INVESTIGATIONS INTO THE PERFORMANCE
OF THE REVERBERATION CHAMBER
OF THE INTEGRATED ACOUSTICS LABORATORY

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INVESTIGATIONS INTO THE PERFORMANCE
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SUMMARY

This thesis details the performance of the reverberation chamber of the Integrated Acoustics Laboratory (IAL), equipped with experimental lightweight diffusers. Reverberation chambers are generally equipped with dense baffles, called diffusers, which are designed to reflect but not absorb sound, in an effort to create a sound field in the chamber with uniform energy density. Industry standards, such as ASTM C423, ISO 354, and ISO 3741 for sound absorption and sound power testing in reverberation chambers, recommend the use of stationary and rotating diffusers, made of a material with high surface density and low absorption. Instead, lightweight fiberglass diffuser panels were installed in the IAL reverberation chamber because they are safer, less expensive and more flexible; their performance in the IAL chamber was evaluated. Preliminary testing of the IAL instrumentation chain and analysis techniques documented their acceptable performance. Qualification testing per the abovementioned standards proved that the IAL chamber, equipped with stationary lightweight diffusers, was fit for testing sound power but not sound absorption. However, when equipped with a combination of stationary and rotating lightweight diffusers, the chamber qualified for sound absorption tests. Optimization of absorption testing methodology showed that the area of a specimen did not significantly affect the measured sound absorption coefficient unless the specimen was highly absorptive or the area was significantly less than the recommended 6.69 m^2. Also, increasing the "empty room" absorption of the acoustically hard IAL chamber did not improve the reproducibility of absorption measurements. With regard to length of test, an absorption test in the IAL chamber should include the measurement of 225 decays to attain the representative repeatability values of ASTM C423 for frequencies 315 Hz and higher. Comparative absorption testing showed that the chamber reproduced sound absorption results well; when round robin testing was replicated in the

chamber, results were not statistically different from other laboratories. However, the reproducibility was worse for highly absorptive specimens. Sound power testing in the chamber produced highly reproducible results, well within the limits of reproducibility of the standard. It can be concluded that a combination of stationary and rotating lightweight diffusers made the IAL chamber fit for sound absorption and sound power testing.

1. INTRODUCTION

Reverberation chambers are chambers designed for acoustic testing, such as sound absorption, sound power, transmission loss, and many others. The purpose of a reverberation chamber is to create a sound field for which there is uniform net energy flow at all points in the field[1]. The diffuse field is generated through a combination of acoustically hard surfaces for the chamber walls and the use of heavy, highly reflective baffles, called diffusers. While standards for sound absorption and sound power tests call for the implementation of stationary and/or rotating heavy diffusers to induce a statistically uniform sound field, they are heavy and expensive, making them impractical for educational facilities such as Georgia Tech. Thus, for the newly constructed Integrated Acoustics Laboratory (IAL), it was of interest whether lightweight diffusers were an effective substitute for heavy diffusers. This thesis reports on the performance of the IAL reverberation chamber equipped with lightweight diffusers.

It is assumed that the sound field within the reverberation chamber is diffuse. To promote diffusion, diffuser panels are oriented randomly throughout a reverberation chamber, where these diffusers generally have a high surface density and minimal damping. Their function is to disperse but not absorb sound [2]. For the work summarized in this thesis, lightweight fiberglass diffuser panels were used instead of the traditional heavy diffusers. The surface density of the experimental lightweight diffusers was 0.69 kg/m^2 compared with the 5 kg/m^2 recommended by international standards[3-5]. The diffuser material was the corrugated fiberglass sheet commonly used for construction of sheds, greenhouses, and the like. The corrugated fiberglass siding was chosen, because it contains desirable stiffness, absorptivity, density, and diffuser properties. The corrugation was desirable since it stiffened the diffusers, but as an added advantage, corrugated boundaries diffuse sound more than flat boundaries. This work was intended to determine if fiberglass panels are suitable as diffusers, and if so, how the IAL reverberation chamber performs when equipped with these diffusers.

The motivations for using lightweight diffusers in reverberation chambers are: greater flexibility, simplicity, and economy. Currently in reverberation chambers, heavy, dense diffusers are rigidly mounted at random locations and at random orientations throughout the chamber. These configurations must be robust and are generally permanent. Frequently, the sound field is not sufficiently diffuse with stationary diffusers alone, requiring the use of a rotating diffuser vane. Rotation of the diffuser often requires external mounting of a motor, with the diffuser attaching to a drive shaft that runs through the chamber ceiling. This is both cumbersome and costly. For flexibility, simplicity and economy, lightweight diffusers would be more advantageous, provided they perform the same function as heavy diffusers, i.e. that they increase chamber diffusion.

Before research on diffusers can commence, an intimate understanding of reverberation chambers and sound absorption and power standards is required. Chapter 2 is a literature review of past work conducted in reverberation chambers, followed by summaries of the standards applicable to sound absorption and sound power. Chapters 3 and 4 are overviews of the common experimental setup, instrumentation, data acquisition and analysis techniques specific to the IAL chamber; these apply to most of the testing described in this thesis. The remainder of the report contains several sections, some with unique setup, procedure, results, and conclusion subsections which complement Chapters 3 and 4. Each of these sections details a specific test conducted to better characterize the IAL chamber and equipment and the impact of lightweight diffusers on the chamber performance. Finally, there is a conclusion chapter that summarizes the major findings.

2. LITERATURE REVIEW

Reverberation chambers have been heavily researched since the early 1900's because of their usefulness in architectural acoustics and noise control,. Still, many consider their performance optimization to be an art rather than an exact science. This chapter summarizes research of reverberation chambers, including preliminary research, suggestions for chamber design, and diffuser design. The chapter continues with background information on the repeatability of sound absorption measurements and the conduct of round robin testing in reverberation chambers.

2.1. REVERBERATION CHAMBERS

2.1.1. Preliminary research

Research into the science of reverberation chambers was pioneered by Wallace Clement Sabine at Harvard University. As a young physics researcher in 1894, Sabine was assigned the task of improving the acoustics of the new but poorly designed Fogg Lecture Hall. He experimented with the addition of seat cushions as absorbers and noted the change in the reverberation times of the hall with a varying number of seat cushions. The experimental results aligned well with the theoretical energy balance. The energy supplied to a room, by a speaker or other source, must be equal to the amount of energy absorbed by the room's surfaces and the amount of increase in the room's energy density. If the source energy input is set to zero, the change of energy density in the room is due to the absorption by the room's surfaces. From this energy balance, the decay rate of sound can be found or similarly the equivalent absorption area of the sample can be found according to

$$A = \frac{55.3V}{T_{60}\,c} = \frac{0.921V\,d}{c} \tag{1}$$

where A = equivalent absorption of absorbing material (metric Sabines)
V = room volume (m^3)
T_{60} = reverberation time (s)
c = speed of sound (m/s)
d = decay rate (dB/s).

The Sabine equation was originally written in terms of the reverberation time but more recently in terms of the decay rate. The variable, A, is the equivalent absorption area of a specimen of material. For a given specimen, the equivalent absorption area is the size of a perfect absorber that would be needed to produce the same room decay rate as that produced by the specimen. Normalizing A by dividing by the specimen area, S, yields the dimensionless absorption coefficient, α,.

$$\alpha = \frac{A}{S} = \frac{0.921Vd}{cS} \tag{2}$$

The Sabine equation is based on the assumption that the sound field in the room is diffuse, i.e. there is equal probability of energy flow on each part of the absorbing sample and the angle of incidence is random [6]. It is also assumed that there is negligible sound energy loss along the mean free path. Finally, the assumption is made that the total absorption of the room surfaces is the simple sum of absorption of individual pieces [7].

Other absorption coefficient equations have been developed, the most notable from C.F. Eyring and R.F. Norris[7]. Their derivation is based on the mean free path and the attenuation of reflections. The total energy attenuation is

$$\left(1-\overline{\alpha}_E\right)^{Nt}, \tag{3}$$

where N is the number of reflections per second and $\overline{\alpha}_E$ is the average absorption coefficient for the Eyring-Norris derivation. Therefore,

$$\overline{\alpha}_E = 1 - \exp\left(0.00268\frac{Vd}{S}\right). \tag{4}$$

This equation is consistent with the Sabine equation for small values of α_E. For large values of α_E, the Eyring-Norris equation yields a slightly smaller value for the absorption coefficient than the Sabine equation [1, 8]. When the sound field in the room is less diffuse, the Eyring-Norris formula predicts the absorption coefficient of the material more accurately than the Sabine equation [9]. Thus, the Eyring-Norris equation is used commonly for architectural acoustics. However, for absorption testing in reverberation chambers, where the sound field is very nearly diffuse, the Sabine equation is accurate and computationally straightforward.

