QUALIFICATION OF A LIGHTWEIGHT NINETY-FOUR CUBIC METER REVERBERATION CHAMBER FOR DETERMINATION OF SOUND POWER LEVELS OF SMALL NOISE SOURCES

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ABSTRACT

QUALIFICATION OF A LIGHTWEIGHT NINETY-FOUR CUBIC METER REVERBERATION CHAMBER FOR DETERMINATION OF SOUND POWER LEVELS OF SMALL NOISE SOURCES

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The qualification of a 94 m^3 reverberation chamber for pure tone and broadband sound power testing in accordance with American National Standard S1.21-1972 was achieved. The room modifications required were a rotating diffuser, low frequency panel absorbers and Helmholtz resonators. The effect of these modifications is documented and discussed in light of current theory and previous research.

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INTRODUCTION

The sound power output of a noise source is an essential piece of information for the acoustical engineer when designing areas for noise control. Sound power, for most noise sources, is relatively independent of the acoustical environment surrounding the source, and thus unequivocally characterizes the noise emissions of the source, unlike sound pressure, which is highly dependent on the acoustical characteristics of the surroundings, hence where a sound pressure measurement is made.

Unfortunately, sound power is not directly measurable, as there is currently no practical method of measuring acoustic power or intensity over the wide frequency range (100 Hz - 10 kHz) generally used in noise control work. However, the determination of the sound power emitted by a source may be made via the measurement of sound pressure and back-calculation through known relationships. This approach restricts the surroundings in which the measurement of sound pressure may be made to either of two "ideal" acoustic environments: that of the free-field, achievable outdoors or in an anechoic chamber; or a statistically diffuse field, achievable in a highly reverberant room. In either case, the chamber in question must be put through a "qualification" procedure to ensure that the results obtained are statistically satisfactory (in the case of the anechoic chamber, this would amount to ensuring free-field conditions).

The purpose of this thesis work was to develop the ninety-four cubic meter chamber of the transmission loss suite at the Centre for Building Studies, Concordia University, to the point where it would be qualifiable for both pure tone and broadband spectrum sound power measurement, according to guidelines specified by a North American standard. The project was primarily developmental in nature, although preliminary measurements of the effects of modifiers on the chamber characteristics were carried out in the process.

The thesis following is subdivided into four chapters. The first chapter presents the background to sound power measurement, both from a theoretical viewpoint and from the experience of other researchers. The second chapter describes the standard to which the chamber was qualified, and the instrumentation and facilities used. The third and fourth chapters present, respectively, the results and discussion, and conclusions of the study.

CHAPTER 1

BACKGROUND TO SOUND POWER MEASUREMENT IN REVERBERATION CHAMBERS

1.1 General

It will be of use further in this section to first present several relevant parameters developed from the wave theory of acoustics. These parameters are widely used in reference to acoustic processes in reverberation chambers.

A bounded air volume, such as in a reverberant room, will have many resonant frequencies, or normal modes. A mode may be thought of as a travelling wave of particular frequency which, having started at a particular point, eventually passes through the starting point in the same direction as it left, effectively a "closed loop" path. It can be shown that a rectangular parallelepiped of dimensions ℓ_x, ℓ_y, ℓ_z having perfectly smooth, rigid, boundaries has resonant frequencies given by[1]:

$$f = \frac{c}{2}\left[\left(\frac{n_x}{\ell_x}\right)^2 + \left(\frac{n_y}{\ell_y}\right)^2 + \left(\frac{n_z}{\ell_z}\right)^2\right]^{\frac{1}{2}} \qquad (1)$$

where

f = frequency, Hz

n_x, n_y, n_z = positive integers, 0, 1, 2, 3, ...

ℓ_x ℓ_y ℓ_z = room dimensions, m

c = speed of sound in air, m/s

The integers n_x, n_y, n_z indicate wave direction relative to the normalized room boundaries. Thus, a mode with one n_i non-zero and the other two equal to zero indicates a wave travelling parallel to one axis, and is known as an axial mode. Similarly, a wave moves parallel to one pair of room boundary planes when two n_i are non-zero and the last is equal to zero - a tangential mode. When all the n_i are non-zero, the wave does not move parallel to any axis or room planes, and is called an oblique mode.

The number of modes below a given frequency can be expressed by[1]:

$$N = \frac{4\pi V}{3c^3} f^3 + \frac{\pi S}{4c^2} f^2 + \frac{L}{8c} f \qquad (2)$$

where

N = number of modes below frequency f

V = room volume, m^3

$S = 2\,(\ell_x \ell_y + \ell_y \ell_z + \ell_x \ell_z)$, m^2

$L = 4\,(\ell_x + \ell_y + \ell_z)$, m

For narrow bandwidths of frequency, Equation 2 can be differentiated to obtain the number of modes within the bandwidth, or modal density. For larger bandwidths, e.g. 1/3-octave, the modal density is better obtained by subtracting the values of N given by Equation 2 evaluated at the upper and lower frequency limits of the band, and dividing by the bandwidth. This expression for η, the modal density is thus:

$$\eta = \frac{\frac{4\pi V}{3c^3}\left(f_2^3-f_1^3\right) + \frac{\pi S}{4c^2}\left(f_2^2-f_1^2\right) + \frac{L}{8c}\left(f_2-f_1\right)}{f_2-f_1} \tag{3}$$

$$\eta = \frac{4\pi V}{3c^3}\left(f_2^2+f_1f_2+f_1^2\right) + \frac{\pi S}{4c^2}\left(f_2+f_1\right) + \frac{L}{8c} \tag{4}$$

where

f_2, f_1 = upper, lower band limits, Hz

By inspection of Equation 2 and Equation 4, it can be seen that both the number of modes and the modal density increase greatly with frequency, the former predominantly by an f^3 term, and the latter by an f^2 term.

The half-power bandwidth of an individual mode, B_r, is defined as the width in frequency between the points 3 dB down in amplitude from the peak of the amplitude response of the mode. An expression for this bandwidth has been derived(2), assuming a random absorption coefficient less than 0.16, and is given by:

$$B_r = \frac{\bar{\alpha}c}{8\pi}\left(\frac{\varepsilon_x}{\ell_x} + \frac{\varepsilon_y}{\ell_y} + \frac{\varepsilon_z}{\ell_z}\right) \tag{5}$$

where

B_r = half-power bandwidth, Hz

$\bar{\alpha}$ = Sabine random incidence absorption coefficient

ε_i = 0 if $n_i = 0$, and $\varepsilon_i = 2$ if $n_i \neq 0$

ℓ_x, ℓ_y, ℓ_z = room dimensions, m

Now if

$$\bar{\alpha} = \frac{55.2\ V}{T_{60}\ Sc} \quad (6)$$

where

T_{60} = reverberation time, s

and if the assumptions are made that

$\varepsilon_x = \varepsilon_y = \varepsilon_z = 2$, i.e. an oblique mode

$\ell_x = \ell_y = \ell_z = V^{1/3}$

and

$S = 6\ V^{2/3}$

then

$$B_r = 2.2/T_{60} \quad (7)$$

Thus, the bandwidth of a typical mode may be expressed in terms of the reverberation time, which is an easily measured quantity.

Ideally, the response of a reverberation room would be linear with frequency. Due to the modal behaviour, this is, of course, not the case. However, if the modes of the room which have finite bandwidths B_r tend to overlap one another, then the response of the room will become more uniform. Thus, it is desirable that the separation in frequency between adjacent modes be less, by some amount, than the mode bandwidth B_r. This is expressed by:

$$M = B_r n = 2.2n/T_{60} \quad (8)$$

where

M = modal overlap index

Clearly, for any given degree of modal overlap and frequency, the maximum reverberation time can be evaluated and is given by[3]:

$$T_{60} \leq 0.705 \times 10^{-6} \frac{Vf^2}{M} \tag{9}$$

Conversely, for a given reverberation time, a modal overlap of M will only exist above a frequency

$$f \geq 1190 \left(\frac{MT_{60}}{V}\right)^{\frac{1}{2}} \tag{10}$$

With the modal properties of such a bounded enclosure defined in such a manner, the effects on noise source power output and distribution of sound pressure in the room may be investigated.

1.2 Variations in Power Output of a Source in a Reverberation Room

In the free field, the power output of a point monopole can be expressed as[1]:

$$W_o = Q^2 R_o \tag{11}$$

where

W_o = power output, watts

Q = source volume velocity, m^3/s

R_o = real part of the complex radiation impedance, mks rayls/m^2

For a source having high internal impedance such that Q is a constant regardless of the impedance into which it is radiating, the ratio of sound power radiated in a reverberant room to that of a free-field is[2]:

$$\frac{W}{W_o} = \frac{R}{R_o} \tag{12}$$

where

W = reverberant room sound power output, watts

R = real component of radiation impedance in reverberant room, mks rayls/m²

If

$$R = R_o + R_r \tag{13}$$

where

R_r = real component of radiation impedance due to reflected waves, mks rayls/m²

Therefore[4]

$$\frac{W}{W_o} = 1 + \frac{R_r}{R_o} \tag{14}$$

The reflected radiation impedance depends on frequency and location of the source with respect to the room boundaries. It has been shown theoretically [2] that a point monopole source located on a flat plane radiates twice the power, when considering a pure tone, than in the free-field, i.e. $W/W_o = 2$ or $10 \log(W/W_o) = 3$ dB, assuming that modes are well overlapped. In a source located at the junction of two walls, $10 \log(W/W_o) = 6$ dB, and for a trihedral corner of a room, the value is 9 dB. In all cases W/W_o approaches 1 as the source is moved greater than one wavelength (λ) away from the walls. Also at approximately $\frac{\lambda}{2}$ away from the walls, $10 \log(W/W_o)$ can vary from -1 to -12 dB.

Another study has shown that W/W_o is very nearly 1 for source positions located within a volume defined by[5]

$$\left\{\begin{array}{lcl} 0.25\ \ell_x & < x < & 0.75\ \ell_x \\ 0.25\ \ell_y & < y < & 0.75\ \ell_y \\ 0.25\ \ell_z & < z < & 0.75\ \ell_z \end{array}\right\}$$

where

$x, y, z \equiv$ source position coordinates

It has also been shown theoretically that the ratio W/W_o varies considerably over frequency with the amount of absorption in the room[2,3]. The random incidence absorption coefficient is related to the normal admittance of a surface, if $\bar{\alpha}$ is less than 0.16 and assuming the conditions imposed upon Equation 7, by[3]:

$$\bar{\alpha} = 8\ \mathrm{Re}(\beta) \qquad (15)$$

where

β = normal admittance

Over a range of 60-160 Hz, the ratio $10 \log(W/W_o)$ for a particular source position was found to vary by +12 to -19 dB for β=0.002 ($\bar{\alpha}$=0.016) where as it only varied by +4 to -9 dB for β-0.02 ($\bar{\alpha}$=0.16)[2]. On a space average basis, the ratio was found to vary from 0.1 to 10.0, with values tending towards 1 for increasing β.

A study of point dipole sources[4] indicated that W/W_o also varies highly for different source locations and dipole orientations. Again, at high frequencies, the value of W/W_o tends to 1.

It should be noted that W/W_o for a broadband source tends to be much closer to 1 even at lower frequencies as many more modes are excited, thus averaging the power output over the varying response levels of the modes.

A statistical approach is used to obtain expected space-average deviations of sound power output of a source, i.e. the variation over source locations. This can be expressed by(7):

$$\sigma_w^2 = 27\ g(M)/16\ M \qquad (16)$$

where

σ_w^2 = normalized space-average variance of sound power ratio W/W_o

assuming that the mode spacings are "next neighbour" Poisson distributed. It can be shown that with respect to reverberation time and room volume(8)

$$M = 1.1\ (V/T_{60})(f/1000)^2 \qquad (17)$$

and thus

$$\sigma_w^2 = 1.56\ g(M)(T_{60}/V)(1000/f)^2 \qquad (18)$$

The factor g(M), shown in Figure 1(7), is evaluated from a "next neighbour" Poisson distribution for a given degree of modal overlap.

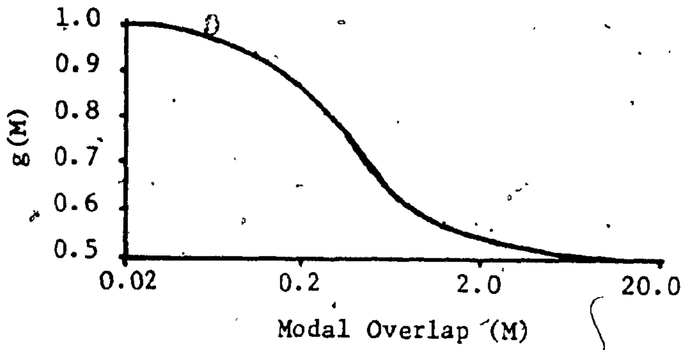


Figure 1. Values of g(M) as a Function of Modal Overlap

The value of σ_w^2 is a "worst case" value[8], i.e. for a point monopole source radiating a pure tone. It should be noted that under the assumption of pure Poisson modal spacing, i.e. g(M) = 1

$$\sigma_w^2 = 27/16\ M \tag{19}$$

However, the values of σ_w^2 derived using the "next neighbour" distribution appear to more closely agree with similar estimates made using mode summation techniques[8].

Another approach[5] attempts to define σ_w^2 in terms of a normalized space-average variance due to source position, and one due to room characteristics, with independency assumed, i.e.

$$\sigma_w^2 = \sigma_s^2 + \sigma_r^2 \tag{20}$$

where σ_s^2 = normalized source position variance

σ_r^2 = normalized room variance

Empirical relations found between σ_s^2 and σ_r^2, and β, over an average of six reverberation chambers of different configuration are

$$\sigma_s^2 \simeq 0.008/\beta \qquad (21)$$

$$\sigma_r^2 \simeq 0.0004/\beta \qquad (22)$$

for values of β between 0.00125 and 0.02. Agreement between these results and that predicted by Equation 18 was not very good for $\beta \geq 0.0025$, unless g(M) was given the value 0.84. This was attributed to the fact of ignoring axial and tangential modes in the normal mode analysis. It was also pointed out(5) that room dimensions, temperature, and pure tone oscillator stability must be very accurately controlled in order to accurately predict modal resonances and perform appropriate tests.

Typical requirements at low frequencies are that the room dimensions be known within 1 mm, the temperature be maintained within 0.10°C, and that oscillator deviations be kept within

$$\Delta f_{osc} \leq 4\beta c/5\pi L \qquad (23)$$

where

Δf_{osc} = oscillation deviation, Hz

L = $V^{1/3}$, m

Also, humidity fluctuations affect the speed of sound c, which shifts modes in frequency. Severe examples of modal shifting were presented, and the possibility of using these shifts via temperature changes for averaging of the sound power output of a source is examined. This method was found to be as effective in hard-walled rooms in averaging source output in order to reduce deviations as was alteration of the room boundary geometry, which inherently changed the modal response of the room. However, temperature averaging required inordinately high temperature differences for the moderately hard-walled room.

1.3 The Sound Pressure Field in Reverberant Rooms

The determination of sound power in a reverberant room is dependent on an accurate measure of the space/time average squared pressure in the reverberant field related by:

$$W = \frac{\{p^2\}\, S\bar{\alpha}}{4\rho c} \qquad (24)$$

where

$\{p^2\}$ = true space/time average sound pressure square, Pa^2 ({ } denotes average)

ρc = characteristic impedance of air, mks rayls

The above relationship is obtained under the assumption that the sound field is diffuse, that is, that the energy density (potential and kinetic) is uniform throughout the room, that the probability of energy flowing and impinging on the room surfaces is equal for any direction and angle of incidence, that the sound field can be considered as a superposition of an infinite number of plane progressive waves having propagation directions that are equally probable, and that at any point in the room, the phase relations between the waves are equally probable (i.e. random)[9]. Thus, if these assumptions are valid, and the absorption, temperature and humidity remain constant (i.e. ρc = constant), then W can be determined solely by a measure of $\{p^2\}$.

Since for small values of $\bar{\alpha}$, the Sabine reverberation equations hold, the sound power W can also be expressed by:

$$W = \frac{\{p^2\}\ V}{24.8\ \rho c\ T_{60}} \tag{25}$$

It is the expansion of Equation 25 which leads to the expression for sound power level in current standards (see 2.1).

The assumptions made in the derivation of Equation 24 are not generally valid. It has been shown[4] that due to lack of phase randomness at the room boundaries, that the energy density within $\frac{\lambda}{2}$ of the boundaries will be non-uniform and higher than that in the rest of the sound field, whether or not pure tone or broadband source characteristics are used. Furthermore, the sparsity of room modes at low frequencies precludes the possibility of having equal energy flow in all directions. If the sound pressure is measured only over a volume lying at least $\frac{\lambda}{2}$ from every boundary, the resulting calculated sound power will be lower. This is the rationale for the Waterhouse correction[4] used in the calculation in current standards, given by

$$10 \log \left(1 + \frac{S\lambda}{8V}\right) \tag{26}$$

It can be seen that the correction only has significance at lower frequencies when λ becomes appreciably larger.

If the modal density, and consequently, overlap, is sufficiently high, then a statistical viewpoint may be taken in order to determine deviation parameters about $\{p^2\}$. Above the Schroeder cut-off frequency, where the modal overlap M=3, given by:

$$f_c = 11900 \, (T_{60}/V)^{\frac{1}{2}} \qquad (27)$$

where

$$f_c = \text{cut-off frequency, Hz}$$

The probability density function for pure tone excitation was found both theoretically and experimentally to be exponential[10]. For more than one injected tone, i.e. multitone excitation, the probability density function was found to be chi-squared distributed (special case of the gamma distribution) only if the response to each tone in terms of squared pressure had an identical mean, and that each tone was uncorrelated from the next. The latter condition requires that the tones be well-spaced, such that no more than one tone excites a single mode.

From a knowledge of the probability density functions of sound pressure distribution, variances can be derived to enable prediction of the requirements for spatial averaging. It can be shown[4] that the probability of being within 1 dB of the mean of the distributed population of squared pressures for pure tone excitation and one sampling position is only 16%. Thus many sampling points are likely to be required, and the basis for pursuing the statistical approach is to determine how best to sample the sound field in order to reduce the error in the estimate of $\{p^2\}$, hence W.

The normalized variance of reverberant sound pressure squared is given by[11,12]:

$$\sigma_{p^2}^{\;2} = V_R^{\;2}/Neq \tag{28}$$

where

$\sigma_{p^2}^{\;2}$ = normalized variance of space-averaged reverberant sound pressure squared

$V_R^{\;2}$ = normalized variance of reverberant sound pressure squared

Neq = number of uncorrelated sampling points

The factor $V_R^{\;2}$ depends on room parameters and bandwith of the source signal, while Neq is a reducing factor based upon the effectiveness of the particular sampling configuration and is discussed later. In all cases considered, both $\{p^2\}$ and its estimate, p^2, are assumed to be time averaged.

The parameter $V_R^{\;2}$ can be defined as:

$$V_R^{\;2} = \{(p^2 - \{p^2\})^2\}/\{p^2\}^2 \tag{29}$$

and is the mean-square deviation of a measured p^2 from the true room average $\{p^2\}$. When modal overlap is high, i.e. $f > f_c$, the so-called statistical control region[11], the variance V_R^2 for multitone excitation can be shown to be[13]:

$$V_R^2 = \sum_{j=1}^{R} \sum_{k=1}^{R} A_j A_k \rho\left(f_j - f_k\right) / \left(\sum_{1}^{R} A_r\right)^2 \qquad (30)$$

where

A_j = room-average pressure squared, $\{p^2\}$, for the j'th tone, Pa^2

f_j = frequency of j'th tone, Hz

$\rho(f_j - f_k)$ = Schroeder frequency autocorrelation function

$$= \left[1 + \left(\frac{f_j - f_k}{B_r}\right)^2\right]^{-1}$$

R = number of tones

Several points are illustrated by Equation 30. First, since the autocorrelation function can only take on values $0 < \rho(f_j - f_j) < 1$, the maximum value of V_R^2 is 1 when only a single tone is present. If the multitones are well separated, i.e. $f_j - f_k >> B_r$, then $\rho(f_j - f_j) \to 0$, and then depending on the particular magnitudes of the individual tones, the variance is bounded by:

$$\frac{1}{R} \leq V_R^2 \leq 1 \qquad (31)$$

However, should the tones not be well separated, the variance V_R^2 is increased by a factor depending on the value of the autocorrelation function. Since B_r is inversely proportional to reverberation time, the variance rises as reverberation time is lowered.

For noise of bandwidth B, it can be shown that[13]:

$$V_R^2 \approx \left[1 + B\ T_{60}/6.9\right]^{-1} \qquad (32)$$

or

$$V_R^2 \approx \left[1 + 0.32\ B/B_r\right]^{-1} \qquad (33)$$

Clearly, as B becomes large relative to B_r, the variance decreases. This is attributed to the fact that a sufficiently wide signal bandwidth will excite uncorrelated room responses with respect to modal frequency separation[17]. The process may be thought of as a group of narrow bandwidths of noise exciting uncorrelated response with the resultant total squared pressure at a location being the sum of many narrower bandwidths. In effect, this reduces the variation at the location relative to the room average.

At low frequencies ($f < f_c$), there may be regions where modes do not overlap, because of the sparsity of modes available. Statistically, this lack of modes reduces the predictability of spatial variance, and a rigorous treatment of variance in this range has yet to be done. A crude estimate of V_R^2 for noise excitation has been made[11] and is expressed by:

$$V_R^2 \approx (1 + B\eta/\pi)^{-1},\ 0.2\ f_c \lesssim f \lesssim 0.5\ f_c \qquad (34)$$

At high frequencies, air absorption and rising coefficients of room boundary materials may give rise to semi-reverberant conditions, where a direct field bias is introduced. A distance of

$$d = 0.08\,(V/T_{60})^{\frac{1}{2}} \qquad (35)$$

will introduce a 3 dB bias error into the measurement(11). Expressions have also been derived(11) for the pressure squared variance when averaging takes place in the far field along a radial line to the source. This is given by:

$$\sigma_{p^2}^{\;2} = \frac{(\rho - 1)^2\,\bar{D}^2}{3\rho\,(1 + \bar{D})^2} + \frac{V_R^{\;2}}{(1 + \bar{D})^2} \qquad (36)$$

where

$\bar{D}$ = $p_o^{\;2} r_o^{\;2}/\{p_R^{\;2}\} r_1 r_2$

p_o = direct field pressure, Pa

r_o = reference distance for measurement of p_o, m

$\{p_R^{\;2}\}$ = room average of reverberant p^2, Pa^2

$r_1 r_2$ = endpoints of a radial line segment from the acoustic centre of a source, both in the far field, m

for uncorrelated direct and reverberant fields. As the direct field begins to dominate, the variance $\sigma_{p^2}^{\;2}$ begins to rise.

The variance $V_R^{\;2}$ can be effectively reduced by sampling over a volume of the room away from the boundaries. Statistically, by sampling N squared pressures which are independent and each have variance V_R^2, then the variance of the mean squared pressure is V_R^2/N (Equation 28). Since statistical independence is difficult to prove, it is sufficient that the sampled squared pressures be uncorrelated. The number of equivalent sampling points (for any sampling technique) which give uncorrelated squared pressures is denoted by Neq.

The normalized spatial covariance function[12]:

$$R(r) = \left[\sin(kr)/kr\right]^2 \qquad (37)$$

where

$R(r)$ = normalized spatial covariance function of squared pressure as a result of a separation distance r in meters

k = wavenumber

The function R(r) is plotted in Figure 2 as a function of r in terms of wavelength.

Clearly, if two sampling points are spaced exactly $\frac{\lambda}{2}$ apart, the squared pressures are uncorrelated, and moreover, for greater separations, the squared pressures are correlated only to an extremely small degree ($R(r) \leq 0.05$). At lesser spacings, squared pressures become highly correlated, that is, if a squared pressure p^2 is higher than the room average $\{p^2\}$, then a highly correlated point will also tend to have a squared pressure higher than $\{p^2\}$. The sampling of highly correlated points then tends to obtain squared pressures whose variance about the room average is higher than for uncorrelated points.

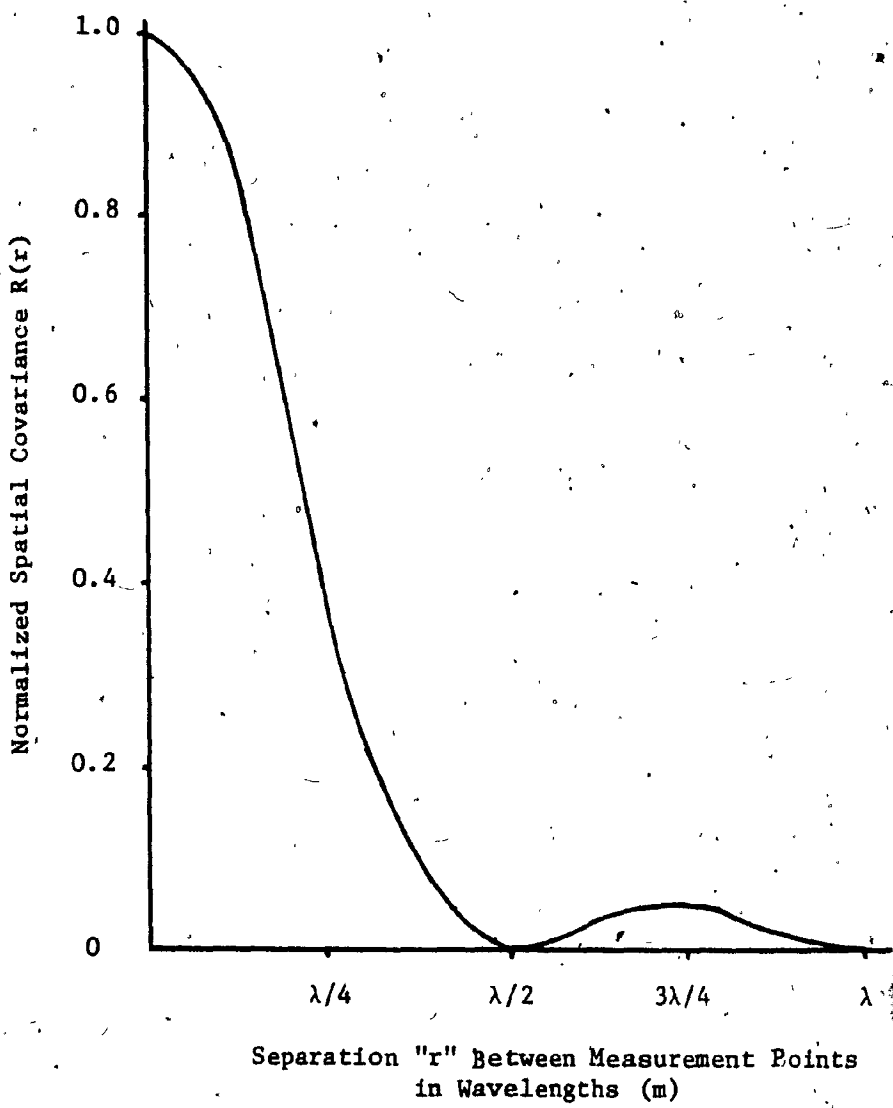


Figure 2. The Normalized Spatial Covariance Function

The number of uncorrelated samples available for various sampling techniques has been studied[12,14,15,16]. For a linear traverse of length L, the number of uncorrelated samples Neq is bounded by:

$$2L/\lambda < Neq < 1 + 2L/\lambda \qquad (38)$$

For a circular path of circumference L,

$$Neq \approx \begin{cases} 1 & \text{for } 2L/\lambda < 1 \\ 2L/\lambda & \text{for } 2L/\lambda \geq 1 \end{cases} \qquad (39)$$

For averaging over the surface of a disc of perimeter length L

$$Neq \approx 1 + (L/\lambda)^2/\pi \qquad (40)$$

While the above approximations are reasonably accurate for design purposes, evaluation of exact expressions indicate that for a path length L, the linear traverse is always superior to the circular traverse, and the circular traverse is superior to surface-of-disc averaging for $L/\lambda < 4.6$, where surface averaging becomes superior to both linear and circular averaging[15]. However, it should be noted that for a given available space, a linear path of length L or a circular path of <u>diameter</u> L may be used, and thus the effective path length for the circular traverse becomes πL, making it the better choice.

Discrete microphone arrays are also extensively used. For m microphones spaced $\frac{\lambda}{2}$ apart, Neq = m. Unlike traversing microphones., the number of uncorrelated samplings does not rise with frequency (i.e. λ getting smaller). However, the discrete array does become superior to the linear traverse of length L, for example, when approximately

$$f < \frac{mc}{2L} \tag{41}$$

Thus, there is somewhat of a trade-off using a discrete array. Should a sufficient path length not be available, a discrete array can perform better at low frequencies, but with a loss in uncorrelated samples at high frequencies.

1.4 Total Error in Sound Power Measurement

Indigenous to all current standards is the relation for total variance in sound power determination, given by:

$$\sigma_t^2 = \frac{1}{N_s}\left(\sigma_w^2 + \sigma_{p^2}^2\right) \tag{42}$$

where

σ_t^2 = total variance in measured sound power

N_s = number of source positions

σ_w^2 = variance in sound power output

$\sigma_{p^2}^2$ = variance in mean square pressure determination

The assumption made in Equation 42 is that the variation in sound power output and the variation in pressure determination are independent or uncorrelated with respect to source position. This assumption may hold at high frequencies (high modal overlap), but is not necessarily a good assumption at low frequencies[17], since there is some evidence to show that there is a high correlation between mean squared pressure and sound power output with source position[18].

It is also assumed that the errors involved in determination of reverberation time are negligible with respect to σ_w^2 and $\sigma_{p^2}^2$. Reverberation time measurements can be made very accurately, and results are repeatable[19]. The other required parameter for the calculation of sound power level, the room static pressure, can also be measured extremely accurately.

It might be noted at this point that the well documented[20,21] deviations seen in reverberant room sound power measurements from free-field measurements at low frequencies, may well be attributed to the choice of T_{60} reverberation time rather than the early decay time[21]. This is an area which warrants further study.

1.5 Effects of Rotating Diffusers

More than any other means, the rotating diffuser has enabled improved measurement precision for sound power in reverberant rooms. A complete theory of how the diffuser affects both the radiated sound power and pressure distributions in a room remains to be developed, but research to date does provide some insight as to reasons for diffuser effectiveness.

It has been shown experimentally that at low frequencies, a rotating diffuser alters the radiation impedance seen by a source in a cyclical manner, the particular impedance depending on a particular diffuser orientation[22]. The cyclical alterations were found to have an averaging effect on the radiation impedance, hence on the power output, and greater averaging was obtained with higher rotational speeds. It appeared that the diffuser caused a cyclical shifting in modal response from that of the bare-room condition, which would account for changing radiation impedance. Diffusers were found to be primarily effective down to frequencies where the vanes (i.e. panels) had dimensions in the order of $\frac{\lambda}{2}$.

With respect to the sound pressure field, it has been shown that diffusers modulate the pressure in both amplitude and frequency [13,23], with greater effects as source frequency increases. At low diffuser speeds, the amplitude distribution is independent of diffuser rotational speed, while at higher speeds, a dependence exists. Frequency sidebands appear about the source frequency (assuming a pure tone), and are spaced at intervals corresponding to the diffuser rotational speed in revolutions per second. The resultant sound field is that of a multitone distribution, resulting in reduced spatial variance.

At low frequencies, then, a reduction in σ_w^2 may be expected, but there is insufficient data to be able to quantify the amount. At high frequencies, a reduction in $\sigma_{p^2}^2$ may be obtained. The room averaged variance of pressure squared, $\sigma_{p^2}^2$ may then be expressed by[11]:

$$\sigma_{p^2}^2 = V_R^2/M' \, Neq \tag{43}$$

where

M' = figure of merit for rotation diffuser (RD) - pure tone only

$$= \left. V_R^2 \right|_{RD \text{ stationary}} \Big/ \left. V_R^2 \right|_{RD \text{ rotating}} \qquad (44)$$

Typical values for M' are in the range of 2 and 4, although values above 10 have been found[11]. This benefit has proven essential in qualifying many reverberation rooms, where a variety of diffuser configurations have been used[24,25,26,27]. At present, there is still no complete information on the effect of diffuser design parameters (e.g. vane shape, size, orientation) on achievable figure of merit.

1.6 Stationary Diffusers

Stationary diffusers have been used to encourage diffuseness in reverberant room sound pressure fields, primarily in European facilities. They have been found effective[9], but are awkward with respect to size and number of panels required. Moreover, rotating diffusers are found to be more effective[9] and occupy lesser amounts of space.

CHAPTER 2

EXPERIMENTAL METHODOLOGY AND FACILITIES

2.1 Description of Qualification Standard

The qualification of the reverberation room for sound power testing was made following guidelines set down in American National Standard S1.21-1972, "Methods for the Determination of Sound Power Levels of Small Sources in Reverberation Rooms"(29), published by the American National Standards Institute, Inc. (ANSI), and included in Appendix A. The standard provides guidelines for room design and detailed procedures for experimental measurement in both 1/3 and 1/1 octave bands. It is similar in scope to standards published by the International Standards Organization (ISO), namely ISO 3741, 3742, and 3743(30,31,32). A brief review of the provisions of ANSI S1.21-1972 for 1/3 octave bands is presented below for completeness.

2.1.1 General

Specified reverberation room requirements are summarized as follows:

i) Preferable room volume for measurement in the 125 Hz octave band is 200 m^3.

ii) The absorption coefficient of the room should not exceed 0.06 except below a frequency of

$$f = 2000/V^{1/3} \qquad (45)$$

where V = room volume, m^3

where the coefficient may rise as high as 0.16. Also, the absorption coefficient of the floor must not exceed 0.06, and no other surface should have a coefficient outside the range of 0.5 to 1.5 times the mean absorption coefficient of the room.

iii) The background noise in the room must be at least 6 dB, preferably 12 dB, below testing levels.

iv) The product of temperature (°C) plus 5°C and relative humidity during testing must be within 10% of the same product obtained at the time of reverberation time testing.

The standard also presents proportional ratios of room dimensions which have been found to facilitate qualification.

Measurement equipment provisions state frequency response tolerances ranging from -2 to + 1.5 dB over the range of 100-8000 Hz (but depending on the individual 1/3-octave frequency band) for the complete instrumentation system. Precision microphones and high-quality filters are specified according to existing instrumentation standards. Signal averaging is allowed either by integration over a fixed time interval (preferred method) or by continuous averaging of the squared signal voltage. In the former case, the standard deviation of a steady-state sine wave input must be less than 0.25 dB. Calibration of the measurement instrumentation must be made before each set of measurements using an acoustical calibrator with accuracy greater than 0.5 dB, and electrical and acoustical calibrations of the entire measurement system must be performed over the frequency range of interest annually.

