Acoustic parameters and uncertainties associated with determining sound power level in hemi-anechoic rooms

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ABSTRACT

Where it is necessary to accurately quantify the sound power output of a noise source, it is common in practice to use hemi-anechoic rooms. In such specialist facilities the acoustical performance is carefully designed around the assumption that no sound power is absorbed or transmitted through the floor, that the effects of ground reflection are neglected where the source is placed on the floor, and that hemispherical sound propagation is uninhibited, such that environmental effects due to the room can largely be ignored. However, prior to accepting that such effects are negligible, the acoustical performance of such facilities must be tested for compliance with the design following construction or prior to making measurements on particular machines. Commonly, reference will be made to the international standard ISO 3745. This describes methods for the assessment of room performance stipulating qualification criteria and specifying precision methods for determining sound power levels. The standard does not however provide information on how measurement uncertainty associated with sound power level determination is related to the room performance criteria. This being the case, users of the standards will not know to what degree their test facility will affect the measured sound power result. The practical implications of having this information are important, where uncertainty values are used in practice, to derive the final guaranteed sound power level, which is used as an absolute indicator on noise labels affixed to the machine.

The research described in this report is designed as a contribution to current efforts aimed at improving existing sound power standards. NPL have conducted an extensive series of measurements, examining the effect of varying the performance of a hemi-anechoic room on sound power determinations for a range of noise sources. A series of conclusions have been drawn and it is proposed that the output of the work be used as part of the improved treatment of measurement uncertainty in the ISO 3740 series of standards.

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Approved on behalf of the Managing Director, NPL
by Dr B Zeqiri, authorised by Director, Quality of Life Division

CONTENTS

1 INTRODUCTION

This report initially provides some brief background on the facilities required for the measurement of noise emission from machinery and goes on to present the rationale for the research which investigated the correlation between the acoustic performance of a test facility and the associated uncertainty in sound power determination. Section 2 provides a brief outline of the methodology employed for the investigation. More detailed information on the experimental procedure is given in section 3. The results from an extensive series of measurements are presented and analysed in section 4. Section 5 sets out the project conclusions and recommendations are given in section 6.

1.1 FACILITIES FOR NOISE TESTING

Where it is necessary to accurately quantify the sound power output of a noise source, it will generally be necessary to use specialist facilities where the acoustical environment is controlled. In determining machinery noise emission levels, it is common that measurements are made in a hemi-anechoic environment where the ground plane is acoustically reflective and all other propagation directions are acoustically absorptive. Where sound pressure level measurements are made at several positions on an enveloping surface of radius r, and assuming that no sound power is absorbed or transmitted through the ground and the effects of ground reflection are neglected, then the sound power level, L_W can be expressed as:

$$L_w = \overline{L_p} + 10\log_{10} 2\pi r^2 \quad (1)$$

where;

$$\overline{L_p} = 10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} 10^{0.L_{pi}}\right) \quad (2)$$

where;

$\overline{L_p}$ = Mean (energy average) of the time-averaged sound pressure levels at all the microphone positions on the measurement surface

L_{pi} = the time-averaged sound pressure level at the *i*th microphone position on the measurement surface from the noise source under test

n = the number of microphone positions

To facilitate acoustically and environmentally controlled conditions in practice, carefully designed hemi-anechoic chambers are employed, where the floor is hard and flat (generally concrete with smooth screed finish) and the wall and ceiling boundaries are constructed from porous foam wedges, which are highly effective at absorbing acoustic energy. Well established methods for assessing the acoustical performance of such facilities are provided in international specification standards, particularly ISO 3745:2003(1) part of the ISO 3740 series(1-7) of sound power standards.

1.2 RATIONALE FOR INVESTIGATION

The ISO 3740 series, comprising seven standards primarily sets out methods for measuring the sound power of machines and equipment by determining the sound pressure level over a measurement surface enveloping the source, within different environments. This series of standards is currently under short-term revision, with research to assist in the development, being coordinated by the ISO Working Group 28 (ISO/TC43/SC1/WG28). There are also proposals for longer-term revision, including reduction of the series from eight to four standards, with the aim being to simplify what is considered at present an excessively complicated and inflexible range of standards.

High on the agenda in respect to short term revision is the proposed introduction of full uncertainty budgets consistent with the ISO "Guide to the expression of uncertainty in measurement"(8). A considerable international research effort leading up to the production of draft standards has been focused on evaluating recognised errors and known uncertainties associated with test methods described in the ISO 3740 series.

In ISO 3745:2003, eight categories of uncertainty have been identified that could potentially effect the result of a sound power measurement. It is proposed, at this stage that the general expression for the calculation of the sound power level, L_W, be given by the following equation:

$$L_W = \overline{L_p} + 10\lg\left(\frac{S}{S_0}\right) + C_1 + C_2 + \delta_{slm} + \delta_{rep} + \delta_{boun} + \delta_{mic} + \delta_{met} + \delta_{angle} + \delta_{imp} + \delta_A \quad \text{dB} \qquad (3)$$

where,

$\overline{L_p}$	is the surface sound pressure level,
S	is the area of the measurement surface, in square metres,
S_0	= 1 m^2,
δ_{slm}	is an input quantity to allow for any error in the measuring instrumentation,
δ_{rep}	is an input quantity to allow for any error in the operating conditions of the noise source under test,
δ_{boun}	is an input quantity to allow for any error in the influence of the test room boundaries,
δ_{mic}	is an input quantity to allow for any error in the finite number of microphone positions,
δ_{met}	is an input quantity to allow for any error in the meteorological conditions,
δ_{angle}	is an input quantity to allow for any difference of angle between the direction in which the sound is emitted by the source and the normal to the measurement surface,
δ_{imp}	is an input quantity to allow for any error in the impedance of the surroundings into which the source is emitting sound energy,
δ_A	is an input quantity to allow for any error in the determination of the A-weighted sound power level from frequency bands.
C1, C2	are constants that are dependent on atmospheric pressure and temperature

All of the uncertainties listed above, have been identified by users and experts of the ISO Working Group as being important factors to consider when making a sound power determination. It is acknowledged by the Working Group that there may be others and that there may be interdependencies between each of the components.

The influence of the test room boundaries on the determination of sound power level is accounted for in Equation 3 by the parameter δ_{boun}. Currently ISO 3745:2003 and it's predecessor ISO 3745:1977[9] describe methods for the assessment of room performance and give criteria for anechoic and hemi-anechoic rooms. The standard does not, however, provide information on how measurement uncertainty associated with sound power level determination is related to these criteria. This being the case, users of the standards will not know to what degree their test facility will affect the measured sound power result. In any measurement it is useful to know what the causes of uncertainty are, and which components of uncertainty are dominant. The practical implications of having this information are important.

Firstly, uncertainty values are used in practice, where they are added to the sound power level determined from measurements to derive the final guaranteed (or declared) sound power level, which is used as an absolute indicator on noise labels affixed to the machine. Secondly, the user can, if the information is available, prioritise the various uncertainty contributions, and target particular components to improve the overall accuracy of the measurement result. From a practical perspective, if information on how a room affects the uncertainty of sound power determination was available, industry could tailor the room to their needs. A manufacturer of machinery may be willing to accept a slightly higher degree of uncertainty if it meant that he did not have to construct a specialised test facility. Conversely, the availability of such information may encourage a business to invest in developing an improved facility to enhance the accuracy of their measured sound power level, which they must declare for regulatory purposes.

The implication of having no evidential correlation is that the level of stringency, set down in the specification requirements of ISO 3745[5, 9] may not be based on practical considerations. Overly stringent requirements in the performance of a hemi-anechoic room could lead to an overly engineered test facility resulting in unnecessary construction costs. As part of the process of improving the commonly used ISO 3740 series of sound power standards, there was clearly a need to address the issue of behalf of UK industry using hemi-anechoic rooms to conduct sound power determinations and it was considered important that data should be obtained on actual measurement uncertainty for particular rooms.

The research described in this report is designed as a contribution to current efforts aimed at an improvement of current sound power standards. NPL have conducted an extensive series of measurements, examining the effect on sound power determinations of varying the performance of a hemi-anechoic room for a range of sources. The acoustic characteristics of the room were determined in accordance with the qualification requirements given in ISO 3745, which essentially involved sound pressure level measurements along traverses from the centre of a specially constructed cavity sound source to room boundary. It is proposed that the output of the work conducted be used as part of the improved treatment of measurement uncertainty in the ISO 3740 series. It is also considered that the research may provide a useful contribution to future development of a dedicated standardised procedure for characterising free field test facilities.

2 OUTLINE OF METHODOLOGY

The main purpose of the study was to examine the relationship between uncertainty in the determination of a sound power level and the acoustical performance of the environment in which it is made.

In order to assess this relationship it was necessary to conduct sound power determinations in a variety of acoustical environments. This could be achieved by performing measurements in different rooms and outdoor sites. However, this approach was unfeasible because of cost, timescale and condition controllability considerations.

An alternative approach was taken, employing the use of variable room acoustics produced by modifying a hemi-anechoic chamber at NPL. Annex A gives details of the initial room specification.

2.1 GENERATION OF VARIABLE ACOUSTIC ENVIRONMENT

The aim was to generate a range of acoustic conditions effectively simulating independent rooms with different acoustic signatures. Absorbent wedges were removed from the walls and ceiling of the room, so as to ‘degrade’ the acoustic performance up to and beyond the point where the room qualified as a being hemi-anechoic. The wedges were detached from the hard chamber wall making the space more acoustically reflective. Section 4.1 describes the schedule of removal and provides an indication of the resultant changes in surface absorption at each stage of room degradation. The results of room response measurements are provided in section 4.2.

2.2 CHARACTERISATION OF ROOM PERFORMANCE

The acoustic performance of each room state has been characterised using three methods, which are outlined below.

2.2.1 Inverse square sound decay rate

It is common to assess the sound decay rate as a measure of the acoustic response or signature of the room. The principle of this test is based on the assumption that for spherical propagation from a point source, the sound intensity is inversely proportional to the square of the distance between source and receiver. In practice, any measured deviation from the predicted sound level would be due to the effect of additional reflections from the environment and to some extent, on problems associated with a practical sound source. The latter problem is considered to be negligible where the source used was carefully designed to generate a sound pressure level sufficiently stable as a function of time.

The method for conducting the inverse square law test as part of the procedure for qualifying anechoic and hemi-anechoic rooms has for over 20 years been given by ISO 3745:1977. This standard was, however, under revision during the course of the research, which included changes to the room qualification method (the revision has now been published). Although the revision project was led by the Japanese experts on WG28, NPL was involved in the revision process and has had access therefore to amendments being introduced. Reference has been made to both methods for the investigation.

The revised methods set out in ISO 3745:2003 requires a linear regression calculation using the measured data, which effectively places a best-fit line through sound pressure levels measured along specified traverses originating from the source. Tolerances are set on the deviations of the measured sound pressure levels from predicted levels. These procedures are described in more detail in sub-section 3.3.1.

2.2.2 Environmental correction factor (K_2)

As the room was progressively changed measurements were conducted to enable assessment of the environmental correction factor (K_2). Expressed in decibels, this is a frequency dependent correction term applied to the mean (energy-average) of the time-averaged sound pressure levels at all the microphone positions on the measurement surface, to account for the influence of reflected or absorbed sound. ISO 3744[5] describes a number of methods for determining K_2. The method used to determine K_2 for this study is described in sub-section 3.3.4.

2.2.3 Reverberation time

The use of reverberation time measurements to assess room performance was examined although it is not strictly applicable to highly absorbent environments. More detail on the measurements is given sub-section 3.3.5.

2.3 SOUND POWER LEVEL MEASUREMENT

Measurements were conducted to determine sound power levels of selected noise sources, which are described in sub-section 3.1, under a spread of different room conditions.

The procedure adopted was based on the use of a hemispherical enveloping measurement surface over a reflecting plane, as described in ISO 3744. The microphone array coordinates used were the 10 key microphone positions specified in the normative annexes of ISO 3744. Determination of multiple sound power levels were made by incremental rotation of the array relative to the source. The analysis approach is discussed in more detail in sub-section 3.4. Potential uncertainty in the determination of K_2 has also been closely observed.

2.4 MACHINE LIMITATIONS

It must be noted that only three noise sources were used in the study. However, the sources were chosen to cover a range of directivity indexes. Measurements carried out using the RSS as a noise source are used to determine the environmental correction factor, K_2. It is accepted that the relationship between room performance and measurement uncertainty may be dependent on the frequency spectrum of the noise source in which case the results of this study, while providing a good indication of the probable relationship, may be limited in application and may indicate the need for a more comprehensive study in the future.

3 EXPERIMENTAL PROCEDURE

This section describes in more detail, the noise sources used in the investigation, the experimental procedure employed to characterise the acoustical performance of the room as the surface absorption properties were degraded, and the adapted method for determining the sound power uncertainties for a range of source types.

3.1 NOISE SOURCES

The investigation employs the use of four different noise emission sources.

- Cavity point source
- Reference Sound Source (RSS)
- Electric Drill
- Simulated machine (RSS in box)

3.1.1 Cavity point source

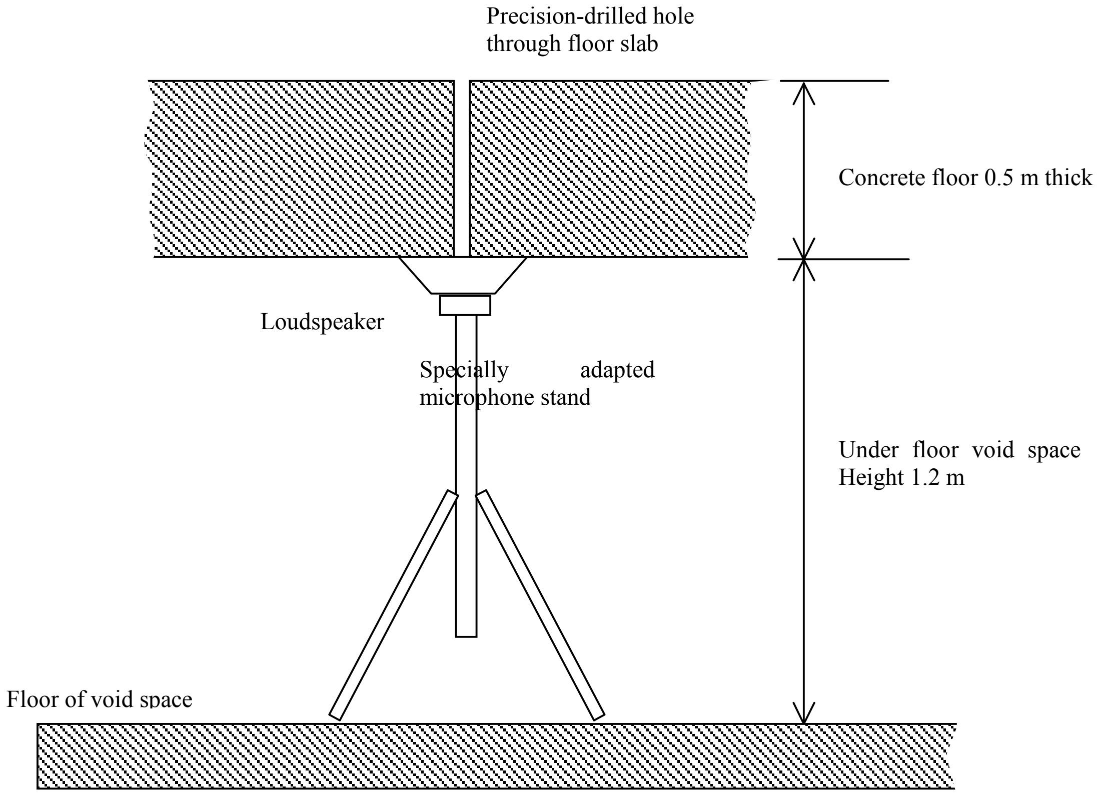
The general procedure for qualification of free-field and hemi-free field rooms as set out in ISO 3745:2003 states that a sound source approximating a point source over the frequency range of interest shall be used for the qualification test. Performance requirements are provided but the standard states that it is the responsibility of the laboratory to design or select the sound source. Ideally it is preferable to install a source whose radiating surface is in the plane of the floor. NPL developed a special “cavity point source” to achieve this objective.

The process of developing the cavity point source involved the selection of a suitable loudspeaker device and the subsequent installation and testing. It was acknowledged that the test source had to offer suitable omni-directionality, signal level and that ground reflection interference effects be avoided. To eliminate interference effects it was necessary to locate the acoustic centre of the source, flush with the ground plane. A number of alternative sound sources were considered for use in the room qualification measurements, including:

- Calibrated Reference Sound Source
- Electrical sound source B&K 4205
- Ball hydrophone
- Horn driver with tubing (plastic and brass)
- Small inverted / enclosed Loudspeaker

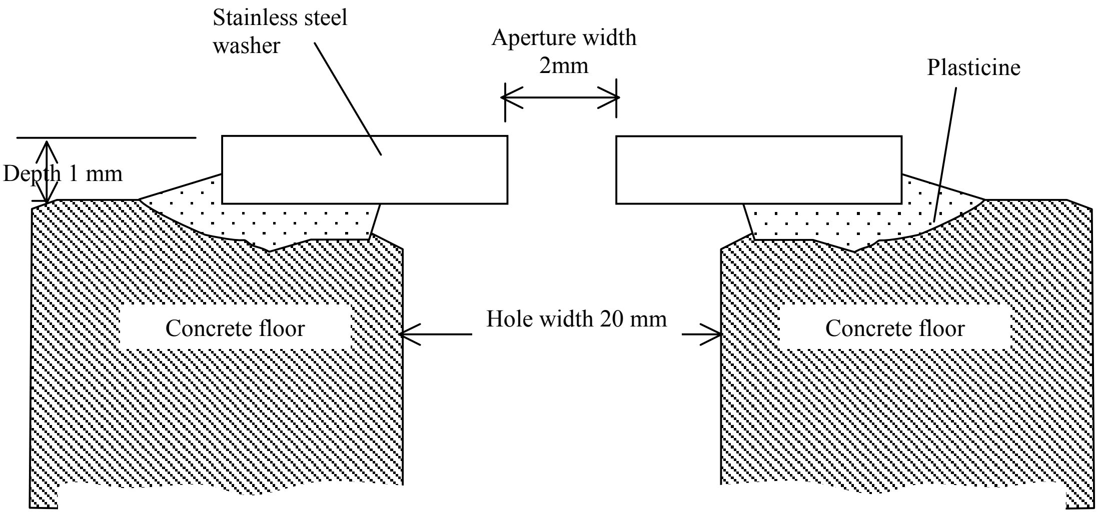
After careful consideration of the practicalities, and differences in directivity and signal performance, it was deemed optimal to develop a special cavity source using a small inverted loudspeaker attached to the underside of the hemi-anechoic room floor driving an acoustic signal through a precision drilled hole in the floor, emitting from a small point aperture at the floor plane, as illustrated in Figure 1. The loudspeaker was coupled to the underside of the concrete floor with a single layer of draft-excluding material making a seal.

