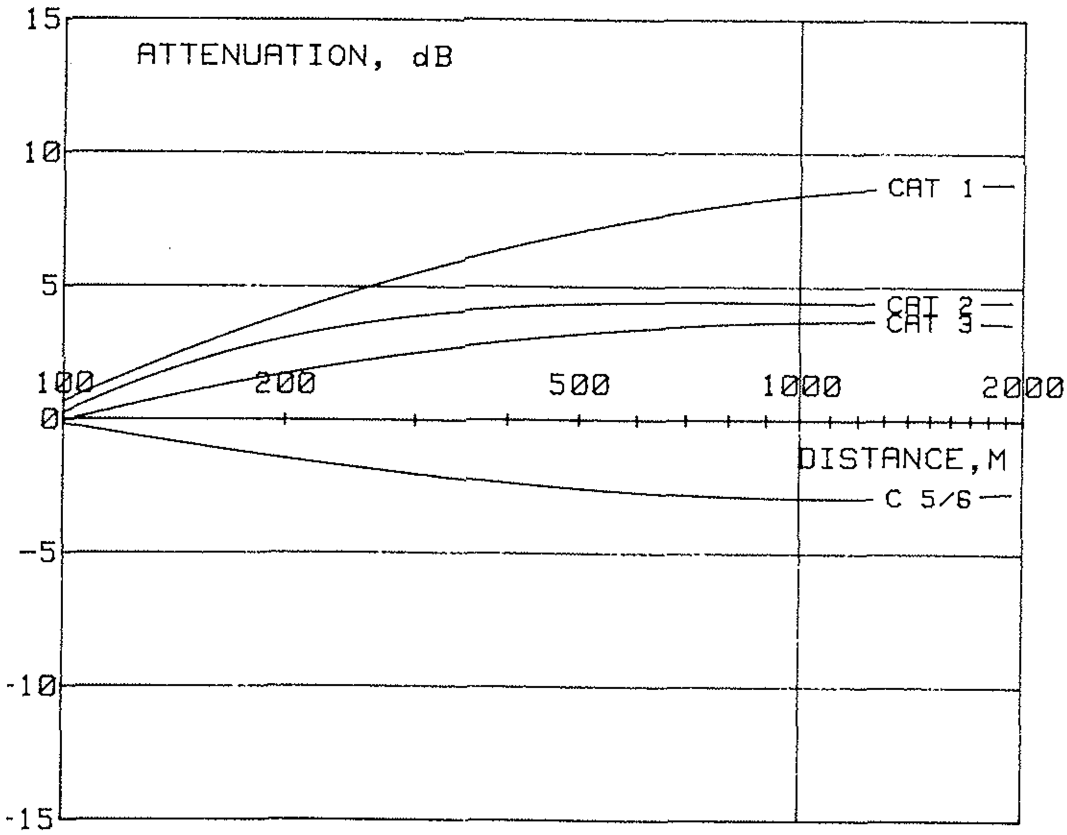
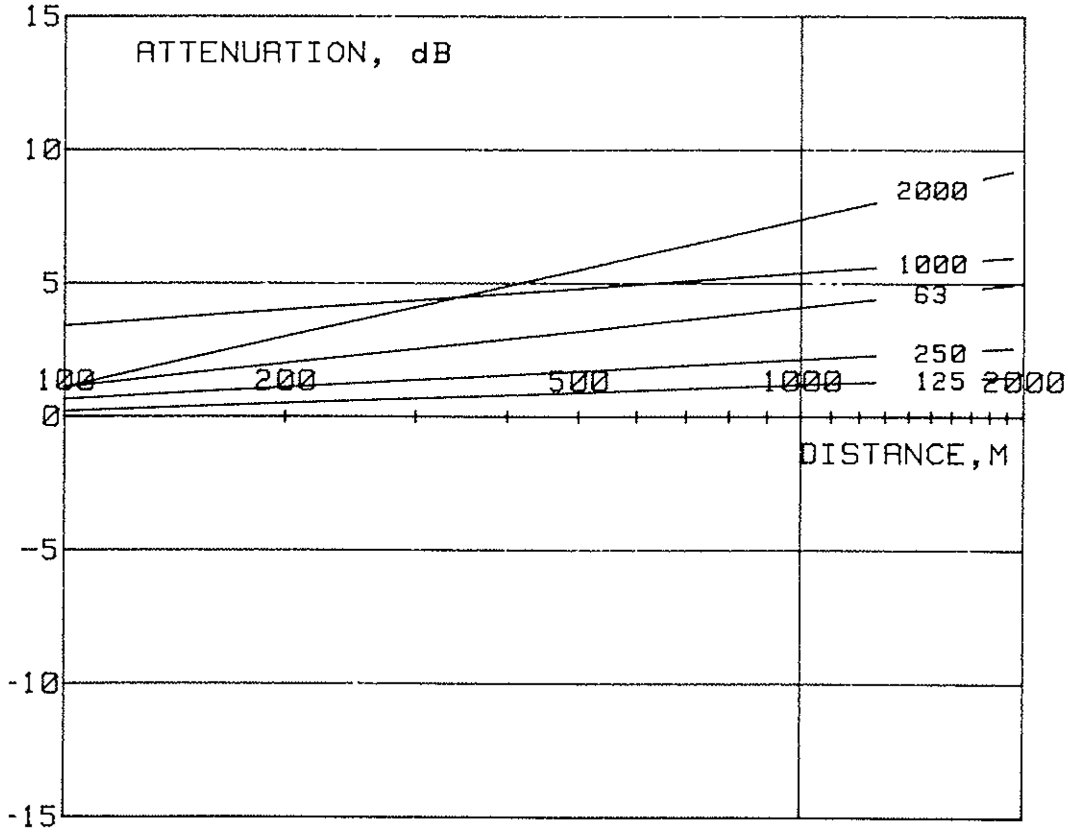