Space-averaging techniques can be either a fixed microphone array consisting of at least three microphones spaced at a minimum of a half-wavelength of the lowest frequency of interest apart, or a microphone traverse of at least three meters in length. Instrumentation averaging must take place over a whole number of traverses or scans of the array (integration over a fixed time interval), or the period of the traverse or scan must be less than twice the time constant of the analyzer (continuous averaging). Also, no measurement microphone must be closer to the source than

$$d_{min} = 0.08\sqrt{V/T} \text{ meters} \tag{46}$$

where V = room volume, m^3

T = reverberation time, seconds

The plane of the traverse or array should not lie within 10° of any room surface, nor should any microphone be within a half-wavelength of the lowest frequency of interest of any room surface.

The source should not be placed within 1.5 meters of any wall of the room, should not be located on a geometric room center line, and source locations must be at least one quarter-wavelength apart at the lowest frequency of interest.

2.1.2 Provisions for Pure Tone Qualification

The standard describes two methods for qualification for pure tone sound power measurement. The first method entails the calculation of the number of source positions and microphone positions/traverse length required to ensure meeting the specified uncertainty requirements. The second method, the one used in this study, involves the direct determination of the uncertainty in measurement of a pure tone in a 1/3-octave. The near-field frequency response of a loudspeaker is measured at between 22 and 27 individual frequencies in each 1/3-octave over the frequency range of 100-2500 Hz. The speaker is acceptable if adjacent pressure level measurements differ by no more than 1 dB. The measurements provide correction factors to remove the loudspeaker response characteristic when using it for room qualification. Also, the terminal voltages across the loudspeaker voice coil are maintained at the same levels for subsequent tests to avoid any non-linear efficiency characteristics.

The same frequencies are then input to the room, and a space-time average is made via the microphone traverse (or array) and frequency analyzer. The standard deviation in each 1/3-octave band is then obtained from:

$$S = (n - 1)^{-\frac{1}{2}} \left[\sum_{i=1}^{n} (L_i - L_m)^2 \right]^{\frac{1}{2}} \tag{47}$$

where

S = standard deviation, dB

L_i = space-time averaged sound pressure level at a frequency in a 1/3-octave band, dB

L_m = mean of the L_i's within a 1/3-octave band, dB

n = number of test frequencies within a 1/3-octave band

Multiple source positions can be used in an effort to average the power output of the loudspeaker. Individual L_i's for different source positions may then first be averaged on a pressure-squared basis prior to evaluating the standard deviation for the band.

The standard deviations below which qualification is achieved are shown in Table I.

TABLE I

MAXIMUM ACCEPTABLE STANDARD DEVIATIONS FOR PURE TONE QUALIFICATION

1/3 Octave Center Frequency (Hz)	Maximum Acceptable Standard Deviation (dB)
100 to 160	3.0
200 to 315	2.0
400 to 630	1.5
800 to 2500	1.0

It should be noted that this qualification procedure need only be carried out below the larger of

$$f = 6000/\ell \tag{48}$$

and

$$f = 5000\ (V)^{-1/3} \tag{49}$$

where

ℓ = traverse length, m

V = room volume, m^3

The room response is assumed to be adequately diffuse above these frequencies to ensure acceptable deviations in measurement.

2.1.3 Broadband Qualification

A reference sound source is used in this procedure to generate noise of a broadband frequency characteristic. Eight or more source positions are used, with a space-time measurement in 1/3-octave bands made for each position. The standard deviation in each 1/3-octave band is obtained using

$$S = (n - 1)^{-\frac{1}{2}} \left[\sum_{i=1}^{n} (L_i - L_m)^2 \right]^{\frac{1}{2}} \qquad (50)$$

where

S = standard deviation, dB

L_i = sound pressure level in a 1/3-octave band at a source position, dB

L_m = mean of L_i's for a 1/3-octave band, dB

n = number of source positions

The room is said to qualify for broadband sound power measurement if it meets the target standard deviations shown in Table II.

TABLE II

MAXIMUM ACCEPTABLE STANDARD DEVIATIONS
FOR BROADBAND QUALIFICATION

1/3 Octave Center Frequency (Hz)	Maximum Acceptable Standard Deviation (dB)
100 to 160	1.5
200 to 630	1.0
800 to 2500	0.5

2.1.4 Calculation of Sound Power Levels

Once a qualified room is put to use to measure sound power output of noise sources, the calculation of sound power level is provided via:

$$L_w = L_p - 10 \log (T) + 10 \log (V) + 10 \log (1 + S\lambda/8V) + 10 \log (B/1000) - 14 \quad (51)$$

where

L_w = sound power level in a 1/3-octave band, dB re 1pW

L_p = space-time averaged sound pressure level in a 1/3-octave band, dB re 20 μPa

T = reverberation time, s

V = room volume, m^3

λ = wavelength at the center frequency of a 1/3-octave band, m

S = total surface area of room, m^2

B = barometric pressure, mbars

It should be noted that the sound power level of an unknown source may also be obtained using a reference sound source in a previously qualified room.

2.2 Reverberation Room and Instrumentation

The reverberation room is the larger of two rooms comprising the transmission loss suite in the acoustics laboratory at the Center for Building Studies. Its construction details have previously been reported[33], and are summarized herein.

The enclosure is rectangular with a volume of about 94 cubic meters, and dimensions of 5.10 x 6.14 x 3.00 m. The dimensional ratio of 0.83 : 1 : 49 is very close to that suggested in the aforementioned ANSI standard. The room has a 3 x 2.5 m opening to the smaller room, currently filled with a wall constructed of 50.8 x 101.6 mm studs covered on both sides by 15.87 mm gyproc, and the cavity filled with fibreglas insulation. The walls of the room proper are of staggered stud/gyproc construction. The outer surface is 12.7 mm gyproc fastened on spring clips, while the interior is a laminate of 12.7 and 15.87 mm gyproc. Again, fibreglas fills the cavity. The ceiling is of similar construction but suspended from the building structure on vibration hangers. The walls and ceiling are covered with 0.81 mm aluminum sheet. The poured concrete slab, forming the floor surface and supporting the walls, is isolated from the building structure on compressed fibreglas blocks. A triple solid-wood door system, with appropriate gaskets and seals, provide access to the room.

The microphone traverse runs linearly along the major body diagonal of the room. The microphone is cable-driven from a small electric motor controlled by an in-house designed and fabricated digital circuitry. Endpoints for the traversing microphone, velocity, and number of repetitive cycles are panel selectable. Due to room size, a 3 m path length cannot be achieved under the provision of ANSI S1.21-1972 necessitating a half-wavelength minimum distance between microphone and nearest room boundary. With a 3 m path length, the distance in this room is reduced to a quarter-wavelength, which has been recommended in another study([34]).

The instrumentation system is shown in Figure 3. The 12.77 mm microphone, a Bruel and Kjaer (B & K) 4134, and B & K 2619 preamplifier ride in the traverse mounting and are cabled to a B & K 2131 digital 1/3-octave frequency analyzer. This analyzer is digitally controlled by a Hewlett-Packard (HP) 9825A desktop calculator via the IEC interface. Data storage and software programs are achieved through the integral tape mechanism of the 9825A and through a parallel interface with an HP 9885M flexible disk drive. Data output is available on either the 2131 CRT, the 9825A internal printer, a Tektronix 4662 digital plotter on the IEC interface, or on a Centronics 306C line printer.

Pure tones were generated by a B & K 1022 beat frequency oscillator. For all 1/3-octave bands except 250 Hz, the signal was fed through a B & K 4205 sound power source to its matched loudspeaker. This loudspeaker was qualifiable in all 1/3-octave bands except 250 Hz. In this band, the signal was fed through a B & K 2706 amplifier to an Electro-Voice EVM-12L loudspeaker. The period or frequency of the pure tones were monitored with an HP 5512A counter, while the terminal voltages of the speakers were measured with a Fluke 8600A DVM.

For the broadband testing, an ILG reference sound source was used.

Programs for the HP 9825A were written to control the B & K 2131 during data acquisition and storage, and for data retrieval and calculation of standard deviations. Another program was developed to automate reverberation time measurements through the B & K 2131, and to calculate appropriate statistical parameters. The program listings are included in Appendix B.

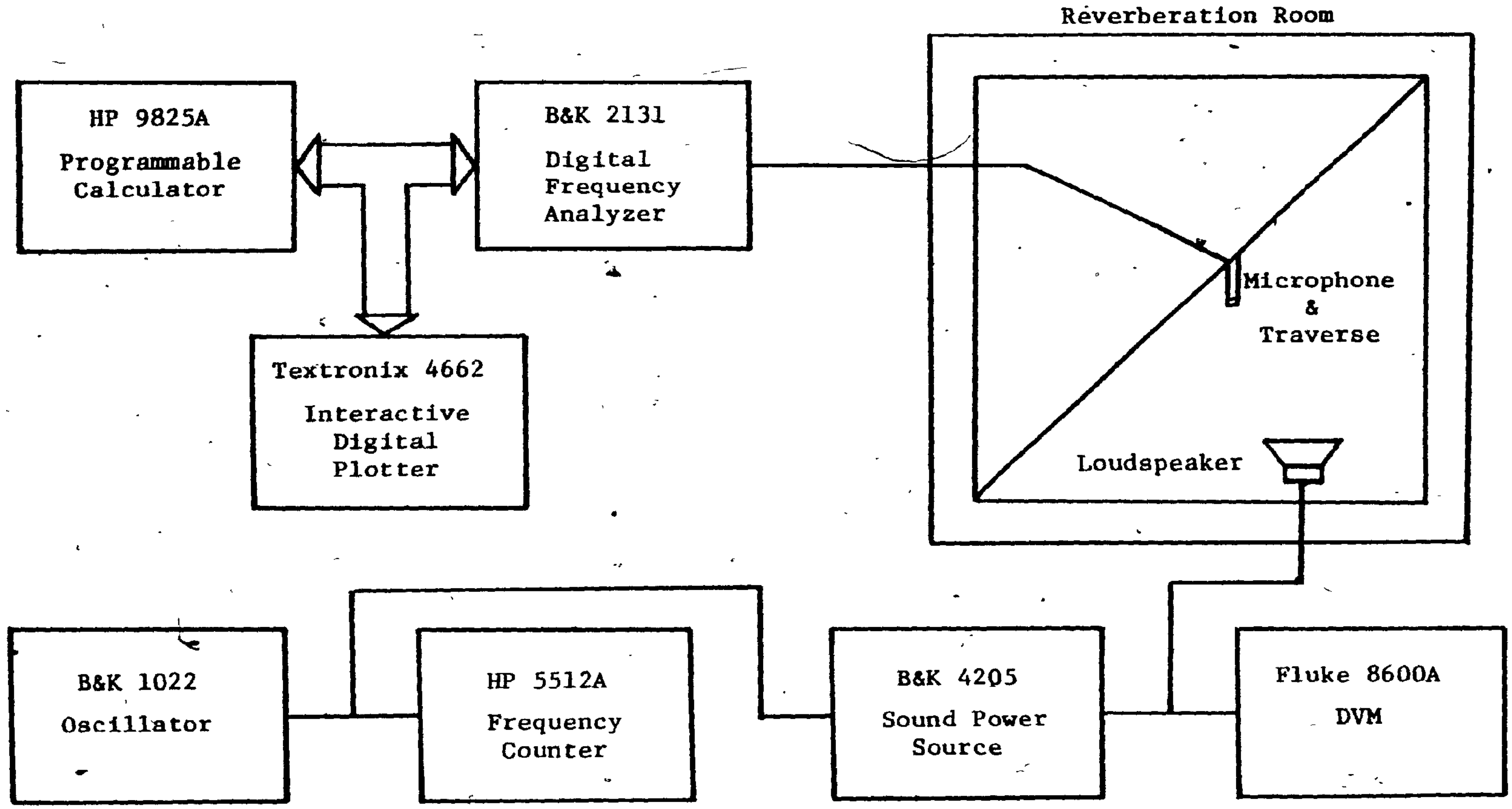


Figure 3. Schematic of Instrumentation for Sound Power Qualification

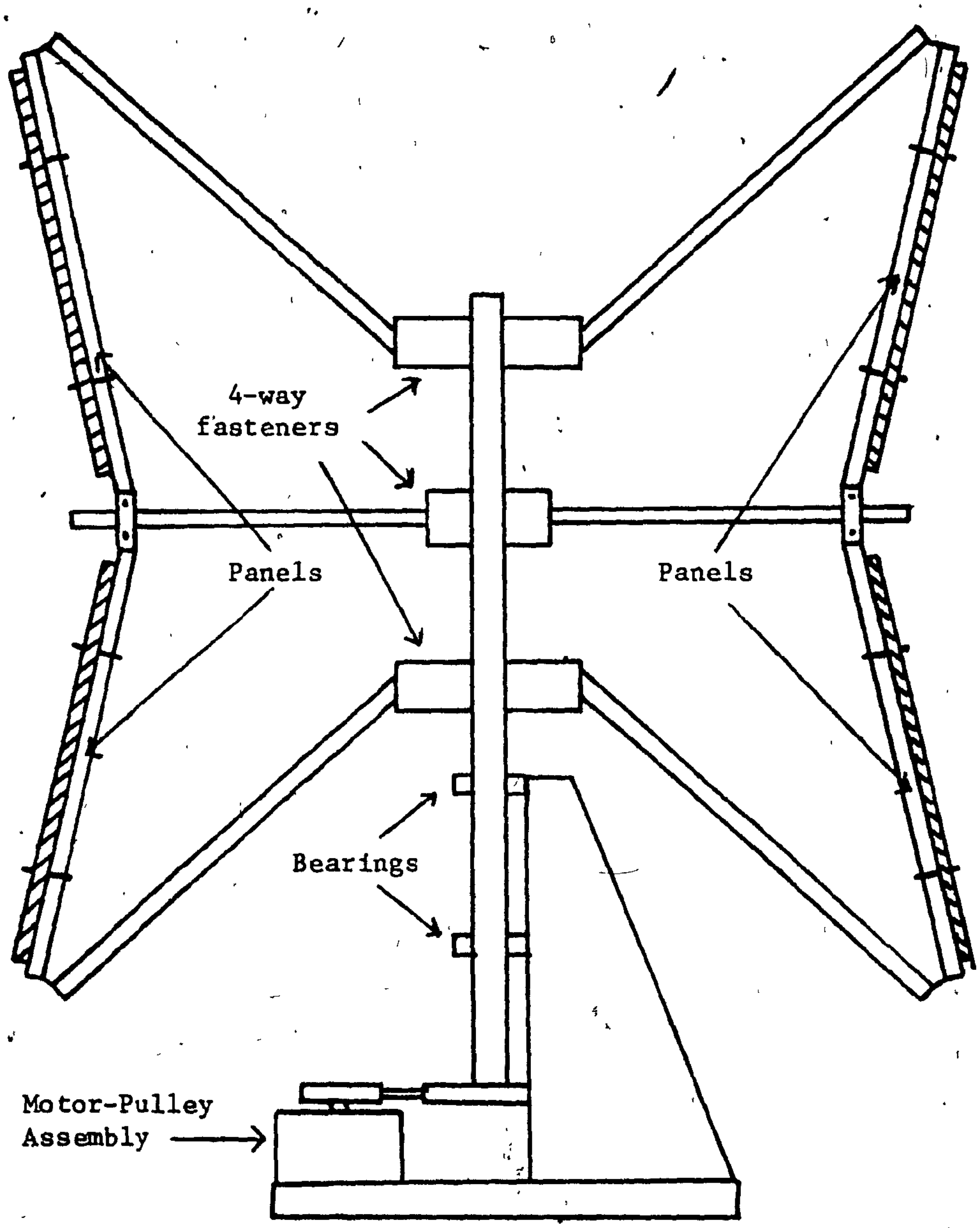
2.3 Rotating Diffuser

The rotating diffuser in the acoustics laboratory was designed not only to assist in the qualification of the reverberation room but also to offer enough flexibility in its parameters to enable further research into diffusion and diffuser performance subsequent to this study.

The diffuser, as shown in Figure 4, is essentially biconically shaped. It consists of a central steel shaft supported by two thrust ball bearings. Three standard four-way pipe fittings are welded onto the shaft. Four pipe arms are connected to the upper and lower fittings by 45° elbows and pipe nipples. At the end of each of the eight arms, a steel hinge is welded, with the moveable flap drilled to accept two threaded U-bolts. From the center four-way fitting, four threaded rods extend horizontally. The panel support rods are centrally connected to a fitting which slides along the threaded rod and can be positioned with two nuts. The other ends of the rods are fastened to the aforementioned hinges with the U-bolts.

The panels, eight in total, are trapezoidal shaped: 0.75 m maximum width, 0.375 m minimum width, and 1 m in length, and are made of 19 mm plywood sealed with a polyurethane coating to avoid high frequency absorption. They are fastened to the support rods with U-bolts. The panels are moveable along a 15°-35° arc from the vertical, and can rotate about their support rods over a total arc of approximately 120°.

The central shaft is rotated via an AC electric motor pulley driving a 10:1 gear reducer box, and a reducing pulley arrangement.



Note: Same symmetry in plane perpendicular to this section.

Figure 4. Schematic Section of Rotating Diffuser Showing Layout of Major Components

Rotational velocities are changed by altering the pulley configuration between the gearbox and the idler and/or changing the diameter of the split-sheeve pulley on the motor shaft. Standard speeds for this study were 7.5, 15, and 30 rpm.

2.4 Low Frequency Absorbers

Two different types of low frequency absorption were introduced into the room in its final configuration. Two panel absorbers, each measuring 0.93 x 1.22 m, were constructed using 9.5 mm plywood as a backplate, 27 mm thick softwood as framing members, and 3.2 mm plexiglas as the panel. This combination gives a resonant peak, according to theory([35]), of about 200 Hz. Fibreglas of 25.4 mm thickness was placed in the cavities to increase the absorption. The exteriors were sealed with polyurethane varnish, and joints of individual pieces were sealed.

Bottle absorbers, 143 in total, were used to add extra absorption around 200 Hz. The volume of each is about 356,000 mm^3, with a neck length of 28 mm, and a neck area of 239.5 mm^2. This gives, according to theory([35]), a fundamental resonance of 215 Hz. Small pieces of fibreglas were placed in each bottle to increase the bandwidth of the effective absorption.

2.5 General Procedures

The loudspeaker qualification was done outdoors as no semi-anechoic facility was available. Measurements of the sound pressure level at a distance of 15 mm on a central axis from the speaker face and speaker terminal voltage were made for each of the 361 test tones. Correction factors normalized to the center-band frequency for the loudspeaker were obtained and applied to later measurements in the reverberation room via the program software.

Measurements in the reverberation chamber used primarily the 3 m traversing distance and 32 s linear average. The output voltage of the oscillator, whose output was previously checked with an oscilloscope to ensure a sinusoidal characteristic, was varied to match the previously measured speaker terminal voltages. Correction factors for rolloff of the digital recursive filters in the frequency analyzer were also obtained as a function of tone frequency normalized to the center band frequency. The appropriate correction factors were then added to each measured sound pressure level average and stored via the calculator tape facility. Subsequent calculations were software controlled.

Calibration of instrumentation and measurement of humidity were performed before and after each group of measurements.

CHAPTER 3

RESULTS AND DISCUSSION

3.1 Loudspeaker Qualification

Two loudspeakers were used since the B & K 4205 speaker did not qualify in the 250 Hz band. Correction factors for the two loudspeakers used are listed in Appendix C. In the process of testing for standard deviations, it was found that the deviations were abnormally high in the 1000 Hz and 2000 Hz bands, since modal overlap in the room at these frequencies would be expected to be great. The loudspeaker qualification routine was repeated using five microphone positions which divided up the speaker face into equal areas. An area weighted correction factor for each frequency within these bands was then obtained, and resulted in significantly lower standard deviations. It is possible that this discrepancy occurs due to interference patterns set up at these frequencies, causing an increase in the on axis response, or an effect caused by the speaker housing vertical dimension being about 0.3 m, i.e. λ and $\frac{\lambda}{2}$, for the 1000 Hz and 2000 Hz bands respectively. The data for this requalification is also included in Appendix C.

It should be noted that there is some controversy as to the provision of the standard requiring the microphone to be positioned between 10-20 mm from the speaker face. The rationale for this is that the free-field radiation impedance in the near field of a loudspeaker will be constant and frequency independent for $ka<1$, where "a" is the effective speaker radius. While experimental evidence supports this theory[18], it is argued[27] that the microphone should be no closer than $\frac{a^2}{\lambda}$ to the source due to speaker beaming. Whether or not the 10-20 mm distance and $\frac{a^2}{\lambda}$ criteria are both met depends upon the speaker diameter. In the case of the speakers used here, a speaker of approximately 63.5 mm effective radius is used up to about 1500 Hz, except for the 250 Hz band. This diameter requires a minimum separation of about 17.5 mm at 1500 Hz. At frequencies above 1500 Hz, up to a maximum of 2780 Hz, the minimum required separation for the dome tweeter of approximately 12.7 mm diameter (at 2780 Hz) is about 1.5 mm. At 250 Hz for the EVM12L loudspeaker with an effective radius of approximately 133 mm, the separation should be in the order of 13 mm.

Since a separation of 15 mm was used for all speakers, it can be seen that both criteria are met, or almost met, over the entire frequency range of interest.

3.2 Pure Tone Qualification Results - Unmodified Room

The modal densities, reverberation times, absorption coefficients, and modal overlaps for the unmodified room are shown in Table III for V = 93.9 m^3 and S = 130 m^2.

The absorption coefficient values rise at low frequencies, which is likely attributable to the admittance of the room walls. The double wall construction with fibreglas filler appears to be reacting in much the same manner as low frequency absorber panels.

TABLE III

VALUES OF UNMODIFIED ROOM PARAMETERS

Center Freq. (Hz)	n	T_{60}*	$\bar{\alpha}$	M
100	0.49	1.86	0.06	0.58
125	0.70	2.33	0.05	0.66
160	1.06	2.69	0.04	0.87
200	1.56	3.18	0.04	1.08
250	2.32	4.56	0.03	1.12
315	3.53	5.05	0.02	1.54
400	5.48	5.09	0.02	2.37
500	8.34	5.27	0.02	3.48
630	12.94	4.68	0.02	6.08
800	20.48	4.01	0.03	11.24
1000	31.55	3.69	0.03	18.81
1250	48.73	3.40	0.03	31.53
1600	79.05	2.92	0.04	59.56
2000	122.62	2.09	0.06	129.07
2500	190.49	1.95	0.06	214.91

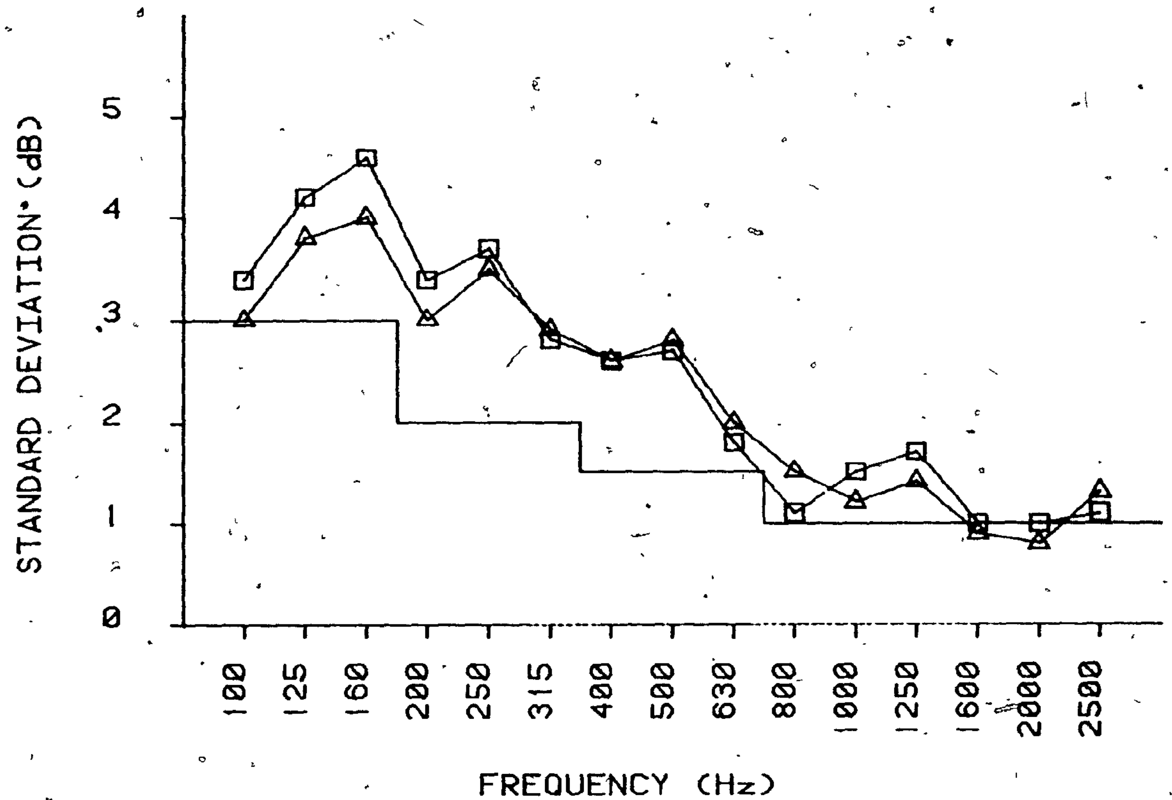
* measured using corner microphone technique

The measured total standard deviations for four source positions are plotted against the allowable limits of ANSI S1.21 in Figures 5 and 6. The raw data used in calculating all deviations are included in Appendix D. The source locations are shown in Figure 7.

A malfunction of the 200 Hz filter in the B & K 2131 originally gave erroneous results in this frequency band. Further measure-

STANDARD DEVIATIONS (dB)

FREQ. (Hz)	□	△
100	3.4	3.0
125	4.2	3.8
160	4.6	4.0
200	3.4	3.0
250	3.7	3.5
315	2.8	2.9
400	2.6	2.6
500	2.7	2.8
630	1.8	2.0
800	1.1	1.5
1000	1.5	1.2
1250	1.7	1.4
1600	1.0	0.9
2000	1.0	0.8
2500	1.1	1.3



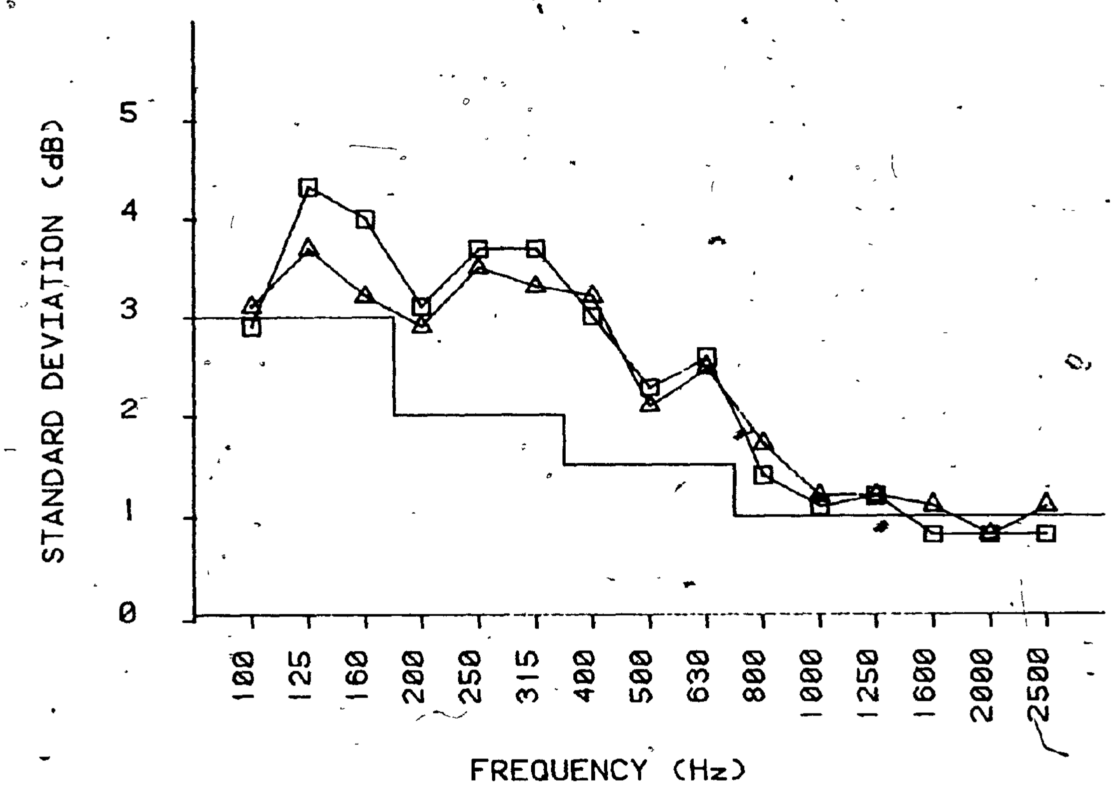
LEGEND

□—□ Position 1
△—△ Position 2

FIGURE 5 : STANDARD DEVIATIONS FOR UNMODIFIED ROOM

STANDARD DEVIATIONS (dB)

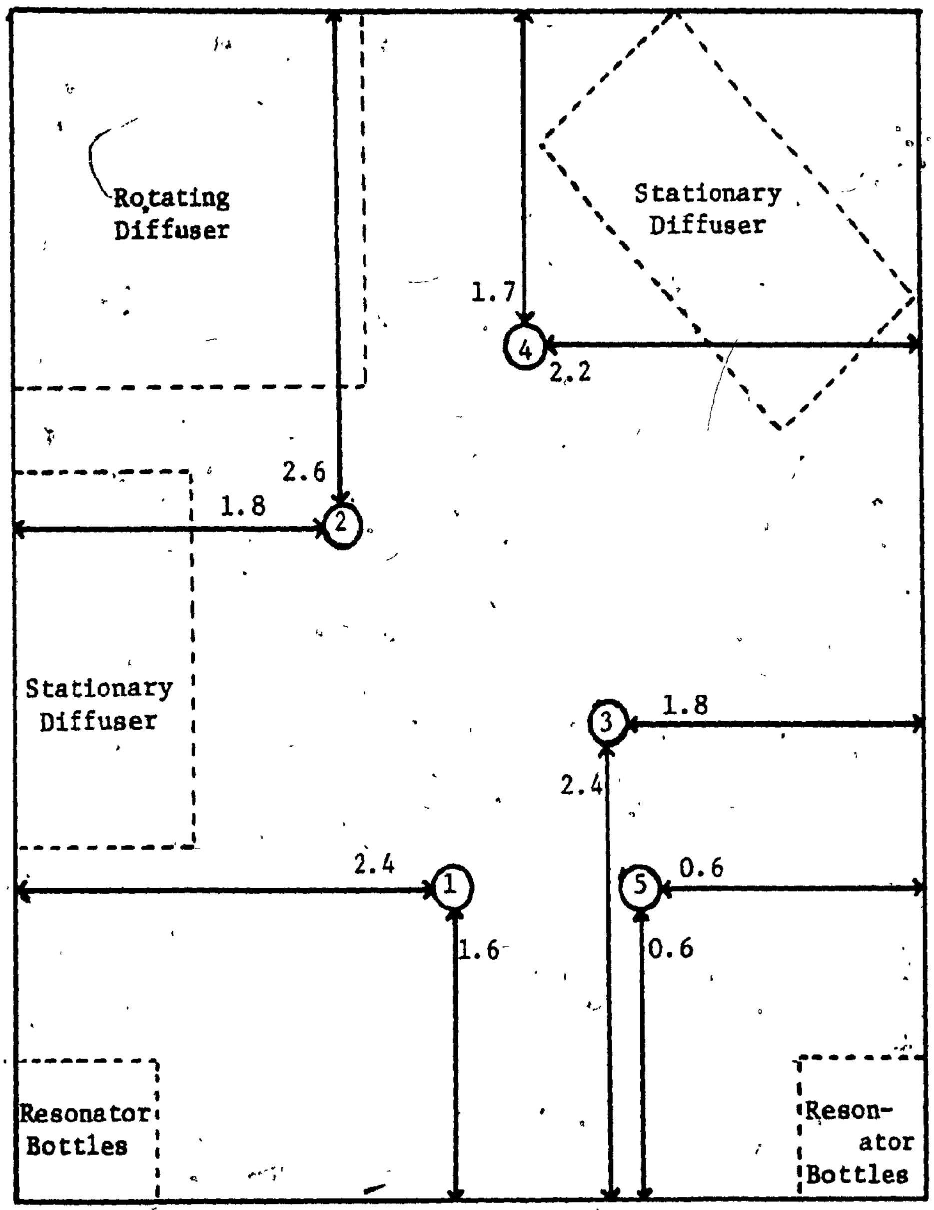
FREQ. (Hz)	□	△
100	2.9	3.1
125	4.3	3.7
160	4.0	3.2
200	3.1	2.9
250	3.7	3.5
315	3.7	3.3
400	3.0	3.2
500	2.3	2.1
630	2.6	2.5
800	1.4	1.7
1000	1.1	1.2
1250	1.2	1.2
1600	0.8	1.1
2000	0.8	0.8
2500	0.8	1.1



LEGEND

□——□ Position 3
△——△ Position 4

FIGURE 6 : STANDARD DEVIATIONS FOR UNMODIFIED ROOM



Note: All distances in meters

Figure 7. Source Position and Room Modifier Locations on 5.1 x 6.1 Meter Floor of Reverberation Room

ments were made towards the end of this study for the sake of completeness, and are included in all data reported herein.

The deviations for the four source positions are very similar in the bands higher than 500 Hz. This is to be expected as the onset of sufficient modal overlap (i.e. $M=3$) occurs in the 400 Hz band. In this range, the modes should sufficiently overlap such that W/W_0 tends to 1. Of course, $\sigma_W^2=0$ for a single source position. It should be noted that current theory does not provide for variation in σ_W^2 with frequency at a single position, although it is recognized that this occurs([8]), and in fact is included in the total measurement error obtained by the procedures specified by ANSI S1.21-1972. Nevertheless, at high frequencies, this variation is small, and the error is dominated by uncertainty in the sampling of the sound field. From Equation 28, this uncertainty $\sigma_{p^2}^2$, the normalized spatial variance, will decrease as Neq increases. The trend of decreasing standard deviation in the bands above 800 Hz can thus be attributed to the increasing values of Neq with frequency. Table IV shows the approximate number of uncorrelated samples vs. frequency for the 3 m traverse, as evaluated from Equation 38.

Clearly the increased sampling of the reverberant field will reduce $\sigma_{p^2}^2$. Unfortunately the use of a microphone traverse as opposed to a discrete microphone array allows no direct estimate of $\sigma_{p^2}^2$, or V_R^2, to be made.