Figure 1. Cavity source configuration



The cavity was constructed by carefully drilling through the 0.5 m thick floor of the hemi-anechoic room through to a void space below. The source was designed such that the point of emission was flush with the floor surface and that the aperture diameter was small (~2mm) compared to the smallest signal wavelength. The aperture was engineered from stainless steel and fixed rigidly as shown in Figure 2.

Figure 2. Cavity source aperture



To enable comprehensive testing of the acoustical performance of the room, the cavity source was configured to produce both tonal signal and noise signals. A bespoke computer program was written to control the amplitude and frequency settings on a function generator to produce pure tone signals. Broadband 'white' noise was generated from a looped audio file playing back from the control PC sound card.

The dimensions and geometry of the cylindrical hole bored through the floor means that the hole is inefficient at radiating sound produced by the loudspeaker, and it was found that the system acted as a resonator, and so corrections were applied to the spectral content of the signal. The amplitude at each frequency for pure tone signals was set by measuring the signal level in the hemi-anechoic room prior to degradation, with microphones positioned at four heights on a hemispherical measurement surface of radius 1.5 m. The measured sound pressure levels were averaged in order to reduce cancellation effects from the ground plane.

The levels were set so that the reference level was achieved at all the frequencies of interest. One reference sound pressure level was chosen for tones and another for broad-band noise. It is a requirement of ISO 3745 for the acoustical signal to be at least 10 dB above ambient acoustical background level. For pure tones a reference level of 50 dB was chosen. The SPL was set at each frequency by adjusting the signal voltage at the function generator. The power amplifier gain was fixed prior to start of measurements. For broadband noise there would have to be less energy in each frequency band to produce the same total energy, so a level of 40 dB was chosen. The broadband noise was created in software as white noise and then filtered through a one-third octave-band software graphic equalizer to achieve the required spectral flatness.

Prior to using the source for the investigation, it was necessary that the test source was uniform to within the allowable deviations specified in ISO 3745. The results of directivity tests conducted in accordance with the method set down in ISO 3745 are shown in Annex B. The results are shown for both pure tones and broadband noise generated through the cavity point source as well as the RSS. The test results indicated that the source directivity was poor at low frequency. However, it is considered more likely that the higher values observed at low frequency were due to limitations of the measurement method and the reduced hemi-anechoic room performance at low frequencies. It was found that the RSS failed to meet the required directivity criteria for frequencies below 1 kHz with the exception of 250 Hz.

3.1.2 Reference Sound Source (RSS)

A Bruel and Kjaer Reference Sound Source (RSS), Type 4204 was used for the determination of the environmental correction K_2 as part of the room characterisation measurements. The RSS was also considered as a noise source for the purpose of the investigation into a potential correlation between room performance and measurement uncertainty. The surface averaged L_{eq} and maximum Directivity Index for the RSS in hemi-anechoic conditions are shown in Figures 4 and 5 in the summary sub-section 3.1.5.

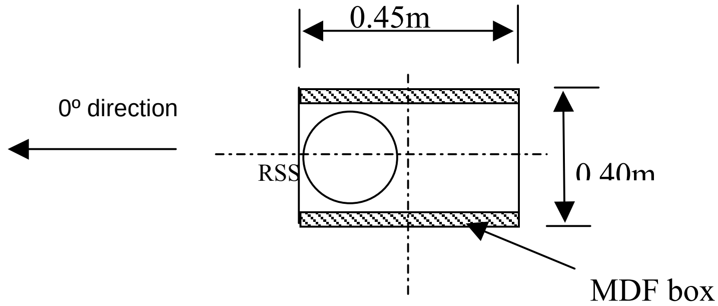
3.1.3 Electric Drill (Drill)

The drill used was a 550W mains powered electric drill. It was securely attached to its drill stand which had a wooden base plate of dimension 300mm x 250mm x 20mm. The drill was operated in the non-hammer mode with the speed trigger secured fully at maximum rpm. The surfaced averaged L_{eq} and max D.I. for the drill in hemi-anechoic conditions are shown in Figures 4 and 5 in the summary sub-section 3.1.5. The max D.I. for lower frequencies are not displayed because of the lack of acoustic energy in those frequency bands.

3.1.4 Simulated noise source (Box)

A modified RSS was used to simulate a noise source with directional and tonal characteristics. The RSS was mounted in a 0.4 m square section box, 0.45 m in length constructed from 0.02 m thick Medium Density Fibreboard (MDF), with both ends left open. Figure 3 shows schematically, the design for the simulated noise source. The surface averaged L_{eq} and max D.I. for the simulated machine in hemi-anechoic conditions are shown in the summary sub-section 3.1.5.

Figure 3. Plan view of section of 'box' source



3.1.5 Summary of source acoustic characteristics

The acoustic characteristics of the selected noise sources have been considered in terms of spectral content over frequency range 100 Hz to 10,000 Hz, and maximum directivity index (D.I.), where D.I. in one-third octave-bands, is defined by:

$$\text{D.I.} = L_{pi} - \overline{L_p} \qquad (4)$$

where:

L_{pi} is the measured one-third octave-band SPL at microphone position *i*.

$\overline{L_p}$ is the surface average sound pressure level

Figure 4 indicates the relative frequency characteristics of each of the selected noise sources in terms of the $\overline{L_p}$ measured over a 1.5m radius hemisphere. It can be seen that the spectral distribution of the simulated noise source comprising a RSS in a box and the RSS exhibit relatively similar spectral characteristics, while the drill differs, and has negligible low frequency energy.

Figure 5 shows the D.I. for each of the selected noise sources. It can be seen that there is variation between one-third octave bands but as a general indication of the directivity of each source, average values of approximately 2 dB, 3 dB, and 4 dB may be taken for the RSS, drill and box respectively.

The simulated box source exhibits the greatest directivity response with values of around 6dB at 500 Hz and 1250 Hz. Results for the drill are valid only above 250 Hz, as levels measured below this frequency were too low to derive reliable directivity data.

Figure 4. Frequency spectra of selected machines determined under hemi-anechoic conditions

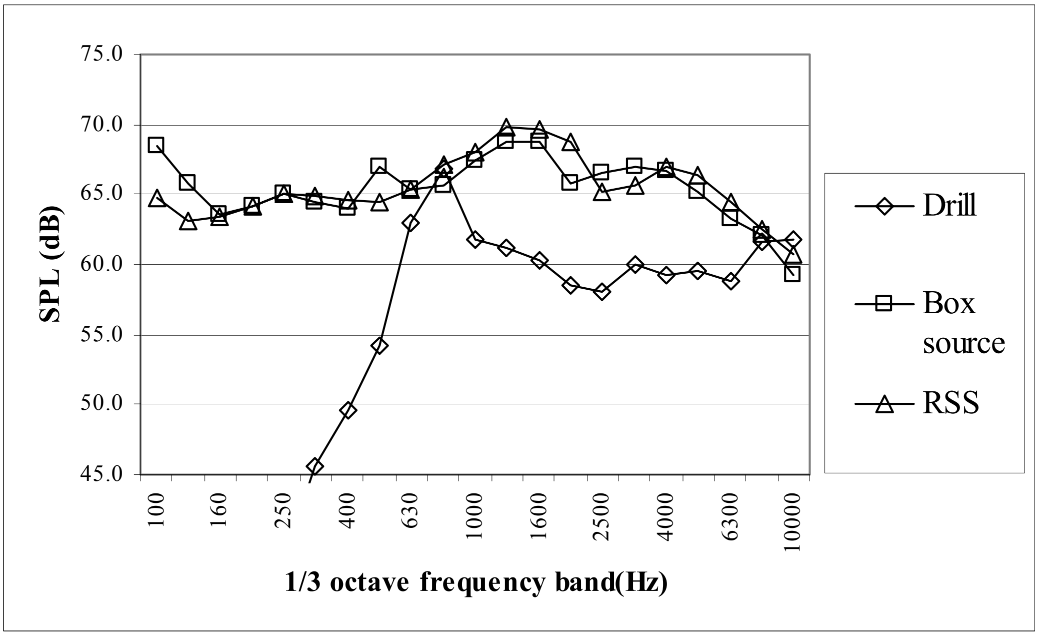
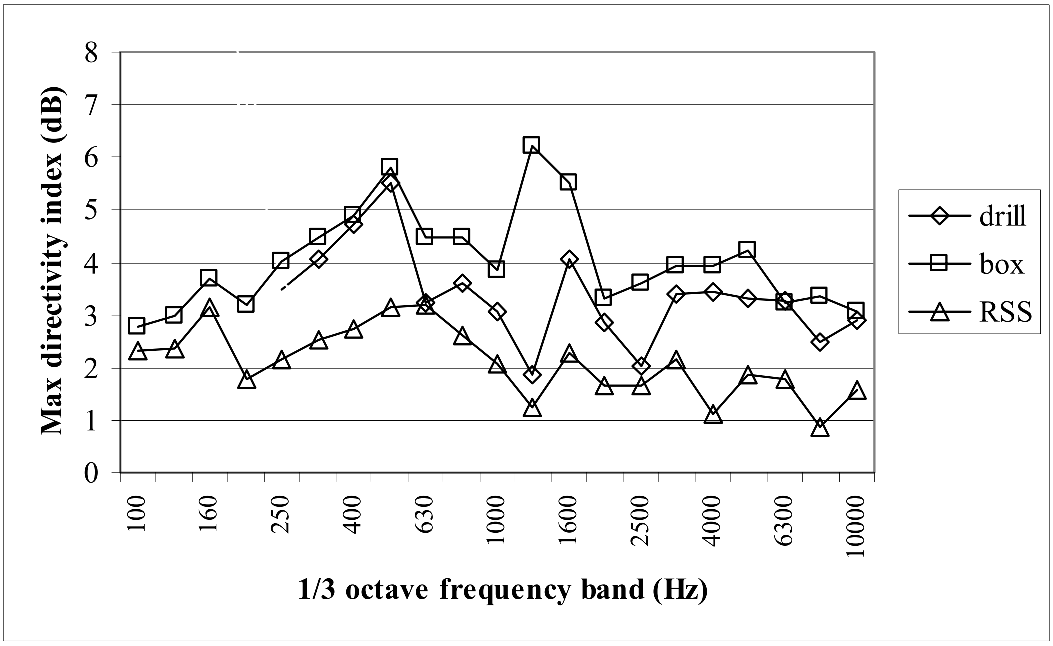


Figure 5. Directivity characteristics of selected noise sources



3.2 MEASUREMENT APPARATUS

Despite the limited number of sources, the experimental programme required a vast number of acoustic measurements resulting in a large amount of data. It was therefore necessary to acquire data efficiently, and that compiled data were well managed to enable proficient analysis.

To achieve these objectives, the following two distinct actions were taken.

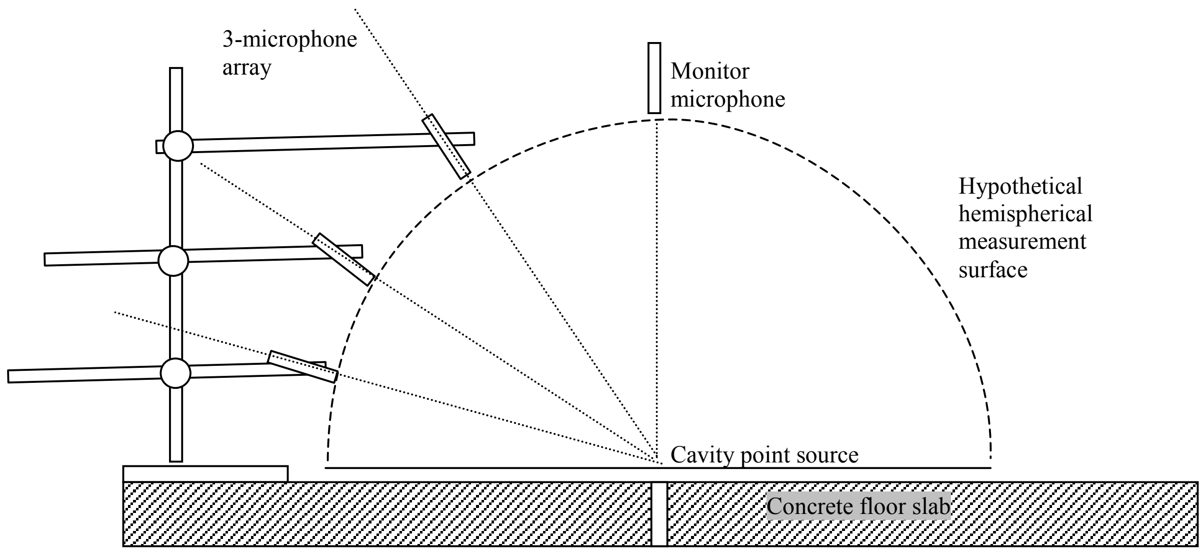
1. Set up apparatus to enable simultaneous measurement of sound pressure levels of noise sources at multiple positions.

2. Implementation of measurement automation, and storage of results in well-structured databases.

3.2.1 Microphone array

Sound pressure measurements were made using an array of three microphones, and a fourth microphone suspended from the ceiling, as illustrated in Figure 6. The arrayed microphones were mounted on a specially adapted stand. These microphones were all located on a segment of a vertical arc of the hemispherical measurement surface, i.e. they all are located 1.5m from the cavity source. An array of a larger number of microphones was considered, but would have required a more cumbersome positioning system, such that it may have influenced sound propagation.

Figure 6. Microphone array set-up.



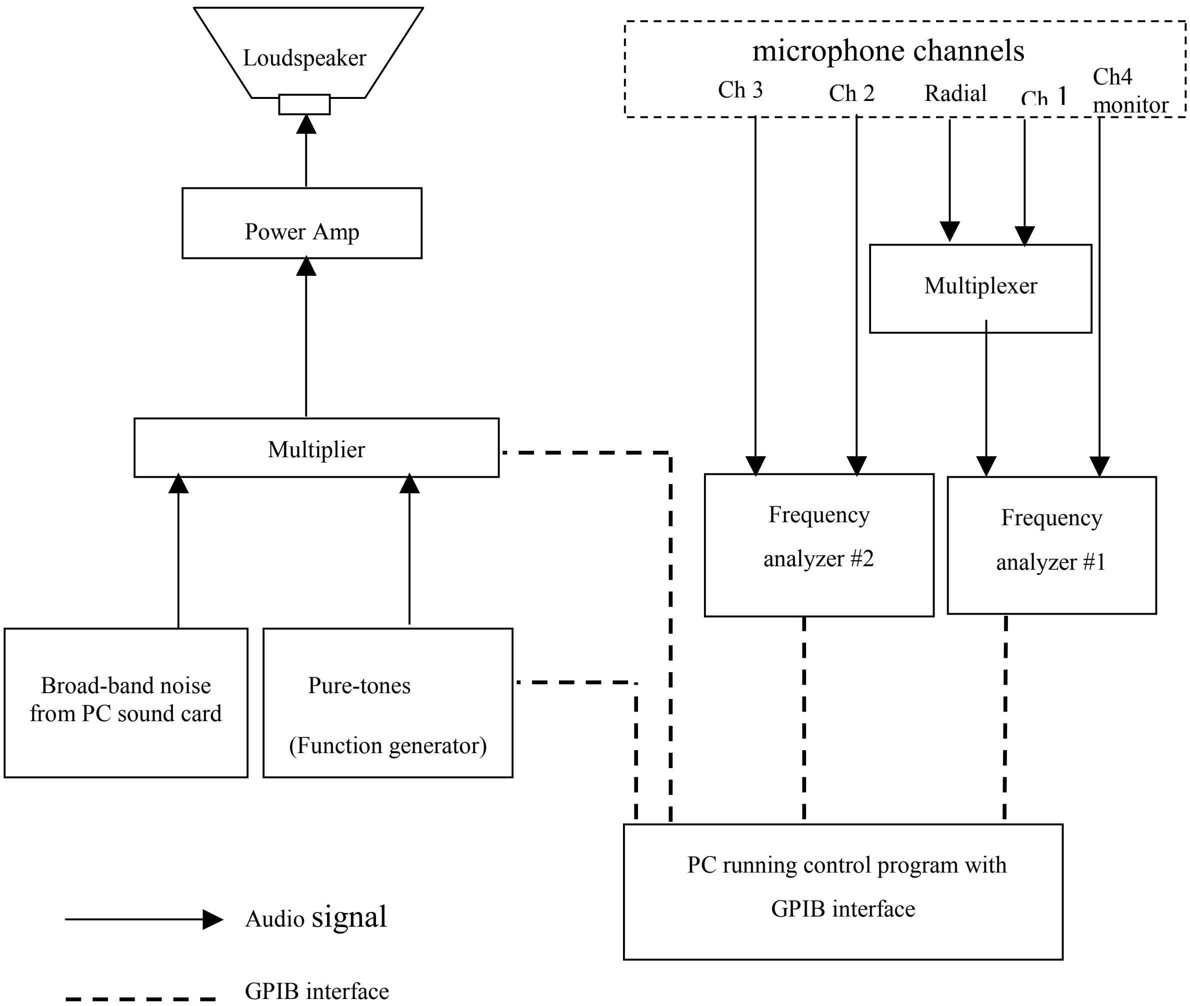
The suspended fourth microphone had two purposes. Firstly, it provided the overhead microphone position for the sound power determinations i.e. position numbers 10, 20, 30 and 40 of the ISO 3745 array. Secondly it provided a fixed reference or monitor position throughout the duration of the project. The sound pressure level was measured at this monitor position during every radial measurement position for the inverse square test, as well as every time the array position levels were measured for a sound power level determination. This provided a check of source stability between the start and end time of measurements for each state of room degradation.

The overall measurement time was dramatically reduced where measurements were made simultaneously using the three-microphone array, and the monitor microphone.

3.2.2 Measurement & analysis system

As it was necessary to obtain a large amount of data for the project, it was important that the collected data was efficiently managed and analysed quickly. A high degree of measurement automation was introduced. A control program was developed to control and manage the measurement procedures for all the measurements. Figure 7 shows the measurement system developed to handle the measurements for the project.

Figure 7. Schematic diagram of measurement system



The digital frequency analysers employed to analyse the microphone signals were controlled using the 'GPIB' IEEE interface. A control program was developed to control and manage the measurement procedures for all the measurements (except reverberation time). The system, written on a PC running Windows Operating System, employed Visual Basic (VB6), with additional National Instruments 'Measurement Studio' and Microsoft 'Dataobjects' software components. The control program also controlled the function generator that produced some of the signals for the cavity source. A multiplexer was also remotely controlled so that the amplifier input could be switched between the function generator and the PC soundCard source.

The measurement type, configuration, parameters and measurement results were stored in a database created specially for the project.