2.1.2. Design of Reverberation Chambers

As stated, reverberation chambers are intended to produce a diffuse sound field. Their design and construction can be optimized to best achieve a diffuse field. Intuitively, its surfaces should be highly reflective, i.e. very hard. Concrete and steel panel are most commonly used for the chamber surfaces. Also, the chamber shape should not be a simple shape, not a cube, sphere or cylinder. Simple shaped rooms have dominant room modes that make the sound field highly dependent on position in the room. Rectangular rooms are common. Optimal dimension ratios for rectangular rooms are given in the sound power standard, ISO 3741 Annex D. Also, rooms with dimensions that are large compared to the longest wavelength of interest are more diffuse than small rooms.

The diffusion of a room increases when the room dimensions are carefully chosen to separate room modes and equalize the frequency response of the room. Diffusion increases as the frequency spacing between room modes decreases and the bandwidth of room modes increases, i.e. the frequency response approaches a delta function. With regard to frequency spacing, 20 room modes per one-third octave band is a suggested lower limit for a "diffuse" field [1]. This is the case for

$$V \geq 4\lambda^3 \tag{5}$$

where V = chamber volume
λ= longest wavelength of interest

To have 20 room modes in the 100 Hz band, where the lowest frequency is 89 Hz, a room must have a volume greater than 230 m^3. M.R. Schroeder found an empirical relation between the volume and decay rate of a room to determine a cutoff frequency above which a diffuse field could be expected. He showed that for a given room frequency response, when the average frequency spacing between natural modes is less than about one third the bandwidth of a mode, the sound field is diffuse. Below a certain frequency, referred to as the Schroeder frequency of a room, the spacing between natural modes is more than one-third of the bandwidth of a mode. This frequency is

$$f_s = 2000\sqrt{60/Vd} \tag{6}$$

where the decay rate, d, is the decay rate at 500 Hz [10, 11]. Below the Schroeder frequency of a room, the repeatability and reproducibility decline because of insufficient diffusion. Equation 6 shows that increasing the room volume or increasing the decay rate, i.e. adding absorption, lowers the Schroeder frequency which is advantageous. It must be noted that with larger rooms, atmospheric attenuation contributes significantly to the decay rate of sound of frequencies above 2000 Hz. This violates the assumption of negligible energy loss along the mean free path used for the derivation of the Sabine equation [1]. So, increasing the volume of the chamber extends its operable range to lower frequencies but makes high frequency data less accurate.

With regard to the bandwidth of room modes, they can be increased by adding absorption to the room. This technique is used to increase the bandwidth of low frequency modes, since the modal density is low at low frequencies.

2.1.3. Diffusers

The most effective means for increasing diffusion in a reverberation chamber is the introduction of reflecting surfaces called diffusers. Diffusers are highly reflective objects that are randomly dispersed throughout the chamber, designed to reflect, not absorb, sound waves. They are intended to minimize concentrations and disturb standing waves without absorbing sound [12]. It is highly debated in the literature whether diffusers are effective at increasing diffusion when stationary. Dodd and Doak found that fixed diffusers do not affect the spatial or frequency variations in sound pressure [13, 14]. Also, Beranek reports that fixed diffusers do not affect the variance of sound pressure level or decay rate [15]. However, when there is a concentration of absorptive material, as is the case for sound absorption testing, stationary diffusers restore the directional isotropy of the sound field [14]. Therefore, standards for sound absorption testing, ASTM C423 and ISO 354, strongly recommend the use of stationary diffuser panels. Their locations are not significant, but random orientation is critical [13].

Rotating diffusers are highly recommended in sound absorption and sound power standards. As they rotate, they constantly vary the apparent shape of the chambers, and thus vary the standing waves that result. When several sound measurements are taken over a period of time, each measurement seems to come from a room of a different shape. The anomalies of the room are less evident in the average, and the true performance of the test specimen is measurable. This has the same effect as moving a sound source to different locations around the room for sound power testing [16]. It is recommended that rotating vanes be made of dense, non-absorbing material. Their dimensions should be comparable to at least half of a wavelength of the frequency that they are intended to affect [17]. ISO 3741 acknowledges the complexity of quietly rotating a large, heavy diffuser rapidly; it suggests making the rotating diffusers conical to simplify the rotation process[3]. As a word of caution, if there are significant discrete frequency components to a sound field in chambers with rotating diffusers, amplitude modulation of sound pressure signals can occur [16]. So, for broadband tests like sound absorption and broadband sound power, it is desirable to use rotating diffusers; for pure tone sound power tests, it is undesirable.

Corrugation of diffusers is a suggested means of increasing diffusion because of what is called the picket fence effect [5, 18]. A perfectly flat, rigid surface reflects an incident wave, changing its direction only. When a corrugated surface reflects an incident wave, interference between reflections from the corrugations result in modulations of the reflected wave's frequency. This effect further diffuses sound and is desirable for broadband testing in reverberation chambers.

When designing diffusers, not only is the material important, the area and distribution of the diffusers influences their effectiveness as well. Sound absorption test standards provide guidelines for optimizing diffuser area and distribution. ASTM C423 and ISO 354 recommend measuring the absorption of a specimen several times, each time increasing the diffuser area until the average absorption coefficient reaches a maximum and thereafter remains constant or begins to decrease. The diffuser area that first gives the maximum coefficient is the optimal diffuser area. J.L. Davy *et al*.[19] investigated the suggested methods of ISO 354 and found an empirical value for the optimal diffuser-to-chamber floor surface area ratio. Davy defined δ as the ratio of the total diffuser area (both sides) to the chamber floor area. He tested the absorption of a specimen, varying δ from 0 to 1.75 in two chambers, with volumes of 200 and 600 m^3. He found that for both chambers the sound absorption coefficient of a specimen increased linearly with δ until δ was approximately 1.25±0.14 and remained constant thereafter [13]. Therefore, the optimum value of δ was 1.25. For comparison, ASTM C423 and ISO 354 state that, in general, the optimum diffuser area is 15-25% of the total chamber surface area ([5] Note X1.1; [4] Note A.1). Although the exact relationship depends on the chamber shape, these two conclusions are not incompatible.

2.2. REPEATABILITY OF SOUND ABSORPTION MEASUREMENT

As with all standardized measurements, it is necessary to determine the repeatability of measurements from a reverberation chamber. Annex C of ISO 354 describes how to determine the repeatability of sound absorption measurements. The repeatability is determined from five measurements of sound absorption of a specimen conducted within a short period of time. The test method and condition of the specimen should be as consistent as possible. The repeatability is then

$$r = t\sqrt{2}\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(\alpha_i - \overline{\alpha})^2} \tag{7}$$

where t = Student distribution factor; 2.78 for n=5 and 2.23 for n=10.

S.M. Brown and K.D. Steckler performed a convergence study to determine the repeatability of sound absorption measurements in their chamber[20]. They were also interested in the relationship between the number of decays in their average and the repeatability on the resulting absorption coefficient. In 1978 when their research was performed, it was common practice to define the absorption coefficient in terms of the reverberation time, T_{60}. Also, when their study was conducted, limitations on computational power made experimental determination of confidence intervals inefficient and costly. Instead, Brown and Steckler used propagation of error techniques to determine their repeatability. According to the Sabine equation, the sound absorption coefficient of a specimen can be represented as

$$\alpha = 0.921\frac{V}{c}\left(\frac{60}{T_{60SI}} - \frac{60}{T_{60SO}}\right) \tag{8}$$

where T_{60SI} = reverberation time with sample in
T_{60SO} = reverberation time with sample out.

Thus, if the confidence interval for each of the reverberation times is known, one can use propagation of error to approximate the repeatability for the absorption coefficient. Based on ASTM C423-66, Brown used a 90% confidence interval, which was calculated assuming normality and using the *t*-statistic. Brown's method of propagation of error, first introduced by Ku and Cramer [21, 22], does not take into account systematic measurement errors, only random errors. So, the actual repeatability was expected to be worse than that predicted by this method.