TABLE IV

NUMBER UNCORRELATED SAMPLES VS. FREQUENCY

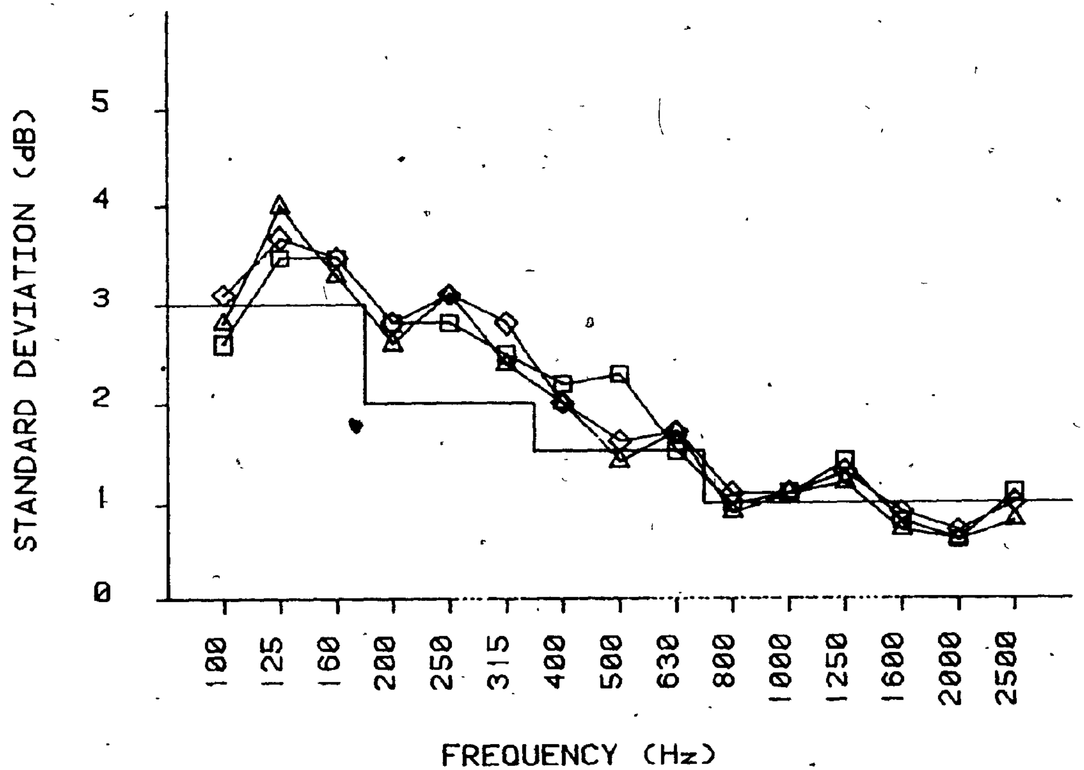
Freq. (Hz)	Neq.
100	2.7
125	3.2
160	3.8
200	4.5
250	5.4
315	6.5
400	8.0
500	9.7
630	12.0
800	15.0
1000	18.5
1250	22.9
1600	29.0
2000	36.0
2500	44.7

At frequencies below the Schroeder cut-off (i.e. M=3), the variation in standard deviation from position to position becomes higher, and is attributable both to the relative power output of the source at each position with respect to each individual mode, and to the decreased effectiveness in sampling squared pressure as evidenced by Neq in Table IV. A source at a particular location in the room will excite the available number of modes, but quite possibly to a different degree as compared to another position. Over the frequency band, therefore, one source position may excite modes more evenly than another position, effectively offering a more uniform radiation impedance to the source. This effect can be seen in the curves for all four positions. It would be expected for a constant absorption at all frequencies that the standard deviation would rise as frequency was decreased from the 400 Hz band down to the 100 Hz band, since the number of uncorrelated samples is decreasing. However, the absorption in the room increases with lower frequency and, as has been shown in Chapter 1, the variation in power output with frequency decreases with increased absorption. Thus, the peak in deviation in the range of 160-200 Hz is a trade-off point between errors. Above the peak in frequency, the increasing effectiveness of the spatial average and decreasing fluctuations in power output at these higher frequencies results in decreasing standard deviations. Below the peak, the rising absorption appears to be sufficient to offset the slightly increasing uncertainty due to reduced spatial averaging effectiveness.

According to Equation 42, the measurement error should be reduceable by averaging the squared pressures at each frequency over source position. The effectiveness of this averaging depends upon the degree of correlation between the frequency characteristics of sound power output and the measured squared pressure. The averages over source position for pairwise, three-way and four-way averages are shown in Figures 8 and 9, 10 and 11, and 12, respectively. In general, the standard deviations of the averages are lower than for single positions alone, over the entire frequency range. The reason for better averaging over some positions at certain frequencies is shown in Figures 13 and 14. In the

STANDARD DEVIATIONS (dB)

FREQ. (Hz)	□	△	◇
100	2.6	2.8	3.1
125	3.5	4.0	3.7
160	3.5	3.3	3.5
200	2.8	2.6	2.8
250	2.8	3.1	3.1
315	2.5	2.4	2.8
400	2.2	2.0	2.0
500	2.3	1.4	1.6
630	1.5	1.7	1.7
800	1.0	0.9	1.1
1000	1.1	1.1	1.1
1250	1.4	1.2	1.3
1600	0.8	0.7	0.9
2000	0.6	0.6	0.7
2500	1.1	0.8	1.0



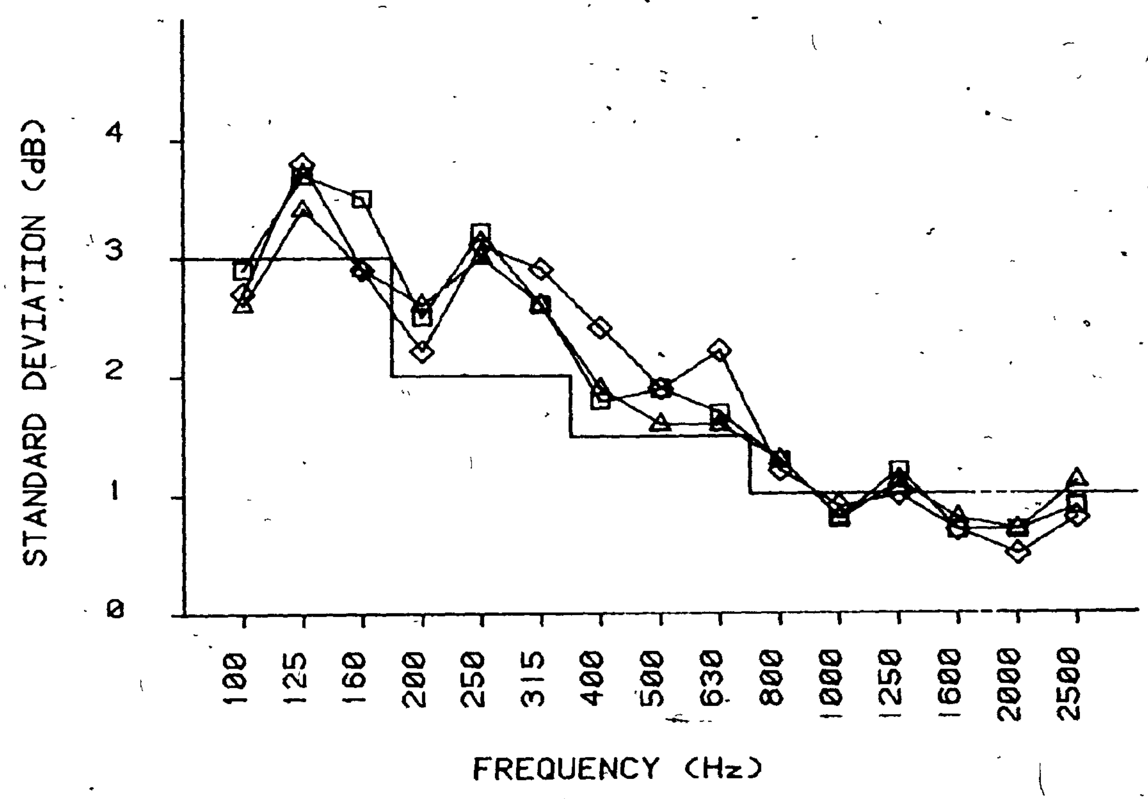
LEGEND

- □ Average of positions 1 and 2
- △ Average of positions 1 and 3
- ◇ Average of positions 1 and 4

FIGURE 8 : DEVIATIONS FOR PAIRWISE AVERAGES IN UNMODIFIED ROOM

STANDARD DEVIATIONS (dB)

FREQ. (Hz)	□	△	◇
100	2.9	2.6	2.7
125	3.7	3.4	3.8
160	3.5	2.9	2.9
200	2.5	2.6	2.2
250	3.2	3.0	3.1
315	2.6	2.6	2.9
400	1.[illegible]	1.9	2.4
500	1.[illegible]	1.6	1.9
630	1.7	1.6	2.2
800	1.3	1.3	1.2
1000	0.8	0.8	0.9
1250	1.2	1.1	1.0
1600	0.7	0.8	0.7
2000	0.7	0.7	0.5
2500	0.9	1.1	0.8



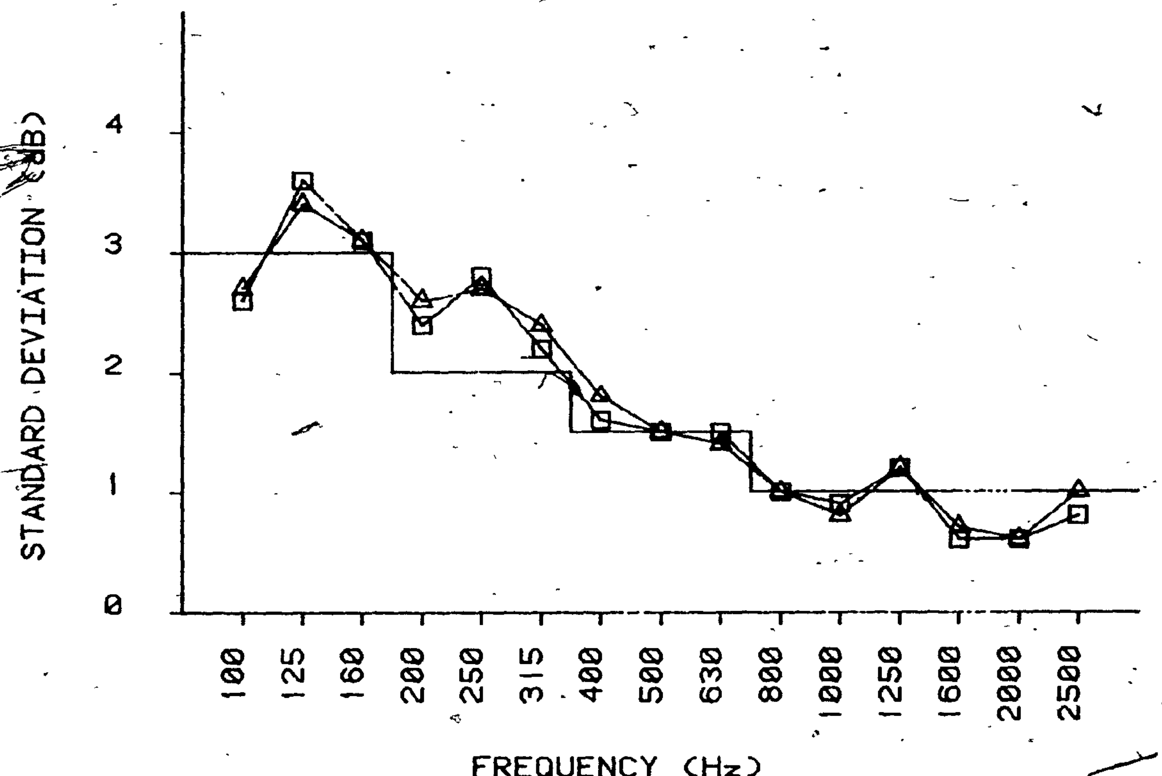
LEGEND

- □—□ Average of positions 2 and 3
- △—△ Average of positions 2 and 4
- ◇—◇ Average of positions 3 and 4

FIGURE 9 : DEVIATIONS FOR PAIRWISE AVERAGES IN UNMODIFIED ROOM.

STANDARD DEVIATIONS (dB)

FREQ. (Hz)	□	△
100	2.6	2.7
125	3.6	3.4
160	3.1	3.1
200	2.4	2.6
250	2.8	2.7
315	2.2	2.4
400	1.6	1.8
500	1.5	1.5
630	1.5	1.4
800	1.0	1.0
1000	0.9	0.8
1250	1.2	1.2
1600	0.6	0.7
2000	0.6	0.6
2500	0.8	1.0



LEGEND

□——□ Average of positions 1,2 and 3
△——△ Average of positions 1,2 and 4

FIGURE 10 : DEVIATIONS FOR THREE-WAY AVERAGES IN UNMODIFIED ROOM

STANDARD DEVIATIONS (dB)

FREQ. (Hz)	□	△
100	2.8	2.6
125	3.7	3.5
160	3.0	2.8
200	2.3	2.1
250	2.9	2.9
315	2.5	2.5
400	1.8	1.5
500	1.4	1.6
630	1.6	1.7
800	0.9	1.1
1000	0.9	0.7
1250	1.1	1.0
1600	0.7	0.6
2000	0.5	0.5
2500	0.8	0.9

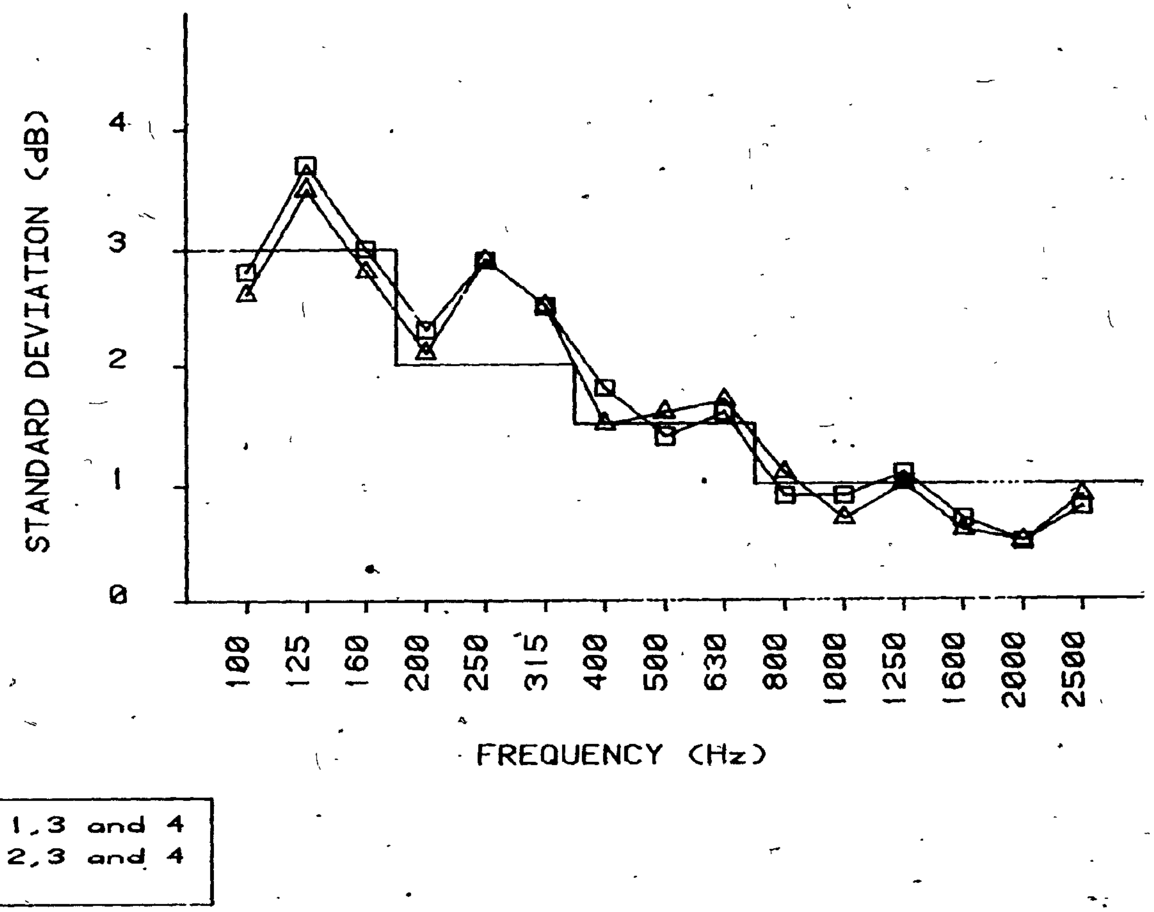
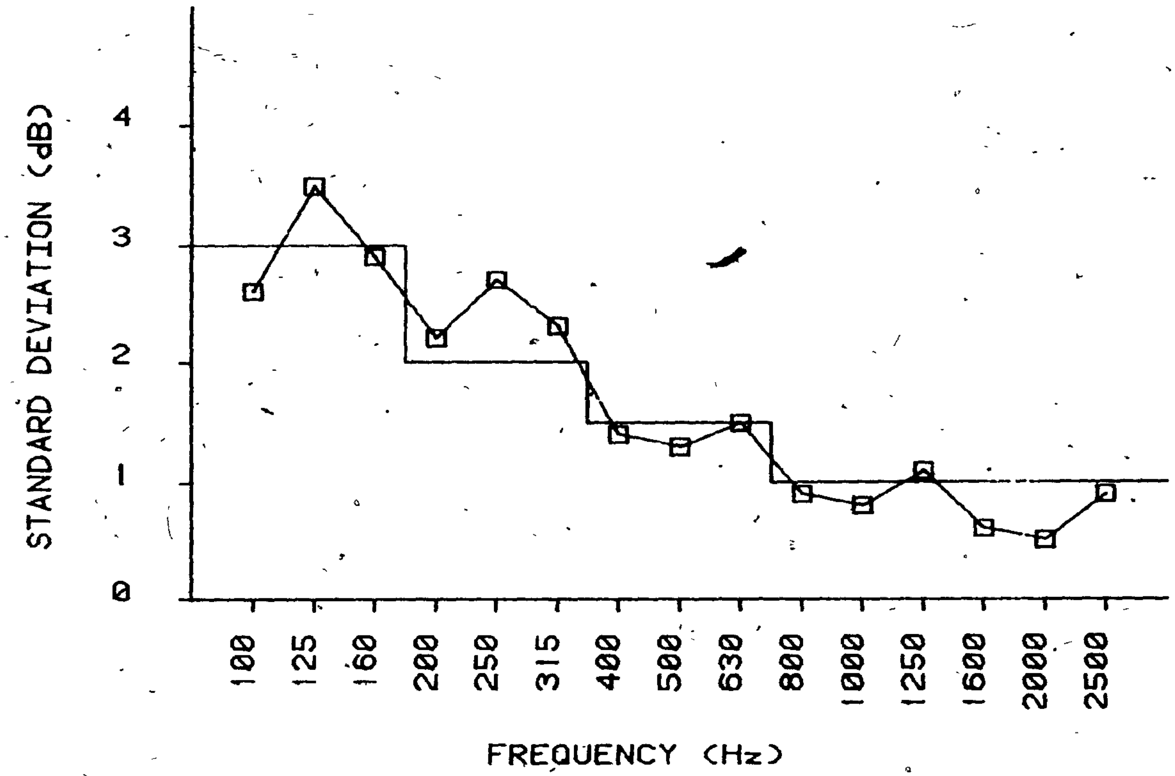


FIGURE 11 : DEVIATIONS FOR THREE-WAY AVERAGES IN UNMODIFIED ROOM

STANDARD DEVIATIONS (dB)

FREQ.(Hz)	□
100	2.6
125	3.5
160	2.9
200	2.2
250	2.7
315	2.3
400	1.4
500	1.3
630	1.5
800	0.9
1000	0.8
1250	1.1
1600	0.6
2000	0.5
2500	0.9



LEGEND

□——□ Average of positions 1,2,3 and 4

FIGURE 12 : DEVIATIONS FOR FOUR-WAY AVERAGE IN UNMODIFIED ROOM

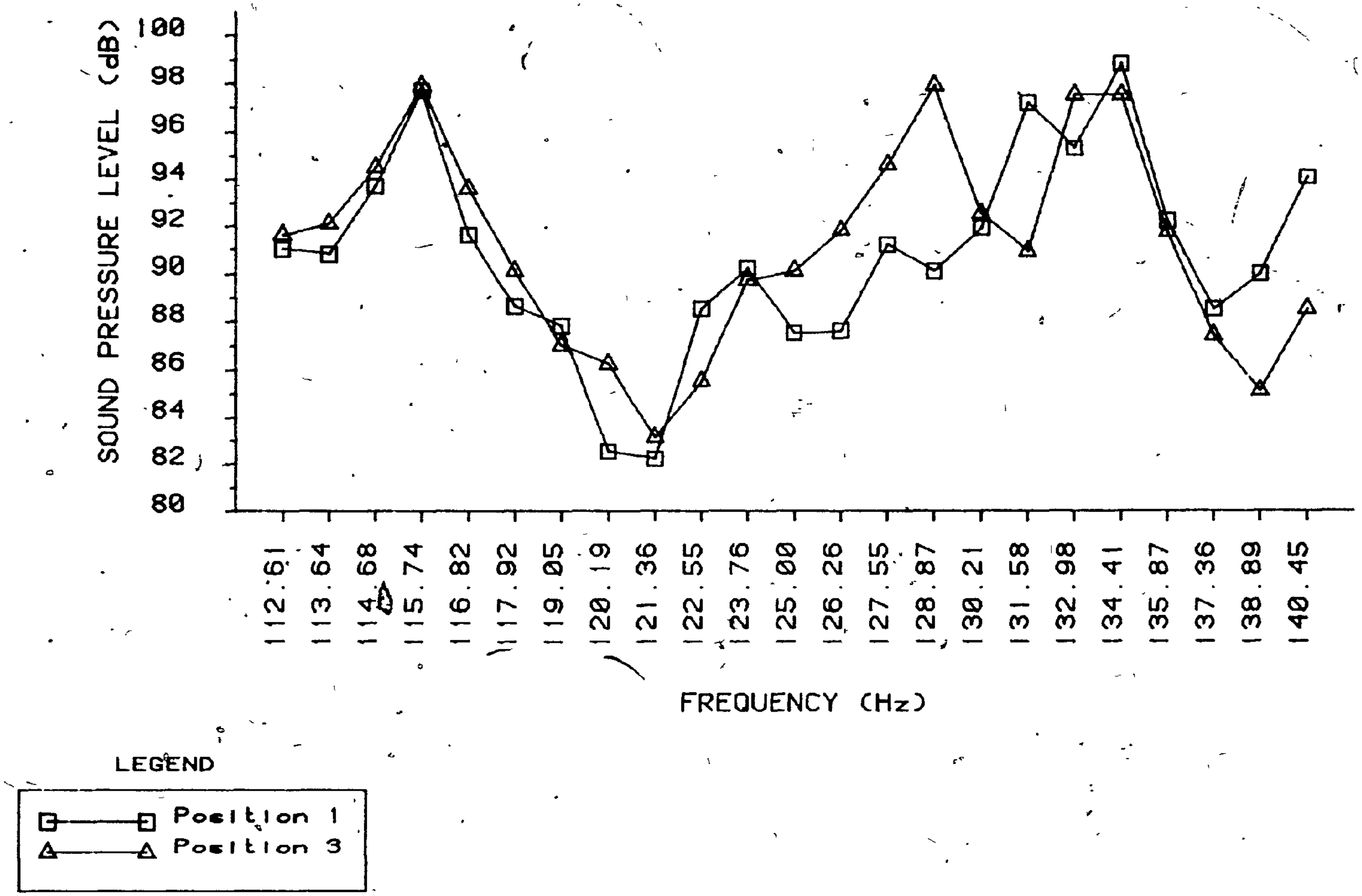


FIGURE 13 : MEASURED SOUND PRESSURE LEVELS AT 125 HZ

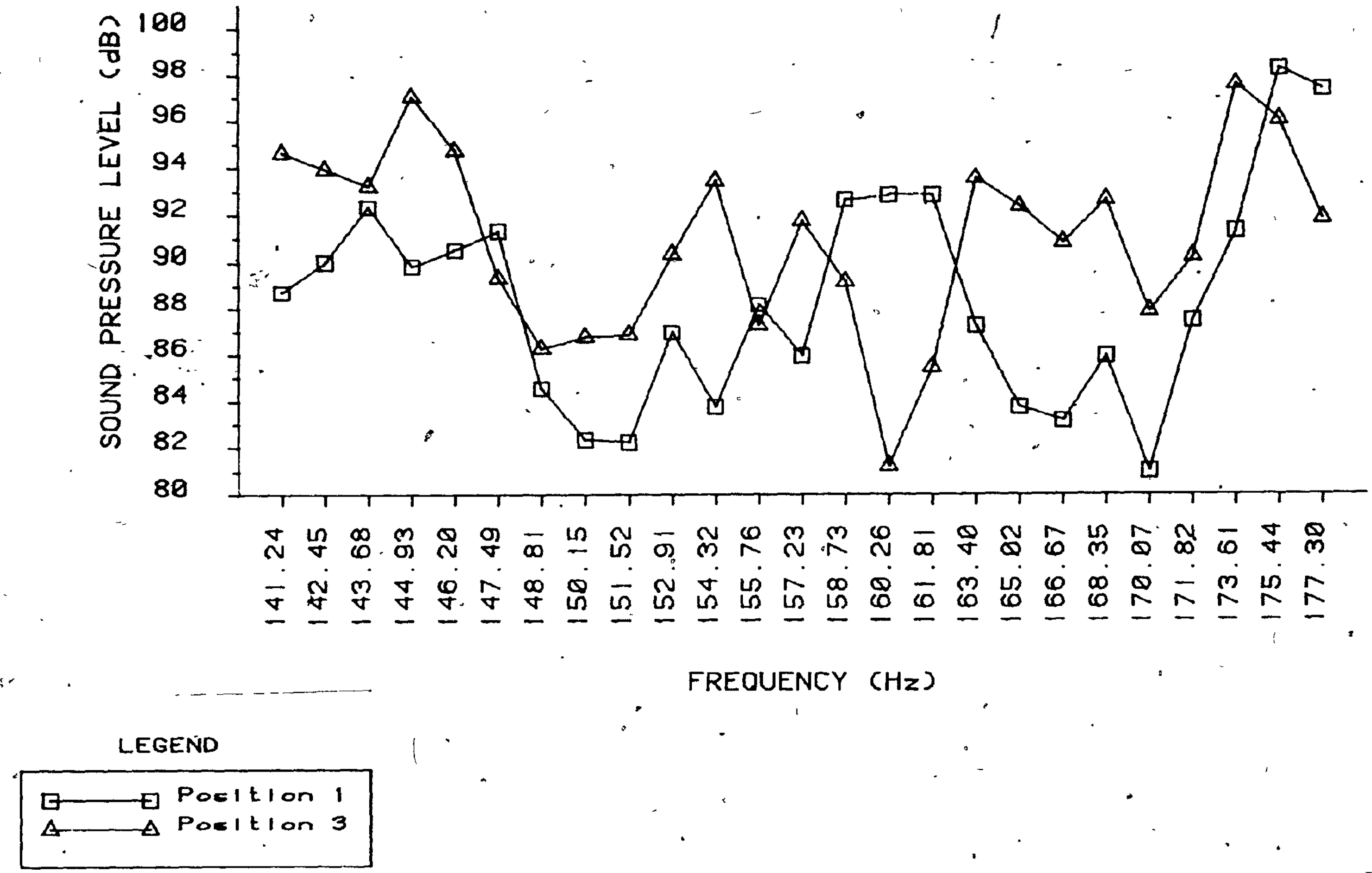


FIGURE 14 : MEASURED SOUND PRESSURE LEVELS AT 160 HZ

125 Hz band, the squared pressure, hence levels, are highly correlated for source positions 1 and 3. Therefore, the average over these two positions does not substantially reduce the total measured deviation. The averaged value is 2.8 (Figure 8) compared to the single position values of 3.4 at position 1 and 2.9 at position 3 (Figures 5,6). It can not be concluded that at low frequencies the squared pressure is always highly correlated over source positions. In the 160 Hz band, the squared pressures (hence levels) for positions 1 and 3 are not correlated to nearly as great a degree as in the previous case. Thus, a greater benefit is obtained in averaging the two positions. The standard deviation for the averaged positions is 3.3 (Figure 8) compared to the single position values of 4.6 at position 1 and 4.0 at position 3 (Figure 5).

At higher frequencies, the correlation between source position and squared pressure over frequency is virtually nonexistent, as evidenced by Figure 15. In the 2000 Hz band, it can be seen that there is virtually no correlation between the curves for position 1 and position 3.

Due to the relative ineffectiveness of the traverse at low frequencies (i.e. Neq), it is difficult to say whether or not the major portion of the total error can be attributed to $\sigma_{p^2}^2$ or σ_w^2, when multiple source positions are considered. However, it can be seen from Equation 42 that the total variance σ_t^2 should decrease by a factor of $1/N_s$, where N_s is the number of source positions over which an average is made. Shown in Figure 16 is the calculated reduction factor for

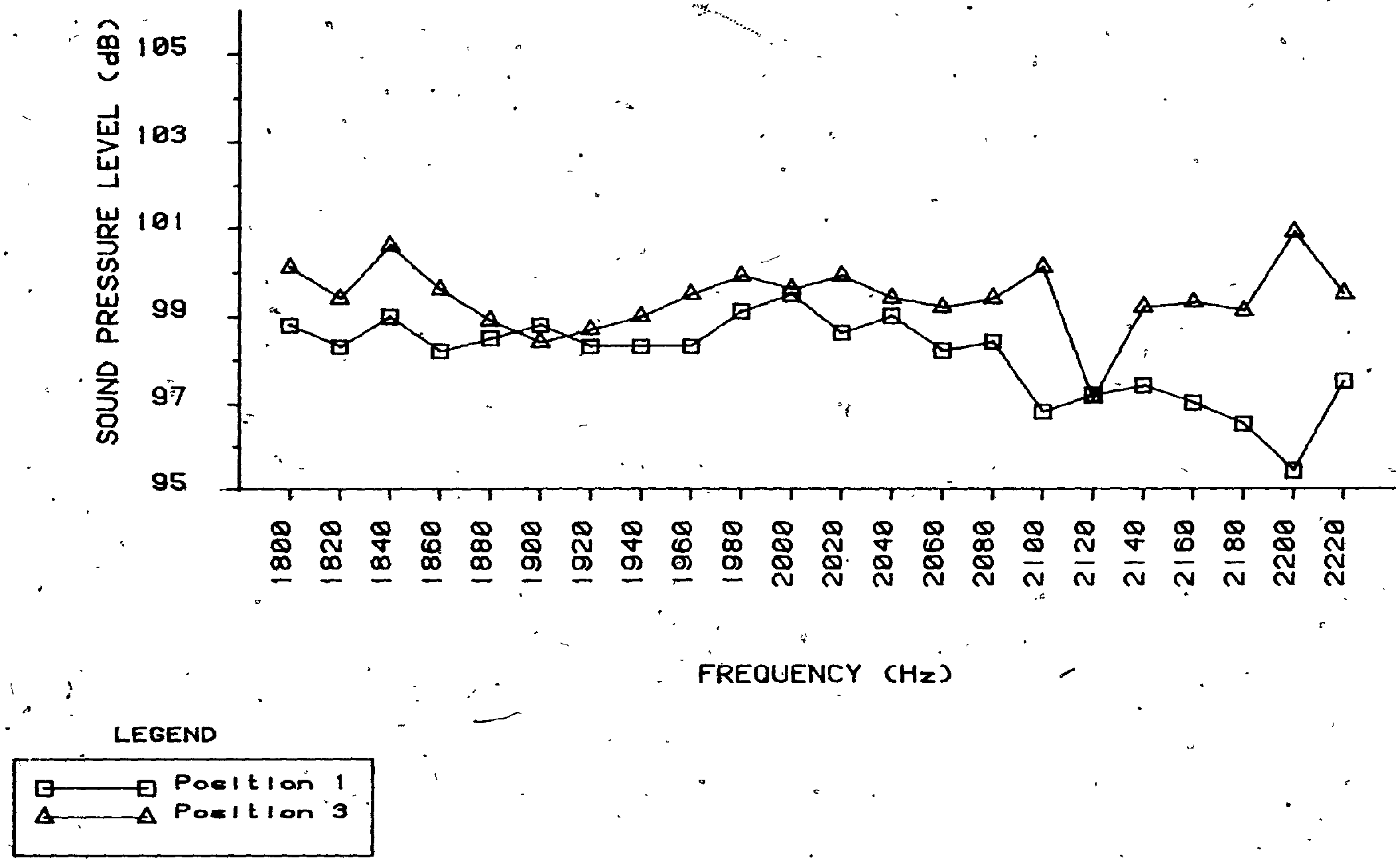


FIGURE 15 : MEASURED SOUND PRESSURE LEVELS AT 2000 HZ

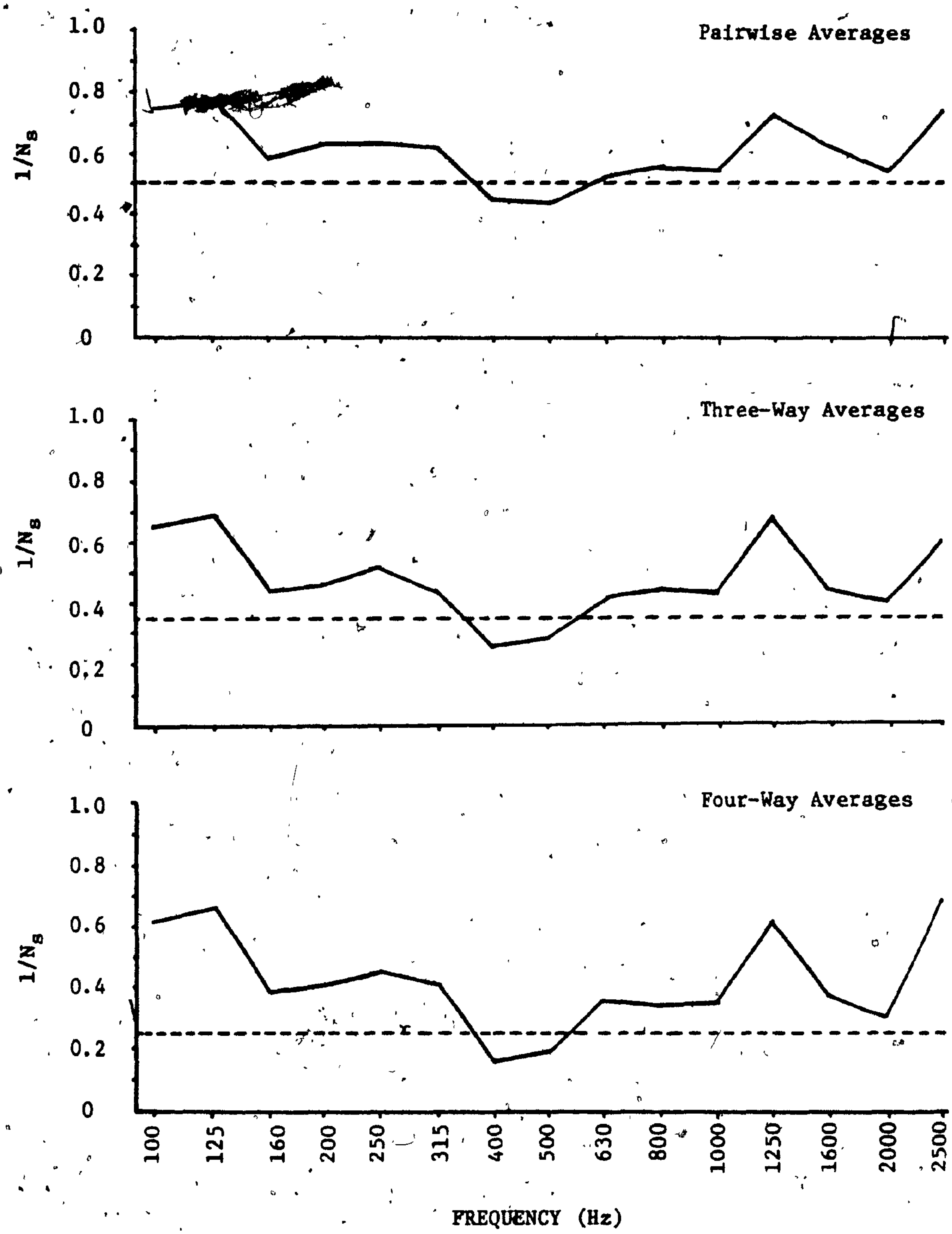


Figure 16. Comparison of Calculated $1/N_s$ Values With Theoretical (-------) - Unmodified Room

source position averaging compared to the theoretical value of $1/N_s$. The factors shown are average values over all combinations of pairwise, three-way, and four-way combinations. The theoretical values are only approached in the ranges of 315-800 Hz, and 1250-1600 Hz. It can be seen from Figures 8 - 12 that these are the ranges where the most effective reduction in deviation due to source position averaging can be achieved. With reference to the measured level values in Appendix D for each source position, it can be shown that the theoretical value of $1/N_s$ is approached when correlation between measured levels at individual frequencies and source position is least, and consequently, the most effective averaging is achieved when correlation of room frequency response with source position tends to zero.