A separate application was used to analyse the data. This application, called 'Dataview' was designed for the project although it does have wider use for storing, managing and analysing acoustical noise levels acquired at discrete points. The application (also developed using VB6) enabled interrogation of the database, reporting the analysis in graphical format, as well as enabling export to a spreadsheet. The instruments used in this system complied the type 1 specifications according to IEC 60651:1994[(10)] and IEC 60804:1994[(11)].

3.3 ROOM ACOUSTIC MEASUREMENTS

The acoustical performance of the hemi-anechoic room was degraded in stages, by removal of absorbent wedges from the walls and ceiling of the room. At each stage measurements were performed to characterise the acoustical response of the room.

The method employed to characterise the room response primarily involved measurements to enable correlation with the inverse square law, a well-established method for quantifying the acoustical performance of anechoic and hemi-anechoic rooms. The procedure for such measurements is set out in ISO 3745:1977. This standard had been under revision during the course of this research programme and a revised document has now been published. NPL has been directly involved in the revision process and has had access therefore to amendments being introduced. A brief description of the old method is described below in sub-section 3.3.1, and the changes applied to provide the new document are discussed in sub-section 3.3.2. The room qualification measurements made for this project have primarily been made with reference to the new method in ISO 3745:2003, although the deviations from the inverse square law have been calculated using procedures for both versions so that the difference between them can be assessed.

3.3.1 Inverse Square Law Test

The methods specified by both ISO 3745:1977 and ISO 3745:2003 have been referred to for this investigation. Table 1 provides a summary of the general procedures.

Table 1. Summary of the Inverse square law test according to ISO 3745:1977 and ISO 3745:2003

ISO 3745:1977	ISO 3745:2003
The test source should radiate sound omni-directionally with a deviation of less than ± 1 dB, and should be placed in the centre of the room immediately above the plane of the reflecting plane. (No test measurement procedure to obtain directionality is specified). Microphone traverses should be made for at least eight straight paths away from the centre of the test source, and include paths to the (upper) corners. The test source should produce discrete frequencies over the entire range of interest using octave bands between 125 Hz and 4k Hz and Third octaves outside this range. If the machine under test radiates only broadband noise the procedure may be carried out for one-third octave-band and noise or octave-band noise instead of discrete frequencies. The microphone should be moved continuously along the paths for each frequency and the measured sound level compared with the level predicted by the inverse square law. (No prediction method is specified)	The test source directivity should be measured and meet the requirements specified in ISO3745:2003. The test source should be situated as close as possible to, but in any case should not be greater than 150 mm from, the reflecting floor. The microphone traverses shall be made along at least five straight paths away from the acoustic centre of the test sound source in different directions. These will include the (upper) corners. The measurement of sound pressure level shall be carried out starting 0,5 m from the acoustic centre of the sound source and ending at or beyond the measurement surface. Sound pressure levels shall be measured along each microphone traverse using equally spaced measurement points. The measurement surface must enclose at least ten measurement points along each of the five microphone traverses (a total of at least 50 points). In addition, the spacing between measurement points shall not exceed 0,1 m. Alternatively, the microphone shall be moved slowly and continuously along the traverse and the sound pressure levels recorded. Except for the requirements of pure tone qualification procedures, the test source should produce random noise. Analysis shall be made in one-third octave bands in sequential steps that cover the entire frequency range over which the room is being qualified. Below 125 Hz and above 4000 Hz, the sequential steps shall correspond to the midband frequencies of contiguous one-third-octave bands, and between 125 Hz and 4 000 Hz, the steps shall correspond to the midband frequencies of octave bands (i.e., between 125 Hz dB and 4 000 Hz, not all one-third octave bands need be used). Sound pressure levels based on the inverse square law shall be determined for each direction of measurement from the following equation: $L_p(r) = 20 \lg \left[\frac{a}{r - r_0} \right]$ dB (5) *where* $a = \frac{\left(\sum_{i=1}^{N} r_i \right)^2 - N \sum_{i=1}^{N} r_i^2}{\sum_{i=1}^{N} r_i \sum_{i=1}^{N} q_i - N \sum_{i=1}^{N} r_i q_i}$ r_0 is the collinear offset of the acoustic centre along the axis of the microphone traverse. It is a measurement of the separation between the acoustic centre of the source and the centre of the measurement sphere or hemisphere. It is given by the following equation $r_0 = -\left[\frac{\sum_{i=1}^{N} r_i \sum_{i=1}^{N} q_i - \sum_{i=1}^{N} r_i^2 \sum_{i=1}^{N} q_i}{\sum_{i=1}^{N} r_i \sum_{i=1}^{N} q_i - N \sum_{i=1}^{N} r_i q_i} \right]$ q_i $= 10^{-0,05 L_{pi}}$ L_{pi} is the sound pressure level at the *i*th measurement position (dB); r_i is the distance of the *i*th measurement position from the centre of the measurement sphere or hemisphere; N is the number of measurement positions along each microphone traverse. Using the estimation of sound pressure levels based on the inverse square law, deviations of the sound pressure levels at all measurement positions from the inverse square law are determined by the following equation: $\Delta L_{pi} = L_{pi} - L_p(r_i)$ dB (6) *where* L_{pi} is the deviation from the inverse square law (dB); L_{pi} is the sound pressure level at the *i*th measurement position (dB); $L_p(r_i)$ is the sound pressure level at distance r_i estimated by the inverse square law (dB). The standard notes that other methods may be used to estimate the sound pressure level on the basis of the inverse square law provided they allow calculation of *Lp*(*r*) as in Equation (5).

The deviations of measured sound pressure levels from those estimated using the inverse square law, in both the case of ISO 3745:1977 and ISO 3745:2003 are as given in Table 2.

Table 2 ISO 3745 inverse square test tolerance limits

Frequency range (Hz)	Allowable deviations
<= 630	2.5
800 to 5000	2.0
>= 6300	3.0

3.3.2 Summary of changes to ISO 3745 qualification procedures

The data analysis procedures according to ISO 3745:1977 and ISO 3745:2003 are quite different, even though the criteria defining the maximum allowable deviations from the inverse square law remain relatively unchanged.

The ISO 3745:2003 calculation procedures are more elaborate than those in the ISO 3745:1977 version. Prior to assessing measured inverse square data against the allowable deviation criteria, the results obtained by determining sound pressure level decrease along a traverse must now be referenced back to the acoustic centre of the test source, by applying a linear regression equation. It is now a requirement to define r_0, the ‘collinear offset of the acoustic centre’. Previously, ISO 3745:1977 assumed the acoustic centre to be at the centre of the ground plane enveloped by the measurement surface. This assumption simplifies the calculation of the ‘best-fit’ line since the gradient of the line should always be 6dB for each doubling of measurement distance.

3.3.3 Inverse Square Test procedures adopted for study

The measurement procedures set out in ISO 3745:2003 were followed for the purposes of the investigation.

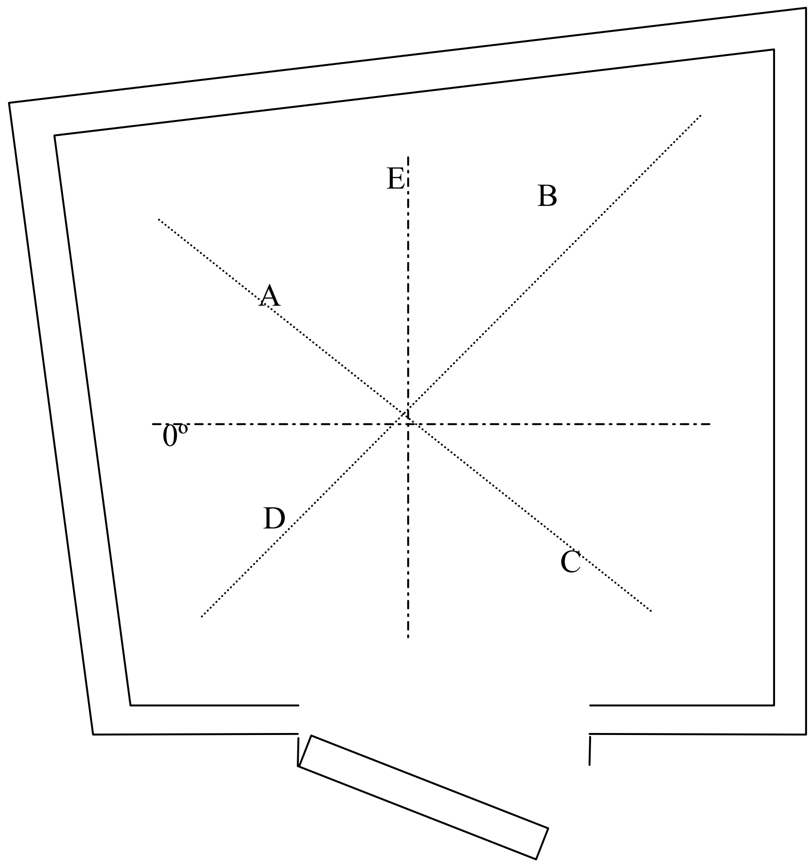
To strictly comply with the requirement that the test source should be situated as close as possible to the reflecting floor, such that the radiating surface is in the plane of the floor, a ‘cavity point source’ was developed. Details of the design and functionality are provided in sub-section 3.1.1. The cavity source was configured to produce tones and broadband noise. The sequentially emitted tones had the following frequencies:125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, 8 kHz and 10 kHz. Alternatively the cavity source emitted a near flat spectrum of broadband noise.

Additionally, for comparison purposes, a limited number of measurements were made using the RSS placed directly over the cavity.

Measurements of sound pressure level were made at discrete points along the radial lines. The measurement distance was between 1m and 3m at 0.2m intervals. Initially all five radial paths, as indicated in Figure 8 were measured. Four of the lines were oriented towards the upper corners of the room, represented by lines A, B, C and D. The fifth line was chosen arbitrarily in direction E, at 90º. The angle of inclination for all five lines was set to 45º in order to simplify the measurements. No specific guidance is given traverse orientation in the standards.

The procedures to determine the characteristics of a hemi-anechoic room in accordance with ISO 3745 requires extensive measurements, which demands significant measurement effort and time. It was not possible, due primarily to economic constraints on the project, to conduct the full qualification procedure for each iteration. As a compromise, a single radial traverse measurement was used on a number of occasions to quantify the relative change in room response. Analysis has been conducted to assess the use of reduced measurement data, and is detailed in sub-section 5.1.

Figure 8. Plan view of hemi-anechoic room showing directions for the radial lines



3.3.4 Assessment of the Environmental Correction (K_2)

The difference between the sound power level determined for the RSS in-situ in each of the degraded room states and the sound power level of the RSS determined in true hemi-anechoic conditions provides the values of environmental correction K_2.

The correction, in frequency bands or A-weighted is given by:

$$K_2 = L^*_W - L_{Wr} \tag{7}$$

where

L_{Wr} is the sound power level of the RSS under hemi-anechoic conditions

L^*_W is the uncorrected sound power level of the RSS in-situ, measured over the same surface.

Having established K_2, for each room configuration, corrections may be applied to the determined machine sound power level to account for the difference in acoustical environment from hemi-anechoic conditions. These data are discussed in sub-section 4.4.2.

3.3.5 Reverberation time measurement

It is generally the case that reverberation time (RT) measurements are avoided for characterising room response in hemi-anechoic facilities due to the inherent lack of reverberant energy and resulting short RT. However, as the room was to undergo changes from hemi-free-field conditions to a room with semi-reverberant conditions, it was considered worthwhile to observe the reverberation time as the condition became more reverberant. Furthermore, the instrumentation employed for the investigation enabled quick and efficient measurement of RT.

3.4 SOUND POWER DETERMINATIONS & ASSOCIATED UNCERTAINTIES

Measurements were made to determine the sound power level of the selected noise sources described in sub-section 3.1 in a range of room acoustical conditions.

3.4.1 Reference values

The measurement method used for determining sound power levels was based on the specifications set out in ISO 3744, using a 1.5 m radius enveloping hemispherical measurement surface with 10-microphone positions. The surface average sound pressure level determined for each machine at room state 1, where no degradation had taken place, has been considered as the reference "sound power level" (i.e. it has been assumed to represent the true value).

3.4.2 Influence indicators

Primarily, the investigation was designed to evaluate the influence of room performance on measurement uncertainties associated with the determination of sound power. Two different indicators were considered to quantify this influence.

i. Standard deviation of multiple sound power determinations for each room state,

ii. Level difference between sound power levels determined in each room state.

3.4.2.1 Multiple sound power determinations

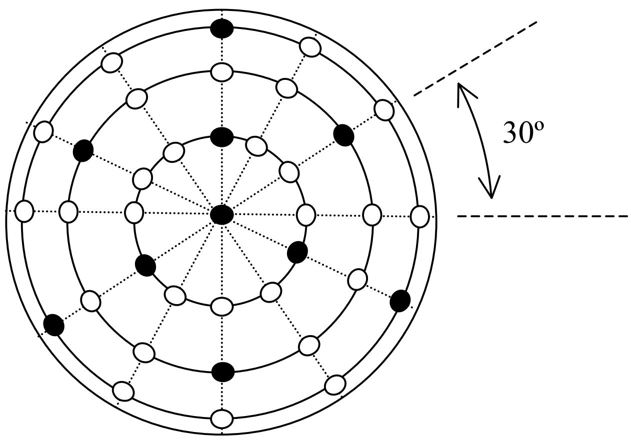
It was considered that analysis of multiple determinations of sound power level for each room state would provide an indication of the relative effect of different room conditions on the determined sound power level. The experimental programme was designed such as to enable calculation of the mean and standard deviation from four source orientations for each room state, with the aim of enabling evaluation of the uncertainty associated with the acoustical performance of the room.

For each iteration of room change, sound power levels for each test source were determined in four orientations within the room over a 10-microphone measurement array. The 10-point array used the 10 key positions described in ISO 3744. It consists of microphone locations at four heights, one of which was located directly above the source under test. At the other heights there were three locations spaced 120º apart around the vertical axis of the hemisphere. For 30º rotational increments of this array relative to the source, the array may be moved four times before the locations of the microphone positions are repeated. With these four orientations, 37 different microphone positions are obtained. However, the various configurations result in the overhead position being measured four times, one for each set of 10, and as such increased the total number of sound pressure measurements to 40.

From the multiple determinations of sound power levels the arithmetic mean and standard deviation of those levels obtained using the four sets of 10-point arrays could be determined.

The complete array is shown in Figure 9. The black circles represent one of the four 10-point arrays.

Figure 9. Plan view of microphone array



3.4.2.2 Level difference

The standard deviation calculation described in sub-section 3.4.1.1 is a measure of the variability of sound power levels determined using each array orientation about the mean of all orientations. From this an assessment can be made of how similar to the mean value estimates from a single array determination are likely to be.

However, this does not allow an assessment as to the accuracy of the determination. The sound power level determinations from all the arrays in each room state (and therefore the mean value) may be in error (i.e. different from the reference, room state 1, value). In order to account for this, the difference between the mean sound power level for each room state and that for room state 1, ΔL was calculated. These differences permit an assessment of how similar the sound power levels determined in each room state are to the true value.

4 MEASUREMENT RESUTS & ANALYSIS

This section gives a summary of the measurement results, providing initially, a quantitative schedule of the room degradation process. Results of measurements to characterise the room using the inverse square test method are then set out with consideration given to the behavioural characteristics of both broadband noise and tonal test sources under different room conditions. Particular attention is given to the maximum deviations obtained from equation 5 in Table 1. Additionally, variation in K_2, and reverberation time measurements are considered in the assessment of change in room response. The results of sound power determinations for selected noise sources are then detailed, with particular consideration paid to measurement repeatability under variable room conditions.

4.1 ESTABLISHING A VARIABLE ACOUSTIC ENVIRONMENT

As discussed earlier, this study involved the generation of a variable acoustic environment within the NPL hemi-anechoic chamber. The initial state of the room was defined as being hemi-anechoic in accordance with ISO 3745:1977 and ISO 3745:2003. The room construction and specifications are detailed in Annex A. The room was changed in 11 stages and, at each iteration, measurements were made to characterise the acoustic response of the room. For the most, the variable room response was characterised by assessing the sound decay with respect to the inverse square law. Additionally, the environmental correction K_2, as defined in ISO 3744, was evaluated and also the relative change in reverberation time was determined. At the end point of the study the room response had been degraded, by removal of absorptive wedges, to such an extent that the acoustic response could be classified as having semi reverberant characteristics. A quantitative description of the room degradation process is provided later in Table 3 of the summary sub-section 4.1.3.

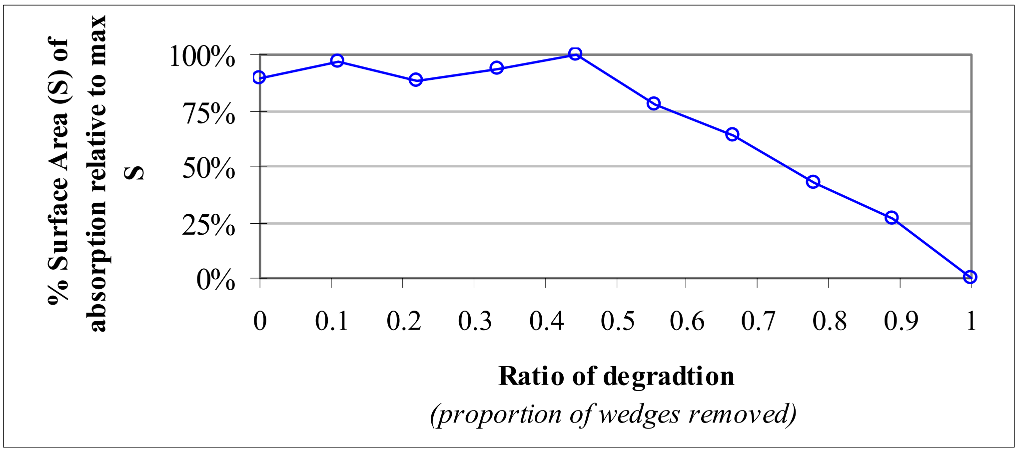
4.1.1 Limitations to characterising the change in acoustical performance

At the outset, it was submitted that the inverse square law test procedures would require extensive measurements demanding significant measurement effort and time. Due primarily to economic constraints on the project, a compromise was made, whereby a single radial traverse measurement was used on a number of occasions to quantify the relative change in room response. The same traverse was used for all iterations of room change. Additionally, however the measurement schedule was designed to also include three full qualification procedures during the course of the room degradation process.

4.1.2 Estimated change in acoustic absorption

A basic model has been derived which estimates the relationship between the number of wedges removed (exposing reflective surface area) and acoustic absorption in the room. It is assumed that the room absorption area is dependent only upon the exposed wedge surface area. Figure 10 shows the percentage absorption against the percentage number of wedges removed.