Brown concluded that increasing the number of decays decreased the confidence interval width on the low frequency α values of a highly absorptive sample. He also found that data from smaller specimens (44 ft^3) was less repeatable than that for larger samples. Finally, the use of 100 decay rates was sufficient for his repeatability to be as tight as that in ASTM C423-66. The repeatabilities of ASTM C423-66 and C423-02a are tabulated in Table 1. The values of ASTM C423-02a are easier to attain than those from the 1966 version of the standard, ASTM C423-66.

Table 1. Estimates of Repeatability, *r*, of Sound Absorption Coefficients of a Specimen in a Type A Mounting for the 1966 and the 2002 versions of ASTM C423

	ASTM C423-66	ASTM C423-02a
Mid-Band Frequency, Hz	*r* 90%	*r* 95%
125	0.04	0.06
250	0.02	0.05
500	0.02	0.06
1000	0.02	0.05
2000	0.02	0.05
4000	0.04	0.07

2.3. ROUND ROBIN TESTING

Comparative testing between qualified laboratories is common to quantify the reproducibility of test methods. It is also used when developing qualification requirements for standardized testing. Such comparative tests are sometimes called round robins. A test sample is sent to several qualified laboratories and tested at each lab multiple times per the applicable standard. Typical values for repeatability and reproducibility can then be calculated from the resulting data. For this thesis, several round robin tests were duplicated in the IAL reverberation chamber. First, simulated and prerecorded decays were analyzed using the IAL instrumentation to determine its ability to accurately measure decay rate. Secondly, a 2003 unpublished ASTM C423 round robin test was duplicated in the IAL chamber. The round robin material was Certainteed CertaPro® fiberglass insulation board (Product # 906583). Thirdly, the 1999 ASTM C423 round robin, organized by the National Voluntary Laboratory Accreditation Program (NVLAP), was replicated. The sample was Armstrong® ceiling tile (item number 1910). The results of these three round robin tests show how the IAL reverberation chamber compared with other laboratories in its ability to repeat and reproduce decay rate and sound absorption measurements.

3. SUMMARY OF APPLICABLE STANDARDS

Organizations such as the American Society for Testing and Materials (ASTM) and the International Organization for Standardization (ISO) provide standards for sound absorption and sound power testing in reverberation chambers. Below are summaries of the qualification and testing requirements of ASTM C423 for sound absorption testing and ISO 3741 for sound power testing.

3.1. ASTM C423 Sound Absorption Testing

ASTM C423 and ISO 354 outline requirements for sound absorption testing. Their requirements are similar, but ASTM C423 is used more widely in laboratories in the United States and is thus the focus here.

3.1.1. Absorption Coefficient Calculation

The parameter of interest during ASTM C423 sound absorption testing is the decay rate of sound in the chamber. The decay rate in each band is calculated according to ASTM C423.11 as the slope of the linear portion of the average sound pressure level, $L_p(t)$, during the decay of sound from the room. The average sound pressure level is defined as the linear average level, according to

$$L_i = \frac{1}{N}\sum_{j=0}^{N} L_{ij} \tag{9}$$

The decay rate is found using first-order regression over a decay of 25 dB, according to

$$d = \frac{6}{M\left(M^2-1\right)\Delta t}\left[(M+1)\sum_{i=1}^{M}(L_i) - 2\sum_{i=1}^{M} i(L_i)\right] \tag{10}$$

where d=unadjusted decay rate

M=number of data points in the average decays

The decay rate is then adjusted for atmospheric absorption as needed, per C423.6.2, 11.4.1 and ANSI S1.26[23].

The sound absorption area, A, is calculated from the decay rate in the chamber according to the Sabine formula, Equation 2. The sound absorption of a test specimen is the difference in the sound absorption of the chamber with and without the specimen.

The sound absorption coefficient, α, is a commonly tabulated value for a material. Physically, it is a ratio of the energy absorbed by a specimen to the energy incident on its surface. The absorption coefficient of a specimen is

$$\alpha = \frac{A_2 - A_1}{S} \tag{11}$$

where A_2 = absorption of chamber with test specimen
A_1 = absorption of chamber without test specimen
S = area of test specimen

Due to diffraction effects at the specimen's edges, the absorption coefficient can be greater than unity. The average sound absorption coefficient is found by averaging the absorption coefficient over one-third octave frequency bands with center frequencies of 500 to 4000 Hz.

3.1.2. Relative Standard Deviation Calculations

The relative standard deviation of the decay rate within the chamber is used to verify that the sound field in the chamber is sufficiently independent of measurement, specimen and loudspeaker position. Each of these factors is assessed separately, but the relative standard deviation has a common form for each factor assessment, calculated as

$$s_{XX} = \left(\frac{1}{N_{XX} - 1} \sum_{i=1}^{N_{XX}} \left(d_{XXi} - \left(d_{XX} \right) \right)^2 \right)^{\frac{1}{2}} \tag{12}$$

where XX = a subscript indicating whether the test is with respect to the number of microphone (M), specimen (S), or speaker (SS) positions
N_{XX} = number of positions for the particular factor
d_{XXi} = decay rate at the ith factor position, and
$(d_{XX}) = \frac{1}{N_{XX}} \sum_{i=1}^{N_{XX}} d_{XXi}$ = the decay rate averaged over all positions.

The relative standard deviation in a given frequency band is the standard deviation divided by the average decay rate in that band, s_{XX} / d_{XX} .

3.1.3. Recommendations and Qualification Procedures

The following is a summary of the mandatory and non-mandatory tests and suggestions outlined in ASTM C423 for the qualification of a reverberation chamber. In the body of the standard, the installation of sound reflecting panels is encouraged as a means of promoting diffusion. Diffusers are described as "damped sheets of a material with low sound absorption." They should have a surface area of approximately 3 m^2 and weigh at least 5 kg/m^2. The diffusers can be corrugated to promote further randomness. The standard strongly encourages the use of rotating diffusers as well. C423 7.4 states that diffusers will increase the rate and randomness of energy exchange between room surfaces. It also suggests that the total surface area of the diffusers be approximately 25% of the surface area of the room.

Appendix X1-Exploration of Performance

Appendix X1 of ASTM C423-02a suggests tests that can be conducted to explore the performance of the chamber, focusing on determining the appropriate number of diffusers and quantifying the dependence of the sound field on loudspeaker position. The standard recommends optimizing the room configuration before attempting to qualify the chamber. To determine the appropriate number of diffusers, the mean sound absorption coefficient of a test specimen should be experimentally determined for different numbers of diffusers. Diffusers should be added to the room, approximately 5 m^2 at a time, and the sound absorption of a test specimen should be measured after the addition of each diffuser. The average sound absorption coefficient will reach a maximum with a certain number of diffusers, and will remain constant or decrease with the addition of diffusers. The configuration that yields the first maximum sound absorption coefficient is the optimal room configuration.

To note the effect of the source position on chamber performance, the empty-room decay rate should be measured with the source in several different positions. The relative standard deviation of decay rate over these source positions is indicative of how source position affects performance. The standard does not limit the values for the relative standard deviation with respect to source position.

Appendix A3-Diffusion Testing

Appendix A3 outlines the qualification requirements for sound absorption testing. It calls for diffusion testing to verify that the chamber has a sufficiently uniform sound field throughout its volume, requiring the variation of the decay rate be small with respect to microphone and test specimen positions.

To determine the variation of the decay rate with respect to microphone position, no specimen should be in the room. The standard requires that at least five microphone positions be included in the calculation of s_m/d_m, according to Equation 12; they must be at least 1.5 m apart and at least 0.75 m from any surface of the chamber or diffusers. The relative standard deviation must be lower than the specified values in order for the reverberation chamber to qualify.

Likewise, the sound field must be sufficiently independent of the specimen position. To quantify this, the decay rate must be tested at three or more specimen positions, evenly distributed throughout the chamber and ideally overlapping by no more than 25%. The relative standard deviation must be less than specified values for the chamber to qualify. If the requirements of Appendix A3 are satisfied, the chamber qualifies as a reverberation chamber according to C423 and is therefore suitable for sound absorption measurements.

3.1.4. Repeatability and Reproducibility

In Table 2 of ASTM C423 or Table 2 below, are typical repeatability and reproducibility values for measured absorption coefficients, representing 95% confidence intervals. The standard defines repeatability as the "value below which the absolute difference between two single test results obtained with the same method on identical test material, under the same conditions can be expected to lie with a probability of 95%."[5] The reproducibility is the "value below which the absolute difference between two single test results obtained with the same method on identical test material in a different laboratory may be expected to lie with a probability of 95%." [5] They were obtained from a round robin test conducted in 1980 and are provided in the standard as a guideline for comparison only.