Figure 11: Vector Wind Model, Meteorological Category I,
Wind Speed, <-1m/s



Note: The curve for the 250 Hz octave band is also valid for the 500 Hz octave band and the 2000 Hz curve is valid for the 4000 Hz octave band.

Figure 12: Vector Wind Model, Meteorological Category III, Wind Speed, > 1m/s

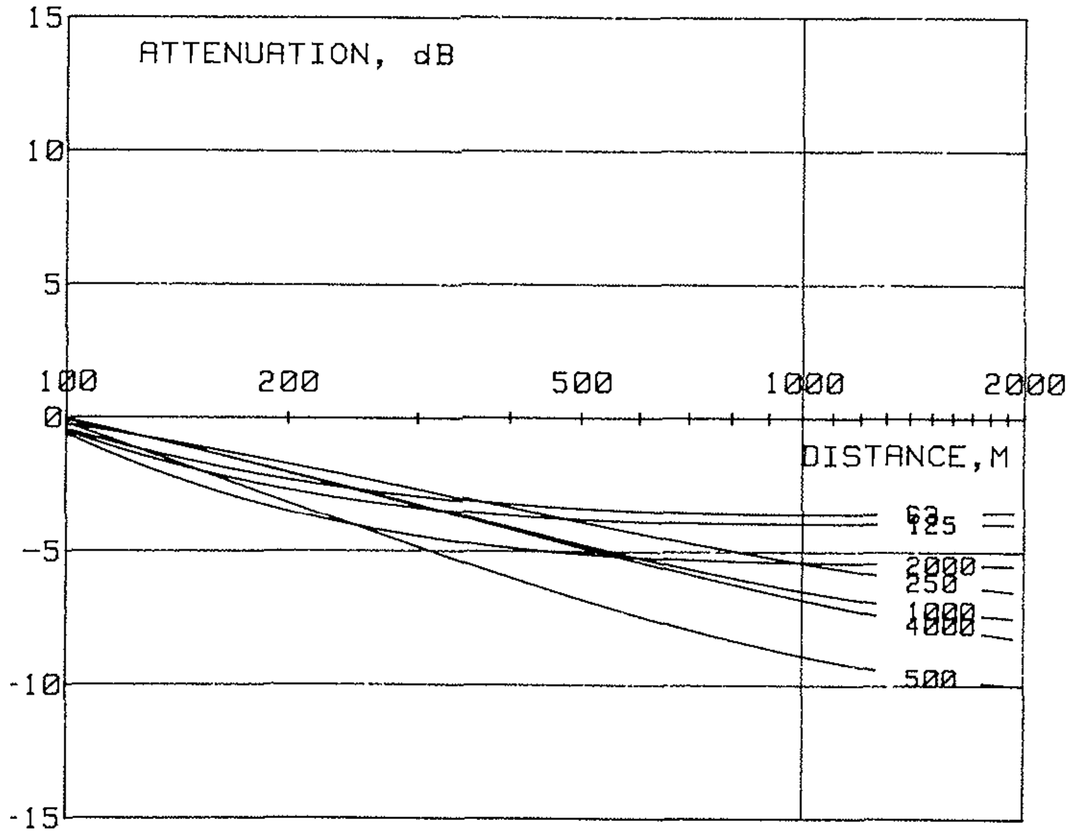


Figure 13: Maekawa's Chart for Sound Attenuation by Barriers (Fresnel Numbers <100)