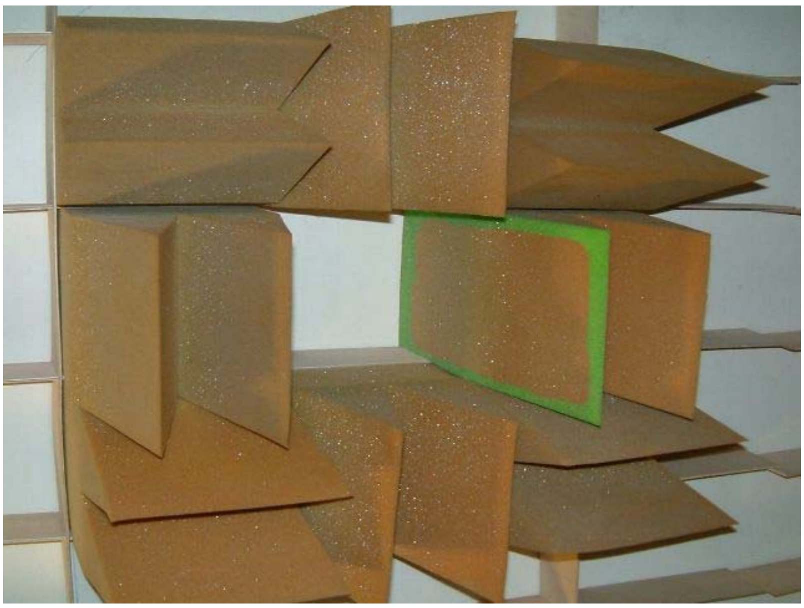
Figure 10. Exposed wedge surface area within the room



According to the simplified model, the absorption area remains relatively constant from the original state until the room has around half of the wedges removed. Indeed, the estimate suggests a marginal increase in exposed absorptive area. This is explained by the fact that removal of the absorptive wedges as detailed in Annex A, effectively exposed 'hidden' faces of adjacent wedges and when only a few wedges are removed this actually increased the absorption area. In addition, where such was the case, as illustrated in Figure 11, it is considered likely that acoustic reflections from the exposed hard wall could have been absorbed on exit by the side panels of the remaining wedges. Thus the actual available acoustical absorption would not necessarily have reduced until significant areas of hard reflecting wall became accessible.

It is interesting here to note the possibility that, for a wedge lined room, the hemi-anechoic performance may not be seriously affected if some wedges are removed such that each space is surrounded by wedges so that a large area of wall is not exposed. This may prove useful when considering the provision of power supplies for both acoustic instrumentation and for the machine under test.

Figure 11. Illustration of additional exposed part of absorbing wedge.



Following the half way change point, the available absorption is estimated to decrease linearly to a state of having negligible acoustic absorption. The estimated change in available absorption is discussed in relation to the measured results, later in section 4.4.

4.1.3 Summary of the room changes and measurement schedule

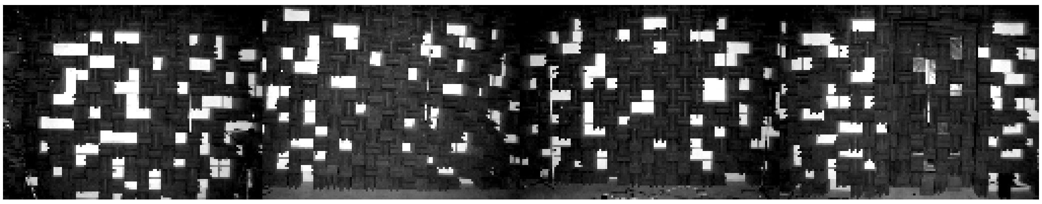
Table 3 sets out the measurements conducted at each stage, indicating the number of wedges removed and associated percentage change, and the number of radial traverses measured according to the test source. Single radial traverse where conducted in direction C as indicated in Figure 8.

Table 3. Room degradation states

Room State			**Inverse Square measurements**	
Iteration	Number of Wedges removed	Wedges removed %	Radial Lines using cavity source	Radial lines using RSS
1	0	0	5	1
2	40	2	-	-
3	120	5	5	-
4	224	9	1	-
5	336	13	1	-
6	560	21	1	-
7	1008	38	5	1
8	1300	50	1	-
9	1450	55	1	1
10	2000	76	-	-
11	2626	100	1	-

As an indication of the room degradation process, Figure 12 shows the pattern for room state 5, where 336 wedges had been removed.

Figure 12. Panoramic composite view of walls with 336 wedges removed



4.2 Room Response Measurements

As explained in sub-section 3.3, the room response was quantified primarily with respect to inverse square test criteria. Measurements of sound pressure level were made along radial traverses from the geometrical centre of the source to the room boundary to quantify the sound decay. Additionally, the environmental correction K_2, as defined in ISO 3744 was evaluated and the relative change in reverberation time was observed as the room was progressively degraded.

4.2.1 Variation in inverse square sound decay response

As an example, Figures 13 and 14 show the results of sound pressure levels at 1 kHz one-third octave frequency band for broad-band noise and for the tonal source respectively, measured along a radial traverse in the direction towards the corner directly left of the chamber door (see Figure 8), for 8 different stages of room response. The results are representative of the sound decay rates quantified for broadband noise in one-third octave-bands and pure tones.

It is observed that the rate of decay remained relatively constant for the early iterations of room change. It is shown that broad-band noise deviates less than pure tones, which is most likely due to averaging of the interference between the limits of the frequency band being analysed, whereas for tones such an effect is not allowed for.

Clearly deviations from the original state increased with increased removal of the wedges. Not surprisingly, in terms of noise at 1 kHz, the measured absolute sound pressure level generally increased correspondingly with removal of absorbing wedges, which can be attributed to the additional contribution of reflected acoustical energy from the room boundaries. At the final room state, where all the wedges had been removed such as to generate a semi-reverberant environment the rate of sound decay had reduced from around 6 dB per doubling of distance to around 3 dB.

Also the greatest deviations of the sound decay rate from that of the initial state were observed at greater distances from the source. This again can be attributed to effect of the room boundaries where the ratio of direct to reflected signal is increasing with radius towards the room boundary.

Figure 13. Change in sound decay at 1 kHz for a broad-band noise source generated using the cavity source

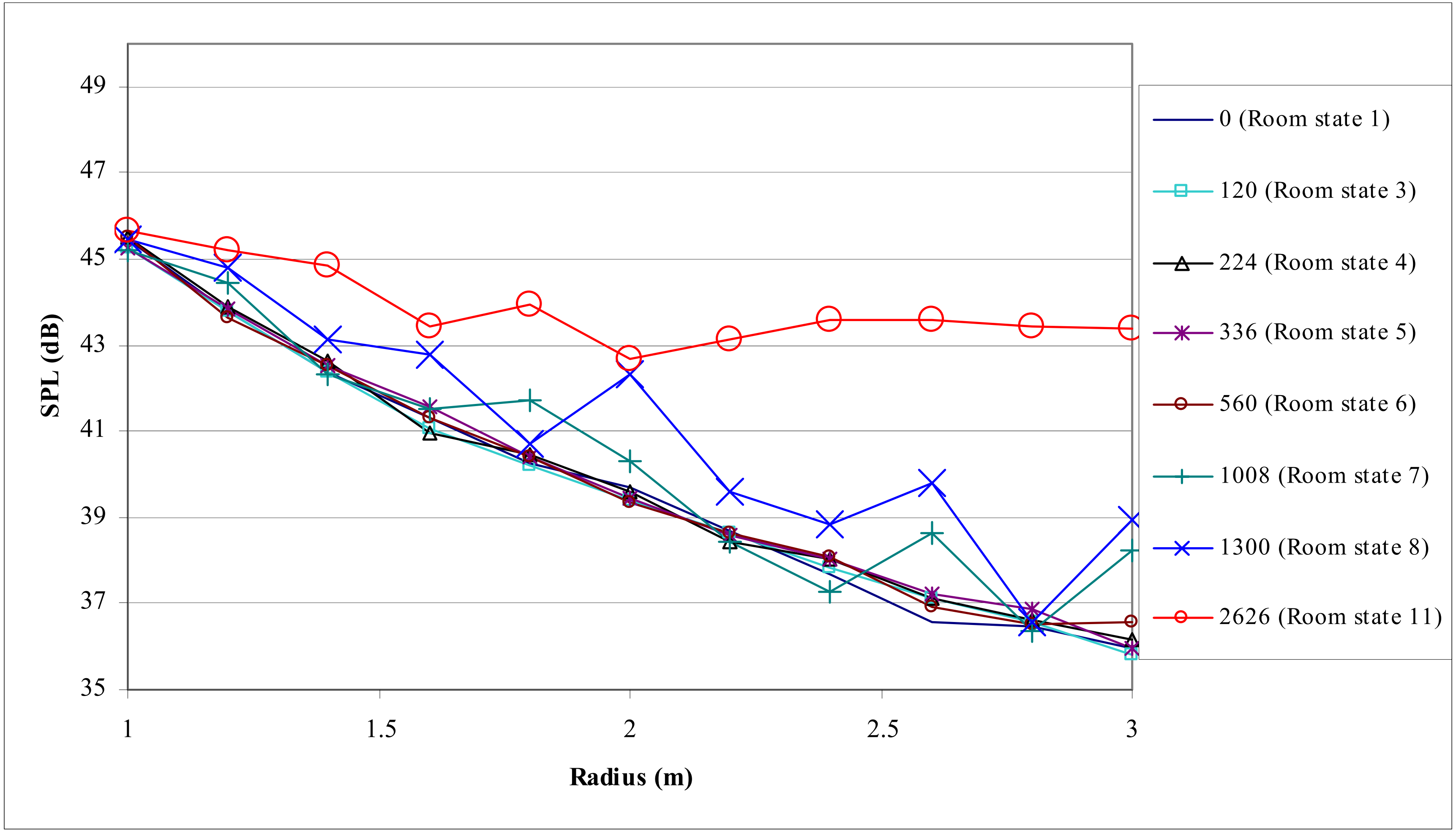
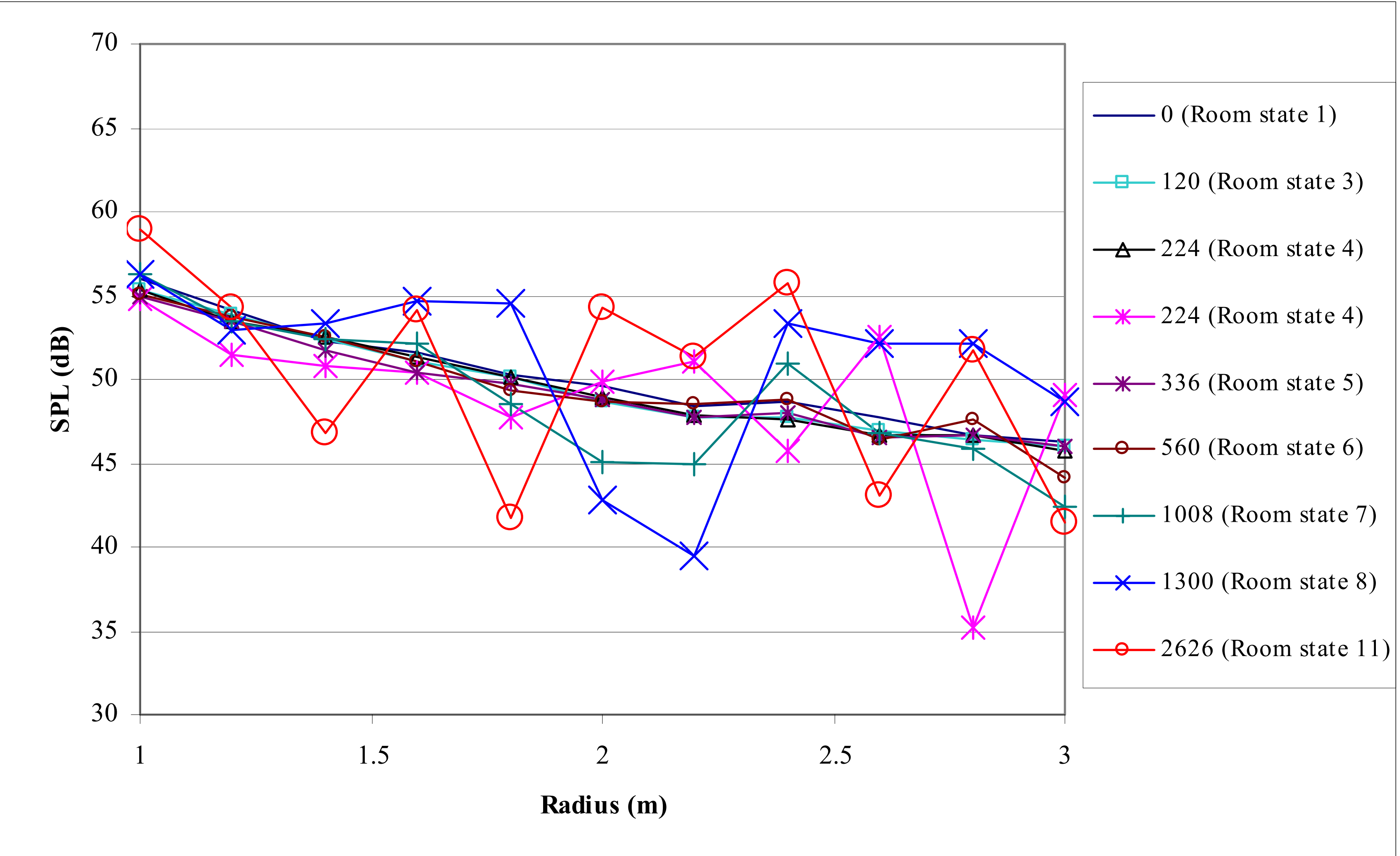


Figure 14. Change in sound decay at 1 kHz for a pure tone generated using the cavity source



4.2.1.1 Assessment of decay rate against qualification criteria

The results of the measurements conducted in accordance with the qualification procedures as set out in ISO 3745, and described in Table 1, have been assessed against limiting criteria, which define acceptable hemi-anechoic conditions and range from 2 dB between 800 Hz and 5000 Hz to 3 dB above 6300 Hz, (these are summarised in Table 2).

It is however, acknowledged that the values used in the assessment are based on individual draw away traverses in a single direction towards the room corner, as indicated in Figure 8, as opposed to the nominally required five traverses to each room corner plus one other direction. However, some tests were carried out comparing room conformity using one draw away with that achieved using five and for the room states used for these tests no difference was observed in the pass/fail assessment.

Tables 4, and 5 provide calculated values of the maximum deviation from the inverse square best-fit line calculated according to ISO 3745:2003 for broad-band noise and tones respectively. The results are given in terms of one-third-octave band centre frequencies against number of wedges removed (room state). Where the measured results were found to exceed the limits defining hemi-anechoic conditions as summarised in Tables 1 and 2, the values are represented in greyed-out bold font.

Table 4 Maximum deviations for broadband noise according to ISO3745:2003

Frequency (Hz)	**Number of wedges removed (Room state)**									
	0 (1)	**40 (2)**	**120 (3)**	**224 (4)**	**336 (5)**	**560 (6)**	**1008 (7)**	**1300 (8)**	**1450 (9)**	**2626 (11)**
125	1.9	1.4	0.8	1.4	1.8	1.2	**3.7**	**2.8**	2.5	1.2
250	1.3	1.6	1.7	1.0	0.8	1.2	2.1	2.1	2	1.3
500	0.4	0.5	0.5	0.3	0.7	1.1	1.2	2.2	1.7	1.2
1000	0.5	0.2	0.4	0.4	0.2	0.5	1.4	1.6	2	1.1
2000	0.6	0.3	0.5	0.4	0.8	0.5	1.0	1.1	1.5	1.2
4000	0.5	1.0	0.6	0.3	0.6	0.7	0.5	1.9	1	0.7
8000	0.3	0.3	0.7	0.5	0.7	0.3	0.2	0.6	0.8	0.5
10000	0.7	0.4	0.6	0.4	0.4	0.3	0.2	0.4	0.5	0.6

Table 5 Maximum deviations for pure tones according to ISO3745: 2003

Frequency (Hz)	**Number of wedges removed (Room state)**									
	0 (1)	**40 (2)**	**120 (3)**	**224 (4)**	**336 (5)**	**560 (6)**	**1008 (7)**	**1300 (8)**	**1450 (9)**	**2626 (11)**
125	1.8	**2.8**	1.0	**4.5**	**4.9**	**4.8**	**4.4**	**2.8**	**3.4**	**4.6**
250	2.0	2.2	2.3	**4.1**	1.5	1.9	**4.8**	**6.4**	**9.3**	**12.1**
500	0.5	0.7	1.0	0.8	1.2	2.1	**4.7**	**8.3**	**9.8**	**6.5**
1000	0.6	1.0	0.9	0.4	0.6	1.5	**4.7**	**9.2**	**10.5**	**9**
2000	0.7	0.6	1.2	0.8	1.1	1.8	**4.0**	**6.9**	**7**	**8.2**
4000	1.5	1.4	1.7	0.8	1.8	**2.8**	**3.0**	**5.6**	**6.5**	**6.5**
8000	1.3	0.8	1.3	1.3	2.5	2.8	**3.5**	**3.8**	**14.3**	**8.4**
10000	0.6	1.4	2.0	1.2	2.0	1.3	2.9	**3.6**	**7.8**	**6.4**

Calculated values of the maximum deviation from the inverse square law according the procedures set out in ISO 3745:1977 have been obtained using the procedure outlined below.

The estimation of sound pressure levels based on the inverse square law was determined from the following equation:

$$L_{pr} = c - 20 \lg r_i \text{ dB} \quad (8)$$

where

L_{pr} is the sound pressure level based on the inverse square law associated with a measurement position located at a distance r_i from the centre of the measurement sphere or hemisphere;

c is a constant and is the intercept of the best fit line based on the inverse square law and is given by:

$$c = \frac{\left(\sum_{i=1}^{N} 20 \lg r_i + \sum_{i=1}^{N} L_{p_i} \right)}{N} \text{ dB} \quad (9)$$

where

L_{pi} is the sound pressure level at the i th measurement position (dB);

N is the number of measurement positions along each microphone traverse.

Using these estimates of sound pressure level based on the inverse square law, deviations of the sound pressure levels at all measurement positions from the inverse square law are determined by the following equation:

$$\Delta L_{pi} = L_{pi} - L_{pr} \text{ dB} \quad (10)$$

where

ΔL_{pi} is the deviation from the inverse square law at the ith measurement position (dB) ;

The results of using this procedure are listed in Tables 6 and 7 for broad-band noise and tones respectively. As for the previous two tables, the results are given in terms of one-third-octave band centre frequencies against number of wedges removed (room state). Where the measured results were found to exceed the limits defined hemi-anechoic conditions as summarised in Tables 1 and 2, the values are represented in greyed-out bold font.