Table 2. Estimates of Reproducibility, *R*, and Repeatability, *r*, of the Sound Absorption Coefficients of a Specimen in a Type A Mounting

Mid-Band Frequency, Hz	Absorption Coefficient	*R*	*r*
125	0.27	0.14	0.06
250	0.82	0.18	0.05
500	1.1	0.12	0.06
1000	1.03	0.1	0.05
2000	0.97	0.1	0.05
4000	0.95	0.13	0.07

3.2. ISO 3741 FOR SOUND POWER TESTING

The applicable standard for sound power testing is ISO 3741. The calculations and chamber qualification requirements for sound power measurements on sources with no significant discrete frequency components are outlined below.

3.2.1. Calculation of Sound Power

For measurements from a reverberation chamber, the sound power of a source is calculated by

$$L_w = \overline{L_p} + \left\{ 10\lg\frac{A}{A_0} + 4.34\frac{A}{S_{chamber}} + 10\lg\left(1 + \frac{S_{chamber}\cdot c}{8\cdot V\cdot f}\right) - 25\lg\left[\frac{427}{400}\sqrt{\frac{273}{273+\Theta}\cdot\frac{B}{B_0}}\right] - 6dB \right. \tag{13}$$

where L_w=the sound power level of the sound source (dB)

$\overline{L_p}$ = average sound pressure level in the chamber (dB)

A = the equivalent absorption area of the chamber (m^2) (Equation 2)

A_o = 1m^2

$S_{chamber}$ = the total surface area of chamber (m^2)

V = the volume of the chamber (m^3)

f = the midband frequency of measurement (Hz)

c = the speed of sound at temperature Θ

$c = 20.05\sqrt{273+\Theta}$ m/s

Θ = the temperature (°C)

B = the atmospheric pressure (Pa)

B_o =101.3 kPa.

The average sound pressure level, $\overline{L_p}$, used in Equation 13 is calculated by

$$\overline{L}_p = 10\log\left[\frac{1}{N_M}\sum_{i=1}^{N_M}10^{0.1L_{pi}}\right]dB - K_1 \tag{14}$$

where $\overline{L}_p$ = the average sound pressure level over all microphone positions or traverses in a given frequency band:
L_{pi} = the time averaged sound pressure level in a given frequency band at the *i*th microphone position for the *j*th source position
K_1 = background noise correction in a given frequency band
N_M = the number of fixed microphone positions or transverses for each source position.

These calculations require knowledge of the environmental conditions of the chamber during testing, the sound pressure level generated by the sound source, and the absorption characteristics of the reverberation chamber.

3.2.2. Chamber Design Recommendations and Qualification Requirements

ISO 3741 gives guidelines for chamber design and qualification requirements. ISO 3741.5.3 states that it is critical that the absorption of the empty chamber be sufficiently low to provide an adequate reverberant field, but at low frequencies some absorption is desirable to reduce the severity of standing waves. In Annex D, this low frequency region is defined by a maximum frequency, *f*, where

$$f = \frac{2000}{V^{1/3}} \tag{15}$$

This value is 316 Hz for the IAL chamber. Annex D suggests that the chamber absorption coefficient be less than 0.16 for frequencies below *f* and 0.06 for higher frequencies; for qualification ISO 3741.5.3 requires

$$T_{60} \geq \frac{V}{S_{chamber}} \tag{16}$$

or equivalently the average absorption coefficient to be less than 0.16 for all one-third octave bands. If this is so, the chamber is qualified for sound power testing of sources with no significant discrete frequency components; if not, the qualification procedure in Annex E must be carried out.

Annex E requires demonstration that the average sound pressure level measured by a traversing microphone does not vary significantly with sound source position. The standard deviation of the sound pressure levels measured with the source in six different positions must be less than the maximum values specified in Table E.1 of ISO 3741 or Table 3 here. If this is demonstrated, the chamber is qualified for sound power testing of sources with no significant discrete frequency components.

Table 3. Maximum Allowable Standard Deviation of L_{pi} for XX Microphone Positions per ISO 3741 Annex E

Mid-Band Frequency, Hz	Maximum Allowable Standard Deviation, dB
125	1.5
250	1.0
500	1.0
1000	0.5
2000	0.5
4000	1.0
8000	1.0

The standards outlined above were used to qualify the IAL chamber, equipped with lightweight diffusers, for sound absorption and broadband sound power testing. They were also used as a guide while comparative and exploratory tests were performed in the chamber. Their limits of repeatability and reproducibility were used to evaluate the IAL chamber's performance and compare it with other laboratories. With this background information, let us focus specifically on the IAL reverberation chamber, its setup and instrumentation.

4. EXPERIMENTAL SETUP, INSTRUMENTATION, AND COMMON PROCEDURES

The following is a description of the common experimental setup, and instrumentation in the IAL, with a description of the same for Lab A; there is also a description of the procedures for data acquisition and analysis.

4.1. IAL Common Experimental Setup and Instrumentation

The reverberation chamber in the Integrated Acoustics Laboratory has a modular design with steel panel construction for its walls and ceiling. The floor is a concrete slab, isolated from the host space by a 3 Hz isolation system. The inside room dimensions are 8 m by 6.3 m by 5 m, as shown in Figure 1, for a volume of 254 m^3.

The setup of the IAL chamber and the related instrumentation were similar for most testing described in this thesis. The lightweight diffuser panels were made of 2.1 m by 2.1 m sheets of corrugated fiberglass with a mass of 5.9 kg (13 lb_m). This equates to a surface density of 0.67 kg/m^2, compared with the 5 kg/m^2 that is recommended in ASTM C423, ISO 3741 and ISO 354. As shown in Figure 2, the diffusers were suspended from the ceiling with nylon string and oriented at random angles; a string was attached to the bottom center of the diffuser to secure the diffuser's position. When rotating diffusers were used, the same corrugated fiberglass panels were suspended freely by nylon string from small disco ball motors, which were mounted to the chamber ceiling, as sketched in Figure 3. The motors cost \$10 and turned at a nominal speed of 3 rpm.