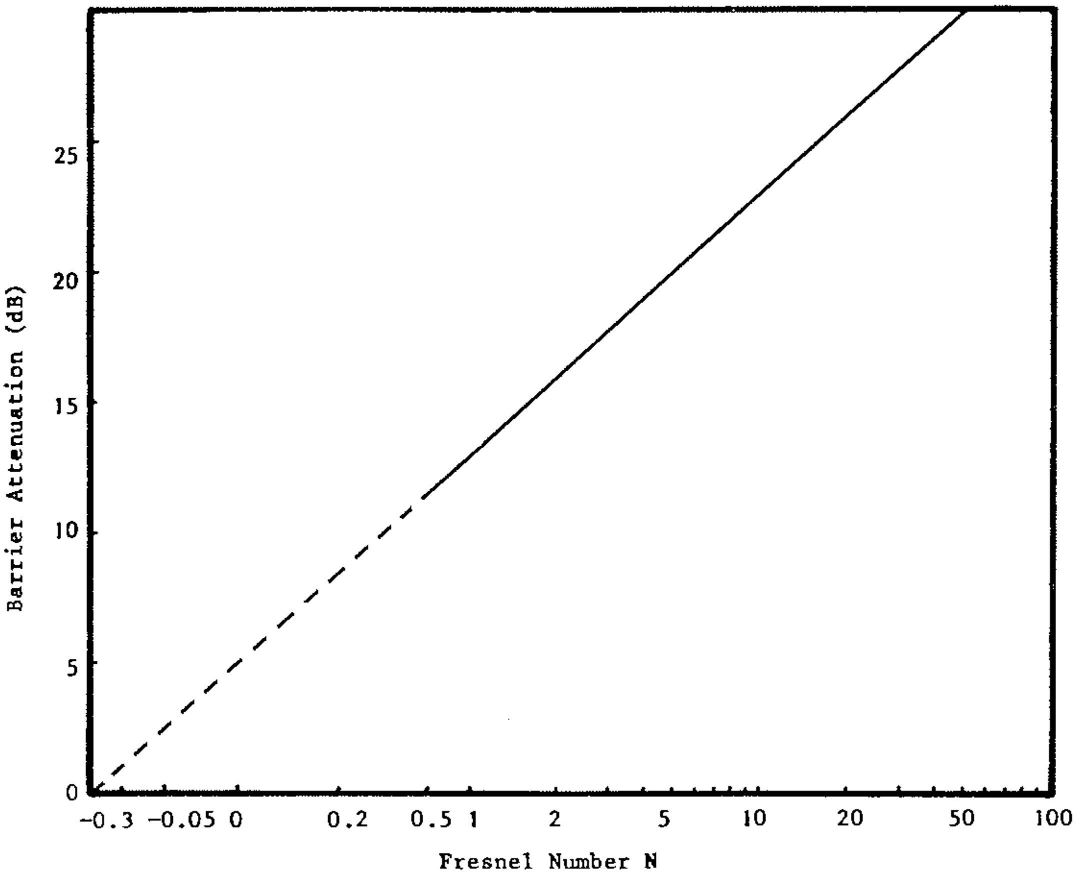
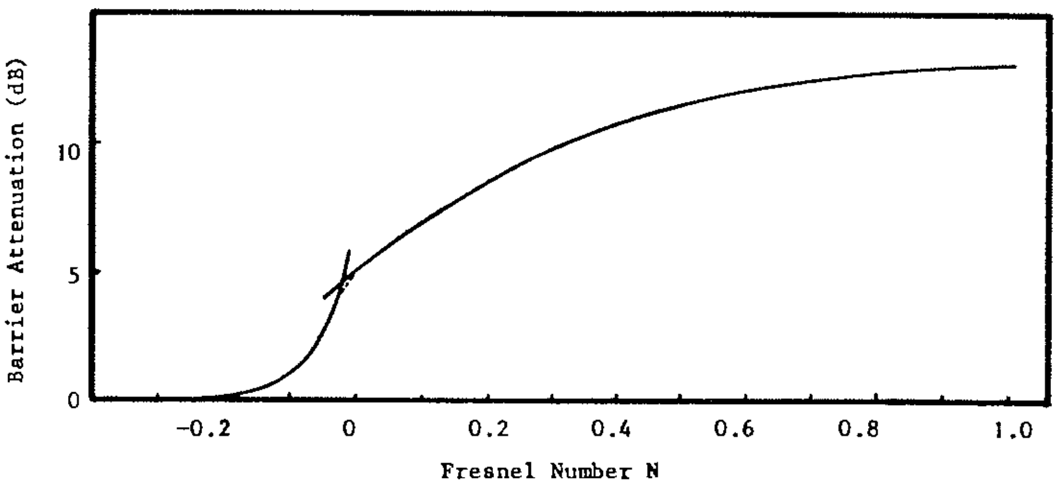


Figure 14: Maekawa's Chart for Sound Attenuation by Barriers (Fresnel Numbers <1.0)



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APPENDIX I: STATISTICAL ANALYSIS METHODS

1. ADEQUACY OF FIT BETWEEN THE MODEL AND EXPERIMENTAL DATA

The prediction model involves a number of inter-related variables (wind speed, wind direction, temperature gradient, ground cover, source height etc.) which may be noted mathematically by v_1, v_2........ v_m. The dependent variable (the received sound pressure level) may be denoted y such that:

$$y = f\,(v_1,\ v_2,\ \ldots\ldots\ldots\ v_m)$$

Measured values of y have been obtained for a large number, n, of values of the variables v_1, v_2 .... v_m, and the resulting set of experimental data may therefore be denoted by:

$$(y_i,\ v_{1i},\ v_{2i}\ \ldots\ldots\ldots\ v_{mi}),\ \text{for } i = 1,\ \ldots\ldots\ldots\ n$$