Table 6. Maximum deviations for broad-band noise according to ISO 3745:1977

Frequency (Hz)	Number of wedges removed (Room state)									
	0 (1)	40 (2)	120 (3)	224 (4)	336 (5)	560 (6)	1008 (7)	1300 (8)	1450 (9)	2626 (11)
125	**3.6**	**4.1**	**4.3**	**4.3**	**5.6**	2.5	**7.6**	**5.3**	**3.4**	**4.6**
250	1.3	1.6	1.7	1.7	0.9	1.3	2.2	**2.8**	**4.5**	**5.1**
500	0.5	0.5	0.4	1.1	0.7	0.6	1.3	2.3	**3.8**	**4.4**
1000	0.5	0.2	0.3	0.3	0.3	0.9	1.8	1.8	**3.3**	**3.8**
2000	0.6	0.3	0.4	0.4	0.7	0.6	1.0	1.4	**3.9**	**4.7**
4000	0.6	0.9	0.8	0.8	0.9	0.7	0.6	2.2	**2.9**	**3.7**
8000	0.4	0.3	0.8	0.7	0.7	0.6	0.2	0.9	1.8	2.8
10000	0.8	0.5	0.7	0.8	0.5		0.2	0.7	1.3	2.2

Table 7. Maximum deviations for pure tones according to ISO 3745:1977

Frequency (Hz)	Number of wedges removed (Room state)									
	0 (1)	40 (2)	120 (3)	224 (4)	336 (5)	560 (6)	1008 (7)	1300 (8)	1450 (9)	2626 (11)
125	1.5	2.2	???	**3.2**	**5.1**	**3.6**	**5.5**	**4.7**	**3.7**	**4.4**
250	2.5	**2.6**	**2.8**	**2.8**	2.4	2.5	**4.9**	**5.4**	**10.0**	**15.3**
500	0.5	0.7	1.1	1.1	1.2	1.3	**5.0**	**10.4**	**12.5**	**7.5**
1000	0.6	0.7	0.8	0.9	0.7	0.6	**4.0**	**10.1**	**12.0**	**9.0**
2000	0.7	0.5	1.1	1.1	1.3	0.8	**3.7**	**10.9**	**8.5**	**9.8**
4000	0.6	1.9	1.4	1.4	1.7	2.4	**3.3**	**5.9**	**12.1**	**7.5**
8000	1.5	0.8	1.5	1.1	2.6	1.4	**3.7**	**4.1**	**20.8**	**8.0**
10000	0.7	1.7	1.7	1.6	2.0	0.7	**3.2**	**3.6**	**10.4**	**6.3**

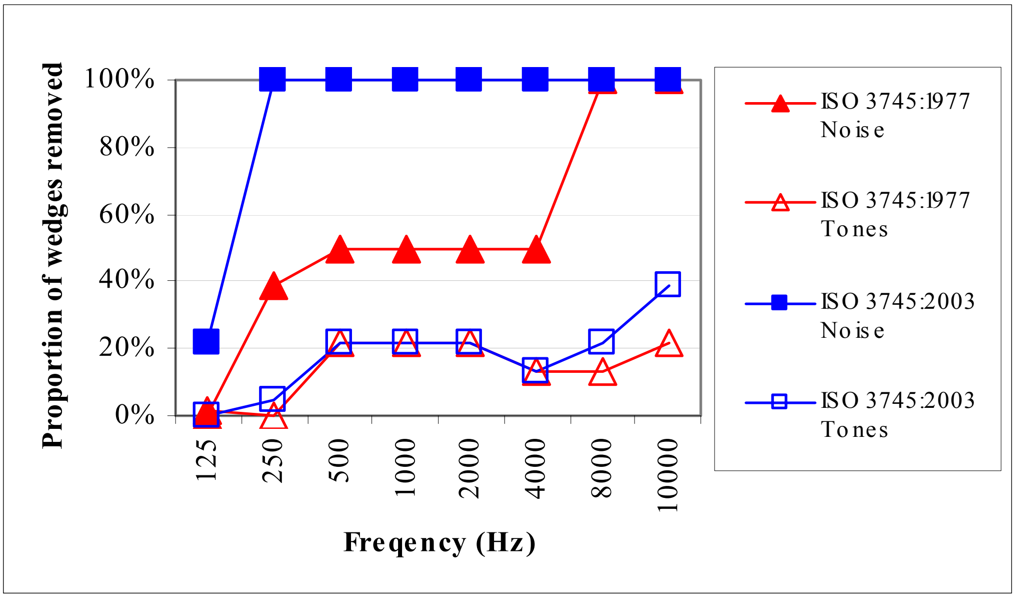
The data listed in Tables 4 to 7 are summarised in graphical form in Figure 15 which indicates the point at which the room fails to meet the criteria according to the procedures of either ISO 3745:2003 or ISO 3745:1977.

It can be seen that the outcome of the assessment by the two different methods for pure tones is relatively close, but is significantly different for broadband noise.

The assessment indicated that for pure tone signals above 250 Hz, room failure occurred at the point where around 20% of the absorptive wedges had been removed, which corresponds with room state 6. Below 250 Hz, the room failed before the 20% point.

In assessing to the room performance using noise signals, it can be seen that using the method specified in ISO 3745:1977, from 250 Hz up to 4 kHz the room met the criteria up to the point where around 50% of the absorptive wedges had been removed, which corresponded with room state 8. Surprisingly, at 8 kHz and 10 kHz, all room states were assessed as acceptable for testing broadband noise sources.

Figure 15. Summary of results assessed against criteria



Most significantly, Figure 15 shows that when the assessment procedures in ISO 3745:2003 are followed, all room states were found to meet the performance criteria at all frequencies except 125 Hz, even when all the absorptive wedges had been removed, in which case the room could be considered semi-reverberant. Analysis indicates that this is a consequence of the derivation of the collinear offset of the acoustic centre, r_0 along the axis of the microphone traverse. Where no limits are placed on this parameter, the resultant effect is that a 'best-fit' linear regression line is formed around the measured data and this line may not have a gradient corresponding to 6 dB per doubling of distance.

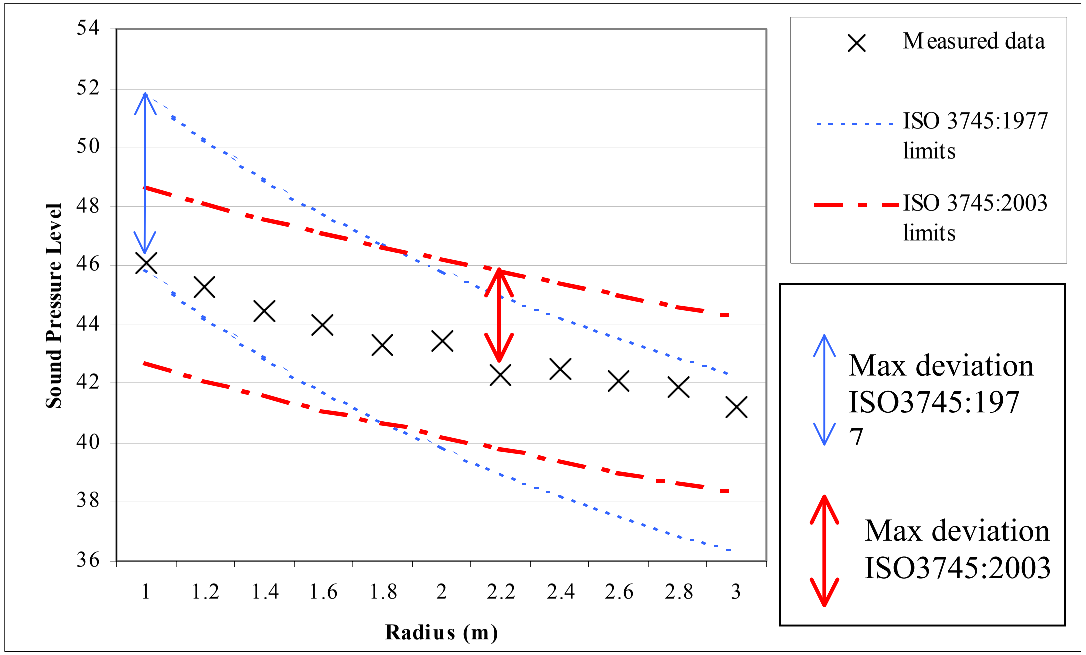
Figure 16 provides an example, which compares the observed differences resulting from the two methods for an 8 kHz noise signal. Two different best-fit lines have been calculated around the measured data, the first using a simple least squares regression method which has a gradient corresponding to 6 dB per doubling of distance, the second using the more complex linear regression method as required by procedures set out in ISO 3745:2003. In both cases the curves representing the criterion of ± 3 dB are shown in Figure 16.

It can be seen that both of the assessment methods indicate that the room is apparently hemi-anechoic at 8 kHz, where the limiting 3 dB criterion is achieved, but observation of the data clearly shows that the rate of sound decay is much less than 6 dB per doubling of distance in the case of the ISO 3745:2003 method. The limit values shown are related to a curve that is effectively a best fit of the measured data and does not have a gradient corresponding to 6 dB per doubling of distance, and as such, the criterion is easily achieved.

At an early stage in the revision of the ISO 3745:1977, it was proposed in ISO/DIS 3745.2[12] that limits be set on the collinear offset of the acoustic centre r_0 stipulating that r_0 be numerically less than half the major source dimension for the qualification test to pass. This requirement was tested on the measurement results obtained from the first five iterations of room degradation. The diameter of the cavity source used for the qualification measurements as recommended in the standard aperture was 0.006 m and this was taken to be the major dimension. As such it was necessary for r_0 to be less than 0.003 m. Using this source size, it was found that for broadband noise that the qualification criteria for r_0 could not be achieved at any frequency even for room state 1. The source used fully complied with the requirements specified in the standard (see Annex B) and so, it is considered that there is a fundamental problem with the room qualification procedure or at least it is not appropriate for such a small source, which is in effect two-dimensional, and as such it is recommended that where such limits are to be employed the limitations with respect to cavity sources should be made clear to users of the standard.

It is apparent that the method in ISO 3745:2003, with or without limits placed on collinear offset of the acoustic centre r_0 , does not provide an adequate assessment of the hemi-anechoic performance of a room, and that further work is needed to develop a more robust method.

Figure 16. Example of difference between the two methods[1,9] for a noise signal.



4.2.2 Variation in Environmental Correction (K_2)

The environmental correction, K_2 has been determined for one-third-octave frequency bands and the value of K_{2A} for A-weighted levels. The hemi-anechoic room is used in the NPL RSS calibration service and so, by definition, all values of K_2 are zero for room state 1. The values listed in Table 8 for other room states are, therefore, all shown relative to sound power levels determined in room state 1.

Table 8. Environmental Correction (K_2) values for different room states

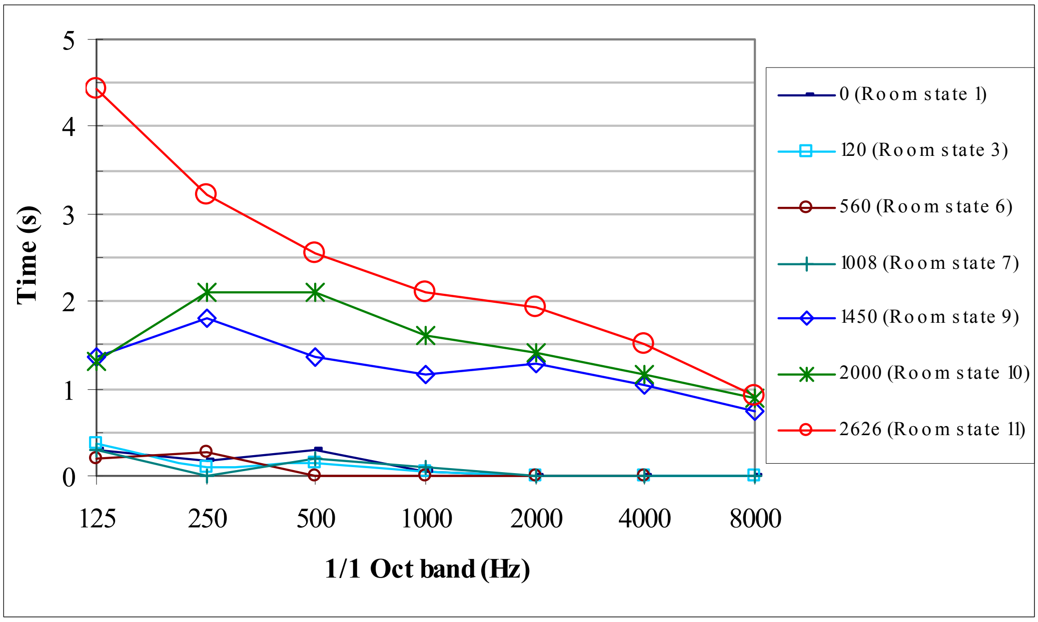
Frequency 1/3 oct (Hz)	**Number of wedges removed (Room state)**							
	0 (1)	224 (4)	330 (5)	560 (6)	1008 (7)	1300 (8)	1450 (9)	2626 (11)
100	0.0	0.5	0.9	1.7	2.9	3.8	4.6	10.0
125	0.0	-0.2	-0.4	-0.3	0.4	1.1	2.8	8.4
160	0.0	0.3	0.4	0.7	1.4	2.7	5.2	10.6
200	0.0	0.2	0.2	0.6	1.9	3.4	6.3	10.1
250	0.0	0.1	-0.1	-0.1	0.2	1.6	5.0	9.0
315	0.0	0.1	0.0	0.2	0.7	1.9	5.8	9.2
400	0.0	0.2	0.1	0.3	0.7	1.8	5.7	8.8
500	0.0	0.2	0.1	0.3	0.7	1.9	5.4	8.0
630	0.0	0.1	0.0	0.3	0.6	1.6	4.7	7.3
800	0.0	0.1	0.1	0.1	0.4	1.3	4.2	8.1
1000	0.0	0.1	0.0	-0.1	0.5	1.5	4.3	7.9
1250	0.0	0.2	0.0	-0.4	0.4	1.3	3.9	7.3
1600	0.0	0.2	0.0	-0.2	0.3	1.1	3.5	7.8
2000	0.0	0.2	0.2	0.5	0.5	1.1	3.3	7.0
2500	0.0	0.1	0.1	0.7	0.7	1.7	4.3	8.6
3150	0.0	0.0	-0.3	-0.9	0.3	1.5	3.6	7.0
4000	0.0	-0.2	-0.3	-0.2	0.2	1.1	2.7	5.4
5000	0.0	0.1	0.1	0.1	0.5	1.2	2.5	4.5
6300	0.0	0.4	0.3	0.4	0.7	1.4	2.8	4.2
8000	0.0	0.2	0.1	0.1	0.5	1.3	2.4	3.5
10000	0.0	0.1	0.1	0.1	0.4	1.1	1.9	2.6
Max	**0.0**	**0.4**	**0.4**	**0.7**	**1.9**	**3.4**	**6.3**	**10.6**
A wtg	**0.0**	**0.1**	**0.0**	**0.0**	**0.4**	**1.3**	**3.7**	**7.2**

It was observed that the change in K_2 was relatively insignificant up to the point where around half of the absorbing wedges had been removed. Following the halfway stage, K_{2A} for example, increased from 0.4 dB to 7.2 dB.

4.2.3 Variation in Reverberation Time (RT)

As the room was to undergo changes from initially having hemi free-field conditions to a room with semi-reverberant conditions, it was considered appropriate to measure the reverberation time. This was carried out for each room state. The results are analysed in one-octave frequency bands. The white noise acoustic signal, generated using a Bruel & Kjaer type 4205 sound source was measured at the fixed monitor microphone location, in its fixed "over-head" position. The Reverberation time results are plotted in Figure 17, and are shown for each stage of room degradation with the number of wedges removed (room state) as a parameter.

Figure 17. Reverberation time measurement results



The reverberation time, not surprisingly, was generally very low even with the removal of 1008 the absorptive wedges. Indeed, above 1 kHz the RT was too low to capture with the measurement system. At the point where 1450 wedges were removed, which represents just over half the total number of wedges, the reverberation time was found increase significantly.

4.3 SOUND POWER DETERMINATIONS UNDER DIFFERENT ROOM CONDITIONS

Sound power levels were determined for each of the selected noise sources under each room condition. In each, case, the sound power was determined with the source in four orientations relative to the 10-microphone measurement array, and the mean calculated. The results for each machine and selected room conditions are given in sub-section 4.3.2.

4.3.1 Reference sound power values

As discussed earlier, data obtained in room state 1 have generally been accepted as reference values. So, the surface average sound pressure level ($\overline{L_p}$) determined for each machine in room state 1, where no wedges had been removed, has been considered as the reference sound power level. Reference sound power levels for the RSS, drill and box source are listed under the "room state 1" column in Tables 9, 10 and 11 in sub-section 4.3.2.

4.3.2 Sound power level determinations

Tables 9, 10 and 11 show the average one-third-octave-band and A-weighted sound power levels uncorrected for environmental conditions, determined for the RSS, drill and box source under different hemi-anechoic conditions.