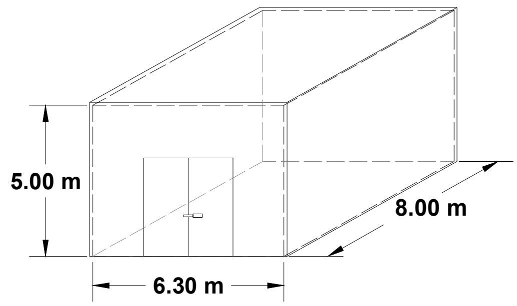

Figure 1. IAL Reverberation Chamber Interior Dimensions

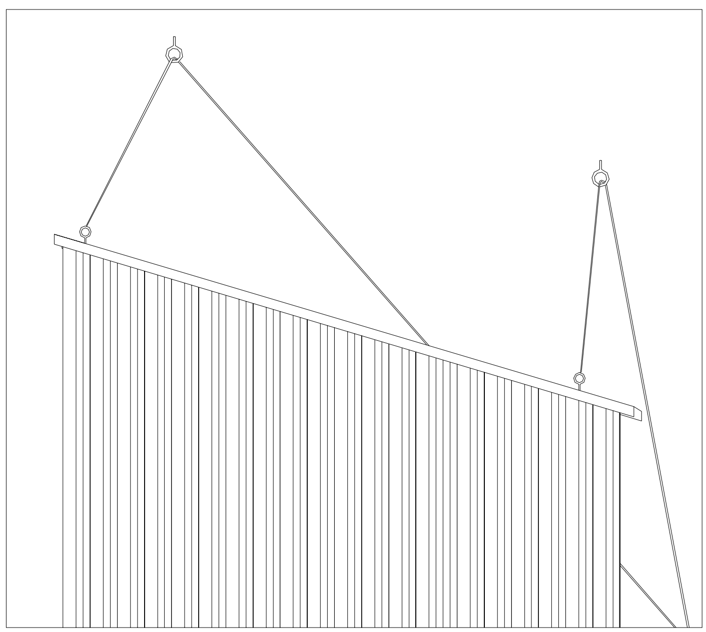

Figure 2. Stationary Diffuser Hung from Eyebolts in Ceiling

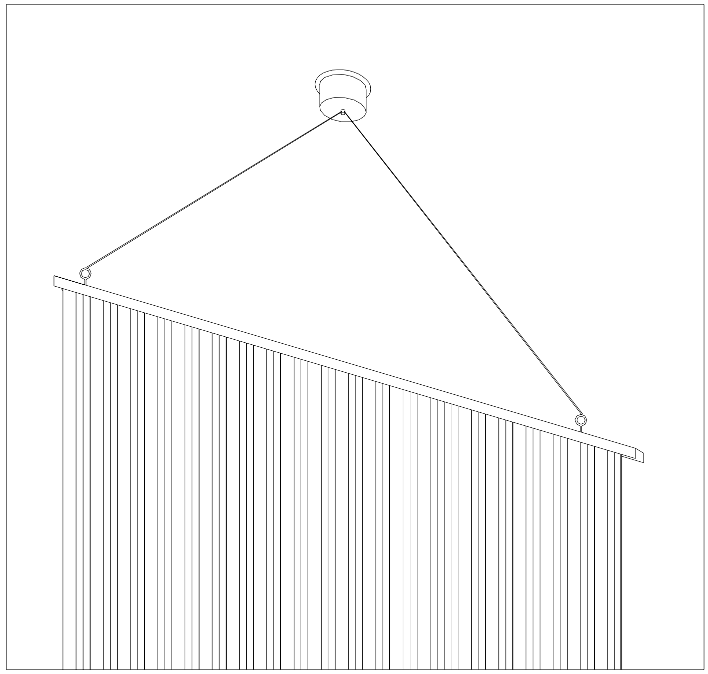

Figure 3. Rotating Diffuser Hung from Disco Ball Motor

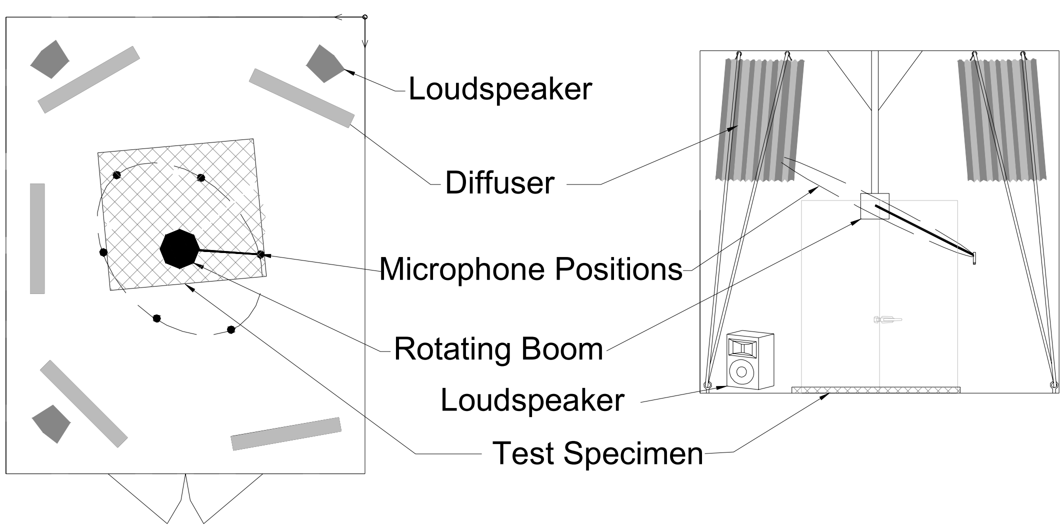

Figure 4. Layout of IAL Reverberation Chamber

Figure 4 depicts the layout of the reverberation chamber, showing the location of the loudspeakers, the rotating microphone, and a representative diffuser configuration. Three speakers sat on the chamber floor and faced three of the chamber's corners. A rotating boom of radius 1.5 m continuously moved the microphone on a circular path through the center of the chamber. Its rotating plane was at an angle of 30 degrees from horizontal and rotated at 1 rpm. A random incidence condenser microphone (Larson Davis 2560) was attached to the end of the boom. A stand alone humidifier was used when necessary to raise the humidity in the room before tests were performed. During tests, it was present in the chamber but never operating.

For absorption testing, a highly absorptive reference specimen was often used. This specimen was comprised of four rectangular pieces of rockwool encased in sheet metal with the top perforated. The dimensions of the four pieces were 1.22 x 1.37 x 0.10 m. When laid together, they formed a 2.44 x 2.74 x 0.10 m specimen, the standard size recommended by ASTM C423. The specimen was A-mounted according to ASTM E-795. The metal casing of the reference specimen served as flashing; the seams between specimen sections and the seams between the specimen and the floor were sealed with duct tape. The locations of all absorption specimens were the same unless otherwise noted. Figure 5 and Table 4 detail this exact position.

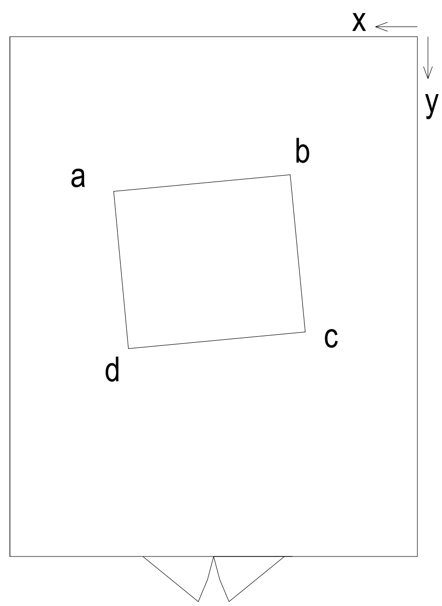

Figure 5. Absorption Specimen Location

Table 4. Location of Corners of 6.69 m^2 Specimen in Chamber (meters)

Coordinate	Corner label a	b	c	d
x	4.69	1.96	1.73	4.47
y	2.38	2.13	4.56	4.82

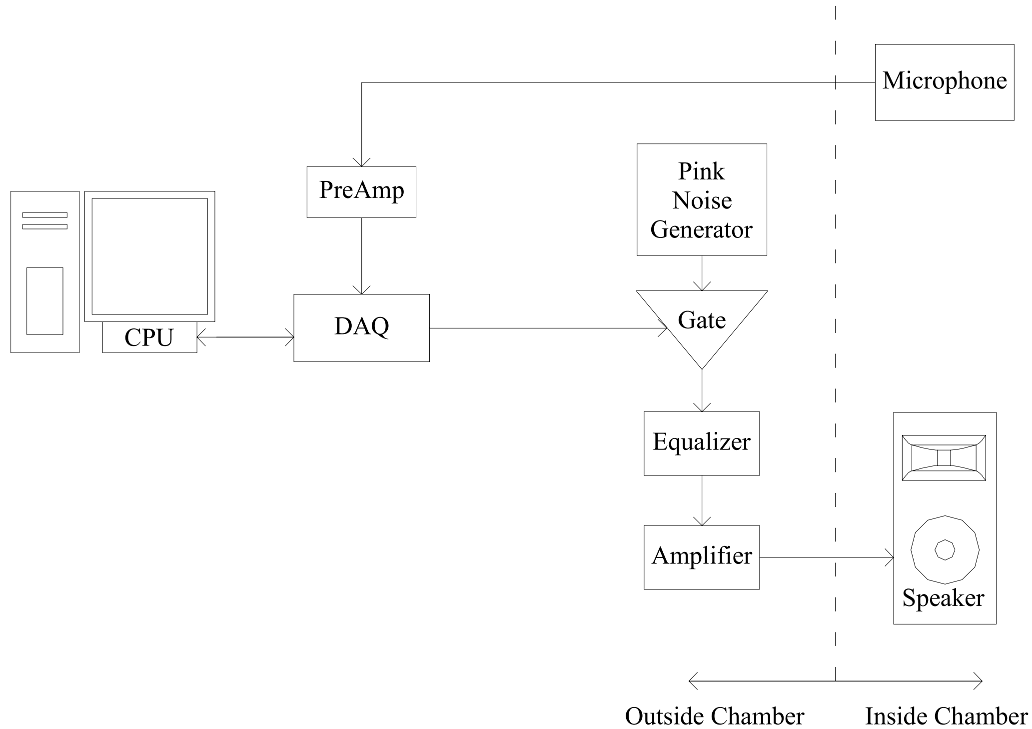

Figure 6. Instrumentation Chain for IAL Reverberation Chamber

Instrumentation for the reverberation chamber included a data acquisition and control system and a sound excitation system, as shown in Figure 6. The data acquisition and control system was run by a Labview Virtual Instrumentation program written by Acoustics Systems of Austin TX, named Spartan. The program ran on a PC in conjunction with a National Instruments PCI-4551 data acquisition card. The noise generation system was also controlled by Spartan. Its components included the computer, sound generator, gate, equalizer, amplifier, and three loudspeakers. The sound generator sent a pink noise signal to the gate, and while the gate simultaneously received a trigger from the controlling computer, it opened, allowing the sound signal to pass to the equalizer, amplifier, and on to the speakers. This setup and instrumentation were used for all testing unless otherwise specified.