In each case the model has been used to predict the values of y. Let these predicted values be denoted by:

$$y_i' = f\,(v_{1i},\ v_{2i},\ \ldots\ldots\ldots\ v_{mi})$$

All the information on the adequacy of the fit of a model is contained in the residuals which are defined as the differences between the experimental (or observed) values and the predicted values.

i.e. $r_i = y_i - y_i'$ for $i = 1, \ldots\ldots\ldots n$

In assessing the adequacy of a model it is necessary to consider not only the magnitudes of r_i, but also whether there are any patterns or trends in these residuals.

The set of experimental data is divided into sub-sets for which the variables v_1, v_2 .... v_m all take the same value, i.e. the model groups a range of variables into a single category, and predicts the same value of y_i' for all the points within the sub-set. The variation in these sub-sets of points provides a measure of the 'random' variation in the sound pressure levels which cannot be explained by the model involving v_1, v_2........v_m.

If the model is a good fit to the data then the variations in the residuals, r_i, will be mainly due to random variation. However, if the model is not a good fit, the residuals will contain a systematic component as well as a random component. The variation in the residuals will be measured by a sum of squares and the residual mean square is defined as:

$$\text{Residual mean square} = \sum_{i=1}^{n} r_i^2/n$$

and has n degrees of freedom. Note that this is similar to the definition of a variance and that since the experimental data was not used to estimate the form of the original model, the number of degrees of freedom associated with this residual mean square is equal to the number of observations.

The adequacy of the model may be assessed by examining the magnitude of the residual mean squares and comparing it with a measure of the random variation obtained from the sub-set of points with equal values of v_1, v_2 .... v_m. If the residual mean square is inflated because it contains systematic errors the model does not fit and improvement will be necessary. If the residual mean square is of the same order of magnitude as the random variation, the model fits as well as can be expected using the variables v_1, v_2 .... v_m.

The method of comparison between residual mean square and random error is now considered in detail.

Suppose that y_{ℓ_1}, y_{ℓ_2}, ... $y_{\ell_{n_i}}$ are the experimental data values for a sub-set of points with the same levels of all variables v_1, v_2, ... v_m. The random variation of these values is estimated by:

$$s_\ell^2 = \sum_{j=1}^{n_i} \frac{(y_{\ell j} - \bar{y}_\ell)^2}{n_\ell - 1} \quad \text{where} \quad \overline{y_\ell} = \frac{\sum_{j=1}^{n_i} y_{\ell_j}}{n_\ell}$$

Provided that these s_ℓ^2 values are reasonably consistent with each other, they may be combined in a weighted sum to give an overall estimate of random variation. This is defined as:

$$s^2 = \frac{\sum_{\ell=1}^{L} (n_\ell - 1)\, s_\ell^2}{\sum_{\ell=1}^{L} (n_\ell - 1)}$$

where L is the total number of sub-sets of points being considered.

This estimate of random variation has $\sum_{\ell=1}^{L} (n_\ell - 1) = n_L$ degrees of freedom. The comparison of the residual mean square and s^2 is carried out as follows:

Define the <u>lack of fit</u> component of $\sum_{i=1}^{n} r_i^2$ as

$$LF = \sum_{i=1}^{n} r_i^2 - \sum_{i=1}^{L} (n_\ell - 1)\, s_\ell^2$$

i.e. $$LF = \sum_{i=1}^{n} r_i^2 - n_L\, s^2$$

This compound has $n - n_L$ degrees of freedom.

The <u>average lack of fit</u>, i.e. $\left(\frac{LF}{n-n_L}\right)$ and the <u>ratio of fit</u>,

(i.e. average lack of fit divided by s^2) are computed.

For a perfect fit of the prediction to the experimental data, for the number of degrees of freedom in this case, the ratio of fit would be of the order of 2 - 3. Because of the number of inter-related variables, it was considered that a value of 10-15 would constitute a 'good fit', and values substantially larger would indicate that there was scope for improvement of the prediction model. A sample of the output format is given in <u>Table A.</u>

Table A: Sample Plot of Statistical Analysis Output

ACOUSTIC TECHNOLOGY
NOISE PROPAGATION SURVEY
FEB 1, 1980

SITE B METEOROLOGICAL CATEGORY 5

	SOUND LEVEL	OCTAVE BAND CENTRE FREQUENCIES (Hz)						
	dB(A)	63	125	250	500	1k	2k	4k
LINES	109.0	109.0	109.0	109.0	109.0	109.0	109.0	109.0
PROPORTION	94.0	94.0	94.0	94.0	94.0	94.0	94.0	94.0
RESIDUALS	932.8	1038.9	1907.6	1899.3	1969.4	1062.2	1503.6	3117.6
WEIGHTED VARIANCE	4.52	6.07	6.91	7.86	7.84	6.01	6.24	17.01
LACK OF FIT	507.6	468.1	1257.7	1160.1	1232.6	497.2	917.3	1518.8
AV. LACK OF FIT	33.8	31.2	83.8	77.3	82.2	33.1	61.2	101.3
RATIO OF FIT	7.5	5.1	12.1	9.8	10.5	5.5	9.8	6.0