Table 9. Average sound power levels determined for the RSS in different room states

Frequency 1/3 oct (Hz)	(RSS Lp) Number of wedges removed (Room state)									
	0 (1)	120 (3)	224 (4)	330 (5)	560 (6)	1008 (7)	1300 (8)	1450 (9)	2000 (10)	2626 (11)
100	64.8	65.4	65.3	65.7	66.5	67.8	68.6	69.4	71.4	74.9
125	63.2	63.4	62.9	62.8	62.8	63.5	64.3	66.0	66.9	71.6
160	63.4	63.8	63.7	63.8	64.0	64.8	66.1	68.6	70.2	73.9
200	64.2	64.6	64.4	64.4	64.8	66.0	67.5	70.5	71.2	74.2
250	65.0	65.4	65.1	64.9	65.0	65.3	66.6	70.0	70.4	74.0
315	65.0	65.3	65.1	65.0	65.2	65.6	66.8	70.8	70.9	74.2
400	64.6	65.1	64.8	64.8	65.0	65.3	66.5	70.4	70.7	73.4
500	64.5	64.9	64.7	64.6	64.8	65.2	66.4	69.9	70.1	72.5
630	65.3	65.5	65.4	65.3	65.5	65.9	66.9	70.0	70.2	72.6
800	67.1	67.1	67.2	67.2	67.2	67.5	68.4	71.3	71.5	75.2
1000	68.0	68.3	68.1	68.0	67.9	68.4	69.4	72.3	72.4	75.9
1250	69.7	69.9	69.9	69.8	69.3	70.1	71.0	73.6	73.8	77.1
1600	69.6	69.7	69.8	69.6	69.4	69.9	70.7	73.1	73.2	77.4
2000	68.8	69.0	69.0	69.0	69.3	69.3	70.0	72.2	72.3	75.8
2500	65.1	65.2	65.3	65.3	65.8	65.8	66.8	69.4	70.0	73.7
3150	65.7	65.6	65.6	65.4	64.8	66.0	67.1	69.3	69.8	72.7
4000	67.0	66.9	66.8	66.7	66.8	67.2	68.1	69.7	70.1	72.4
5000	66.3	66.8	66.5	66.4	66.5	66.9	67.5	68.9	69.2	70.8
6300	64.4	65.1	64.8	64.8	64.8	65.1	65.9	67.2	67.3	68.6
8000	62.5	62.8	62.6	62.5	62.5	62.9	63.7	64.9	65.1	66.0
10000	60.8	61.2	60.9	60.9	60.9	61.2	61.9	62.7	62.9	63.3
A wtg	78.7	78.9	78.8	78.7	78.7	79.1	80.0	82.4	82.7	85.9

Table 10. Average sound power levels determined for the drill in different room states

Frequency 1/3 oct (Hz)	(Drill) Number of wedges removed (Room state)								
	0 (1)	(120) (3)	224 (4)	330 (5)	560 (6)	1300 (8)	1450 (9)	2000 (10)	2626 (11)
100	33.1	36.9	33.1	37.2	36.9	40.1	36.5	43.2	47.5
125	30.0	35.1	30.1	29.1	30.8	32.8	34.7	38.9	42.7
160	33.4	34.0	33.2	34.5	34.8	35.4	37.6	40.6	46.0
200	35.1	35.0	34.6	36.7	36.2	38.3	40.7	41.8	47.3
250	38.9	38.5	39.2	38.3	39.0	40.8	45.2	45.1	49.7
315	45.6	44.9	45.7	45.0	45.7	47.8	51.5	51.8	55.9
400	49.5	49.4	49.5	49.2	49.1	51.2	55.2	55.5	58.0
500	54.2	54.2	54.2	54.3	54.6	56.0	59.8	59.9	62.4
630	63.0	63.1	63.1	63.2	63.5	64.9	67.7	68.0	70.7
800	66.9	67.0	66.8	66.6	65.9	67.4	70.3	70.6	74.0
1000	61.9	61.8	61.8	61.4	60.5	62.3	65.3	65.5	68.8
1250	61.2	61.5	60.9	60.9	60.3	62.1	64.1	64.4	68.1
1600	60.3	60.5	60.1	59.5	59.1	60.4	62.2	62.4	66.9
2000	58.5	58.3	58.3	58.6	58.5	59.5	61.8	62.1	65.9
2500	58.0	57.6	57.9	57.8	57.9	59.9	62.0	62.6	66.2
3150	60.0	59.8	59.8	59.7	59.4	61.1	62.4	62.8	65.8
4000	59.3	59.1	59.0	59.1	58.9	59.9	61.2	61.5	64.1
5000	59.5	59.5	59.5	59.9	59.1	60.1	61.1	61.3	63.2
6300	58.9	59.1	59.0	59.1	58.5	59.9	61.0	61.1	63.0
8000	61.6	61.2	61.2	60.9	60.6	61.9	62.8	63.2	64.3
10000	61.7	61.9	61.9	61.4	61.2	62.4	63.1	63.1	63.9
A wtg	72.5	72.5	72.4	72.3	71.9	73.3	75.5	75.8	78.9

Table 11. Average sound power levels determined for box source in different room states

Frequency 1/3 oct (Hz)	(Box Lp) Number of wedges removed (Room state)								
	0 (1)	120 (3)	224 (4)	330 (5)	560 (6)	1300 (8)	1450 (9)	2000 (10)	2626 (11)
100	68.4	69.2	69.5	69.9	70.5	71.9	71.7	75.0	78.2
125	65.8	65.9	65.2	65.7	66.1	69.3	70.1	71.6	74.4
160	63.5	63.9	63.9	64.1	64.3	66.5	68.8	70.6	73.3
200	64.2	64.6	64.6	64.7	65.0	67.7	71.0	71.7	75.3
250	65.0	65.1	65.4	65.3	65.1	66.9	70.2	70.3	74.7
315	64.5	64.7	64.4	64.4	64.5	66.4	69.7	69.8	73.7
400	63.9	63.9	64.3	64.4	64.6	66.3	69.7	70.3	73.3
500	66.9	66.9	66.9	67.0	67.3	69.1	72.0	72.5	75.4
630	65.4	65.6	65.4	65.3	65.5	66.8	69.7	69.9	72.7
800	65.6	65.8	65.5	65.3	65.5	67.1	70.3	70.2	73.4
1000	67.5	67.6	67.6	67.4	67.5	69.1	72.0	72.1	75.5
1250	68.7	69.0	68.9	68.7	68.5	70.3	73.0	73.1	76.4
1600	68.7	68.8	68.8	68.7	68.6	69.9	71.9	72.1	76.5
2000	65.9	65.9	67.0	67.4	67.7	68.4	70.7	71.0	74.6
2500	66.5	66.4	65.8	65.8	66.1	67.2	69.4	70.2	73.9
3150	66.9	66.8	66.6	66.4	66.4	67.9	69.4	70.1	73.1
4000	66.7	66.6	66.5	66.5	66.7	67.9	69.1	69.7	72.0
5000	65.1	65.3	65.5	65.5	65.6	66.5	67.7	68.2	69.9
6300	63.3	63.4	63.5	63.4	63.5	64.4	65.8	66.1	67.6
8000	62.0	62.0	61.8	61.8	61.9	62.8	63.9	64.2	65.2
10000	59.2	59.3	59.5	59.3	59.4	60.2	61.1	61.2	61.9
A wtg	78.1	78.2	78.2	78.1	78.2	79.6	81.8	82.2	85.4

It can be seen from these three Tables that sound power level determinations only show a significant change (an increase in level) when approximately half the wedges had been removed. It can be seen from Figure 10 that it is at this level of room degradation that the surface absorption area of the room begins to decrease. So, it may be assumed that the increase in sound power level determination from this room state on may be attributed to increased reflected energy over the measurement surface.

4.4 INFLUENCE OF ROOM ON SOUND POWER MEASUREMENT UNCERTAINTY

The measurements carried out to assess the relationship between room performance and measurement uncertainty associated with sound power determination were based on sound power level determinations in a number of rooms, having different acoustical performance. This was, in fact, achieved by applying changes to a single hemi-anechoic room. Section 4.2 sets out in quantitative terms, the relative change in room response achieved. Section 4.3 goes on to present results of sound power determinations. This section is concerned with the influence of relative change in room response on sound power determination and on the relationship between the measurement uncertainty associated with a sound power determination, as defined in sub-section 3.4.2.1, and the room performance indicators of ISO 3745.

4.4.1 Range of generated rooms

An analysis of room response measurement results for 11 iterations of room change has been conducted using a number of different methods. Two standardised approaches, based on the measurement of the rate of the decay of noise level with distance, were used to judge the hemi-anechoic performance of each simulated room, and the results presented and discussed in section 4.2. It was observed that the two methods gave different results. Using the ISO 3745:1977 method and criteria, it was determined that around eight rooms (depending on frequency) were sufficiently hemi-anechoic for broadband noise sources, where the point of failure corresponded with removal of approximately 50% of the acoustically absorptive wedges. The method set out in ISO 3745:2003 indicated that for broadband noise sources all the rooms met the hemi-anechoic criteria. This was clearly not the case, as at the later stages of room change, significant reverberation times could be measured. If the analysis of the influence of room conditions on the determination of sound power level, L_w had been based on the sound power levels obtained in all the rooms that were considered hemi-anechoic according to ISO 3745:2003 the influence of the room would have been shown to be substantial. That is to say, significantly higher sound power levels were determined at the latter stages of room change, due to increased reflected energy contributions. It is considered that the ISO 3745:2003 method is to some degree flawed, and that it is not appropriate to use when the qualification test is conducted using a cavity point source. The rationale for this conclusion is summarised earlier in sub-section 4.2.1.2.

Some room states passed the qualification criteria and some failed depending on frequency. The analysis of the influence of room response has been carried out (and discussed in sub-section 4.4.2) using only data from room states that passed.

4.4.2 Sound power level variation in hemi-anechoic rooms

Two indicators have been considered in the analysis of the influence of room boundary conditions on the determination of sound power levels.

1. Standard deviations, as described in sub-section 3.4.2.1, obtained from multiple measurements in each hemi-anechoic room.

2. Level differences ΔL, between data obtained in the degraded hemi-anechoic room states and those from the reference room (state 1).

4.4.2.1 Multiple measurements in different rooms

As explained in the section 4.3, a large number of sound power levels were determined for each of the selected noise sources under each room condition. In each case, the sound power was determined with each test machine in four orientations relative to the microphone array (see sub-clause 3.4.2.1). At the outset, it was considered that analysis of repeat determinations of sound power level for each room state would provide an indication of the relative effect of different room conditions on the determined sound power level, and thus enable evaluation of the uncertainty associated with the acoustical performance of the room. However it is acknowledged that using this approach to gain an indication of the measurement uncertainty is not wholly in line with well established statistical methods. The results obtained from the repeat measurements cannot be taken as a straightforward repeatability uncertainty. The standard deviations calculated for each room state were determined from different orientations of the source relative to the microphone array. To strictly assess uncertainty in terms of the repeatability for each room, it would have been necessary to conduct repeat measurements using a single fixed set up. With the approach that was taken it was considered that the sound power levels obtained from each orientation would be different, and this would have been primarily due the effect of room boundaries, although it could also have to some degree been the effect of the source. By moving the orientation the average effect of the change in room conditions was accounted for. It was also acknowledged that in changing the room response by removing absorptive wedges, the correlation between sound power levels at each orientation may not remain constant between room states. However, by calculating the mean and standard deviation from the four orientations for each room state, it was considered that the results would provide a relative indication of the effect of the change in room boundary conditions on the determined sound power levels. However, these estimates of measurement uncertainty will certainly not be less than those obtained under strict repeatability conditions and so may be considered as an upper limit.

Figure 20, 21 and 22 show the standard deviations σ_r obtained from four source orientations in different room states for the drill, box, and RSS sources respectively.

Figure 20. Standard Deviations determined from 4 repeat sound power determinations for the Drill in rooms that qualified for broadband noise sources

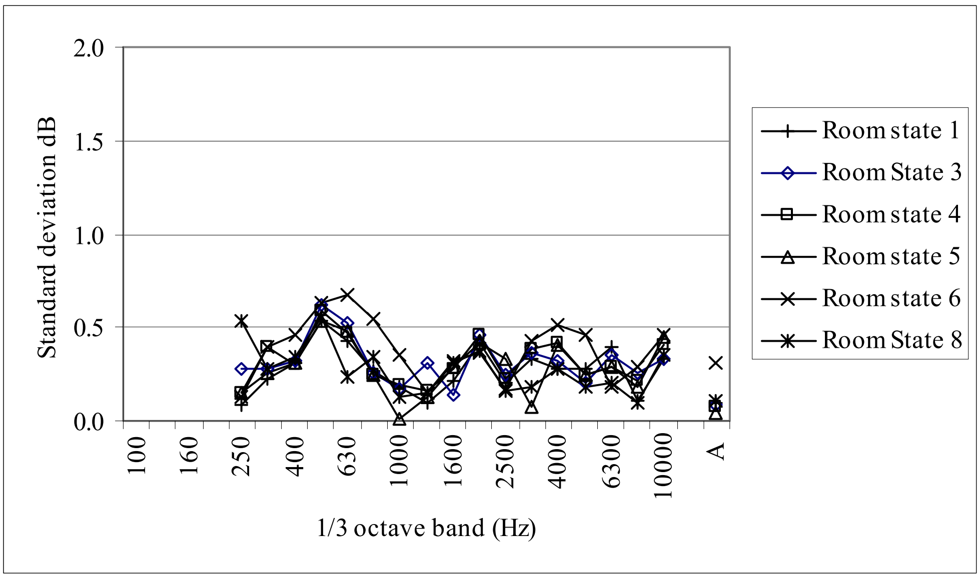


Figure 21. Standard Deviations determined from 4 repeat sound power determinations for the Box in rooms that qualified for broadband noise sources

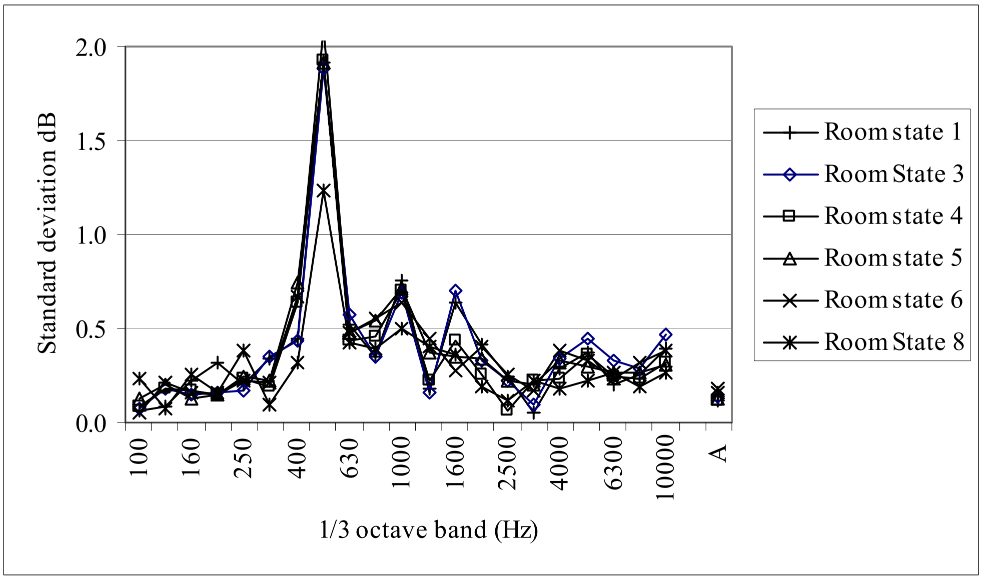
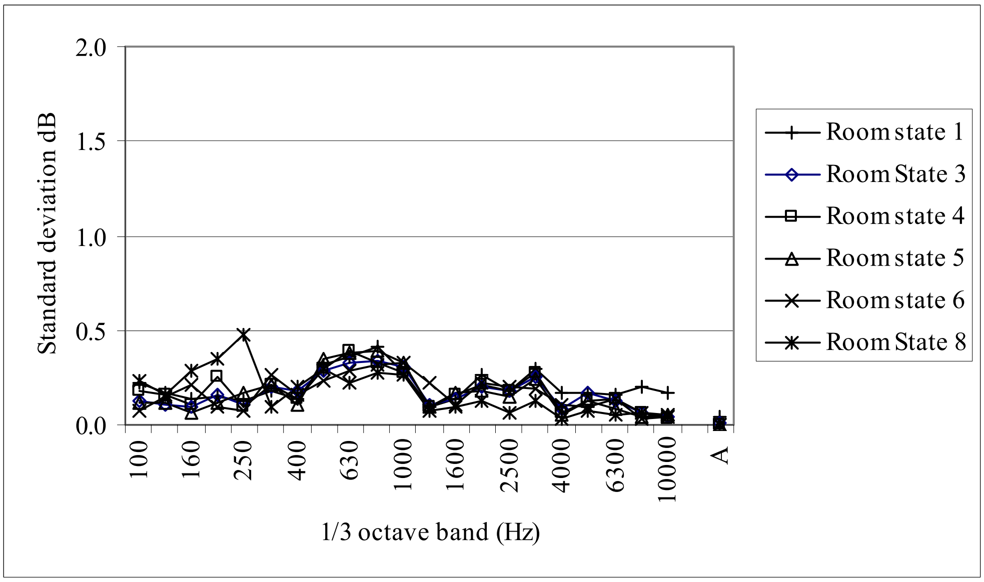


Figure 22. Standard Deviations determined from 4 repeat sound power determinations for the RSS in rooms that qualified for broadband noise sources



It can be seen that the standard deviation obtained from repeat measurements in the various room states was in most cases less than 1 dB, and often below 0.5 dB. Higher values of up to around 2 dB were determined at 500 Hz for the box source. The box source was resonant at 500 Hz where it was observed that the direct energy emitted was the dominant contributor to the overall level during for some of the initial room states. As the room became more reverberant, the resonance effect was reduced and the contribution of reflected diffuse acoustic energy had a greater influence on the overall level.

The most significant observation from the results was the apparent lack of difference in standard deviation between the different room states. The calculated standard deviation values remaining relatively constant from the initial room state to the final iteration of room change. A more detailed inspection shows that values determined for the drill increased slightly with the progressive removal of absorptive wedges, although the same trend did not hold for the more directional box source, suggesting that the directional characteristics of the source contribute to the performance determined in the different room states.

These results do not indicate that the increase in reflective energy within the room and thus on the measurement surface had any marked effect on the determined sound power levels. It was considered, therefore, that the use of these standard deviation values (obtained from repeat spatial sampling within the room for a number of different sources) may not provide a true indication of the influence of the room on the sound power measurement uncertainty. As such alternative indicators were also examined (see the following sub-section).

4.4.2.2 Level difference in hemi-anechoic rooms

A more significant variation than that indicated by the standard deviation associated with multiple measurements in each room, was the variation in the absolute sound power levels (Δ_L) determined in the different room states. Figures 23, 24 and 25 show values of ΔL, defined as the surface average sound pressure level relative to the reference surface average sound pressure level (which was the level determined for each machine at room state 1) plotted as a function of one-third octave frequency band, for the Drill, Box source and RSS respectively for a tonal noise source.