3.3 Pure Tone Qualification Results - Room with Rotating and Stationary Diffusers

The reverberation times and absorption coefficients for the reverberation room with both rotating and stationary diffusers installed are shown in Table V. The rotating diffuser was operated at 30 rpm, with panels set at 15° to the vertical and 30° rotated about the vertical axis.

The introduction of the diffusing elements has very slightly raised the absorption of the room, comparing the values in Table V with those in Table III. The effect of the rotating diffuser on the reverberation time appears to be insignificant.

TABLE V

ROOM PARAMETERS WITH DIFFUSERS INSTALLED

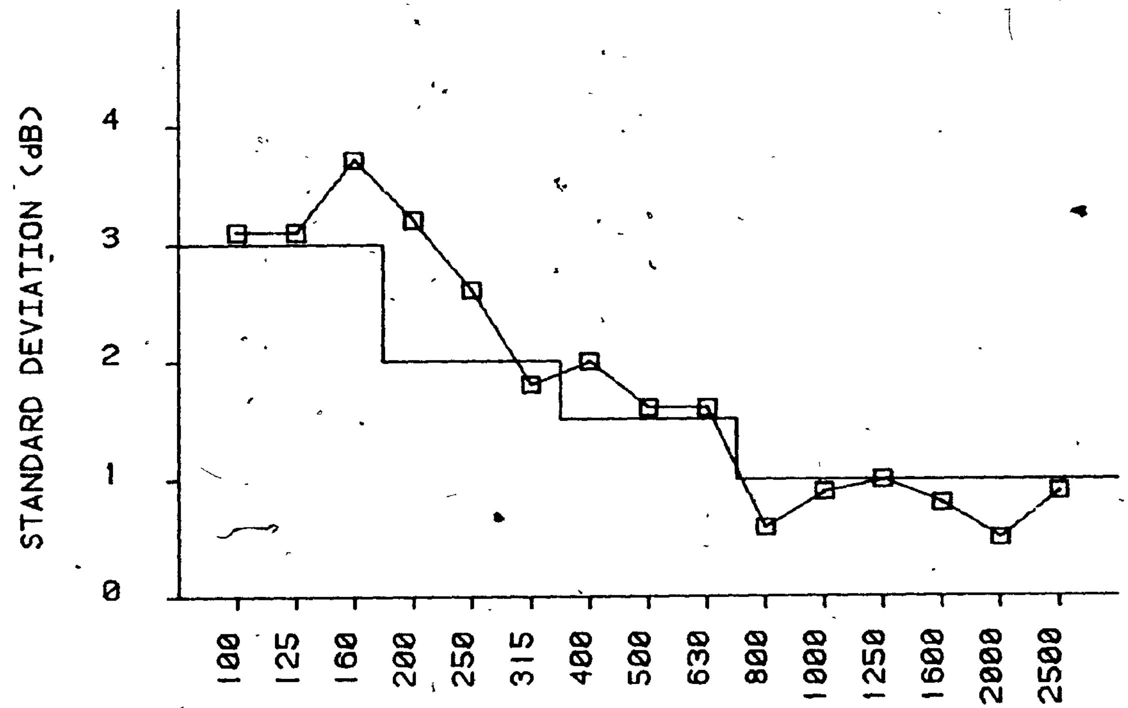
Freq. (Hz)	Rotating Diffuser Stopped		Rotating Diffuser @ 30 rpm	
	T_{60}	$\bar{\alpha}$	T_{60} *	$\bar{\alpha}$
100	1.89	0.06	1.95	0.06
125	1.82	0.06	1.94	0.06
160	2.79	0.04	2.78	0.04
200	3.05	0.04	2.98	0.04
250	4.04	0.03	3.85	0.03
315	4.07	0.03	4.03	0.03
400	4.20	0.03	4.15	0.03
500	4.23	0.03	4.16	0.03
630	3.85	0.03	4.02	0.03
800	3.46	0.03	3.61	0.03
1000	3.28	0.04	3.33	0.04
1250	3.16	0.04	3.17	0.04
1600	2.87	0.04	2.98	0.04
2000	2.62	0.04	2.63	0.04
2500	2.42	0.05	2.41	0.05

* space average measurements

The standard deviations for positions 1, 2, and 3 are shown in Figures 17, 18, and 19, respectively, along with their respective deviations for the unmodified room. Except for positions 2 at 125 Hz and 3 at 200 Hz, there is improvement at all frequencies for all positions when compared with the unmodified room results in Figures 5 and 6. The decrease in deviation can be attributed to the existence of sidebands around the source frequency caused by modulation of the source

STANDARD DEVIATIONS (dB)

FREQ.(Hz)	□
100	3.1
125	3.1
160	3.7
200	3.2
250	2.6
315	1.8
400	2.0
500	1.6
630	1.6
800	0.6
1000	0.9
1250	1.0
1600	0.8
2000	0.5
2500	0.9



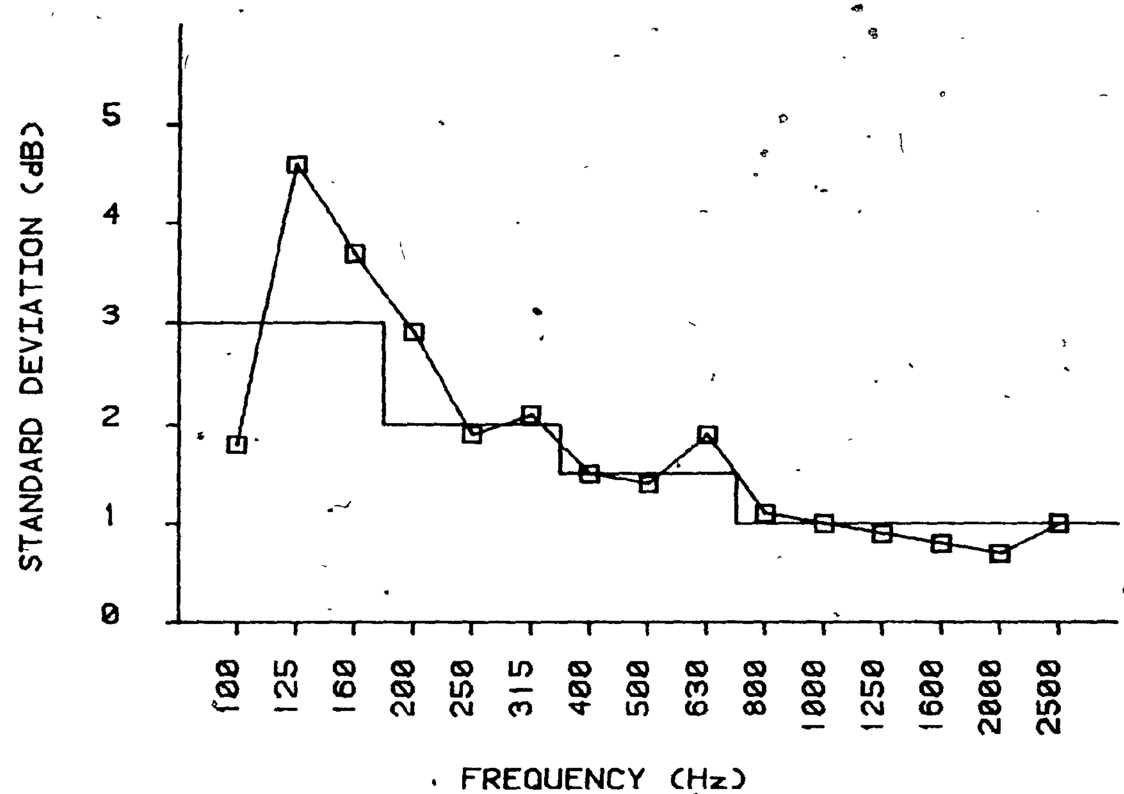
LEGEND

□——□ Position 1, rotating diffuser at 30rpm

FIGURE 17 : DEVIATIONS WITH DIFFUSERS ADDED TO ROOM

STANDARD DEVIATIONS (dB)

FREQ.(Hz)	□
100	1.8
125	4.6
160	3.7
200	2.9
250	1.9
315	2.1
400	1.5
500	1.4
630	1.9
800	1.1
1000	1.0
1250	0.9
1600	0.8
2000	0.7
2500	1.0



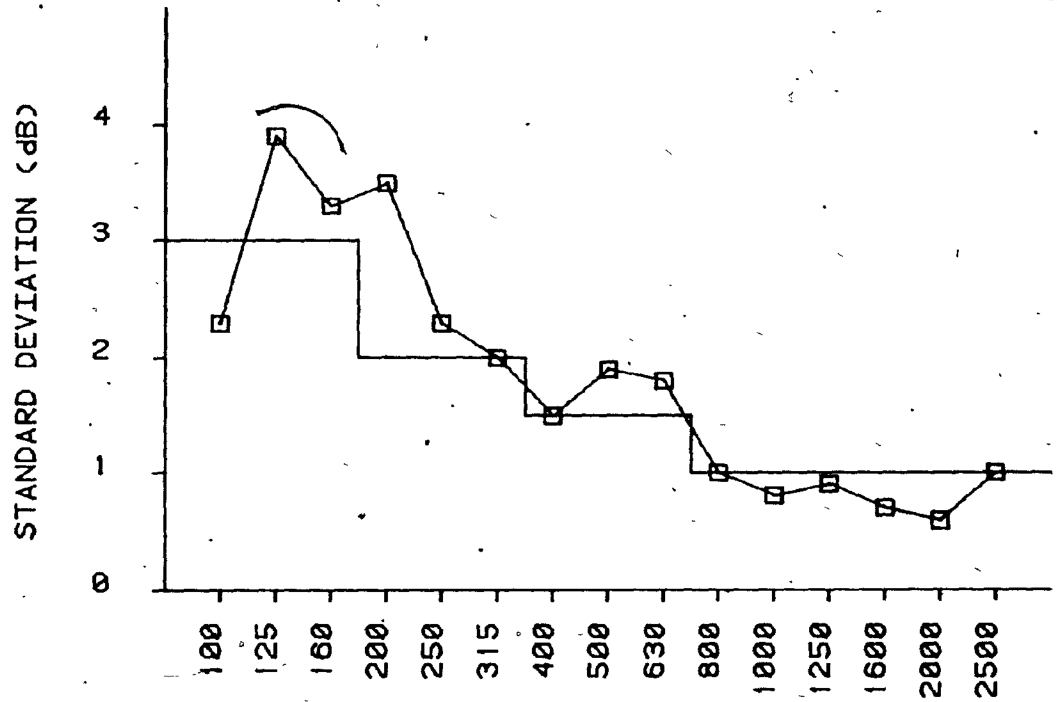
LEGEND

Position 2, rotating diffuser at 30rpm

FIGURE 18 : DEVIATIONS WITH DIFFUSERS ADDED TO ROOM

STANDARD DEVIATIONS (dB)

FREQ. (Hz)	□
100	2.3
125	3.9
160	3.3
200	3.5
250	2.3
315	2.0
400	1.5
500	1.9
630	1.8
800	1.0
1000	0.8
1250	0.9
1600	0.7
2000	0.6
2500	1.0



LEGEND

□——□ Position 3, rotating diffuser at 30rpm

FIGURE 19 : DEVIATIONS WITH DIFFUSERS ADDED TO ROOM

tone by the diffuser vanes, a process which has been confirmed experimentally[23]. A pure-tone spectrum is thus changed to a multi-tone spectrum, with a corresponding decrease in normalized spatial variance V_R^2 (Equation 31). That is, $V_R^2 = 1$ for a pure tone, and if R sideband tones are generated, the value of V_R^2 may go as low as 1/R if the tones are well separated. Also, as discussed in Chapter 1, the diffuser should modulate the amplitude of the tone and sidebands performing an averaging effect. The diffuser should also time-vary the power output of the source.

If it is assumed that the entire error at all frequencies is error due to spatial sampling, then the figure of merit, M', (Equation 44) for the diffuser may be estimated. The calculated values are listed in Table VI for positions 1, 2, and 3.

The averages are simply arithmetic averages of the figures of merit for the three positions. It can be seen that the highest average figure of merit is approximately above 200 Hz. This corresponds reasonably well with the premise that the largest panel dimension should be in the order of $\frac{\lambda}{2}$ at the lowest frequency of interest to ensure good diffuser performance. With the rotating diffuser used in this room, the $\frac{\lambda}{2}$ frequency is about 172 Hz. The diffuser becomes generally less effective as frequency, hence modal overlap, increases.

The standard deviations for averages over source position are shown for pairwise averages in Figures 20, 21, and 22, and for the three-way average in Figure 23. The averaging process is generally effective over the entire frequency range, but that no combination of

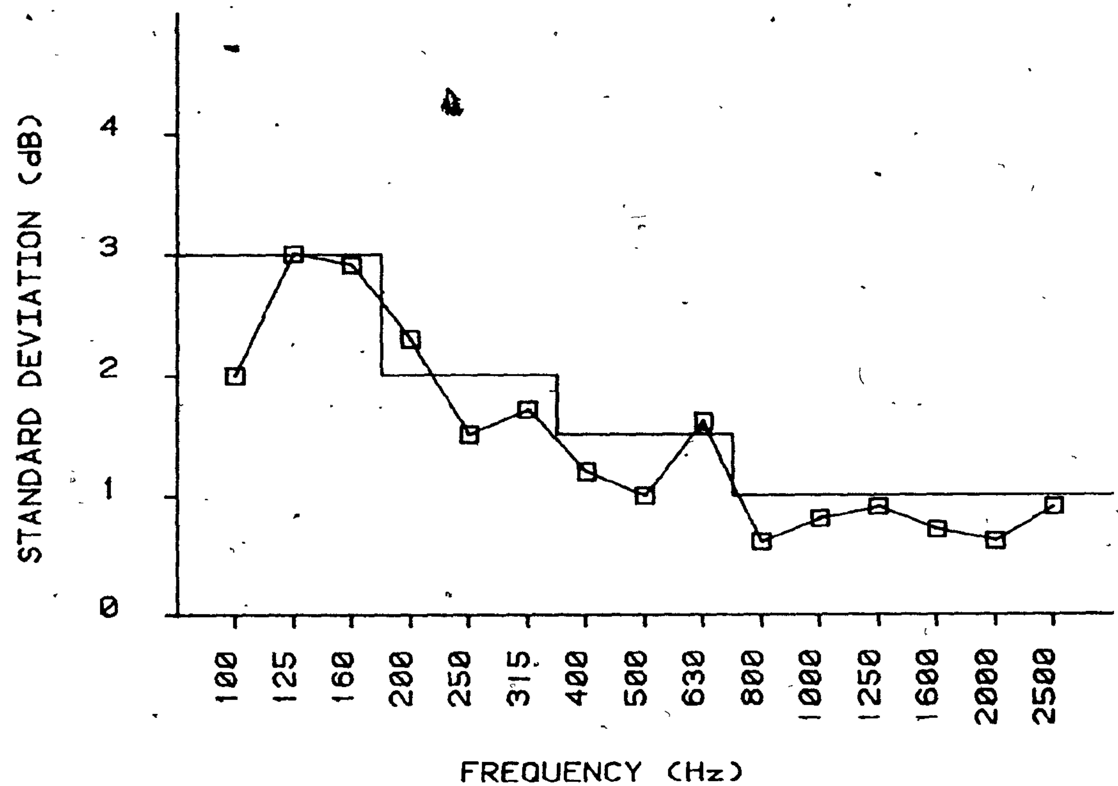
TABLE VI

DIFFUSER FIGURES OF MERIT

Freq. (Hz)	Position 1	Position 2	Position 3
100	1.3	3.8	1.9
125	2.4	0.6	1.4
160	2.0	1.3	1.8
200	1.2	1.1	0.7
250	2.7	5.1	3.7
315	3.1	2.3	5.3
400	2.4	3.9	5.8
500	3.7	5.7	1.6
630	1.3	1.1	2.5
800	3.8	2.0	2.2
1000	3.2	1.5	2.0
1250	3.4	2.7	1.9
1600	1.6	1.3	1.3
2000	4.5	1.3	1.9
2500	1.6	1.8	0.6

STANDARD DEVIATIONS (dB)

FREQ.(Hz)	□
100	2.0
125	3.0
160	2.9
200	2.3
250	1.5
315	1.7
400	1.2
500	1.0
630	1.6
800	0.6
1000	0.8
1250	0.9
1600	0.7
2000	0.6
2500	0.9



LEGEND

□—□ Average of positions 1 and 2

FIGURE 20 : PAIRWISE AVERAGE DEVIATIONS WITH DIFFUSERS ADDED TO ROOM

STANDARD DEVIATIONS (dB)

FREQ. (Hz)	□
100	2.3
125	3.2
160	2.7
200	2.8
250	1.8
315	1.3
400	1.2
500	1.1
630	1.4
800	0.6
1000	0.7
1250	0.9
1600	0.7
2000	0.5
2500	0.9

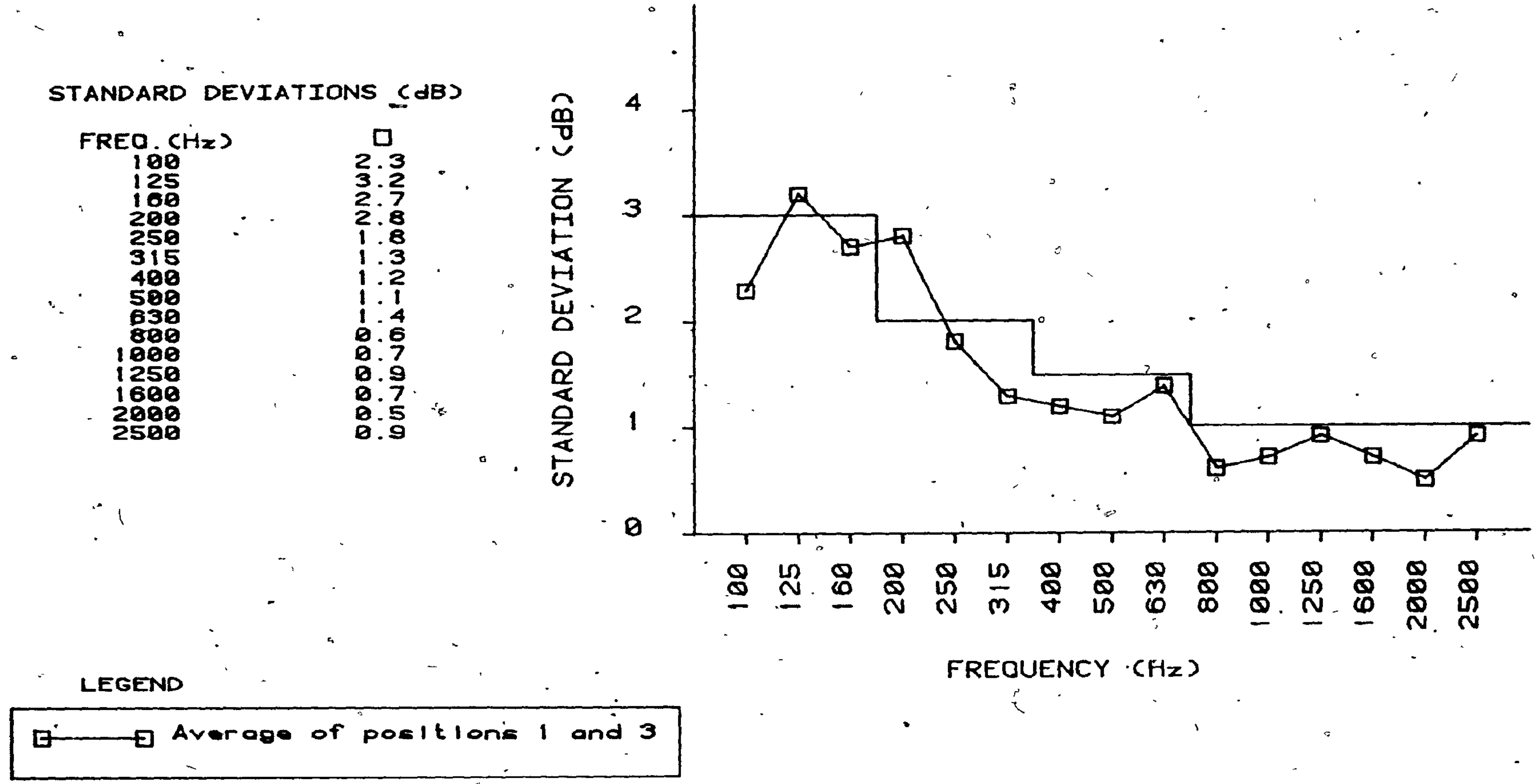
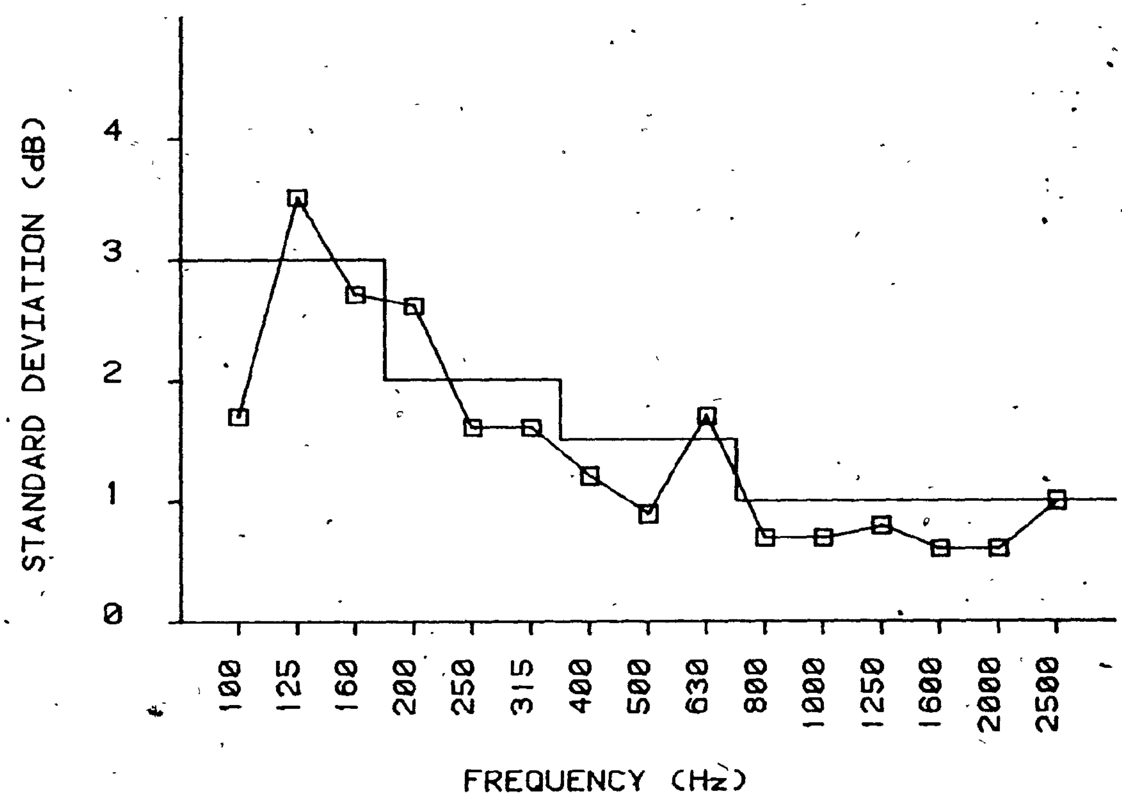


FIGURE 21 : PAIRWISE AVERAGE DEVIATIONS WITH DIFFUSERS ADDED TO ROOM

STANDARD DEVIATIONS (dB)

FREQ.(Hz)	□
100	1.7
125	3.5
160	2.7
200	2.6
250	1.6
315	1.6
400	1.2
500	0.9
630	1.7
800	0.7
1000	0.7
1250	0.8
1600	0.6
2000	0.6
2500	1.0



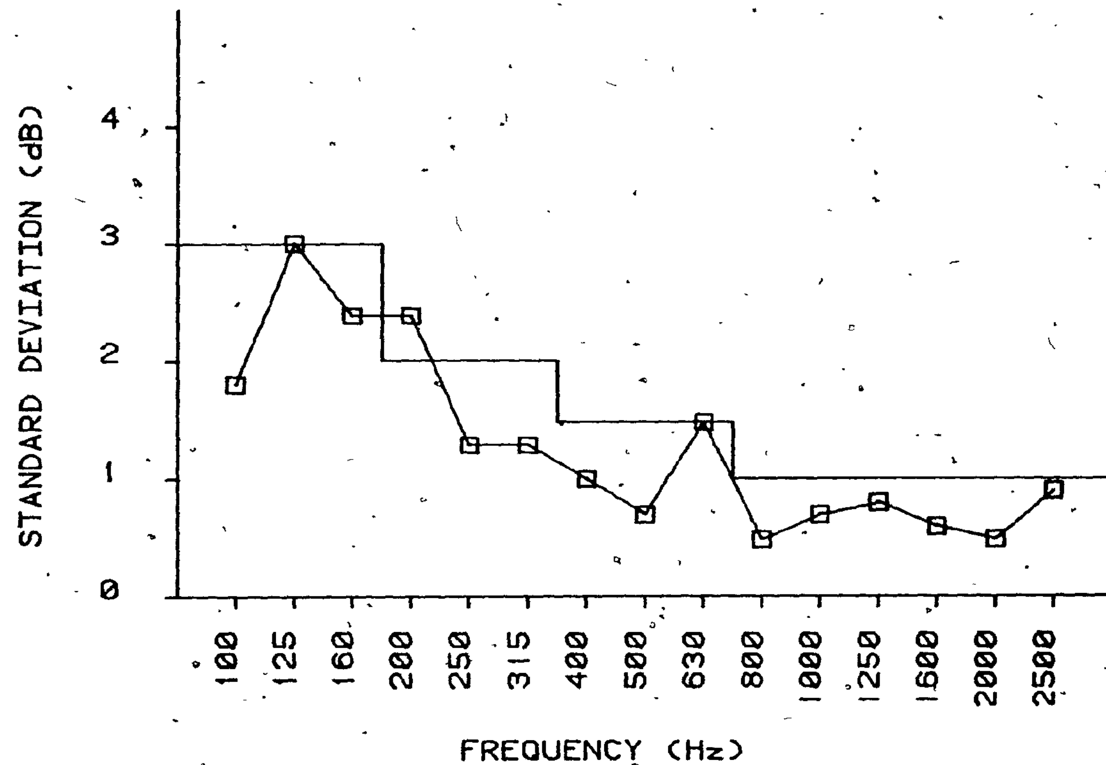
LEGEND

□——□ Average of positions 2 and 3

FIGURE 22 : PAIRWISE AVERAGE DEVIATIONS WITH DIFFUSERS ADDED TO ROOM

STANDARD DEVIATIONS (dB)

FREQ.(Hz)	□
100	1.8
125	3.0
160	2.4
200	2.4
250	1.3
315	1.3
400	1.0
500	0.7
630	1.5
800	0.5
1000	0.7
1250	0.8
1600	0.6
2000	0.5
2500	0.9



LEGEND

Average of positions 1,2 and 3

FIGURE 23 : THREE-WAY AVERAGE DEVIATIONS WITH DIFFUSERS ADDED TO ROOM

positions will make the room entirely qualifiable. However, the three-way average leaves only the 200 Hz band unqualifiable.

Shown in Figure 24 are the responses at individual frequencies in the 125 Hz band for source positions 1 and 3.

A comparison of Figures 13 and 24 shows that the combination of rotating and stationary diffusers has uncorrelated positions 1 and 3 to a certain degree at the low end of the band, and has reduced the amplitude of the sharp resonances at 115.74 Hz and 121.36 Hz. The sharp peak around 133 Hz has not been affected significantly. The reduction at the low end of the band accounts for the reduction in measured deviation, at each individual position, but averaging of the two positions is still not particularly effective as the two positions remain highly correlated at the higher end of the band.

Similar results for the 160 Hz band, shown in Figure 25, indicate that the room response for positions 1 and 3 are not so nearly correlated in this frequency range. Again, in comparison with Figure 14, the sharp resonant peaks at the lower end of the frequency band have been reduced in amplitude, resulting in lower total error. However, in this frequency band, it is difficult to assess any significant change in correlation with respect to source position.