<u>Note:</u> LINES - n

PROPORTION n_L

RESIDUALS - Σr_i^2

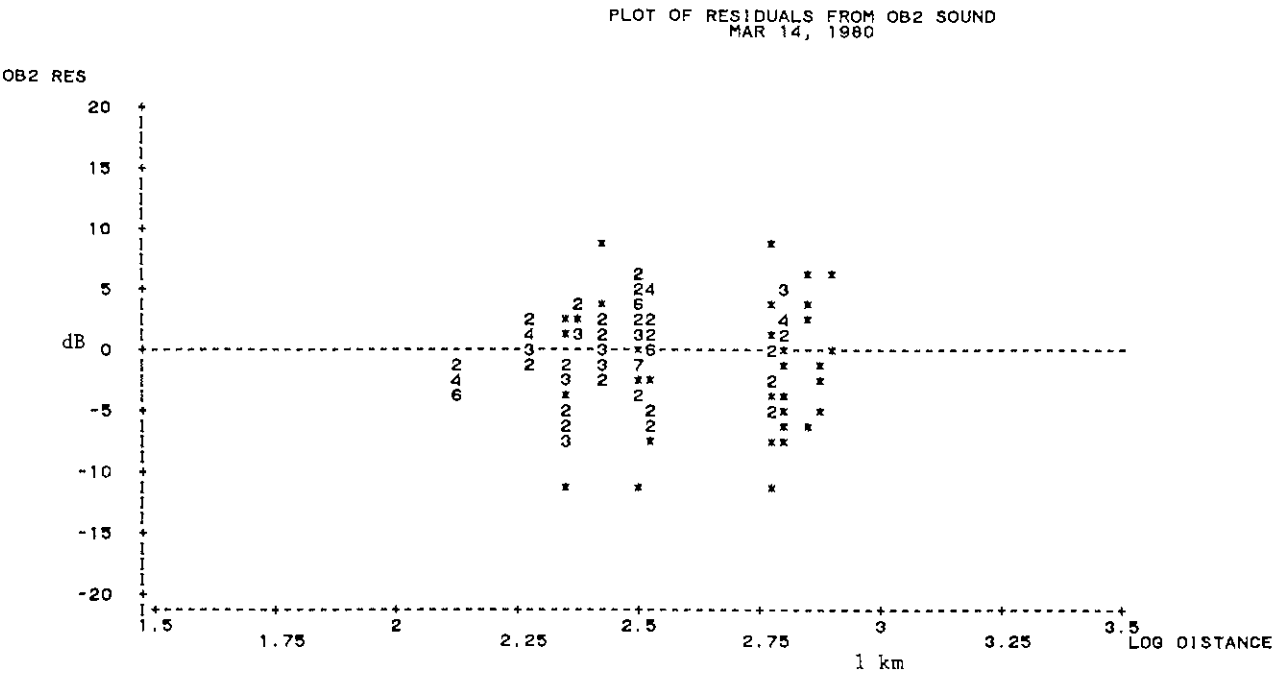
WEIGHTED VARIANCE - s^2

2. IMPROVEMENT OF PREDICTION MODEL

If there is an indication that the model does not fit the data very well it is necessary to consider whether adjustments may be made. The information about the adequacy of fit is contained in the residuals and insight may be obtained by plotting the residuals against the variables for groups of data. To examine the fit of the predicted attenuation K_3 and K_4, the residuals for each of the meteorological categories and octave bands were plotted as a function of distance, an example plot is shown in Figure 1 of this Appendix. For a perfect fit, the residuals would be scattered about a mean zero line. A constant error or a slope in the plot indicates the form of the change required to the prediction equation. Such changes were made, the predictions re-run, and further plots obtained. Thus an iterative model building exercise took place until no further improvements could be made to the model. In this context it was important not to 'overfit' the model to the data, since it was not the intention to base the prediction model on the experimental data, but to use the latter to test and improve the original model. To have formed a model directly from the experimental data would have required a much larger experimental study and regression analysis techniques. In improving the fit, the philosophy behind the equations was maintained and where, for example, the residual plots indicated that a function was not continuous this had to be ignored.

