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The Establishment of a Rapid Method of Making Sound Power Measurements of Machinery Noise Emission

Richard Payne and Dan Simmons

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NPL 
National Physical Laboratory

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ABSTRACT

This report examines in detail the methods described in the ISO 3740 and ISO 9614 series of standards with the principal aims of identifying an efficient standardized measurement technique to obtain rapid sound power measurements, with acceptable levels of measurement uncertainty, suitable for presentation of noise information in accordance with EC directives.

Sound power determinations have been carried out using 32 noise sources with Directivity Index (DI) ranging from 0.8 dB to 8 dB, in acoustic environments with values of K_{2A} from zero to 9.6 dB. The effect on measured sound power levels and on measurement uncertainty of several factors including the number of measurement positions, measurement position orientation relative to source, area and type of enveloping surface, scan distribution and speed and the number of circular, spiral, meridional or rectangular paths, has been assessed. Results show that sound power level determinations performed in a wide range of acoustical environments when the number of measurements is significantly less than recommended in current international standards are of engineering grade accuracy for noise sources with a DI up to 4 dB and of survey-grade accuracy for noise sources with a DI of up to 8 dB.

It is concluded that the present series of standards describing methods for determining sound power levels of noise sources using sound pressure measurements is inadequate to meet present and foreseen regulatory requirements concerning the noise emission of machinery and equipment. The sub-division of standards into separate documents for different acoustic environments and different broad grades of accuracy raises unnecessary complications and makes it difficult for a user to interpret which standard is best suited to a particular application. A new series of standards is proposed, comprising only four documents, ultimately to replace all the existing ones. The measurement methods would relate the number of measurements of sound pressure level to the repeatability of the resultant sound power determination, allowing the number to be increased in order to achieve improved repeatability if required.

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Approved on behalf of the Managing Director, NPL
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1 INTRODUCTION

In recent years a large number of European Directives have been published, containing requirements for determining the sound power levels of machines. The forerunner was Directive 79/113/EEC¹, which included a general method of determining the sound power level of construction plant and equipment. This was implemented by Directive 84/532/EEC² and several subsequent related directives, which imposed sound power limits on a wide range of machines used on construction sites. Separately from these, Directive 86/594/EEC³ made provision for labelling household appliances with their sound power level on a voluntary basis, and this was followed by Directive 92/75/EEC⁴ which made the noise labelling mandatory. Directive 89/392/EEC⁵ (the Machinery Directive) covers the safety of a wide range of machinery types, and it requires manufacturers to give information on the sound power level if the sound pressure level at the work station of a machine exceeds 85 dB(A). In addition to all these, there is another new directive now under consideration which will address the noise emitted by machinery used outdoors⁶. This is intended to supersede some of the earlier directives and will include some new noise limits.

The Machinery Directive is one of the “new approach” kind, which allows manufacturers to refer to standards in order to demonstrate compliance with the requirements. The UK intends that the new directive on machinery used outdoors will similarly refer to published standards. In order to produce the necessary standard noise test specifications, CEN and ISO are working closely together on various methods of measurement, to suit different acoustical conditions. The standards of interest for present purposes are all type B within the CEN hierarchy, that is they apply in principle to the noise of a wide range of machinery types. Type C standards, giving detailed machinery-specific methods will be based on these, and they will select and refer to individual type B standards for the appropriate method of noise measurement.

The ISO 3740⁷⁻¹⁵ series of standards describes methods of determining sound power levels from measurements of sound pressure level around the machinery. The various parts are designed for different acoustic environments and achieve different levels of accuracy. The ISO 9614^{16,17} series of standards describes methods of determining sound power level by sound intensity level measurement. The restrictions on test environment, noise source size and character and background noise are more relaxed than those that apply to the ISO 3740 series.

All these standards are considered by many users as being too complicated and time consuming to use. The usefulness of a sound power measurement standard depends on the speed and accuracy with which results are obtained. The sound power of a noise source is usually determined by carrying out a series of measurements over a hypothetical surface surrounding the source. The shape and size of this surface and the way in which the sound field is sampled affects the accuracy and speed of the measurement. Generally, the more samples that are taken, the higher the grade of accuracy and the longer the measurement takes. The principal aim of the work discussed in this report was to identify an efficient standardized measurement

technique to obtain rapid and accurate sound power measurements suitable for presentation of noise information in accordance with the various EC directives.

Measurement of the noise emission of machinery is of considerable economic importance because machinery cannot now be marketed within the EC unless it carries a conformity mark. The total sales by UK manufacturers including exports of the wide range of machinery covered by the Machinery Directive amounted to more than £18,000M in 1996¹⁸. Noise testing may be carried out by manufacturers or specialist testing laboratories. The cost of noise testing and validation by approved bodies is dependent on machine type but is estimated to be around 3% of the sale price. Given this work load and cost, it is important that the measurement methods are accurate, reproducible, rapid, cost-effective and well understood.

This project examined in detail the methods described in the ISO 3740 and ISO 9614 series of standards with the following principal objectives:

- to investigate, through experiment, methods for conducting sound power measurements rapidly,
- to quantify the accuracy associated with these rapid measurement method(s),
- to document procedure(s) for making these rapid methods.

These objectives were achieved by assessing the accuracy of various sampling techniques against speed of operation. However, it is clear that although a particular technique may provide data quickly, if it is costly in respect of personnel and equipment it may not be attractive to the industrial user. So, in selecting a preferred technique account was taken of:

- the achievable measurement uncertainty
- the time taken to carry out a complete measurement, including setting up the equipment,
- the time taken to carry out a measurement assuming a permanent dedicated facility,
- the cost of equipment needed,
- the requirements of the measurement facility or site,
- expertise (and cost) of personnel.

2 BACKGROUND TO RELEVANT INTERNATIONAL STANDARDS

The two main series of international standards defining generic methods of sound power level determination are the eight standards in the ISO 3740 series for methods using sound pressure level measurements and two in the ISO 9614 series, for methods using sound intensity level measurements. The ISO 3740 series dates back originally to the 1970s and is at present undergoing major revision. The ISO 9614 standards are of much more recent origin; part 1 was published in 1993, and part 2 in 1996.

ISO 3740⁷ serves only as an introduction to the series and does not include any test specifications. The present published version describes the original series and no new version has yet appeared. ISO 3741⁸ and ISO 3742⁹ have not yet been revised and describe precision methods for laboratory reverberation rooms, one applying to machines which emit sound over a broad frequency range with no strong tones and the other specific to machines which emit tones and sound in narrow frequency bands. In both standards, the reverberation room has to be of minimum volume 200 m³, detailed specifications are given for its construction, and the atmospheric temperature and humidity within the room have to be controlled. In ISO 3741, the measurements can be made with either a microphone swept along a path at least 3 m in length, or with an array of at least three fixed microphones. In some cases, the reverberation time of the room must also be measured, or in other cases the sound output of the machine under test can be compared with that of a reference sound source of known sound power output. In ISO 3742, an iterative process is used involving first one position in the room for the machine under test and a minimum of three microphone positions for the measurements, and then extra microphone and machine locations if the overall spread of measured sound pressure levels exceeds given amounts. While in principle there is no restriction as to the kind of machine which can be tested by these methods, the cost of building a chamber conforming to the rigorous requirements is high, the measurement processes are complex, and in consequence the standards are only used for special applications. The type of equipment to which they are most commonly applied is components of heating and ventilation systems, where the amount of noise emitted from grilles and duct terminations is of interest and difficult to measure reproducibly by other means. A draft of a single new standard to replace these two has now been issued by ISO (ISO/DIS 3741:1998) but it appears that the complexity and cost of the new method will be just as great as those of the old ones.

ISO 3743 was conceived as a method for small movable machines in reverberant sound fields, such that less rigorous requirements could be accepted for both the room itself and the measurement method, leading to engineering grade accuracy. The standard was recently revised and new versions issued in two parts, part 1¹⁰ requiring "hard-walled" test rooms of minimum volume 40 m³, and part 2¹¹ giving methods for "special" reverberation rooms of minimum volume 70 m³. In fact, part 2 is merely the original version of ISO 3743 reproduced under a different number, and differs little from ISO 3741 except for the smaller room size allowed. It has been retained in this way because some manufacturers of household electrical appliances have adopted it for quality control and routine production testing. In reality, it is little more "user-friendly"

than the full precision method, and the new part 1 was produced to make the method more practical. The method of measurement in the latter is again based upon a comparison with a reference sound source; in general, measurements are made at only three microphone positions, but more may be required if the machine generates sound tones or is directional in its sound output. For the smallest test rooms, the method is applicable to machines having a largest dimension not greater than 1 m. The standard is so new that it is not yet clear how widely it will be adopted by industry.

ISO 3744¹², ISO 3745¹³ and ISO 3746¹⁴ form a group of standards which address free-field, hemi-free-field and approximately hemi-free-field test environments, using similar measurement methods in all cases. ISO 3745 is the precision method, for laboratory anechoic and hemi-anechoic rooms constructed according to strict requirements, and the conditions achieved in the rooms have to be qualified experimentally; the atmospheric conditions in the rooms also have to be controlled. No environmental correction is made to the results because the performance of a room has to be demonstrably ideal, but a correction is imposed for atmospheric temperatures and humidities where they differ from the reference values. ISO 3744 is the engineering method for a hemi-free field. An environmental correction, K_2 , is defined to allow for deviations of the test conditions from the ideal ones specified, and this is not allowed to exceed 2 dB. For open test sites consisting of a hard, flat ground surface, such as asphalt or concrete, and with no sound-reflecting objects nearby, the standard assumes that K_2 is less than or equal to 0.5 dB and is negligible. There are no restrictions, nor corrections for atmospheric conditions. The survey method is ISO 3746, where the environmental requirements are substantially relaxed and a correction of up to 7 dB is allowed. This allows measurements to be made with machinery in situ in its working conditions. The methods of measurement are essentially similar in all three standards, with more microphone positions required for the higher grades of accuracy. Microphones are arrayed over a measurement surface in the form of a sphere or hemisphere for ISO 3745, or over a hemisphere or rectangular box for ISO 3744 and ISO 3746. The numbers of positions generally increase with the size of the machine under test, but the minimum requirements are for twenty positions on a sphere for ISO 3745, ten on a hemisphere for ISO 3744 and four on a hemisphere for ISO 3746. There are now many laboratory rooms or outdoor test sites in the UK that conform with ISO 3744, but only a few complying with ISO 3745. While the application of the latter standard is restricted almost entirely to research, ISO 3744 and ISO 3746 are used to test a very wide range of machine types and together these methods are by far the most commonly used ones for sound power determinations, certainly in the UK and probably throughout the world.

ISO 3747¹⁵ is another survey method, this time using a calibrated reference sound source and therefore involving comparison measurements with the machine under test. According to the present standard, there is no restriction on the acoustic environment, and the method is said to be applicable in ordinary rooms, industrial workshops, and confined outdoor spaces. The measurement method is first to place the reference sound source on, or very close to, or even in the position to be occupied by the machine under test, measure the sound pressure levels it generates at a minimum of five positions on a rectangular surface around the source, and so determine its sound power level in that

position. The difference from the calibrated sound power level gives a "correction" applicable to that environment. A similar sound power determination is then performed on the machine under test and the correction is applied. ISO 3747 is now almost 10 years old and experience has shown that it only yields reliable results in approximately reverberant surroundings. It is therefore being revised with this restriction, but this and ISO 3746 together cover many practical circumstances where sound power levels have to be obtained in situ.

The great advantage claimed for sound power determinations using sound intensity measurements is freedom from restriction on the environment. The methods given in ISO 9614-1¹⁶ and ISO 9614-2¹⁷ are said to be applicable to any machine anywhere, so long as a physically stationary measurement surface can be defined, the noise output is stable with time, and the probe used for the measurements does not have to be placed in a gas flow of unacceptable speed. The standards call for the use of an intensity probe which meets the requirements of IEC 61043¹⁹. While there are different types of probe on the market, the only conforming type at present is one consisting of two closely matched microphones spaced a short distance apart. ISO 9614-1 requires measurements at discrete positions on a measurement surface, and ISO 9614-2 specifies procedures for continuous measurements whilst the probe is scanned across segments of a surface. In both cases, an initial test is performed using a trial surface, with at least ten uniformly distributed discrete positions for the probe or scans of duration not less than 20 s at specified speeds over the various segments. The results of these initial tests are used to check the adequacy of the measuring equipment, the suitability of the measurement surface, the adequacy of the array of measurement positions, and for concentrations of partial sound power emitted over small areas. The standards define certain "field indicators" for these purposes, and give instructions for more extensive measurements to be made or an alternative measurement surface to be used to satisfy the requirements and to achieve a desired grade of accuracy. If the requirements are satisfied in the initial test, then the results can be processed immediately to yield the sound power level of the machine, but in general an iterative process is necessary, possibly requiring measurements at up to 100 positions or more, or slow scans requiring motorised control over closely defined segments. The measuring equipment for sound intensity methods is more costly than that for sound pressure methods, and the former call for much greater technical skill on the part of the personnel who perform them. On the other hand, sound intensity measurements do not require the capitally expensive laboratory facilities that are necessary to the standards producing high accuracy with sound pressure measurements.

3 GENERAL PROGRAMME DESIGN CONSIDERATIONS

3.1 INDUSTRIAL CONSULTATION EXERCISE

Before finalising details of the experimental programme discussed in this report an industry consultation exercise was carried out to ascertain the measurement procedures currently used, the type of measurement equipment and the level of expertise in making sound power level determinations. Detailed results of this consultation are reported by Higginson²⁰⁻²¹ but are briefly outlined below.

In all, thirteen organisations were visited. These covered a wide range and included companies engaged in mass production and others producing one-off machines to order, companies producing very large machines (with dimensions of several metres) as well as quite small ones, companies with sophisticated test facilities and others with no acoustical laboratory and only basic noise measuring instruments, companies which carry out type testing only and others who undertake production testing as well, and test houses and a university department offering consultancy services.

Test facilities and techniques varied widely with one company carrying out measurements in-situ on the factory floor, three using the semi-reverberant procedures of the ISO 3740 series and nine using the hemi-anechoic procedure of ISO 3744. Reservations about sound intensity methods were widely held, but many of those visited possessed the necessary equipment.

Regarding the time taken to undertake noise emission tests almost all the organisations emphasised the time consuming effort needed to set up the machines and to achieve stable running conditions. Some need for a rapid turn-round time of testing was expressed by companies engaged in volume production and requiring to test routinely for noise following final assembly, but more generally, all companies were anxious to pursue any efficiency gains that might be achievable. Possible applications for a rapid method of sound power determination would also include routine production testing.

None of the organisations could be said to have investigated thoroughly their measurement uncertainties, though in fairness none had been asked to supply such data by any of their customers.

3.2 OUTLINE OF THE EXPERIMENTAL WORK PROGRAMME

The objective of the experimental work programme was to identify a rapid (cost-effective) measurement technique to obtain accurate sound power measurements suitable for noise information purposes. This experimental objective was achieved by an extensive analysis of factors affecting sound power determined using several International Standards chosen from the ISO 3740 series and the ISO 9614 series. Table 1 summarises the applicability of the ISO 3740 series and includes information, where

Table 1 Summary of the applicability of the ISO 3740 series of standards

International Standard	Classification of method	Test environment	Volume of source	Character of noise	Sound power levels obtainable	Optional information available
3741	Precision (grade 1) $\sigma_R = 0.5 \text{ dB}$ 3742, $\sigma_R = 1.5 \text{ dB}^*$	Reverberation room meeting specified requirements	Preferably less than 1% of test room volume	Steady, broad-band	In one-third octave or octave bands	A-weighted sound power level
3742				Steady, discrete frequency or narrow-band		
3743-1	Engineering (grade 2) 3743-1, $\sigma_R = 1.5 \text{ dB}$ 3743-2, $\sigma_R = 2.0 \text{ dB}$	Hard-walled test room		Steady, broad-band, narrow-band or discrete frequency	A-weighted and in octave bands	Other weighted sound power levels
3743-2		Special reverberation test room				
3744	Engineering (grade 2) $\sigma_R = 1.5 \text{ dB}$	Outdoors or in large room, on a hard surface	No restrictions; limited only by available test environment	Any	A-weighted and in one-third octave or octave bands	Directivity information and sound pressure levels as a function of time; other weighted sound power levels
3745	Precision (grade 1) $\sigma_R = 1.0 \text{ dB}^*$	Outdoors or semi-anechoic room	Preferably less than 0.5% of test room volume	Any		
3746	Survey (grade 3) $\sigma_R = 4 \text{ dB}$	No special test environment	No restrictions; limited only by available test environment	Any	A-weighted	Sound pressure levels as a function of time; other weighted sound power levels
3747	Survey (grade 3) $\sigma_R = 4 \text{ dB}$	No special test environment: source under test not moveable	No restrictions	Steady, broad-band, narrow-band or discrete frequency	A-weighted	Sound power levels in octave bands
σ_R , is the reproducibility standard deviation for A-weighted sound power levels (* estimated from 1 kHz values) Note: ISO 3741 and ISO 3742 are to be combined in a single standard and ISO 3745 and ISO 3747 are under revision.						

available, on the estimates of reproducibility uncertainty, σ_R , for each standard. ISO 3740 itself is not considered as it serves only as an introduction to the series and does not include any test specifications.

ISO 3741, ISO 3742 and ISO 3745 describe precision (grade 1) methods, the first two for laboratory reverberation rooms and the third for laboratory anechoic rooms. While in principle there is no restriction as to the kinds of machine which can be tested by these methods, the cost of building chambers conforming to the rigorous requirements is high, the measurement processes are complex, and in consequence the standards are only used for special applications. They will not normally be used by machinery manufacturers to make sound power measurements for the purpose of the Machinery Directive and are, therefore, not considered in this report. A draft of a new standard to replace ISO 3741 and ISO 3742 has now been issued by ISO, but it appears that the complexity and cost of the new method will be just as great as those of the old ones.

ISO 3743-1 and ISO 3743-2 are grade 2 methods applicable to a reverberant test environment and suitable for small (dimensions 1 m to 2 m) machines. The test room itself may be as small as 40 m³ for sources whose largest dimension does not exceed 1 m.

ISO 3744 (grade 2 accuracy) and ISO 3746 (grade 3 accuracy) address hemi-free-field and approximately hemi-free-field test environments, and use similar measurement methods. There are now many laboratory rooms or outdoor test sites in the UK that conform with these two Standards and they are currently used to test a very wide range of machine types and together these methods are by far the most commonly used ones for sound power determinations, certainly in the UK and probably throughout the world.

ISO 3747 is a survey (grade 3) method with no restriction on acoustical environment, in which a comparison is made with the output of a calibrated reference sound source. In practice, it has been shown to yield reliable results only in approximately reverberant surroundings. However, this includes many practical workshop surroundings. This standard is currently under revision and will become an engineering-grade method.

As sound intensity based methods, ISO 9614-1 and ISO 9614-2 are applicable to a wide range of environments and will also tolerate the presence of extraneous noise, though the grade of accuracy achieved (grades 1 to 3 for part 1, grades 2 to 3 for part 2) deteriorate as the conditions become more extreme.

The Standards considered in this report are therefore the sound-pressure based methods of ISO 3743-1, ISO 3743-2, ISO 3744, ISO 3746 and ISO 3747 and the sound-intensity based methods of ISO 9614-1 and ISO 9614-2.

However, since ISO 3744 is currently one of the most widely used standards (see Section 3.1) and ISO 9614-1 and ISO 9614-2 represent the “new wave” of intensity based standards with potential for application to a wide range of sources and acoustic environments, it is these which were investigated in greatest depth, to identify ways of speeding up the measurement process without unduly jeopardising accuracy. The

objective of the programme was to devise a technique with an accuracy in the range grade 2 to grade 3, recognising that machinery noise test codes already exist that claim either grade 2 or grade 3 accuracy. The programme focused on hemispherical and parallelepiped measurement surfaces since these underpin all of the sound-pressure based standards; other measurement surfaces can be regarded as derivatives of these two basic types.

Techniques based on sound pressure measurements to ISO 3744 and to ISO 9614-1 and ISO 9614-2 were evaluated, addressing hemispherical and parallelepiped surfaces. Baseline sound power levels and associated measurement uncertainties (to include random uncertainties obtained by repeat measurements) were determined strictly according to the Standards. These standards permit measurements to be made employing either a hemisphere or a parallelepiped as the enveloping surface. A wide range of surface sizes may be chosen. There is however, a minimum surface area which is governed by the dimensions of the machine. The machine dimensions are described in the standards in terms of the size of the "reference box" and d_0 , the "characteristic dimension". The reference box is a hypothetical surface which is the smallest rectangular parallelepiped that just encloses the source and terminates on the reflecting plane. The characteristic dimension is half the length of the diagonal of the box consisting of the reference box and its images in adjoining reflecting planes. The radius, r of the hemispherical measurement surface must be greater than or equal to twice the characteristic dimension and not less than 1 m. For the parallelepiped surface the measurement distance, d (the perpendicular distance between the reference box and the measurement surface) must be at least 0.25 m. Typical measurement configurations for a hemispherical surface and for a parallelepiped surface are shown in Figures 1 and 2 respectively.

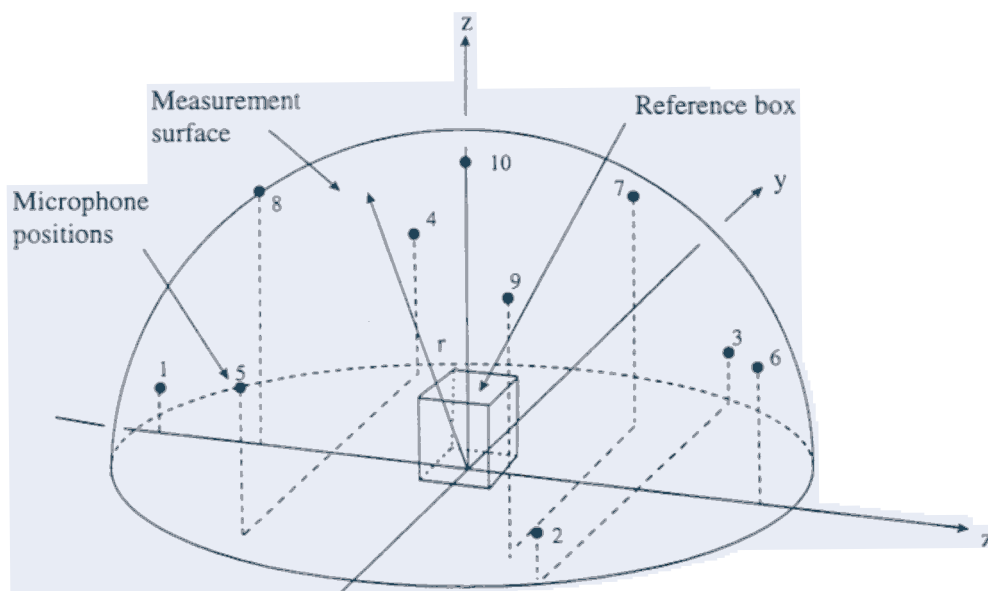


Figure 1.
Typical hemispherical measurement surface

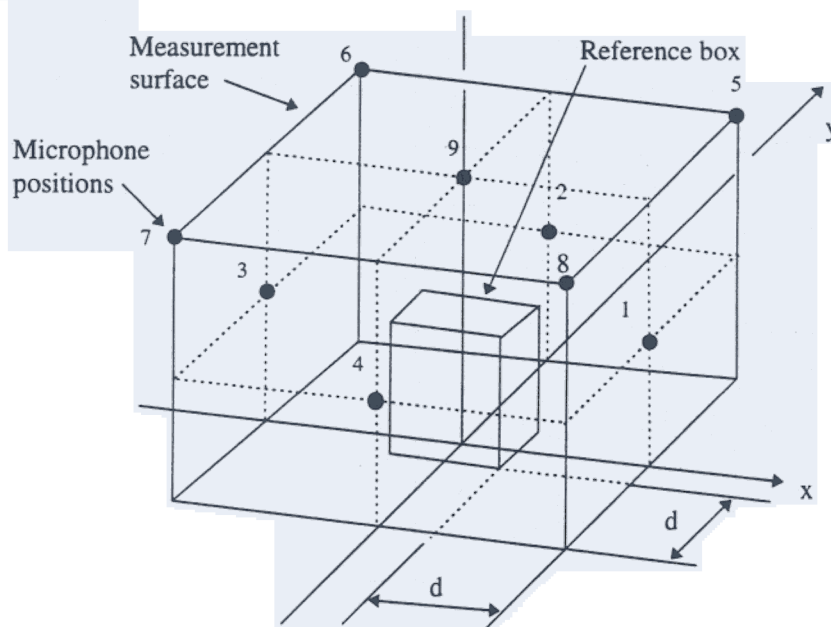


Figure 2. Typical parallelepiped measurement surface

Further measurements were then made to assess the effect on measured sound power level and measurement uncertainties of varying the following parameters.

For measurements at discrete points:

- number of measurement positions,
- measurement position orientation relative to source (hemisphere only),
- area of enveloping surface,
- measurement averaging time
- environmental correction factor (K_2)
- the use of microphone arrays

For measurements by scanning:

- number of circular/spiral paths (hemisphere only)
- number of meridional paths (hemisphere only)
- number of rectangular paths (parallelepiped only)
- scan distribution (parallelepiped only)
- scan speed
- area of enveloping surface
- mechanical scan
- manual scan

These initial assessments were carried out using a small number of machines that were considered as reasonably acoustically complex noise sources and typical of the type of machines that will be subject to compliance with noise limits and measurement procedures set out in numerous EC Directives. The range of machines and acoustic environments was extended during the final assessment phase of the experimental programme and this is discussed in detail in the Sections 6 and 7 of this report.

These assessments were followed by a series of measurements according ISO 3743-1, ISO 3743-2, ISO 3746 and ISO 3747 in several acoustic environments ranging from hemi-anechoic to semi-reverberant.

Baseline sound power levels and associated measurement uncertainties were determined according to these four Standards and were compared with data obtained using the preferred rapid sampling technique in order to assess the effectiveness of the technique for these standards. Conclusions regarding the preferred technique were assessed in the light of these results.

Finally the performance of the preferred rapid technique was thoroughly assessed using a large number of machines covering a wide range of Directivity Index and in acoustical environments from hemi-anechoic to reverberant. The accuracy (measurement uncertainty) of the preferred method was determined and compared with that obtained using other spatial sampling arrangements.

Details of noise sources and description of indoor and outdoor measurement sites used in the various stages of this investigation are included in the discussion of the experimental results in Sections 4 to 7.

4 OUTDOOR MEASUREMENTS IN HEMI-ANECHOIC CONDITIONS

4.1 MEASUREMENT SITE AND INSTRUMENTATION

Measurement site

All the initial hemi-anechoic measurements described in this Section were carried out on an outdoor hemi-anechoic site at NPL. This site consists of a large flat surface covered with concrete to a depth of at least 0.2 m and approximately 50 m square with no sound-reflecting objects.

Instrumentation

There is an inherent requirement for all instrumentation to adhere to the specifications described in the various standards under examination. The instrumentation used to carry out the basic noise measurements discussed in this report complied with these specifications and where necessary had current traceable calibration certificates. Brief details of the instrumentation used are listed below.

For sound power determination using measurements of sound pressure level:

dual channel frequency analyser	Brüel & Kjær	type 2144,
microphone(s)	Brüel & Kjær	type 4165,
microphone preamplifier(s)	Brüel & Kjær	type 2639,
pistonphone	Brüel & Kjær	type 4228.

For sound power determination using measurements of sound intensity level:

dual channel frequency analyser	Brüel & Kjær	type 2144,
microphones (matched pair)	Brüel & Kjær	type 4181,
sound intensity probe	Brüel & Kjær	type 3548,
sound intensity calibrator	Brüel & Kjær	type 3541.

For sound power determinations using a sound level meter:

sound level meter (with sound power software)	Norsonic	type 116,
microphone preamplifier	Norsonic	type 1201,
microphone	Norsonic	type 1220,
sound calibrator	Norsonic	type 1250.

The data was stored and processed on a pc using Lotus 1-2-3 release 4.

4.2 MACHINES USED FOR THE HEMI-ANECHOIC MEASUREMENTS

Initially, the majority of tests were conducted on a diesel-engined electrical power generator. This was considered as a reasonably acoustically complex engine-powered noise source and is typical of the type of machine that will be subject to compliance with noise limits and measurement procedures set out in numerous EC Directives. Unless otherwise stated measured data in this Section have been obtained using the generator as the noise source. Most measurement configurations were repeated using a reference sound source. This is a stable, calibrated, omnidirectional broad-band source that provides a common point of reference. Finally a limited series of measurements were carried out on two other machines, a two-stroke petrol-engined lawnmower and a diesel-engined air compressor. All these noise sources were used free-standing on the floor of the test area. Approximate overall sizes (in length, breadth and height order) and brief details of each machine are listed below.

Reference sound source

Manufacturer:	Brüel & Kjær
Type:	4204
Power requirement:	240 volt mains
Size:	0.3 m: 0.3 m: 0.3 m

Electrical power generator

Manufacturer:	Lombardini (engine).
Type:	GLD360.
Power requirement:	diesel fuel, SAE grade 15/40 oil.
Size:	0.5 m: 0.7 m: 0.7 m

Two-stroke petrol-engined lawnmower

Manufacturer:	Siag (lawnmower), Briggs and Stratton (engine).
Type:	Harry.
Power requirement:	Unleaded petrol in 50:1 ratio with a two stroke oil.
Size:	0.5 m: 0.7 m: 0.4 m

Diesel-engined air compressor

Manufacturer:	Atlas Copco.
Type:	XAS 35 Air Compressor.
Power requirement:	diesel fuel, SAE 15/40 motor oil, hydraulic oil of ISO recommended viscosity of VG32.
Size:	1.2 m: 1.6 m: 1.2 m

4.3 EFFECT OF THE SIZE OF THE ENVELOPING SURFACE

Hemispherical surfaces

Sound power determinations were performed according to ISO 3744 using three hemispherical enveloping surfaces, with radii of 2 m, 4 m and 6 m. In each case a ten microphone array was used. The 2 m radius is the smallest permitted by ISO 3744, and the other two are the next two larger preferred values. Three independent sound power determinations were carried out at each radius. The standard deviation of repeatability was found to be 0.04 dB for the 2 m and 4 m radii data and 0.16 dB for data obtained using the 6 m radius, an average of 0.08 dB. These data suggest that the smaller radii provide the more repeatable results. However, there was no statistically significant variation in sound power level determination between data obtained from the three radii, although on inspection there was a tendency for the sound power level to decrease with increasing radii, the value at 6 m being 0.3 dB higher than that at 2 m. This may be because the influence of meteorological conditions has a greater effect on the sound propagation at the larger distance. The standard deviation about the mean sound power level from all three radii was 0.15 dB.

It is concluded that the effect on sound power level of variations in radii (permitted by ISO 3744) is negligible and it was decided therefore to concentrate further experimental investigations on measurements using the smallest permitted radius. With the smaller radius the microphones are closer together and therefore potentially require less time to set up. Furthermore, if a single microphone (or sound level meter) is used less time is taken moving between positions. In addition, a smaller measurement site may be used. This is especially important if a hemi-anechoic room is required. This is the case for a number of machinery manufacturers and test houses²⁰⁻²¹.

Parallelepiped surfaces

Sound power determinations were also performed using parallelepiped enveloping surfaces. Three parallelepipeds were used with measurement distances of 0.25 m, 1 m and 2 m. The smallest measurement distance permitted by ISO 3744 is 0.25 m, 1 m is the preferred distance and 2 m is the next larger value. The number of microphone positions used were as required by ISO 3744 and varied between thirty-seven and nine. Three independent sound power determinations were carried out at each measurement distance. The repeatability standard deviations were 0.2 dB, 0.23 dB and 0.1 dB for measurement distances of 0.25 m, 1 m and 2 m respectively, an average of 0.18 dB. Here the larger distance would appear to provide slightly less repeatable results than for data obtained from the hemispherical surface but the difference in the average results suggest that this is not significant. The standard deviation about the mean is 0.36 dB and there was no statistical significant difference between results, and for this case there is no obvious trend.

It was decided, therefore, to concentrate the experimental investigation into establishing

a rapid method of sound power determination on measurements using the 1 m measurement distance. This is the preferred ISO 3744 value and requires less microphone locations than the smaller measurement distance, the 0.25 m distance requires thirty-seven positions whilst the 1 m distance requires only nine.

Initial comparison of results from the two surface shapes

It is interesting at this point to briefly compare data from the two methods. Sound power levels determined using a hemispherical surface are slightly more repeatable with an average repeatability standard deviation of 0.08 dB compared with 0.18 dB for the parallelepiped but not statistically significant. However, a comparison of absolute sound power level shows a difference of approximately 1 dB between the mean values with the parallelepiped providing the larger estimate. The standard deviations of 0.36 dB and 0.15 dB indicate that this is just statistically significant at the 95% confidence level. These differences between the two methods are discussed in more detail in Section 4.4.6.

4.4 THE EFFECT OF THE NUMBER OF MEASUREMENT LOCATIONS

Sound pressure level measurements on a hemispherical surface

An examination of the effect on measured sound power level of the varying the number of microphones used for measurements on a hemispherical enveloping surface was carried out using the twenty microphone array of ISO 3744. Sound power levels determined with this array were used as reference levels to which data from other arrays and configurations are compared and furthermore, are assumed to be true values. In fact the twenty microphone positions are formed from two sets of ten microphone positions each having a microphone directly over the machine at a height equal to the hemisphere radius, so this array actually has nineteen discrete positions. The coordinates of the twenty microphone positions, described as a function of the hemisphere radius r , are listed in Table 2 in terms of their x , y and z coordinates (see Figure 1) the ten positions shown in Figure 1 are designated numbers 1 to 10.

Eight independent sound power determinations were made with the machine rotated by 45° between each determination in order to assess the effect of the orientation of the machine relative to the microphone array. This will give a measure of the sampling accuracy of the microphone distribution. It will be expected that there will be a variation in measured sound power levels if there are not enough microphone locations. Initially each measurement was repeated three times to assess the level of repeatability.

Table 2 Coordinates of microphone positions according to ISO 3744

microphone position	x/r	y/r	z/r
1	-0.99	0	0.15
2	0.50	-0.86	0.15
3	0.50	0.86	0.15
4	-0.45	0.77	0.45
5	-0.45	-0.77	0.45
6	0.89	0	0.45
7	0.33	0.57	0.75
8	-0.66	0	0.75
9	0.33	-0.57	0.75
10	0	0	1.0
11	0.99	0	0.15
12	-0.50	0.86	0.15
13	-0.50	-0.86	0.15
14	0.45	-0.77	0.45
15	0.45	0.77	0.45
16	-0.89	0	0.45
17	-0.33	-0.57	0.75
18	0.66	0	0.75
19	-0.33	0.57	0.75
20	0	0	1.0

The repeatability was found to be of the order of 0.05 dB which compares favourably with previous estimates (see Section 4.3.1). The prime factor to be assessed is how well any particular sound power level determination approximates the true value. The actual absolute sound power level of the source is of little interest here. Therefore, all sound power determinations have been expressed relative to the appropriate 20-microphone assessment. The values of sound power level obtained from these measurements that were determined using sound pressure level data from all twenty microphone positions are shown as a function of orientation angle in column two (headed "1-20") of Table 3. The standard deviation about the mean of the nine sound power level determinations listed in column 2 of 0.1 dB is similar to the standard deviation for repeatability

discussed in Section 4.3.1. This indicates that the twenty microphone array is sufficient to adequately describe the sound power level over the enveloping surface and should provide a true determination of the sound power level of the generator. Thus the use of this array as the reference (true) value is justified and the mean sound power level at the bottom of column 2 is therefore taken as the reference to which all other determinations will be compared. Hence, the mean sound power level determined using the 20 microphone, ISO 3744 array is listed in Table 3 as zero.