The diffuser then, at low frequencies, must be averaging the source power output with frequency, and/or providing a more diffuse sound field via multitone generation. The resultant reductions in measured error at each source position depend upon the extent of power averaging effectiveness and/or diffusivity over the range of frequencies within

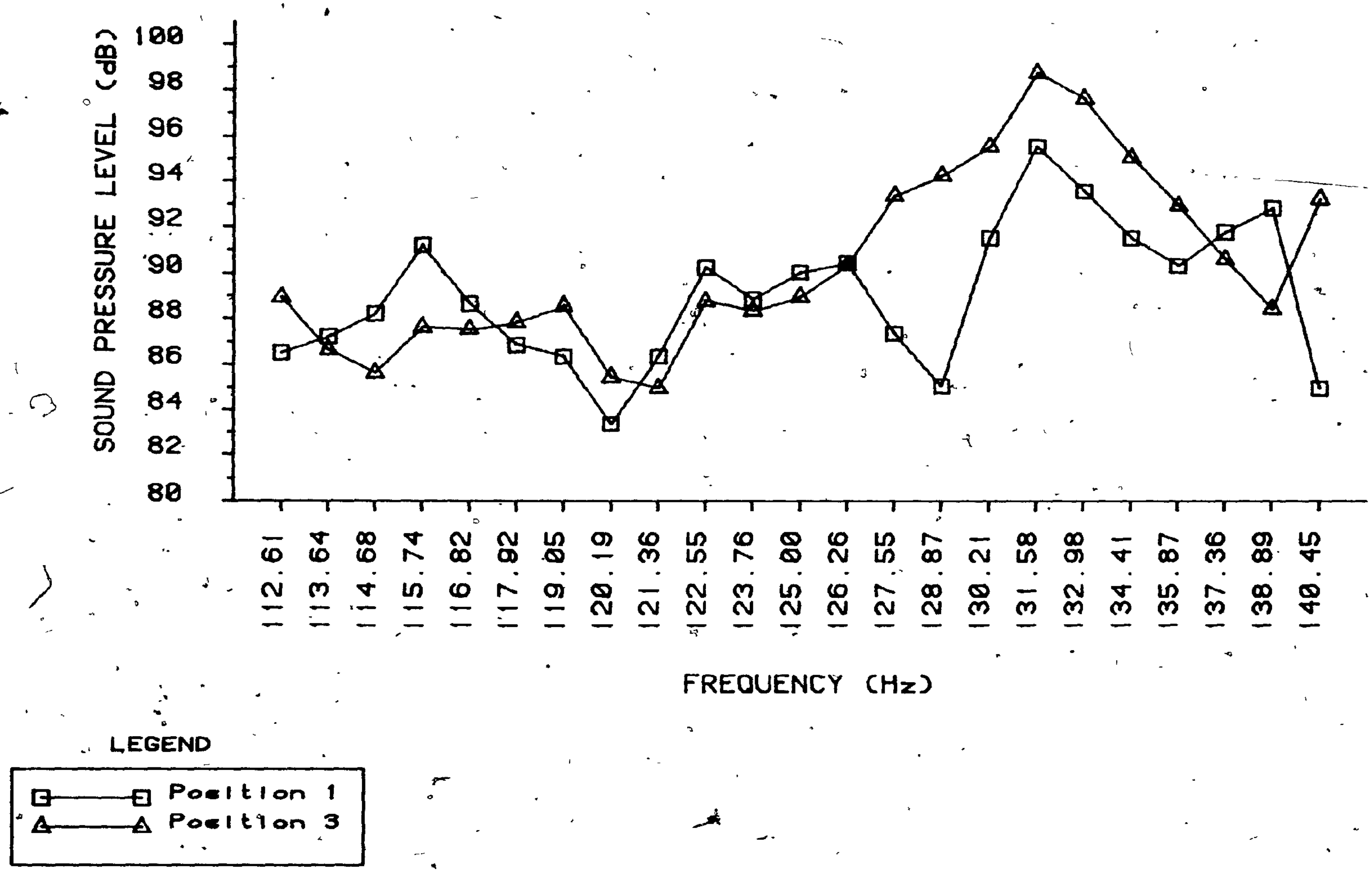


FIGURE 24 : LEVELS AT 125 HZ WITH DIFFUSERS IN ROOM

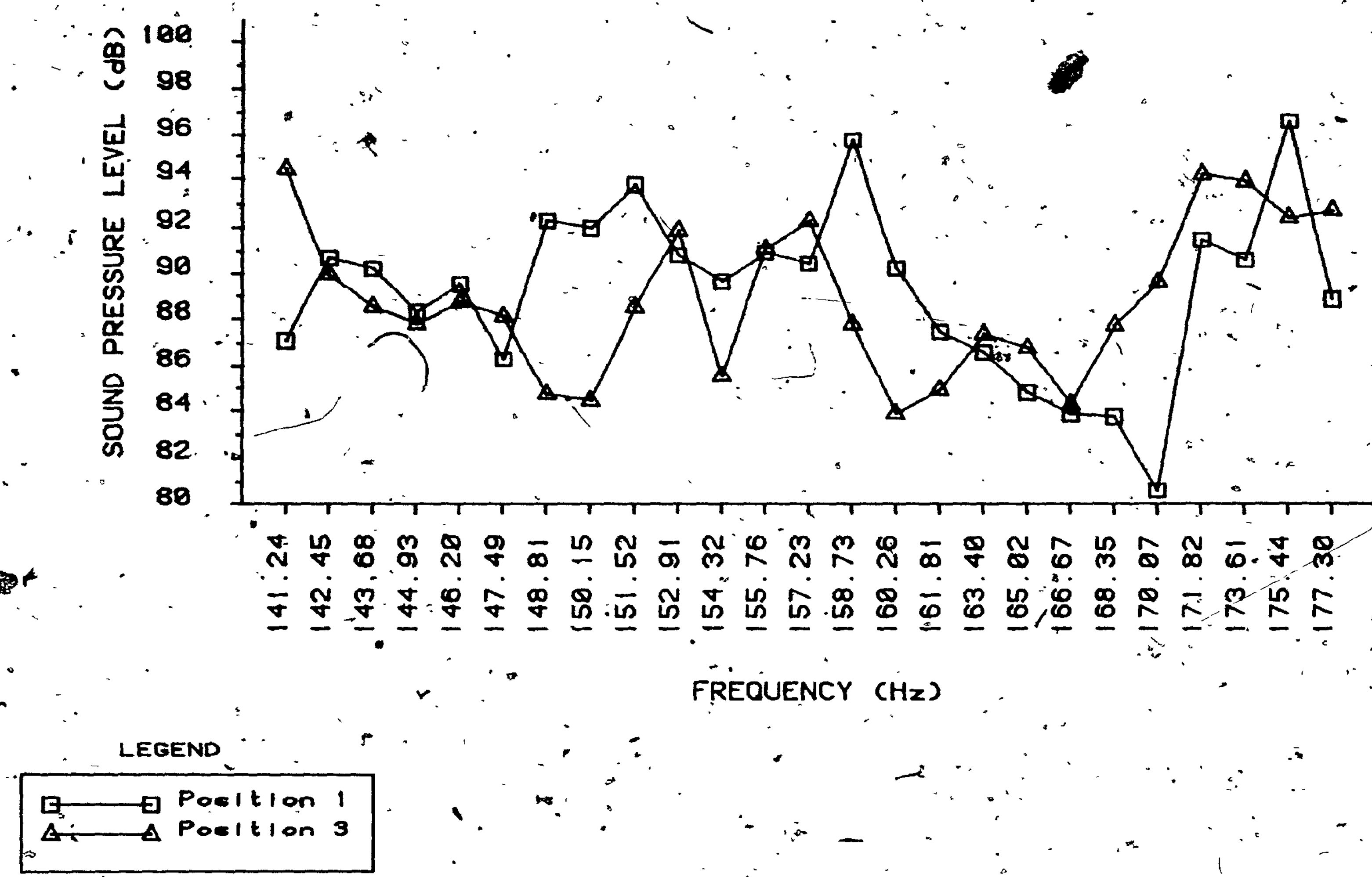


FIGURE 25 : LEVELS AT 160 HZ WITH DIFFUSERS IN ROOM

each 1/3-octave band. The reduction in total error available via averaging over source position depends upon the degree of correlation of room responses with source position. Of course, at low frequencies degree of correlation between source positions will depend upon the efficiency of coupling available to any given mode at each respective position which is a function of the source position and room parameters. Thus, power output would appear, as for example in Figures 13 and 24, to be correlated with measured squared pressure. It is for this reason that the total error given by Equation 42 may underestimate the true error since it assumes uncorrelation, hence addition of σ_W^2 and σ_p^2. It is for the same reason that the calculated values of N_s do not tend to the theoretical at low frequencies, because they are reduced by the correlation effect.

At high frequencies, for example in the 2000 Hz band, it is found that averaging over source position is generally less effective with the diffusers in the room than without, although the deviations at single positions are lower with the diffusers in the room. This can be attributed to the fact that as the frequency responses of the room get "flatter" at each source position, the responses are effectively getting more correlated, and hence averaging becomes less effective. However, if the diffuser is reducing spatial averaged variation with frequency to the order of 1.0 dB at 2000 Hz, there is no necessity to use more than one source position.

The calculated $1/N_s$ factors are shown in Figure 26 for pairwise and three-way averages. When compared to those for the unmodified room in Figure 16, the values of $1/N_s$ more closely approach the theo-

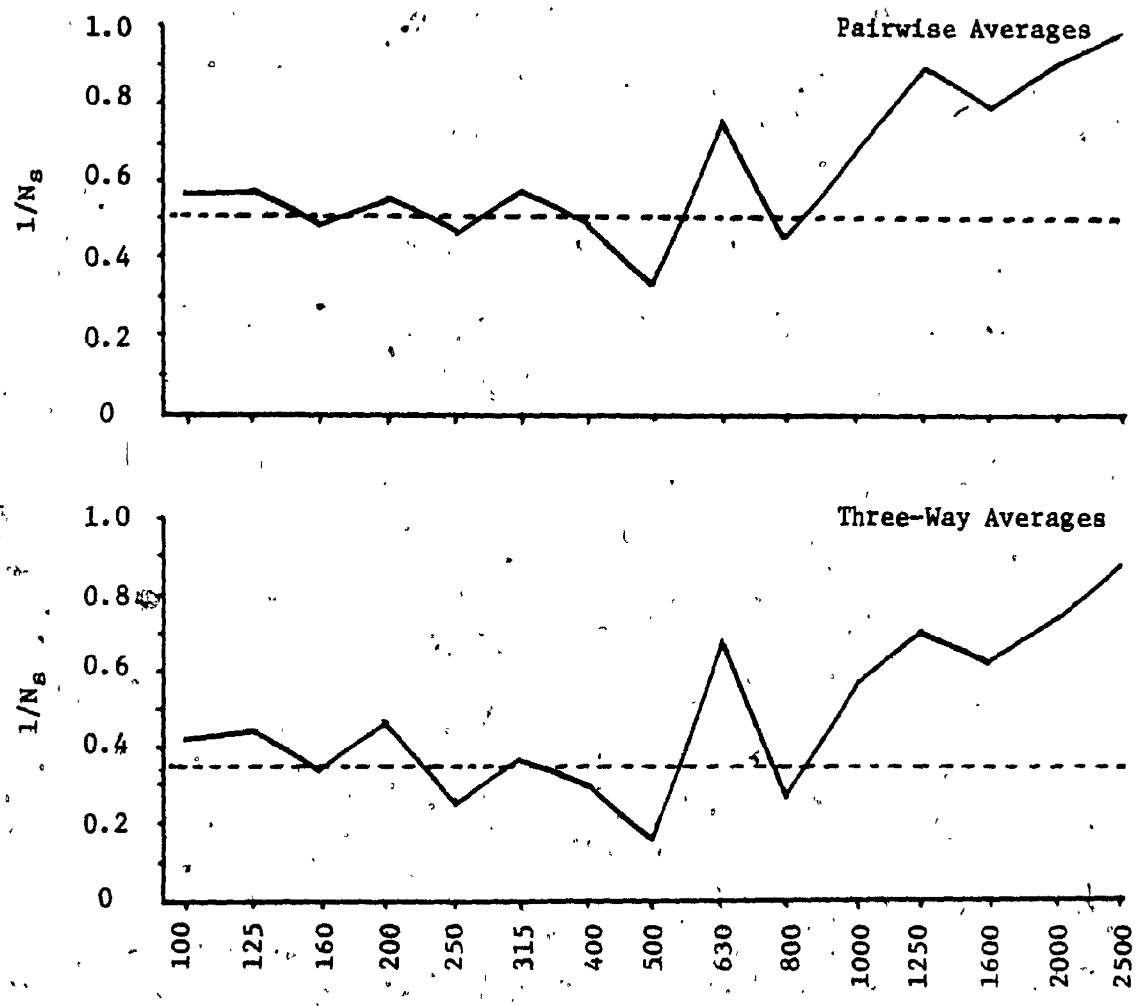


Figure 26. Co[illegible]ison of Calculated $1/N_s$ Values With Th[illegible]tical (-------) - Room With Diffusers Only

retical at low frequencies, and generally diverge more highly at the highest frequencies for the reasons discussed above.

It might also be noted here that the particular diffuser configuration used for the previous measurements resulted from error measurements made in the 200 Hz band, for different diffuser configurations. This frequency band was selected because it was recognized from previous measurements that the 200 Hz band would likely be the stumbling block to qualification throughout the total frequency range, as the diffuser was particularly ineffective in this band.

For each diffuser panel configuration and the swept volume per panel per second at a diffuser speed of 15 rpm was evaluated, and is plotted in Figure 27 against measured standard deviation at a single source position. There does not appear to be any correlation between swept volume and total standard deviation. As a result of this curve, the panels were left set to provide a maximum swept volume per second of 0.586 m^3/s at 30 rpm, compared to half that at 15 rpm. The 30 rpm point at this swept volume is also shown in Figure 27 and illustrates that the larger increases in swept volume available via increased rotational speed as compared to alteration of panel configuration result in more effective reduction in error.

3.4 Pure Tone Qualification Results - Final Room Configuration - Addition of Low Frequency Absorption

The reverberation times and absorption coefficients for the room with resonator bottles and panel absorbers plus resonator bottles are shown in Table VII.

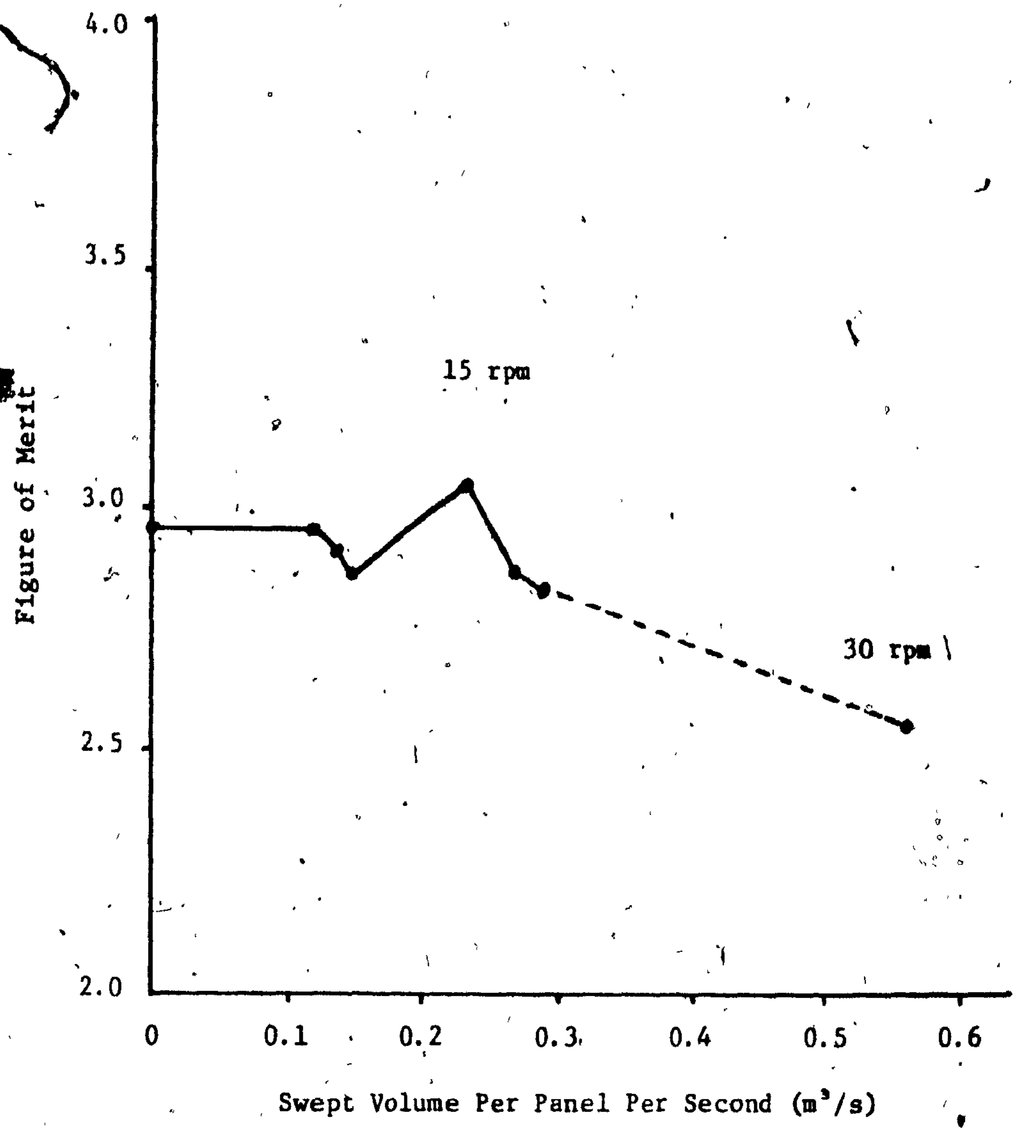


Figure 27. Diffuser Figure of Merit Versus Swept Panel Volume at 200 Hz

TABLE VII

ROOM PARAMETERS WITH LOW FREQUENCY ABSORPTION

Freq. (Hz)	Resonator Bottles Only		Final Configuration Panel Absorbers + Resonator Bottles	
	T_{60}	$\bar{\alpha}$	T_{60}	$\bar{\alpha}$
100	1.84	0.06	1.89	0.06
125	1.76	0.06	1.78	0.06
160	2.59	0.05	2.32	0.05
200	2.40	0.05	2.06	0.06
250	3.73	0.03	3.02	0.04
315	3.76	0.03	3.42	0.03
400	4.11	0.03	3.76	0.03
500	3.99	0.03	3.79	0.03
630	3.70	0.03	3.58	0.03
800	3.31	0.04	3.25	0.04
1000	3.17	0.04	3.13	0.04
1250	3.10	0.04	3.09	0.04
1600	2.82	0.04	2.78	0.04
2000	2.53	0.05	2.49	0.05
2500	2.34	0.05	2.30	0.05

In comparison with the values in Table V, the panels and bottles can be seen to be only slightly effective in reducing reverberation times, and the absorption coefficients differ generally by no more than 0.01. At 200 Hz, the particular band of interest since it was the only one not to qualify with the diffuser only, the absorption coefficient was only raised by 0.02. Although the rise in absorption appears small, the effect upon standard deviation at some source positions was substantial. For one configuration of panel absorbers and resonator bottles, the deviations shown in Table VIII were measured.

TABLE VIII

EFFECT OF SMALL INCREASE IN ABSORPTION ON MEASUREMENT ERROR AT 200 Hz

POSITION #1		POSITION #2		POSITION #3	
W/o Absorption	W Absorption	W/o Absorption	W Absorption	W/o Absorption	W Absorption
3.2	2.1	2.9	3.1	3.5	3.0
Error (db)		Error (db)		Error (db)	

While position 2 is actually adversely affected, there is a dramatic reduction in deviation at position 1, and a moderate reduction at position 3. The reason for this reduction is shown in Figure 28. The measured levels over frequency are shown for the room with and without the low frequency absorption. Also shown is the absorption curve for a typical resonator bottle as measured in a standing wave tube. The absorption broadens the modal response over the entire band, and is

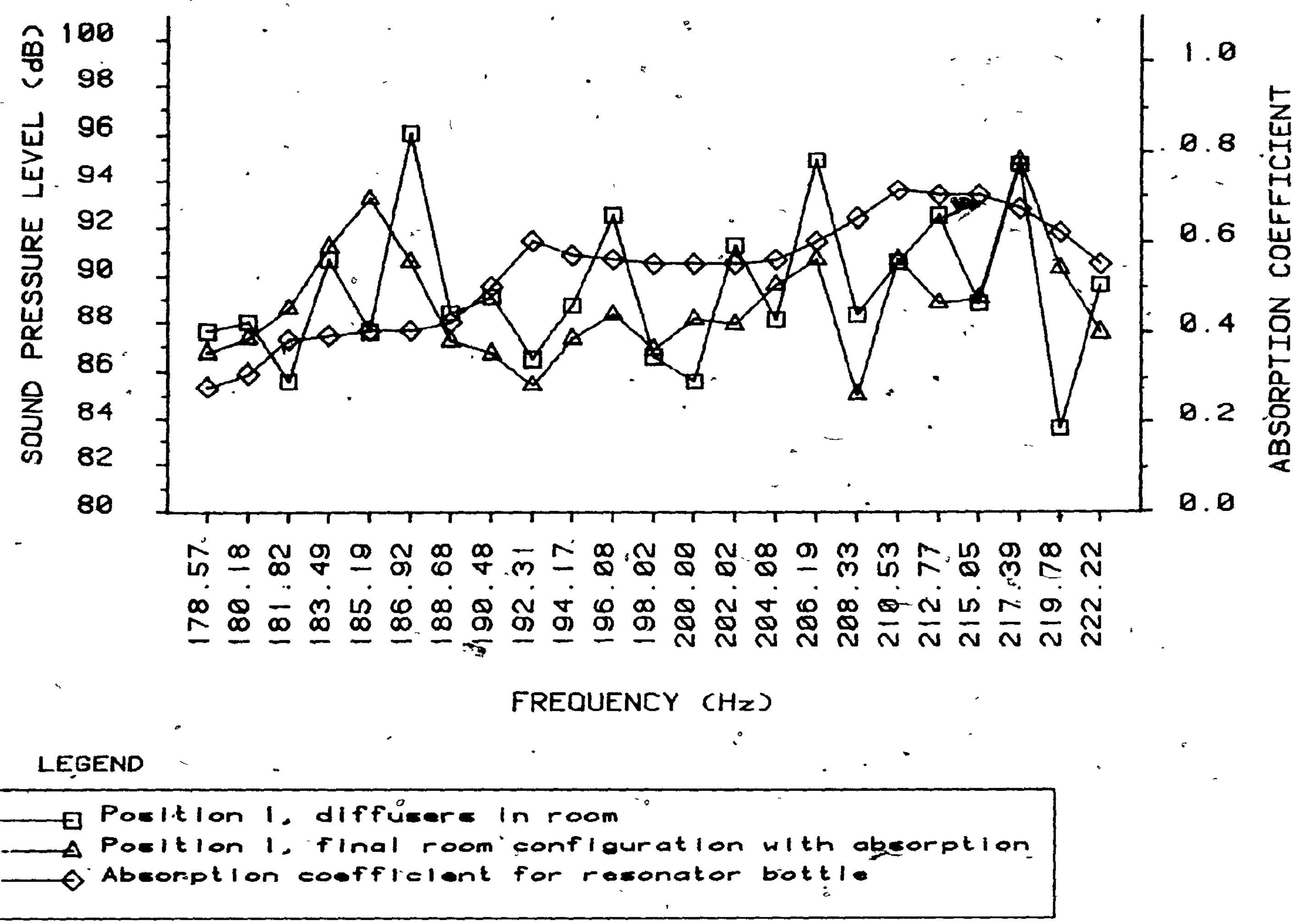


FIGURE 28 : EFFECT OF ABSORPTION ON SOUND PRESSURE LEVELS AT 200 HZ

effective in reducing the spike-like response over approximately two-thirds of the band.

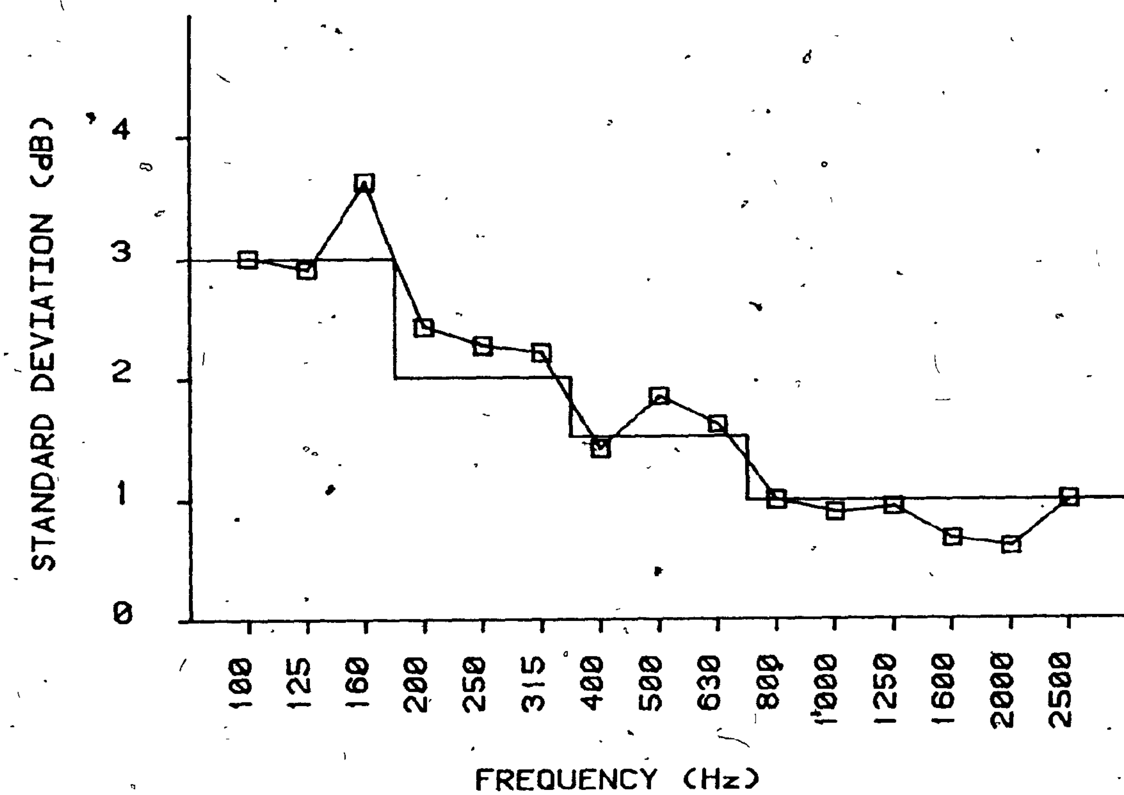
Despite the beneficial effects of absorption at the one position, the averages over any combination of these source positions still failed to qualify the band to the ANSI S1.21-1972 limit of 2.0 dB. Two larger panel absorbers were fabricated and installed in the room but failed to achieve any further success at this frequency. Also, the inclusion of large surface areas of the panel absorber material was increasing high frequency absorption beyond that desired, and the considerable size was occupying more of the already limited space available in the room. At this point it was decided to try other source positions as a route to qualification in the 200 Hz band, as position 1 had already demonstrated that values approaching the required limit could be achieved even at a single source position.

The final positions used were 1, 4, and 5 (Figure 7). The measure deviations for these positions are shown in Figures 29, 30, and 31, respectively. Again, no single position will enable qualification over the entire frequency range. The deviations at 125 Hz and 200 Hz for position 1 have been appreciably lowered by the addition of low frequency absorption. It is likely that the modal broadening effect of the low frequency absorption is also responsible for the low deviations at these frequencies for the other two positions.

The pairwise averages over source position are shown in Figures 32, 33, and 34. Only the average of positions 4 and 5 does not qualify at every frequency except 200 Hz, the other exception in this

STANDARD DEVIATIONS (dB)

FREQ. (Hz)	□
100	3.0
125	2.9
160	3.6
200	2.4
250	2.3
315	2.2
400	1.4
500	1.9
630	1.6
800	1.0
1000	0.9
1250	1.0
1600	0.7
2000	0.6
2500	1.0



LEGEND

□——□ Position 1

FIGURE 29 : DEVIATIONS FOR FINAL ROOM CONFIGURATION

STANDARD DEVIATIONS (dB)

FREQ. (Hz)	□
100	3.1
125	2.8
160	3.1
200	2.6
250	2.3
315	2.0
400	1.6
500	1.9
630	1.8
800	1.1
1000	0.7
1250	0.9
1600	0.8
2000	0.6
2500	1.2

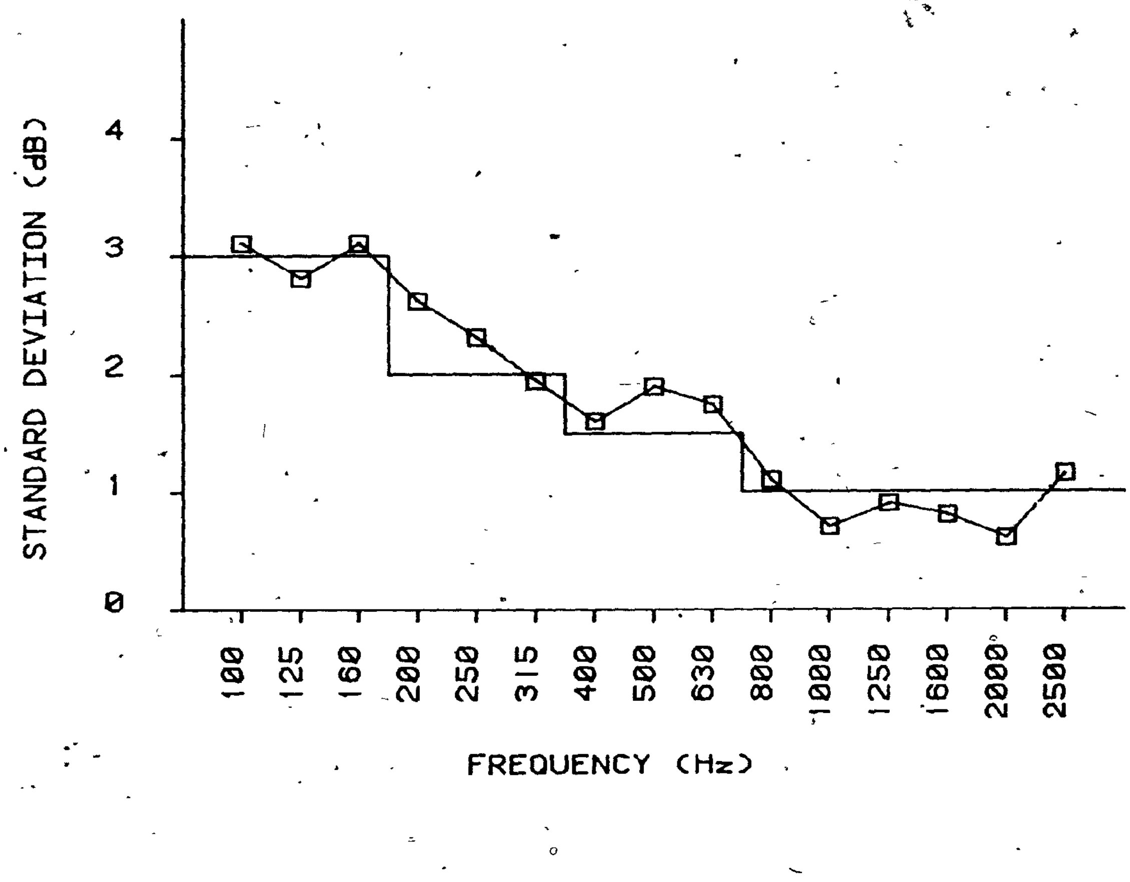
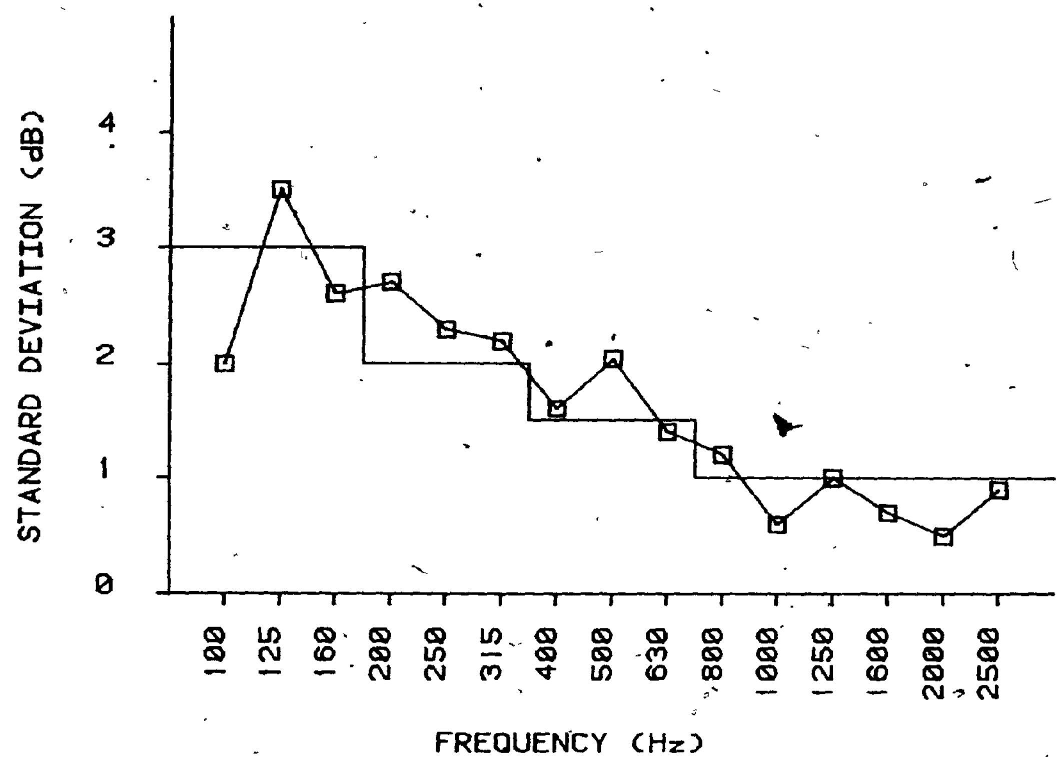


FIGURE 30 : DEVIATIONS FOR FINAL ROOM CONFIGURATION

STANDARD DEVIATIONS (dB)

FREQ. (Hz)	□
100	2.0
125	3.5
160	2.6
200	2.7
250	2.3
315	2.2
400	1.6
500	2.1
630	1.4
800	1.2
1000	0.6
1250	1.0
1600	0.7
2000	0.5
2500	0.9



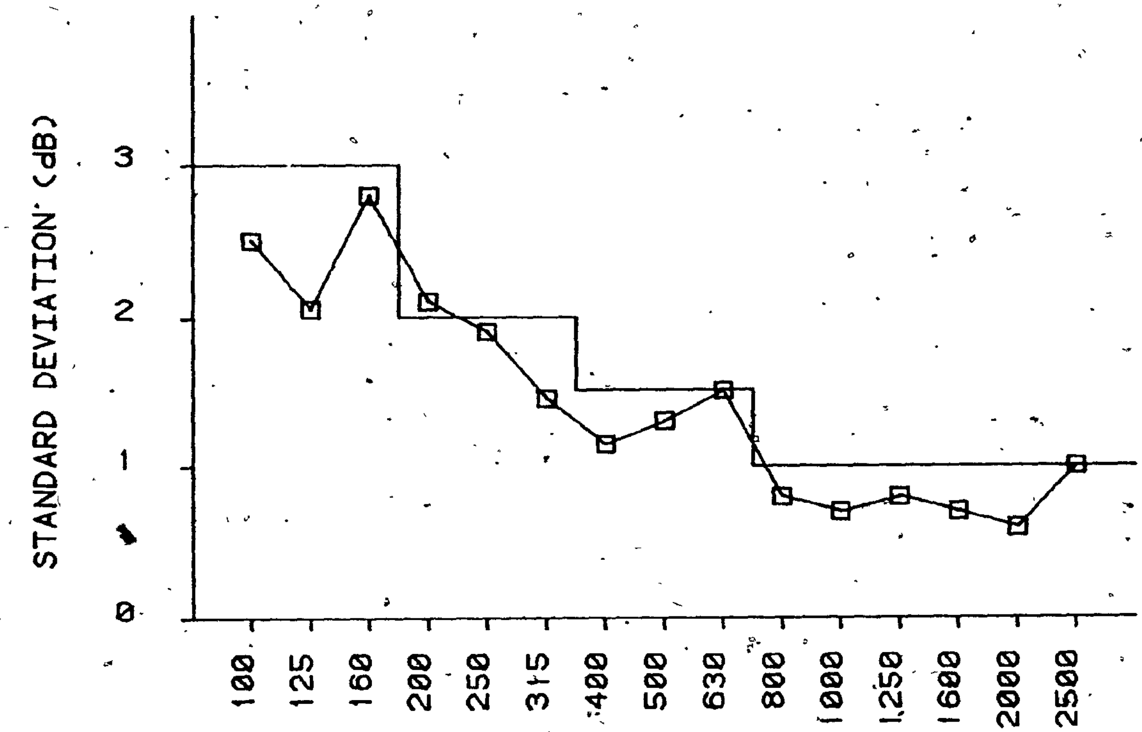
LEGEND

□—□ Position 5

FIGURE 31 : DEVIATIONS FOR FINAL ROOM CONFIGURATION

STANDARD DEVIATIONS (dB)

FREQ. (Hz)	□
100	2.5
125	2.1
160	2.8
200	2.1
250	1.9
315	1.5
400	1.2
500	1.3
630	1.5
800	0.8
1000	0.7
1250	0.8
1600	0.7
2000	0.6
2500	1.0



LEGEND

□——□ Average of positions 1 and 4

FIGURE 32 : PAIRWISE AVERAGE DEVIATIONS FOR FINAL ROOM CONFIGURATION

STANDARD DEVIATIONS (dB)

FREQ.(Hz)	□
100	2.4
125	3.0
160	2.4
200	2.2
250	1.8
315	1.5
400	1.2
500	1.7
630	1.4
800	0.9
1000	0.6
1250	0.9
1600	0.6
2000	0.5
2500	0.9