Figure 1: Sample Plot of Residuals as a Function of Distance

SITE "A" and MET "5"



3. CONFIDENCE INTERVALS OF MODELS

The accuracy of the prediction model may be investigated by computing the following parameter:

$$\frac{\sum_{\ell=1}^{L} n_\ell \left(\bar{y}_\ell - \hat{y}_\ell\right)^2}{\sum_{\ell=1}^{L} n_\ell}$$

where $\bar{y}_\ell$ is the average experimental value for a given location and category.

n_ℓ is the number of samples making up that average.

$\hat{y}$ is the prediction for that location and category.

L is the total number of such locations and categories.

This may be shown to be equal to the lack of fit divided by the total number of observations, n.

Confidence intervals may, therefore, be established from the following:

$$\hat{y} \pm C\sqrt{\frac{\text{lack of fit}}{n}}$$

For 95% confidence intervals C = 2.*

The assumption in the above relationship is that there is no mean error between the predicted values and the experimental one, which would inflate these confidence intervals. To check this assumption overall mean differences for all the models described in this report were computed. For the Phase 2 model these mean differences were less than 1 dB, and for the simplified models, less than 2 dB. A bias of this order would have only a small effect on the computed confidence intervals.

For the comparison with OCMA and VDI models however, there were considerable mean differences, which inflated the confidence intervals significantly.

*Note: The quantity: $2\sqrt{\frac{\text{lack of fit}}{n}}$ is quoted in the report as "confidence limit".

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APPENDIX II: EQUATIONS FOR ATTENUATION CURVES

EQUATIONS FOR ATTENUATION CURVES (not to be used for distances, d, below 100 m.)

1. Phase 2 Model

Ground effects:

63 Hz : $K_3 = 33.4 - 35.04 (\log d) + 9.159 (\log d)^2 - 0.3508 (\log d)^3$

125 Hz : $K_3 = 8.96 - 35.8 (\log d) + 20.4 (\log d)^2 - 2.85 (\log d)^3$

250 Hz : $K_3 = - 64.2 + 48.6 (\log d) - 9.53 (\log d)^2 + 0.634 (\log d)^3$

500 Hz : $K_3 = - 74.9 + 82.23 (\log d) - 26.921 (\log d)^2 + 2.9258 (\log d)^3$

1 kHz : $K_3 = - 100.1 + 104.68 (\log d) - 34.693 (\log d)^2 + 3.8068 (\log d)^3$

2 kHz : $K_3 = - 7.0 + 3.5 (\log d)$

4 kHz : $K_3 = - 16.9 + 6.7 (\log d)$

Meteorological effects:

63 Hz

Meteorological Category 1: $K_4 = - 38.9 + 26.4 (\log d) - 2.84 (\log d)^2 - 0.234 (\log d)^3$

Meteorological Category 2: $K_4 = 16.1 - 28.43 (\log d) + 14.4 (\log d)^2 - 2.1 (\log d)^3$

Meteorological Category 3: $K_4 = - 4 + 2 (\log d)$

Meteorological Category 5: $K_4 = 3.35 - 2.26 (\log d) + 0.407 (\log d)^2 - 0.0572 (\log d)^3$

Meteorological Category 6: $K_4 = 69.3 - 73.2 (\log d) + 24.688 (\log d)^2 - 2.7531 (\log d)^3$

125 Hz

Meteorological Category 1: $K_4 = - 137 + 142 (\log d) - 46.8 (\log d)^2 + 5.14 (\log d)^3$

Meteorological Category 2: $K_4 = -23.2 + 19.53 (\log d) - 4.646 (\log d)^2 + 0.3358 (\log d)^3$

Meteorological Category 3: $K_4 = -3 + 1.5 (\log d)$

Meteorological Category 5: $K_4 = 6.8 - 3.4 (\log d)$

Meteorological Category 6: $K_4 = 29.5 - 25.62 (\log d) + 6.286 (\log d)^2 - 0.4904 (\log d)^3$

250 Hz

Meteorological Category 1: $K_4 = -104 + 100 (\log d) - 30.3 (\log d)^2 + 3.03 (\log d)^3$

Meteorological Category 2: $K_4 = -84.8 + 91.93 (\log d) - 30.873 (\log d)^2 + 3.4295 (\log d)^3$

Meteorological Category 3: $K_4 = -100.6 + 101.23 (\log d) - 32.352 (\log d)^2 + 3.4306 (\log d)^3$

Meteorological Category 5: $K_4 = 7.4 - 4.2 (\log d)$

Meteorological Category 6: $K_4 = 31.7 - 23.81 (\log d) + 4.055 (\log d)^2 - 0.1043 (\log d)^3$

500 Hz

Meteorological Category 1: $K_4 = -20.9 + 3.86 (\log d) + 6.39 (\log d)^2 - 1.43 (\log d)^3$

Meteorological Category 2: $K_4 = -133.7 + 142.63 (\log d) - 47.851 (\log d)^2 + 5.3118 (\log d)^3$

Meteorological Category 3: $K_4 = -96.8 + 102.98 (\log d) - 34.868 (\log d)^2 + 3.9016 (\log d)^3$