Table 3. Sound power level re true values for pressure level measurements

Angle (deg)	microphone positions					
	1 to 20	1 to 10	11 to 20	4,5,6,10 14,15,16,20	4,5,6,10	14,15,16,20
0	0.2	-0.2	0.5	0.8	0.5	1.0
30	-0.1	-0.1	-0.1	0.6	0.5	0.6
45	0.2	0.0	0.4	0.7	0.5	1.0
90	0.0	0.4	-0.4	0.2	0.5	-0.1
135	0.2	0.3	0.0	1.0	1.4	0.5
180	-0.1	0.2	-0.3	0.3	0.5	0.2
225	0.0	0.0	0.1	0.6	0.5	0.7
270	-0.1	0.4	-0.2	0.4	0.6	0.2
315	0.0	0.4	-0.4	0.6	0.9	0.2
mean	0	0.2	0.0	0.6	0.7	0.5
sd	0.1	0.2	0.3	0.2	0.3	0.4

For comparison purposes the third column of Table 3 shows sound power level determinations using microphones 1-10 (the "key" positions of ISO 3744) and column four shows sound power levels determined using microphones 11-20 (the "additional" positions of ISO 3744). Column five lists sound power levels determined using all eight possible positions according to ISO 3746 with data for the four "key" positions in the sixth column and "additional" four positions in column seven. For each case the mean value for all eight orientation angles and the standard deviation about this mean is given in the bottom two rows of Table 3.

From Table 3 it can be seen that the values of standard deviation generally tend to increase as the number of microphone positions is reduced, as may be expected, and for the twenty microphone position (ISO 3744 array) is the smallest.

The standard deviations for the two 10 microphone arrays of 0.2 dB and 0.3 dB are slightly higher but the sound power levels with differences of 0.2 dB and 0.0 dB are similar to the true value and certainly statistically identical. The standard deviation for the eight microphone ISO 3746 array is similar to the ten microphone values and the two variants of the four microphone arrays have slightly higher standard deviations. The latter is a clear indication that the four microphone arrays do not provide an adequate representation of the sound power levels over the enveloping surface, although the magnitude of the standard deviations is not excessively large and may still result in an acceptable level of accuracy and should be adequate for noise labelling purposes that do not involve compliance with noise limits.

However, if we now consider the sound power levels obtained using these ISO 3746 arrays (the last three columns of Table 3) it can be seen that they are on average 0.6 dB higher than the reference value. This difference is statistically significant and indicates that although the repeatability standard deviations relating to variations in orientation are perhaps acceptable the sound power level determination is not. The reason for this is that the distribution of the microphones on the surface of the hemisphere is not sufficient to account for vertical variation in source output. Positions 10 and 20 are directly above the source but the other six are at the same height. Results are repeatable at each source orientation as the microphones positions, while not completely accounting for horizontal directivity, do provide repeatable sound pressure levels at each of the four positions.

For comparison purposes the above measurements were repeated using a more limited range of combinations of measurement positions and orientation to determine sound power levels of a reference sound source. The results are shown in Table 4 again relative to the mean "1 to 20" value.

Table 4. Sound power level re true values for the reference sound source

Angle (deg)	Microphone positions					
	1 to 20	1 to 10	11 to 20	4,5,6,10 14,15,16,20	4,5,6,10	14,15,16,20
0	-0.2	-0.2	-0.2	0.0	0.0	-0.4
45	0.2	0.2	0.1	0.5	0.4	0.0
90	0.1	0.2	0.0	0.4	0.4	0.2
mean	0	0.1	0.0	0.2	0.3	-0.2
sd	0.2	0.2	0.2	0.3	0.2	0.2

It can be seen that the standard deviations are very similar to those associated with the generator but for the reference sound source there is no significant variation in sound power level with orientation angle or sub-set. This result is to be expected as the

reference sound source is, by definition, acoustically omnidirectional.

The twenty microphone array provides the possibility of obtaining six sub-sets of four microphone positions that are evenly distributed in both horizontal and vertical planes. In each sub-set the microphone directly over the source is used with the remaining microphone positions at three different heights in each case. Sound power level determinations were made for each of these six arrays for each of five source orientations with 45° variations covering an range of 180° . The array distributions are such that the additional three angles required to cover the full 360° are, in effect, repeat combinations. The combinations (by ISO 3744 microphone position number) are shown in the first column of Table 5.

Table 5. Sound power level re true values using sub-sets of four-microphones

microphone numbers	machine orientation (degrees)						mean	sd
	0	30	45	90	135	180		
1, 15, 9, 20	0.3	0.0	0.1	-0.3	-0.2	0.1	0.0	0.2
12, 6, 17, 20	0.6	0.5	0.1	-0.3	-0.3	-0.4	-0.1	0.4
3, 14, 8, 20	0.0	-0.1	0.0	-0.4	0.1	-0.1	-0.1	0.2
11, 5, 19, 20	0.2	-0.3	-0.1	-0.6	0.6	-0.3	-0.1	0.5
2, 16, 7, 20	0.2	0.1	0.2	-0.2	-0.3	0.0	0.0	0.2
13, 4, 18, 20	0.5	0.0	0.1	-0.1	0.6	-0.3	0.2	0.5
mean	0.3	0.0	0.1	-0.3	0.1	-0.2		
sd	0.2	0.3	0.1	0.2	0.4	0.2		
mean (all 20)	-0.1	-0.2	0.1	-0.1	0.1	-0.2		

The sound power levels determined from these thirty-six sets of measurements are shown in Table 5 together with two sets of means and standard deviations; the last two columns are mean values for each sub-set across machine orientation with associated standard deviation, the two rows before the last row are the mean values for each orientation across all sub-sets and associated standard deviation. The last row represents the value of sound power determined for each orientation using all twenty microphone locations. All values in the Table are expressed relative to the mean of these six twenty-microphone determinations.

It can be seen from Table 5 that the variation of all mean values is reasonably small with standard deviations between 0.1 dB and 0.5 dB. The overall standard deviation of all thirty-six determinations is 0.3 dB. It may be concluded, therefore, that the measured sound power level is not significantly dependent on which four-microphone sub-set is used or on the orientation of the machine. Thus it would appear that an array of only

four microphones such that each microphone is at a different height produces repeatable estimates of sound power level. A similar conclusion was made regarding the four-microphone array from ISO 3746 (see Table 3). However, it can be seen from Table 5, that the sound power level determinations are almost identical to the reference (true) value when the microphones are at differing heights. The mean sound power level of all thirty-six measured values in Table 5 is the same as the mean value for the same five orientations of the twenty-microphone array (from Table 3).

The measurements discussed above using the six sub-sets were repeated using the reference sound source. The mean of the six determinations was the same as the mean value from Table 5 with a standard deviation of 0.3 dB. As would be expected for this “omni-directional” source, these values compare well with the twenty microphone array data in Table 5.

4.4.2 Sound intensity level measurements on a hemispherical surface

The combinations of measurement positions and machine orientation described in Section 4.4.1 were repeated using measurements of sound intensity levels to determine sound power levels. These measurements were carried out using commercial software according to ISO 9614-1. As would be expected the results for the reduced number of microphone positions were accompanied by numerous field indicator fail messages, these messages were ignored and results are shown in Table 6 in the same format as used in Table 3, expressed relative to the mean value determined using the twenty microphone array.

A comparison with the corresponding estimates of sound power level obtained from sound pressure level measurements, shown in Table 3 shows good agreement with identical standard deviations but with slightly higher (0.2 dB) value of sound power level for the 20-microphone (reference) array. This small difference is probably the result of the acoustic environment (not perfectly hemi-anechoic). An environmental correction factor (K_2 in ISO 3744) is required for the pressure level technique but is not necessary for the intensity level technique. However, the size of measurement uncertainties involved precludes a meaningful assessment of such a small value of K_2 .

The four-microphone array data corresponding to Table 5 is shown in Table 7 with results in the same format as used in Table 5, expressed relative to the mean value determined using the twenty microphone array. Here the intensity level results are almost identical to the pressure level data in Table 5, with an overall mean sound power level only 0.1 dB less than the pressure level value and with the same value of standard deviation, of 0.3 dB.

Table 6. Sound power level re true values for intensity level measurements

Angle (deg)	microphone positions					
	1 to 20	1 to 10	11 to 20	4,5,6,10 14,15,16,20	4,5,6,10	14,15,16,20
0	0.2	-0.2	0.5	0.7	0.4	0.9
30	-0.2	-0.2	-0.3	0.3	0.4	0.3
45	0.3	0.0	0.3	0.6	0.4	0.8
90	0.1	0.4	-0.3	0.3	0.4	0.1
135	0.1	0.3	-0.1	0.9	1.4	0.3
180	0.0	0.3	-0.3	0.3	0.4	0.1
225	0.0	0.0	0.1	0.6	0.5	0.7
270	-0.1	0.4	-0.2	0.3	0.5	0.1
315	-0.1	0.3	-0.5	0.3	0.7	-0.1
mean	0	0.1	-0.1	0.5	0.6	0.4
sd	0.2	0.2	0.3	0.2	0.3	0.4

Table 7. Sound power level re true values for intensity level measurements using sub-sets of four-microphones

machine number	machine orientation (degrees)						mean	sd
	0	30	45	90	135	180		
1, 15, 9, 20	0.3	0.0	0.1	-0.2	-0.1	0.2	0.1	0.2
12, 6, 17, 20	0.6	0.3	0.3	-0.2	-0.3	-0.2	0.0	0.4
3, 14, 8, 20	0.2	-0.5	0.0	-0.1	0.0	0.0	0.0	0.1
11, 5, 19, 20	0.3	-0.2	0.1	-0.6	0.7	-0.3	0.0	0.5
2, 16, 7, 20	0.3	-0.1	0.3	-0.1	-0.4	0.0	0.0	0.3
13, 4, 18, 20	0.6	-0.1	0.3	-0.1	0.7	-0.3	0.1	0.4
mean	0.4	-0.1	0.2	-0.2	0.1	-0.1		
sd	0.2	0.3	0.1	0.2	0.5	0.2		
mean (20 pos)	0.1	-0.3	0.2	0.0	0.0	-0.1		

Effect of reducing the radius of hemispherical surfaces below the ISO 3744 minimum using a four-microphone array.

As discussed in Section 4.3, the effect of the size of the hemispherical enveloping surface on measurements of sound power level was found to be negligible. The minimum radius permitted by ISO 3744 was chosen to investigate the effect of array size and machine orientation. The four-microphone-different-height array was found to provide good estimates of sound power level with reasonable repeatability standard deviations at this minimum radius (by inference, this should also be the case for larger radii). Although sound power level evaluations using the four-microphone array may be performed very quickly, it was decided to investigate the effect of reducing the radius still further, which should be accompanied by a further reduction in measurement time.

Sound power level evaluations using sound pressure level and sound intensity level techniques were carried out using the four-microphone array with hemispheres of radii of 1.5 and 1 m, and results compared with data previously obtained using the 2 m hemisphere. The sound power level determinations using measurements of sound pressure level increased by 0.2 dB using the 1.5 m radius and 0.4 dB for the 1 m radius. These increases are the result of near field effects which affect measurements made using sound pressure. The corresponding results for the intensity technique showed no variation with the change in radius.

Summary of measurements on the effect of the number of measurement locations on a hemispherical surface.

Sound power levels determined using only four microphone positions chosen from the ISO 3744 twenty-microphone array such that all are at different heights and on radii that have equal angular spacing were found to be on average within 0.1 dB of true values. The average of the standard deviations of these determinations were found to be 0.3 dB but may be as high as 0.5 dB. If hemispheres with radii less than the ISO 3744 minimum are used the sound power level obtained using measurements of sound pressure level increases; those determined using intensity techniques remain constant.

Sound pressure and intensity level measurements on a parallelepiped surface

ISO 3744 and ISO 3746 have two main options for the shape of the enveloping surface; a hemisphere and a parallelepiped. The effect of reducing the number of microphone positions on the surface of the hemispheres has been discussed in Sections 4.4.1 and 4.4.2 and a potential more rapid procedure identified. The number of microphone positions that are required when considering parallelepiped surfaces is dependent on the machine dimensions and the area of the enveloping measurement surface (measurement distance) and on the Standard adopted. The measurement distance, d , is the distance from the reference box to a box-shaped measurement surface; where the reference box is the smallest rectangular parallelepiped that just encloses the source and terminates on the reflecting plane. ISO 3744 recommends a value of d of 1 m

but permits a minimum of 0.25 m. With a measurement distance of 0.25 m the minimum number of microphone positions required by ISO 3744 is thirty-seven. This number can be reduced while still maintaining an even distribution around the parallelepiped in three steps, first to twenty, then nine and finally to five, the latter corresponding to the ISO 3746 requirement. With a measurement distance of 1 m the ISO 3744 minimum is reduced to nine positions with the ISO 3746 requirement remaining at five. In this case the orientation of the machine to the microphone array is governed by the box shape and no variations are possible.

Sound power level determinations have been performed using measurement distances of 0.25 m and 1 m, and for comparison purposes, up to thirty-seven positions have been used for both parallelepipeds. Sound power level determinations were obtained using measurements of sound pressure level and using measurements of sound intensity level. The distribution requirements of the probe positions for intensity level measurements precluded measurements at the parallelepiped corners and hence the determinations for this technique could only been carried out using arrays with twenty and with five positions. Results for both techniques are shown in Table 8. Here to keep some continuity and to permit comparisons between sound power levels determined using the various procedures, data is listed in Table 8 relative to the twenty microphone hemisphere array used in Section 4.4.1 and 4.4.2.

Table 8. Sound power level re true values from measurements using parallelepiped surfaces with varying numbers of measurement positions

measurement distance : 1 m				
number of positions	37	20	9	5
"pressure"	0.8	0.8	1.0	2.5
"intensity"	-	-0.1	-	1.9
measurement distance : 0.25 m				
number of positions	37	20	9	5
"pressure"	0.6	0.8	0.7	2.1
"intensity"	-	-0.4	-	1.5

It can be seen that the sound power level determined using pressure level increases by approximately 1.5 dB when only five microphones are used and is reasonably constant for the other three arrays. This is the case for both values of measurement distance. Clearly at least nine positions are required. Similar observations may be made for the intensity level data, which show a mean increase of approximately 2 dB although in this case there is a more consistent difference between the two parallelepipeds, up to 0.4 dB.

4.4.6 Difference between sound power levels obtained using hemispherical and parallelepiped surfaces

It is interesting to look more closely at the differences in sound power levels determined using hemispherical and parallelepiped surfaces for both techniques. With a measurement distance of 1 m and a twenty position array, the intensity technique provides a sound power level of 0.9 dB less than that obtained using the pressure technique. The difference between the reference values used for pressure and intensity was only 0.1 dB. This indicates that the parallelepiped pressure data are in error (see also Section 4.3.3).

As a check on this apparent error the measurements were repeated using the reference sound source and similar results were obtained. Sound power levels obtained using only five microphones were too high and there was a difference of approximately 1 dB between pressure and intensity determinations.

The larger value of sound power level determined using measurements of sound pressure level on a parallelepiped surface may result from differences in propagation distance (source to receiver) when compared with those for a hemispherical surface. Sound pressure levels will vary with propagation distance because of the effect of spherical spreading and may result in errors in sound power evaluations. For example, consider the geometry of the parallelepiped with a measurement distance of 1 m (with twenty microphone positions) and the 2 m radius hemisphere (with a twenty microphone array). For the parallelepiped, the distance from the microphone to the nearest part of the reference box varies from 1.14 m to 1.28 m. For the 2 m radius hemisphere the corresponding distance range is from 1.2 m to 1.73 m. Summing the individual sound pressure levels with due allowance for spherical spreading, over the appropriate propagation distance, results in a predicted difference of approximately 1 dB between average surface sound pressure levels for the two surfaces. The surface areas are 24.4 m² and 25.1 m² for the parallelepiped and hemisphere respectively. These areas result in surface area corrections that are applied to the average surface sound pressure level to provide a sound power level, of 13.9 dB and 14 dB for the parallelepiped and hemisphere respectively. Thus there will also be approximately 1 dB between the two sound power level determinations. This result is similar to the average measured difference of 0.8 dB shown in Table 8.

While these calculations are approximate, as it is assumed that the noise is radiating from the surface of the reference box and this is unlikely, it is clear that for the relatively small values of the measurement distance used for a parallelepiped, the propagation distances are not sufficiently constant to provide accurate estimates of sound power level. As the measurement distance increases, the effects of variations in propagation distance on sound power level will reduce and determinations should approach the true value. However, the use of large values of measurement distance will require a large measurement site (or room), and will increase measurement time (because of the increase in the time taken to move from one microphone location to the next) and, for outdoor facilities, measurements will become more susceptible to meteorological effects.

Effect of operator on sound power measurements

The measurements discussed in Section 4.4 were performed using remote microphones fixed in position on a stand with extension cables transmitting the output signals to a real-time analysis system. Selected measurements were repeated with the operator holding the microphone and also using a simple hand-held sound level meter. No significant differences were observed between sound power level determinations.

Summary of measurements on the effect of the number of measurement locations on a parallelepiped surface

The sound power level determined using parallelepiped enveloping surfaces was found to be independent of the number of microphone positions provided this number was greater than or equal to nine. However, for the values of measurement distance examined the sound power level values were approximately 1 dB too high. The precise magnitude of this error will be dependent on the measurement distance (hence the distribution of the microphone positions) and the size of the noise source. The use of a parallelepiped measurement surface for discrete microphone locations is therefore not recommended as a basis for a rapid method.

4.5 SOUND POWER DETERMINATION USING SCANNING TECHNIQUES

Scanning techniques have been investigated using pressure and intensity techniques with parallelepiped surfaces and only measurements of sound pressure level for hemispherical surfaces. There are several scanning sweeps and patterns that are approved by the relevant Standards and these are discussed for each type of enveloping surface in the following three sub-sections.

Scanning around hemispherical surfaces

There are three basic scanning techniques, meridional paths, spiral paths and coaxial paths. The latter is recommended in ISO 3744 and all are described in ISO 6926²². The performance of all three is considered.

The meridional path scan is achieved by traversing the microphone along an arc on the surface of the hemisphere from the top centre to the plane of the reflecting surface. The traverse should be conducted such that the microphone moves at a constant vertical speed (ie the angular speed is inversely proportional to the sine of the angle between the angular position of the microphone and the vertical axis of the measurement surface). If the traverse is made at a constant angular speed, a sine potentiometer (or its electrical or mathematical equivalent) must be used to obtain proper weighting for the surface area associated with the time required for the microphone to traverse a given arc length. The hardware required for the meridional traverse is not commercially

available and it will be difficult to design a system that can be adapted to differing radii. It is estimated that the cost of the hardware for a fixed radius would be in excess of £10,000. This would not include the mechanism (computer controlled stepper motor) required to control the speed of the traverse.

The spiral path is formed by traversing the microphone along one meridional path as the source is rotated through 360°, thus forming a spiral path around the vertical axis. It is probable that it will not generally be convenient to rotate the noise source either because of weight or size or associated external supplies (eg electrical or hydraulic).

Coaxial paths may be formed using a rotating boom (in the horizontal plane) with the length of the boom (radius) reduced as the microphone height is increased. The use of a rotating boom will require the rotation system to be located above the machine supported by some form of tripod. A boom will then require a right angle along its length to obtain circular traverses at low microphone heights. This arrangement may prove inconvenient for a number of machines.

All these scanning techniques require the use of fairly sophisticated hardware and perhaps associated computer software dedicated solely to the task of determining sound power level. They will be expensive to set up and will probably be difficult to adapt to accommodate variations in machine size. They do not, at first sight appear to form the basis of a rapid (and inexpensive) method of sound power determination. However, the coaxial scan method does lend itself to a manual microphone movement system (i.e. the operator simply walking around the machine with a hand held sound level meter). The use of a sound level meter was shown in Section 4.4.7 to provide satisfactory results. This method of scanning has, therefore, been used in an initial assessment of the potential of scanning techniques. The five paths recommended in ISO 3744 were used on a 2 m hemisphere. The height of each circular path used is shown in Table 9 together with the time taken to complete each path.

Each determination was repeated three times and a mean and standard deviation calculated assuming each circular sweep is sufficient to describe the enveloping surface as well as the values for the ISO 3744 recommended procedure using all five sweeps. The mean sound power level data are expressed, as in previous Tables, relative to the true (twenty-microphone array) value and are shown in Table 9.

It can be seen that sound power levels obtained from each sweep have a range of 2.6 dB. Clearly one sweep is inadequate. The combination of all five sweeps, however, provides values that compare favourably with those obtained for the discrete measurements in Section 4.4.1. This method of sweeping will obviously not be feasible for machines that require an enveloping surface with a diameter greater than 2 m because of the physical difficulty involved with the operator reaching the higher circular sweeps. In this case the discrete four position method will be more convenient.

Table 9. Sound power level re true values from measurements made by using scanning along horizontal paths

Approximate scan time (secs)	height (m)	level re true value (dB)	sd
40	0.2	-1.2	0.2
38	0.6	0.0	0.3
30	1	-0.2	0.3
20	1.4	0.5	0.1
20	1.8	1.4	0.3
ISO 3744 result (mean of five paths)		0.2	0.1

If the sound power level is determined from the middle three sweeps a value of only 0.1 dB greater than the true value is obtained with a standard deviation of 0.1 dB. These middle three sweeps, at heights of 0.6 m, 1 m and 1.4 m, provide an approximation of the height range of the three lower microphones (ie not including the overhead microphone) in the four-position array used in Section 4.4.1 and listed in Table 5 (ie 0.3 m, 0.9 m and 1.5 m). To investigate the possibility of reducing the number of sweeps below five, the feasibility of a single sweep in a plane inclined to the ground surface that encompasses (for example) the ISO 3744 discrete microphone positions 1, 15 and 9 (see Table 2) was assessed.

Inclined sweeps were carried out with different start positions and each repeated to obtain repeatability standard deviations. The sweeps were carried out manually using a sound level meter. The overall mean of the three start positions was 0.2 dB greater than the true value with a standard deviation of 0.1 dB. These values compare favourably with values obtained using the four-microphone array and depending on machine size may be executed more easily. The time taken for each sweep varied from 35 s to 45 s. These times are unlikely to be improved by using the more controlled meridional or spiral sweeps and considering the difficulties and expense involved with these other methods they were not considered worth pursuing. They are unlikely to provide estimates of sound power level that are significantly closer to true values or more repeatable.

The measurements were repeated using the reference sound source with similar results but here the sound power levels between individual sweeps had a range of 0.9 dB with a five sweep average value 0.3 dB higher than the true value. The reduced range obtained from individual sweeps is in accord with the source being more omnidirectional but there is still a requirement to use the average of all five sweeps for an accurate determination.

4.5.2 Scanning around parallelepiped surfaces

For parallelepiped surfaces sound power levels were determined using pressure and intensity techniques. Two sweep methods were used: following horizontal paths around the parallelepiped as defined in ISO 3744 (carried out for pressure level measurements only) and, for both techniques, along prescribed paths on each side of the parallelepiped as described in ISO 9614-2. For the ISO 9614-2 sweeps both horizontal and vertical patterns were used. These are referred to as "a" and "b" paths respectively in the results Tables in this Section.

The ISO 3744 paths were used on a parallelepiped with a measurement distance of 1 m. The Standard requires four horizontal closed rectangular paths equally spaced to cover the height of the parallelepiped and a separate series of sweeps to cover the top surface. The height of each sweep is listed in Table 10 as a function of the height, h of the reference box, and the measurement distance, d . The sweeps were carried out manually and repeated to obtain standard deviation of repeatability. To assess the effect on sound power level, of reducing the number of sweeps, sound power levels were calculated for each individual sweep and for several combinations (including ISO 3744 requirement) Results are shown in Table 10 relative to true values.

Table 10. Sound power level re true values from measurements made by scanning along horizontal paths of a parallelepiped with $d = 1$ m

path	height	level re true	sd
1	$(h+d)/4$	1.8	0.2
2	$(h+d)/2$	1.3	0
3	$3(h+d)/4$	0.1	0.1
4	$h+d$	-0.3	0.1
5 (top surface)	$h+d$	1.5	0.1
ISO 3744 (all sweeps)		1.0	0.1
2, 3, 4		0.4	0.1
2, 4		0.6	0

It can be seen from Table 10 that sound power levels for the individual sweeps have a range of 2.1 dB with a mean of 1 dB greater than the true value and a standard deviation of 0.9 dB. However, the standard deviation about the mean values for each sweep is 0.2 dB or less, indicating that the manual sweep, despite inherent variations in the exact path followed and time taken, is sufficiently accurate. Obviously a combination of more than one sweep is required to obtain a reliable determination of sound power level.

Sound power levels obtained from the several combinations can be seen from Table 10 to be far more consistent but as found for the discrete methods (see Section 4.4.6) values

of sound power level are approaching 1 dB too high.

Using a parallelepiped with measurement distance of 0.25 m produced similar results with the ISO 3744 combination of sweeps again resulting in a mean sound power level 1 dB too high.

These measurements were repeated using the reference sound source and similar results obtained. The sound power level was approximately 0.8 dB too high but with a reduced variation between sweeps resulting in a standard deviation of 0.6 dB.

The second scanning method involves scanning over each parallelepiped surface in turn and summing the resultant sound pressure levels. This was achieved using horizontal and vertical scanning paths as discussed above. Each measurement was repeated three times to obtain a standard deviation which, in effect, describes the variability of the manual scanning. Each of the five surfaces of the parallelepiped was scanned using both horizontal and vertical paths. The resultant sound power levels are shown, relative to true levels, for both pressure and intensity techniques in Table 11.

Table 11. Sound power level re true values from measurements made by scanning the five surfaces of a parallelepiped with $d = 1$ m

	"Pressure"		"Intensity"	
path	level re true	sd	level re true	sd
a	-0.5	0.2	0.7	0.1
b	-0.4	0.1	0.9	0.1
a+b	-0.4	0.1	0.8	0.1

It can be seen that similar sound power levels are obtained by both scanning orientations (a and b) with overall mean values of 0.4 dB too low for intensity and 0.8 dB too high for pressure. The associated standard deviations are 0.2 dB or less. These sound power levels compare well with previous discrete and scanning methods, with the sound power level using pressure resulting in an overestimate.

The series of measurements was repeated with a measurement distance of 0.25 m. Here mean values were 0.1 dB too low for intensity and 1.1 dB too high for pressure, both sound power levels were slightly higher than the data for the larger parallelepiped, and so still showing an overestimate for the pressure data.

Measurements were carried out using a reference sound source with the larger parallelepiped and mean sound power levels were 0.4 dB too high for intensity and 0.8 dB too high for pressure. These results are in accord with the data from discrete microphone positions and other scanning procedures.

Summary of measurements using scanning techniques

All sweep methods used for parallelepiped surfaces provided sound power levels that were approximately 1 dB too high. Their use is therefore not recommended as a basis for a rapid method. This was also the case for the discrete sampling methods discussed in Section 4.4.6. The only viable scanning technique for hemispherical surfaces was coaxial circular paths. Sound power level values determined discounting the lowest and highest paths were close to true values but a single inclined circular path also provided accurate estimates of sound power level with acceptable standard deviation.

INITIAL TRIALS OF THE FOUR-MICROPHONE ARRAY

While the diesel generator is probably acoustically representative of the type of machine used outdoors that will be subject to conformity with EC Directives, two other machines were used as source, namely a two-stroke petrol-engined lawnmower and a diesel-engined air compressor. For this trial only sound pressure level measurements were used on one hemisphere, with one orientation angle. Results for both machines are shown in Table 12 relative to the twenty microphone array determination ("1 to 20").

Table 12. Sound power level re true values for the lawn mower and compressor

Lawn mower 2 m radius hemisphere						
microphone positions						
four position sub-sets						
mean	sd	1 to 10	11 to 20	4,5,6,10	14,15,16,20	1 to 20
-0.1	0.2	0.0	0.1	-0.2	-0.4	0
Compressor 3 m radius hemisphere						
microphone positions						
four position sub-sets						
mean	sd	1 to 10	11 to 20	4,5,6,10	14,15,16,20	1 to 20
-0.1	0.1	0.1	-0.1	-0.3	-0.2	0

A 2 m radius hemisphere was used for the mower and a 3 m radius hemisphere for the compressor. The microphone position combinations used to obtain the data for the four-position sub-sets column are the same six listed in Table 5. It can be seen that for these two machines all variations provide good estimates of the sound power level determined using the twenty-microphone array of ISO 3744. The standard deviation associated with the six possible four-microphone arrays was 0.2 dB for the mower and 0.1 dB for the compressor. While the two sets of measurements do not show the four-microphone array to provide more accurate sound power determinations than those

obtained using the ISO 3746 array they do confirm their use as a potential measurement method. This initial trial using two extra machines provides little in the way of evidence to support the use of a four-microphone array but a far more rigorous assessment is discussed in Sections 6 and 7, where the performance of the potential rapid method is assessed using twenty-six noise sources with a range of Directivity Index from 0.8 dB to 8.0 dB and in acoustic environments with environmental correction factors ranging from approximately zero to 9.6 dB.

4.7 CONCLUSIONS FROM THE INITIAL OUTDOOR MEASUREMENTS IN HEMI-ANECHOIC CONDITIONS

The effect on sound power level of variations in radii or measurement distance (permitted by ISO 3744) is negligible and therefore, the experimental investigation into establishing a rapid method of sound power determination was centred on measurements using the smallest permitted radius and the ISO 3744 recommended measurement distance.

Sound power levels determined using only four microphone positions chosen from the ISO 3744 twenty-microphone array such that all are at different heights and on radii that have equal angular spacing were found to be on average within 0.1 dB of true values. These determinations are estimated to be of engineering grade accuracy with average repeatability standard deviations of 0.3 dB.

If hemispheres with radii less than the ISO 3744 minimum are used the sound power level obtained using measurements of sound pressure level increases; those determined using intensity techniques remain constant.

The sound power level determined using parallelepiped enveloping surfaces was found to be independent of the number of microphone positions provided this number was greater than or equal to nine. For the values of measurement distance examined the sound power level values were approximately 1 dB too high. The precise magnitude of this error will be dependent on the measurement distance and the size of the noise source.

The use of a parallelepiped measurement surface for discrete microphone locations is not recommended as a basis for a rapid method.

No significant differences were observed between sound power levels determined with an operator using a sound level meter and those using remote microphones.

The only viable scanning technique for hemispherical surfaces was coaxial circular paths. Sound power levels determined using the three mid-height paths were close to true values and a single inclined circular path also provided accurate estimates of sound power level with acceptable levels of standard deviations.

5 INDOOR MEASUREMENTS IN SEMI-REVERBERANT CONDITIONS

The measurements discussed in section 4 were carried out on the NPL outdoor hemi-anechoic site. The measurements described in this Section were all carried out indoors to assess the performance of several ISO Standards that define methods for the determination of the sound power level of machines in semi-reverberant conditions in order to assess the performance of the potential rapid (reduced sampling) technique that emerged from the measurements performed outdoors under hemi-anechoic conditions. The machines used for the outdoor measurements could not be used indoors (see Section 5.2) and so some initial hemi-anechoic measurements were required to obtain the sound power levels that are to be used as the true values.

5.1 STANDARDS USED FOR INDOOR MEASUREMENTS

A series of sound power level determinations were performed indoors in acoustic environments ranging from hemi-anechoic to semi-reverberant. The main purpose of these determinations was to assess the use of Standards concerned with the measurement of sound power level in semi-reverberant environments and then to assess the use of the four-microphone array that emerged as a potential rapid method from the measurements discussed in Section 4. The standards considered are discussed in some detail in Section 2 and are ISO 3743-1, ISO 3743-2, ISO 3746 and ISO 3747. A brief description of each Standard is given in the following sub-section. There are some similarities between these "semi-reverberant" standards and these are discussed later. In addition, measurements in a hemi-anechoic room were made according to ISO 3744 and the resultant sound power levels compared to those performed in semi-reverberant conditions and to those made outdoors.

5.1.1 Brief description of the Standards used

ISO 3743 is a method designed for small movable machines in reverberant sound fields and is of engineering grade accuracy. The standard was recently revised and the new version issued in two parts, part 1 requiring "hard-walled test rooms" of minimum volume 40 m³, and part 2 giving methods for "special reverberation test rooms" of minimum volume 70 m³. The method of measurement is based upon a comparison with a reference sound source (although in part 2 sound power levels may be calculated directly using reverberation time). The standard is new and it is not yet clear how widely it will be adopted by industry.

ISO 3746 is an enveloping surface method, it may require the use of only four microphone locations and is of survey grade accuracy. For this Standard measurements may be carried out in acoustic environments with values of K_{2A} of up to 7 dB. This may allow measurements to be made with machinery in situ under typical working conditions.

ISO 3747 is being revised and will be an engineering grade method and, like ISO 3743, involves a comparison with sound pressure level measurements of a reference sound source. The Standard generally requires a room with a volume greater than 10000 m³ although there are other criteria that may allow the use of smaller rooms. The measurement method is to determine the average sound pressure level of the machine then to place the reference sound source on, or very close to, or even in the position to be occupied by the machine under test and determine the average sound pressure level of the reference sound source. The difference between these two average sound pressure levels is the used together with the calibrated sound power level of the reference sound source to obtain the sound power of the machine under test.

5.2 MACHINES USED FOR THE INDOOR MEASUREMENTS

The machines used for the outdoor measurements all produced noxious exhaust fumes and so were unsuitable for use indoors. In addition the use of different machines also serves to expand the range of machines to include domestic appliances. Several electrical powered machines were considered for the indoor tests. The machine would have to be "typical" of those subject to noise emission tests for EC purposes and for the purposes of the current study have repeatable, measurable sound power levels that are not dependent on a specific operation. Because of the facilities available machines that required plumbing-in were considered unsuitable. Machines examined included a garden shredder, chain saw and an electrical air compressor. For various reasons these all proved unsuitable and eventually two machines were selected, a hand held electric drill and a cylinder vacuum cleaner. Details are given below together with approximate overall sizes (reference box) in length width and height order.