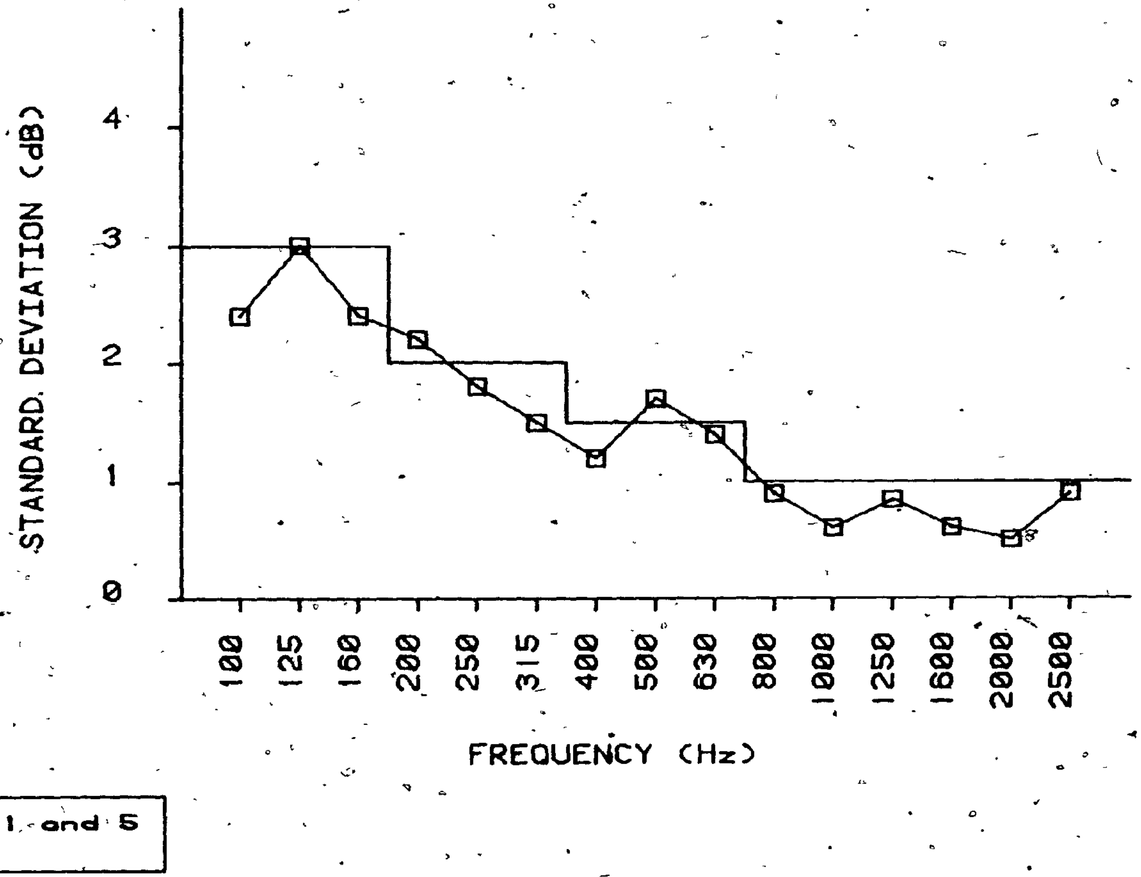
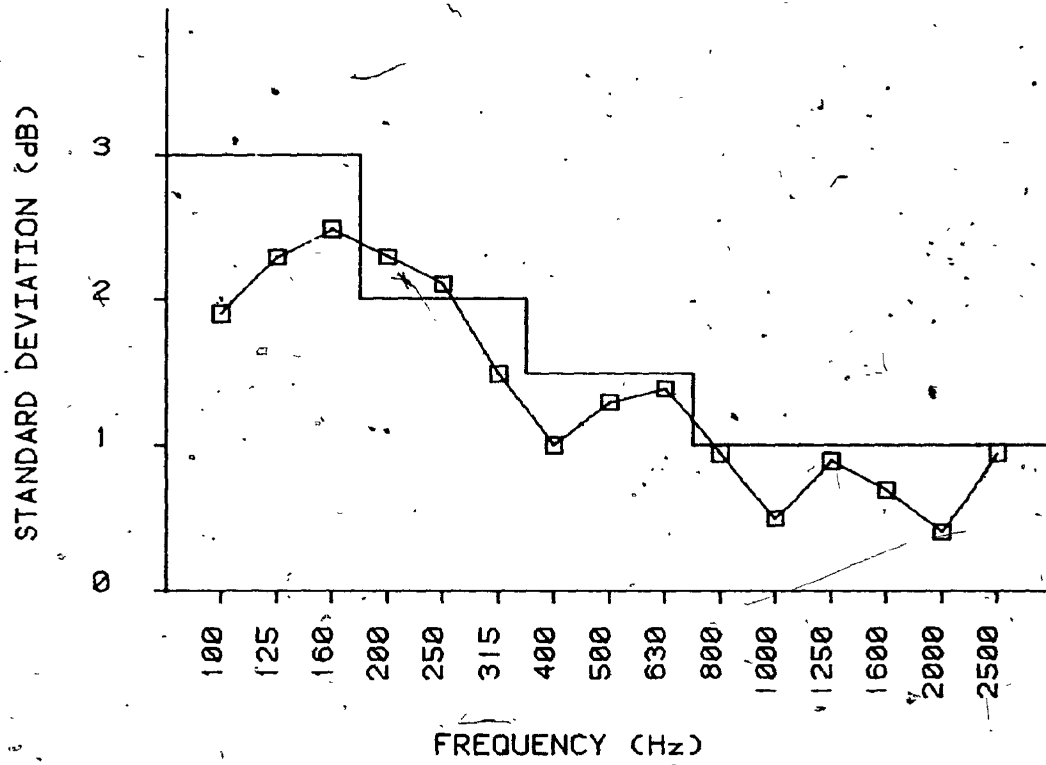


FIGURE 33 : PAIRWISE AVERAGE DEVIATIONS FOR FINAL ROOM CONFIGURATION

STANDARD DEVIATIONS (dB)

FREQ. (Hz)	□
100	1.9
125	2.3
160	2.5
200	2.3
250	2.1
315	1.5
400	1.0
500	1.3
630	1.4
800	1.0
1000	0.5
1250	0.9
1600	0.7
2000	0.4
2500	1.0



LEGEND

□——□ Average of positions 4 and 5

FIGURE 34 : PAIRWISE AVERAGE DEVIATIONS FOR FINAL ROOM CONFIGURATION

case being the 500 Hz band. The three-way average is shown in Figure 35. The deviation in the 200 Hz band is lowered just to the 2.0 dB limit as a result of the slight absorption increase in the band. The deviations at other frequencies are not significantly different from those seen in Figure 23 for the room without low frequency absorption, except at 125 Hz. The three-way average is reduced from 3.0 to 2.4 at this frequency, and is attributable to reduced correlation between the source positions 1 and 4 used in the final qualification as compared to any combination of positions 1, 2, or 3 previously used. The average of positions 1 and 4, with single position standard deviations of 2.9 and 2.8 respectively, is 2.1 dB, giving a calculated $1/N_s$ value of 0.45, very close to the theoretical of 0.50. Thus, the two positions give uncorrelated responses. The addition to the average of position 5 actually raises the error, indicating that it is at least partially correlated with the other positions. An examination of the other pairwise averages shows that position 5 is most highly correlated with position 1.

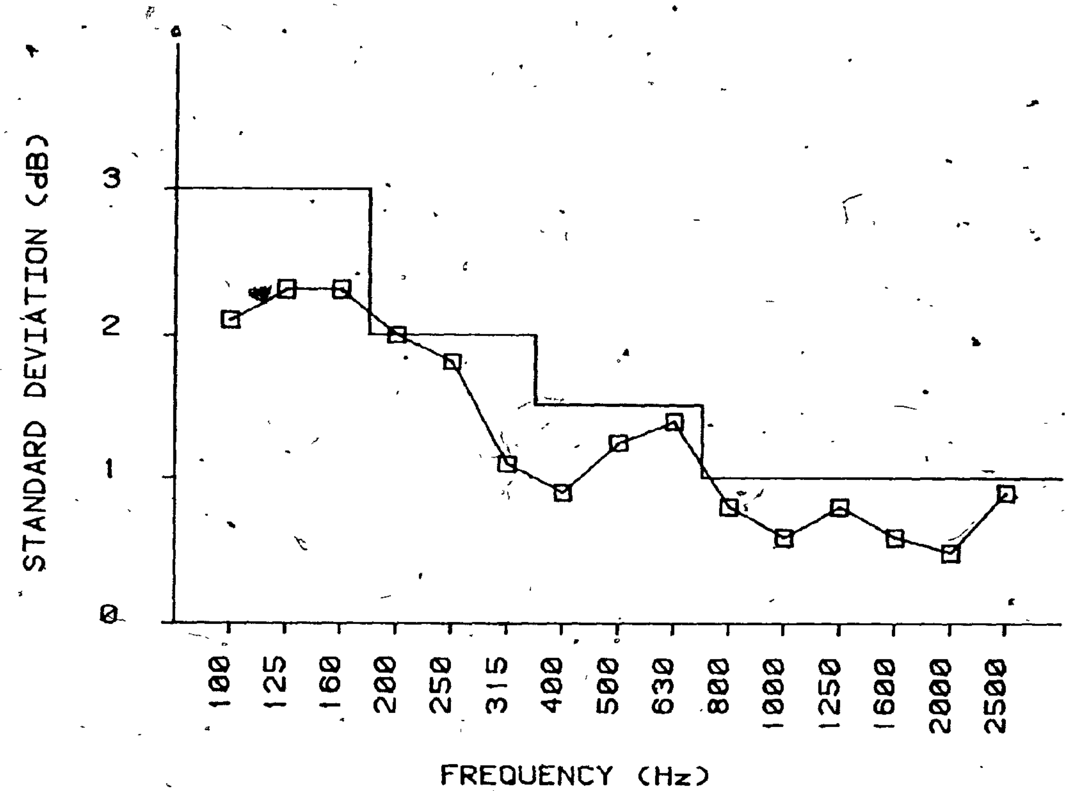
In summary, the final qualification of the 94 m^3 reverberation chamber resulted from a small increase in absorption in the 200 Hz band causing increased modal overlap and consequent reductions in spatial variation of squared pressure and fluctuations in source power output. Reduced variation at the lowest frequencies resulted from improved uncorrelation of room response with respect to the chosen source positions.

3.5 Room Qualification for Broadband Excitation

Broadband excitation results in considerably lower error estimates. This can be seen from Equations 31 and 32. For a pure tone,

STANDARD DEVIATIONS (dB)

FREQ. (Hz)	□
100	2.1
125	2.3
160	2.3
200	2.0
250	1.8
315	1.1
400	0.9
500	1.3
630	1.4
800	0.8
1000	0.6
1250	0.8
1600	0.6
2000	0.5
2500	0.9



LEGEND

□—□ Average of positions 1,4 and 5

FIGURE 35 : THREE-WAY AVERAGE DEVIATIONS FOR FINAL ROOM CONFIGURATION

$V_R^2 = 1$, where as for a 1/3-octave band of noise centred, in the worst case considered for sound power estimation at 100 Hz, $V_R^2 = 0.22$. This reduction in spatial variance occurs because the band of noise simultaneously excites many more modes than a pure tone, thus developing a more uniform response in the room. Also, the variations in sound power output over frequency tend to average under noise excitation. Thus both factors affecting the total measurement error are reduced. It has been shown experimentally([11]) that there is close agreement between predicted spatial variance and measured values over the entire frequency range of interest.

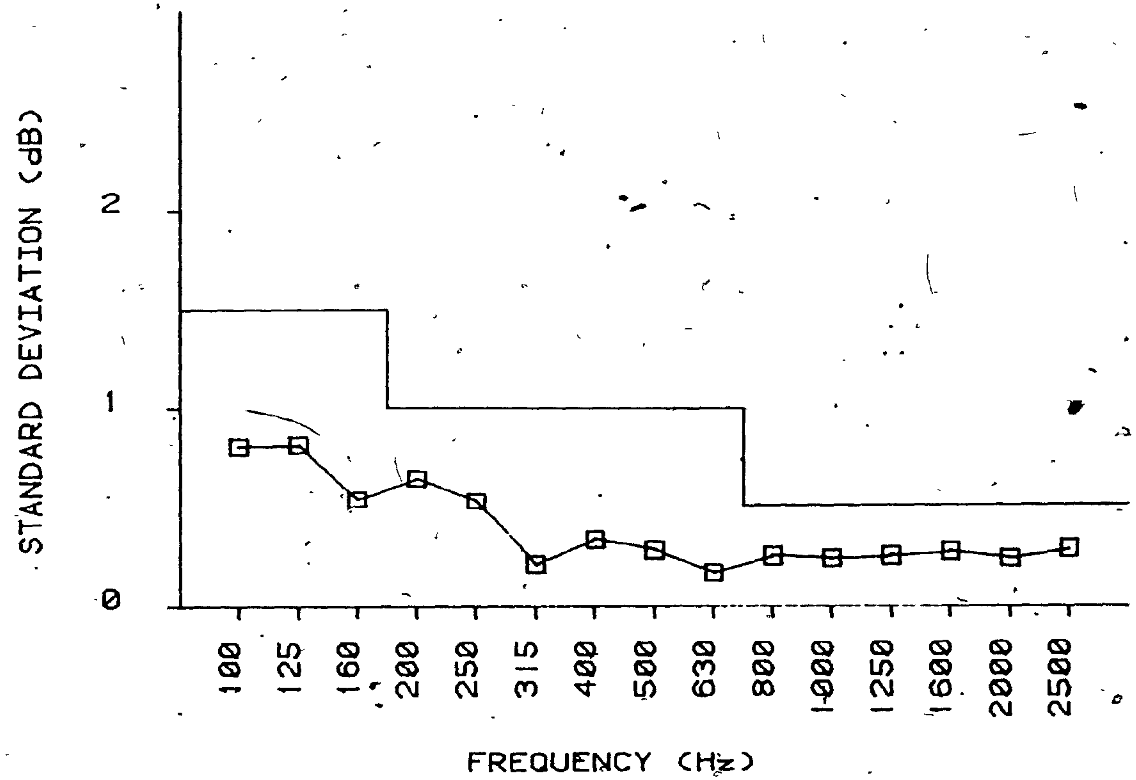
Shown in Figure 36 is the measured standard deviations versus frequency and specified limit of ANSI S1.21-1972. An ILG reference sound source was used to generate broadband excitation at eight source locations spaced 1 m apart, corresponding to $\frac{\lambda}{4}$ at the lower frequency edge of the 100 Hz band. The source was also kept at the required minimum distance from the microphone.

It is not surprising in light of the fact that the room qualifies for pure tone measurement that the standard deviations are substantially lower than those promulgated by the standard. It is likely that due to the expected reduction in spatial variance for noise excitation, many of the modifications required for pure-tone qualification would not be necessary for broadband qualification.

Since the sound power output of the ILG reference sound source is well-documented([36]), it is of interest to check the calculated values of sound power from the reverberation room measurements. The sound power

STANDARD DEVIATIONS (dB)

FREQ.(Hz)	□
100	0.8
125	0.8
160	0.5
200	0.7
250	0.5
315	0.2
400	0.3
500	0.3
630	0.2
800	0.3
1000	0.2
1250	0.3
1600	0.3
2000	0.2
2500	0.3



LEGEND

□——□ Average over eight source positions

FIGURE 36 : MEASURED STANDARD DEVIATIONS FOR BROADBAND EXCITATION

levels are calculated from the average pressure levels determined during the broadband qualification process, and the final configuration reverberation times in Table VII, using Equation 51. The comparison is shown in Table IX.

TABLE IX

COMPARISON OF CALCULATED SOUND POWER LEVELS OF ILG [illegible]ERENCE SOUND SOURCE USING FREE-FIELD AND [illegible] REVERBERANT ROOM METHODS[36]

Freq. (Hz)	SOUND POWER LEVEL (dB re 1pW)		
	Free-Field	Other Reverberation Rooms	Concordia CBS Reverberation Room
100	76	71	72.9
125	76	72	74.2
160	76	73	74.2
200	76	74	75.5
250	76	74	74.9
315	76	75	75.9
400	76	75	75.2
500	76	75	75.2
630	76	74	75.1
800	76	74	74.9
1000	76	75	75.3
1250	76	76	75.8
1600	76	75	75.7
2000	76	75	75.6
2500	76	74	75.4

In all cases, the calculated values lie between the free-field power levels and the average values based on measurements in a number of reverberation rooms. The calculated power levels are also seen to roll-off from the free-field values at the lowest frequencies, an occurrence well documented for reverberant room sound power measurement[20]. The roll-off is of sufficient magnitude that the Waterhouse correction is inadequate to compensate. This discrepancy may be attributable to an actual reduction in power output due to inadequate coupling to the sparse number of modes at low frequencies, or perhaps because the 60 dB reverberation time is an inappropriate measure to use - an early decay time has been suggested[21]. This is an area which requires further research.

In summary, the room configuration used for pure tone measurement also enables accurate sound power measurement of broadband sources, with standard deviation of measurement well below the specified limits of ANSI S1.21-1972. It might also be noted here that for the final measurements of both the broadband and pure tone qualification procedures, the product

$$RH\ (t + 5°C)$$

where

RH = relative humidity, %

t = ambient temperature, °C

remained within ± 10% of the same product measured during reverberation time testing. This was fortunate as no provision for humidity control is available in the reverberation room.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The 94 m^3 reverberation chamber under study is, to the author's knowledge, the first of its size to be qualified for discrete frequency sound power measurement under the conditions of ANSI S1.21-1972. The predominant reasons for the success in qualification are that:

i) the lightweight wall construction provides inherent low frequency absorption which would otherwise have to be added by space-occupying modifiers such as panel absorbers. This low frequency absorption sufficiently broadens modal response in this range to reduce measured standard deviations to levels which can successfully be further reduced to qualifiable limits via the use of other room modifiers. Small increases in room absorption at low frequencies can have dramatic effects in reducing overall error. This is substantiated by another study[24] where qualification for a room of similar volume was unattainable at 100 Hz, but where the absorption coefficient at this frequency is about 0.57 times the value in the room considered here. At other frequencies, the absorptions are similar. Consequently, it appears that the use of lightweight construction for small reverberation rooms should be considered in the design stage of a room, to avoid the problem of having to introduce an inordinate number of low frequency absorbers.

ii) it was fortunate to find source positions that gave reasonably uncorrelated room responses at low frequencies, since there is currently no method of determining where these positions are located with respect to one another. The use of such positions is highly beneficial in improving overall error when averages over source position are required. The criteria of $\frac{\lambda}{4}$ separation is not adequate in ensuring this uncorrelation.

The figures of merit for the rotating diffuser were found to be comparable to others reported in the literature. No correlation between diffuser swept volume and overall error were found for simple measurements in the 200 Hz band. The error appears to be more dependent upon diffuser rotational speed.

Broadband qualification for a room having previously been qualified for pure tone measurement is assured, and calculated sound power levels of broadband sources can then be accurately determined. The discrepancy between free-field and reverberant sound power at low frequencies remains to be resolved.

Although ANSI S1.21-1972 recommends a minimum room volume of 180 m^3, the results of this study support the potential use of a room of this size for both pure tone and broadband sound power measurement, even for frequency bands as low as the 100 Hz band. In particular, the calculated sound power of a broadband reference source was found to be extremely accurate over the frequency range of interest (unfortunately, there is presently no reference pure tone source). The room will accommodate sources with dimensions of about 0.45 x 0.61 x 0.61 m for pure tone measurement, encompassing, for example, such sources as compressed air tools, and will accommodate sources with dimensions of about 1 x 1 x 1 m for broadband measurement. The difference in dimensions relates to the fact that three specific source positions spaced $\frac{\lambda}{4}$ apart at the lowest frequency of interest, 1.5 m from any wall, and 0.6 m from the nearest microphone traverse point, must be used for pure tone sound power measurement, while only one position located at least 1.5 m from any wall and 0.6 m from the nearest microphone traverse point is required.

The measured pressure levels for a source in question must be at least 10 dB greater than the current background levels, shown in Table X.

If reduction in the rotating diffuser noise, which predominates the background noise, is made, then sources with correspondingly lower sound power outputs, hence measured pressure levels, can be made.

Sound power measurements made in this room should be annotated as having been made in accordance with ANSI S1.21-1972 except for the room size criterion and the minimum microphone distance from the room surfaces. This is recommended as $\frac{\lambda}{2}$ at the lowest frequency of interest in the standard, while room size restricted the distance to $\frac{\lambda}{4}$ in this case.

TABLE X

BACKGROUND SOUND PRESSURE LEVELS (re 20μPa)

Freq. (Hz)	Level (dB)
100	52
125	67
160	54
200	52
250	51
315	54
400	58
500	59
630	60
800	55
1000	48
1250	48
1600	46
2000	44
2500	41

There can be no quarrel with the provisions of ANSI S1.21-1972. There is at present inadequate theoretical background for predicting overall error, sound power output variance, and spatial variance at low frequencies. Until the understanding of these processes and their intercorrelation is obtained, it would appear pointless to attempt to tighten qualification limits or alter measurement procedures.

4.2 Recommendations for Future Research

The following areas are suggested for future research in the area of sound power determination in reverberant rooms:

i) The correlation between source location and room response should be examined in order to enable selection of "optimum" source locations.

ii) The variation in sound power output of a source as a function of frequency should be examined in order to quantify the significance of this variable.

iii) The variation in sound power output as a function of source position should be analyzed. Current theory would appear to overestimate this variation.

iv) The discrepancy between free-field and reverberant sound power measurement should be reviewed in light of recent proposals for the use of early decay time in place of T_{60} for sound power calculations.

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APPENDIX A

AMERICAN NATIONAL STANDARD

METHODS FOR THE DETERMINATION OF

SOUND POWER LEVELS OF SMALL SOURCES IN

REVERBERATION ROOMS

APPENDIX A

Readers are asked to consult a copy of the American National Standard, published by the American National Standards Institute, 1430 Broadway, New York, New York 10018

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APPENDIX B

SOUND POWER PROGRAM SOFTWARE
(written in HPL)

```
0: dsp "*****SOUND POWER DATA ACQUISITION PROGRAM*****"
1: trk 0
2: dsp "Please insert ""HERBIE 1"" tape";wait 3000;stp
3: dim B$(318),P(27,15),S(15),M(15),C(361),X(50),Y(50),E(27),H$(2);fxd 2
4: dim A$(2)
5: dim I$(1),C$(1),D$(1),S$(2)
6: dim N(15)
7: .3=C(1);.2=C(2)=C(3)=C(4)=C(5);.1=C(6)=C(7)=C(8)=C(9)
8: .1=C(14)=C(15)=C(16)=C(17);.2=C(18)=C(19)=C(20);.3=C(21)=C(22)
9: -.7=C(23);-.6=C(24)=C(25)=C(26);-.5=C(27)=C(28);-.4=C(29);-.3=C(30)
10: -.2=C(31);-.1=C(32);-.2=C(33);.1=C(36)=C(37)=C(39)=C(40);.2=C(41)
11: .3=C(42)=C(43)=C(44);.4=C(45)
12: -.5=C(46)=C(47)=C(48);-.4=C(49);-.3=C(50);-.2=C(51)=C(52)=C(53)
13: -.1=C(54);.1=C(59);.2=C(60)=C(61);.3=C(62)=C(63)=C(64);.2=C(65)
14: .3=C(66);.4=C(67)=C(68)=C(69)=C(70)
15: -.3=C(71)=C(72)=C(73)=C(74);-.2=C(75);-.3=C(76);-.2=C(77);-.1=C(78)=C(79)
16: .1=C(85);.2=C(86)=C(87)=C(88)=C(89)=C(90);.3=C(91);.2=C(92)=C(93)
17: -.1=C(94)=C(95)=C(96)=C(98)=C(99)=C(100)=C(101)=C(102)=C(103)=C(104)
18: -.1=C(105)=C(107)=C(108)=C(109)=C(110)=C(111);-.2=C(112);-.3=C(113)
19: -.3=C(114);-.2=C(115)=C(116)=C(117)
20: -.1=C(118)=C(119);.1=C(121)=C(123);-.1=C(136)=C(137)=C(138);-.2=C(139)
21: -.2=C(140);-.3=C(141)=C(142)
22: .5=C(143);.6=C(144);.5=C(145)=C(146);.4=C(147);.3=C(148)=C(149)
23: .2=C(150)=C(151)=C(152)=C(153);.1=C(154);-.2=C(156)=C(157)=C(158)=C(159)
24: -.3=C(160)=C(161)=C(162);-.4=C(163)=C(164)=C(165);-.5=C(166);-.6=C(167)
25: .6=C(168);.7=C(169);.8=C(170)=C(171);.7=C(172);.6=C(173);.4=C(174)
26: .3=C(175)=C(176);.1=C(177);-.1=C(180);-.2=C(181);-.3=C(182);-.4=C(183)
27: -.6=C(184);-.9=C(185);-1=C(186);-1.2=C(187)=C(188);-1.3=C(189)
28: 1.5=C(190)=C(191);1.3=C(192);1.2=C(193);1=C(194);.9=C(195);.8=C(196)
29: .7=C(197);.4=C(198);.2=C(199);.1=C(200);-.1=C(202);-.3=C(203);-.4=C(204)
30: -.5=C(205)=C(206);-.6=C(207);-.7=C(208);-.8=C(209);-.9=C(210)=C(211)
31: -1.2=C(212);-1.3=C(213);-1.4=C(214)
32: 2=C(215);1.9=C(216);1.7=C(217);1.5=C(218);1.3=C(219);1.1=C(220);.9=C(221)
33: .8=C(222);.3=C(223)=C(224);-.2=C(226);-.4=C(227);-.6=C(228);-.7=C(229)
34: -1=C(230);-1.1=C(231);-1.2=C(232);-1.4=C(233)=C(234);-1.5=C(235)
35: -1.6=C(236);-1.9=C(237);1.73=C(238);1.59=C(239);1.43=C(240)
36: 1.29=C(241);1.12=C(242);.97=C(243);.78=C(244)
37: .67=C(245);.5=C(246);.27=C(247);-.31=C(249);-.64=C(250);-1.01=C(251)
38: -1.23=C(252);-1.41=C(253);-1.56=C(254);-1.47=C(255)
39: -1.29=C(256);-.78=C(257);-.33=C(258);.29=C(259)
40: -1.9=C(260);-1.6=C(261);-1.3=C(262);-1.2=C(263);-.9=C(264);-.7=C(265)
41: -.5=C(266);-.4=C(267);-.2=C(268);-.1=C(270)=C(271)
42: .1=C(274)=C(275)=C(276)=C(277)=C(278)=C(279)=C(280);-.2=C(281);-.1=C(282)
43: -.1=C(284)=C(285)=C(286)
44: .7=C(287);.6=C(288)=C(289);.7=C(290);.6=C(291)=C(292);.5=C(293)=C(294)
45: .3=C(295);.2=C(296);.1=C(297);-.1=C(300)=C(301);-.3=C(302)=C(303)=C(304)
46: -.2=C(305)=C(306)=C(307)=C(308);-.1=C(309);-.2=C(310)=C(312)
47: -1.21=C(313);-1.14=C(314);-1.07=C(315);-1=C(316);-.81=C(317);-.68=C(318)
48: -.54=C(319);-.4=C(320);-.28=C(321);-.16=C(322);.18=C(324)
49: .38=C(325);.57=C(326);.76=C(327)
50: .89=C(328);1.06=C(329);1.36=C(330);1.57=C(331);1.82=C(332)
```

```
51: 1.94=C(333);2.06=C(334)
52: 1.8=C(335)=C(336);1.6=C(337);1.3=C(338);1=C(339)=C(340);.8=C(341)
53: .7=C(342);.5=C(343);.2=C(344);-.1=C(345);-.2=C(346);-.1=C(347)=C(349)
54: -.1=C(350);.1=C(352);.2=C(353);.3=C(354);.6=C(355);.8=C(356)
55: .9=C(357);1.1=C(358);1.3=C(359);1.5=C(360);1.7=C(361)
56: for I=1 to 50
57: 1.135-.005I=X(I)
58: next I
59: 3.1=Y(1);2.4=Y(2);1.7=Y(3);1.3=Y(4);.7=Y(5);.4=Y(6);.1=Y(7)
60: -.1=Y(9)=Y(10)=Y(11);-.005=Y(12);.1=Y(14)=Y(15)=Y(16)
61: .2=Y(17)=Y(18)=Y(19)=Y(20)=Y(21)=Y(22);.1=Y(23)=Y(24)=Y(25)=Y(26)
62: -.1=Y(28)=Y(29)=Y(30)=Y(31)=Y(32)=Y(33)=Y(34)=Y(35)=Y(36)
63: .1=Y(41)=Y(42)=Y(43);.2=Y(44);.4=Y(45);.8=Y(46);1.3=Y(47);1.9=Y(48)
64: 2.6=Y(49);3.3=Y(50)
65: 22=N(1)=N(8)=N(11)=N(14);23=N(2)=N(4)=N(10);25=N(3)=N(6)=N(7)=N(9)
66: 24=N(5);27=N(12)=N(15);26=N(13)
67: ent "AVERAGING TIME (32,64or128s) ?",D
68: if D=32;"0="=S$
69: if D=64;"0>"=S$
70: if D=128;"0?"=S$
71: buf "in",B$,3
72: ent "RUN#",Z;(Z-1)*361=E
73: 0=W
74: if Z>=4;(Z-4)*361=E;trk 1;1=W
75: ent "1/3 OCTAVE BAND IN HZ?",L
76: if L=100;22=N;11.1=A;10.0793=B;.1=U;1=K;gto 92
77: if L=125;23=N;8.88=A;8=B;.08=U;2=K;gto 92
78: if L=160;25=N;7.08=A;6.3496=B;.06=U;3=K;gto 92
79: if L=200;23=N;5.6=A;5.0397=B;.05=U;4=K;gto 92
80: if L=250;24=N;4.48=A;4=B;.04=U;5=K;gto 92
81: if L=315;25=N;3.54=A;3.1748=B;.03=U;6=K;gto 92
82: if L=400;25=N;2.76=A;2.5198=B;.02=U;7=K;gto 92
83: if L=500;22=N;2.22=A;2=B;.02=U;8=K;gto 92
84: if L=630;25=N;564=A;629.961=B;-6=U;9=K;gto 92
85: if L=800;23=N;712=A;793.701=B;-8=U;10=K;gto 92
86: if L=1000;22=N;900=A;1000=B;-10=U;11=K;gto 92
87: if L=1250;27=N;1130=A;1259.921=B;-10=U;12=K;gto 92
88: if L=1600;26=N;1410=A;1587.401=B;-15=U;13=K;gto 92
89: if L=2000;22=N;1800=A;2000=B;-20=U;14=K;gto 92
90: if L=2500;27=N;2260=A;2519.842=B;-20=U;15=K;gto 92
91: dsp "INVALID FREQ. ";wait 1000;gto 75
92: ent "TONE # IN BAND?",V
93: for J=V to N
94: 0=Q
95: if L>500;gto 97
96: dsp "PERIOD #",J,"TONE:",A-(V-1)*U,"ms";wait 1000;gto 98
97: dsp "#",int(J),"TEST FREQ =",A-(V-1)*U,"HZ";wait 1000;gto 99
98: B/(A-(V-1)*U)=C;gto 100
99: (A-(V-1)*U)/B=C
100: for I=1 to 50
```

```
101: if X(I)<=C; gto 103
102: next I
103: (C-X(I-1))/(X(I)-X(I-1))*(Y(I)-Y(I-1))+Y(I-1)=E(J)
104: clr 7;wait 50;cli 7;wait 50
105: for I=1 to 17+K
106: wrt 717,"D>"
107: next I
108: if L=250;wrt 717,"N;";gto 110
109: wrt 717,"N<",wait 100
110: wrt 717,"M?",S$,"L?M>";stp
111: wrt 717,"M="
112: if D=32;wait 20000,wait 20000
113: if D=64;wait 20000;wait 20000;wait 15000;wait 16000
114: if D=128;wait 32000;wait 32000,wait 32000,wait 32000,wait 15000
115: wrt 717,"E?";wait 100
116: buf "in"
117: tfr 716,"in",302
118: jmp rds("in")#-1
119: wrt 717,"E=";wait 100
120: for I=1 to 35-K,wrt 717,"D?";next I
121: 127+7K=I
122: for R=1 to K-1,N(R)+Q=Q,next R
123: prt C,prt E(J),prt C(Q+J)
124: val(B$[I,I+6])+E(J)+C(Q+J)=P(J,K)
125: A-U=A
126: fti (10*P(J,K))=A$
127: if H=3,Q-70=Q
128: dsp "NEXT FILE# =",Q+J+E,"TRACK",H,wait 2000
129: ent "RECORD (YorN)?",D$
130: if num(D$)=78 or num(D$)=110,gto 132
131: prt "Last file=",Q+J+E
132: rcf Q+J+E A$
133: ent "LAST MEASUREMENT? (Y or N)",I$
134: if num(I$)=89 or num(I$)=121,gto 137
135: next J
136: gto 75
137: end
```

```
0: dsp "*****SOUND POWER QUALIFICATION CALCULATION*****"
1: wait 2000
2: dim A$(2)
3: dim N(16),D(15),C$(1),W(15),R$(1),F$(4),S$(4),H$(4),V$(4),L$(16)
4: "FREQ"=F$;"(HZ)"=H$;"STD"=S$;"DEV"=V$;"----------------"=L$
5: trk 0
6: fmt 1,c8,c8
7: fmt 2,c16
8: fmt 3,f8.0,f8.2
9: 100=W(1);125=W(2);160=W(3);200=W(4);250=W(5);315=W(6)
10: 400=W(7);500=W(8);630=W(9);800=W(10);1000=W(11)
11: 1250=W(12);1600=W(13);2000=W(14);2500=W(15)
12: 0=N(1);22=N(2);45=N(3);70=N(4);93=N(5);117=N(6)
13: 142=N(7);167=N(8);180=N(9);214=N(10);237=N(11)
14: 259=N(12);286=N(13);312=N(14);334=N(15);361=N(16)
15: ent "SINGLE BANDS ONLY (YorN)?",R$
16: if num(R$)=78 or num(R$)=110;cll 'allband';end
17: 1=C
18: ent "# OF SOURCE POSITIONS",R
19: if C>1,gto 21
20: dim T(15),P(361),N$(15)
21: ent "RUN #'s IN SEQUENCE",N$
22: for I=1 to R;val(N$(I,I))=T(I);next I
23: ent "1/3 OCTAVE BAND ?",L
24: if L=100;2=A;gto 40
25: if L=125;3=A;gto 40
26: if L=160;4=A;gto 40
27: if L=200;5=A;gto 40
28: if L=250;6=A;gto 40
29: if L=315;7=A;gto 40
30: if L=400;8=A;gto 40
31: if L=500;9=A;gto 40
32: if L=630;10=A;gto 40
33: if L=800;11=A;gto 40
34: if L=1000;12=A;gto 40
35: if L=1250;13=A;gto 40
36: if L=1600;14=A;gto 40
37: if L=2000;15=A;gto 40
38: if L=2500;16=A;gto 40
39: dsp "INVALID FREQUENCY";wait 2000;gto 23
40: ina P
41: for D=1 to R
42: (T(D)-1)*361=E
43: if T(D)>=4;(T(D)-4)*361=E;trk 1
44: ent "CHANGE TAPE (YorN)?",C$
45: if num(C$)=78 or num(C$)=110;gto 50
46: ent "TAPE CARTRIDGE # ?",H
47: ent "TRACK #",W
48: trk W
49: 0=S=P=T
50: if H=2;(T(D)-5)*23+722=E;2=A;23=N(A)
```

```
51: for I=1+N<A-1> to N<A>
52: prt I+E
53: ldf I+E,A$
54: P<I>+1/R*tn↑(itf(A$)/100)=P<I>
55: next I
56: next D
57: 0=S=P=T
58: for I=1+N<A-1> to N<A>
59: P+(10log(P<I>)=C)=P
60: prt C
61: S+(10log(P<I>))↑2=S
62: next I
63: N<A>-N<A-1>=T;P↑2=P
64: !((S-P/T)/(T-1))=D<A-1>
65: wrt 16.1,F$,S$;wrt 16.1,H$,V$
66: wrt 16.2,L$
67: wrt 16.3,L,D<A-1>
68: ent "LAST CALCULATION (YorN) ?",C$
69: if num(C$)=89 or num(C$)=121;gto 71
70: C+1=C;1=H;" "=N$<1,15>;gto 18
71: end
72: "allband":
73: ent "# OF SOURCE POSITIONS",R
74: dim P<R,361>,N$<R>,T<R>,S<R,361>
75: ent "RUN #'s IN SEQUENCE",N$
76: for I=1 to R;val(N$<I,I>)=T<I>;next I
77: wrt 16.1,F$,S$;wrt 16.1,H$,V$
78: wrt 16.2,L$
79: for D=1 to R
80: (T<D>-1)*361=E
81: ent "CHANGE TAPE (YorN)?",C$
82: if num(C$)=78 or num(C$)=110;gto 86
83: ent "TAPE CARTRIDGE # ?",H
84: ent "TRACK #",W
85: trk W
86: if H=2,(T<D>-4)*361=E
87: for A=2 to 16
88: for I=1+N<A-1> to N<A>
89: ldf I+E,A$
90: itf(A$)/10=P<D,I>
91: next I
92: next A
93: next D
94: for D=1 to 361
95: 0=X
96: for I=1 to R
97: X+tn↑(P<I,D>/10)/R=X
98: next I
99: 10log(X)=P<1,D>
100: next D
```

```
101: for A=2 to 16
102: 0=S=P=T
103: for I=1+N<A-1> to N<A>
104: P+P<1,I>=P
105: S+P<1,I>↑2=S
106: next I
107: N<A>-N<A-1>=T;P↑2=P
108: √((S-P/T)/(T-1))=D<A-1>
109: wrt 16.3,W<A-1>,D<A-1>
110: next A
111: ret
```

```
0: dsp "*****REVERBERATION TIME PROGRAM*****"
1: dim A[21],B[21],B$[318],W[21],F$[2],F[10]
2: dim P[45,21],C[21],D[21],X[21]
3: dim A$[6700],Y[21],Z[21]
4: dim R$[1],T$[2],U$[2],S[21],U[21],T[21],L[21],R[10]
5: 100=W[1];125=W[2];160=W[3];200=W[4];250=W[5];315=W[6];400=W[7]
6: 500=W[8];630=W[9];800=W[10];1000=W[11];1250=W[12];1600=W[13]
7: 2000=W[14];2500=W[15];3150=W[16];4000=W[17];5000=W[18]
8: 6300=W[19];8000=W[20];10000=W[21]
9: ent "NO.OF MIC.POSITIONS?",O
10: fxd 1;trk 1
11: clr 7;wait 100;cli 7;wait 100;lcl 7;wait 1000
12: dsp "SET GEN/AMP A BIT BELOW CLIPPING";wait 5000;dsp " "
13: 1=U
14: cll 'set'(U)
15: T$[1,2]=U$[1,2];650-(10+10num(U$[2,2]))=V
16: buf "in",B$,3
17: 1=A
18: for G=1 to O
19: 1=U
20: ent "MIC POSITION #",F[A]
21: for R=1 to 30000
22: cll 'lin'
23: B$[134,280]=A$[1,147]
24: for I=1 to 21;val(A$[7I-6,7I])=T[I];next I
25: clr 7;wait 100;cli 7;wait 100
26: wrt 717,U$;wait 50;lcl 7
27: wrt 717,"04";wait 5000
28: cll 'time'
29: for I=1 to 21;for J=1 to 45;147J+7I-153=X;X+6=Y
30: val(A$[X,Y])=P[J,I];next J;next I
31: clr 7;wait 100;cli 7;wait 100
32: rem 7;wait 3000
33: if U>1;gto 41
34: cll 'set'
35: cll 'lin'
36: B$[127,273]=A$[1,147]
37: for I=1 to 21;val(A$[7I-6,7I])=L[I]
38: if 650-10num(U$[2,2])>L[I];650-10num(U$[2,2])=L[I]
39: next I
40: if U=1;gto 64
41: trk 1;ldf 5+F[A],A$,Y[*],Z[*]
42: for I=1 to 21;for J=1 to 45;90I-90+2J-1=X;X+1=Y
43: 10log(1/R*(tn↑(itf(A$[X,Y])/100)+tn↑(P[J,I]/10)))=P[J,I]
44: next J;next I
45: for I=1 to 18
46: 0=M=L=C=D=E=N
47: for K=5 to 43
48: if P[K,I]+5>T[I];gto 54
49: if P[K+1,I]+5>T[I] or P[K+2,I]>T[I];gto 54
50: if P[K,I]-10<L[I];gto 55
```

```
51: N+1=N
52: M+P(K,I)=M;L+.0625*N=L;E+.0625*N*P(K,I)=E
53: C+P(K,I)↑2=C;D+(.0625*N)↑2=D
54: next K
55: (E-M*L/N)/(D-L↑2/N)=B
56: if B>=0;0=X(I);gto 61
57: (C-M↑2/N-B*(E-M*L/N))/((N-2)*(D-L↑2/N))=S
58: B↑2=B(I);-B=X(I);N=Y(I);K-N-1=Z(I);S=S(I)
59: if K=44;43-N-1=Z(I)
60: 196*!S(I)/(X(I)*!R)=S(I);60/X(I)=X(I)
61: next I
62: if U=1;gto 64
63: if U>1;gto 69
64: for I=1 to 18;for J=1 to 45
65: 90I-90+2J-1=X;X+1=Y
66: fti (10P(J,I))=A$(X,Y)
67: next J;next I
68: gto 73
69: for I=1 to 18;for J=1 to 45
70: 90I-90+2J-1=X;X+1=Y
71. fti (100los(Rtn↑(P(J,I)/10)))=A$(X,Y)
72: next J;next I
73: trk 1;rcf 5+F(A),A$,Y(*),Z(*)
74: U+1=U
75: if R=1;gto 83
76: for I=1 to 4
77: if S(I)>4;gto 83
78: next I
79: for I=5 to 18
80: if S(I)>2;gto 83
81: next I
82: gto 84
83: next R
84: cll 'revl'
85: R=R(A)
86: for I=1 to 18
87: C(I)+X(I)=C(I);D(I)+X(I)↑2=D(I)
88: next I
89: if O=1;for I=1 to 18;X(I)=C(I);S(I)=D(I);next I;gto 112
90: if F(A)=0;gto 95
91: dsp "MOVE MIC TO NEW POSITION";wait 4000
92: dsp "PRESS CONTINUE TO RESUME";wait 4000;stp
93: A+1=A
94: next G
95: for I=1 to 18
96: !((D(I)-C(I)↑2/O)/(O-1))=D(I)
97: C(I)/O=C(I)
98: next I
99: prt "AVERAGE OF      SPATIAL REV.TIME";spc 3
100: for A=1 to O
```

```
101: prt "MIC POSITION=",F(A)
102: prt "# OF DECAYS=",R(A);spc 2
103: next A
104: for I=1 to 18
105: fxd 0;prt "CHANNEL NO.",I;prt "FREQ (HZ)",W(I)
106: if C(I)=0;gto 108
107: gto 109
108: fxd 1;prt "REV. TIME=     ***";prt "STD.  DEV= ***";spc 1;gto 110
109: fxd 2;prt "REV. TIME=",C(I);prt "STD.  DEV.=",D(I);spc 1
110: next I
111: prt "*** =CALCULATION IMPOSSIBLE"
112: ent "DISPLAY:MIC POSITION #",O
113: trk 1;ldf 5+O,A$,Y(*),Z(*);cll 'display';gto 112
114: end
115: "set":
116: if U=1;lcl 7;wait 1000
117: for I=53 to 63;116-I=I;"N"=T$(1,1);char(I)=T$(2,2)
118: wrt 717,T$;wait 1000;"à"=R$;wrt 717,R$;wait 1000
119: red 717,R$;wait 500
120: if num(R$)=62;gto 122
121: 116-I=I;next I
122: ret T$
123: "time":
124: for J=1 to 45
125: wrt 717,"E?"
126: buf "in"
127: tfr 716,"in",302
128: jmp rds("in")#-1
129: if J=5;rem 7
130: wrt 717,"E="
131: wait .01858
132: B$(134,280)=A$(147J-146,147J)
133: next J
134: ret A$
135: "lin":
136: if U=1 or U=0;U-1=U
137: clr 7;wait 50;cli 7;wait 50
138: if U=-1;wrt 717,T$;wait 50;gto 140
139: wrt 717,U$;wait 50
140: if U#-1;lcl 7;wait 5000
141. wrt 717,"M?0:L?";wait 7000
142: wrt 717,"E?";wait 100
143: buf "in"
144: tfr 716,"in",302
145: jmp rds("in")#-1
146: wrt 717,"E=";wait 100
147: wrt 717,"M?03L>"
148: rem 7
149: if U=-1;U+2=U
150: ret B$
```

```
151: "display":
152: ldk 0;1=I
153: "A":I-1=I;gto 155
154: "B":I+1=I
155: clr 7;wait 500;cli 7;wait 500
156: wrt 717,"F>J?"
157: fmt 1,fz5.1
158: wrt 716.1,V
159: if I=0;1=I
160: if I=19;18=I
161: for J=1 to 42;wrt 716.1,P(J,I);next J
162: fxd 0;dsp "TIMEAXIS AT",W(I),"HZ.";fxd 1
163: for J=1 to Z(I);wrt 717,"D>";wait 50;next J
164: for K=1 to 3
165: if Z(I)+Y(I)>30;cll 'two';gto 169
166: for J=1 to Y(I)-1;wrt 717,"D>";wait 50;next J;wait 500
167: for J=1 to Y(I)-1;wrt 717,"D?";wait 50;next J;wait 500
168: next K
169: dsp "USE F0 & F1 FOR OTHER TIMEAXES";wait 2000
170: dsp "USE F2 TO RETURN TO PROGRAM";wait 2000;stp
171: gto 155
172: "C":
173: ret
174: "two":
175: for K=1 to 3
176: for W=1 to 29-Z(I);wrt 717,"D>";wait 50;next W
177: wrt 717,"J>"
178: for W=1 to Z(I)+Y(I)-30;wrt 717,"D>";wait 50;next W;wait 500
179: for W=1 to Z(I)+Y(I)-30;wrt 717,"D?";wait 50;next W
180: wrt 717,"J?"
181: for W=1 to 29-Z(I);wrt 717,"D?";wait 50;next W;wait 500
182: next K
183: ret
184: "rev1":
185: prt "MIC POSITION=",F(A)
186: prt "NO. OF DECAYS=",R;spc 2
187: for I=1 to 18
188: fxd 0;prt "CHANNEL NO.",I;prt "FREQ(HZ)",W(I)
189: if X(I)=0;gto 191
190: gto 192
191: fxd 1;prt "REV.TIME=    ***";prt "% UNCERT'Y=***";spc 1;gto 193
192: fxd 2;prt "REV.TIME=",X(I);prt "% UNCERT'Y=",S(I);spc 2
193: next I
194: prt "***=CALCULATION IMPOSSIBLE"
195: ret
```