Meteorological Category 5: $K_4 = 7.4 - 4.2 (\log d)$

Meteorological Category 6: $K_4 = 19.8 - 8.8 (\log d) - 2.035 (\log d)^2 + 0.6747 (\log d)^3$

1 kHz

Meteorological Category 1: $K_4 = -54.3 + 39 (\log d) - 4.92 (\log d)^2 - 0.239 (\log d)^3$

Meteorological Category 2: $K_4 = -148.2 + 164.99 (\log d) - 56.287 (\log d)^2 + 6.3422 (\log d)^3$

Meteorological Category 3: $K_4 = -150 + 160.95 (\log d) - 54.786 (\log d)^2 + 6.1604 (\log d)^3$

Meteorological Category 5: $K_4 = 104.6 - 108.03 (\log d) + 35.295 (\log d)^2 - 3.8227 (\log d)^3$

Meteorological Category 6: $K_4 = 123.4 - 127.6 (\log d) + 42.017 (\log d)^2 - 4.584 (\log d)^3$

2 kHz

Meteorological Category 1: $K_4 = -69.9 + 63.6 (\log d) - 16.9 (\log d)^2 + 1.43 (\log d)^3$

Meteorological Category 2: $K_4 = -143.0 + 142.18 (\log d) - 44.509 (\log d)^2 + 4.6195 (\log d)^3$

Meteorological Category 3: $K_4 = -116.3 + 120.85 (\log d) - 39.944 (\log d)^2 + 4.378 (\log d)^3$

Meteorological Category 5: $K_4 = 60.3 - 64.07 (\log d) + 21.458 (\log d)^2 - 2.3784 (\log d)^3$

Meteorological Category 6: $K_4 = 82.3 - 90.98 (\log d) + 31.444 (\log d)^2 - 3.584 (\log d)^3$

4 kHz

Meteorological Category 1: $K_4 = -126 + 128 (\log d) - 40.4 (\log d)^2 + 4.24 (\log d)^3$

Meteorological Category 2: $K_4 = -125.4 + 124.74 (\log d) - 38.807 (\log d)^2 + 4.017 (\log d)^3$

Meteorological Category 3: $K_4 = -127.5 + 135.12 (\log d) - 45.709 (\log d)^2 + 5.1113 (\log d)^3$

Meteorological Category 5: $K_4 = 28.7 - 20.1 (\log d) + 2.68 (\log d)^2 + 0.0957 (\log d)^3$

Meteorological Category 6: $K_4 = 66.4 - 60.77 (\log d) + 16.409 (\log d)^2 - 1.4457 (\log d)^3$

2. Model Having K_4 Independent of Frequency

Meteorological Category 1: $K_4 = -38.9 + 26.4 (\log d) - 2.84 (\log d)^2 - 0.234 (\log d)^3$

Meteorological Category 2: $K_4 = -114 + 119 (\log d) - 39.8 (\log d)^2 + 4.43 (\log d)^3$

Meteorological Category 3: $K_4 = -28 + 21.3 (\log d) - 3.85 (\log d)^2 + 0.0903 (\log d)^3$

Meteorological Category 5/6: $K_4 = 8.21 - 1.14 (\log d) - 2.87 (\log d)^2 + 0.671 (\log d)^3$

3. Vector Wind Model

Meteorological Category 1

63 Hz : $K_4 = -4.9 + 3 (\log d)$

125 Hz : $K_4 = -1.8 + 1 (\log d)$

250 Hz : $K_4 = -2.35 + 1.5 (\log d)$

500 Hz + $K_4 = -2.35 + 1.5 (\log d)$

1 kHz : $K_4 = -0.6 + 2 (\log d)$

2 kHz : $K_4 = -11.5 + 6.3 (\log d)$

4 kHz : $K_4 = -11.5 + 6.3 (\log d)$

Meteorological Category 3

63 Hz : $K_4 = 53.7 - 52.8 (\log d) + 16.113 (\log d)^2 - 1.6262 (\log d)^3$

125 Hz : $K_4 = 76.3 - 78.32 (\log d) + 25.475 (\log d)^2 - 2.7615 (\log d)^3$

250 Hz : $K_4 = -15 + 25.4 (\log d) - 12.235 (\log d)^2 + 1.6109 (\log d)^3$

500 Hz : $K_4 = -4.8 + 23.12 (\log d) - 14.925 (\log d)^2 + 2.2542 (\log d)^3$

1 kHz : $K_4 = -18.6 + 33.25 (\log d) - 16.527 (\log d)^2 + 2.2637 (\log d)^3$

2 kHz : $K_4 = 97.1 - 98.91 (\log d) + 31.91 (\log d)^2 - 3.443 (\log d)^3$

4 kHz : $K_4 = -11.8 + 24.46 (\log d) - 12.695 (\log d)^2 + 1.699 (\log d)^3$

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APPENDIX III GUIDE TO THE APPLICATION OF THE NOISE PROPAGATION MODEL

1. BASIC DATA

For a successful application of the noise propagation model described in this report, some basic information should be available:

a) the sound power level(s) of the noise source(s)

b) a description, in broad terms, of the area under consideration as well as the location and size of major buildings, tank farms etc.

c) the type of requirements applicable to the area under consideration e.g., long term average noise level, "down-wind" noise level etc. which may be statutory

d) meteorological data

A further description of the basic data is given below.