Electric drill

Manufacturer	Black and Decker
Type	BD163V
Power requirement	240 volt, 50 Hz electrical power
Size	0.3 m; 0.05 m: 0.3 m

Vacuum cleaner

Manufacturer	VacKing
Type	CVAC - 20V
Power requirement	240 volt, 50 Hz electrical supply
Size	0.3 m: 0.3 m: 0.5 m

5.3 BASELINE MEASUREMENTS IN HEMI-ANECHOIC CONDITIONS

Measurements were performed in a hemi-anechoic room that satisfies the requirements of ISO 3744 for a hemispherical enveloping surface over a reflecting plane with radii up to 1.5 m. The room is an acoustically isolated asymmetrical, 92 m³ chamber consisting of acoustically absorbent wedges on the walls and ceiling and a painted hard concrete

floor. The purpose of these sound power level determinations was to assess further the performance of the four-microphone array that emerged from the tests performed outdoors and to establish baseline sound power levels for comparison with the determinations performed in semi-reverberant environments.

Sound power level determinations were carried out using the twenty microphone array of ISO 3744 on a hemispherical enveloping surface of 1.5 m radius. This is the largest hemispherical surface that is permitted in the hemi-anechoic room and satisfies the size requirement of ISO 3744 (the radius must be greater than or equal to twice the largest dimension of the reference box). From the sound pressure level measurements at the twenty positions, values of sound power level were calculated for the several microphone position sub-sets examined in the outdoor measurements (see Section 4.4). Results for both machines are shown in Table 13 with data expressed relative to the twenty-microphone array determination (so the "1 to 20" row in Table 13 is zero).

Table 13 Sound power level re true values in a hemi-anechoic room

		level re true value	
number of positions and short description	position numbers	machine	
		vacuum	drill
20: all ISO 3744 positions	1 to 20	0	0
10: key ISO 3744 positions	1 to 10	0.1	0.1
10: additional ISO 3744 positions	11 to 20	0.0	0.0
4: key ISO 3746 positions	4,5,6,10	0.3	-0.4
4: additional ISO 3746 positions	14,15,16,20	0.0	0.0
4: positions at four different heights	1,15,9,20	0.2	0.1
	12,6,17,20	-0.2	-0.5
	3,14,8,20	0.2	-0.2
	11,5,19,20	0.6	-0.3
	2,16,7,20	0.2	0.1
	13,4,18,20	0.3	-0.3
	mean	0.2	-0.2
	sd	0.2	0.2

Each sub-set is briefly described in Table 13 using the ISO 3744 microphone position number. The last two rows show the mean and standard deviation for the group of six four-microphone sub-sets that have each microphone at a different height.

Repeatability standard deviations were approximately 0.1 dB for each sound power level determination, similar to those obtained outdoors.

It can be seen from Table 13 that the sound power levels determined from all sub-sets for each machine are similar to those obtained for the “reference” twenty microphone array. On average, the sound power levels determined using the four-microphone arrays that had each microphone at a different height differed from the true value by 0.2 dB. The standard deviation about the mean value of the six possible combinations was 0.2 dB.

Sound power levels were also determined using an inclined circular sweep (see Section 4.5.1). Here repeatability standard deviations increased to approximately 0.3 dB, perhaps indicating that the manual sweep was not accurate enough, although this repeatability is probably still of engineering grade accuracy. The average sound power levels were 0.2 dB lower for the drill and just over 1 dB greater for the vacuum cleaner. Clearly an overhead measurement position is required for the vacuum cleaner. The air intake is on the top surface of the vacuum cleaner and outlet on the side. It is clear that their relative contribution to the sound power is not fully taken into account by the inclined sweep. The air movement associated with this intake also has an effect on sound propagation which results in a time dependent variation in the distribution of sound pressure levels in the room which may, in turn, cause the measurement uncertainty to increase with the time taken to perform a complete sound power level determination.

Difficulties were experienced in determining the sound power level of the air compressor (see Section 5.2) due to problems caused by air vents associated with the machine. The temperature of the air emanating from these vents varied during operation with a general tendency to increase with time. The resultant variation in the distribution of sound pressure levels in the room was far greater than that observed for the vacuum cleaner and caused unacceptable variations in measurement uncertainty. The effect of this temperature variation in the moving air is especially critical in semi-reverberant conditions where there will be a significant effect on the position of the room modes. The air compressor, therefore, was not used in this study.

The conclusions based on the outdoor measurements, regarding the use of a simple four-microphone array are reinforced by these results, but care must be taken when considering the inclined sweep method.

5.4 MEASUREMENTS IN SEMI-REVERBERANT CONDITIONS

5.4.1 Method of determination of A-weighted sound power.

The Standards considered in this Section are briefly described in Section 5.1 but are all dependent on the use of a calibrated reference sound source. In the case of ISO 3743

and ISO 3747 the difference between the average sound pressure levels of the machine and the reference sound source (measured at specified positions) is added to the calibrated sound power level of the reference sound source. For ISO 3746 the sound power level of the machine is determined using four microphone locations from the ISO 3744 twenty point array (three at the same height and one “overhead”) and the A-weighted environmental correction factor, K_{2A} added to the result. K_{2A} is evaluated by replacing the machine with a reference sound source, determining its sound power and comparing it to the calibrated value; the difference is K_{2A} .

It can be seen that, although described in slightly different terms in the Standards, the processes required are essentially identical. There is, however, one important difference. For ISO 3743 and ISO 3747 an A-weighted value is calculated from a weighted energy summation of octave band data individually corrected for the environment using values of K_2 determined for each octave band frequency, while for ISO 3746 it is calculated from the weighted energy summation of individual octave bands or measured directly with an A-weighting network. The resultant sound power determination may depend on which method is used to evaluate A-weighted levels. This is discussed further in Section 5.4.3.

5.4.2 Measurement procedures

The measurement procedures in all three standards are essentially similar. The requirement is to measure sound pressure levels in the far field of the source (in an approximately reverberant sound field). The number of microphone positions is dependent on the characteristics of the noise produced by the source and the room characteristics but, for the type of machine that is likely to require the use of these “semi-reverberant” sound power standards, will generally be between three and five. So, the choice of which Standard to use may depend on the size of the room available or on the acoustic environment that exists in the room. A summary of these requirements is given in Table 14.

Values of the constants in Table 14 for the room used for the semi-reverberant measurements in this report are listed in parenthesis. It can be seen that the room at NPL would appear suitable for all four Standards.

The measurement surface areas used resulted in values of K_{2A} between 5 dB and 8 dB. Although the latter is greater than the ISO 3746 criterion, the sound power levels were found to be in reasonable agreement with the “reference” values (see Section 5.4.5). There are, however, significant restrictions on the values of reverberation time that must be achieved for ISO 3743-2, which specifies a method for use in “special reverberation test rooms”. These are discussed in more detail in Section 5.4.4.

Table 14 Criteria for test environment

Standard			
ISO 3743-1	ISO 3743-2	ISO 3746	ISO 3747
$V > 40 \text{ m}^3$	$300 \text{ m}^3 > V > 70 \text{ m}^3$	$K_2 \leq 7 \text{ dB}$	$V \leq 10000 \text{ m}^3$
$V/V_M > 40$	$V/V_S > 100$	$A/S \geq 1$	$d_{\max}/d_{\min} \leq 5$
$\alpha_f < 0.2$	restriction on reverberant behaviour (see Section 5.4)		$\alpha_f \leq 0.3$
Where, V is the volume of the test room in m^3 (274) V_M is the volume of the reference box in m^3 (0.0045) V_S is the volume of the test source in m^3 (≈ 0.0045) α_f is the absorption coefficient at frequency f ($0.03 < \alpha_f < 0.17$) A is sound absorption area of room in m^2 ($A = 0.16 (V/T)$) S is area of measurement surface in m^2 ($5 < S < 19$) $d_{\max}$ is maximum dimension of room (7.2 m) $d_{\min}$ is minimum dimension of room (5.5 m)			

5.4.3 Measurements according to ISO 3743-1

The sound power levels of the drill and the vacuum cleaner were determined strictly according to the Standard. Several repeat measurements were made resulting in average sound power levels of 0.6 dB and 0.7 dB respectively greater than true values, with repeatability standard deviations of 0.2 dB. ISO 3743-1 requires that A-weighted sound power level, L_{WA} , is calculated from octave band data according to:

$$L_{WA} = 10 \log \left\{ \sum 10^{0.1(L_W + A)} \right\}$$

where A is the appropriate A-weighting value for each octave band and L_W is the octave band sound power level given by:

$$L_W = L_{W(RSS)} - L_{p(RSS)} + L_{p(ST)}$$

where,

$L_{W(RSS)}$ is the calibrated octave band sound power level of the reference sound source,

$L_{p(RSS)}$ is the octave band sound pressure level of the reference sound source averaged over the microphone positions,

$L_{p(ST)}$ is the octave band sound pressure level of the machine averaged over the microphone positions.

It can be seen that a sound power level is calculated for each octave band and then these values summed to obtain the A-weighted sound power level.

In addition to these sound power level determinations, the A-weighted sound power was also determined from direct measurements of A-weighted sound pressure level according to:

$$L_{WA} = L_{WA(RSS)} - L_{pA(RSS)} + L_{pA(ST)}$$

where,

$L_{WA(RSS)}$ is the calibrated A-weighted sound power level of the reference sound source,

$L_{pA(RSS)}$ is the A-weighted sound pressure level of the reference sound source averaged over the microphone positions,

$L_{pA(ST)}$ is the A-weighted sound pressure level of the machine averaged over the microphone positions.

Here the values of sound power were 0.1 dB greater than the true level, and 0.5 dB less than the true value, for the drill and vacuum cleaner respectively. The sound power determinations are 0.5 dB and 1.2 dB lower than those calculated according to the Standard (see above), and closer to the values obtained in hemi-anechoic conditions. If the octave band data were summed with the appropriate A-weighting correction to obtain $L_{pA(RSS)}$ and $L_{pA(ST)}$ the resultant sound power levels are the same as those obtained from the direct measurements. The true A-weighted value will be obtained by direct measurement using an A-weighting function. The error involved in assigning a single value of the A-weighting function is dependent on the shape of the frequency spectrum across a band. The summations above indicate that the variation in sound power level determinations does not result from the approximations involved in assigning a single A-weighting correction to an octave band.

The magnitude of the difference between sound power levels obtained from direct A-weighted sound pressure levels and those according to the Standard are dependent on the frequency spectrum of the noise sources involved and on the characteristics of the room. If the energy distributions of the noise source and the reference sound source are the same or the value of K_2 is constant across the frequency range of interest then there will be no difference in the sound power level determinations. For all other cases there will be a difference.

It is unreasonable to expect a machine to have the same energy distribution as a reference sound source and most rooms have a frequency dependent value of K_2 , so the determined sound power level will usually be dependent on the method of calculation.

However, it is estimated that for the vast majority of machines this difference will be less than 1 dB. The difference may be larger than this if the energy distribution of the machine is very variable. For instance, consider a hypothetical machine that has a spectrum that either rises or falls at a rate of 6 dB/octave. This will result in a (calculated) difference of approximately ± 2.5 dB between the two ways of determining the A-weighted sound power. It must be remembered that this must be considered an extreme case as here the calculation procedure assumes a large variation of K_2 , a 7 dB range from 125 Hz to 8 kHz, and a band level difference in excess of 20 dB between the "machine" noise source and the reference sound source (the spectra are normalised to have a zero difference at 1 kHz). To put this in context the Standard recommends the use of octave bands to calculate an A-weighted level if the band level difference between the two noise sources exceeds only 5 dB. For spectra where this criteria is just exceeded in one band the difference in A-weighting estimates is dependent on the band (because of the effect of the frequency dependent A-weighting) and varies from zero to 1 dB.

Differences from true levels that result from the method of obtaining the A-weighted level may be included as part of the measurement uncertainty. However, if it turns out that the measurement uncertainty is too high for the particular application then measurements will have to be made using octave bands. The magnitude of measurement uncertainty and the effect of the method of obtaining an A-weighted value are discussed in more detail in Section 7.

Sound pressure levels measured using an A-weighting function should be more accurate than those obtained from summing band limited levels and, more importantly for the current investigation, sound power levels determined from direct measurements of A-weighted levels may be made more quickly and with less sophisticated instrumentation, and so, should be encouraged.

5.4.4 Measurements to ISO 3743-2

The Standard requires that the reverberation time, T lies between two curves defined by:

$$T = 0.9 \times R \times T_{\text{nom}} \quad \text{and} \quad T = 1.1 \times R \times T_{\text{nom}}$$

where the quantity, R , the "reverberation parameter" is given by:

$$R = 1 + 257 (f \times V^{1/3}).$$

The nominal reverberation time of the room, T_{nom} , is determined by centring the measured values of T (normalised to the reverberation time at 1 kHz) within the limiting curves defined above and shall be between 0.5 s and 1.0 s. The end result of these criteria is that these "special" rooms are required to have an essentially constant value of T from approximately 500 Hz to 5000 Hz and that variations outside this range

are limited to a change of around 40 %. Values of “R” and the reverberation times of the NPL room are shown in Table 15 together with average absorption coefficient.

Table 15 Characteristics of the NPL semi-reverberant room

Frequency (Hz)	R	Reverberation time (sec)	absorption coefficient
100	1.48	3.6	0.05
125	1.38	4.4	0.04
200	1.24	4.2	0.04
500	1.10	6.5	0.03
630	1.08	6.7	0.03
1000	1.05	5.8	0.03
2000	1.02	3.9	0.04
4000	1.01	1	0.17
5000	1.01	1.5	0.11
6300	1.01	2.2	0.08

The acoustics of the NPL room are fairly typical for an empty room and it can be seen from Table 15, that the room needs adapting to considerably reduce the reverberation time at middle frequencies and to a lesser extent at lower frequencies. For middle frequencies this can be achieved by using specially designed perforated panels with mineral wool interiors and for lower frequencies with wooden framed membrane absorbers.

It is clear that rooms that are qualified for ISO 3743-2 are indeed “special” and are not in general use. In fact ISO 3743-2 is used mainly for determining the noise emission of air conditioning units. It is used because methods defined in other Standards are considered impractical for testing equipment that has to be connected to ducts and/or refrigerant piping. The survey reported by Higginson²⁰⁻²¹ indicated that the use of ISO 3743-2 was very limited in the UK and furthermore, is not referenced in any EC Directive related to noise labelling of machinery. For these reasons no attempt has been made to adapt a room to ensure it qualifies to ISO 3743-2 and measurements have not been carried out to assess the performance of the standard.

5.4.5 Measurements according to ISO 3746

The sound power levels of the drill and the vacuum cleaner were determined strictly according to the Standard. Measurements were carried out using a 1 m radius

hemispherical enveloping surface and using two parallelepiped surfaces with measurement distances of 0.5 m and 1.0 m. Values of K_{2A} were measured using the same measurement surfaces with a reference sound source as the noise source (as required by the standard). Values of K_{2A} were 4.5 dB for the hemisphere and the 0.5 m measurement distance parallelepiped and 8 dB for the 1 m measurement distance parallelepiped. While this latter value is strictly outside the range permitted (ISO 3746 requires that $K_2 < 7$ dB) measurements were still carried out. Several repeat measurements were performed, the average sound power levels, expressed relative to the true level, and associated repeatability standard deviations are shown in Table 16.

Table 16 Results of measurements according to ISO 3746

surface	drill		vacuum cleaner	
	Level re true values	sd	Level re true values	sd
d = 0.5 m	0.5	0.1	-0.2	0.2
d = 1.0 m	0.5	0	-0.2	0.1
r = 1.0 m	-0.1	0.1	-0.6	0.2

Here it can be seen that the sound power levels obtained using the two parallelepiped surfaces are the identical. This indicates that the criterion of $K_2 < 7$ dB (for $d = 1$ m, $K_2 = 8$ dB) may be too stringent and ISO 3746 may be used in more reverberant conditions. Here it should be remembered that the "rapid" technique that emerged from the outdoor measurements is based on an enveloping surface and may therefore be suitable for semi-reverberant conditions with the application of a suitable environmental correction factor (see Section 6). The sound power levels obtained using the hemispherical surface can be seen to be approximately 0.5 dB lower than those obtained using the parallelepiped surfaces. This is in accord with the outdoor measurements discussed in Section 4.3.3.

5.4.6 Measurements according to ISO 3747

The sound power levels of the drill and the vacuum cleaner were determined strictly according to the Standard. Several repeat measurements were made. The average sound power levels were 0.3 dB and 0.4 dB higher than true levels respectively with repeatability standard deviations of 0.2 dB. In order to obtain a completely separate set of measured data the microphone positions used were not the same as those for ISO 3743-1. The values above are 0.3 dB lower than those obtained for ISO 3743-1 even though the measurements carried out for both standards have the same criteria regarding microphone location. However, this difference is not statistically significant at the 95 % confidence level. Sound power levels were also determined from direct

measurements of A-weighted sound pressure level (see Section 5.4.3) and were 0.1 dB higher than the true level and 0.6 dB lower respectively.

Summary of semi-reverberant measurements

The average of the sound power levels for the drill and the vacuum cleaner determined from all three standards are 0.5 dB and 0.3 dB higher than true levels respectively with associated standard deviations of 0.2 dB and 0.5 dB. While this shows there are differences between the three standards the repeatability standard deviations obtained from the measurements for each standard are such that the differences are not statistically significant at the 95 % confidence level. If the sound power levels determined from direct measurements of A-weighted sound pressure levels are considered then these average differences values reduce to 0.2 dB and 0.4 dB with an associated standard deviation of 0.2 dB for both machines. The slightly reduced difference between methods indicates that the use of A-weighted networks should be investigated further.

The use of the "rapid" technique for indoor measurements.

The four-microphone array that emerged from the outdoor measurements as a potential basis for a rapid technique was used in the semi-reverberant room. A hemispherical enveloping surface with a 2 m radius was used with microphone positions 1, 9, 15 and 20 (see Table 2). The number of microphone locations used is similar to those required by the three Standards examined in previous Sections of this Report so, apart from measuring sound power level from direct measurement of A-weighted sound pressure level, the time taken to perform a complete set of measurements will be essentially similar. Several repeat measurements were performed and the average sound power levels were 0.1 dB and 0.3 dB higher than true levels for the drill and vacuum cleaner respectively, with associated repeatability standard deviations of 0.2 dB and 0.3 dB. It may be concluded, therefore, that the four-microphone array that emerged from the outdoor (hemi-anechoic) measurements provides good estimates of sound power level in semi-reverberant conditions.

It must be borne in mind that the "rapid" four microphone array has only been assessed on a fairly limited number of machines, an electrical power generator, a two-stroke petrol-engined lawnmower, a diesel-engined air compressor, a portable electric drill a vacuum cleaner and a reference sound source. While these machines may be representative of large volume production equipment that require noise emission measurements in order to comply with the requirements of certain EC Directives, it is desirable to increase the range of types of machines in order to increase confidence on the suitability of the method and to formulate criteria on its use. To this end, measurements have been carried out on a large number of machines to assess the accuracy of sound powers determined using the four-microphone array and these are discussed in Sections 6 and 7.

5.4.9 Conclusions from indoor measurements

Sound power levels determined in a hemi-anechoic room, using only four microphone positions chosen from the ISO 3744 twenty-microphone array such that all are at different heights and on radii that have equal angular spacing were found to be on average within 0.2 dB of "true" values. These determinations are estimated to be of engineering grade accuracy with average repeatability standard deviations of 0.2 dB.

In semi-reverberant conditions, sound power levels were up to 0.5 dB different from the true values determined in the hemi-anechoic room with repeatability standard deviations of 0.2 dB. The differences were not considered to be statistically significant at the 95 % confidence interval.

The A-weighted sound power levels determined using ISO 3743-1 and ISO 3747 are dependent on the method used to obtain A-weighted sound pressure level. Sound power levels determined using an A-weighting function may be made more quickly and with less sophisticated instrumentation than those obtained from summing band limited levels. Measurements using an A-weighting function should, therefore, be encouraged. However, the difference between direct and octave-band derived values must be determined or an allowance made in the assessment of measurement uncertainties.

Rooms that qualify for measurements according to ISO 3743-2 are acoustically very special and are mainly used only for measurements on air conditioning systems. Therefore, no attempt has been made to adapt a room to ensure that it qualifies to ISO 3743-2 and measurements have not been carried out to assess the performance of this standard.

Sound power levels determined in semi-reverberant conditions (with values of K_{2A} up to 8 dB) using only four microphone positions chosen from the ISO 3744 twenty-microphone array such that all are at different heights and on radii that have equal angular spacing were found to be on average within 0.3 dB of true values. These determinations are estimated to be of engineering grade accuracy with average repeatability standard deviations of 0.3 dB.

6 VALIDATION OF THE FOUR-MICROPHONE ARRAY IN HEMI-ANECHOIC CONDITIONS

This Section describes measurements made indoors under hemi-anechoic conditions to assess the performance of the four-microphone array that emerged from the measurements discussed earlier in this report as forming the basis for a rapid method of determining sound power of machinery. The performance was compared with that of several other spatial sampling arrangements. The sound power level of a reference sound source and twelve machines and fourteen other specially constructed noise sources were determined and resultant measurement uncertainties assessed and compared. The prime objective of the measurements reported here was to assess the accuracy of the rapid method using a variety of machines to cover a wide range of Directivity Index with a view to developing a procedure that enables the measurement uncertainty associated with a sound power determination made with a known number of sound pressure level measurements on a hemispherical enveloping surface to be estimated from a knowledge of the Directivity Index of the noise source. This procedure may then be used to estimate the grade accuracy associated with the sound power determination.

6.1 THE IMPORTANCE OF MEASUREMENT UNCERTAINTY

As discussed in the Introduction to this report, a new EU Directive is soon to come into force that concerns the noise emitted by machinery outdoors. This new Directive requires the manufacturer to label his machine with a guaranteed sound power level, L_d , and it is this guaranteed level that will be used to determine compliance with noise limits. This guaranteed level is obtained by adding a correction to the measured value to account for measurement uncertainty. The magnitude of this correction is dependent on the particular procedure used in the measurement and will involve defining several statistical parameters. Values of measurement uncertainty are listed in all B-type Standards. For a Grade 2 accuracy method (eg, the ISO 3744 ten measurement position array), it is estimated to be approximately 1.5 dB whilst for Grade 3 accuracy (eg, the ISO 3746 four measurement position array), it is estimated to be between 3 dB and 4 dB depending on the type of machine. For C-type Standards, values are not generally given but they may be inferred from the appropriate framework B-type Standard.

The proposed Directive requires that the statistical procedures of ISO 4871²³ are followed for the purposes of declaration and verification of noise levels. This Standard assumes a generally accepted specific set of statistical parameters in conjunction with the measurement uncertainty to ensure that the correction to be applied is such that verification procedures ensure that there is a 95% probability of acceptance, and in addition, for the case of batch testing, no more than 6.5% of the sound power levels in a batch will exceed the labelled value. An accurate assessment of the measurement uncertainty is therefore of prime importance as it will have a direct effect on the labelled value. If there are limits it is this labelled value, not the measured value, that must not exceed the limit. Therefore, there may be cases where it is also important to ensure that

the value of measurement uncertainty is small. This may to some extent dictate the method used to determine the sound power.

6.2 MACHINES AND ENVIRONMENTS

Sound power level determinations discussed in this report have been carried out on a limited number of machines in a range of acoustic environments and a preferred rapid (reduced sampling) technique has emerged. Seven noise sources have been used in this investigation, for the purposes of completeness they are listed below:

Reference sound source
 Diesel-engined electrical power generator
 Two-stroke petrol-engined lawnmower
 Diesel-engined air compressor
 Hand held electric drill
 Upright cylinder vacuum cleaner

While these machines represent a range of equipment that is subject to the requirements of EU Directives and provide evidence to support the use of the more rapid method, it necessary carry out a series of measurements on a wider range of machines in order to increase confidence in the rapid method and to enable an assessment of potential limitations regarding Directivity Index (DI) and machine size. The majority of measurements reported in this Section have been carried out in the NPL hemi-anechoic room with the addition of some that were performed at manufacturers premises using their hemi-anechoic facilities.

Twenty-seven noise sources have been used in this series of measurements. These consist of a reference sound source, twelve actual machines and fourteen specially constructed noise sources. These fourteen constructed sources used the reference sound source as a noise source fixed in the bottom of a variety of boxes. The boxes were made of either 5 mm thick low density board (LDB) or of a more solid construction using 20 mm thick MDF material. The shape, size and orientation of the boxes were chosen to cover a range of Directivity Index. In particular the Directivity Index of these sources was at the upper end (up to 8 dB) of the range considered practical for actual machines. In fact the Directivity Index of the actual machines was generally in the range 1 dB to 4 dB. This is an observation that must be born in mind when considering the performance (ie the grade of accuracy) of a measurement method. It may not be necessary to have a method that provides, say, an engineering grade of accuracy over a wide range of Directivity Index. If a method becomes less accurate at high values of Directivity Index this may not be a problem especially when it appears that a typical value of Directivity Index is about 2 dB and the vast majority of machines have a Directivity Index that is less than about 4 dB.

Brief details of all noise sources used for this accuracy assessment are given below.

Reference sound source

Manufacturer: Bruel & Kjaer
 Type: 4204
 Size: 300 mm x 300 mm x 300 mm

Domestic garden shredder

Manufacturer: Black and Decker
 Type: GA 100 - 1020 W
 Size: 800 mm x 350 mm x 200 mm

Hedge trimmer

Manufacturer: Black and Decker
 Type: DNJ450G - 315 W
 Size: 570 mm x 200 mm x 170 mm

Hand held jig-saw

Manufacturer: Black and Decker
 Type: BD531 - 350 W
 Size: 200 mm x 200 mm x 90 mm

Hand-held hair drier

Manufacturer: Carmen
 Type: 1500 professional - 1500 W
 Size: 280 mm x 280 mm x 70 mm

Food processor

Manufacturer: Braun
 Type: 4243 - 400 W
 Size: 300 mm x 150 mm x 200 mm

Electric razor

Manufacturer: Philips
 Type: PH1604
 Size: 120 mm x 60 mm x 50 mm

Personal computer processor

Manufacturer: Elonex
 Type: PC - 425
 Size: 350 mm x 390 mm x 140 mm

Dot matrix printer

Manufacturer: Epson
 Type: LQ850
 Size: 450 mm x 300 mm x 100 mm

Hand-held vacuum cleaner

Manufacturer: Royal
 Type: Dust Devil
 Size: 400 mm x 170 mm x 250 mm

Vacuum pump

Manufacturer:	Edwards High Vacuum International
Type:	IH80
Size:	780 mm x 390 mm x 530 mm

Fan-ventilated computer cabinet

Manufacturer:	ICL
Type:	(purpose built cabinet)
Size:	1400 mm x 750 mm x 750 mm

Floor buffing machine

Manufacturer:	Nilfisk
Type:	Numatic standard floor buffing machine
Size:	400 mm x 400 mm x 1200 mm

MDF box 1 to MDF box 7

40 mm square section tube constructed of 20 mm thick MDF material. Seven configurations were used in order to obtain a range of Directivity Index. The tube was orientated on its side with either both ends open or with one end open or upright with only the top end open. The length / height of the tube was varied between 230 mm and 690 mm.

LDB box 1 to LDB box 7

As above but constructed of a thin (5 mm) low density board. These sources provided values of Directivity Index that augmented those obtained using the MDF material.

6.3 MEASUREMENT PROCEDURES

Measurements were performed in hemi-anechoic rooms that satisfy the requirements of ISO 3744 for a hemispherical enveloping surface over a reflecting plane. With the exception of the vacuum pump and the computer cabinet all sound power determinations were carried out using a 1.5 m hemisphere in the NPL hemi-anechoic room, this is the largest hemispherical surface that is permitted in the hemi-anechoic room and also satisfies the size requirement of ISO 3744 (the radius must be greater than or equal to twice the largest dimension of the reference box). Sound power level determinations carried out in the NPL hemi-anechoic room used the twenty-microphone array of ISO 3744 on a hemispherical enveloping surface. Microphone positions are described as a function of the hemisphere radius r , in Table 2.

Each sound power level determination was repeated three times in order to assess measurement repeatability. From the sound pressure level measurements made using twenty positions, values of sound power level were calculated for several microphone position sub-sets, including that for the preferred (four-microphone array) method.

As discussed in Section 6 above, the performances of several spatial sampling arrangements have been investigated. Six microphone position sub-sets were used, each sub-set is described in the following list using the ISO 3744 microphone position numbers from Table 2.

Ten positions	The key and additional positions of ISO 3744 Positions 1 to 10 Positions 11 to 20
Six positions	Six positions on each of the three complete hemispherical arcs Positions 12, 4, 19, 9, 14 and 2 3, 15, 7, 17, 5, and 13 11, 6, 18, 9, 16 and 1
Four positions	The key and additional positions of ISO 3746 Positions 4, 5, 6 and 10 Positions 14, 15, 16 and 20
Four positions	The "rapid method" all four positions at different heights Positions 1, 5, 9 and 20 12, 6, 17 and 20 3, 14, 8 and 20 11, 5, 19 and 20 2, 16, 7 and 20 13, 4, 18 and 20
Three positions	Three positions on each of the six half hemispherical arcs Positions 3, 15 and 7 11, 6 and 18 2, 14 and 9 13, 5 and 17 1, 16 and 8 12, 14 and 9
One position	Each of the twenty ISO 3744 positions Positions individually, 1 through 20

In addition to the sound power level determinations, the Directivity Index of each noise source was estimated from the 20 microphone array using:

$$\text{Directivity Index} = L_p - L_{pm}$$

where, L_p is the maximum of the sound pressure levels measured at the 20 positions, and L_{pm} is the surface sound pressure level for an enveloping hemisphere radius r . The microphone height at which this maximum level occurred was noted in order to describe the type of directionality (ie in the horizontal or vertical plane) and the result

coded as 1, 2, 3 or 4 for microphone heights of 0.15r, 0.45r, 0.75r and overhead respectively.

6.3.1 Calculations of measurement uncertainty

Standard deviations, σ , were calculated from the sound power level data in order to assess the measurement uncertainty of each sub-set. Two standard deviations were used. Firstly, a standard deviation about the mean, σ_M . This is a measure of the variability of data from each individual sound power determination of the sub-set about the mean for that sub-set. For instance, for the preferred method, this will involve the standard deviation of the six sound power determinations about the mean of the six determinations. From this value an assessment can be made of how similar to the mean value estimates from a single four microphone determination are likely to be.

However, this does not allow an assessment as to the accuracy of the determination. All six determinations (and therefore, the mean value) may be in error. To account for this possibility it is assumed that the sound power level calculated using all 20 microphone positions, μ , is correct (the true level) and a standard deviation about μ , σ_μ is calculated. This value permits an assessment of how similar to the true value estimates of sound power level from a single four microphone determination are likely to be. This standard deviation is essentially a combination of the variability of a single sub-set sound power determination and the difference between the mean of all sub-set combinations and the true value. This standard deviation is the quantity that is to be compared to the requirements of the ISO Standards to assess the grade of accuracy of the measurement. In ISO 3740, standard deviations of 0.5 dB, 1.5 dB and 3 dB correspond to precision-, engineering- and survey-grade accuracy respectively.

6.3.2 Hemi-anechoic measurement results

As discussed in previous Sections, the prime factor to be assessed is how well any particular sound power level determination approximates the true value. The actual absolute sound power level of each source is of little interest. Therefore, all sound power determinations have been expressed relative to the appropriate 20 microphone assessment. Hence, reported sound power levels determined using the 20 microphone, ISO 3744 array (designated as μ in the results Tables) are all zero.

Results for measurements on actual machines are shown in Tables 17 to 22, those for the reference sound source in Table 23, those for the sources constructed using MDF in Tables 24 to 26 and those using LDB in Tables 27 to 29. The standard deviations of repeatability for the actual machines, shown in the fourth and sixth columns of Tables 17 to 23, were found to be approximately 0.1 dB. This indicates that the noise levels were reasonably constant and the measurement instrumentation provided reliable data. It was decided, therefore, to make only one sound power determination for the noise sources using the reference sound source as this is, by definition, a steady

source, and in addition, the same instrumentation was used. With this exception the same format is used in all thirteen tables. The first data row represents the sound power level obtained using all 20 microphones and is designated "(=μ)" and is always zero (see above). The next two shaded rows show the Directivity Index and the microphone location code (see Section 6.3 above). The following rows contain data corresponding to the sub-sets described in measurements all expressed relative to μ. The remaining three shaded areas contain the results of the calculations of σ_M and σ_μ .

There are only two arrays for the 10-microphone sub-set and for the 4-microphone sub-set according to ISO 3746. It is, therefore, not feasible to perform any meaningful statistical analysis. However, for the 10-microphone arrays, it can be seen from the Tables that differences from μ are small and so the measurement uncertainty for these arrays can be considered similar to those estimated in ISO 3744. For the 4-microphone arrays of ISO 3746 the differences can be quite large (certainly larger than those associated with the "preferred" array) and so for the purposes of this analysis these arrays will not be considered further.