4.2. Lab A Setup and Instrumentation

The performance of the IAL reverberation chamber was compared to a similar reverberation chamber, owned by Acoustic Systems. Acoustic Systems of Austin, TX designed and built the IAL reverberation chamber. They have a nearly identical chamber hereafter referred to as Lab A. The dimensions, instrumentation, and microphone traverse system are the same for Lab A and the IAL. The main difference between the two facilities is the surface density of the diffusers used. Lab A uses stationary heavy diffusers, as recommended in ASTM C423 and others, while the IAL chamber was equipped with the lightweight diffusers. To evaluate the performance and diagnose possible problems with the performance of the IAL chamber equipped with lightweight diffusers, comparison testing of sound absorption and sound power specimens were performed in the IAL chamber and Lab A.

4.3. IAL Common Data Acquisition and Analysis Procedures

Sound absorption and sound power testing used common data acquisition systems; the analysis techniques were unique for each type of test. To measure the sound pressure level in the chamber as a function of time, the pressure signal from the microphone was sampled by the NI board which outputted one-third octave band L_{eq} values at 20 ms intervals.

Sound absorption testing required measurement of the decay rate of sound, using the following methodology. The sound generation system produced sound in the chamber for three seconds to allow the sound field to reach steady state. Then, the sound was turned off, and the sound pressure level was recorded during the subsequent decay for five seconds at 20ms intervals. Figure 7, Figure 8, and Figure 9 are plots of representative decay curves for the 100, 1000 and 10000 Hz bands respectively. The variation of the individual decays decreased with increasing frequency, indicating higher temporal variability at low frequencies and a need for more decays for convergence at low frequencies. A total of 160 decays were recorded, unless otherwise stated. Then the decay rate was found by applying linear regression to the average decay curve, according to Equation 10. The absorption area was calculated from Equation 1. The absorption areas with and without the test specimen were compared, and the coefficients were then calculated using Equation 11.

For sound power tests, it was necessary to find the average sound pressure level in the chamber and measure the empty room sound absorption. The average sound pressure level was found by computing the average of the L_{eq}'s, according to Equation 13. The absorption area of the empty room and the average sound pressure level produced by the source were used to calculate the sources sound power according to Equation 13.