APPENDIX C

LOUDSPEAKER QUALIFICATION AND EVALUATION OF CORRECTION FACTORS

APPENDIX C

LOUDSPEAKER QUALIFICATION AND EVALUATION OF CORRECTION FACTORS

The loudspeaker of the B & K 4205 Sound Power Source was tested outdoors on the Loyola Campus of Concordia University to determine if it could be qualified according to the specifications of ANSI S1.21-1972. Shown in Figure C-1(a) are the results of measurements made to determine if the test site chosen was indeed a free-field. Octave bands of noise were generated and the sound pressure levels were measured at progressively doubling distances. The average drops in sound pressure levels over the five octave bands from 125 Hz to 2000 Hz are plotted in Figure C-1(a), and agree very closely with the theoretical line of 6 dB per doubling of distance. The speaker rested upon hard-packed ground, closely approximating a highly reflecting surface.

The loudspeaker did not qualify in the 250 Hz 1/3-octave band. A 2 dB step was observed in this band, and might be attributed to a cone or basket resonance. As a result, an EVM12L loudspeaker was qualified in the 250 Hz band. The test site for this qualification was on the roof of the Center for Building Studies facility. The free-field response of this area is shown in Figure C-1(b), and was evaluated as previously described. Again, the agreement with free-field theory is excellent. The roof surface is gravel and tar, resulting in an excellent reflecting plane.

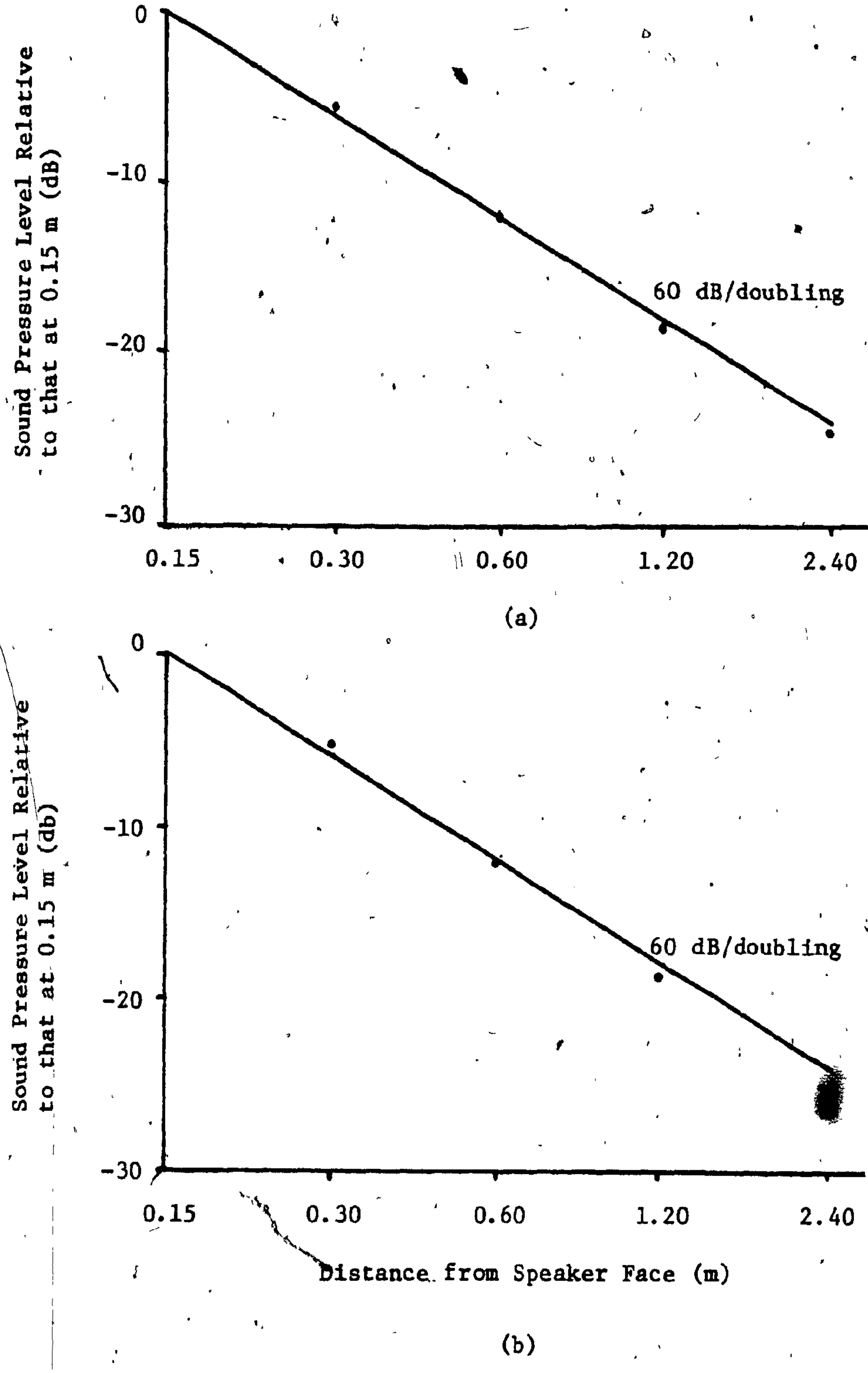
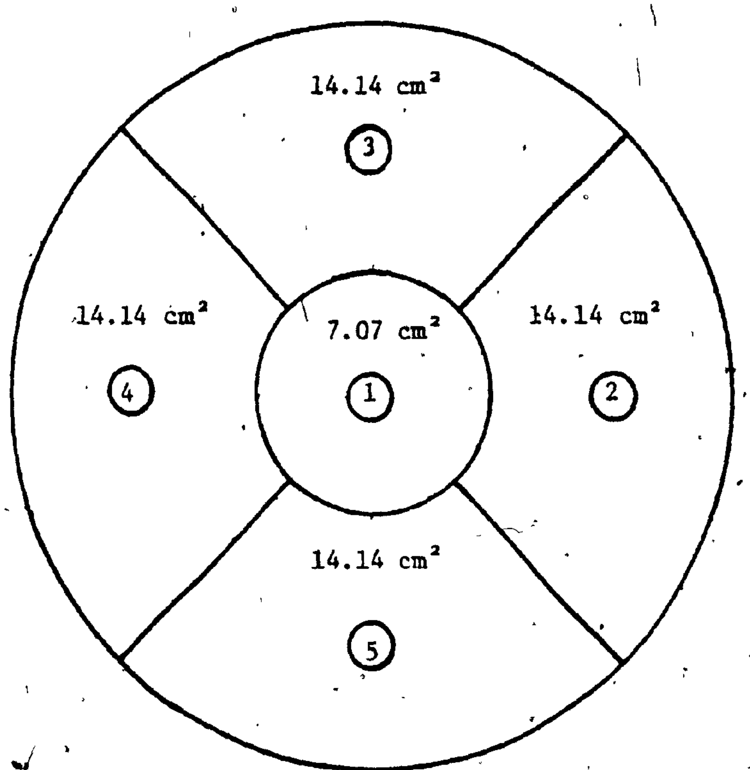


Figure C-1. Free-Field Measurements at (a) Loyola Campus and (b) CBS Roof

It was discovered during the course of room qualification that the 1000 Hz and 2000 Hz bands would not qualify, even with the rotating diffuser installed. This was distinctly peculiar as the modal overlaps at these frequencies was high and other bands such as 1600 Hz qualified easily. Moreover, the measured levels in the 1000 Hz band consistently decreased from the lower end of the band to the upper, while in the 2000 Hz band the levels rose across the band. In the 1600 Hz band, the levels were essentially uniform across the band. As a result, it was decided to make a space-average over the face of the speaker in both the "bad" 1000 Hz and 2000 Hz bands, and in the "good" 1600 Hz bands. The microphone locations and face areas for weighting purposes are shown in Figure C-2. The correction factors for each frequency in the band at each microphone position and average correction factors are shown in Tables C-I, C-II, and C-III; for the 1000, 1600, and 2000 Hz bands, respectively.

It can be seen that at microphone position 1, the on-axis position, the correction factors at 1000 Hz and 2000 Hz are distinctly different from the off-axis positions, which are reasonably similar to each other. Conversely, at 1600 Hz all microphone positions give reasonably similar correction factors.

These discrepancies could be attributed to the particular distribution of cone break-up at these high frequencies, where the cone does not act like a rigid piston. At particular locations in the near field, the waves generated by various areas of the cone will add or cancel to some degree depending upon their phase relation. Thus, large fluctua-



Notes: 1. All peripheral microphones are at 3 cm from the central one

2. Overall diameter = 9 cm

Figure C-2. Microphone Locations and Area Divisions for Measurement of Space Average Loudspeaker Correction Factors

TABLE C-I

CORRECTION FACTORS OVER LOUDSPEAKER FACE AT 1000 HZ

MICROPHONE POSITION NUMBER

1	2	3	4	5	AVG.
2.00	1.70	1.60	1.50	2.00	1.73
1.90	1.40	1.50	1.40	1.90	1.59
1.70	1.30	1.40	1.20	1.70	1.43
1.60	1.20	1.20	1.00	1.60	1.29
1.50	1.10	1.10	0.80	1.30	1.12
1.30	1.00	0.90	0.70	1.10	0.97
1.00	0.80	0.70	0.50	1.00	0.78
0.80	0.70	0.50	0.50	0.90	0.67
0.50	0.50	0.40	0.40	0.70	0.50
0.20	0.30	0.20	0.20	0.40	0.27
0.00	0.00	0.00	0.00	0.00	0.00
-0.40	-0.10	-0.40	-0.50	-0.20	-0.31
-0.80	-0.40	-0.80	-0.90	-0.40	-0.64
-1.30	-0.80	-1.00	-1.10	-1.00	-1.01
-1.70	-1.00	-1.30	-1.30	-1.10	-1.23
-2.10	-1.10	-1.40	-1.60	-1.20	-1.41
-2.60	-1.30	-1.50	-1.70	-1.20	-1.56
-2.80	-1.10	-1.30	-1.60	-1.20	-1.47
-2.80	-0.90	-1.00	-1.40	-1.10	-1.29
-2.80	-0.30	-0.60	-0.80	-0.40	-0.78
-2.40	0.20	-0.20	-0.40	0.10	-0.33
-2.00	0.70	0.60	0.10	0.90	0.29

TABLE C-II

CORRECTION FACTORS OVER LOUDSPEAKER FACE AT 1600 HZ

MICROPHONE POSITION NUMBER

1	2	3	4	5	AVG.
0.30	0.90	0.90	0.70	0.70	0.74
0.30	0.60	0.80	0.70	0.60	0.63
0.30	0.60	0.80	0.60	0.50	0.59
0.30	0.60	0.70	0.40	0.50	0.52
0.20	0.50	0.70	0.40	0.40	0.47
0.20	0.50	0.60	0.40	0.30	0.42
0.20	0.40	0.50	0.40	0.20	0.36
0.20	0.30	0.30	0.20	0.20	0.24
0.20	0.30	0.30	0.10	0.10	0.20
0.10	0.20	0.30	0.10	0.10	0.17
0.10	0.10	0.20	0.00	0.00	0.08
0.10	0.00	0.10	0.00	0.00	0.03
0.00	0.00	0.00	0.00	0.00	0.00
0.00	-0.10	0.00	-0.10	-0.10	-0.07
0.00	-0.20	-0.10	-0.20	-0.10	-0.13
0.00	-0.20	-0.20	-0.30	-0.10	-0.18
0.00	-0.30	-0.30	-0.30	-0.20	-0.24
0.00	-0.30	-0.40	-0.20	-0.20	-0.24
0.10	-0.40	-0.50	-0.20	-0.10	-0.26
0.10	-0.10	-0.50	-0.10	-0.10	-0.17
0.10	-0.10	-0.70	-0.10	-0.10	-0.21
0.10	-0.10	-0.70	-0.10	-0.10	-0.21
0.00	0.00	-0.60	-0.10	-0.10	-0.18
0.00	-0.10	-0.60	-0.10	0.00	-0.18
0.00	-0.10	-0.50	-0.10	0.00	-0.16
0.10	-0.10	-0.60	-0.10	0.00	-0.17

TABLE C-III

CORRECTION FACTORS OVER LOUDSPEAKER FACE AT 2000 HZ

MICROPHONE POSITION NUMBER

1	2	3	4	5	AVG.
-1.10	-1.20	-1.30	-1.10	-1.30	-1.21
-1.10	-1.20	-1.20	-1.10	-1.10	-1.14
-1.00	-1.10	-1.10	-1.10	-1.00	-1.07
-1.00	-1.00	-1.00	-1.10	-0.90	-1.00
-0.90	-0.80	-0.90	-0.80	-0.70	-0.81
-0.70	-0.70	-0.80	-0.70	-0.50	-0.68
-0.50	-0.60	-0.60	-0.60	-0.40	-0.54
-0.40	-0.50	-0.40	-0.40	-0.30	-0.40
-0.30	-0.30	-0.30	-0.20	-0.30	-0.28
-0.20	-0.20	-0.10	-0.10	-0.20	-0.16
0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.10	0.30	0.20	0.20	0.18
0.00	0.40	0.50	0.40	0.40	0.38
0.10	0.60	0.70	0.60	0.60	0.57
0.20	0.90	0.90	0.80	0.70	0.76
0.20	1.10	1.10	0.90	0.80	0.89
0.30	1.20	1.20	1.20	1.00	1.06
0.40	1.50	1.60	1.50	1.30	1.36
0.50	1.70	1.80	1.80	1.50	1.57
0.60	1.90	2.10	2.10	1.80	1.82
0.50	2.10	2.20	2.30	1.90	1.94
0.50	2.20	2.20	2.60	2.00	2.06

tions in measured sound pressure level will occur. Also, these discrepancies may be caused by interference patterns as a result of the speaker face height above the reflecting plane being in the order of λ at 1000 Hz and $\frac{\lambda}{2}$ at 2000 Hz.

Using the space average corrections at 1000 Hz and 2000 Hz, the measured deviations were substantially reduced, and qualification enabled in these bands. The final correction factors for all bands are shown in Table C-IV (note that zeroes at bottom of columns are not corrections factors - number of tones in each band are different).

TABLE C-IV

FINAL LOUDSPEAKER CORRECTION FACTORS

1/3 OCTAVE CENTER FREQUENCY (HZ)

100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500
0.30	-0.70	-0.50	-0.30	-0.10	-0.10	0.50	0.60	1.50	2.00	1.73	-1.90	0.70	-1.21	1.80
0.20	-0.60	-0.50	-0.30	-0.10	-0.10	0.60	0.70	1.50	1.90	1.59	-1.60	0.60	-1.14	1.80
0.20	-0.60	-0.50	-0.30	-0.10	0.00	0.50	0.80	1.30	1.70	1.43	-1.30	0.60	-1.07	1.60
0.20	-0.60	-0.40	-0.30	0.00	0.10	0.50	0.80	1.20	1.50	1.29	-1.20	0.70	-1.00	1.30
0.20	-0.50	-0.30	-0.20	-0.10	0.00	0.40	0.70	1.00	1.30	1.12	-0.90	0.60	-0.81	1.00
0.10	-0.50	-0.20	-0.30	-0.10	0.10	0.30	0.60	0.90	1.10	0.97	-0.70	0.60	-0.68	1.00
0.10	-0.40	-0.20	-0.20	-0.10	0.00	0.30	0.40	0.80	0.90	0.78	-0.50	0.50	-0.54	0.80
0.10	-0.30	-0.20	-0.10	-0.10	0.00	0.20	0.30	0.70	0.80	0.67	-0.40	0.50	-0.40	0.70
0.10	-0.20	-0.10	-0.10	-0.10	0.00	0.20	0.30	0.40	0.30	0.50	-0.20	0.30	-0.28	0.50
0.00	-0.10	0.00	0.00	-0.10	0.00	0.20	0.10	0.20	0.30	0.27	0.00	0.20	-0.16	0.20
0.00	-0.20	0.00	0.00	-0.10	0.00	0.20	0.00	0.10	0.00	0.00	-0.10	0.10	0.00	-0.10
0.00	0.00	0.00	0.00	-0.10	0.00	0.10	0.00	0.00	-0.20	-0.31	-0.10	0.00	0.18	-0.20
0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.10	-0.10	-0.40	-0.64	0.00	0.00	0.38	-0.10
0.10	0.10	0.10	0.00	-0.10	0.00	-0.20	-0.20	-0.30	-0.60	-1.01	0.00	-0.10	0.57	0.00
0.10	0.10	0.20	0.10	-0.10	0.00	-0.20	-0.30	-0.40	-0.70	-1.23	0.10	-0.10	0.76	-0.10
0.10	0.00	0.20	0.20	-0.10	0.00	-0.20	-0.40	-0.50	-1.00	-1.41	0.10	-0.30	0.89	-0.10
0.10	0.10	0.30	0.20	-0.10	0.00	-0.20	-0.60	-0.50	-1.10	-1.56	0.10	-0.30	1.06	0.00
0.20	0.10	0.30	0.20	-0.10	0.00	-0.30	-0.90	-0.60	-1.20	-1.47	0.10	-0.30	1.36	0.10
0.20	0.20	0.30	0.20	-0.20	-0.10	-0.30	-1.00	-0.70	-1.40	-1.29	0.10	-0.20	1.57	0.20
0.20	0.30	0.20	0.20	-0.30	-0.10	-0.30	-1.20	-0.80	-1.40	-0.78	0.10	-0.20	1.82	0.30
0.30	0.30	0.30	0.30	-0.30	-0.10	-0.40	-1.20	-0.90	-1.50	-0.33	0.10	-0.20	1.94	0.60
0.30	0.30	0.40	0.20	-0.20	-0.20	-0.40	-1.30	-0.90	-1.60	0.29	-0.20	-0.20	2.06	0.80
0.00	0.40	0.40	0.20	-0.20	-0.20	-0.40	0.00	-1.20	-1.90	0.00	-0.10	-0.10	0.00	0.90
0.00	0.00	0.40	0.00	-0.20	-0.30	-0.50	0.00	-1.30	0.00	0.00	0.00	-0.20	0.00	1.10
0.00	0.00	0.40	0.00	0.00	-0.30	-0.60	0.00	-1.40	0.00	0.00	-0.10	0.00	0.00	1.30
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.10	-0.20	0.00	1.50
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.10	0.00	0.00	1.70

APPENDIX D

RAW DATA FOR PURE TONE

SOUND POWER QUALIFICATION

TABLE D-I

UNMODIFIED ROOM - SOUND PRESSURE LEVELS AT POSITION 1

1/3 OCTAVE CENTER FREQUENCY (HZ)

100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500
90.8	91.0	88.7	90.9	100.8	94.6	95.5	93.7	97.4	98.2	103.5	97.4	95.0	98.8	92.4
89.0	90.8	90.0	83.9	111.3	92.6	91.7	91.2	93.6	96.0	100.1	99.1	95.5	98.3	92.7
87.6	93.7	92.3	85.2	110.3	94.2	93.4	94.9	95.4	94.5	100.0	99.2	94.8	99.0	92.4
86.6	97.7	89.8	91.1	104.1	90.6	90.8	94.8	94.6	97.1	102.9	97.3	95.9	98.2	92.4
86.8	91.6	90.5	85.5	103.0	96.0	90.1	93.3	95.6	99.2	99.8	97.1	96.8	98.5	91.5
86.4	88.6	91.3	89.1	111.4	91.4	91.2	93.0	98.0	99.5	99.6	97.2	95.5	98.8	91.0
85.3	87.8	84.5	85.3	111.4	90.6	90.2	87.7	96.8	98.6	100.1	96.5	95.1	98.3	91.1
84.1	82.5	82.3	84.7	108.0	83.7	85.2	95.8	96.5	98.3	104.3	96.5	97.0	98.3	90.5
83.4	82.2	82.2	85.8	110.9	91.2	89.7	96.1	94.4	97.3	101.8	95.7	96.1	98.3	90.9
82.8	88.5	86.9	86.9	110.2	87.8	94.3	91.8	95.9	99.1	101.9	96.6	95.0	99.1	92.3
82.7	90.2	83.7	89.9	110.2	92.2	92.7	90.8	95.4	98.8	100.9	95.9	95.6	99.5	92.9
83.4	87.5	88.1	93.4	111.3	89.4	91.8	87.7	96.7	96.5	100.5	93.3	95.7	98.6	91.7
85.5	87.6	85.9	85.0	108.5	92.0	91.9	93.5	95.6	97.2	101.6	93.9	96.6	99.0	92.8
88.8	91.2	92.6	86.5	108.1	89.8	87.6	93.3	96.1	96.3	98.3	94.0	97.6	98.2	92.6
89.7	90.1	92.8	94.8	103.6	89.3	88.5	92.1	95.5	96.9	100.3	94.3	93.6	98.4	92.8
87.9	91.9	92.8	89.4	104.5	92.1	93.4	94.1	96.9	98.2	99.9	94.2	95.0	96.8	93.7
87.5	97.2	87.2	87.3	107.5	87.7	93.0	90.5	95.5	97.8	100.4	95.7	96.5	97.2	91.7
89.9	95.3	83.7	92.7	116.0	91.1	91.2	92.3	92.8	97.8	98.7	92.9	96.8	97.4	93.2
93.0	98.8	83.1	95.1	109.0	92.7	91.1	94.6	94.8	97.9	98.9	94.9	95.7	97.0	93.9
93.3	92.2	85.9	84.2	103.8	97.1	93.3	94.4	94.9	98.2	100.3	94.7	96.4	96.5	92.9
92.7	88.5	81.0	86.6	107.3	88.5	89.3	93.8	95.5	98.0	99.2	94.9	95.7	95.4	93.0
92.5	90.0	87.4	89.2	104.2	92.6	85.8	96.9	98.8	97.7	99.7	93.6	95.2	97.5	93.6
0.0	94.1	91.3	88.5	110.3	91.8	93.8	0.0	96.1	98.0	0.0	95.4	97.8	0.0	94.4
0.0	0.0	98.2	0.0	103.2	91.0	92.3	0.0	97.3	0.0	0.0	95.8	95.6	0.0	93.3
0.0	0.0	97.3	0.0	0.0	93.7	93.9	0.0	95.4	0.0	0.0	94.9	97.6	0.0	94.7
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	94.6	96.3	0.0	93.9
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	93.7	0.0	0.0	93.7

TABLE D-II

UNMODIFIED ROOM - SOUND PRESSURE LEVELS AT POSITION 2

1/3 OCTAVE CENTER FREQUENCY (HZ)