Table 17 Results for the electric razor and the jigsaw

microphone positions		Electric razor		Jig saw	
		level re true (dB)	σ (dB)	level re true (dB)	σ (dB)
according to ISO 3745	20 positions (= μ)	0.0	0.2	0.0	0.1
	directivity index	3.1	0.2	2.0	0.3
	height of max level	1		1	
according to ISO 3744	10 key positions	-0.1	0.3	0.0	0.2
	10 extra positions	0.0	0.1	0.0	0.1
according to ISO 3746	4 key positions	-0.3	0.4	-0.4	0.3
	4 extra positions	-1.0	0.3	-0.5	0.1
4 positions different heights (rapid method)	1st combination	-0.9	0.1	0.1	0.2
	2nd combination	-0.7	0.2	0.2	0.1
	3rd combination	-0.7	0.3	0.1	0.1
	4th combination	0.3	0.2	-0.4	0.1
	5th combination	0.0	0.2	-0.2	0.2
	6th combination	-0.1	0.1	0.0	0.1
	mean of all six	-0.3	0.2	0.0	0.1
	σ about mean	0.5	0.0	0.2	0.0
	σ about μ	0.5	0.0	0.2	0.0
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	0.1	0.1	-0.2	0.1
	2nd combination	0.2	0.3	0.0	0.1
	3rd combination	0.1	0.2	0.1	0.1
	mean of all three	0.1	0.2	-0.1	0.1
	σ about mean	0.1	0.1	0.2	0.0
	σ about μ	0.2	0.0	0.1	0.0
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	-1.1	0.2	-0.2	0.1
	2nd combination	1.4	0.4	-0.6	0.2
	3rd combination	-0.4	0.4	0.6	0.2
	4th combination	1.0	0.1	-0.3	0.1
	5th combination	-1.5	0.1	0.5	0.1
	6th combination	0.6	0.1	-0.4	0.1
	mean of all six	0.0	0.2	-0.1	0.1
	σ about mean	1.2	0.0	0.5	0.0
	σ about μ	1.2	0.0	0.5	0.0
one position (x 20)	σ about μ	1.7	0.1	1.2	0.0

Table 18 Results for the shredder and the hedge trimmer

microphone positions		shredder		Hedge trimmer	
		level re true (dB)	σ (dB)	level re true (dB)	σ (dB)
according to ISO 3745	20 positions (= μ)	0.0	0.0	0.0	0.3
	directivity index	1.7	0.1	1.7	0.2
	height of max level	2		2	
according to ISO 3744	10 key positions	-0.1	0.0	-0.2	0.2
	10 extra positions	0.0	0.0	0.1	0.4
according to ISO 3746	4 key positions	-0.3	0.0	0.2	0.1
	4 extra positions	0.0	0.1	-0.1	0.4
4 positions different heights (rapid method)	1st combination	-0.1	0.1	-0.3	0.3
	2nd combination	-0.6	0.1	0.6	0.3
	3rd combination	-0.2	0.0	0.1	0.3
	4th combination	-0.6	0.1	0.2	0.3
	5th combination	-0.9	0.1	-0.3	0.3
	6th combination	-0.3	0.0	0.3	0.4
	mean of all six	-0.5	0.0	0.1	0.3
	σ about mean	0.3	0.1	0.4	0.0
	σ about μ	0.5	0.0	0.4	0.0
6 positions three opposite sets of three at each hight (not including the overhead position)	1st combination	0.4	0.1	0.0	0.3
	2nd combination	0.2	0.1	-0.3	0.4
	3rd combination	0.1	0.1	-0.1	0.2
	mean of all three	0.2	0.0	-0.1	0.3
	σ about mean	0.2	0.1	0.2	0.0
	σ about μ	0.3	0.0	0.1	0.0
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	0.2	0.1	-0.6	0.3
	2nd combination	0.2	0.0	-1.0	0.3
	3rd combination	0.2	0.0	0.7	0.1
	4th combination	0.7	0.1	0.6	0.3
	5th combination	0.3	0.1	0.4	0.4
	6th combination	0.0	0.1	-1.0	0.4
	mean of all six	0.2	0.0	-0.2	0.3
	σ about mean	0.2	0.0	0.8	0.0
	σ about μ	0.3	0.0	0.8	0.0
one position (x20)	σ about μ	1.5	0.0	1.3	0.1

Table 19 Results for the hair drier and the food processor

microphone positions		hair drier		food processor	
		level re true (dB)	σ (dB)	level re true (dB)	σ (dB)
according to ISO 3745	20 positions (= μ)	0.0	0.1	0.0	0.1
	directivity index	2.0	0.3	2.0	0.2
	height of max level	3		1	
according to ISO 3744	10 key positions	-0.1	0.0	-0.1	0.1
	10 extra positions	0.2	0.1	0.2	0.0
according to ISO 3746	4 key positions	0.2	0.0	-0.4	0.1
	4 extra positions	0.7	0.1	-0.2	0.0
4 positions different heights (rapid method)	1st combination	-0.1	0.1	-0.4	0.2
	2nd combination	0.3	0.1	-0.5	0.0
	3rd combination	0.1	0.0	0.2	0.1
	4th combination	0.3	0.1	0.1	0.1
	5th combination	0.4	0.1	-0.5	0.0
	6th combination	0.1	0.1	-0.2	0.2
	mean of all six	0.2	0.0	-0.2	0.1
	σ about mean	0.2	0.0	0.3	0.0
	σ about μ	0.2	0.0	0.4	0.0
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	0.0	0.1	0.2	0.0
	2nd combination	-0.2	0.0	0.1	0.0
	3rd combination	0.0	0.2	0.1	0.2
	mean of all three	-0.1	0.1	0.1	0.1
	σ about mean	-0.2	0.0	0.1	0.0
	σ about μ	-0.2	0.0	0.2	0.0
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	0.0	0.2	-0.5	0.3
	2nd combination	0.1	0.1	-0.2	0.1
	3rd combination	-0.8	0.1	0.5	0.2
	4th combination	0.0	0.2	0.8	0.1
	5th combination	-0.6	0.0	0.3	0.0
	6th combination	0.7	0.3	-0.3	0.3
	mean of all six	-0.1	0.1	0.1	0.1
	σ about mean	0.5	0.1	0.5	0.1
	σ about μ	0.5	0.1	0.5	0.1
one position (x20)	σ about μ	1.6	0.1	0.9	0.1

Table 20 Results for the pc processor and the dot matrix printer

microphone positions		PC processor		printer	
		level re true (dB)	σ (dB)	level re true (dB)	σ (dB)
according to ISO 3745	20 positions (= μ)	0.0	0.1	0.0	0.4
	directivity index	3.9	0.2	4.3	0.9
	height of max level	1	0.0	1	0.0
according to ISO 3744	10 key positions	0.0	0.2	-0.6	0.6
	10 extra positions	0.0	0.1	0.6	0.2
according to ISO 3746	4 key positions	0.0	0.2	-1.3	0.6
	4 extra positions	-0.6	0.1	-0.4	0.3
4 positions different heights (rapid method)	1st combination	0.0	0.2	-0.2	0.5
	2nd combination	-0.2	0.1	0.9	0.8
	3rd combination	-1.2	0.1	0.1	0.8
	4th combination	-0.2	0.1	-0.2	0.1
	5th combination	-0.5	0.1	-1.5	0.3
	6th combination	0.1	0.1	-0.6	0.4
	mean of all six	-0.3	0.1	-0.2	0.2
	σ about mean	0.5	0.0	0.9	0.2
	σ about μ	0.6	0.0	0.9	0.2
6 positions three opposite sets of three at each hight (not including the overhead position)	1st combination	0.5	0.2	-0.3	0.2
	2nd combination	0.0	0.1	0.8	0.5
	3rd combination	0.1	0.1	-0.2	0.5
	mean of all three	0.2	0.1	0.1	0.3
	σ about mean	0.3	0.0	0.6	0.2
	σ about μ	0.3	0.0	0.5	0.1
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	1.6	0.2	-0.5	0.3
	2nd combination	0.4	0.2	-2.4	1.3
	3rd combination	-2.2	0.1	0.6	0.8
	4th combination	-0.9	0.1	-0.1	0.4
	5th combination	-0.5	0.1	2.6	0.4
	6th combination	1.6	0.1	-1.1	0.1
	mean of all six	0.0	0.1	-0.2	0.4
	σ about mean	1.5	0.0	1.8	0.2
	σ about μ	1.4	0.0	1.6	0.2
one position (x20)	σ about μ	2.3	0.1	2.7	0.2

Table 21 Results for the hand-held cleaner and the floor buffing machine

microphone positions		hand held cleaner		Floor buffer	
		level re true (dB)	σ (dB)	level re true (dB)	σ (dB)
according to ISO 3745	20 positions ($= \mu$)	0.0	0.1	0.0	0.6
	directivity index	4.6	0.1	2.5	0.3
	height of max level	1		1	
according to ISO 3744	10 key positions	-0.3	0.0	-0.2	0.2
	10 extra positions	0.3	0.2	0.2	1.0
according to ISO 3746	4 key positions	0.9	0.2	-0.8	0.1
	4 extra positions	-0.7	0.2	-0.2	1.0
4 positions different heights (rapid method)	1st combination	0.5	0.1	0.1	0.5
	2nd combination	1.3	0.3	-0.1	0.7
	3rd combination	-0.9	0.2	-0.3	0.6
	4th combination	1.7	0.2	0.0	0.8
	5th combination	-0.4	0.1	0.0	0.6
	6th combination	0.9	0.1	0.2	0.9
	mean of all six	0.5	0.2	0.0	0.7
	σ about mean	1.0	0.0	0.2	0.1
	σ about μ	1.0	0.1	0.0	0.0
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	0.5	0.2	0.0	0.5
	2nd combination	-1.3	0.2	0.3	0.5
	3rd combination	-0.5	0.1	-0.2	0.9
	mean of all three	-0.4	0.1	0.0	0.6
	σ about mean	0.9	0.1	0.3	0.1
	σ about μ	0.9	0.1	0.2	0.1
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	-0.3	0.3	0.1	0.1
	2nd combination	-2.9	0.1	0.2	0.1
	3rd combination	0.3	0.2	-0.9	0.2
	4th combination	1.2	0.3	-0.1	0.9
	5th combination	-0.1	0.2	0.3	0.8
	6th combination	-1.5	0.1	0.3	1.4
	mean of all six	-0.6	0.1	0.0	0.6
	σ about mean	1.4	0.1	0.6	0.3
	σ about μ	1.4	0.1	0.5	0.3
one position (x20)	σ about μ	2.6	0.0	1.3	0.1

Table 22 Results for the computer cabinet and the vacuum pump

microphone positions		computer cabinet		vacuum pump	
		level re true (dB)	σ (dB)	level re true (dB)	σ (dB)
according to ISO 3745	20 positions (= μ)	0.0	0.1	0.0	0.4
	directivity index	8.0	0.2	4.7	0.9
	height of max level	4		1	
according to ISO 3744	10 key positions	0.1	0.3	-0.4	0.2
	10 extra positions	0.0	0.1	0.2	0.2
according to ISO 3746	4 key positions	2.5	0.1	0.1	0.3
	4 extra positions	2.3	0.1	0.2	0.1
4 positions different heights (rapid method)	1st combination	2.9	0.1	-0.1	0.2
	2nd combination	2.5	0.1	-1.0	0.3
	3rd combination	2.6	0.1	-1.2	0.3
	4th combination	2.8	0.1	0.0	0.5
	5th combination	2.7	0.1	-0.8	0.5
	6th combination	2.4	0.1	1.4	0.5
	mean of all six	2.6	0.1	-0.3	0.3
	σ about mean	0.2	0.0	1.0	0.1
	σ about μ	2.6	0.2	1.0	0.1
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	-2.6	0.2	0.7	0.5
	2nd combination	-4.3	0.1	0.3	0.5
	3rd combination	-3.8	0.2	-0.7	0.4
	mean of all three	-3.6	0.1	0.1	0.4
	σ about mean	0.9	0.1	0.7	0.2
	σ about μ	3.7	0.2	0.6	0.2
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	-2.5	0.5	-1.8	0.2
	2nd combination	-3.5	0.0	0.7	0.6
	3rd combination	-4.5	0.2	-0.3	0.1
	4th combination	-2.8	0.2	2.3	0.7
	5th combination	-5.2	0.1	-0.1	0.4
	6th combination	-3.2	0.3	-1.2	0.9
	mean of all six	-3.6	0.1	-0.1	0.4
	σ about mean	1.1	0.1	1.5	0.2
	σ about μ	3.8	0.2	2.6	1.3
one position (x20)	σ about μ	5.0	0.0	2.8	0.2

Table 23 Results for the reference sound source

microphone positions		level re true (dB)
according to ISO 3745	20 positions (= μ)	0.0
	directivity index	0.8
	height of max level	2
according to ISO 3744	10 key positions	0.1
	10 extra positions	0.0
according to ISO 3746	4 key positions	0.1
	4 extra positions	0.1
4 positions different heights (rapid method)	1st combination	0.0
	2nd combination	-0.3
	3rd combination	-0.2
	4th combination	-0.1
	5th combination	-0.2
	6th combination	-0.2
	mean of all six	-0.2
	σ about mean	0.1
	σ about μ	0.2
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	0.2
	2nd combination	0.2
	3rd combination	0.2
	mean of all three	0.2
	σ about mean	0.0
	σ about μ	0.2
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	0.3
	2nd combination	0.2
	3rd combination	0.2
	4th combination	0.1
	5th combination	0.2
	6th combination	0.2
	mean of all six	0.2
	σ about mean	0.1
	σ about μ	0.2
one position (x20)	σ about μ	0.8

Table 24. Results for MDF boxes 1 and 2 with a Directivity Index of 2.5 dB and 2.8 dB.

microphone positions		box 1	box 2
		level re true (dB)	level re true (dB)
according to ISO 3745	20 positions ($= \mu$)	0.0	0.0
	directivity index	2.5	2.8
	height of max level	4	1
according to ISO 3744	10 key positions	0.0	0.0
	10 extra positions	0.0	-0.1
according to ISO 3746	4 key positions	0.5	-0.2
	4 extra positions	0.5	-0.2
4 positions different heights (rapid method)	1st combination	0.6	-0.8
	2nd combination	0.6	-0.5
	3rd combination	0.6	-0.6
	4th combination	0.6	-0.9
	5th combination	0.5	-0.6
	6th combination	0.4	-0.7
	mean of all six	0.5	-0.7
	σ about mean	0.1	0.2
	σ about μ	0.5	0.6
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	-0.4	0.2
	2nd combination	-0.4	0.5
	3rd combination	-0.4	0.3
	mean of all three	-0.4	0.3
	σ about mean	0.0	0.1
	σ about μ	0.4	0.4
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	-0.4	0.2
	2nd combination	-0.2	0.4
	3rd combination	-0.4	0.4
	4th combination	-0.4	0.2
	5th combination	-0.6	0.5
	6th combination	-0.4	0.3
	mean of all six	-0.4	0.3
	σ about mean	0.1	0.1
	σ about μ	0.4	0.4
one position (x20)	σ about μ	2.0	3.1

Table 25 Results for MDF boxes 3, 4 and 5 with a Directivity Index of 3.8 dB, 5.2 dB and 6.4 dB.

microphone positions		box 5	box 4	box 3
		level re true (dB)	level re true (dB)	level re true (dB)
according to ISO 3745	20 positions (= μ)	0.0	0.0	0.0
	directivity index	6.4	5.2	3.8
	height of max level	1.0	4.0	1.0
according to ISO 3744	10 key positions	0.3	0.0	0.0
	10 extra positions	-0.3	0.0	0.0
according to ISO 3746	4 key positions	-1.5	0.8	-0.4
	4 extra positions	0.5	0.7	-0.6
4 positions different heights (rapid method)	1st combination	0.8	1.3	-0.7
	2nd combination	-1.8	1.6	-0.3
	3rd combination	-0.9	1.4	-1.0
	4th combination	-2.6	1.3	-0.5
	5th combination	0.6	1.6	-0.5
	6th combination	-0.9	1.4	-0.9
	mean of all six	-0.8	1.4	-0.7
	σ about mean	1.3	0.1	0.3
	σ about μ	1.5	1.4	0.7
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	0.5	-1.0	0.4
	2nd combination	0.2	-1.3	0.2
	3rd combination	0.5	-1.6	0.6
	mean of all three	0.4	-1.3	0.4
	σ about mean	0.2	0.3	0.2
	σ about μ	0.4	1.3	0.4
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	2.8	-1.0	0.4
	2nd combination	1.6	-1.3	0.2
	3rd combination	-8.9	-1.5	0.5
	4th combination	-5.2	-0.9	0.4
	5th combination	-1.9	-1.2	0.2
	6th combination	3.2	-1.7	0.6
	mean of all six	-1.4	-1.3	0.4
	σ about mean	4.9	0.3	0.2
	σ about μ	4.7	1.3	0.4
one position (x20)	σ about μ	7.1	4.6	3.9

Table 26 Results for MDF boxes 6 and 7 with a Directivity Index of 7.4 dB and 7.5 dB.

microphone positions		box 7	box 6
		level re true (dB)	level re true (dB)
according to ISO 3745	20 positions (= μ)	0.0	0.0
	directivity index	7.5	7.4
	height of max level	1.0	4.0
according to ISO 3744	10 key positions	0.4	0.1
	10 extra positions	-0.4	0.0
according to ISO 3746	4 key positions	-2.7	1.9
	4 extra positions	0.3	1.9
4 positions different heights (rapid method)	1st combination	1.8	2.4
	2nd combination	-3.0	2.5
	3rd combination	-1.1	2.5
	4th combination	-4.0	2.4
	5th combination	1.2	2.5
	6th combination	-1.7	2.4
	mean of all six	-1.1	2.4
	σ about mean	2.3	0.1
	σ about μ	2.4	2.4
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	0.9	-2.7
	2nd combination	-0.6	-2.9
	3rd combination	0.7	-3.3
	mean of all three	0.3	-2.9
	σ about mean	0.8	0.3
	σ about μ	0.7	3.0
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	3.5	-2.7
	2nd combination	0.9	-2.8
	3rd combination	-8.9	-3.3
	4th combination	-6.7	-2.8
	5th combination	-2.9	-3.0
	6th combination	3.5	-3.2
	mean of all six	-1.8	-2.9
	σ about mean	5.3	0.3
	σ about μ	5.1	3.0
one position (x20)	σ about μ	7.4	6.2

Table 27 Results for the LDB boxes 1, 2 and 3 with a Directivity Index of 2.3 dB, 2.6 dB and 3.6 dB.

microphone positions		box 1	box 2	box 3
		level re true (dB)	level re true (dB)	level re true (dB)
according to ISO 3745	20 positions (= μ)	0.0	0.0	0.0
	directivity index	2.3	2.6	3.6
	height of max level	1	4	4
according to ISO 3744	10 key positions	0.0	0.0	0.0
	10 extra positions	0.0	0.1	0.0
according to ISO 3746	4 key positions	-0.2	0.3	0.1
	4 extra positions	-0.2	0.3	0.3
4 positions different heights (rapid method)	1st combination	-0.5	0.5	0.7
	2nd combination	-0.2	0.6	0.8
	3rd combination	-0.7	0.7	1.1
	4th combination	-0.6	0.5	0.7
	5th combination	-0.2	0.6	0.8
	6th combination	-0.7	0.8	1.1
	mean of all six	-0.5	0.6	0.9
	σ about mean	0.3	0.1	0.2
	σ about μ	0.5	0.6	0.9
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	0.1	-0.4	-1.0
	2nd combination	0.5	-0.1	-0.2
	3rd combination	0.1	-0.5	-0.7
	mean of all three	0.3	-0.4	-0.6
	σ about mean	0.2	0.2	0.4
	σ about μ	0.3	0.4	0.7
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	0.2	-0.4	-1.0
	2nd combination	0.5	-0.1	-0.2
	3rd combination	0.1	-0.5	-0.7
	4th combination	0.1	-0.4	-1.0
	5th combination	0.5	-0.1	-0.2
	6th combination	0.1	-0.5	-0.7
	mean of all six	0.3	-0.4	-0.6
	σ about mean	0.2	0.2	0.4
	σ about μ	0.3	0.4	0.7
one position (x20)	σ about μ	2.0	1.7	2.2

Table 28 Results for the LDB boxes 4 and 5 with a Directivity Index of 5.9 dB and 6.2 dB.

microphone positions		box 4	box 5
		level re true (dB)	level re true (dB)
according to ISO 3745	20 positions (= μ)	0.0	0.0
	directivity index	5.9	6.2
	height of max level	2	2
according to ISO 3744	10 key positions	0.1	-0.1
	10 extra positions	-0.1	0.0
according to ISO 3746	4 key positions	0.8	1.0
	4 extra positions	-1.5	-1.2
4 positions different heights (rapid method)	1st combination	-1.5	-1.9
	2nd combination	0.9	1.1
	3rd combination	-0.5	-1.0
	4th combination	0.1	0.7
	5th combination	-1.2	-1.5
	6th combination	-1.0	-1.4
	mean of all six	-0.5	-0.7
	σ about mean	0.9	1.3
	σ about μ	1.0	1.3
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	0.2	0.4
	2nd combination	-0.2	-0.5
	3rd combination	0.8	0.8
	mean of all three	0.3	0.2
	σ about mean	0.5	0.6
	σ about μ	0.5	0.6
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	-3.3	-3.7
	2nd combination	-1.7	-1.7
	3rd combination	3.3	3.2
	4th combination	2.2	2.5
	5th combination	0.8	0.5
	6th combination	-5.5	-5.2
	mean of all six	-0.7	-0.7
	σ about mean	3.4	3.4
	σ about μ	3.2	3.2
one position (x20)	σ about μ	4.6	4.6

Table 29 Results for the LDB boxes with a Directivity Index of 6.4 dB and 6.8 dB.

microphone positions		box 6	box 7
		level re true (dB)	level re true (dB)
according to ISO 3745	20 positions (= μ)	0.0	0.0
	directivity index	6.4	6.8
	height of max level	4	1
according to ISO 3744	10 key positions	0.0	-0.1
	10 extra positions	0.0	0.2
according to ISO 3746	4 key positions	1.6	1.4
	4 extra positions	1.6	-2.3
4 positions different heights (rapid method)	1st combination	1.8	-3.1
	2nd combination	1.8	1.5
	3rd combination	2.1	-1.5
	4th combination	1.8	1.6
	5th combination	1.8	-2.1
	6th combination	2.1	-1.4
	mean of all six	1.9	-0.8
	σ about mean	0.2	2.0
	σ about μ	2.0	2.0
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	-2.3	1.0
	2nd combination	-1.7	-1.0
	3rd combination	-2.4	0.9
	mean of all three	-2.1	0.3
	σ about mean	0.4	1.1
	σ about μ	2.1	1.0
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	-2.3	-3.7
	2nd combination	-1.6	-2.0
	3rd combination	-2.4	3.1
	4th combination	-2.3	3.2
	5th combination	-1.7	-0.3
	6th combination	-2.4	-4.1
	mean of all six	-2.1	-0.6
	σ about mean	0.3	3.2
	σ about μ	2.1	3.0
one position (x20)	σ about μ	3.3	4.2

From an examination of the data in these Tables it can be seen that generally where the directionality of the source varies in the horizontal plane (code 1 and 2) the mean differences from μ , for the sub-set combinations, are small (especially when Directivity Index is below about 5 dB) and the values of both the standard deviations are similar. For sources where the directionality is in the vertical plane this is not the case. Here the differences from μ are large and this is reflected in a difference between the two standard deviation calculations. For these sources the variation between individual sub-set estimations is small as the sound pressure level variation is in the vertical plane and so at first sight measurement uncertainty of the sound power determinations (σ_M) is small. See for example the 4-microphone position, 6-combination data for the source with a Directivity Index of 7.4 dB in Table 26, where σ_M is only 0.1 dB. However, this is not a true reflection of the measurement uncertainty because of the large differences from the value of μ . The standard deviation, σ_μ does reflect this difference and for this example is 2.4 dB.

It can also be seen that the value of σ_μ tends to increase as the value of Directivity Index increases, an indication that as the source becomes more directional the uncertainty involved with a given sound power determination procedure increases. It can also be seen that for a given source the measurement uncertainty increases as the number of microphones used in the sub-set decreases. Both these observations are to be expected, but it is interesting to examine more closely the relationship between these three parameters. This may be seen more clearly in Table 30 where the values of σ_μ are listed for each machine and each sub-set arrangement together with the Directivity Index. The above observations are now more clear. For example, consider a change in Directivity Index from about 1 dB (the reference sound source) to about 6 dB (MDF box 5 for example), the value of σ_μ for the one microphone sub-set increases from about 1 dB to 7 dB with corresponding values for the three, four and six sub-set combinations decreasing from 0.2 dB to 4.7 dB, 1.5 dB and 0.4 dB respectively.

Table 30 Directivity Index and uncertainty values for all sources and sub-sets

source	DI	one-mic	three-mics	four-mics	six-mics
1. rss	0.8	0.8	0.2	0.2	0.2
2. shredder	1.7	1.5	0.3	0.5	0.4
3. hedge	1.7	1.3	0.8	0.4	0.1
4. jigsaw	2.0	1.2	0.5	0.2	0.1
5. hair	2.0	1.6	0.5	0.2	0.2
6. food	2.0	0.9	0.5	0.4	0.2
7. floor	2.5	1.3	0.5	0.0	0.2
8. razor	3.1	1.7	1.2	0.5	0.2
9. pc	3.9	2.3	1.4	0.6	0.3
10. print	4.3	2.7	1.6	0.9	0.5
11. cleaner	4.6	2.6	1.4	1.0	0.9
12. pump	4.7	2.8	2.6	1.0	0.6
13. cabinet	8.0	5.0	3.8	2.6	3.7
14. MDF box 1	2.5	2.0	0.4	0.5	0.4
15. MDF box 2	2.8	3.1	0.4	0.6	0.4
16. MDF box 3	3.8	3.9	0.4	0.7	0.4
17. MDF box 4	5.2	4.6	1.3	1.4	1.3
18. MDF box 5	6.4	7.1	4.7	1.5	0.4
19. MDF box 6	7.4	6.2	3.0	2.4	3.0
20. MDF box 7	7.5	7.4	5.1	2.4	0.7
21. LDB box 1	2.3	2.0	0.3	0.5	0.3
22. LDB box 2	2.6	1.7	0.4	0.6	0.4
23. LDB box 3	3.6	2.2	0.7	0.9	0.7
24. LDB box 4	5.9	4.6	3.2	1.0	0.5
25. LDB box 5	6.2	4.6	3.2	1.3	0.6
26. LDB box 6	6.4	3.3	2.1	2.0	2.0
27. LDB box 7	6.8	4.2	3.0	2.0	1.0

From the data in Table 30 it would appear that the sub-set arrangement with six microphones generally provides sound power levels with the smaller measurement uncertainty. However, the difference between the calculated measurement uncertainties for four and six microphone sub-sets is small. In fact, it can be seen that there are some variations of this dependency of σ_p on Directivity Index and sub-set arrangements. This can be better appreciated by examining the data in graphical form. This also provides the opportunity to assess the potential accuracy of each sub set in the terms used in ISO Standards (engineering-, or survey-grade). The data for all sub-sets is shown in Figure 3 with measurement uncertainty (σ_p) plotted as a function of Directivity Index with the number of microphones in a sub-set as parameter. A least squares linear best fit line has been fitted to each data set. As an indication as to the goodness of fit the standard deviation of the differences of each data point from this line has been calculated. The best fit lines are of the form $y = mx + C$. The constants m and C are listed in Table 31 together with the associated standard deviation.

Table 31 Constants and standard deviations for best fit lines

array	m	C	sd (dB)
1 microphone	0.7859	-0.1631	0.87
3 microphones	0.6190	-0.9268	0.66
4 microphones	0.3311	-0.3833	0.26
6 microphones	0.3035	-0.4937	0.63

The significance of the lower standard deviation for the four-microphone sub-set is discussed later when assessing the grade of accuracy.

From Figure 3, the increase of uncertainty with Directivity Index is clear as is the decrease in uncertainty with the number of microphones in the sub-set. Clearly the one microphone data is associated with the largest uncertainty followed by the three microphone data and with fairly similar results for the other two sub-sets. It can be seen that there is some variation of individual data points about the best fit lines.

To examine this data variation more closely these data are displayed for individual sub-sets in Figures 4 to 7 together with the best fit lines from Figure 3. The variation about the best fit lines is now more apparent especially for high values of Directivity Index. One major factor causing these variations is differences between data from sources with a horizontal directionality (codes 1 and 2 in the results Tables) compared with those with a vertical directionality (code 4). This is best illustrated from an examination of the six-microphone data in Figure 7. Here the data points that are above the best fit line at the highest values of Directivity Index are for sources with a horizontal directionality and those under the line for sources with a vertical directionality. It may be that the way Directivity Index is defined, as a difference between the average sound pressure level and the maximum sound pressure level, may not be a sufficiently accurate metric. However, it is a generally accepted and well established descriptor so it will be used

in this Report. It is worthy of note, however, that the variation of individual data points is slightly reduced by replacing Directivity Index with the difference between the maximum and minimum sound pressure levels measured using the 20-microphone array. However, the choice of the descriptor does not affect the conclusions regarding the potential measurement uncertainties involved in the determination of sound power levels.

In order to take account of these data variations it is interesting to consider the goodness of fit of the data points by the use of the standard deviation of the differences of individual data points to the best fit line (see Table 31). The effect of these standard deviations is shown in Figures 4 to 7 where twice the standard deviation has been added to, and taken from, the constant C thus providing two lines representing a $\pm$ two standard deviation limit. Statistically, this means that 95% of data points would be expected to lie within these two lines. An examination of the four figures tends to bear this out. For the current purposes (see Section 6.1) it is the upper limit (plus two standard deviations) that is of interest as statistically it can be expected that data points should lie below the upper limit line. These lines can, therefore, be used with a high level of statistical confidence to assess the measurement uncertainty associated with a particular measurement arrangement. This means that the machinery manufacturer can be confident with a labelled value if it is obtained using this upper limit to assess measurement uncertainty.

This can be more fully appreciated from an examination of Figure 8 where the plus two standard deviation lines are plotted for each of the four sub-set arrangements on the same axes. It can be seen that the arrangement that provides the lowest uncertainty is the four microphone sub-set (the preferred arrangement) and not the six microphone sub-set as indicated from Figure 3. This is a result of the larger data scatter and subsequent higher standard deviation associated with the goodness of fit for the six-microphone sub-set. As discussed above, the larger data scatter was in part due to the differences between horizontal and vertical directionality sources. The reason for these large differences is the absence of an overhead microphone in the array (ISO 3744 position 10 or 20) and so for sources with a vertical directionality the energy radiated in an upwards direction is not adequately accounted for.

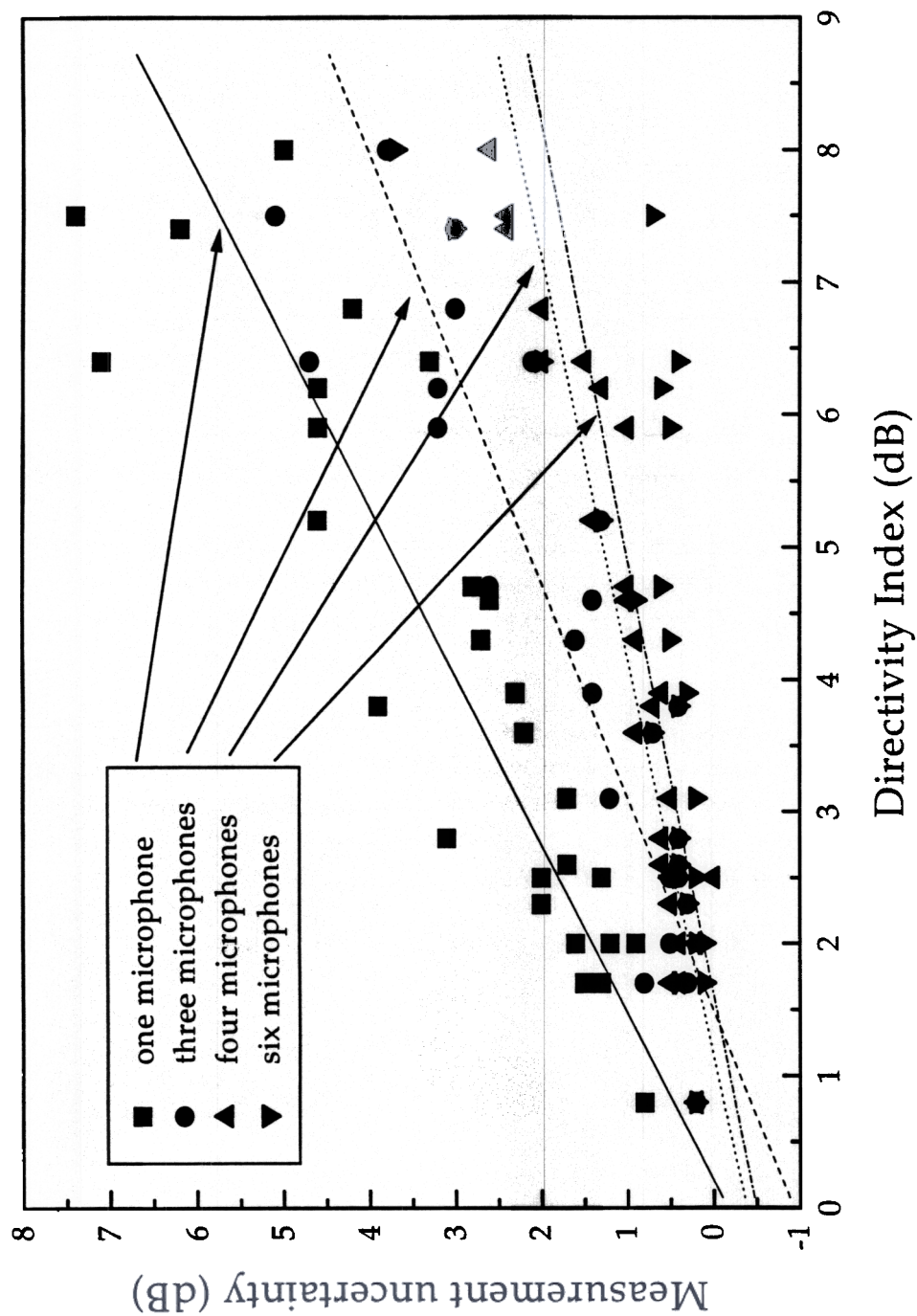


Figure 3 Variation of measurement uncertainty as a function of Directivity Index with microphone sub-set as a parameter

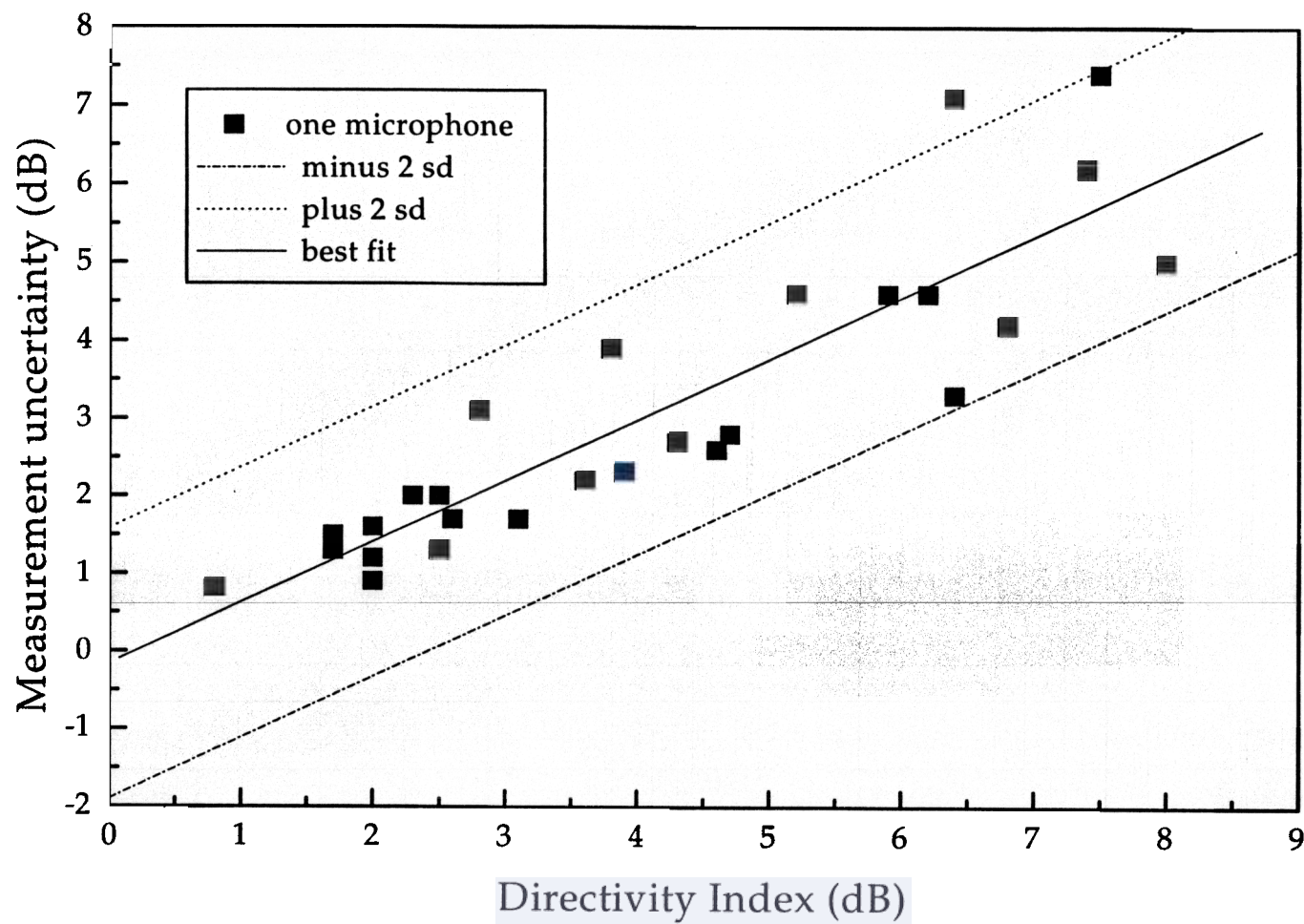


Figure 4 Variation of measurement uncertainty as a function of Directivity Index for the one microphone sub-set with a best fit line and plus and minus two standard deviation lines