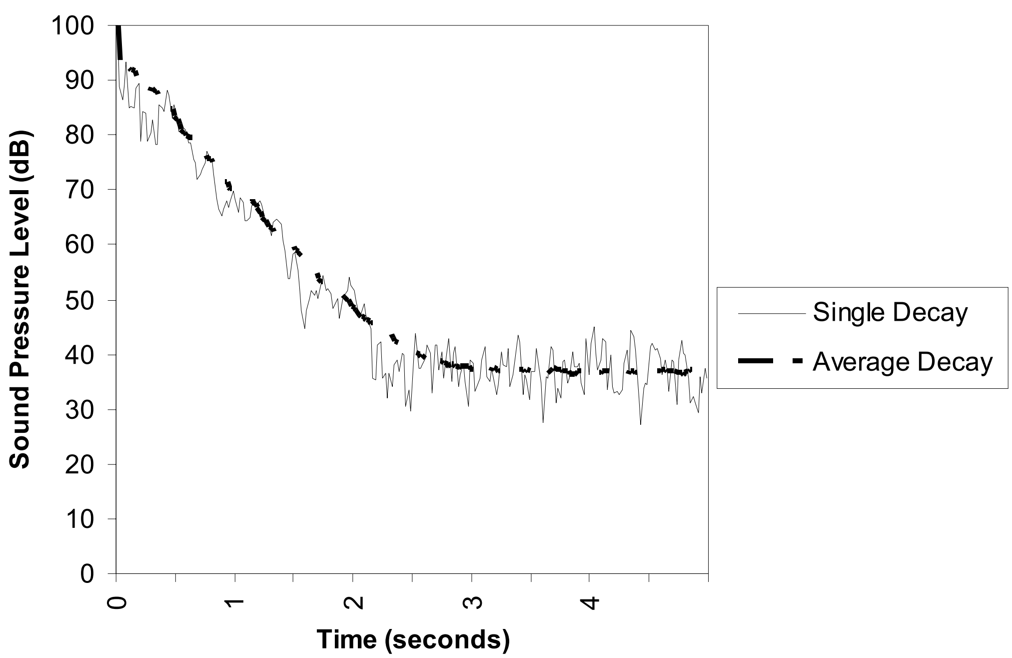

Figure 7. Representative Decays for 100 Hz Band

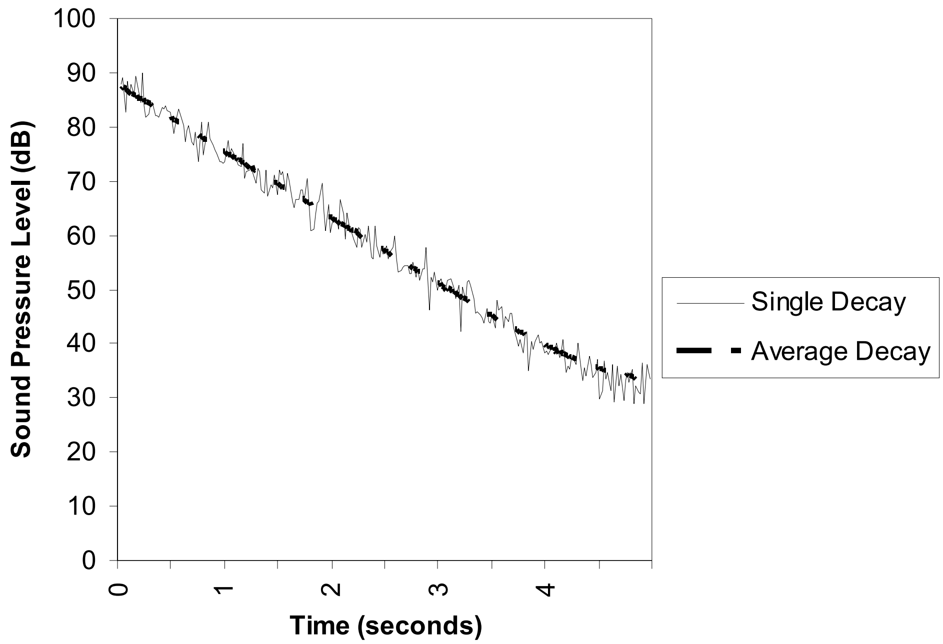

Figure 8. Representative Decays for 1000 Hz Band

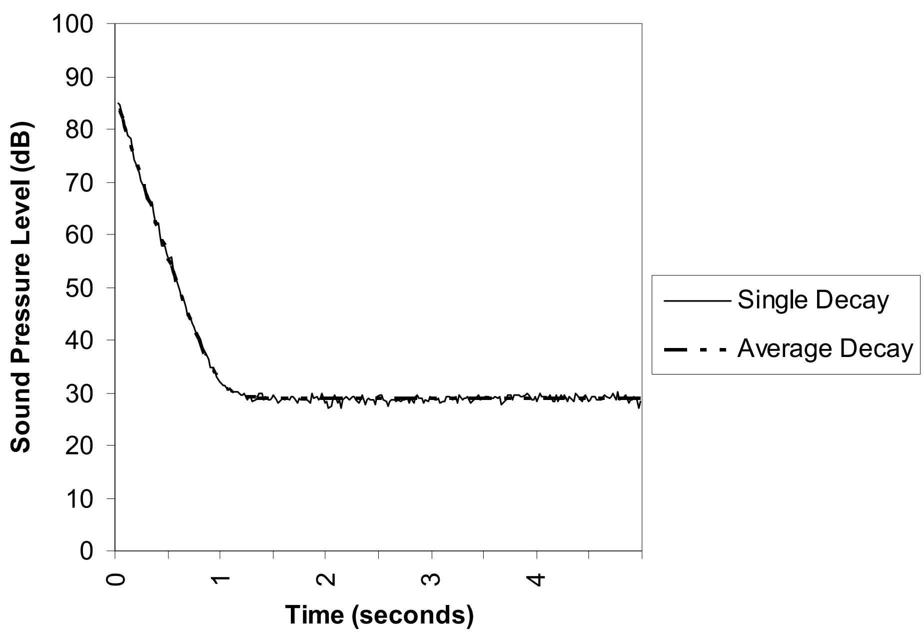

Figure 9. Representative Decays for 10000 Hz Band

5. TESTING OF THE DATA ACQUISITION INSTRUMENT CHAIN AND DATA ANALYSIS TECHNIQUES

In preparing for qualification testing specific to standards for sound absorption and sound power, it was desirable to characterize the data acquisition instrument chain and verify the accuracy of the data acquisition and analysis; the results are described below. Testing of the data acquisition instrument chain included characterizing the latency and decay rate of its electrical components. Verification of the accuracy of the data acquisition and analysis included measurement of decay rates in the IAL chamber with both the IAL instrumentation/analysis techniques and a sound level meter. It also included comparing the measured decay rates of recorded decays to results from Lab A. Finally, the rotation rate of the microphone boom was varied to note its effect on the variation of measurements.

5.1. LATENCY AND DECAY RATE OF INSTRUMENT CHAIN

Tests were conducted to verify that the decay rates measured with the data acquisition system were not affected significantly by the inherent imperfections of the noise generation instrument chain. There is a finite length of time between the noise-off command and the start of the decay in the measured signal. The latency of a piece of instrumentation is defined as the time between the off command and the beginning of the decay in the electrical signal. The decay rate is defined as the slope of the linear portion of the decay curve, computed using linear regression as in Equation 10. Latency and decay rate tests were performed on the instrument chain to determine the latency of the system for IAL records and to verify that the decay rate of the instrument chain was at least three times faster than a decay rate that would be measured in the chamber, as required by ASTM C423-02a.8.4.1Note3.

5.1.1. Setup and Procedure

The latency and decay rate of the data acquisition board was tested by connecting its output directly to its input. Spartan was configured to perform a sound absorption test, consisting of 20 ensembles of single decays. As during all sound absorption tests, Spartan sent a trigger signal for three seconds, then cut the trigger signal off and recorded signal levels in one-third octave bands at 20 ms intervals. This test was repeated with the gate connected in series with the data acquisition board, and their combined latency and decay rates were tested. Then the equalizer was connected in series with the gate and the board, and the three instruments were tested.

5.1.2. Analysis

The latency was found by plotting the twenty individual decays and manually noting when the signal began to decay, i.e. after (x) 20 ms samples the signal began to decay. The signal decay rate was found by computing the slope of the average decay curve, using linear regression as in Equation 10.

To determine whether the decay rate of the instrument chain was fast enough, the fastest expected decay rate in the chamber was determined. Because the chamber is not perfectly rigid, it has an empty room decay rate, d_{empty}, which is small but not negligible. The fastest decay rate occurs with a highly absorptive specimen in the chamber. The addition of a test specimen increases the decay rate of sound in the chamber by an amount proportional to the added absorption area according to Sabine's equation. Theoretically, the maximum added absorption due to a standard 6.69 m^2 specimen would be 6.69 metric Sabines. However, diffraction effects often cause the measured absorption to be significantly higher than the specimen area but not larger than twice.

Thus, it is reasonable to assume that the fastest decay rate in the chamber would result from a specimen with an absorption area of 13.5 metric Sabines. The fastest decay rate for the IAL chamber is then

$$d_{fast} = d_{empty}(f) + 13.5\ Sabines \cdot \frac{340\, m/s}{254\, m^3 \cdot 0.9210} \tag{17}$$

and according to ASTM C423-02a.8.4.1Note3, the decay rate of the instrumentation chain must be greater than three times d_{fast}, where d_{fast} was frequency dependent but nominally 20 dB/s. Therefore, the decay of the instruments must be greater than 60 dB/s.

5.1.3. Results

Latency results are shown in Figure 10. The latency of the data acquisition board is undetectable with the sample rate of 20ms; the signal's decay begins within the first sampling period. The gate introduces some latency at frequencies less than 2500 Hz, but never more than 60 ms. The equalizer introduces latency in the 125, 1600, 2000, and 2500 Hz one-third octave bands, and the latency is no more than 60 ms. Since ASTM C423 advises that the analysis of decay rate not include the first 100 ms and the latency never exceeds 60 ms, the latency of the instrumentation chain does not affect the decay measurements in the chamber.