100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500
94.8	89.4	90.2	89.7	107.4	95.5	90.7	87.2	93.4	97.3	102.6	99.2	95.1	99.8	96.2
93.5	92.3	89.2	92.6	106.8	89.4	89.5	93.1	97.4	98.5	102.7	99.7	96.4	98.7	93.7
90.8	95.7	92.2	84.0	107.5	92.3	91.5	95.7	96.4	96.7	102.2	97.7	97.1	99.1	94.3
89.0	98.2	98.7	92.2	112.9	88.7	93.8	95.8	98.2	94.6	102.2	98.4	96.0	99.3	92.4
88.2	95.4	92.0	86.1	105.9	93.1	94.4	95.8	96.9	99.8	100.1	96.6	97.3	99.5	92.7
87.4	91.9	87.7	89.7	109.4	92.3	91.3	91.6	95.6	101.4	100.7	97.4	96.5	100.0	91.3
86.9	90.0	85.5	89.3	102.9	94.3	92.3	90.9	96.7	97.1	101.8	96.6	96.4	99.0	92.6
86.7	89.9	85.5	88.7	108.0	88.3	87.2	92.6	90.5	95.7	102.0	95.6	97.1	98.0	91.8
86.9	87.0	92.6	84.5	113.3	93.2	90.0	94.2	94.6	98.2	101.3	97.1	96.5	98.5	92.8
87.2	88.2	95.4	84.4	101.9	87.0	95.8	93.1	95.5	98.6	100.7	97.5	94.7	99.3	93.1
88.5	84.9	89.8	86.4	107.5	95.3	98.5	91.8	95.6	97.4	102.6	95.9	96.7	100.0	92.2
90.7	85.8	92.8	89.6	111.7	87.3	90.6	88.3	95.4	97.0	99.9	95.3	97.3	98.9	92.6
95.0	89.5	89.8	83.8	115.4	91.7	93.6	95.3	99.5	99.3	99.2	95.3	96.1	99.4	91.7
95.8	92.5	82.4	90.6	105.0	89.6	92.8	93.2	95.9	97.7	100.8	97.1	98.0	99.7	91.6
92.6	95.5	86.3	92.1	103.8	87.7	91.0	93.0	96.4	97.4	101.3	97.2	96.4	98.4	93.4
89.5	89.7	91.3	88.8	107.6	88.7	93.4	96.1	97.9	96.2	99.5	95.6	96.0	100.7	93.3
91.1	94.5	96.4	88.9	109.1	86.0	95.9	93.1	95.8	96.7	100.9	95.2	96.2	97.3	95.1
91.3	95.2	89.3	91.6	106.5	95.5	96.4	90.9	94.0	98.4	102.7	94.8	96.8	99.3	93.3
90.2	92.4	89.1	93.1	106.7	88.8	90.8	96.3	94.4	99.4	100.6	95.2	97.8	99.7	92.8
86.5	86.1	93.1	90.3	109.3	88.9	91.7	96.8	97.1	96.8	99.0	94.6	97.1	98.8	93.5
85.8	86.0	86.8	89.7	102.7	87.4	94.5	95.4	95.4	98.1	101.8	94.3	97.4	99.6	94.6
87.6	87.6	90.2	93.7	105.9	91.6	91.6	94.6	96.4	96.9	101.0	95.7	97.8	97.7	94.4
0.0	95.0	98.0	91.6	113.5	91.9	95.4	0.0	97.7	96.8	0.0	95.0	97.8	0.0	93.5
0.0	0.0	94.0	0.0	108.3	87.7	96.5	0.0	97.0	0.0	0.0	96.5	98.9	0.0	94.9
0.0	0.0	90.6	0.0	0.0	88.1	94.2	0.0	96.7	0.0	0.0	97.5	96.9	0.0	94.9
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	95.5	96.7	0.0	95.5
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	95.6	0.0	0.0	95.0

TABLE D-III

UNMODIFIED ROOM - SOUND PRESSURE LEVELS AT POSITION 3

1/3 OCTAVE CENTER FREQUENCY (HZ)

100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500
95.2	91.6	94.6	88.8	104.0	93.3	88.4	92.1	98.1	99.1	103.4	99.8	95.9	100.1	95.4
93.2	92.1	93.9	89.7	111.1	85.7	94.9	95.6	98.2	100.3	101.3	98.7	96.3	99.4	95.0
92.0	94.5	93.2	89.5	105.5	89.4	87.3	96.9	97.8	98.5	103.8	97.0	99.1	100.6	96.1
90.0	97.9	97.0	91.8	112.6	90.7	94.5	94.6	100.4	96.1	102.1	98.6	98.0	99.6	94.3
89.0	93.6	94.7	90.7	101.9	89.0	87.4	95.6	97.5	99.7	101.5	97.6	97.4	98.9	94.1
88.3	90.1	89.3	92.3	110.8	86.6	94.6	89.9	95.6	101.1	103.3	99.3	97.0	98.4	94.9
87.3	87.0	86.2	92.5	109.3	91.1	92.4	95.1	94.9	95.5	100.6	96.9	96.8	98.7	92.7
87.0	86.2	86.7	90.2	108.5	87.6	95.0	91.1	99.6	98.6	102.5	95.7	98.1	99.0	95.0
86.8	83.1	86.8	80.7	109.0	95.8	93.4	95.8	96.6	97.5	103.5	96.0	97.4	99.5	94.5
86.8	85.5	90.3	90.1	102.1	93.3	91.4	95.4	93.7	101.1	102.1	96.5	97.0	99.9	95.5
87.5	89.7	93.4	95.0	102.7	89.9	87.0	92.6	96.0	97.9	102.0	97.0	97.3	99.6	93.5
89.4	90.1	87.2	91.6	112.7	95.9	96.3	96.3	91.9	99.3	102.2	96.8	98.0	99.9	95.4
93.2	91.8	91.7	87.4	112.8	86.9	91.7	91.0	97.0	97.9	103.9	95.9	97.9	99.4	93.4
96.3	94.6	89.1	91.5	101.4	83.0	88.2	94.2	93.9	98.2	101.8	97.3	98.0	99.2	95.2
94.8	97.9	81.2	87.6	107.6	95.0	85.7	98.5	96.1	98.1	100.5	97.2	98.0	99.4	94.6
93.3	92.5	85.4	94.0	104.8	90.8	94.1	95.4	96.9	98.2	102.7	95.1	98.0	100.1	94.0
92.0	90.9	93.5	92.5	104.9	85.5	91.9	93.2	97.2	96.4	100.2	96.2	98.6	97.1	95.0
89.9	97.5	92.3	91.7	106.2	90.0	95.1	91.9	94.8	97.7	101.1	96.2	97.9	99.2	95.5
89.4	97.5	90.8	93.7	106.4	92.0	88.0	87.4	95.9	98.1	100.5	95.0	98.2	99.3	94.5
89.7	91.7	92.6	86.7	104.8	89.7	93.1	95.2	94.6	98.7	101.4	94.6	97.0	99.1	95.4
88.6	87.4	87.8	87.7	102.5	84.4	90.8	94.6	93.6	98.8	102.1	97.2	96.5	100.9	94.3
89.9	85.1	90.2	91.9	102.0	91.1	90.3	90.6	95.2	97.7	102.1	96.0	96.6	99.5	95.2
0.0	88.5	97.5	93.8	106.2	96.0	91.0	0.0	95.2	99.0	0.0	96.6	97.2	0.0	96.3
0.0	0.0	96.0	0.0	106.4	92.8	91.0	0.0	97.3	0.0	0.0	96.9	98.6	0.0	95.3
0.0	0.0	91.8	0.0	0.0	86.3	91.2	0.0	94.3	0.0	0.0	97.4	98.0	0.0	95.4
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.9	97.2	0.0	95.6
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.3	0.0	0.0	95.7

TABLE D-IV

UNMODIFIED ROOM - SOUND PRESSURE LEVELS AT POSITION 4

1/3 OCTAVE CENTER FREQUENCY (HZ)

100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500
91.2	92.9	88.6	90.1	107.5	90.8	91.7	96.6	100.5	96.8	99.9	98.9	95.9	100.8	96.3
89.3	92.6	90.7	88.0	112.0	88.0	92.1	96.8	99.4	98.6	99.9	98.3	95.0	99.6	94.5
89.4	94.3	93.4	85.8	108.1	92.1	91.9	94.6	99.1	98.9	103.9	98.1	97.5	99.3	95.2
89.1	98.2	91.5	90.2	107.9	92.3	93.6	92.5	91.2	98.7	103.7	96.6	96.7	98.4	94.7
88.1	91.6	92.2	84.4	102.9	89.6	88.1	94.2	98.9	99.9	102.0	99.7	97.4	100.2	93.2
85.9	89.9	90.9	91.4	109.7	90.8	93.3	88.8	94.8	101.9	101.9	97.1	95.9	100.1	93.1
84.6	89.4	83.6	90.0	105.9	88.1	93.1	92.2	93.6	96.6	102.7	97.7	96.8	99.9	93.7
84.4	88.6	85.0	91.7	109.9	82.6	91.8	92.5	98.2	95.1	100.9	98.7	98.0	99.8	92.9
84.5	83.3	87.1	90.7	109.2	91.2	89.6	92.9	93.8	99.0	102.4	96.0	97.3	99.3	94.0
84.6	89.1	89.8	86.4	104.6	88.4	88.6	94.9	97.8	96.9	101.5	97.5	98.0	98.7	93.8
85.4	91.4	89.8	88.9	112.1	90.5	84.8	92.4	95.1	100.2	101.4	97.4	95.0	100.0	93.9
86.4	87.3	87.9	92.1	109.7	94.7	90.6	94.1	98.9	100.1	101.2	96.1	96.2	99.2	94.0
89.1	86.3	87.0	84.8	109.8	92.4	93.5	93.1	96.6	97.4	100.6	95.6	98.1	100.7	94.8
91.5	89.1	95.3	89.0	108.5	91.8	87.4	95.8	95.4	96.0	100.0	95.8	98.4	99.9	93.7
88.2	90.4	92.4	91.4	102.9	90.4	91.9	96.4	96.5	97.4	101.6	96.9	95.5	99.3	94.9
87.7	88.7	91.4	94.8	104.0	95.7	91.5	93.7	98.0	97.6	102.2	96.5	96.6	98.4	93.9
89.3	94.5	89.4	92.9	106.8	86.9	91.0	96.7	95.7	100.8	99.6	95.0	95.6	99.1	94.3
88.8	93.6	88.9	92.6	112.8	92.1	87.3	90.9	97.0	97.2	100.6	96.4	95.9	100.9	95.1
91.9	98.5	88.7	93.3	110.8	94.2	92.7	91.2	96.6	97.6	100.6	94.4	96.3	98.9	95.8
93.8	93.5	91.7	87.0	109.6	96.4	95.5	97.1	95.8	97.5	101.4	98.2	95.7	99.6	95.1
93.5	87.0	93.1	92.3	105.2	87.1	95.5	97.4	94.6	96.5	100.8	96.7	97.3	99.6	94.6
93.9	87.3	85.4	93.5	97.6	96.3	94.7	92.6	97.5	96.6	101.7	96.0	98.5	97.6	94.0
0.0	89.6	90.2	89.7	106.9	93.9	94.1	0.0	95.8	98.6	0.0	97.1	96.0	0.0	96.3
0.0	0.0	97.4	0.0	105.4	88.5	97.9	0.0	100.8	0.0	0.0	97.2	97.5	0.0	96.0
0.0	0.0	93.9	0.0	0.0	87.3	97.3	0.0	95.1	0.0	0.0	96.1	98.8	0.0	96.1
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.2	97.5	0.0	96.4
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	96.0	0.0	0.0	96.2

TABLE D-V

DIFFUSERS ONLY - SOUND PRESSURE LEVELS AT POSITION 1

1/3 OCTAVE CENTER FREQUENCY (HZ)

100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500
88.2	86.5	87.1	87.6	104.9	90.0	89.8	92.8	95.4	96.3	101.0	97.5	94.4	95.6	95.0
88.5	87.2	90.7	88.0	104.1	90.1	92.4	94.4	94.3	97.9	100.9	97.9	95.5	96.2	94.3
88.5	88.2	90.2	85.6	107.9	89.3	94.7	94.0	95.4	97.9	101.2	95.9	95.5	95.8	93.6
89.0	91.2	88.3	90.7	107.9	92.6	89.5	91.6	97.8	97.0	101.0	97.6	96.6	96.0	92.8
88.1	88.6	89.5	87.6	108.2	87.5	90.5	94.4	94.9	97.7	101.8	96.2	96.9	95.8	93.0
87.8	86.8	86.3	96.1	109.3	92.7	86.6	90.6	95.0	98.5	101.0	95.7	96.7	97.2	93.0
89.6	86.3	92.3	88.4	105.2	89.0	88.6	91.1	95.6	97.6	102.6	95.4	96.0	95.9	93.1
89.9	83.3	92.0	89.1	107.2	87.3	90.8	91.5	94.5	98.5	102.0	95.8	97.0	95.9	93.6
86.1	86.3	93.8	86.5	109.5	88.3	88.7	93.5	94.4	97.0	102.5	95.0	97.1	96.1	93.3
83.7	90.2	90.8	88.7	110.6	88.3	91.2	93.0	95.1	97.4	102.2	94.9	96.0	95.8	93.7
82.5	88.8	89.6	92.5	109.0	89.4	92.8	89.5	95.7	97.4	100.7	94.5	96.7	95.6	93.7
82.9	90.0	90.9	86.6	103.7	90.8	90.4	90.2	94.0	97.3	100.6	94.5	96.6	95.7	93.7
85.8	90.4	90.4	85.6	102.1	88.0	87.7	92.4	95.9	97.6	100.5	95.2	96.8	95.5	94.2
87.3	87.3	95.7	91.3	106.6	86.4	89.2	90.9	94.8	96.1	101.3	94.8	95.9	95.5	93.1
88.3	85.0	90.2	88.1	111.3	88.0	90.5	92.6	95.5	97.2	101.6	94.6	96.3	95.6	94.1
91.2	91.5	87.5	94.9	106.4	89.1	89.0	93.7	94.3	97.1	99.6	96.2	96.8	95.6	94.2
91.2	95.5	86.6	88.3	113.1	85.9	91.4	92.1	94.6	97.6	100.4	95.3	97.6	95.1	93.9
92.2	93.5	84.8	90.6	105.0	88.2	86.3	91.5	92.7	96.7	100.2	93.9	96.2	95.3	94.2
94.4	91.5	83.9	92.5	104.4	89.1	90.7	93.7	94.5	97.6	100.1	94.4	96.8	96.0	94.5
91.3	90.3	83.8	88.8	107.6	92.2	89.5	94.6	92.8	97.8	99.3	94.9	96.5	95.1	94.2
92.7	91.8	80.6	94.7	107.3	89.8	92.3	90.9	95.7	97.3	100.9	95.0	97.6	94.7	95.4
90.9	92.8	91.5	83.5	105.3	90.1	91.9	92.6	95.0	97.5	100.7	96.0	96.9	94.7	94.6
0.0	84.9	90.6	89.6	107.5	87.8	91.8	0.0	96.0	97.1	0.0	95.3	97.2	0.0	94.9
0.0	0.0	96.6	0.0	107.0	90.4	90.4	0.0	94.9	0.0	0.0	96.0	97.4	0.0	94.5
0.0	0.0	88.9	0.0	0.0	91.1	92.2	0.0	92.7	0.0	0.0	95.2	97.5	0.0	95.1
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	95.5	97.7	0.0	96.4
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	94.6	0.0	0.0	95.6

TABLE D-VI

DIFFUSERS ONLY - SOUND PRESSURE LEVELS AT POSITION 2

1/3 OCTAVE CENTER FREQUENCY (HZ)

100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500
92.1	90.4	86.1	88.5	105.9	94.3	90.4	89.0	95.0	98.1	102.9	98.7	95.6	95.7	94.4
89.7	91.8	86.2	87.2	107.3	96.1	90.2	93.5	95.5	96.9	100.6	98.2	95.9	96.6	94.1
89.6	93.6	83.7	92.5	106.8	90.9	90.2	93.9	96.1	99.0	101.9	97.3	97.4	97.3	94.3
89.8	95.8	90.2	87.7	110.9	92.1	92.5	93.5	97.0	98.6	102.0	96.9	96.6	96.0	92.9
90.5	90.4	87.7	93.4	109.9	91.2	89.7	90.9	97.0	99.1	102.2	97.1	97.6	95.9	92.9
91.6	84.4	86.2	88.1	106.8	89.1	90.6	93.1	98.9	97.8	101.4	96.6	96.5	96.7	93.0
92.9	83.0	89.1	86.4	107.7	90.6	88.1	93.5	95.8	95.1	102.6	96.3	96.5	96.7	93.1
91.7	85.0	87.4	88.1	108.3	90.6	90.7	92.0	97.4	98.1	102.7	95.5	97.5	95.4	93.6
89.0	85.4	93.3	86.8	109.3	89.9	88.0	93.4	94.7	98.8	101.3	95.8	97.1	97.0	93.4
87.6	83.4	87.3	84.9	106.8	92.0	92.7	92.3	94.1	98.5	101.9	96.3	95.8	96.2	93.2
87.3	83.0	88.1	86.5	104.1	91.3	93.4	92.5	93.4	99.0	100.6	95.4	97.2	95.5	93.1
87.5	87.5	83.3	84.0	109.9	90.8	90.4	91.4	94.9	96.2	101.7	95.9	97.0	96.4	93.3
87.6	94.0	85.1	89.6	105.9	87.9	91.7	92.0	96.5	97.7	99.9	96.2	96.2	95.2	93.4
87.4	98.1	85.4	90.8	108.6	87.9	90.0	91.1	95.9	96.4	100.3	95.7	96.8	95.7	93.5
90.3	95.6	85.3	93.0	106.7	91.0	90.8	91.5	95.1	97.6	100.3	96.2	98.1	95.7	94.5
90.9	90.6	86.8	92.2	105.7	91.5	92.6	93.8	96.2	97.6	101.4	96.1	96.9	95.3	93.9
88.7	85.7	80.1	93.7	103.7	89.2	91.5	93.6	95.0	95.9	99.6	95.6	96.4	96.2	94.9
89.6	87.2	85.9	92.0	110.4	88.4	92.5	91.2	93.6	96.9	100.6	95.7	98.0	95.0	94.0
89.5	86.8	90.3	93.4	108.3	89.4	88.3	92.3	94.0	98.3	100.1	95.3	96.8	96.0	94.2
86.3	83.3	91.5	88.5	110.3	89.5	91.0	92.4	94.7	97.7	101.4	96.4	96.7	95.3	95.5
86.6	84.3	83.6	91.0	107.0	87.9	89.3	95.2	95.0	97.7	102.0	94.4	98.1	94.5	94.5
89.8	88.7	87.3	92.0	106.1	92.7	89.0	92.9	96.7	98.2	100.5	96.2	98.3	94.8	95.7
0.0	88.5	92.0	89.8	107.8	87.7	90.1	0.0	97.7	96.6	0.0	96.1	97.7	0.0	94.6
0.0	0.0	96.6	0.0	107.3	88.8	90.2	0.0	97.3	0.0	0.0	96.2	96.5	0.0	95.7
0.0	0.0	92.3	0.0	0.0	92.1	91.4	0.0	95.1	0.0	0.0	97.1	97.7	0.0	95.7
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	96.4	98.0	0.0	96.2
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	95.6	0.0	0.0	95.9

TABLE D-VII

DIFFUSERS ONLY - SOUND PRESSURE LEVELS AT POSITION 3

1/3 OCTAVE CENTER FREQUENCY (HZ)

100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500
88.8	88.9	94.4	82.9	106.0	91.7	87.2	94.3	97.8	97.4	102.1	97.9	95.2	96.3	95.2
89.7	86.6	89.9	89.4	104.1	89.6	92.1	92.1	94.7	98.9	100.4	97.2	95.2	96.6	94.6
88.2	85.6	88.5	93.1	109.0	93.0	90.8	91.9	95.4	97.8	100.8	96.9	96.2	96.7	93.8
87.4	87.6	87.8	91.4	108.3	89.0	91.4	95.8	95.6	98.3	102.1	96.1	96.3	96.6	93.4
87.4	87.5	88.7	97.0	108.5	92.7	89.9	95.1	97.3	97.6	101.3	95.9	96.6	96.7	93.5
88.2	87.8	88.1	93.8	109.7	92.2	92.6	92.9	94.9	99.0	102.0	96.2	96.9	96.7	93.4
89.9	88.5	84.7	90.2	105.9	90.4	88.5	92.4	95.2	96.8	101.0	96.0	96.9	97.3	93.8
93.0	85.4	84.4	90.7	107.5	94.7	89.6	93.9	96.5	97.7	101.1	95.1	96.8	95.8	94.1
92.1	84.9	88.5	88.7	105.4	88.7	91.9	91.2	93.7	95.3	101.3	94.8	96.5	96.1	93.4
88.8	88.7	91.9	90.7	104.2	91.1	90.8	93.4	95.1	97.6	101.5	95.4	96.0	96.0	93.9
86.0	88.3	85.5	93.9	107.7	91.6	90.9	93.3	95.9	97.1	102.9	94.5	97.4	96.5	93.0
84.9	88.9	91.1	91.3	112.6	90.6	91.4	95.1	92.9	99.1	100.7	95.3	96.8	96.2	94.3
87.0	90.3	92.3	88.9	107.4	93.6	89.3	88.9	97.9	99.0	101.4	94.0	96.8	96.1	94.2
90.3	93.3	87.8	89.5	102.3	89.6	88.9	93.4	96.7	96.7	100.7	94.6	96.0	96.5	94.6
90.2	94.2	83.9	87.2	104.0	92.4	89.8	90.7	95.5	96.4	100.5	95.2	97.2	95.5	94.7
91.9	95.5	84.9	90.1	104.2	91.5	89.9	92.4	95.0	97.2	100.1	95.2	97.0	95.3	94.3
87.8	98.7	87.4	97.7	105.6	90.1	92.7	95.1	95.4	97.7	100.5	95.6	97.3	95.6	94.9
88.1	97.6	86.8	94.1	103.8	88.5	90.2	92.5	96.9	98.1	100.7	94.2	96.8	95.8	95.4
89.1	95.0	84.3	90.1	106.5	90.0	89.4	91.9	95.6	97.2	100.2	95.0	97.6	95.4	94.8
88.1	92.9	87.8	91.2	103.9	86.5	92.3	92.0	94.3	96.5	99.8	95.7	97.2	96.0	95.2
93.2	90.6	89.6	93.4	105.6	88.2	87.1	93.8	94.0	96.5	100.1	95.9	96.4	96.0	96.0
92.6	88.4	94.3	98.8	107.6	87.2	89.1	92.4	94.7	98.4	101.0	95.4	97.0	95.1	94.8
0.0	93.2	94.0	91.2	107.3	89.5	89.7	0.0	96.9	97.6	0.0	96.3	98.2	0.0	94.7
0.0	0.0	92.5	0.0	107.7	91.7	90.2	0.0	95.5	0.0	0.0	95.0	97.1	0.0	96.6
0.0	0.0	92.8	0.0	0.0	91.6	91.3	0.0	95.6	0.0	0.0	94.7	97.8	0.0	95.5
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	95.9	96.6	0.0	96.2
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	95.8	0.0	0.0	96.9

TABLE D-VIII

FINAL CONFIGURATION - SOUND PRESSURE LEVELS AT POSITION 1

1/3 OCTAVE CENTER FREQUENCY (HZ)

100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500
88.5	86.6	89.1	86.7	103.3	89.8	89.6	92.8	95.1	95.5	101.4	97.2	95.0	95.4	94.9
88.6	87.6	90.7	87.3	104.4	89.4	92.0	93.3	95.2	97.0	100.4	97.5	95.3	96.1	94.5
88.7	90.1	86.3	88.6	104.9	88.9	93.3	94.1	94.6	98.2	99.9	97.3	95.6	97.0	94.0
88.3	92.8	87.9	91.2	107.3	89.9	88.6	93.4	93.9	96.1	102.5	95.9	95.9	96.0	92.9
87.3	90.0	88.5	93.2	106.6	87.7	89.3	93.4	93.5	97.4	101.0	96.1	96.9	94.9	92.7
87.5	89.7	87.5	90.6	108.6	90.6	89.2	89.9	94.1	96.8	101.8	96.2	97.5	96.8	93.5
88.3	87.3	89.3	87.2	105.9	94.1	88.4	89.7	94.7	97.7	100.8	96.1	95.5	96.0	93.4
88.5	82.4	91.1	86.7	106.0	86.2	90.0	91.8	93.7	98.6	100.7	95.8	97.3	95.8	92.8
85.9	86.0	90.9	85.4	105.9	87.8	88.2	94.7	95.7	96.3	102.7	96.4	97.2	95.9	92.9
83.4	88.8	89.0	87.3	110.2	87.6	90.8	91.8	93.7	97.6	101.7	94.9	96.3	95.4	93.0
82.6	88.1	91.4	88.3	109.6	86.4	91.4	88.7	95.5	96.2	100.4	93.9	96.1	95.6	93.7
84.1	89.1	89.2	86.9	102.9	86.4	87.5	90.5	93.4	97.9	100.5	94.4	95.9	95.4	94.3
86.2	88.8	94.7	88.1	104.6	86.3	88.6	91.6	97.6	96.4	100.5	94.8	95.7	95.2	94.2
86.8	86.7	93.1	87.9	102.3	85.8	88.5	89.2	95.9	97.0	100.9	93.9	96.4	95.9	93.5
89.2	88.7	88.8	89.6	107.4	84.9	89.4	92.2	93.7	96.2	100.7	94.9	97.0	95.5	95.1
91.6	94.0	87.7	90.7	106.6	88.1	88.5	91.5	94.0	96.1	99.4	95.2	96.2	95.0	94.2
92.3	93.9	86.5	85.0	111.2	88.7	90.9	90.9	94.0	98.2	100.2	94.7	96.6	95.0	93.8
92.6	92.1	84.0	90.7	105.3	87.2	89.8	92.4	94.6	97.4	100.1	94.7	96.7	95.4	94.7
93.3	92.0	84.1	88.8	103.9	89.6	88.6	93.4	94.1	96.2	99.6	95.2	96.4	94.6	94.8
91.6	91.9	79.3	89.0	104.5	92.5	90.5	92.6	93.2	99.8	99.5	95.0	96.7	95.6	94.4
92.3	92.7	81.9	94.9	104.4	90.0	90.1	93.2	94.5	98.0	99.7	94.9	96.8	94.4	94.4
90.9	92.2	89.2	90.3	104.9	90.5	90.6	91.9	95.0	97.1	100.8	95.4	96.7	94.8	95.9
0.0	87.4	91.8	87.6	106.1	89.6	91.6	0.0	94.7	97.5	0.0	94.9	96.8	0.0	94.8
0.0	0.0	90.9	0.0	105.1	89.3	88.9	0.0	94.9	0.0	0.0	95.0	97.0	0.0	95.3
0.0	0.0	93.3	0.0	0.0	91.7	91.9	0.0	93.8	0.0	0.0	94.5	97.2	0.0	95.7
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	95.8	97.1	0.0	96.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	95.3	0.0	0.0	95.5

TABLE D-IX

FINAL CONFIGURATION - SOUND PRESSURE LEVELS AT POSITION 4

1/3 OCTAVE CENTER FREQUENCY (HZ)

100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500
87.8	90.6	91.8	86.9	107.5	89.2	88.0	91.8	95.8	95.8	100.3	97.5	94.2	96.3	94.1
88.3	91.7	89.2	91.2	105.8	88.0	91.2	90.6	94.9	97.6	100.7	97.7	95.3	96.1	94.9
87.6	93.7	87.1	93.3	107.6	91.8	88.5	92.8	97.4	98.7	101.3	96.7	95.6	97.0	94.0
85.7	93.9	90.2	87.8	105.9	89.5	88.1	93.8	95.0	98.2	102.2	97.0	97.1	95.9	93.3
83.1	87.7	88.9	90.3	102.7	90.7	86.4	94.6	95.4	98.0	101.8	95.9	96.2	95.9	92.5
84.1	85.2	85.7	85.0	105.3	86.5	89.7	90.5	95.5	98.0	101.4	95.7	96.8	96.6	93.0
86.7	87.0	83.1	86.9	110.9	85.2	91.2	93.1	93.5	96.4	100.3	95.1	95.9	96.9	93.5
89.5	85.9	80.7	86.4	109.9	88.5	90.9	89.2	95.4	96.4	101.3	94.1	96.5	95.5	92.6
89.1	87.9	83.3	85.2	107.2	94.4	91.1	91.0	95.8	98.5	101.2	95.4	96.3	96.2	92.8
88.0	89.1	85.6	85.6	108.4	91.8	90.8	93.7	93.6	95.7	100.8	94.6	95.7	95.3	93.1
87.4	86.1	87.0	87.5	107.9	86.2	90.4	92.4	93.6	96.4	100.9	95.8	95.7	95.6	92.5
87.2	90.0	87.6	86.5	105.3	88.3	89.1	92.1	96.9	97.4	100.5	94.4	95.9	95.7	93.5
85.4	91.4	90.8	89.1	103.6	88.9	87.9	88.3	95.3	96.4	100.6	94.5	96.5	95.9	93.8
81.9	92.5	91.9	91.5	106.4	87.2	90.8	91.2	97.6	95.1	100.9	95.0	96.5	95.0	94.3
83.9	89.3	92.8	87.7	106.3	89.7	93.8	91.9	95.5	94.8	101.1	95.7	95.7	95.4	94.2
86.2	87.3	99.0	88.8	105.8	89.3	90.5	94.6	94.3	96.6	100.2	95.7	96.5	95.2	93.9
89.1	86.7	85.1	90.4	107.2	87.7	92.1	91.0	93.4	96.0	99.8	95.2	96.5	95.1	95.2
90.4	91.1	87.0	92.6	108.1	88.5	89.4	92.4	94.9	97.2	100.2	96.0	95.8	95.7	94.2
93.0	89.8	86.4	86.9	104.7	88.3	89.0	92.3	94.5	97.2	100.1	94.7	96.8	95.0	95.1
92.1	82.8	82.6	92.1	104.7	87.8	88.7	92.6	92.5	97.7	99.4	94.2	96.7	95.2	94.8
92.5	86.9	84.8	90.7	100.5	86.9	89.5	91.6	94.6	96.7	100.0	95.6	97.2	95.4	95.0
92.4	91.0	87.6	92.5	103.6	87.7	88.9	92.9	96.5	98.3	101.6	95.5	96.7	94.8	94.7
0.0	89.6	89.9	89.9	107.1	89.4	91.2	0.0	95.8	97.8	0.0	95.9	96.3	0.0	95.3
0.0	0.0	88.5	0.0	104.1	89.6	91.4	0.0	95.9	0.0	0.0	95.3	97.7	0.0	95.6
0.0	0.0	89.8	0.0	0.0	88.7	89.2	0.0	95.1	0.0	0.0	94.8	97.7	0.0	96.1
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	94.6	98.1	0.0	96.9
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	96.2	0.0	0.0	95.6

TABLE D-X

FINAL CONFIGURATION - SOUND PRESSURE LEVELS AT POSITION 5

1/3 OCTAVE CENTER FREQUENCY (HZ)

100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500
90.8	85.8	92.6	88.5	105.8	91.7	91.0	94.9	96.0	94.2	100.7	97.2	94.7	94.4	95.0
90.1	85.2	90.4	86.2	107.2	90.4	91.4	95.1	94.1	98.4	100.5	97.7	94.2	94.9	93.3
88.9	90.0	88.8	84.6	108.3	88.7	92.5	93.9	94.6	98.5	101.9	96.8	96.7	95.1	93.5
88.3	95.6	89.0	87.1	111.8	85.0	93.2	92.9	95.4	96.7	101.3	96.5	96.3	95.4	93.3
88.6	90.4	90.7	87.8	106.5	83.2	89.1	93.1	95.6	98.2	100.2	96.1	96.1	94.9	92.9
89.5	88.2	91.4	83.1	104.6	88.2	87.8	92.5	93.8	97.5	101.2	94.6	96.6	95.6	93.3
90.7	87.7	92.9	85.3	108.9	88.7	87.6	92.4	94.9	97.0	100.9	94.6	97.2	95.3	92.9
90.8	85.3	87.3	83.4	110.3	89.9	89.8	90.5	94.3	98.6	100.7	94.1	96.7	95.1	93.2
87.7	87.2	84.7	83.9	106.2	86.9	90.0	91.9	95.0	97.2	100.6	95.6	95.9	95.5	92.8
84.7	88.5	87.2	84.9	104.5	90.6	89.2	88.4	94.0	98.1	102.2	95.4	95.1	95.2	93.3
83.6	86.6	87.8	81.3	107.0	87.8	89.5	88.8	94.2	97.8	100.9	95.2	95.1	94.7	92.9
85.5	88.8	87.3	84.9	109.1	89.4	90.4	91.0	93.5	96.8	100.2	95.7	96.3	96.2	92.9
87.7	83.8	88.4	83.0	106.0	87.0	87.0	92.0	93.1	95.6	100.8	93.9	96.1	94.4	92.7
87.6	86.2	90.4	82.8	107.1	89.0	87.6	90.3	94.8	96.3	99.8	94.4	96.0	95.8	93.1
89.4	89.4	95.4	83.9	106.9	90.2	88.3	92.2	96.8	95.9	99.9	94.7	96.0	95.1	93.4
88.7	91.6	91.5	85.8	106.6	90.6	89.5	90.9	94.4	97.0	100.1	94.1	96.4	95.8	93.6
87.2	96.1	90.5	85.1	107.0	91.0	90.2	91.8	94.5	94.9	100.0	96.3	96.1	94.8	93.4
89.1	94.0	90.0	85.0	105.9	90.5	89.4	93.2	95.6	95.3	99.9	95.0	96.3	95.2	94.0
89.4	91.2	89.1	88.8	102.8	86.9	91.9	92.2	93.7	95.7	101.2	93.9	95.6	95.7	92.8
89.9	93.1	84.5	89.2	104.7	85.7	90.4	91.6	93.7	97.1	100.4	94.9	96.5	94.8	94.2
91.1	92.7	87.9	91.0	101.7	86.5	90.7	93.6	94.7	97.3	100.9	94.9	96.4	94.6	94.2
90.4	93.1	87.8	91.7	103.0	89.7	90.0	93.6	92.5	96.9	100.8	94.6	97.0	94.1	94.4
0.0	92.0	92.6	88.2	105.3	91.9	88.1	0.0	94.5	97.7	0.0	95.0	96.3	0.0	94.3
0.0	0.0	92.7	0.0	106.7	90.8	88.2	0.0	94.3	0.0	0.0	95.4	96.9	0.0	95.4
0.0	0.0	92.5	0.0	0.0	89.2	88.8	0.0	94.9	0.0	0.0	95.3	96.3	0.0	95.1
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	94.8	96.8	0.0	94.8
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	95.2	0.0	0.0	95.8