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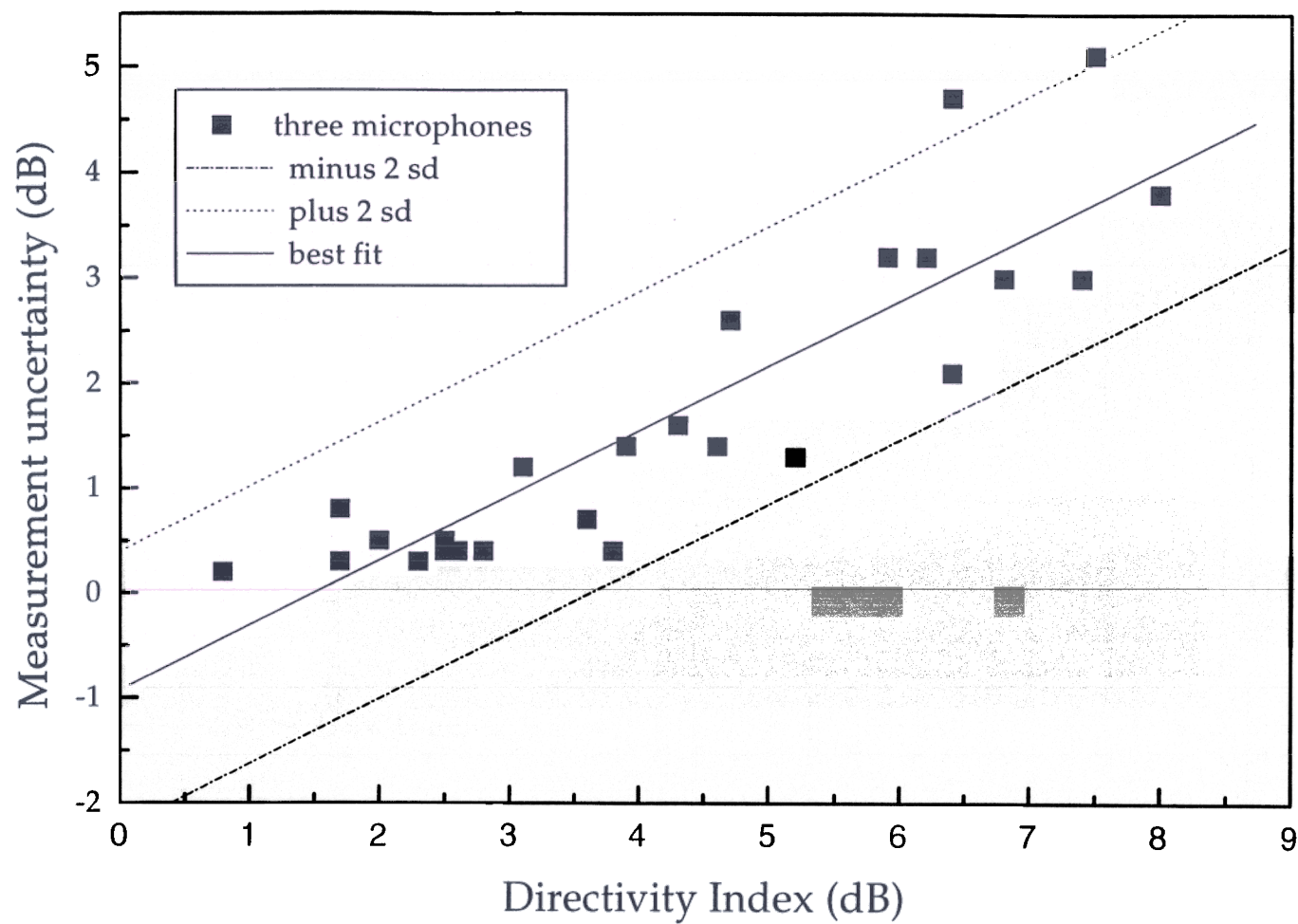


Figure 5 Variation of measurement uncertainty as a function of Directivity Index for the three microphone sub-set with a best fit line and plus and minus two standard deviation lines

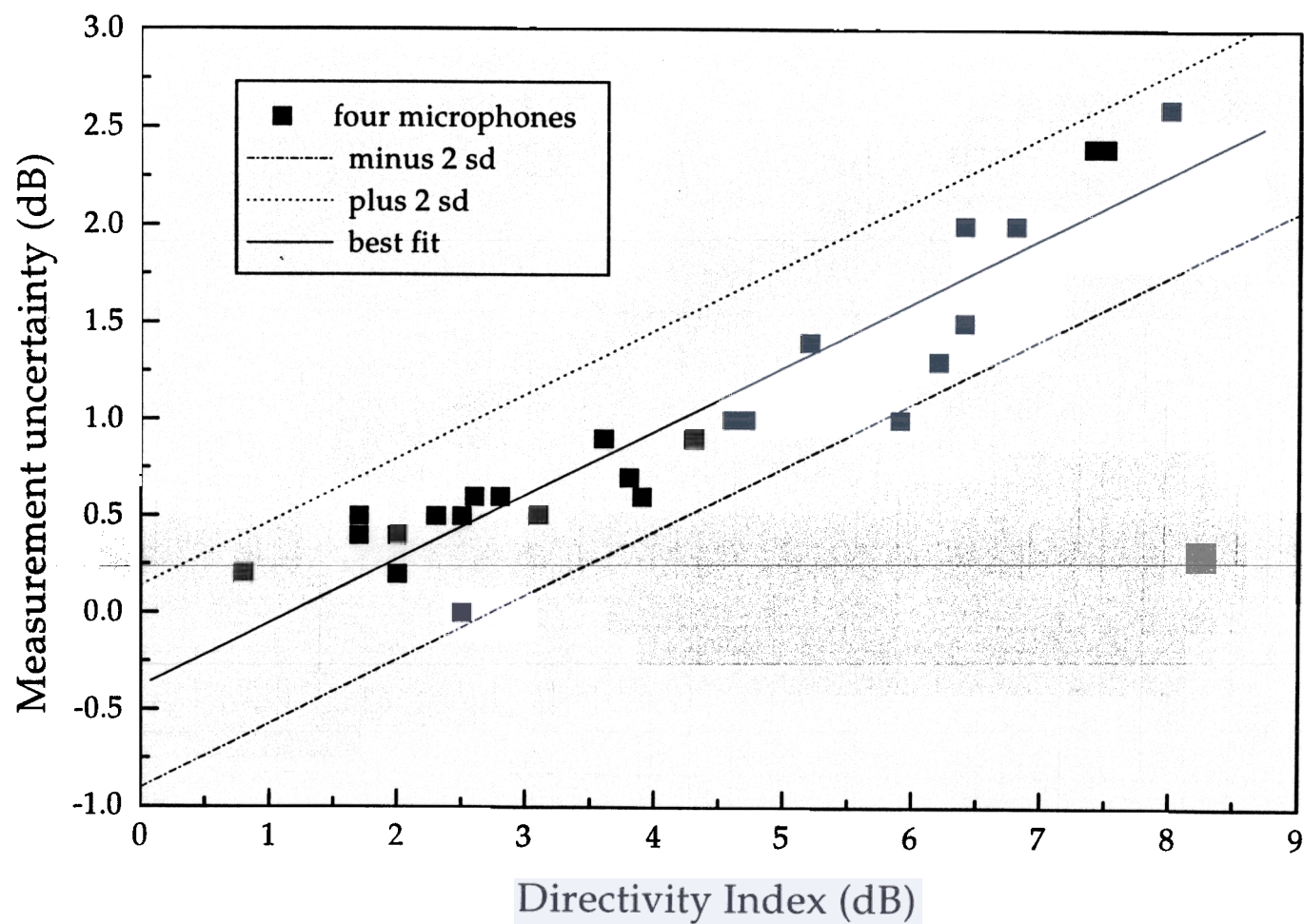


Figure 6 Variation of measurement uncertainty as a function of Directivity Index for the four microphone sub-set with a best fit line and plus and minus two standard deviation lines

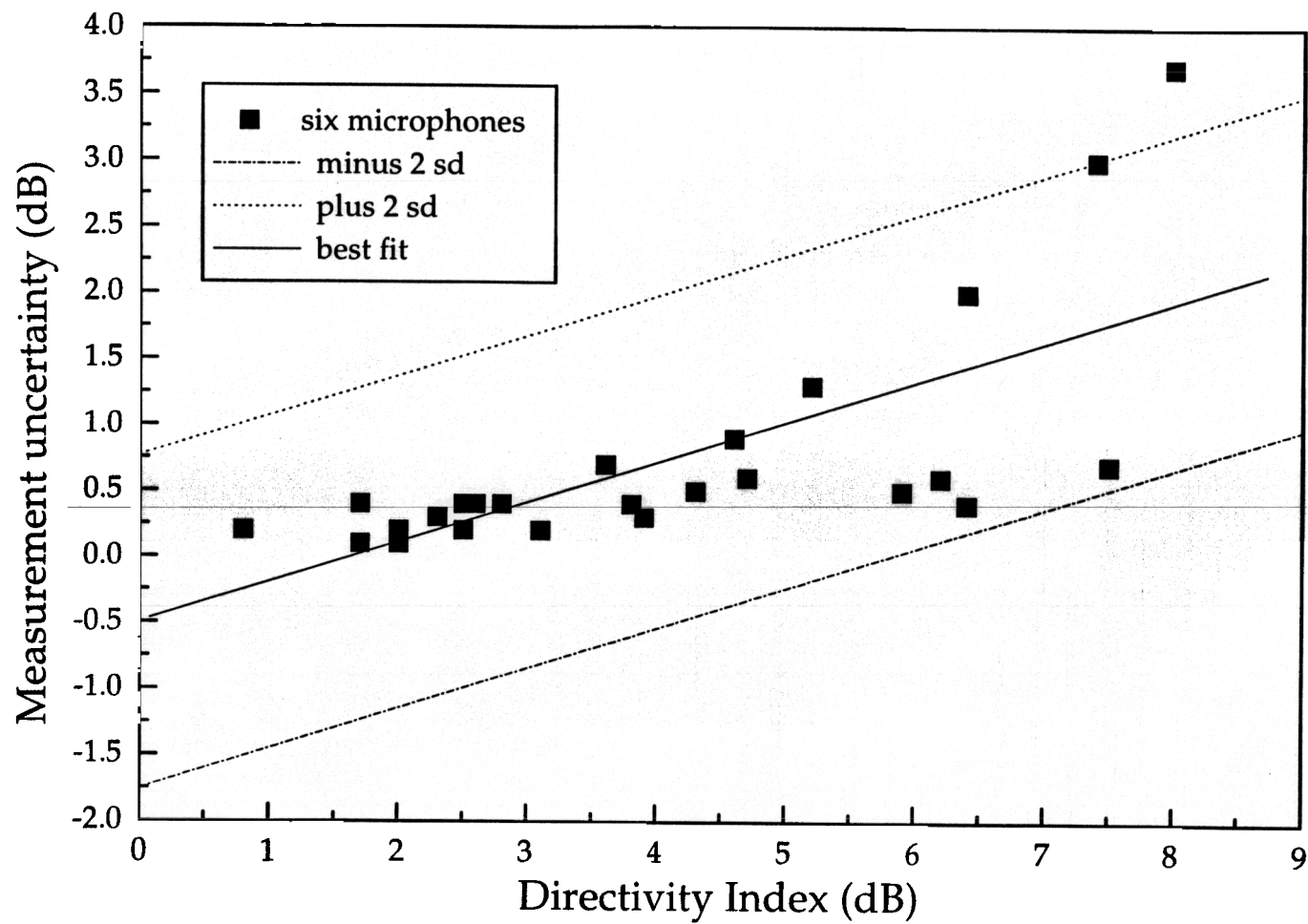


Figure 7 Variation of measurement uncertainty as a function of Directivity Index for the six microphone sub-set with a best fit line and plus and minus two standard deviation lines

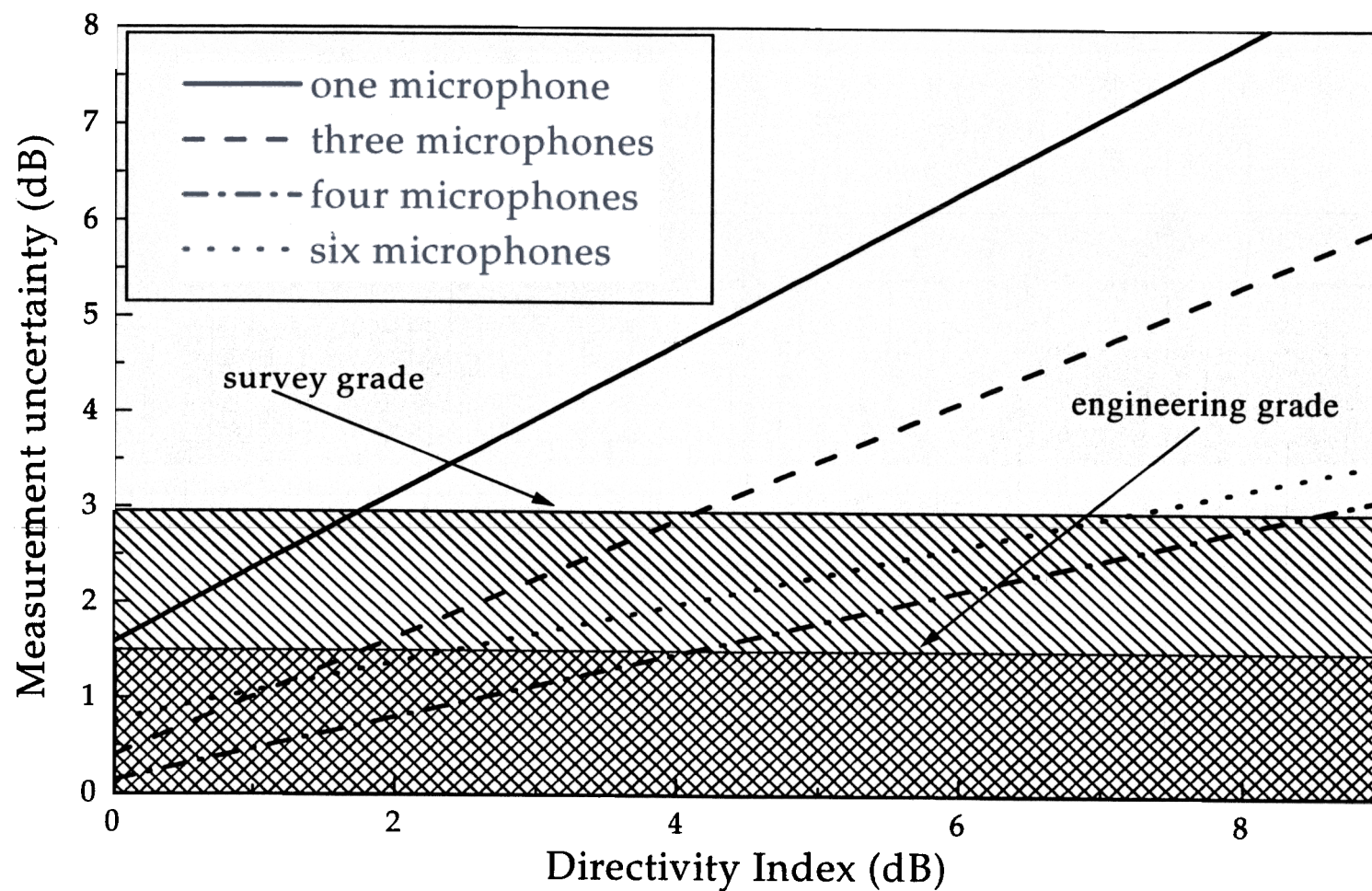


Figure 8 Variation of measurement uncertainty as a function of Directivity Index for the plus two standard deviation lines with sub-set configuration as a parameter and including an ISO accuracy grade mask

Also shown in Figure 8 are two masked regions representing the ISO Standards definition of engineering- and survey-grade accuracy. The expected measurement uncertainty (hence ISO accuracy grade) can be observed from Figure 6. For instance for the preferred microphone arrangement (the four microphone sub-set) it can be seen that an engineering grade accuracy can be attributed to sound power level determinations for noise sources with Directivity Index values up to about 4 dB. This is significant when the data in Table 30 is examined. As here it can be seen that this encompasses the majority of machines tested which in turn are representative of large volume machinery manufacture.

6.4 SUMMARY OF THE VERIFICATION OF THE FOUR-MICROPHONE ARRAY IN HEMI-ANECHOIC CONDITIONS

As the noise source (machine) becomes more directional (the Directivity Index increases) the measurement uncertainty involved with a given sound power determination procedure increases.

For a given noise source the measurement uncertainty increases as the number of microphones used in the sound power determination decreases.

A procedure has been developed that enables the measurement uncertainty associated with a sound power determination made with a known number of sound pressure level measurements on a hemispherical enveloping surface to be estimated from a knowledge of Directivity Index.

Sound power levels determined in a hemi-anechoic room, using only four microphone positions chosen from the ISO 3744 twenty-microphone array such that all are at different heights and on radii that have equal angular spacing (the "preferred" method) are estimated to be of engineering grade accuracy for noise sources with a Directivity Index up to about 4 dB and of survey-grade accuracy for noise sources with a Directivity Index of 8 dB.

7 VALIDATION OF THE FOUR-MICROPHONE ARRAY IN SEMI-REVERBERANT CONDITIONS

In Section 6 it was proposed from an examination of Figure 8 that an ISO engineering-grade of accuracy could be achieved with a 95% statistical confidence for sound power levels determined using only four sound pressure level measurements if the DI of the source was less than approximately 4 dB. This conclusion was based on a series of measurements carried out in hemi-anechoic conditions where the value of K_{2A} was approximately zero. So, from these measurements it is not possible to assess the performance of a reduced number of measurement positions in environments where the value of K_{2A} is not approximately zero. In order to assess how the accuracy of a sound power level measurement is affected by the acoustic environment, sound power level determinations have been carried out in several rooms with values of K_{2A} up to approximately 9 dB.

7.1 ACOUSTIC ENVIRONMENT AND NOISE SOURCES

The sound power levels of ten of the noise sources used in the hemi-anechoic series of validation measurements, chosen to cover a range of DI from 0,8 dB to 7.5 dB, were determined in four rooms with values of K_{2A} ranging from 3.6 dB to 9.6 dB. The noise sources are described in Section 6.2 and are listed in Table 30 as numbers 1, 2, 6, 11, 14, 16, 17, 18, 19, and 20. The four rooms, designated A, B, C, and D, are briefly described below.

Room A,
 $K_{2A} = 6.5$ dB.

A small empty first floor office approximately 4 m square and 3 m high. The walls and ceiling are of painted plaster and the floor covered with carpet.

Room B,
 $K_{2A} = 9.6$ dB.

A small ground floor laboratory again approximately 4 m square but with a wall-to-wall cupboard along one side effectively reducing the floor area to 3 m x 4 m. The room is 3 m high. The noise sources were placed in the centre of the floor. This required careful orientation of the 1.5 m radius measurement surface to avoid some of the microphone locations coinciding with the wall surface.

Room C,
 $K_{2A} = 3.6$ dB.

A large ground floor room used for storage of empty gas canisters, laboratory furniture (benches, tables etc) and wooden packing cases. The room was 7 m high with a floor area of approximately 22 m x 12 m with approximately one-third of this clear of stored artifacts. The noise sources were positioned towards one corner of the room approximately 2 m from the nearest two walls.

Room D,
 $K_{2A} = 8$ dB.

This room was designed for use as a reverberation chamber. It has asymmetric walls and a sloping ceiling all of painted plaster and a painted concrete floor and consequently has a very long reverberation time. Room dimensions are approximately 7 m x 6.5 m x 5.5 m high. All noise sources were positioned in the centre of the floor area.

It can be seen that two of the rooms (A and B) are relatively small compared to the size of the measurement surface, and so all the measurement positions are close to one of the walls and hence the large values of k-factor (6.5 dB and 9.6 dB). One room (C) is very large but to obtain the required value of k-factor (3.6 dB) the source was positioned in a corner close to two walls and so, consequently, are some of the measurement positions. The fourth room (D) is used as a reverberation chamber and in this case a k-factor of 8 dB was achieved with none of the measurement positions close to a wall. It is recognised that the existing "semi-reverberant" sound power Standards require that measurements are not made close to a reflecting surface. However, for the purposes of this evaluation sound power levels will be determined when these conditions are violated. If it turns out that determinations are inaccurate then this will be accounted for in the assessment of measurement uncertainty. The Standards also require that measurements are made with the machine on a reflecting surface. This is clearly not the case for room A. The consequence of this is discussed in Section 7.3.

The value of K_{2A} for each room was estimated using the absolute comparison method. This is a substitution method in which a reference sound source is placed in the same location as the machine under test. The sound power level is determined as described in Clauses 7 & 8 of ISO 3744. The sound power level, L_W , of the reference sound source was determined in each of the four rooms using the 20-microphone array used for the sound power determination of each noise source and the environmental correction, K_{2A} estimated from:

$$K_{2A} = L_{Wr} - L_W$$

where L_{Wr} is the calibrated sound power level of the reference sound source.

Sound power determinations were carried out using the microphone array sub-sets described in Section 6.3. For completeness the Directivity Index was also determined although in these rooms it can only serve as an indication of the increase in K_{2A} , as DI will of course decrease as the acoustic conditions become less anechoic.

The standard deviations of repeatability for the noise sources used in this semi-reverberant series of measurements were estimated in Section 6.3.2 to be small (of the order 0.1 dB). This indicated that the noise levels were reasonably constant and the measurement instrumentation provided reliable data. It was decided, therefore, to make only one sound power determination using each noise source.

7.2 CONSIDERATIONS FOR THE CALCULATION OF MEASUREMENT UNCERTAINTY

As for the sound power determinations carried out for validation in hemi-anechoic conditions (see Section 6.3.1) standard deviations were calculated from the sound power level data in order to assess the measurement uncertainty of each sub-set. Firstly, a standard deviation about the mean, σ_M ; this is a measure of the variability of data from each individual sound power determination of the sub-set about the mean for that sub-set. Then, because this standard deviation does not allow an assessment as to the accuracy of the determination, a second standard deviation, σ_μ about μ , the sound power level calculated using all twenty microphone positions in each room is calculated. This standard deviation permits an assessment of how similar to the true room value, estimates of sound power level from a single array from a sub-set determination are likely to be.

However, σ_μ still does not allow an assessment as to the accuracy of the determination as even the twenty-microphone determination (the true room value) may be in error, as for the purposes of this investigation, it is assumed that the true value is that determined strictly according to ISO 3744 using the twenty-microphone array in an acoustic environment where the value of K_{2A} is approximately zero. So, for these semi-reverberant validation measurements a third standard deviation has been calculated in order to assess the variation of sound power determinations about the value determined using a twenty-microphone array in an environment where $K_{2A} = 0$. This has been termed, $\sigma_{\mu(k=0)}$. This standard deviation is essentially a combination of the variability of a single sub-set sound power determination and the difference between the mean of all sub-set combinations and the true value. It permits an assessment of how similar to the true value estimates of sound power obtained using a sub-set array are likely to be. It is the value of this standard deviation that is to be compared to the requirements of the ISO Standards to assess the grade of accuracy of the measurement. (In ISO 3740, standard deviations of 0.5 dB, 1.5 dB and 3 dB correspond to precision-, engineering- and survey-grade accuracy respectively.)

7.3 SEMI REVERBERANT MEASUREMENT RESULTS

Results for measurements carried out in the rooms where all, or some, of the microphone positions were close to a wall (rooms A, B and C) are shown in Tables 32 to 41, those for the reference sound source in Table 32, those for the actual machine noise sources in Tables 39 to 41 and those for the sources constructed using MDF in Tables 33 to 38. So, for these rooms, each Table contains data for a single source with the appropriate value of K_{2A} as column heading.

Results for room D are shown in Tables 42 to 44, with the actual machines in Table 44 and those for the reference sound source and MDF sources in Tables 42 and 43. So, for this room, each Table contains data for only room D ($K_{2A} = 8$ dB) with the appropriate Directivity Index as column heading.

As discussed in previously, the prime factor to be assessed is how well any particular sound power level determination approximates the true value. The actual absolute sound power level of each source is of little interest. Therefore, all sound power determinations have been expressed relative to the appropriate twenty-microphone assessment (in this case the value determined where K_{2A} is zero). Hence, reported data determined using the twenty-microphone, ISO 3744 array in hemi-anechoic conditions, designated as, " $(= \mu; k = 0)$ " in the Tables, are all zero. The sound power levels used for this reference are those obtained from the measurements described in Section 6 for hemi-anechoic conditions.

The same format is used in all thirteen Tables for each data row, and is similar to that used in Tables 17 to 29 in Section 6.3.2 for the hemi-anechoic data. The first data row represents the sound power level obtained using all twenty microphones in hemi-anechoic conditions and is designated " $(= \mu; k = 0)$ " and is always zero (see above). The next row is the difference between the hemi-anechoic sound power level and that measured in the semi-reverberant conditions. Here the sound power level determined in semi-reverberant conditions is the measured value minus K_{2A} , determined as discussed above. The next two shaded rows show the measured semi-reverberant Directivity Index and the microphone location code (see Section 6.3). The following rows contain sound power level data corresponding to the sub-sets described in Section 6.3 all expressed relative to the twenty-position $(= \mu; k = 0)$ value. The remaining three shaded areas contain the results of the calculations of standard deviations about the mean of each sub-set, σ_M , about μ (the 20-microphone value for the particular room), σ_μ and about " $= \mu; k = 0$ " (the 20-microphone value measured when $k = 0$), $\sigma_{\mu(k=0)}$.

It must be remembered that in all following discussions and assessments of measurement uncertainty, the value of Directivity Index used is the true value. That is the value measured using a twenty-microphone array in hemi-anechoic conditions.

Table 32 Results for a reference sound source in various acoustic environments.

measurement positions		level re true (dB)		
		k = 3.6	k = 6.5	k = 9.6
according to ISO 3745	20 positions ($=\mu$; $k=0$)	0.0	0.0	0.0
	20 positions ($=\mu$)	0.0	0.0	0.0
	directivity index	1.7	0.3	0.5
	height of max level	3	3	1
according to ISO 3744	10 key positions	0.0	0.0	0.0
	10 extra positions	0.0	0.0	-0.1
according to ISO 3746	4 key positions	-0.5	0.0	-0.1
	4 extra positions	-0.5	0.1	-0.2
4 positions different heights (rapid method)	1st combination	-0.3	0.0	-0.2
	2nd combination	-0.2	0.0	0.0
	3rd combination	-0.1	0.0	-0.1
	4th combination	-0.2	0.0	-0.1
	5th combination	-0.2	-0.1	0.0
	6th combination	-0.2	0.0	-0.1
	mean of all six	-0.2	0.0	-0.1
	σ about mean	0.1	0.0	0.1
	σ about μ	0.2	0.0	0.1
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	0.1	0.0	0.0
	2nd combination	0.2	0.1	0.1
	3rd combination	0.2	0.0	-0.1
	mean of all three	0.2	0.0	0.0
	σ about mean	0.0	0.0	0.1
	σ about μ	0.2	0.0	0.1
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	0.1	0.0	-0.1
	2nd combination	0.2	-0.1	0.0
	3rd combination	0.2	0.0	0.1
	4th combination	0.1	-0.1	0.1
	5th combination	0.2	0.2	0.1
	6th combination	0.1	0.1	-0.2
	mean of all six	0.2	0.0	0.0
	σ about mean	0.1	0.1	0.1
	σ about μ	0.2	0.1	0.1
one position (x20)	σ about μ	1.3	0.2	0.2

Table 33 Results for MDF box with DI = 7.5, in various acoustic environments.

measurement positions		level re true (dB)		
		k = 3.6	k = 6.5	k = 9.6
according to ISO 3745	20 positions ($=\mu$; $k=0$)	0.0	0.0	0.0
	20 positions ($=\mu$)	0.0	-0.1	-0.5
	directivity index	7.7	2.8	2.4
	height of max level	3.0	2.0	1.0
according to ISO 3744	10 key positions	0.7	0.0	-0.4
	10 extra positions	-0.9	-0.1	-0.5
according to ISO 3746	4 key positions	-2.1	-0.7	-0.9
	4 extra positions	-0.5	0.3	-0.3
4 positions different heights (rapid method)	1st combination	-1.5	0.3	0.0
	2nd combination	-1.8	-0.5	-0.6
	3rd combination	2.6	-0.1	-0.5
	4th combination	-1.2	-0.5	-0.8
	5th combination	-0.4	0.4	-0.2
	6th combination	-2.3	-0.5	-0.7
	mean of all six	-0.8	-0.1	-0.5
	σ about mean	1.8	0.4	0.3
	σ about μ	1.8	0.4	0.3
	σ about μ ($k=0$)	1.8	0.4	0.6
6 positions three opposite sets of three at each hight (not including the overhead position)	1st combination	-1.0	0.0	-0.3
	2nd combination	1.6	-0.2	-0.6
	3rd combination	-0.3	0.1	-0.5
	mean of all three	0.1	-0.1	-0.4
	σ about mean	1.3	0.2	0.2
	σ about μ	1.1	0.1	0.1
	σ about μ ($k=0$)	1.1	0.2	0.5
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	-0.2	0.5	0.2
	2nd combination	3.7	0.5	-0.4
	3rd combination	-3.4	-1.2	-1.0
	4th combination	-1.9	-0.6	-0.8
	5th combination	-2.9	-1.1	-0.8
	6th combination	1.5	1.0	0.0
	mean of all six	-0.5	-0.1	-0.5
	σ about mean	2.7	0.9	0.5
	σ about μ	2.6	0.9	0.5
	σ about μ ($k=0$)	2.6	0.9	0.7
one position (x20)	σ about μ	3.3	1.3	0.8
	σ about μ ($k=0$)	3.3	1.3	1.0

Table 34 Results for MDF box with DI = 7.4, in various acoustic environments.

measurement positions		level re true (dB)		
		k = 3.6	k = 6.5	k = 9.6
according to ISO 3745	20 positions (=μ ; k=0)	0.0	0.0	0.0
	20 positions (= μ)	-1.8	0.2	-0.7
	directivity index	5.7	2.8	2.1
	height of max level	1.0	4.0	4.0
according to ISO 3744	10 key positions	-1.8	0.2	-0.8
	10 extra positions	-1.8	0.2	-0.7
according to ISO 3746	4 key positions	-0.3	0.4	-0.6
	4 extra positions	-0.3	0.5	-0.4
4 positions different heights (rapid method)	1st combination	-0.1	0.8	-0.4
	2nd combination	-0.2	0.9	-0.3
	3rd combination	-0.2	0.8	-0.2
	4th combination	-0.2	0.7	-0.4
	5th combination	-0.2	0.9	-0.2
	6th combination	-0.2	0.8	-0.3
	mean of all six	-0.2	0.8	-0.3
	σ about mean	0.0	0.1	0.1
	σ about μ	1.6	0.6	0.4
	σ about μ (k=0)	0.2	0.8	0.3
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	-3.4	-0.3	-1.1
	2nd combination	-3.4	-0.2	-0.9
	3rd combination	-3.5	-0.3	-1.1
	mean of all three	-3.4	-0.3	-1.0
	σ about mean	0.1	0.0	0.1
	σ about μ	1.6	0.4	0.3
	σ about μ (k=0)	3.4	0.3	1.1
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	-3.3	-0.3	-1.3
	2nd combination	-3.4	-0.1	-0.9
	3rd combination	-3.5	-0.3	-1.1
	4th combination	-3.4	-0.2	-0.9
	5th combination	-3.3	-0.4	-0.9
	6th combination	-3.5	-0.3	-1.1
	mean of all six	-3.4	-0.3	-1.0
	σ about mean	0.1	0.1	0.2
	σ about μ	1.6	0.4	0.3
	σ about μ (k=0)	3.4	0.3	1.1
one position (x20)	σ about μ	2.4	1.2	0.9
	σ about μ (k=0)	3.5	1.2	1.3

Table 35 Results for MDF box with DI = 6.4, in various acoustic environments.

measurement positions		level re true (dB)		
		k = 3.6	k = 6.5	k = 9.6
according to ISO 3745	20 positions (= μ ; k=0)	0.0	0.0	0.0
	20 positions (= μ)	0.6	0.0	-0.2
	directivity index	6.6	2.2	1.8
	height of max level	3.0	2.0	1.0
according to ISO 3744	10 key positions	0.9	0.0	-0.1
	10 extra positions	0.2	-0.1	-0.2
according to ISO 3746	4 key positions	-1.1	-0.3	-0.5
	4 extra positions	0.2	0.2	-0.3
4 positions different heights (rapid method)	1st combination	-0.7	0.1	0.0
	2nd combination	-0.3	-0.4	-0.3
	3rd combination	2.3	0.0	-0.3
	4th combination	-0.3	-0.3	-0.4
	5th combination	0.4	0.3	0.0
	6th combination	-1.4	-0.2	-0.3
	mean of all six	0.0	-0.1	-0.2
	σ about mean	1.2	0.2	0.2
	σ about μ	1.3	0.2	0.2
	σ about μ (k=0)	1.1	0.2	0.3
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	0.3	-0.1	0.0
	2nd combination	1.5	-0.1	-0.2
	3rd combination	0.6	0.1	-0.2
	mean of all three	0.8	0.0	-0.1
	σ about mean	0.7	0.1	0.1
	σ about μ	0.6	0.1	0.1
	σ about μ (k=0)	0.9	0.1	0.2
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	0.7	0.5	0.4
	2nd combination	3.5	0.5	0.0
	3rd combination	-2.9	-1.2	-0.7
	4th combination	-0.3	-0.7	-0.5
	5th combination	-2.3	-0.8	-0.4
	6th combination	2.5	1.1	0.3
	mean of all six	0.2	-0.1	-0.2
	σ about mean	2.5	0.9	0.5
	σ about μ	2.4	0.8	0.4
	σ about μ (k=0)	2.3	0.8	0.5
one position (x20)	σ about μ	3.3	1.1	0.7
	σ about μ (k=0)	3.1	1.1	0.7