2. SOUND POWER LEVELS

The sound power level is the quantity describing the emission of a source. Extensive procedures, describing how to determine sound power levels, are available from CONCAWE (refs. 14 and 18) and elsewhere (e.g. Ref. 9). For petroleum and petrochemical plants there are three different ways of obtaining sound power levels:

a) For an existing complex it will usually be best to determine the sound power level of individual plants or groups of plants located close together. This may be done using the so-called "perimeter-method" (Ref. 9 App. C). This method is relatively quick, but does not give sound power levels of individual equipment.

b) For a plant in an advanced stage of planning it will usually be possible to get a list of equipment in the future plant. The sound power level of each of the items listed can be obtained, either from the equipment vendor (Ref. 9), by estimation from available correlations, or from measurements on similar equipment.

c) For a plant in an early stage of planning, no details of equipment requirements are available. In some cases the sound power level of a similar plant may be available. Alternatively (but less accurately) the sound power level of the plant could be estimated from the area of the processing units and a typical figure for the sound power emitted per unit area of processing unit. In published literature, (Ref. 19) figures are mentioned ranging from 65 to 75 dB(A) per square metre. The following formula may be used:

$$L_W = L_W^{*} + 10 \log S/S_o$$

where

L_W = the A-weighted sound power level of the plant

L_W^{*} = the typical A-weighted sound power level per square metre of processing area

S = the area of the processing units in m^2

S_o = the reference area = 1 m^2

In addition to the overall A-weighted sound power level it will be necessary to assume a spectrum shape. The following spectrum may be useful for refinery planning purposes:

Octave Band Centre Frequency, Hz	63	125	250	500	1k	2k	4k	8k
Octave Band Power Level minus A-weighted Sound Power Level	+2	– 1	– 2	– 5	– 6	– 7	– 9	– 14

The octave band spectrum is obtained by adding the respective numbers from the above table to the A-weighted sound power level L_W.

In practice the spectrum shape will depend on plant design (water-cooling versus air-cooling, natural draft furnaces versus forced draft furnaces, degree of silencing installed, etc.)

3. TOPOGRAPHY, BUILDINGS

A knowledge of the topography of the area and of the location and size of buildings, tank farms, etc., is required to enable estimates of the attenuation factor K_3, ground effects (see Section 5.1.3) and factor K_6, barrier attenuation (see Section 5.1.6) to be made.

4. TYPE OF NOISE LIMIT REQUIREMENTS

As has been demonstrated in this report, the propagation of noise depends to a large extent on the meterological conditions. Accordingly, at a particular point in the vicinity of a petrochemical plant, the noise level produced by the plant will vary considerably. It is therefore necessary to decide what quantity should be used to describe the situation. This quantity could be the common most unfavourable situation, the year round average noise level, or even long term percentile levels such as L_{50} or L_{10}. L_n is the noise level exceeded n% of the time interval considered.

For the common most-unfavourable situation it will suffice to use the meteorological category 6, as described in this report. For other long term levels it will be necessary to determine the occurrence of all meteorological categories. The noise levels at the neighbourhood points concerned should then be calculated for each of the categories and these should be combined into long term levels. This has been described in section 5.3 of this report.

5. METEOROLOGICAL DATA

The amount of meteorological data required for a calculation depends on the type of noise level required. If only the "down-wind" or the common most-unfavourable noise level is to be determined, no meteorological data are strictly required. If long term averages or percentiles are required, it is necessary to determine the occurrence of the various propagation categories.

This again requires tables of occurrences of Pasquill stabilities, windspeeds and wind directions. These data should be sorted according to the definitions of the propagation categories, (see Section 4). The amount of work involved in sorting the meteorological data may in some cases be reduced. For example, the exercise may be limited to night-data only, when it is clear beforehand that the night situation is controlling, as is usually the case for continuously operating plant with night-time noise limits 5 to 10 dB more stringent than the day-time limits.

6. THE CALCULATION

In principle the calculation is carried out for each combination of source and neighbourhood point. In other words the contribution of each source is calculated for the specified points, after which these contributions are added. In most cases, however, it is possible to combine sources that are located in the same general area, thus reducing the amount of calculation work to be done. It is not recommended to combine sources at largely different elevations, because of the important effect of source height.

Depending on the situation, the attenuation factors for ground effects and barriers may be assumed to be the same for all source-neighbourhood point combinations, e.g. in the case of a dense tank farm between the sources of noise and the neighbourhood, or may have to be calculated individually for each of these combinations separately, e.g. in the case of a few isolated noise barriers.