Figure 23. Level differences, ΔL determined for the Drill in rooms that qualified for tonal noise sources

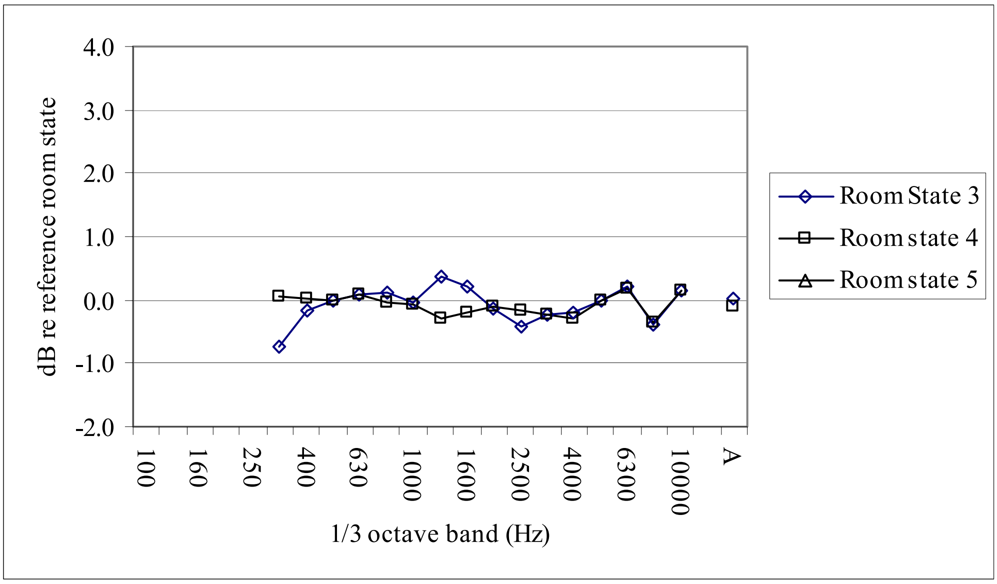


Figure 24. Level differences, ΔL determined for the Box source in rooms that qualified for tonal noise sources

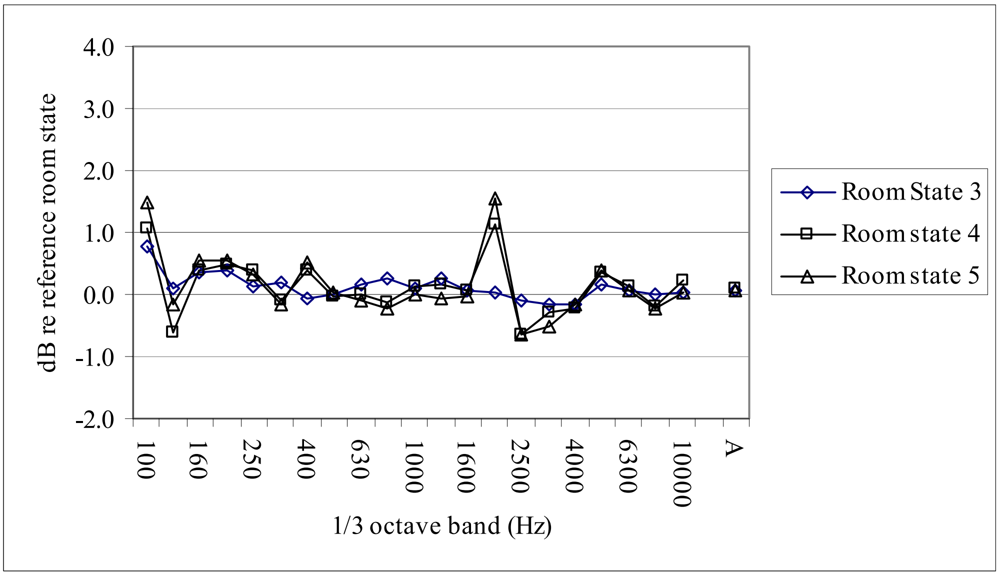
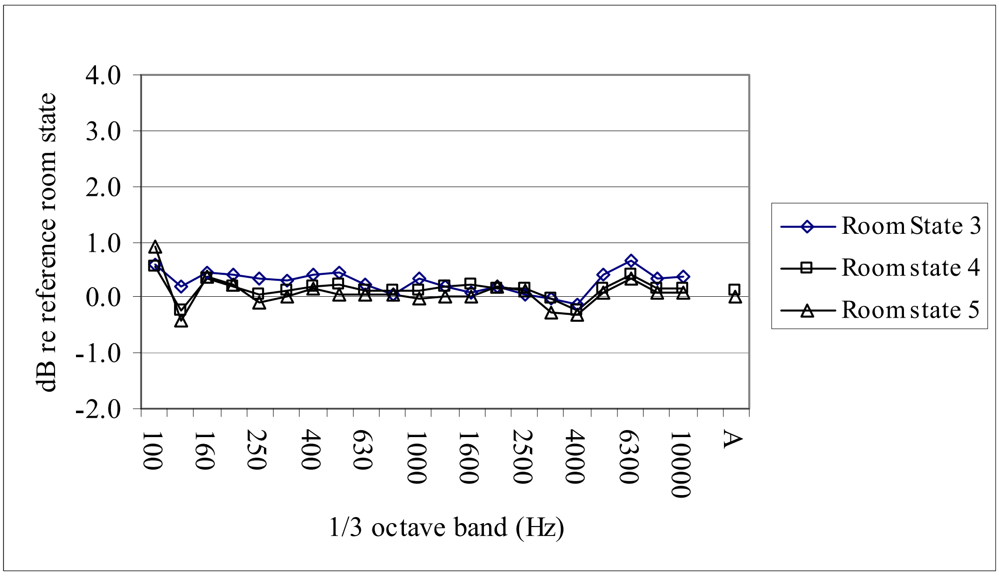


Figure 25. Level differences, ΔL determined for the RSS in rooms that qualified for tonal noise sources



It can be seen from Figures 23, 24 and 25 that values of ΔL are close to zero for all three noise sources. Thus, it may be assumed that if a room has conformed to the qualification requirements for tonal noise sources then sound power levels may be determined with low values of measurement uncertainty resulting from room effects.

These low values of measurement uncertainty are not observed when considering rooms that conform to the requirements for broad band noise sources. Figures 26, 27 and 28 show values of ΔL, defined as the surface average sound pressure level relative to the reference surface average sound pressure level (which was the level determined for each machine at room state 1) plotted as a function of one-third octave frequency band, for the Drill, Box source and RSS respectively for broad-band noise sources. In these three figures, the data with solid lines are for rooms that qualified according to both ISO 3745:1977 and ISO 3745:2003 and those data with dashed lines are those rooms that only qualified according to ISO 3745:2003.

Figure 26. Level differences, ΔL determined for the Drill in rooms that qualified for broadband noise sources

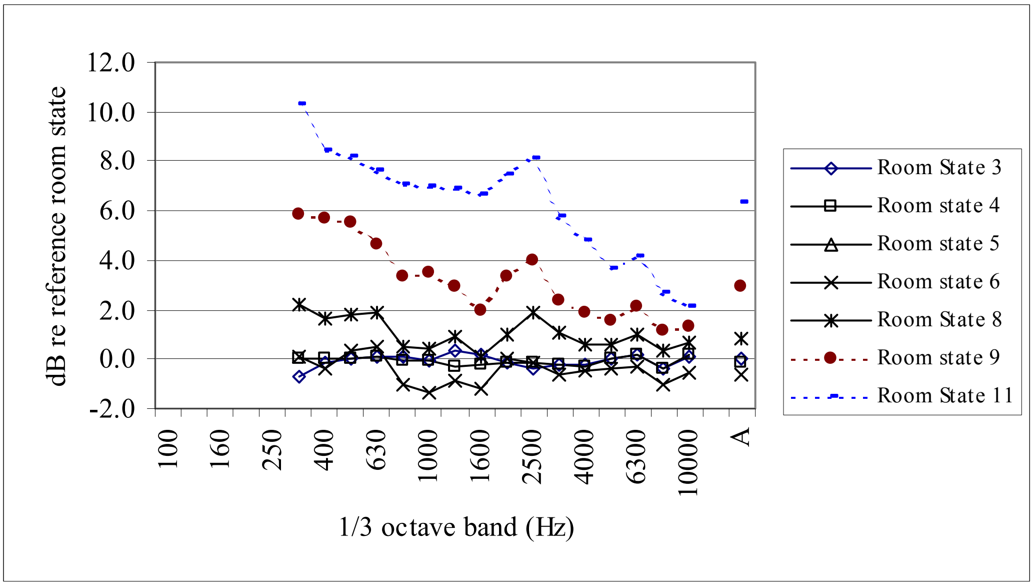


Figure 27. Level differences, ΔL determined for the Box source in rooms that qualified for broadband noise sources

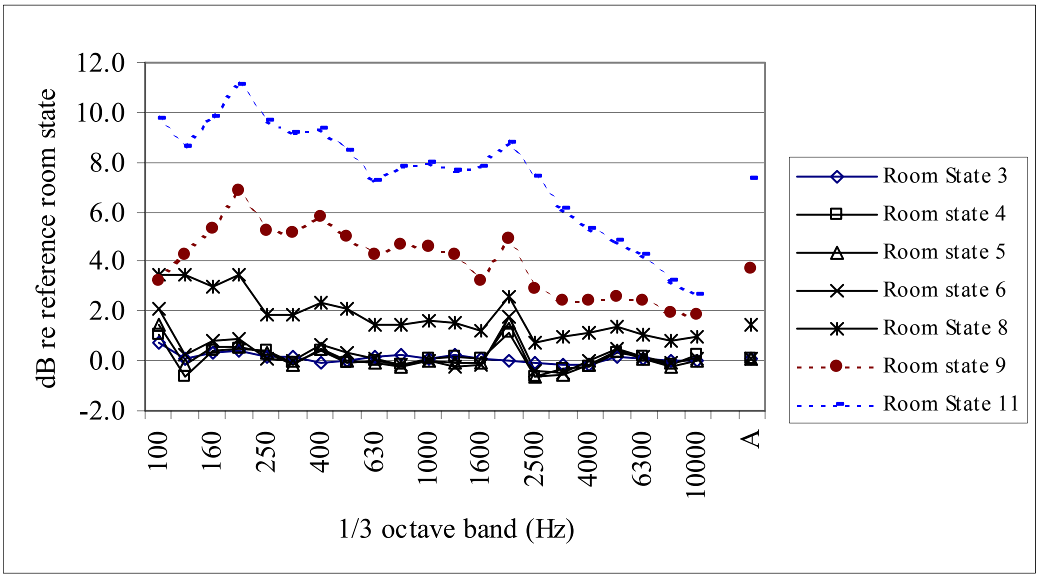
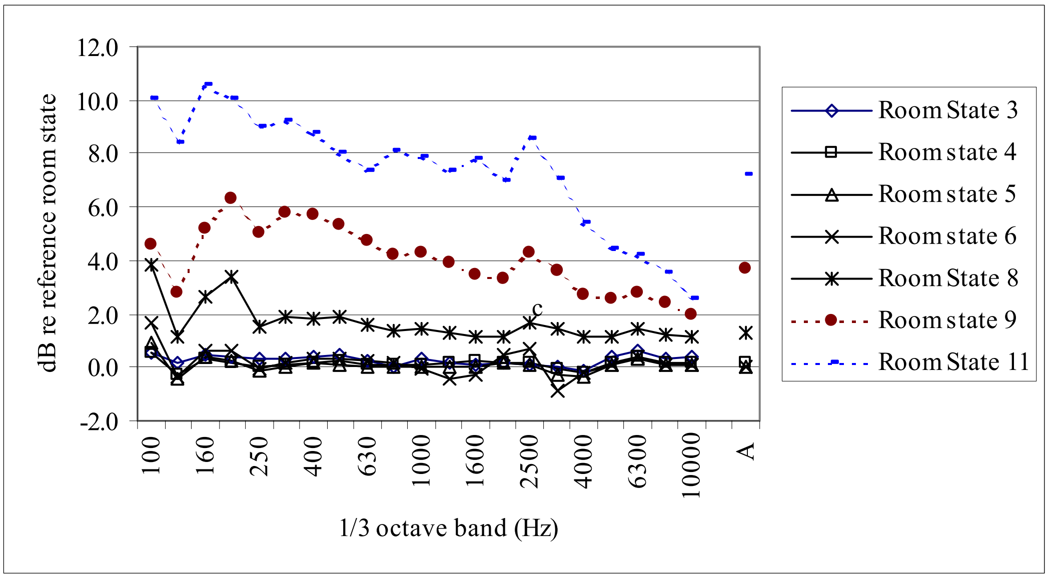


Figure 28. Level differences, ΔL determined for the RSS in rooms that qualified for broadband noise sources



From these Figures it can be seen that there are differences in sound power levels determined in the different rooms, and that there was a increase in absolute sound power level with an increase in the number of wedges removed. It can also be seen that values of ΔL can be much greater for rooms that qualified according to ISO 3745:2003 (dashed lines) than for rooms that conformed to the requirements of ISO 3745;1977. The measured noise emission level in the room is a summation of the direct emission and the reflected component and the increased levels are attributed to the additional contribution of reflected acoustical energy from the room boundaries. Data for the drill for frequencies below approximately 250 Hz have been omitted from the tables because it emitted negligible sound energy in these bands.

These values of ΔL, observed for the different rooms, were considered to be an indication of a systematic error and are certainly a clear indication of the influence of room performance.

The potential of such a systematic error can be appreciated if it is assumed that the 'true' value would be determined in an 'ideal' hemi-anechoic room and a correction could then be applied to levels determined in all other so called hemi-anechoic rooms. Having recognised this, it is important to consider how the problem could actually be dealt with in practice. The potential variation of sound power levels determined in different rooms has serious implications. This can be illustrated by considering the following simple scenario. A 'guaranteed' sound power level is determined for a machine in one room that has been qualified as being hemi-anechoic, and then subsequently the sound power level of the machine is independently checked in another room also qualified as hemi-anechoic. However, the level, which has been guaranteed, may differ in the two rooms due to the influence of the room performance that is not accounted for in the assessment of measurement uncertainty.

There are a number of options open to deal with this issue.

1. Variation of sound power levels due to the influence of the acoustic performance of individual hemi-anechoic test facilities could be corrected by

referencing back to an ideal test facility using a Reference sound source to establish K_2.

2. The qualification criteria could be changed to effectively eliminate the potential for variation between facilities, setting the tolerances to sufficiently limit the range of room performances.

3. Variation in sound power level due to the acoustic performance of the room boundary could be considered as a component in the overall measurement uncertainty.

It terms of the first option, it is considered that in practice, such a corrective requirement would not be appreciated, not only because it adds further burden to those making the measurements, but also in building such a specialist facility, it will be expected that the 'qualified' room will be suitably good for precision measurements. In any case, which facility would be deemed as ideal? There would be a need to have a reference room to which data obtained in all other hemi-anechoic rooms could be corrected. The considered view is that a room, which qualifies with specified criteria, should not need further correction. Correction would suggest that the test criteria are inadequate.

The second option takes the view that the tolerances of the criteria have not been set correctly and that they should be changed to eliminate or at least minimise the potential for variation in sound power levels determined in qualified hemi-anechoic facilities. To justify such an action it is necessary to analyse in some detail the variation in level across a range of rooms that meet the criteria.

The ΔL results presented in Figures 26, 27 and 28 clearly indicate differences in sound power levels determined in different rooms considered to be hemi-anechoic when assessed against the tolerance limits set out in Table 2 of Section 3. To reduce this potential spread of results it could be considered that the tolerance limits be lowered. However, it is likely that such a proposal would be opposed in practice as there are so many facilities which have been qualified as meeting the requirements. It is considered, however that it should be made clear to users of such facilities that although a facility may have been qualified as being hemi-anechoic, the acoustic performance of the room may still have an influence on the determined sound power level.

The third option offering an alternative to correcting for systematic variation or changing the well established tolerance limits, would be to treat any potential differences as source of uncertainty in the measurement procedure. The uncertainty contribution due the boundary conditions would be incorporated into the final guaranteed noise level. In this approach it would be assumed that the user would not necessarily know to what degree the particular facility would influence the determined sound power level. The level difference values obtained from the "hemi-anechoic" rooms simulated in this study could be used to derive an estimation of such an uncertainty.

4.4.2.3 Estimation of standard uncertainty for hemi-anechoic rooms

It has been shown in the previous sections that there is potential for a degree of variation in determined sound power level in different rooms that are considered hemi-anechoic, and it has been suggested that the reasonable approach to dealing with the issue would be to treat any potential differences as a source of uncertainty in the measurement procedure. This sub-section sets out an estimation of standard uncertainty to account for the performance of a hemi-anechoic room.

As stated above in sub-section 4.4.2, two indicators have been considered in the analysis of the influence of room boundary conditions on the determination of sound power levels. It has been suggested that the two indicators are discretely different, and as such the following sets out a brief analysis of the use of each data set for estimating a value of uncertainty.

In the case of the standard deviation based indicator, which has been considered in 4.4.2.1, it was determined that the standard deviations obtained from multiple measurements conducted in each hemi-anechoic room state remained relatively constant for all rooms. In effect the influence of the additional contribution of reflected energy on the measurement surface was not apparent. It was concluded that the use of the standard deviation indicator did not sufficiently reveal the influence of the room response.

However, in observing the absolute level differences between rooms, the influence of the room response was very much apparent. From the measurement results there was a clear indication of the potential for variation in sound power levels determined in different rooms that were considered as hemi-anechoic.

To enable evaluation of the uncertainty using the level difference data, the distribution of ΔL values strictly need to be considered in bilateral terms around a central value, in the form y ± $U_{(\Delta L)}$, where y is the measured value and $U_{(\Delta L)}$ is the uncertainty associated with ΔL. However, for the range of hemi-anechoic room states used in this study, the distribution of ΔL is between zero and the maximum value of ΔL and therefore the distribution is not bilateral in the true sense.

It is considered beyond the scope of the project to conduct a detailed investigation into formulating a suitable statistical analysis of the distribution of ΔL to obtain a precise value to represent the uncertainty associated with influence of room performance on the determination of sound power levels. So, as an alternative, a pragmatic approach to the problem has been taken on the basis that the aim is to obtain a quantitative value of the contribution of uncertainty due to room boundary conditions that while it certainly does not underestimate potential errors it may still be considered as reasonable.

The results discussed in sub-section 4.4.2.2 show that for a range of hemi-anechoic rooms there was a variation in sound power levels up to the maximum value of ΔL (ΔL_{max}). In practical terms this effectively means that as a user, it can be expected that the deviation from the true value could be any value up to ΔL_{max}. To take a pessimistic approach, it could be assumed that this non bi-lateral value of Δl_{max} may be used in an assessment of uncertainty by assuming it represents a semi-range and that ΔL may be described as having a rectangular distribution. Referring to uncertainty evaluation procedures specified in reference 8, the standard uncertainty can be obtained using the following expression:

$$U_{\Delta L} = \frac{\Delta L_{\max}}{\sqrt{3}} \qquad (8)$$

Tables 12 and 13 provide values of ΔL_{max} and the standard uncertainty, from Equation 8, associated with sound power levels determined in a hemi-anechoic room which has been found to meet the performance requirements as specified in ISO 3745:1977 and ISO 3745:2003 respectively for broad-band noise signals for the drill, the box source and the

RSS. Data for the drill for frequencies below approximately 250 Hz have been omitted from the tables because it emitted negligible sound energy in these bands.

It must be remembered, however, that these values of standard uncertainty are only loosely based on accepted statistical theory and as such are only intended as an indication of the magnitude of uncertainties associated with room performance.

It can be seen from Tables 12 and 13 that values of ΔL_{max} vary with frequency and are generally largest at low frequencies, with values just over 3 dB for the ISO 3745:1977 qualification and reaching just over 11 dB for the current ISO 3745:2003 procedure. The metric of prime importance is the A-weighted sound power level as this will be widely used in practice due to the requirements of various noise regulations, such as the Machinery Directive(13) and especially Directive 2000/14/EC(14) relating to the noise from machinery used outdoors. The A-weighted values of ΔL_{max} are 0.8 dB, 1.5 dB and 1.3 dB for the drill, box source and RSS respectively for the ISO 3745:1977 procedure which may be compared to 6.4 dB, 7.3 dB and 7.2 dB for the ISO 3745:2003 procedure.