Table 36 Results for MDF box with DI = 5.2, in various acoustic environments.

measurement positions		level re true (dB)		
		k = 3.6	k = 6.5	k = 9.6
according to ISO 3745	20 positions (=μ ; k=0)	0.0	0.0	0.0
	20 positions (= μ)	1.5	0.5	-0.2
	directivity index	3.5	1.8	1.3
	height of max level	3.0	3.0	1.0
according to ISO 3744	10 key positions	1.5	0.6	-0.2
	10 extra positions	1.5	0.5	-0.2
according to ISO 3746	4 key positions	0.4	0.6	-0.1
	4 extra positions	0.7	0.5	-0.2
4 positions different heights (rapid method)	1st combination	0.9	0.9	-0.1
	2nd combination	0.7	0.9	0.1
	3rd combination	1.7	0.8	0.0
	4th combination	0.7	0.8	0.0
	5th combination	0.9	0.8	0.0
	6th combination	1.5	0.8	0.1
	mean of all six	1.1	0.8	0.0
	σ about mean	0.4	0.0	0.1
	σ about μ	0.6	0.3	0.2
	σ about μ (k=0)	1.1	0.8	0.0
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	1.2	0.3	-0.3
	2nd combination	2.2	0.3	-0.3
	3rd combination	1.8	0.3	-0.4
	mean of all three	1.7	0.3	-0.3
	σ about mean	0.5	0.0	0.1
	σ about μ	0.5	0.2	0.2
	σ about μ (k=0)	1.8	0.3	0.4
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	1.2	0.2	-0.4
	2nd combination	2.3	0.3	-0.3
	3rd combination	1.8	0.4	-0.3
	4th combination	1.2	0.4	-0.2
	5th combination	2.2	0.3	-0.3
	6th combination	1.8	0.2	-0.5
	mean of all six	1.7	0.3	-0.3
	σ about mean	0.5	0.1	0.1
	σ about μ	0.5	0.2	0.2
	σ about μ (k=0)	1.8	0.3	0.4
	σ about μ	2.0	1.0	0.7
	σ about μ (k=0)	2.2	1.1	0.7
one position (x20)				

Table 37 Results for MDF box with DI = 3.8, in various acoustic environments.

measurement positions		level re true (dB)		
		k = 3.6	k = 6.5	k = 9.6
according to ISO 3745	20 positions (=μ ; k=0)	0.0	0.0	0.0
	20 positions (= μ)	0.8	-0.2	0.0
	directivity index	3.5	1.1	1.2
	height of max level	3.0	2.0	1.0
according to ISO 3744	10 key positions	0.8	-0.1	0.0
	10 extra positions	0.8	-0.2	0.0
according to ISO 3746	4 key positions	-0.3	-0.2	-0.2
	4 extra positions	0.0	-0.2	-0.3
4 positions different heights (rapid method)	1st combination	0.2	-0.3	0.0
	2nd combination	0.0	-0.3	0.0
	3rd combination	1.0	-0.4	-0.1
	4th combination	0.0	-0.4	0.0
	5th combination	0.2	-0.2	-0.1
	6th combination	0.8	-0.5	-0.2
	mean of all six	0.4	-0.3	-0.1
	σ about mean	0.4	0.1	0.1
	σ about μ	0.6	0.2	0.1
	σ about μ (k=0)	0.5	0.3	0.1
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	0.5	-0.1	0.1
	2nd combination	1.5	-0.2	-0.1
	3rd combination	1.1	0.0	0.1
	mean of all three	1.0	-0.1	0.1
	σ about mean	0.5	0.1	0.1
	σ about μ	0.5	0.1	0.1
	σ about μ (k=0)	1.1	0.1	0.1
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	0.5	-0.2	0.1
	2nd combination	1.6	0.0	-0.2
	3rd combination	1.1	-0.1	0.3
	4th combination	0.5	0.0	0.2
	5th combination	1.5	-0.3	0.1
	6th combination	1.1	0.0	-0.1
	mean of all six	1.0	-0.1	0.1
	σ about mean	0.5	0.1	0.2
	σ about μ	0.5	0.1	0.2
	σ about μ (k=0)	1.1	0.1	0.2
one position (x20)	σ about μ	2.0	0.6	0.5
	σ about μ (k=0)	2.0	0.6	0.5

Table 38 Results for MDF box with DI = 2.5, in various acoustic environments.

measurement positions		level re true (dB)		
		k = 3.6	k = 6.5	k = 9.6
according to ISO 3745	20 positions ($=\mu$; $k=0$)	0.0	0.0	0.0
	20 positions ($=\mu$)	-1.1	-1.0	-0.4
	directivity index	1.4	2.2	0.5
	height of max level	3.0	2.0	3.0
according to ISO 3744	10 key positions	-1.1	-1.0	-0.4
	10 extra positions	-1.1	-1.1	-0.4
according to ISO 3746	4 key positions	-1.3	-1.3	-0.5
	4 extra positions	-1.0	-0.8	-0.4
4 positions different heights (rapid method)	1st combination	-0.8	-0.9	-4.0
	2nd combination	-0.9	-1.4	-4.5
	3rd combination	-0.8	-1.0	-4.1
	4th combination	-1.0	-1.3	-4.4
	5th combination	-0.9	-0.7	-3.8
	6th combination	-1.0	-1.2	-4.3
	mean of all six	-0.9	-1.1	-4.2
	σ about mean	0.1	0.2	0.2
	σ about μ	0.2	0.2	0.2
	σ about μ ($k=0$)	0.9	1.1	0.3
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	-1.2	-1.1	-0.5
	2nd combination	-1.3	-1.1	-0.5
	3rd combination	-1.3	-0.9	-0.5
	mean of all three	-1.3	-1.0	-0.5
	σ about mean	0.0	0.1	0.0
	σ about μ	0.1	0.1	0.1
	σ about μ ($k=0$)	1.3	1.0	0.5
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	-1.2	-0.5	-0.6
	2nd combination	-1.2	-0.5	-0.5
	3rd combination	-1.3	-2.2	-0.4
	4th combination	-1.2	-1.7	-0.4
	5th combination	-1.3	-1.8	-0.5
	6th combination	-1.3	0.1	-0.6
	mean of all six	-1.3	-1.1	-0.5
	σ about mean	0.0	0.9	0.1
	σ about μ	0.1	0.8	0.1
	σ about μ ($k=0$)	1.3	1.4	0.5
one position (x20)	σ about μ	1.1	1.1	0.4
	σ about μ ($k=0$)	1.7	1.6	0.6

Table 39 Results for the shredder, in various acoustic environments.

measurement positions		level re true (dB)		
		k = 3.6	k = 6.5	k = 9.6
according to ISO 3745	20 positions ($=\mu$; $k=0$)	0.0	0.0	0.0
	20 positions ($=\mu$)	-0.9	-2.1	-1.0
	directivity index	1.9	0.9	0.6
	height of max level	3.0	3.0	3.0
according to ISO 3744	10 key positions	-0.8	-2.2	-1.0
	10 extra positions	-1.0	-2.1	-1.0
according to ISO 3746	4 key positions	-1.4	-2.3	-1.1
	4 extra positions	-1.3	-2.2	-1.1
4 positions different heights (rapid method)	1st combination	-1.3	-2.3	-1.1
	2nd combination	-1.5	-2.2	-0.9
	3rd combination	-0.8	-2.2	-1.0
	4th combination	-1.4	-2.3	-1.0
	5th combination	-1.2	-2.2	-1.1
	6th combination	-1.4	-2.2	-1.1
	mean of all six	-1.3	-2.2	-1.0
	σ about mean	0.2	0.1	0.1
	σ about μ	0.4	0.1	0.1
	σ about μ ($k=0$)	1.3	2.2	1.0
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	-0.6	-2.1	-1.0
	2nd combination	-0.6	-1.9	-0.9
	3rd combination	-0.9	-2.1	-1.0
	mean of all three	-0.7	-2.1	-1.0
	σ about mean	0.2	0.1	0.1
	σ about μ	0.3	0.1	0.1
	σ about μ ($k=0$)	0.7	2.1	1.0
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	-0.5	-2.0	-1.1
	2nd combination	-0.3	-2.0	-0.9
	3rd combination	-1.0	-2.3	-0.9
	4th combination	-0.8	-2.2	-0.9
	5th combination	-0.8	-1.9	-0.9
	6th combination	-0.8	-1.9	-1.2
	mean of all six	-0.7	-2.1	-1.0
	σ about mean	0.2	0.2	0.1
	σ about μ	0.3	0.2	0.1
	σ about μ ($k=0$)	0.7	2.1	1.0
one position (x20)	σ about μ	1.0	0.4	0.3
	σ about μ ($k=0$)	1.4	2.2	1.0

Table 40 Results for the hand-held cleaner, in various acoustic environments.

measurement positions		level re true (dB)	
		k = 6.5	k = 9.6
according to ISO 3745	20 positions (=μ ; k=0)	0.0	0.0
	20 positions (= μ)	-0.7	1.2
	directivity index	3.0	2.2
	height of max level	3.0	3.0
according to ISO 3744	10 key positions	-0.6	1.3
	10 extra positions	-0.8	1.2
according to ISO 3746	4 key positions	-0.9	0.9
	4 extra positions	-1.4	1.0
4 positions different heights (rapid method)	1st combination	-1.0	0.8
	2nd combination	-1.6	0.7
	3rd combination	-0.5	2.0
	4th combination	0.0	1.6
	5th combination	-1.3	1.3
	6th combination	-1.4	0.7
	mean of all six	-1.0	1.2
	σ about mean	0.6	0.5
	σ about μ	0.6	0.5
	σ about μ (k=0)	1.1	1.0
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	-1.2	0.8
	2nd combination	-1.1	1.5
	3rd combination	0.3	1.2
	mean of all three	-0.7	1.1
	σ about mean	0.9	0.4
	σ about μ	0.7	0.3
	σ about μ (k=0)	1.0	0.9
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	-1.4	0.1
	2nd combination	-0.7	2.4
	3rd combination	0.3	0.5
	4th combination	-1.1	1.3
	5th combination	-1.6	0.3
	6th combination	0.3	1.8
	mean of all six	-0.7	1.1
	σ about mean	0.8	0.9
	σ about μ	0.8	0.9
	σ about μ (k=0)	1.0	1.2
one position (x20)	σ about μ	1.3	1.2
	σ about μ (k=0)	1.6	1.4

Table 41 Results for the food processor, in various acoustic environments.

measurement positions		level re true (dB)		
		k = 3.6	k = 6.5	k = 9.6
according to ISO 3745	20 positions ($=\mu$; $k=0$)	0.0	0.0	0.0
	20 positions ($=\mu$)	0.3	-2.2	-0.2
	directivity index	0.7	1.5	1.0
	height of max level	1.0	1.0	3.0
according to ISO 3744	10 key positions	0.5	-2.3	-0.5
	10 extra positions	0.1	-2.1	0.0
according to ISO 3746	4 key positions	0.6	-2.3	-0.3
	4 extra positions	0.1	-2.2	0.1
4 positions different heights (rapid method)	1st combination	0.2	-2.2	-0.1
	2nd combination	0.2	-2.4	0.2
	3rd combination	0.2	-2.5	-0.3
	4th combination	0.0	-1.8	-0.1
	5th combination	0.3	-2.1	-0.3
	6th combination	0.2	-2.0	-0.1
	mean of all six	0.2	-2.2	-0.1
	σ about mean	0.1	0.2	0.2
	σ about μ	0.2	0.2	0.2
	σ about μ ($k=0$)	0.2	2.2	0.2
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	0.4	-2.1	-0.1
	2nd combination	0.5	-2.7	-0.4
	3rd combination	0.2	-2.0	-0.3
	mean of all three	0.4	-2.2	-0.2
	σ about mean	0.1	0.4	0.2
	σ about μ	0.1	0.3	0.1
	σ about μ ($k=0$)	0.4	2.3	0.3
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	0.4	-1.9	-0.3
	2nd combination	0.8	-2.5	-0.7
	3rd combination	0.5	-2.6	-0.4
	4th combination	0.3	-2.2	0.2
	5th combination	0.2	-2.8	-0.1
	6th combination	-0.2	-1.4	-0.1
	mean of all six	0.4	-2.3	-0.2
	σ about mean	0.3	0.5	0.3
	σ about μ	0.3	0.5	0.3
	σ about μ ($k=0$)	0.5	2.3	0.4
one position (x20)	σ about μ	0.4	0.5	0.4
	σ about μ ($k=0$)	0.5	2.3	0.5

Table 42 Results for $K_{2A} = 8$ dB for noise sources with DI of 0.8 dB to 5.2 dB.

measurement positions		level re true (dB)			
		0.8	2.5	2.8	5.2
according to ISO 3745	20 positions ($=\mu$; $k=0$)	0.0	0.0	0.0	0.0
	20 positions ($=\mu$)	0.0	-0.5	-0.3	-0.6
	directivity index	0.1	0.6	0.6	1.4
	height of max level	1.0	3.0	2.0	4.0
according to ISO 3744	10 key positions	0.0	-0.5	-0.3	-0.6
	10 extra positions	0.0	-0.5	-0.3	-0.6
according to ISO 3746	4 key positions	-0.1	-0.5	-0.4	-0.5
	4 extra positions	-0.1	-0.5	-0.4	-0.6
4 positions different heights (rapid method)	1st combination	-0.1	-0.4	-0.5	-0.3
	2nd combination	-0.1	-0.4	-0.4	-0.3
	3rd combination	0.0	-0.4	-0.4	-0.4
	4th combination	-0.1	-0.4	-0.5	-0.3
	5th combination	-0.1	-0.5	-0.4	-0.3
	6th combination	-0.1	-0.4	-0.3	-0.3
	mean of all six	-0.1	-0.4	-0.4	-0.3
	σ about mean	0.1	0.0	0.1	0.0
	σ about μ	0.1	0.1	0.1	0.3
	σ about μ ($k=0$)	0.1	0.4	0.4	0.3
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	0.0	-0.6	-0.3	-0.8
	2nd combination	0.0	-0.4	-0.2	-0.8
	3rd combination	0.0	-0.5	-0.2	-0.8
	mean of all three	0.0	-0.5	-0.2	-0.8
	σ about mean	0.0	0.1	0.0	0.0
	σ about μ	0.0	0.1	0.1	0.2
	σ about μ ($k=0$)	0.0	0.5	0.2	0.8
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	0.0	-0.6	-0.3	-0.8
	2nd combination	0.0	-0.5	-0.3	-0.8
	3rd combination	0.0	-0.5	-0.2	-0.7
	4th combination	0.0	-0.6	-0.3	-0.8
	5th combination	-0.1	-0.4	-0.2	-0.7
	6th combination	0.0	-0.5	-0.2	-0.8
	mean of all six	0.0	-0.5	-0.2	-0.8
	σ about mean	0.0	0.1	0.1	0.0
	σ about μ	0.0	0.1	0.1	0.2
	σ about μ ($k=0$)	0.0	0.5	0.3	0.8
one position (x20)	σ about μ	0.1	0.4	0.4	0.8
	σ about μ ($k=0$)	0.1	0.6	0.5	1.0

Table 43 Results for $K_{2A} = 8$ dB for noise sources with DI of 6.4 dB to 7.5 dB.

measurement positions		level re true (dB)		
		6.4	7.4	7.5
according to ISO 3745	20 positions ($=\mu$; $k=0$)	0.0	0.0	0.0
	20 positions ($=\mu$)	-0.1	-1.1	-0.8
	directivity index	2.1	2.4	2.3
	height of max level	1.0	4.0	1.0
according to ISO 3744	10 key positions	0.0	-1.1	-0.7
	10 extra positions	-0.1	-1.1	-0.8
according to ISO 3746	4 key positions	-0.3	-0.9	-1.1
	4 extra positions	-0.1	-0.8	-0.7
4 positions different heights (rapid method)	1st combination	0.0	-0.6	-0.6
	2nd combination	-0.3	-0.6	-1.1
	3rd combination	-0.2	-0.6	-0.9
	4th combination	-0.4	-0.6	-1.1
	5th combination	0.0	-0.5	-0.6
	6th combination	-0.1	-0.6	-0.8
	mean of all six	-0.2	-0.6	-0.9
	σ about mean	0.2	0.0	0.2
	σ about μ	0.2	0.5	0.2
	σ about μ ($k=0$)	0.2	0.6	0.9
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	0.0	-1.5	-0.6
	2nd combination	-0.1	-1.4	-0.8
	3rd combination	0.1	-1.4	-0.7
	mean of all three	0.0	-1.4	-0.7
	σ about mean	0.1	0.0	0.1
	σ about μ	0.1	0.4	0.1
	σ about μ ($k=0$)	0.1	1.4	0.7
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	0.6	-1.5	0.0
	2nd combination	0.3	-1.4	-0.5
	3rd combination	-0.8	-1.4	-1.7
	4th combination	-0.7	-1.4	-1.4
	5th combination	-0.4	-1.3	-1.1
	6th combination	0.8	-1.5	0.1
	mean of all six	0.0	-1.4	-0.8
	σ about mean	0.7	0.1	0.8
	σ about μ	0.6	0.4	0.7
	σ about μ ($k=0$)	0.6	1.4	1.0
one position (x20)	σ about μ	0.9	1.0	1.0
	σ about μ ($k=0$)	0.9	1.5	1.3

Table 44 Results for $K_{2A} = 8$ dB for the cleaner and the food processor.

measurement positions		level re true (dB)	
		cleaner	processor
according to ISO 3745	20 positions ($=\mu$; $k=0$)	0.0	0.0
	20 positions ($=\mu$)	0.0	0.0
	directivity index	3.7	0.6
	height of max level	3.0	3.0
according to ISO 3744	10 key positions	0.5	0.0
	10 extra positions	-0.7	0.1
according to ISO 3746	4 key positions	0.0	-0.1
	4 extra positions	-1.1	0.0
4 positions different heights (rapid method)	1st combination	-0.2	-0.1
	2nd combination	0.4	0.0
	3rd combination	0.8	0.0
	4th combination	-0.9	-0.1
	5th combination	-0.6	0.0
	6th combination	-1.0	0.0
	mean of all six	-0.2	-0.1
	σ about mean	0.7	0.1
	σ about μ	0.7	0.1
	σ about μ ($k=0$)	0.7	0.1
6 positions three opposite sets of three at each height (not including the overhead position)	1st combination	0.0	0.0
	2nd combination	0.0	0.1
	3rd combination	-0.2	0.2
	mean of all three	-0.1	0.1
	σ about mean	0.1	0.1
	σ about μ	0.1	0.1
	σ about μ ($k=0$)	0.1	0.1
3 positions six sets each on one side with all three heights (not including the overhead position)	1st combination	0.1	-0.2
	2nd combination	1.0	0.2
	3rd combination	0.3	0.1
	4th combination	0.0	0.1
	5th combination	-1.5	0.0
	6th combination	-0.8	0.3
	mean of all six	-0.1	0.1
	σ about mean	0.9	0.2
	σ about μ	0.8	0.1
	σ about μ ($k=0$)	0.8	0.2
one position (x20)	σ about μ	1.4	0.3
	σ about μ ($k=0$)	1.4	0.3

It can be seen that the variation of $\sigma_{\mu(k=0)}$ with Directivity Index is now much less marked than was observed for the hemi-anechoic data discussed in Section 6. Consider for example results for the one-microphone sub-set from room A ($K_{2A} = 3.6$ dB). Here a variation with Directivity Index can be seen (although much less pronounced than that observed for the hemi-anechoic results) with an increase in $\sigma_{\mu(k=0)}$ from around 1 dB for low Directivity Index sources up to approximately 3 dB for the high Directivity Index sources. The increase can be seen to be much less marked for the sub-sets using more microphones. However, if data from room C ($K_{2A} = 9.6$ dB) is considered there is no significant variation of $\sigma_{\mu(k=0)}$ with Directivity Index.

Although there is a tendency for $\sigma_{\mu(k=0)}$ to show a continual increase as the number of microphones in the sub-set is reduced it can be seen from the Tables that the value of $\sigma_{\mu(k=0)}$ remains relatively constant until the number of microphones is reduced to one. Here there is an increase in the value of $\sigma_{\mu(k=0)}$ of between approximately 1 dB and 0.3 dB depending on the value of K_{2A} .

Generally the value of $\sigma_{\mu(k=0)}$ is approximately 1 dB for all sub-sets and environments with a few notable exceptions where values are significantly higher. In particular consider data obtained in room A ($K_{2A} = 6.5$ dB) for the shredder and the food processor. Both these machines have values of $\sigma_{\mu(k=0)}$ of around 2 dB which are greater than those values obtained in rooms B and C that have values of K_{2A} in one case greater than 6.5 dB and in the other case less than 6.5 dB.

It turns out that for the food processor the high value of $\sigma_{\mu(k=0)}$ is simply a result of the floor carpet blocking air vents on the base of the machine. A sound power determination was repeated in the hemi-anechoic room with the processor positioned on a small piece of carpet and it was found that this changed the sound power level of the machine. This change can be seen from an examination of Table 41 where the difference between sound power level estimates using twenty-microphone positions in hemi-anechoic conditions with that determined in room A is -2.2 dB. This is approximately the same magnitude as the value of $\sigma_{\mu(k=0)}$. As discussed above the value of $\sigma_{\mu(k=0)}$ is in effect a combination of the variation in sound power levels to be expected from the use of any single sub-set measurement and the difference from the true twenty-microphone, $K_{2A} = 0$ result. For the food processor it can be seen that the value of σ_M is small (0.2 dB) which indicates that the large value of $\sigma_{\mu(k=0)}$ is a direct result of a difference in the two twenty-microphone sound power level determinations. Because of this change in sound power level the data from the food processor in room A have not been used further in the assessment of the performance of the sub-sets nor in how their accuracy compares to the ISO definitions.

The shredder also displays a large value of $\sigma_{\mu(k=0)}$ in room A and this is again reflected in the difference between the twenty-microphone array assessments in hemi-anechoic conditions and room A. It can be seen from Table 39 that a value of -2.1 dB was obtained. For the shredder the value of $\sigma_{\mu(k=0)}$ is smaller in rooms B and C but unlike the food processor the value of approximately -1 dB is still high. Thus, whilst the carpet may have an effect on the sound power level, measurements carried out in other rooms still provide relatively high values of $\sigma_{\mu(k=0)}$. The reason for this turns out to be a result

of the actual position of the source of the noise for this machine. The shredder is fixed on legs and the noise source is approximately 0.4 m above the ground. The value of K_{2A} should, therefore, be determined by placing the reference sound source at this position in the room and comparing results with a calibration carried out using the same elevated position. Unfortunately, it was not possible to carry out a repeat of the k-factor assessment in the rooms used for this series of measurements but measurements carried out in an acoustic environment similar to room A indicate that the value of K_{2A} will be approximately 1 dB less. This will result in a corresponding difference in the second row of Table 39 and hence a reduced measurement uncertainty, $\sigma_{\mu(k=0)}$. However, in the absence of a correctly measured values of K_{2A} for the case of the shredder, the sound power level data obtained using this machine have not been used in the detailed analysis of results.

It is unlikely that the location of the source of noise for each machine and the reference sound source will be identical. So, it should be born in mind that all measurement uncertainties that have been evaluated for these semi-reverberant conditions do inherently include a contribution that results from errors associated with actual location of the source of noise. For the case of the shredder the difference was large and either should have been accounted for by a reassessment of K_{2A} , or it could have been ignored and a higher measurement uncertainty accepted.

A simple calculation assuming a point source serves as a guide to the magnitude of the difference in sound power level determination resulting from an elevated noise source. In order to adhere to the requirement that the radius, r of the enveloping surface is greater than twice the largest dimension of the source the source elevation may not exceed $r/2$. Over a range of noise source elevation from zero to $r/2$, the change of measured sound power level is approximately linear with elevation with a maximum of approximately 2 dB at an elevation of $r/2$. For the shredder the source elevation is approximately $r/4$, which results in an apparent sound power level change of about 1 dB (cf the experimental assessment above).

At this point it is convenient to consider the data for the 10-microphone arrays. It can be seen from the Tables that large values of $\sigma_{\mu(k=0)}$ are a direct result of differences between the two twenty-microphone array determinations and so the measurement uncertainty for these arrays are similar to those associated with a twenty-microphone array. For the four-microphone arrays of ISO 3746 the differences can be quite large (certainly larger than those associated with the "preferred" array). In any case, there are only two arrays for the ten-microphone sub-set and for the four-microphone sub-set according to ISO 3746. It is, therefore, not feasible to perform any meaningful statistical analysis, and so for the purposes of the assessments of measurement uncertainty carried out in this study, these arrays will not be considered further.

The values of $\sigma_{\mu(k=0)}$ listed in Tables 32 to 44 for each noise source have been extracted and presented in Tables 45 to 48 together with Directivity Index for each microphone sub-set. The observations above may be more easily appreciated from examination of these four Tables.

Table 45 Directivity Index and measurement uncertainty values for the four subsets in an acoustic environment where $k = 3.6$ dB.

source	Directivity Index (dB)	one-mic	three-mics	four-mics	six-mics
		measurement uncertainty (dB)			
rss	0.8	1.3	0.2	0.2	0.2
shredder	1.7	1.4	0.7	1.3	0.7
food	2.0	0.5	0.5	0.2	0.4
MDF box 1	2.5	1.7	1.3	0.9	1.3
MDF box 3	3.8	2.0	1.1	0.5	1.1
MDF box 4	5.2	2.2	1.8	1.1	1.8
MDF box 5	6.4	3.1	2.3	1.1	0.9
MDF box 6	7.4	3.5	3.4	0.2	3.4
MDF box 7	7.5	3.3	2.6	1.8	1.1

Table 46 Directivity Index and measurement uncertainty values for the four subsets in an acoustic environment where $k = 6.5$ dB.

source	Directivity Index (dB)	one-mic	three-mics	four-mics	six-mics
		measurement uncertainty (dB)			
rss	0.8	0.2	0.1	0.0	0.0
shredder	1.7	2.2	2.1	2.2	2.1
food	2.0	2.3	2.3	2.2	2.3
hand	4.6	1.6	1.0	1.1	1.0
MDF box 1	2.5	1.6	1.4	1.1	1.0
MDF box 3	3.8	0.6	0.1	0.3	0.1
MDF box 4	5.2	1.1	0.3	0.8	0.3
MDF box 5	6.4	1.1	0.8	0.2	0.1
MDF box 6	7.4	1.2	0.3	0.8	0.3
MDF box 7	7.5	1.3	0.9	0.4	0.2

Table 47 Directivity Index and measurement uncertainty values for the four subsets in an acoustic environment where $k = 9.6$ dB.

source	Directivity Index (dB)	one-mic	three-mics	four-mics	six-mics
		measurement uncertainty (dB)			
rss	0.8	0.2	0.1	0.1	0.1
shredder	1.7	1.0	1.0	1.0	1.0
food	2.0	0.5	0.4	0.2	0.3
hand	4.6	1.4	1.2	1.0	0.9
MDF box 1	2.5	0.6	0.5	0.3	0.5
MDF box 3	3.8	0.5	0.2	0.1	0.1
MDF box 4	5.2	0.7	0.4	0.0	0.4
MDF box 5	6.4	0.7	0.5	0.3	0.2
MDF box 6	7.4	1.3	1.1	0.3	1.1
MDF box 7	7.5	1.0	0.7	0.6	0.5

Table 48 Directivity Index and measurement uncertainty values for the four subsets in a reverberant acoustic environment where $k = 8.0$ dB.

source	Directivity Index (dB)	one-mic	three-mics	four-mics	six-mics
		measurement uncertainty (dB)			
rss	0.8	0.1	0.0	0.1	0.0
food	2.0	0.3	0.2	0.1	0.1
hand	4.6	1.4	0.8	0.7	0.1
MDF box 1	2.5	0.6	0.5	0.4	0.5
MDF box 3	2.8	0.5	0.3	0.4	0.2
MDF box 4	5.2	1.0	0.8	0.3	0.8
MDF box 5	6.4	0.9	0.6	0.2	0.1
MDF box 6	7.4	1.5	1.4	0.6	1.4
MDF box 7	7.5	1.3	1.0	0.9	0.7

A more detailed analysis may be undertaken by an examination of these data when presented in graphical form. Data has been plotted for each sub-set in Figures 9 to 12. To facilitate a comparison with the corresponding hemi-anechoic data these four Figures are presented using the same vertical and horizontal scales as used for Figures 4 to 7 that show the hemi-anechoic results. Included on the four semi-reverberant data Figures are the appropriate “best-fit plus two standard deviation” curves from the hemi-anechoic results. As discussed in Section 6.3, 95% of measurement uncertainties associated with sound power level determinations carried out in hemi-anechoic conditions will be expected to lie below these curves. The purpose of including these curves is to assess the possibility that the assessment of the ISO accuracy grade descriptions shown in Figure 8 for the hemi-anechoic data will also apply to these semi-reverberant determinations.

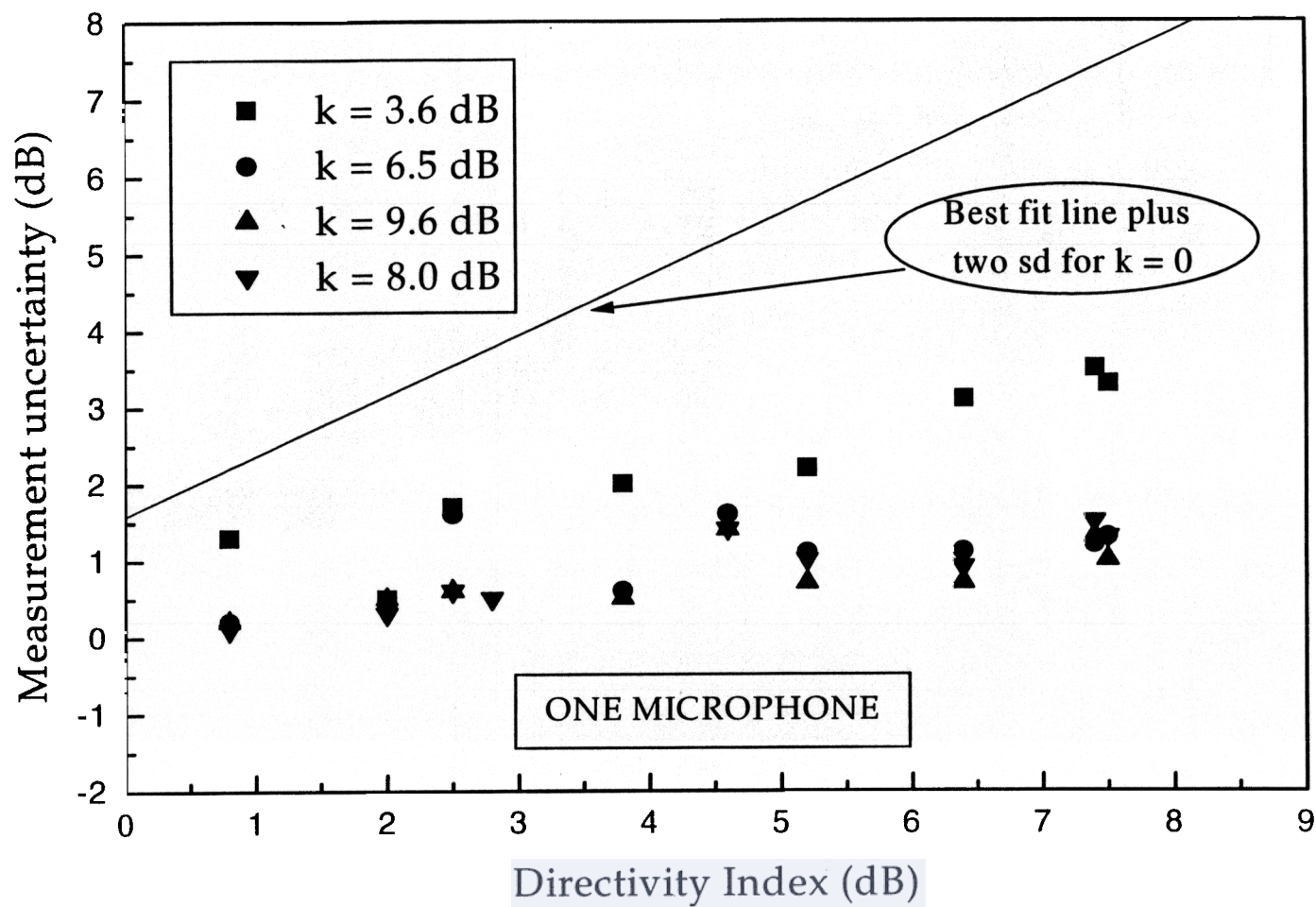


Figure 9

Variation of measurement uncertainty as a function of Directivity Index with k-factor as parameter for the one microphone sub-set with the best fit plus two standard deviation line for $k = 0$.

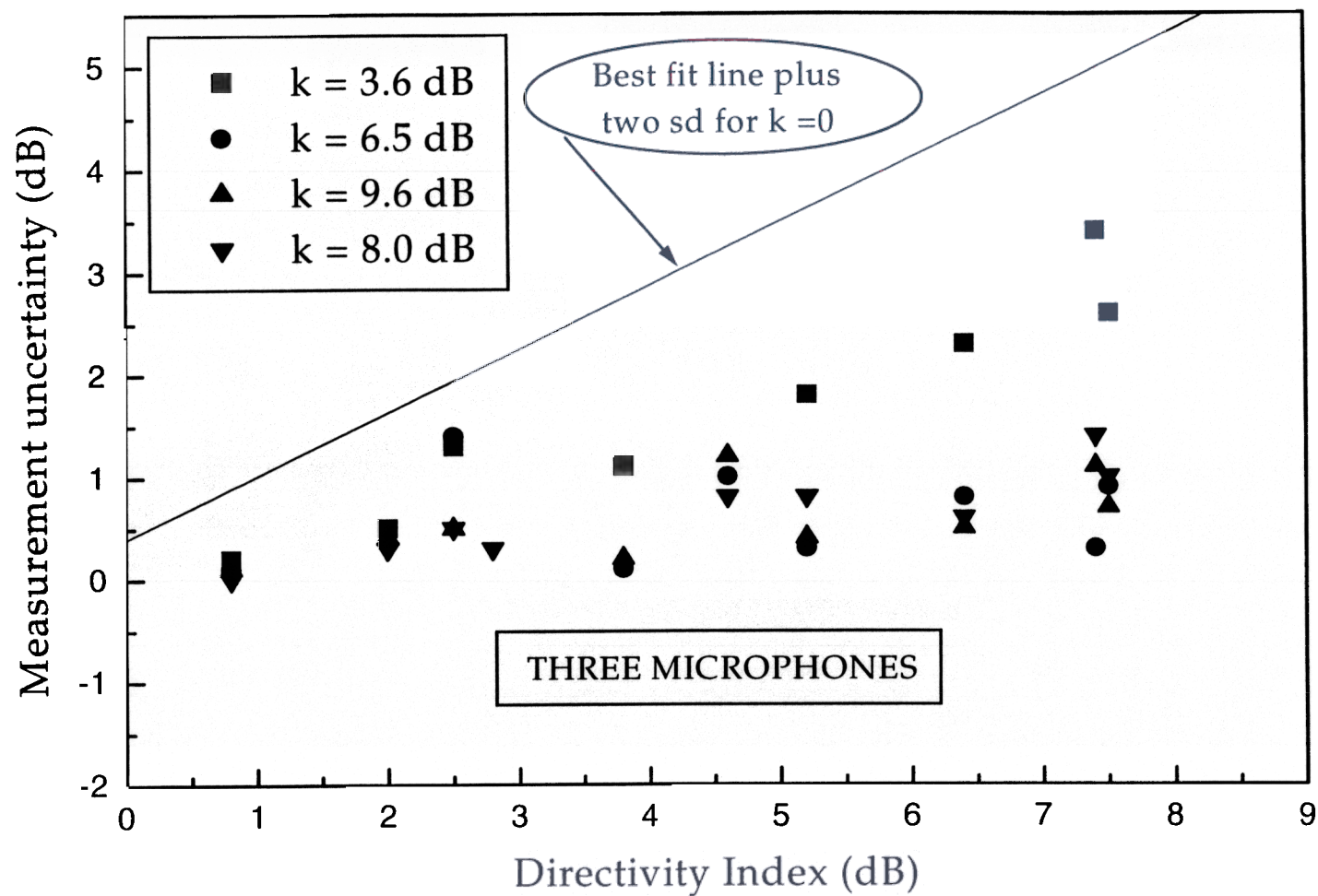


Figure 10 Variation of measurement uncertainty as a function of Directivity Index with k-factor as parameter for the three microphone sub-set with the best fit plus two standard deviation line for $k = 0$.

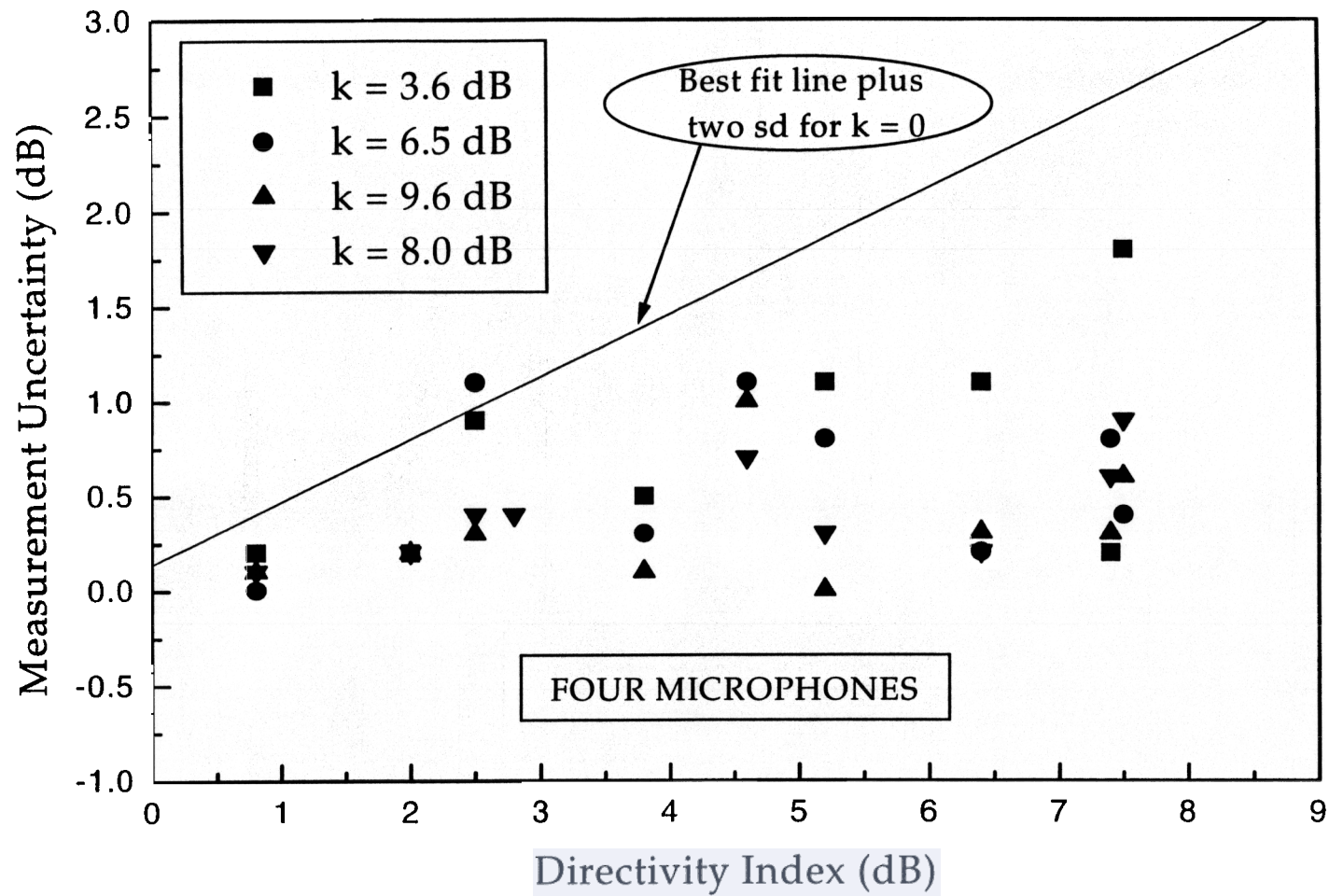


Figure 11 Variation of measurement uncertainty as a function of Directivity Index with k-factor as parameter for the four microphone sub-set with the best fit plus two standard deviation line for k = 0.

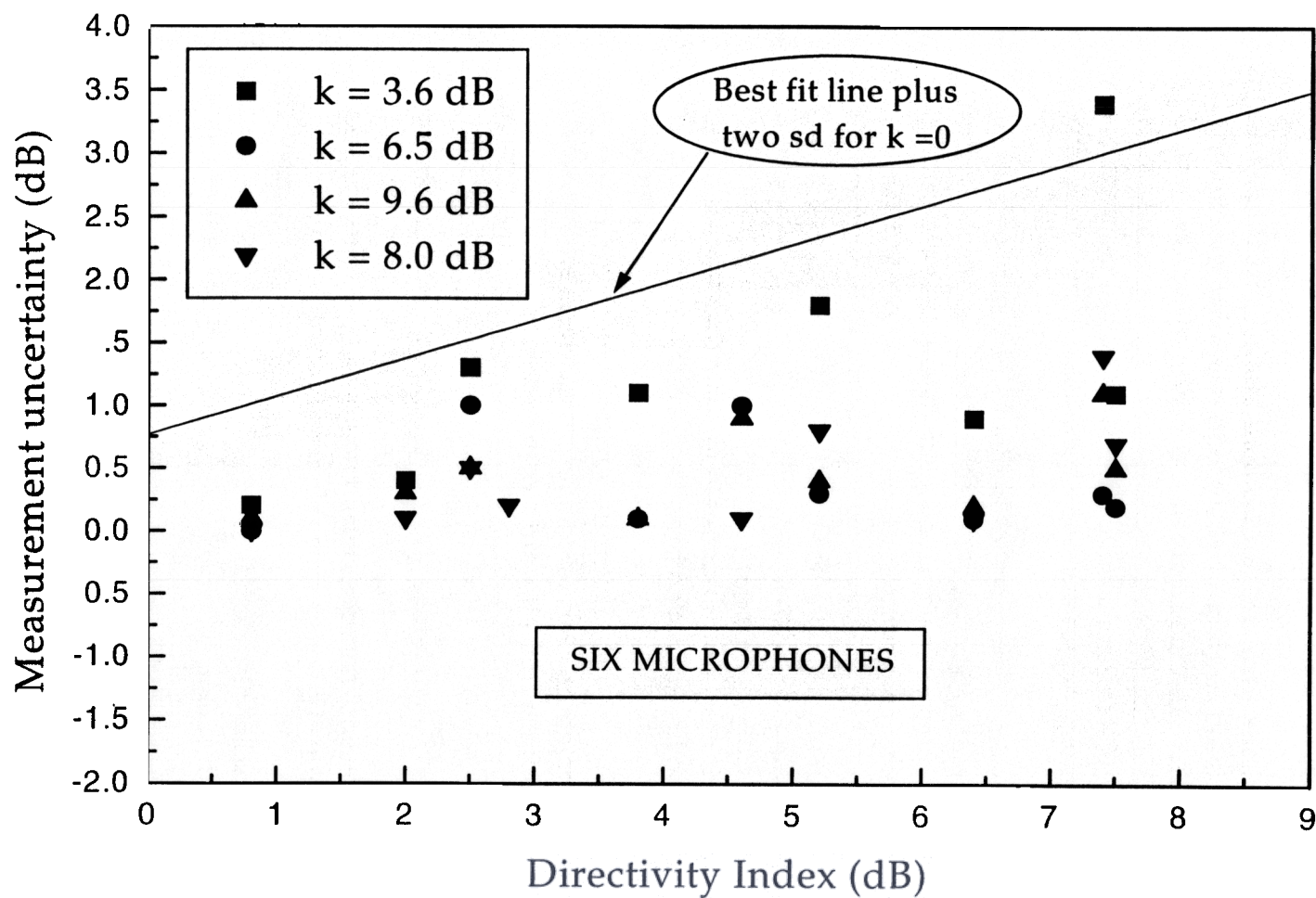


Figure 12 Variation of measurement uncertainty as a function of Directivity Index with k-factor as parameter for the six microphone sub-set with the best fit plus two standard deviation line for $k = 0$.

The relationship between $\sigma_{\mu(k=0)}$ and Directivity Index and its dependence on k-factor, discussed above, can be clearly seen from these four Figures. It can be concluded from these four Figures that 95% of measurement uncertainties associated with the semi-reverberant sound power determinations lie below the hemi-anechoic best-fit plus two standard deviation lines.

As regards the performance of each individual sub-set, this is more difficult to assess from these four Figures because of the spread of the data points and because data for each sub-set is shown on a different figure. The data has, therefore, been replotted, described in terms of the best fit lines (this time to these semi-reverberant data) in Figures 13 to 16, with one Figure for each of the four environments showing the performance of each sub-set in a single environment. Here the performance of each sub-set may be more easily observed. For the data obtained where the K_{2A} was 3.6 dB the relative performance was the same as for the hemi-anechoic results; the four microphone sub-set providing the smallest values of measurement uncertainty followed by the six-, then the three- and lastly the one-microphone sub-set providing the largest values. The values of $\sigma_{\mu(k=0)}$ for the other three rooms are relatively small and exhibit little variation between either sub-set or K_{2A} .

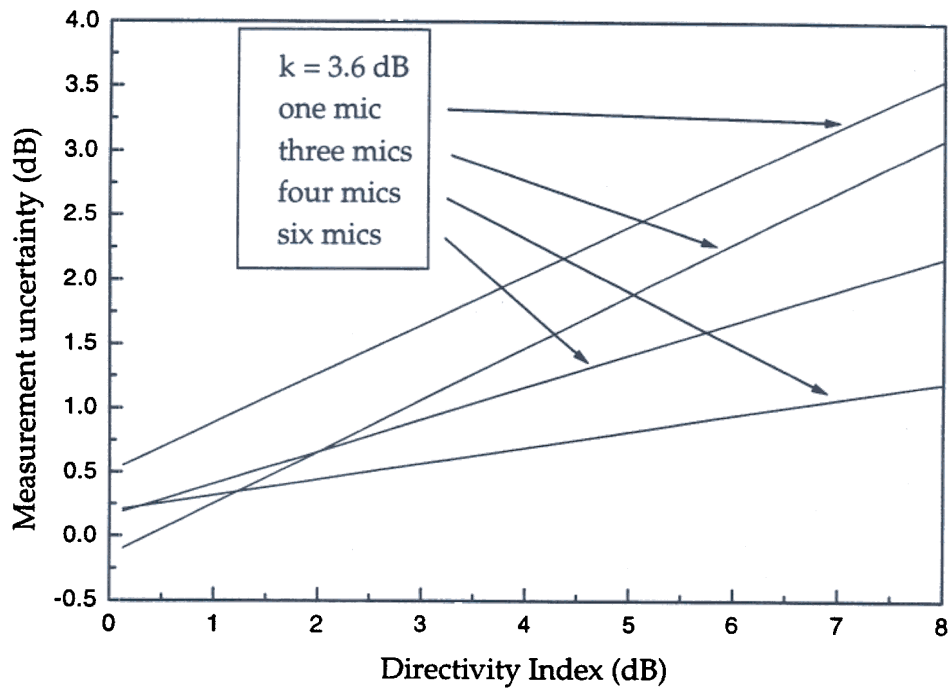


Figure 13 Best fit lines to measured data for Directivity Index of $K_{2A} = 3.6$ dB, with microphone sub-set as parameter.

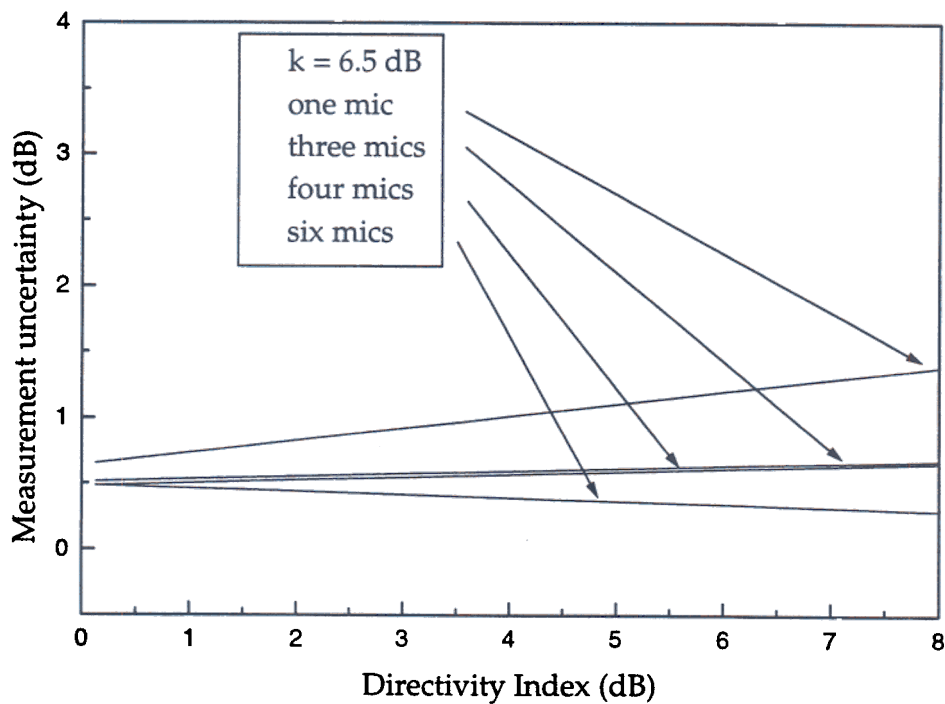


Figure 14 Best fit lines to measured data for Directivity Index of $K_{2A} = 6.5$ dB, with microphone sub-set as parameter.

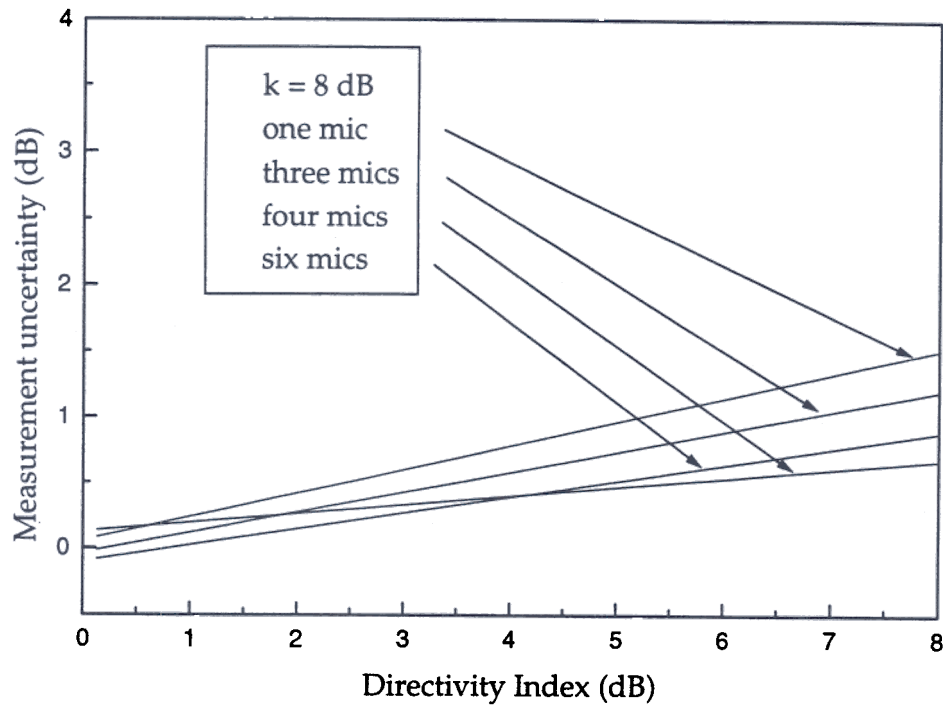


Figure 15 Best fit lines to measured data for Directivity Index of $K_{2A} = 8.0$ dB, with microphone sub-set as parameter.

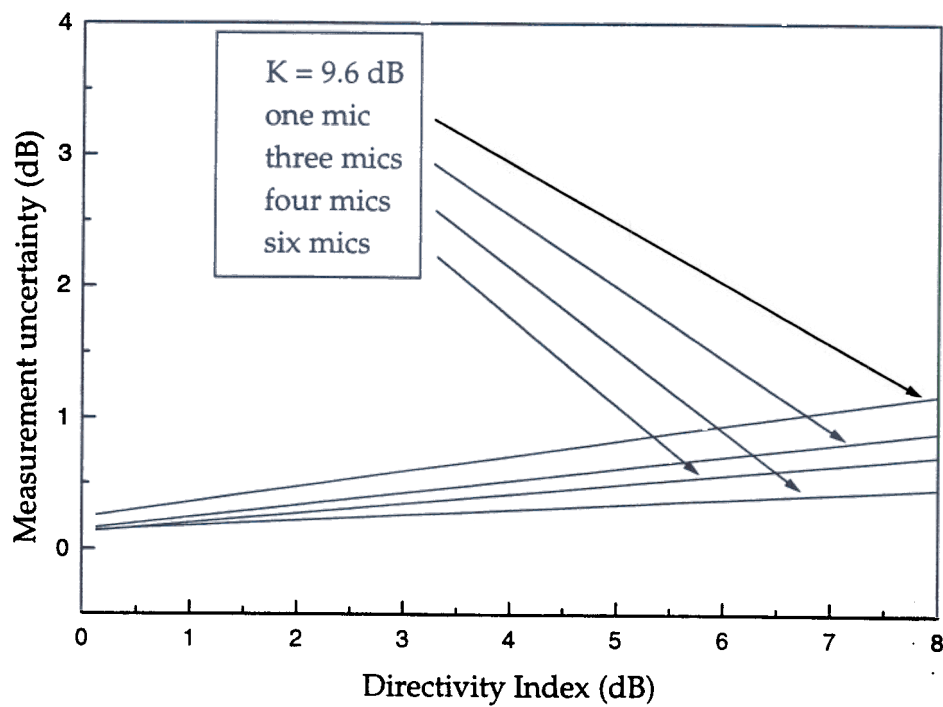


Figure 16 Best fit lines to measured data for Directivity Index of $K_{2A} = 9.6$ dB, with microphone sub-set as parameter.

It may be concluded that, assuming the value of the K_{2A} is determined by the absolute method (described in Section 7.1) with care taken to account for noise sources that are significantly above ground level, the determination of measurement uncertainty and the subsequent assessment of the ISO accuracy descriptor displayed in Figure 8 is not confined only to measurements performed in hemi-anechoic conditions but may be used more generally to include acoustic environments with k-factors up to approximately 10 dB.

8 PROPOSAL FOR A NEW SERIES OF INTERNATIONAL STANDARDS

From the preceding Sections in this report it has become clear that there is a need for a review of the Standards that address the determination of sound power of noise sources. This has been the subject of a separate report, Higginson²⁴ that is reproduced in full as Appendix A. This Section contains a summary of the discussions in both this current report and that of reference 24.

8.1 PROBLEMS WITH THE CURRENT STANDARDS

As discussed in this report, an aspect of sound power testing that has received perhaps secondary consideration until recently is that of the degree of accuracy of the results. On the whole, companies being required to present sound power data have been content to perform a single determination on one machine, to presume that the results are accurate and reliable, and when challenged for an estimate of accuracy to refer simply to the accuracy grade of the measurement method. This approach is acceptable in relation to Directive 89/392/EEC, since manufacturers are only required to state the measurement uncertainty along with the measured sound power level, for information. Circumstances will be different, however, under the proposed Directive relating to the noise of equipment used outdoors. This Directive will require manufacturers of a wide variety of machines intended for domestic and industrial use to mark their products with their "guaranteed" sound power level, and in some cases the level will be required to meet a limit. The guaranteed level must include the uncertainties due to production variation and measurement procedures. These added amounts will be punitive to manufacturers. The standards need to be improved substantially beyond the changes in the present revisions, to give more specific information on uncertainties than at present, and in particular to show how the uncertainties are related to the degree of effort exerted in making the measurements.

The main source of motivation for developing a rapid method of obtaining sound power levels was that of the perceived complexity of the present standards. Even when the series of standards, from ISO 3741 to ISO 3747, has completed its present round of revisions, it will comprise seven different methods of determining the sound power level, and some of those include alternative procedures. There is in addition the method of ISO 4872²⁵, which in part duplicates ISO 3744 and provides further complication by introducing yet another possible arrangement of microphone positions for measurements; even though the latter standard dates from 1978, it is still followed by many companies to the exclusion of more up-to-date methods.

In essence, the functions of the measurement standards in the ISO 3700 series will be, in their revised form, as follows:

ISO 3741 a precision-grade method for use in qualified reverberation rooms, for all kinds of noise source except those emitting impulsive noise;

measurements are made of the reverberant sound field set up by the noise source under test;

- ISO 3743-1 an engineering-grade method for use with small noise sources (of greatest dimension less than 1 m) except those emitting isolated bursts of noise, for use in hard-walled test rooms of volume at least 40 m³; the noise source under test is compared with a calibrated reference sound source;

- ISO 3743-2 an engineering-grade method for use with small noise sources (with volumes up to 1% of that of the test room) except those emitting isolated bursts of noise, for use in reverberation rooms with specified characteristics; measurements may either made of the reverberant sound field set up by the noise source under test or the noise source may be compared with a calibrated reference sound source;

- ISO 3744 an engineering-grade method for all kinds of noise source, for use in an open space (inside a room or outdoors) with a hard floor, but otherwise free from sound reflections; measurements are made of the sound direct from the noise source under test, using microphones positioned on a hemispherical or parallelepiped array;

- ISO 3745 a precision-grade method for all kinds of noise source, for use in qualified free-field (anechoic) rooms or free-field rooms with a hard floor; measurements are made of the sound direct from the noise source under test, using microphones positioned on a spherical or hemispherical array;

- ISO 3746 a survey-grade method for all kinds of noise source for use in situ, provided the acoustic environment meets certain criteria; measurements are made of the sound direct from the noise source under test, using microphones positioned on a hemispherical or parallelepiped array;

- ISO 3747 a method for noise sources emitting sound over a wide frequency range, for use in situ, which might yield either engineering-grade or survey-grade results, depending on the environment; the noise source under test is compared with a calibrated reference sound source.

The philosophy of this series of standards is to present methods separately for the three grades of accuracy and for different acoustic test environments, free-field, reverberant and as found in situ. The standards range from those requiring costly facilities, giving high accuracy but involving substantial measurement effort, to more simple procedures with reduced effort but low accuracy. Some of the standards, particularly at engineering grade, do allow for reduced measurement effort in certain circumstances, but this is only acceptable provided exhaustive validation tests have been conducted.

The synopsis given above illustrates the complexity even of understanding what the respective standards offer. Still further complication arises through ISO 4872. This

standard was produced at a time when a number of European directives were under development, relating to the noise of construction plant and equipment.

It has to be observed that users can only select one standard which is appropriate to a particular application from among all those available provided they have prior knowledge of the kind of environment where tests are to be made, and they understand the level of accuracy to be achieved. If accuracy is important, there is no choice but to observe the full rigours of at least an engineering grade determination. There is no possibility to make a sound power determination from limited measurements, assess the results to see whether they are acceptable, and then make further measurements if refinement is required. The contention here is that a fresh look needs to be taken at the approach to sound power determination using sound pressure measurements, to see whether a more simple approach can be developed that meets the needs of users having to satisfy current and foreseeable regulatory requirements for presenting performance data.

8.2 A PHILOSOPHY FOR A NEW SERIES OF STANDARDS

New standard methods would ideally not involve sub-divisions into different accuracy grades and different acoustic environments, would enable a user to make limited measurements yielding a meaningful result, and allow the measurement effort to be increased if needed, and provide uncertainty data directly in relation to the amount of measurement effort expended. Viewing the ISO 3741-ISO 3747 standards as a whole, there would seem to be a case for retaining the two giving the greatest precision in laboratory environments, reverberant (ISO 3741) and free-field (ISO 3745). These can be regarded as reference methods, involving full corrections for all possible variables, where the extent of the measurement effort is almost immaterial, to be used for such purposes as calibration of standard devices. In so far as facilities of the two different kinds have been established in different industries, and long tradition in their use would make it difficult for the respective practitioners to change, there will continue to be a demand for standards which recognise these two primary approaches, and there is no need for a rapid or simplified method in their application. This report has, however, shown that there are good grounds for collapsing all the other standards into substantially fewer than exist at present.

There are basically two different methods of determining sound power levels using sound pressure measurements. One is that of measuring the sound in the direct field from the source and computing the sound power level from the mean sound pressure level over a measurement surface. This is applied in conditions of an essentially free field over a reflecting plane (as in ISO 3744, ISO 3746 and ISO 4872). The other method is that of comparing the sound pressure levels of the noise source under test with those of a reference sound source already calibrated for its sound power, applied in reverberant conditions (ISO 3743 and ISO 3747). It should be possible to encapsulate these two methods in two standards, one on each, without referring at all in the titles to the test environments.

On the matter of the accuracy grade of the measurements, the approach already adopted in the sound intensity standards gives a pointer for a possible way to develop the sound pressure methods. These standards describe methods of obtaining the three accuracy grades, precision, engineering and survey, and do so without sub-division into separate measurement methods. The approach in both cases is for trial measurements to be made, certain "field indicators" to be evaluated, and then for progression to be made to full measurements. In other words, the accuracy grade is not known in advance, and to some extent it can be improved in the course of the test by making extra measurements to satisfy the field criteria.

The experimental work described in this report shows that a framework for new standard methods along the lines envisaged above could be capable of being fulfilled. It has been shown that measurements of sound pressure level at three microphone positions yield sound power levels to the survey grade of accuracy with sources having a Directivity Index up to 4 dB, and the accuracy grade improves to engineering for the same sources when four microphone positions are used. If the survey grade is acceptable for the purpose of the measurements, this can be achieved for sources with a directivity index up to 8 dB with a four-microphone measurement array. The significance of this is that the measurement uncertainty can be defined in relation to the Directivity Index and the number of microphone positions, and for sources that are more directional or where the uncertainty needs to be reduced, the action to be taken with regard to measurement effort can readily be decided.

A completely new series of standards can be envisaged to replace the seven standards from ISO 3741 to ISO 3747, with titles along the following lines:

- | | |
|-----------|---|
| ISO xxxx1 | Acoustics - Determination of sound power levels of noise sources using sound pressure - Reference method for reverberation rooms. |
| ISO xxxx2 | Acoustics - Determination of sound power levels of noise sources using sound pressure - Reference methods for free-field rooms and hemi-free-field rooms. |
| ISO xxxx3 | Acoustics - Determination of sound power levels of noise sources using sound pressure - Methods using measurements of direct sound from the source. |
| ISO xxxx4 | Acoustics - Determination of sound power levels of noise sources using sound pressure - Methods using a reference sound source for comparison. |

The contents of ISO xxxx1 and ISO xxxx2 would be essentially similar to ISO 3741 and ISO 3745, except that editing would be necessary to conform with the new format of ISO xxxx3 and ISO xxxx4. Much thought and drafting work is needed yet before the latter two standards can be laid out, but preliminary suggestions for their respective scopes are given in by Higginson in Appendix A. As envisaged, the standards would present data of the kind shown in Figure 8, transformed to show directly the dependence of

measurement uncertainty (or at least, the repeatability or reproducibility of the measurements) on the number of microphone positions used, with directivity as a parameter. The extent of the measurement effort could then be decided in relation to the chosen precision of the results, given the sound-emitting characteristics of the source under test.

8.3 PROPOSAL SUMMARY

The present series of standards describing methods for determining sound power levels of noise sources using sound pressure measurements, ISO 3741-ISO 3747 and ISO 4872, is thought to be unsuitable to meet present and foreseen regulatory requirements concerning the noise emission of machinery and equipment, even as it will be made up after the current round of revisions has been completed. The sub-division of standards into separate documents for different acoustic environments and different broad grades of accuracy raises unnecessary complications and makes it difficult for a user to interpret which standard is best suited to a particular application. Moreover, the treatment of measurement uncertainties in the published and soon-to-be published standards is again inadequate for users having to meet regulatory requirements. It is suggested that revisions of the standards already in process be completed as quickly as possible, but that agreement should be sought among the standards producers for a new series of standards to be produced, ultimately to replace all the existing ones. The new series would comprise four documents, two of which would give reference methods for use in fully qualified reverberant and free-field rooms. The other two standards would be for use in environments other than specialised acoustical laboratories, and would be formulated around the measurement methods, one of which would be that of direct measurements of the sound field emitted by the source and the other would be the method of comparison with a calibrated reference sound source. The measurement method in both cases would be to relate the number of measurements of sound pressure level to the repeatability of the resultant sound power determination, allowing the number to be increased in order to achieve improved repeatability if required.

9 CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

9.1.1 General observations

The experimental results discussed in this report have shown that sound power level determinations may be performed in a wide range of acoustical environments with an acceptable level of measurement uncertainty when the number of measurements is significantly less than recommended in current international standards.

The present series of standards describing methods for determining sound power levels of noise sources using sound pressure measurements, ISO 3741-ISO 3747 and ISO 4872, **is inadequate to meet present and foreseen regulatory requirements concerning the noise emission of machinery and equipment.**

The sub-division of standards into separate documents for different acoustic environments and different broad grades of accuracy raises **unnecessary complications and makes it difficult for a user to interpret which standard is best suited to a particular application.** Moreover, the **treatment of measurement uncertainties in the published and soon-to-be published standards is again inadequate** for users having to meet regulatory requirements.

9.1.1 Outdoor measurements in hemi-anechoic conditions

The effects on sound power level of variations in radii or measurement distance (permitted by ISO 3744) are negligible.

If hemispheres with radii less than the ISO 3744 minimum are used the sound power level obtained using measurements of sound pressure level increases; those determined using intensity techniques remain constant.

Sound power levels determined using only four microphone positions chosen from the ISO 3744 twenty-microphone array such that all are at different heights and on radii that have equal angular spacing were found to be on average within 0.1 dB of true values. These determinations are estimated to be of engineering grade accuracy with average repeatability standard deviations of 0.3 dB. **This arrangement is recommended as forming the basis of a rapid method of sound power determination.**

The sound power level determined using parallelepiped enveloping surfaces was found to be independent of the number of microphone positions provided this number was greater than or equal to nine. **For the values of measurement distance examined the sound power level values were approximately 1 dB too high.** The precise magnitude

of this error will be dependent on the measurement distance and the size of the noise source.

The use of a parallelepiped measurement surface for discrete microphone locations is not recommended as a basis for a rapid method.

No significant differences were observed between sound power levels determined with an operator using a sound level meter and those using remote microphones.

The only viable scanning technique for hemispherical surfaces was coaxial circular paths. Sound power levels determined using three mid-height paths were close to true values.

9.1.2 Indoor measurements

Sound power levels determined in a hemi-anechoic room, using the recommended rapid method arrangement were, on average, within 0.2 dB of true values. These determinations are estimated to be of engineering grade accuracy with average repeatability standard deviations of 0.2 dB.

In semi-reverberant conditions, sound power levels were up to 0.5 dB different from true values (determined in a hemi-anechoic room) with repeatability standard deviations of 0.2 dB. The differences were not considered to be statistically significant at the 95 % confidence interval.

The A-weighted sound power levels determined using ISO 3743-1 and ISO 3747 are dependent on the method used to obtain A-weighted sound pressure level. Sound power levels determined using an A-weighting function may be made more quickly and with less sophisticated instrumentation than those obtained from summing band limited levels. Measurements using an A-weighting function should, therefore, be encouraged. However, the difference between direct and octave-band derived values must be determined or an allowance made in the assessment of measurement uncertainties.

Rooms that qualify for measurements according to ISO 3743-2 are acoustically very special and are mainly used only for measurements on air conditioning systems. No attempt has been made to assess the performance of this standard.

Sound power levels determined in semi-reverberant conditions (with values of K_{2A} up to 8 dB) using the recommended rapid method were, on average, within 0.3 dB of true values. These determinations are estimated to be of engineering grade accuracy with average repeatability standard deviations of 0.3 dB.

Verification of the preferred four-microphone array in hemi-anechoic conditions

As the noise source becomes more directional the measurement uncertainty involved with a given sound power determination procedure increases.

For a given noise source the measurement uncertainty increases as the number of microphones used in the sound power determination decreases.

A procedure has been developed that enables the measurement uncertainty associated with a sound power determination made with a known number of sound pressure level measurements on a hemispherical enveloping surface to be estimated from a knowledge of Directivity Index.

Sound power levels determined in a hemi-anechoic room, using the preferred method employing four measurement positions, are estimated to be of engineering grade accuracy for noise sources with a Directivity Index up to about 4 dB and of survey-grade accuracy for noise sources with a Directivity Index of 8 dB.

Verification of the preferred four-microphone array in semi-reverberant conditions

The value of measurement uncertainty increases with Directivity Index for measurements carried out in a room with a value of K_{2A} of 3.6 dB but is relatively constant for measurements carried out in rooms with a higher values of K_{2A} .

From measurements carried out where K_{2A} was 3.6 dB the relative performance of microphone array sub-sets was the same as that for hemi-anechoic conditions; **the preferred (four-microphone) arrangement sub-set providing the smallest values of measurement uncertainty** followed by the six-, then the three- and lastly the one-microphone sub-set providing the largest values. The measurement uncertainties in rooms with higher values of K_{2A} are relatively small and exhibit little variation between either sub-set or K_{2A} .

Assuming the value of the K_{2A} is determined by the absolute method with care taken to account for noise sources that are significantly above ground level, measurement uncertainty and the subsequent assessment of the ISO accuracy descriptor are similar to those for hemi-anechoic conditions for values of K_{2A} up to approximately 10 dB.