Considering the A-weighted standard uncertainty values associated with a sound power level determination, values obtained using the ISO 3745:1977 procedure are 0.5 dB, 0.8 dB and 0.8 dB for the drill, box source and RSS respectively and these may be compared with the corresponding values of 3.7 dB, 4.2 dB and 4.2 dB when considering the ISO 3745:2003 procedure.

Clearly, the current room qualification procedure as specified in ISO 3745:2003 is inadequate and significant errors in sound power level determination may occur.

Table 14 lists data obtained for sources when considering tonal noise signals. In this case because the qualification criteria were only satisfied for room states with less than 20% of the wedges removed, the results are based on a limited data set.

Table 12. Standard uncertainty values associated with sound power level determinations in hemi-anechoic rooms qualified for sources with broad band noise characteristics according to ISO 3745:1977.

	Drill		**Box**		**RSS**	
Frequency	ΔL_{max} dB	Standard uncertainty dB	ΔL_{max} dB	Standard uncertainty dB	ΔL_{max} dB	Standard uncertainty dB
100	7.0	4.1	3.5	2.0	3.8	2.2
125	5.0	2.9	3.5	2.0	1.1	0.6
160	2.0	1.2	3.0	1.7	2.7	1.5
200	3.2	1.9	3.5	2.0	3.4	1.9
250	1.9	1.1	1.9	1.1	1.6	0.9
315	2.2	1.3	1.8	1.1	1.9	1.1
400	1.7	1.0	2.3	1.3	1.8	1.1
500	1.8	1.0	2.1	1.2	1.9	1.1
630	1.9	1.1	1.4	0.8	1.6	0.9
800	0.5	0.3	1.5	0.9	1.3	0.8
1000	0.5	0.3	1.6	0.9	1.5	0.8
1250	0.9	0.5	1.6	0.9	1.3	0.8
1600	0.2	0.1	1.2	0.7	1.1	0.6
2000	1.0	0.6	2.6	1.5	1.1	0.7
2500	1.9	1.1	0.8	0.4	1.7	1.0
3150	1.0	0.6	0.9	0.5	1.5	0.9
4000	0.6	0.3	1.2	0.7	1.1	0.6
5000	0.6	0.3	1.3	0.8	1.2	0.7
6300	1.0	0.6	1.1	0.6	1.4	0.8
8000	0.3	0.2	0.8	0.5	1.3	0.7
10000	0.7	0.4	1.0	0.6	1.1	0.6
A wtg	0.8	**0.5**	1.5	**0.8**	1.3	**0.8**

Table 13. Standard uncertainty values associated with sound power level determinations in hemi-anechoic rooms qualified for sources with broad band noise characteristics according to ISO 3745:2003.

	Drill		Box		RSS	
Frequency	ΔL_{max} dB	Standard uncertainty dB	ΔL_{max} dB	Standard uncertainty dB	ΔL_{max} dB	Standard uncertainty dB
100	14.4	8.3	9.7	5.6	10.0	5.8
125	12.7	7.3	8.6	5.0	8.4	4.9
160	12.6	7.3	9.8	5.7	10.6	6.1
200	12.2	7.1	11.1	6.4	10.1	5.8
250	10.8	6.2	9.7	5.6	9.0	5.2
315	10.3	5.9	9.2	5.3	9.2	5.3
400	8.4	4.9	9.4	5.4	8.8	5.1
500	8.2	4.7	8.4	4.9	8.0	4.6
630	7.7	4.4	7.3	4.2	7.3	4.2
800	7.1	4.1	7.8	4.5	8.1	4.7
1000	7.0	4.0	8.0	4.6	7.9	4.6
1250	6.9	4.0	7.7	4.4	7.3	4.2
1600	6.6	3.8	7.8	4.5	7.8	4.5
2000	7.5	4.3	8.8	5.1	7.0	4.0
2500	8.1	4.7	7.4	4.3	8.6	5.0
3150	5.8	3.3	6.2	3.6	7.0	4.1
4000	4.8	2.8	5.3	3.0	5.4	3.1
5000	3.7	2.1	4.8	2.8	4.5	2.6
6300	4.1	2.4	4.2	2.4	4.2	2.4
8000	2.7	1.5	3.2	1.8	3.5	2.0
10000	2.1	1.2	2.7	1.5	2.6	1.5
A wtg	**6.4**	**3.7**	**7.3**	**4.2**	**7.2**	**4.2**

Table 14 Standard uncertainty values associated with sound power level determinations in hemi-anechoic rooms qualified for sources with pure tone characteristics.

	Drill		Box		RSS	
Frequency	ΔL_{max} dB	Standard uncertainty dB	ΔL_{max} dB	Standard uncertainty dB	ΔL_{max} dB	Standard uncertainty dB
100	4.1	2.4	1.5	0.8	0.9	0.5
125	5.0	2.9	0.1	0.1	-0.4	0.2
160	1.1	0.6	0.6	0.3	0.4	0.2
200	1.6	0.9	0.6	0.3	0.2	0.1
250	0.3	0.2	0.4	0.2	-0.1	0.1
315	0.1	0.0	0.2	0.1	0.0	0.0
400	0.0	0.0	0.5	0.3	0.1	0.1
500	0.1	0.0	0.0	0.0	0.1	0.0
630	0.2	0.1	0.1	0.1	0.0	0.0
800	0.1	0.1	0.3	0.1	0.1	0.0
1000	0.0	0.0	0.1	0.1	0.0	0.0
1250	0.4	0.2	0.3	0.2	0.0	0.0
1600	0.2	0.1	0.1	0.0	0.0	0.0
2000	0.1	0.1	1.5	0.9	0.2	0.1
2500	0.0	0.0	0.0	0.0	0.1	0.1
3150	0.0	0.0	0.0	0.0	-0.3	0.2
4000	0.0	0.0	0.0	0.0	-0.3	0.2
5000	0.4	0.2	0.4	0.2	0.1	0.1
6300	0.3	0.2	0.1	0.1	0.3	0.2
8000	0.0	0.0	0.0	0.0	0.1	0.0
10000	0.1	0.1	0.2	0.1	0.1	0.0
A wtg	0.01	**0.01**	0.09	**0.05**	0.02	**0.01**

It can be seen from Figure 15 in sub-section 4.2.1.2 that the room states which did not conform to the qualification criteria according to either the new and previous ISO 3745 standards are the same, and so the data listed in Table 14 applies to both procedures.
It can be seen from Table 14 that, with the exception of 2 kHz for the box source, values of ΔL_{max} are all very close to zero. A-weighted values of 0.01 db, 0.09 db and 0.02 db were measured for the drill, box source and the RSS respectively.

Considering again the A-weighted standard uncertainty values, levels of uncertainty of 0.01 dB, 0.05 dB and 0.01 dB for the drill, box source and RSS were calculated. The data set considered for the tonal sources was more limited because there were fewer room states that passed the qualification criteria as pure tone signals were affected more than noise signals with the degradation in the acoustic performance of the room. An alternative way to express this would be that the tighter the room qualification criteria, the better the resulting measurement uncertainty associated with sound power levels. However, it may be assumed that the procedures in both standards provide an adequate assessment of room performance and that associated measurement uncertainties are minimal.

In summary, A-weighted sound power levels determined in a range of rooms deemed suitable for testing broad band noise sources indicated an average standard uncertainty of 0.7 dB for the ISO 3745:1977 procedures but this increased to 4 dB when considering the current ISO 3745:2003 standard. However, for rooms deemed suitable for tonal sources, the average standard uncertainty was the same for both standards at a much lower value of 0.02 dB. Clearly there is significant disparity between the uncertainty values derived from the noise and pure tone datasets.

It is concluded that the procedure for qualifying rooms using the broad-band noise methodology is over-tolerant of poor acoustic room performance, especially that specified in ISO 3745:2003, and can lead to unacceptably high levels of measurement uncertainty associated with sound power level determinations.

4.4.2.4 The use of K_2 in room qualification

In the process of varying the acoustic signature of the hemi-anechoic facility, a number of rooms were generated that met the criteria for hemi-anechoic performance but were clearly (both visually and according to the measured value of K_2) not hemi-anechoic. It should be born in mind, however, that the range of simulated rooms was limited and that geometry of the facility, which incorporates non-parallel walls as shown in Figure 8, may not be representative of standard rooms.

Instead of the complicated procedures specified in both versions of ISO 3745 regarding room qualification for broad-band noise sources it may be possible to carry out a simple K_2 assessment and then either correct sound power level data or perhaps define a value of K_2 that shall not be exceeded in order that the room may be deemed as hermi-anechoic. The values of ΔL_{max} listed in Tables 12, 13 and 14 for the RSS are actually values of K_2 and when used to correct the sound power levels of the drill and the box source it can be seen that the values of ΔL_{max} are greatly reduced. Considering the broad-band data of Tables 12 and 13, all corrected values are lower, with A-weighted values for the ISO 3745:1977 procedure reducing from 0.8 dB and 1.5 dB to 0.5 dB and 0.2 dB for the drill and box source respectively and for the ISO 3745:2003 procedure reducing from 6.4 dB and 7.3 dB to 0.8 dB and 0.1 dB. Using Equation 8, values of standard uncertainty associated with the drill and box source are 0.5 dB and 0.1 dB for ISO 3745:2003 and 0.3 dB and 0.1 dB for the ISO 3745:1977 procedure.

Clearly, the use of a RSS in a sound power level determination provides a much more reliable result, even when measurements are carried out in rooms that are clearly not hemi-anechoic.

The reason that the corrected values of ΔL_{max} are machine dependent is thought to be due to the emission characteristics of the machines and to some extent on the repeatability uncertainty associated with each machine. It was considered that sources with pronounced directionality and frequency spectrum characteristics may be affected more by the room response than a RSS. Also, the repeatability uncertainty associated with a RSS is known, from previous measurement to be less than that associated with the selected machines.

The possibility of defining a value of K_2 that must not be exceeded in order that a room may be considered as hemi-anechoic is dependent on the level of measurement uncertainty that is acceptable for a particular application. ISO 3745 is considered to be a precision grade standard and so quotes an A-weighted reproducibility uncertainty of 0.5 dB and so the value of K_2 should certainly be less than this value.

So, where rooms used for determining sound power levels of machines and products are not hemi-anechoic it is possible to apply a correction for environmental effects such as the influence of reflected or absorbed sound on the measurement surface, K_2 to a machine sound power level determined in a non-ideal environment to obtain the true value with relatively low values of measurement uncertainty.

5 SUMMARY & CONCLUSIONS

The main purpose of the study was to examine and quantify the relationship between uncertainty in the determination of a sound power level and the acoustical performance of the environment in which it is made. The investigation involved numerous repeat determinations of sound power levels for a range of noise sources having different emission characteristics in rooms with different acoustical performances. The generation of rooms with different acoustic signatures was achieved by modifying a hemi-anechoic chamber by were progressively removing absorbent wedges from the walls and ceiling of the room.

Observation of the room response measurements indicated that rate of sound decay in room remained relatively constant for the early iterations of room change. It was shown that broadband noise deviated less than pure tones, which could be attributed to averaging of the interference between the limits of the frequency band being analysed. At the final room state, where all the wedges had been removed such as to generate a semi-reverberant environment the rate of sound decay had reduced from around 6 dB per doubling of distance to around 3 dB. The greatest deviations of the sound decay rate from that of the initial state were observed at greater distances from the source.

The results of all inverse square sound decay measurements conducted were assessed against the performance criteria given in ISO 3745:1977 and ISO 3745:2003. The assessment indicated that for pure tone signals above 250 Hz, failure occurred at the point where around 20% of the absorptive wedges had been removed. It was found that the outcome of the assessment by the two different methods was for pure tones, relatively close, but was significantly different for broad-band noise. In assessing the room performance using noise signals, it was determined using the method specified in ISO 3745:1977 that from 250 Hz up to 4 kHz the room met the criteria up to the point where around 50% of the absorptive wedges had been removed. Most significantly, it was found that when the assessment procedures in ISO 3745:2003 were followed, the performance criteria was met at all frequencies except 125 Hz, even when all the absorptive wedges had been removed, such that the room state could be considered semi-reverberant. The room was clearly not hemi-anechoic and as such it was concluded that there was a flaws in the qualification procedure.

It was observed that the change in K_2 was relatively insignificant up to the point where around half of the absorbing wedges had been removed. Following this halfway stage, K_{2A} increased from 1.3 dB to 7.2 dB. So, for a wedge-lined room, the hemi-anechoic performance may not be seriously affected if some wedges are removed such that each space is surrounded by wedges so that a large area of wall is not exposed. This may prove useful when considering the provision of power supplies for both acoustic instrumentation and for the machine under test.

Two indicators were considered in the assessment of hemi-anechoic rooms. The first analysed standard deviations obtained from multiple sound power determinations conducted in each generated environment. It was found that in almost all cases standard deviations were less than 0.5 dB, with A-weighted values less than 0.1 dB and remain relatively constant from the initial room state to the final iteration of room change. The second approach was to consider variation in the absolute sound power levels between different rooms, ΔL. This indicated more significant variation between rooms with progressive increase in absolute sound power level with the increased removal of absorptive wedges. It was concluded that the use of the standard deviation indicator did not sufficiently reveal the influence of the room response.

Standard uncertainty values were derived with reference to the maximum Value of ΔL. Measurement results obtained in a range of rooms deemed suitable for testing broad band noise sources indicated an average A-weighted standard uncertainty of 0.7 dB for ISO 3745:1977 and 4 dB for ISO 3745:2003, yet for rooms deemed suitable for tonal sources, the average standard uncertainty for both standards was much lower at 0.02 dB. Thus, it may be assumed that if a room has conformed to the qualification requirements for tonal noise sources then sound power levels may be determined with low values of measurement uncertainty resulting from room effects. However, It is considered that the procedure for qualifying rooms using the broad-band noise methodology is over-tolerant of poor acoustic performance which can lead to unacceptably high levels of sound power uncertainty.

To reduce this potential spread of results it could be considered that the tolerance limits be lowered. However, it is likely that such a proposal would be opposed in practice as there are so many facilities which have been qualified as meeting the requirements. It is considered, however that it should be made clear to users of such facilities that although a facility may have been qualified as being hemi-anechoic, the acoustic performance of the room may still have an influence on the determined sound power level.

The use of a RSS in a sound power level determination provides a much more reliable result, even when measurements are carried out in rooms that are clearly not hemi-anechoic. So, where rooms used for determining sound power levels of machines and products are not hemi-anechoic it is possible to apply a correction for environmental effects such as the influence of reflected or absorbed sound on the measurement surface, K_2 to a machine sound power level determined in a non-ideal environment to obtain the true value with relatively low values of measurement uncertainty.

6 RECOMMENDATIONS

Annex A in ISO 3745:2003, that describes room qualification procedures based on consideration of sound pressure level decay rates, should be removed from the standard.

Methods to assess the quality of anechoic and hemi-anechoic rooms should be the subject of a future research programme and eventually form part of a new ISO standard concerned with the acoustical properties of indoor environments.

7 ACKNOWLEDGEMENTS

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14 Council Directive 2000/14/EC of 8 May 2000 on the approximation of the laws of the member states relating to the noise emission in the environment by equipment for use outdoors. Official journal of the European Communities, N^{o} L162/1, 3.7.2000.

ANNEX A HEMI- ANECHOIC ROOM SPECIFICATION

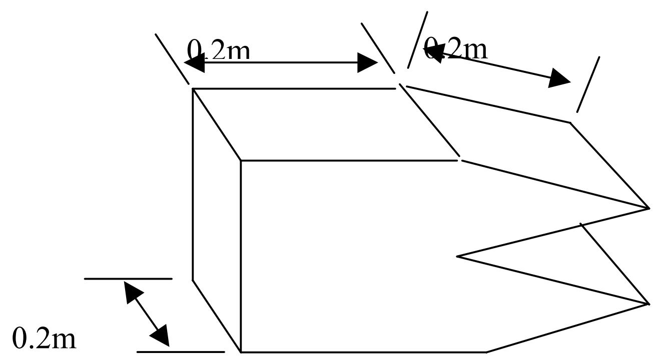
This annex provides information on the specification for the hemi-anechoic chamber at NPL used for the investigation.

The hemi-anechoic room has been determined as satisfying the requirements of ISO 3745[5] for hemispherical measurement surfaces with radii up to 1.5 m. It is an acoustically isolated asymmetrical chamber with a volume of 91.5 m^3. The walls, door and ceiling are covered with foam wedges that are mounted into a lattice of wooden slats. The floor is constructed from concrete. Table A.1 provides a summary of the room specification and Figure A.1 illustrates schematically the dimensions of acoustically absorbent wedges.

Table A.1 Summary of room specification

Surface	**Approximate number of wedges in room**
Ceiling	700
Walls	1926
Total	2626
Surface	**Wall dimensions (units: wedges)**
Wall 1	28*18
Wall 2	26*18
Wall 3	23*18
Wall 4	30*18
Ceiling	25 * 28 (approx)
Total	2626

Figure A.1.1 Dimensions of acoustically absorbent wedges



ANNEX B RESULTS OF CAVITY POINT SOURCE DIRECTIVITY TESTS

Table B.1 Directivity test result for pure tones

Frequency	SPL	Max DI	ISO 3745 Limit (± dB)
125	49.0	2.6	2
160	49.9	2.4	2
200	52.6	2.6	2
250	53.8	2.1	2
500	53.1	0.5	2
1000	51.9	0.6	2.5
2000	50.2	1.0	2.5
4000	51.5	2.0	2.5
5000	50.8	1.3	2.5
6300	50.3	1.7	3
8000	50.5	2.0	3
10000	42.2	1.5	3

Table B.2 Directivity test result for noise

	Cavity point source		RSS		ISO 3745 Limit (± dB)
Frequency	**SPL**	**Max DI**	**SPL**	**Max DI**	
100	24.0	4.4	65.1	2.3	2
125	18.0	2.1	63.5	2.4	2
160	31.7	1.4	63.7	3.1	2
200	39.4	1.8	64.4	1.8	2
250	39.6	1.0	65.3	2.1	2
315	38.9	0.3	65.2	2.5	2
400	38.8	0.6	64.9	2.7	2
500	42.1	0.3	64.8	3.1	2
630	41.2	0.3	65.5	3.2	2
800	38.3	0.2	67.1	2.6	2.5
1000	41.7	0.3	68.2	2.1	2.5
1250	38.8	0.5	69.7	1.3	2.5
1600	41.3	0.5	69.6	2.3	2.5
2000	39.4	0.5	68.9	1.7	2.5
2500	37.6	0.5	65.1	1.7	2.5
3150	38.6	0.7	65.8	2.2	2.5
4000	40.5	1.2	67.2	1.1	2.5
5000	38.7	0.3	66.6	1.9	2.5
6300	40.8	0.5	64.7	1.8	2.5
8000	39.9	0.3	62.7	0.9	3
10000	40.1	0.7	61.0	1.6	3