9.2 RECOMMENDATIONS

Agreement should be sought among the standards producers for **a new series of standards to be produced, ultimately to replace all the existing ones.** The new series would comprise four documents, two of which would give reference methods for use in fully qualified reverberant and free-field rooms. The other two standards would be for use in environments other than specialised acoustical laboratories, and would be

formulated around the measurement methods, one of which would be that of direct measurements of the sound field emitted by the source and the other would be the method of comparison with a calibrated reference sound source. **The measurement method in both cases would be to relate the number of measurements of sound pressure level to the repeatability of the resultant sound power determination,** allowing the number to be increased in order to achieve improved repeatability if required.

Before the work of drafting new standards can begin, the work discussed in this report needs to be extended to ensure that sufficient data are available on a wide variety of practical noise sources and to cover the comparison method as well as the direct sound field measurement method. Three suggested areas of investigation are outlined below.

- ★ For the direct sound field measurement method, the number of test noise sources needs to be enlarged, to include some of greater dimensions and some which are mobile under test; within this set of measurements, machines such as road sweepers and refuse collection vehicles should be included, where the primary noise sources are relatively small compared to the vehicle as a whole and directionality might be particularly strong in a limited direction.
- ★ The experimental data discussed in this report uses Directivity Index as a predictor of measurement uncertainty for the direct sound field measurement method. Confirmation is needed that directivity is sufficient for this purpose where the microphone array is hemispherical, and further investigation is needed to find out what other predictor can be used where the microphones are arrayed on a parallelepiped and directivity cannot be determined.
- ★ Data are needed in relation to applications where sound power levels in frequency bands are required, from measurements made in octaves and one-third-octaves, as opposed to the A-frequency-weighted measurements reported here.

10 ACKNOWLEDGEMENTS

The authors acknowledge the financial support of the National Measurement System Policy Unit of the UK Department of Trade and Industry and the assistance of Roger Higginson of Higginson Acoustics Limited.

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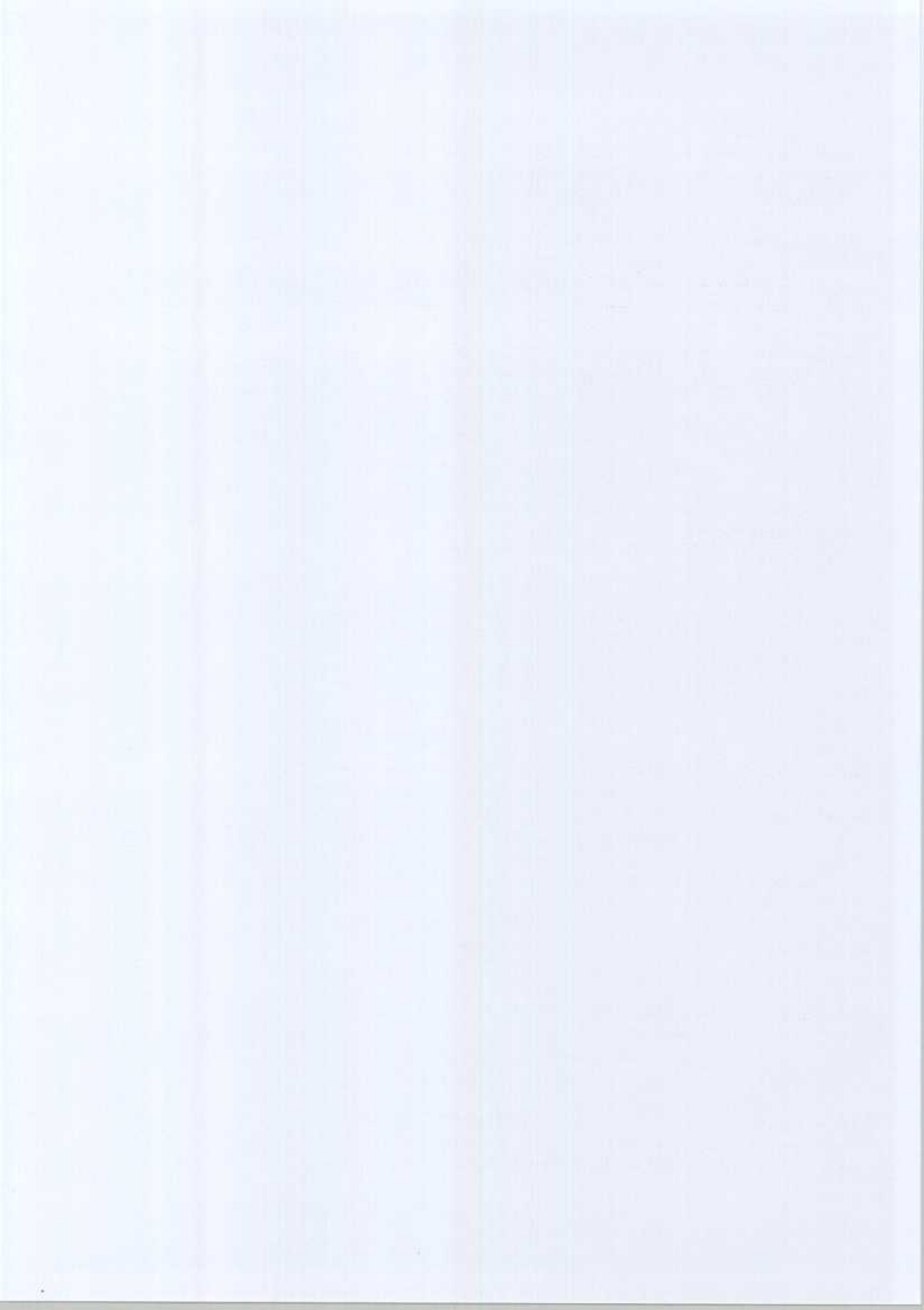
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12 APPENDIX A

The following eighteen pages of this report form an Appendix and comprise a copy of the report supplied by Higginson Acoustics Limited entitled "Towards a new series of international standards specifying methods of determining sound power levels of machinery and equipment". Page numbers and headers are as given in the report by Higginson²⁴.

HIGGINSON ACOUSTICS LIMITED

REPORT NO. 0022/98



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**TOWARDS A NEW SERIES OF INTERNATIONAL STANDARDS
SPECIFYING METHODS OF DETERMINING SOUND POWER LEVELS
OF MACHINERY AND EQUIPMENT**

Summary:

As part of a research project to establish a rapid method of making sound power measurements on machinery, a critique is given of the present standard methods. The standards are found to be too complex, and inadequate in their treatment of measurement uncertainty, to be of use in satisfying current and foreseen European regulatory requirements. Proposals are made for a completely new series of standards intended ultimately to replace the present ones.

Client:	National Physical Laboratory Queens Road Teddington Middlesex, TW11 0LW	
Order:	NPL Agreement S004270, dated 7 August 1996	
Report no.:	0022/98	
Prepared by:	Roger F. Higginson	Date: 18 May 1998
Authorised by:		Date:

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TOWARDS A NEW SERIES OF INTERNATIONAL STANDARDS SPECIFYING METHODS OF DETERMINING SOUND POWER LEVELS OF MACHINERY AND EQUIPMENT

CLIENT'S REQUIREMENTS

The work to be performed was part of Phase 9, Reporting and Dissemination, of the project being undertaken by the National Physical Laboratory (NPL) and Higginson Acoustics Limited (HAL) for the Department of Trade and Industry, National Measurement System Policy Unit (DTI, NMSPU) to establish a rapid method of making sound power measurements of machinery noise emission. Phase 9 is the concluding part of the project and is described in the tender document (1) as follows:

"The final stage of the programme will involve producing an overall report on the project giving conclusions and recommendations, and including at least one measurement procedure document suitable for introduction to the Standards committees network as a working draft."

The experimental programme has been carried out by NPL and the results are reported elsewhere (2). This report reviews the present standards specifying alternative methods of making sound power measurements, draws particular attention to their shortcomings in the light of the background to this project, and makes recommendations for a complete new generation of standards to replace the present ones, based upon the findings of the project. The report is offered as the document to be submitted to the Standards committees network, in order to initiate production of the new standards envisaged.

PRESENT STANDARDS FOR DETERMINATION OF SOUND POWER LEVELS

The variety of standards at present available fall into two groups utilising measurements of two different acoustical quantities, namely sound intensity intensity level (3, 4) and sound pressure level (5-13). It was realised at an early stage in the present project to develop a rapid method of determining sound power levels that measurement techniques using sound intensity have their own problems, generally associated with the need to satisfy certain "field indicators" in order for the measurements to be viable. The tendency in conditions which deviate from those most ideal is for more extensive and detailed measurements to be made before the field indicators can be satisfied, rather than fewer and more simplified ones, and so the technique does not lend itself to a "rapid" method. Hence, the methods of ISO 9614 and its different parts were eliminated from the investigations and attention was concentrated upon the methods using sound pressure measurements, ISO 3741-ISO 3747 and ISO 4872.

The series of standards ISO 3741-ISO 3747 is at present undergoing revision. While the revisions are still in process, it is known that one number in the series (ISO 3742) will disappear altogether and the titles of others will change. ISO 3743-1, ISO 3743-2, ISO 3744 and ISO 3746 have all completed the current round of changes and recent versions have been published, but new versions of ISO 3741, ISO 3745 and ISO 3747 have all still to be finalised. It seems likely that it will not be until the year 2000 that the final versions of all standards in this series will have

been issued, but the numbers and titles now known to be included, with their respective ISO designations indicating their current statuses, are as follows:

ISO/DIS 3741.2	Acoustics - Determination of sound power levels of noise sources using sound pressure - Precision methods for reverberation rooms.
ISO 3743-1:1994	Acoustics - Determination of sound power levels of noise sources Engineering methods for small, movable sources in reverberant fields Part 1: Comparison method for hard-walled test rooms.
ISO 3743-2:1994	Acoustics - Determination of sound power levels of noise sources using sound pressure - Engineering methods for small, movable sources in reverberant fields - Part 2: Methods for special reverberation test rooms.
ISO 3744:1994	Acoustics - Determination of sound power levels of noise sources using sound pressure - Engineering method in an essentially free field over a reflecting plane.
ISO/WD 3745	Acoustics - Determination of sound power levels of noise sources using sound pressure - Precision methods for anechoic and hemi-anechoic rooms.
ISO 3746:1996	Acoustics - Determination of sound power levels of noise sources using sound pressure - Survey method using an enveloping measurement surface over a reflecting plane.
ISO/DIS 3747	Acoustics - Determination of sound power levels of noise sources using sound pressure - Comparison method for use in situ.

The other standard which is sometimes referred to in place of any of the above is:

ISO 4872:1978	Acoustics - Measurement of airborne noise emitted by construction equipment intended for outdoor use - Method for determining compliance with noise limits.
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The years forming part of the standard numbers above are those of publication where applicable. "DIS" indicates Draft International Standard, on which voting is at present taking place for acceptance to be published; in the case of DIS 3741 a second round of voting is necessary, as indicated by the designation ".2". "WD" stands for Working Draft, which means that the draft is still being considered by the working group and a version has not yet emerged for comment or voting.

A CRITIQUE OF THE PRESENT STANDARDS

In the context of the project to establish a "rapid" method of making sound power measurements, the first point at issue is the meaning of "rapid" relating to the practical application of the

standards concerned. The project was set up to meet the needs of machinery manufacturers faced with having to comply with the essential health and safety requirements of European Directive 89/392/EEC (14). One of the requirements is for manufacturers in certain circumstances to provide information on the sound power level, and the DTI felt that the standard methods for obtaining the data were too complicated and time consuming to perform. The aim of the project was therefore to identify an efficient standardised measurement technique, simpler and quicker to perform than those at present available yet without sacrificing the accuracy of results.

Early on in the conduct of the project, HAL reported (15, 16) on visits to nine manufacturing companies, two commercial test companies and one university department, all of which make regular measurements of sound power level. The purpose of the visits was to find out which particular standards were used most commonly and to form an opinion of the scope for improving the efficiency of test methods. The organisations visited covered a broad spectrum of companies engaged in volume production and construction of single machines, machinery varying in size from dimensions of several metres to small, hand-held types, and acoustic test facilities ranging from fully-equipped laboratories to only the most basic measuring instruments. The sound power test methods used were divided evenly between the reverberation room methods of ISO 3741, ISO 3742 and ISO 3743 (current published versions), the hemi-free-field method of ISO 3744 and the in-situ method of ISO 3746. When questioned about the time needed to undertake noise emission tests, almost all the organisations emphasised the relatively long time (often a number of days) to set up the machines and achieve stable running conditions. The need for a rapid turn-round time of testing was expressed by companies engaged in volume production and requiring to test routinely for noise following final assembly, and more generally, all companies were anxious to pursue any efficiency gains that might be achievable.

An aspect of sound power testing that has received perhaps secondary consideration until recently is that of the degree of precision of the results. On the whole, companies being required to present sound power data have been content to perform a single determination on one machine, to presume that the results are accurate and reliable, and when challenged for an estimate of precision to refer simply to the accuracy grade of the measurement method. This approach is acceptable in relation to Directive 89/392/EEC, since manufacturers are only required to state the measurement uncertainty along with the measured sound power level (17), for information. Circumstances will be different, however, under a new European Directive which has been proposed (18) relating to the noise of equipment used outdoors. This Directive will require manufacturers of a wide variety of machines intended for domestic and industrial use to mark their products with their "guaranteed" sound power level, and in some cases the level will be required to meet a limit. The guaranteed level must include the uncertainties due to production variation and measurement procedures. The standards and drafts included above in the revised series ISO 3741-ISO 3747 give broad indications of the standard deviations attainable from repeated measurements, ranging from 0.5 dB on the A-weighted sound power level in the case of the precision grades of accuracy, through 1.5 dB for engineering accuracy, to 3 or 4 dB for survey accuracy. These relate to the reproducibility of the measurement method in different laboratories, whereas the proposed Directive refers to repeatability in the same laboratory, but when combined with the production variability of machines, they will impose additions to the measured sound power levels to obtain the guaranteed levels amounting to around 3 dB even for an engineering grade of accuracy, and considerably more for survey grade. These added amounts will be punitive to manufacturers. The standards need to be improved substantially beyond the

changes in the present revisions, to give more specific information on uncertainties than at present, and in particular to show how the uncertainties are related to the degree of effort exerted in making the measurements.

The other source of motivation for developing a rapid method of obtaining sound power levels was that of the perceived complexity of the present standards. Even when the series of standards, ISO 3741-ISO 3747, has completed its present round of revisions, it will comprise seven different methods of determining the sound power level, and some of those include alternative procedures. There is in addition the method of ISO 4872, which in part duplicates ISO 3744 and in part provides further complication by introducing yet another possible arrangement of microphone positions for measurements; even though the latter standard dates from 1978, it is still followed by many companies to the exclusion of more up-to-date methods.

In essence, the functions of standards ISO 3741-ISO 3747 will be, in their revised form, as follows:

- | | |
|------------|--|
| DIS 3741 | a precision-grade method for use in qualified reverberation rooms, for all kinds of noise source except those emitting impulsive noise; measurements are made of the reverberant sound field set up by the noise source under test; |
| ISO 3743-1 | an engineering-grade method for use with small noise sources (of greatest dimension less than 1 m) except those emitting isolated bursts of noise, for use in hard-walled test rooms of volume at least 40 m ³ ; the noise source under test is compared with a calibrated reference sound source; |
| ISO 3743-2 | an engineering-grade method for use with small noise sources (with volumes up to 1% of that of the test room) except those emitting isolated bursts of noise, for use in reverberation rooms with specified characteristics; measurements may either made of the reverberant sound field set up by the noise source under test or the noise source may be compared with a calibrated reference sound source; |
| ISO 3744 | an engineering-grade method for all kinds of noise source, for use in an open space (inside a room or outdoors) with a hard floor, but otherwise free from sound reflections; measurements are made of the sound direct from the noise source under test, using microphones positioned on a hemispherical or parallelepiped array; |
| WD 3745 | a precision-grade method for all kinds of noise source, for use in qualified free-field (anechoic) rooms or free-field rooms with a hard floor; measurements are made of the sound direct from the noise source under test, using microphones positioned on a spherical or hemispherical array; |
| ISO 3746 | a survey-grade method for all kinds of noise source for use in situ, provided the acoustic environment meets certain criteria; measurements are made of the sound direct from the noise source under test, using |

microphones positioned on a hemispherical or parallelepiped array;

DIS 3747

a method for noise sources emitting sound over a wide frequency range, for use in situ, which might yield either engineering-grade or survey-grade results, depending on the environment; the noise source under test is compared with a calibrated reference sound source.

The philosophy of this series of standards is to present methods separately for the three grades of accuracy and for different acoustic test environments, free-field, reverberant and as found in situ. The standards range from those requiring costly facilities, giving high accuracy but involving substantial measurement effort, to more simple procedures with reduced effort but low precision. Some of the standards, particularly at engineering grade, do allow for reduced measurement effort in certain circumstances, but this is only acceptable provided exhaustive validation tests have been conducted.

The synopsis given above illustrates the complexity even of understanding what the respective standards offer. Still further complication arises through ISO 4872. This standard was produced at a time when a number of European directives were under development, relating to the noise of construction plant and equipment. Those directives were of the "old approach" type which contain the measurement method in all details, and the first of them (19) gave the basic procedure for determining the sound power level. In essence, the method prescribed was that of ISO 3744, where the test environment is an open space outdoors with a hard, sound-reflecting surface on which the machine stands, but because of the sizes and similarities in noise-emitting characteristics of the construction plant to be tested, the array of microphone positions over a hemispherical measurement surface differed from any in ISO 3744. Not only were the microphone positions at different coordinates, they were fewer in number than those deemed theoretically correct in the more classical ISO standard. ISO 4872 evolved from the wishes of the standardising community to remain in step with European regulations, despite reservations felt about theoretical correctness, and so the new microphone array was added as a permitted alternative to that in the pre-existing ISO standard. The alternative array in ISO 4872 and its contemporary European directives has some practical advantages, where safety considerations preclude a measurement position vertically above the machine under test, and also where the machine has to be tested in motion. Some machines are required to be driven through the microphone array to simulate a test under working conditions, and the alternative array allows a clear path to be followed. This alternative array is now specified in the proposed new European Directive (18). Because the microphone positions are all offset to the sides of the machine under test, and any sound emitted directly upwards tends not to be included in the measurements, the sound power level obtained has sometimes been described as an "immission-relevant" sound power level. Such a term has not been formally defined, but it is understood to represent a part of the total sound power level that may be relevant to onlookers positioned at some low elevation relative to the horizontal from the machine.

It has to be observed that users can only select one standard which is appropriate to a particular application from among all those available provided (i) they have prior knowledge of the kind of environment where tests are to be made, (ii) they understand the level of accuracy to be achieved, and (iii) they know whether a full sound power determination is needed or only an "immission-relevant" (that is, a partial) one. If accuracy is important, there is no choice but to

observe the full rigours of at least an engineering grade determination. There is no possibility to make a sound power determination from limited measurements, assess the results to see whether they are acceptable, and then make further measurements if refinement is required. The contention of this review is that a fresh look needs to be taken at the approach to sound power determination using sound pressure measurements, to see whether a more simple approach can be developed that meets the needs of users having to satisfy current and foreseeable regulatory requirements for presenting performance data.

A PHILOSOPHY FOR A NEW SERIES OF STANDARDS

New standard methods would ideally not involve sub-divisions into different accuracy grades and different acoustic environments, would enable a user to make limited measurements yielding a result, allow the measurement effort to be increased if needed, and provide uncertainty data directly in relation to the amount of measurement effort expended. Viewing the ISO 3741-ISO 3747 standards as a whole, there would seem to be a case for retaining the two giving the greatest precision in laboratory environments, reverberant and free-field, the latest versions of which are DIS 3741.2 and WP 3745, respectively. These can be regarded as reference methods, involving full corrections for all possible variables, where the extent of the measurement effort is almost immaterial, to be used for such purposes as calibration of standard devices. In so far as facilities of the two different kinds have been established in different industries, and long tradition in their use would make it difficult for the respective practitioners to change, there will continue to be a demand for standards which recognise these two primary approaches, and there is no need for a rapid or simplified method in their application. There are, however, good grounds for collapsing all the other standards into substantially fewer than exist at present.

There are basically two different methods of determining sound power levels using sound pressure measurements. One is that of measuring the sound in the direct field from the source and computing the sound power level from the mean sound pressure level over a measurement surface. This is applied in conditions of an essentially free field over a reflecting plane (as in ISO 3744, ISO 3746 and ISO 4872). The other method is that of comparing the sound pressure levels of the noise source under test with those of a reference sound source already calibrated for its sound power, applied in reverberant conditions (ISO 3743 and ISO 3747). It should be possible to encapsulate these two methods in two standards, one on each, without referring at all in the titles to the test environments.

On the matter of the accuracy grade of the measurements, the approach already adopted in the sound intensity standards gives a pointer for a possible way to develop the sound pressure methods. One of the existing standards using sound intensity measurements (3) describes methods of obtaining the three accuracy grades, precision, engineering and survey, but it does so without sub-division into separate measurement methods. In the other standard (4) methods are given for engineering and survey grades, again without sub-division into separate documents. The approach in both cases is for trial measurements to be made, certain "field indicators" to be evaluated, and then for progression to be made to full measurements. The precision of the sound power level hinges upon the values found for the field indicators. In other words, the accuracy grade is not known in advance, and to some extent it can be improved in the course of the test by making extra measurements to satisfy the field criteria.

The experimental work undertaken by NPL during the project to establish a "rapid" method of sound power determination (2) shows that a framework for new standard methods along the lines envisaged above could be capable of being fulfilled. The main factors in the noise emission from any test source that can cause the measurement effort to be increased in order to reduce the measurement uncertainty are the directionality of the source (that is, the extent to which the source emits more noise in one direction than in another) and the presence of prominent single-frequency tones or narrow bands of frequencies in the sound energy spectrum. Using a 20-microphone hemispherical measurement array from ISO 3744 as a reference, Payne and Simmons have shown how the measurement uncertainty of the A-weighted sound power level of a wide variety of different sources, obtained in quite different acoustic environments, varies with the directivity index (defined as in ISO 3744) when obtained from sub-sets of microphone positions numbering from six down to one. Figure 1 encapsulates the results of their work relating to direct sound field measurements. As with all their data, the term "measurement uncertainty" relates only to the measurement method and includes no allowance for production variations of noise sources. The bands of uncertainty generally associated with survey-grade accuracy and engineering grade, respectively 3 dB and 1.5 dB, are shown in the figure. Payne and Simmons have found that measurements of sound pressure level at three microphone positions yield sound power levels to the survey grade of accuracy with sources having a directivity index up to 4 dB, and the accuracy grade improves to engineering for the same sources when four microphone positions are used. If the survey grade is acceptable for the purpose of the measurements, this can be achieved for sources with a directivity index up to 8 dB with a four-microphone measurement array. The significance of this work is that the measurement uncertainty can be defined in relation to the directivity index and the number of microphone positions, and for sources that are more directional or where the uncertainty needs to be reduced, the action to be taken with regard to measurement effort can readily be decided.

Before the work of drafting new standards can begin, the work already done by NPL needs to be extended to ensure that sufficient data are available on a wide variety of practical noise sources and to cover the comparison method as well as the direct sound field measurement method:

- 1) For the direct sound field measurement method, the number of test noise sources needs to be enlarged, to include some of greater dimensions and some which are mobile under test; within this set of measurements, machines such as road sweepers and refuse collection vehicles should be included, where the primary noise sources are relatively small compared to the vehicle as a whole and directionality might be particularly strong in a limited direction.
- 2) The experimental data from NPL so far use directivity as a predictor of measurement uncertainty for the direct sound field measurement method. Confirmation is needed that directivity is sufficient for this purpose where the microphone array is hemispherical, and further investigation is needed to find out what other predictor can be used where the microphones are arrayed on a parallelepiped and directivity cannot be determined.
- 3) Data are needed in relation to applications where sound power levels in frequency bands are required, from measurements made in octaves and one-third-octaves, as opposed to the A-frequency-weighted measurements made so far by NPL.

- 4) The approach to the work done so far using the direct sound field measurement method, of making limited measurements, determining the measurement uncertainty, and deciding whether extra measurements can be made to reduce the uncertainty, needs to be tested using the comparison method with a reference sound source; again in this case, an adequate predictor of measurement uncertainty needs to be identified.

Assuming that the above investigations can be completed successfully, to produce further information of the kind shown in Figure 1, a completely new series of standards can be envisaged to replace ISO 3741-ISO 3747, with titles along the following lines:

- | | |
|-----------|---|
| ISO xxxx1 | Acoustics - Determination of sound power levels of noise sources using sound pressure - Reference method for reverberation rooms. |
| ISO xxxx2 | Acoustics - Determination of sound power levels of noise sources using sound pressure - Reference methods for free-field rooms and hemi-free-field rooms. |
| ISO xxxx3 | Acoustics - Determination of sound power levels of noise sources using sound pressure - Methods using measurements of direct sound from the source. |
| ISO xxxx4 | Acoustics - Determination of sound power levels of noise sources using sound pressure - Methods using a reference sound source for comparison. |

As envisaged, the contents of ISO xxxx1 and ISO xxxx2 would be essentially similar to DIS 3741.2 and WD 3745, except that editing would be necessary to conform with the new format of ISO xxxx3 and ISO xxxx4. Much thought and drafting work is needed yet before the latter two standards can be laid out, but preliminary suggestions for their respective scopes are given in Appendices 1 and 2, indicating the directions which the full documents are expected to take. As envisaged, the standards would present data of the kind shown in Figure 1, transformed to show directly the dependence of measurement uncertainty (or at least, the repeatability or reproducibility of the measurements) on the number of microphone positions used, with directivity (or other chosen variable if appropriate) as a parameter. The extent of the measurement effort could then be decided in relation to the chosen precision of the results, given the sound-emitting characteristics of the source under test. ISO xxxx3 would include the determination of partial (or immission-relevant) sound power levels as an option.

CONCLUDING REMARKS

The present series of standards describing methods for determining sound power levels of noise sources using sound pressure measurements, ISO 3741-ISO 3747 and ISO 4872, is thought to be unsuitable to meet present and foreseen regulatory requirements concerning the noise emission of machinery and equipment, even as it will be made up after the current round of revisions has been completed. The sub-division of standards into separate documents for different acoustic environments and different broad grades of accuracy raises unnecessary complications and makes

it difficult for a user to interpret which standard is best suited to a particular application. Moreover, the treatment of measurement uncertainties in the published and soon-to-be published standards is again inadequate for users having to meet regulatory requirements. It is suggested that revisions of the standards already in process be completed as quickly as possible, but that agreement should be sought among the standards producers for a new series of standards to be produced, ultimately to replace all the existing ones. The new series would comprise four documents, two of which would give reference methods for use in fully qualified reverberant and free-field rooms. The other two standards would be for use in environments other than specialised acoustical laboratories, and would be formulated around the measurement methods, one of which would be that of direct measurements of the sound field emitted by the source and the other would be the method of comparison with a calibrated reference sound source. The measurement method in both cases would be to relate the number of measurements of sound pressure level to the repeatability of the resultant sound power determination, allowing the number to be increased in order to achieve improved repeatability if required.

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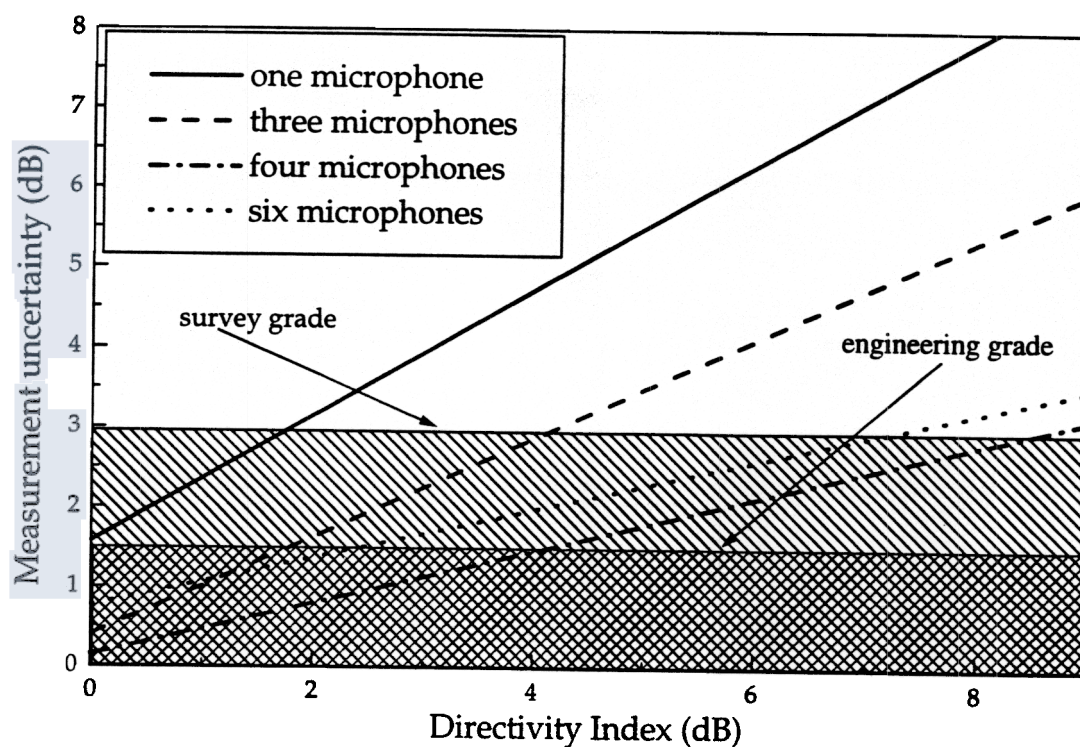


Figure Variation of measurement uncertainty (plus two standard deviations) of sound power levels, as a function of the directivity index of the test noise source, obtained from different numbers of measurements of the surface sound pressure level (from Payne and Simmons, reference 2)

APPENDIX 1

Suggested title, introduction and scope for proposed standard ISO xxxx3

Title: Acoustics - Determination of sound power levels of noise sources using sound pressure - Methods using measurements of direct sound from the source

Introduction

This International Standard is one of a number giving different methods of determining sound power levels of noise sources. When selecting a method, it is necessary to decide which one is most appropriate for the conditions and purposes of the test. General guidelines to assist in the selection are provided in ISO xxxx0. In general, the sound power level of a noise source depends on the conditions under which it is mounted, loaded and operated. This International Standard gives only general principles to be observed in selecting these conditions. Reference should be made to test codes for individual kinds of noise source, if available, for detailed requirements on mounting, loading and operating conditions under which the sound power levels are to be obtained, and to select the appropriate measurement surface from those described in this International Standard.

1 Scope

1.1 This International Standard specifies methods for measuring the sound pressure levels on a measurement surface enveloping a noise source, and for calculating the sound power level produced by the noise source, in frequency bands or frequency-weighted, using those measurements. Requirements are given for the instrumentation, the test environments that are suitable for the measurements are described, and the reproducibility of the results is quantified given the noise-emitting characteristics of the source under test and the number of microphone positions used on the measurement surface.

NOTE Differently shaped measurement surfaces can yield differing estimates of the sound power level of a given noise source and a test code should give detailed information on the selection of the surface.

The reproducibility of the results depends on the directional characteristics of the source under test, on the test environment, and the number of microphone positions used on the measurement surface. The conditions are specified under which A-weighted sound power levels can be determined with standard deviations of reproducibility equal to or less than 1,5 dB, corresponding with grade 2 accuracy according to ISO 12001. Conditions are also defined under which A-weighted sound power levels can be determined with standard deviations of reproducibility extending up to 3 dB, corresponding with grade 3 accuracy. The evaluation of measurement uncertainties from data on standard deviations of reproducibility, for purposes of noise declaration and verification, is described in ISO 4871 and ISO 7574-1 to ISO 7574-4.

1.2 The methods specified in this International Standard are suitable for all types of noise (steady, non-steady, broad-band and narrow-band) defined in ISO 12001.

This International Standard is applicable to all types and sizes of noise source (e.g. static and mobile plant, installation, machine, component, sub-assembly), provided the conditions for the measurements can be met.

NOTE For very tall or very long sources such as chimneys, ducts, conveyors and multi-source industrial plants, it may be appropriate either to determine separately the sound power levels of segments of the source or to determine partial sound power levels in particular directions.

1.3 The test environments that are applicable for measurements made in accordance with this International Standard may be located indoors or outdoors, with one or more sound-reflecting planes present.

APPENDIX 2

Suggested title, introduction and scope for proposed standard ISO xxxx4

Title: Acoustics - Determination of sound power levels of noise sources using sound pressure - Methods using a reference sound source for comparison

Introduction

This International Standard is one of a number giving different methods of determining sound power levels of noise sources. When selecting a method, it is necessary to decide which one is most appropriate for the conditions and purposes of the test. General guidelines to assist in the selection are provided in ISO xxxx0. In general, the sound power level of a noise source depends on the conditions under which it is mounted, loaded and operated. This International Standard gives only general principles to be observed in selecting these conditions. Reference should be made to test codes for individual kinds of noise source, if available, for detailed requirements on mounting, loading and operating conditions under which the sound power levels are to be obtained.

1 Scope

1.1 This International Standard specifies a comparison method for determining the sound power levels in octave bands produced by a noise source. The sound power level is calculated from the measured sound pressure levels at prescribed positions produced by the source under test and by a reference sound source. The difference between these levels is added to the calibrated sound power level of the reference sound source to give the sound power level of the source under test, all measurements and calculations being performed in octave bands. For sources that are small and movable, the test may be undertaken in a hard-walled room meeting specified requirements. Non-movable sources may be tested in situ, provided that the environment can be qualified for the purpose.

The reproducibility of the results depends on the directional characteristics of the source under test and on the test environment, and is evaluated with reference to certain indicators. The conditions are specified under which A-weighted sound power levels can be determined with standard deviations of reproducibility equal to or less than 1,5 dB, corresponding with grade 2 accuracy according to ISO 12001. Conditions are also defined under which A-weighted sound power levels can be determined with standard deviations of reproducibility extending up to 3 dB, corresponding with grade 3 accuracy. The evaluation of measurement uncertainties from data on standard deviations of reproducibility, for purposes of noise declaration and verification, is described in ISO 4871 and ISO 7574-1 to ISO 7574-4.

1.2 The methods specified in this International Standard are most suitable for steady, broad-band noise, as defined in ISO 12001. They can be applied where the noise is narrow-band or contains discrete tones, though the reproducibility is then poorer, but this International Standard

may not be used where the noise is intermittent or impulsive, as defined in ISO 12001

Where the noise source under test is movable and the test can be performed in a suitable hard-walled room, the maximum size of the source depends on the size of the room (see clause 4). Where the noise source has to be tested in situ, the methods of this International Standard may be applied to sources of any size, provided that the enclosure where they are located gives rise to a sound field which is sufficiently reverberant.

1.3 The test environments that are applicable for measurements made in accordance with this International Standard are a suitable hard-walled room, or any other kind of environment where the background noise level is sufficiently low and the sound field is approximately reverberant.