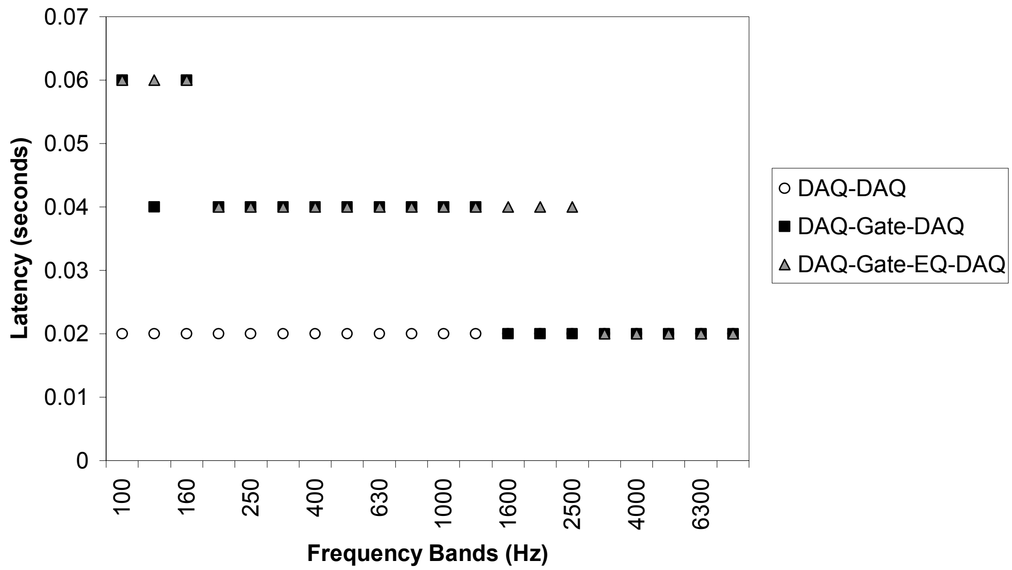

Figure 10. Latency of Instrument Chain

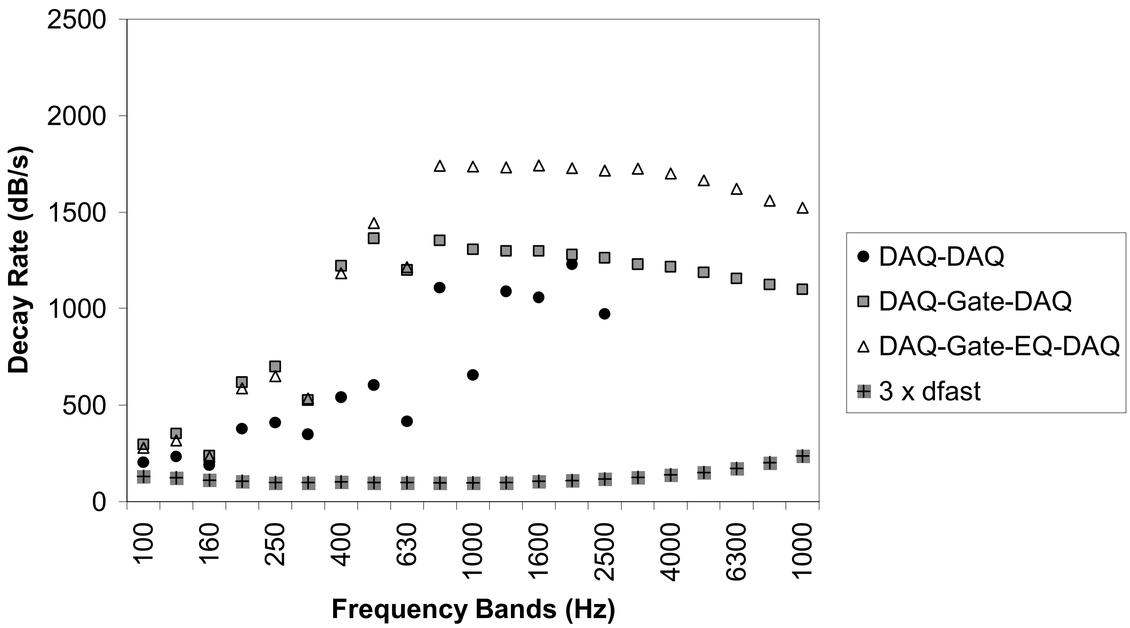

Figure 11. Decay Rates of Instrument Chain

Table 5. Decay Rates of Instrumentation Chain

f	d_{empty}	d_{fast}	DAQ-DAQ	DAQ-Gate-DAQ	DAQ-Gate-EQ-DAQ	DAQ-Gate-EQ-DAQ/d_{fast}
Hz	dB/s	dB/s	dB/s	dB/s	dB/s	
100	23.3	43	204	296	278	6.5
125	21.0	41	233	352	317	7.7
160	17.6	37	188	236	233	6.3
200	15.4	35	376	618	586	16.7
250	13.5	33	408	700	650	19.7
315	13.0	33	348	527	533	16.2
400	14.1	34	539	1220	1182	34.8
500	13.5	33	604	1363	1442	43.7
630	13.1	33	415	1200	1215	36.8
800	12.3	32	1108	1353	1740	54.4
1000	12.3	32	655	1308	1735	54.2
1250	13.2	33	1088	1298	1732	52.5
1600	15.3	35	1057	1297	1743	49.8
2000	16.2	36	1230	1280	1728	48.0
2500	18.8	39	972	1263	1715	44.0
3150	22.1	42		1230	1725	41.1
4000	26.5	46		1218	1700	37.0
5000	30.7	50		1188	1665	33.3
6300	37.6	57		1155	1620	28.4
8000	46.9	67		1125	1560	23.3
10000	59.5	79		1100	1522	19.3

The decay rates of the instrumentation chain are plotted in Figure 11 and tabulated in Table 5. The last column of Table 5 is the ratio of the decay rates for "DAQ-Gate-EQ-DAQ" and d_{fast}. All ratios are greater than three, satisfying the requirements of ASTM C423-02a. The decay rates of the instrument chain at frequencies above 630 Hz were well above the required rate and thus had minimal impact on the measured decay rate of sound in the chamber. The frequency bands of consequence were the 100, 125 and 160 Hz bands. The 160 Hz band had the smallest margin between the decay rate of the instrumentation and d_{fast}, but in this band the ratio was 6.3, far exceeding the requirement of ASTM C423.

Note that the "DAQ-Gate-EQ-DAQ" configuration appears to have a faster decay rate than the "DAQ-Gate-DAQ" configuration at frequencies greater than 630 Hz. In fact, these higher values are a consequence of a difference in background noise levels and a sampling rate that was relatively coarse compared to the signal decay rate. The ambient noise level output from the gate was approximately 40 dB, while the output from the equalizer was approximately 20 dB. The decays from signal to background noise for both the "DAQ-Gate-DAQ" and "DAQ-Gate-EQ-

DAQ" occur over the first two samples (40 ms). Because the difference between signal and background for the "DAQ-Gate-EQ-DAQ" configuration is greater than that for the "DAQ-Gate-DAQ" configuration, the calculated slope for the former is greater than the slope for the latter. This is the reason for the higher decay rates with the equalizer in the instrument chain.

It can be concluded from this testing that the latency and decay rate of the instrumentation have insignificant impacts on the measured decay rate of sound in the IAL chamber. The instrumentation chain is in compliance with ASTM C423 and is fit for measurement of the sound pressure level and sound decay.

5.2. COMPARISON OF DECAY TIMES WITH SOUND LEVEL METER READINGS

To verify the validity of the IAL data acquisition and analysis techniques, a sound level meter, capable of outputting one-third octave band reverberation times, was used to measure the decay of sound in the chamber during simultaneous measurements with Spartan. While Spartan triggered the noise generation and data acquisition systems, the sound level meter (SLM) was manually triggered to measure the reverberation time in the chamber. Its microphone was attached to the traversing microphone. Due to processing and recording time, the SLM measured 15 decays during a Spartan test of 160 decays. For each one-third octave band, the fifteen reverberation times were converted to decay rates and averaged. This procedure was performed with and without the reference specimen. The resulting absorption coefficients were compared with those obtained from the data from Spartan. Figure 12 contains the results with the C423 limits of repeatability (

Table 1) placed around the Spartan results. The SLM data fell within the limits of repeatability in all frequency bands with the exception of the 125, 200, 315 and 5000 Hz bands. There is no general trend for the difference between α from Spartan measurements and SLM measurements. Considering the limited number of measurements made with the SLM, the results do not indicate that there is a systematic problem with the IAL data acquisition and analysis techniques.

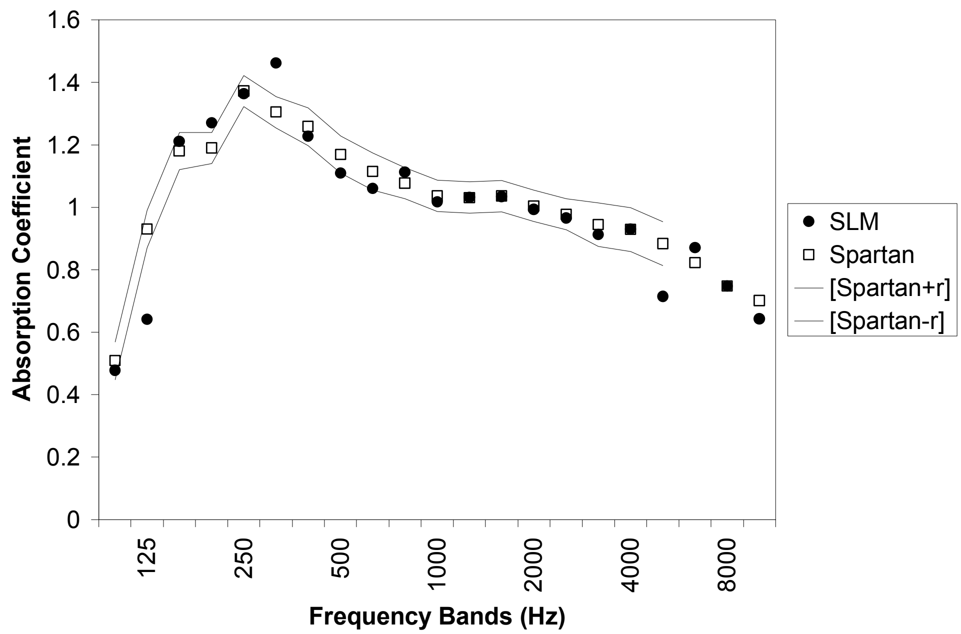

Figure 12. Comparison of Absorption Coefficients Measured with Spartan and Sound Level Meter

5.3. MEASUREMENT OF RECORDED DECAYS

As a way of comparing the identical data acquisition systems of the IAL and Lab A, prerecorded decays were input into the data acquisition systems of each chamber, and the resulting decay rates were compared. Three decaying signals were tested, including one with a rate of about 50 dB/s, one of about 13 dB/s, and one with frequency-dependent rates, representative of reverberation chambers. Figure 13 contains the three measured decay rates for the IAL and Lab A. The "Slow" and "Frequency Dependent" decays were reproducible in the IAL chamber.

However, the measured decay rate of the "Fast" decay was not as reproducible; neither was it as repeatable. This can be attributed to two factors: the small number of data points included in the linear regression and the irregularity in the decay rates. Per ASTM C423, linear regression was performed using Equation 10 over a decay of 25 dB. At a rate of 50 dB/s this included 25 twenty millisecond samples while the slow decay rate of 13 dB/s included about 100 twenty millisecond samples. Thus, it was expected that the fast decay rate measurement would be less repeatable and reproducible than the slow decay rate measurement. Also, within the set of "Fast" prerecorded decays, a few were much faster than the rest. Figure 14 shows three of the prerecorded decays *a*, *b*, and *c*. The measured decay rate of decay *c* was a great source of variation in the data; each attempt to measure the decay rate of this signal would yield a very different result since it occurred over so few samples, explaining the discrepancy between data from Lab A and the IAL. It is noteworthy that with the fast decay rate the IAL measured higher decay rates in the 100 and 125 Hz bands, with a difference of approximately 3.5 dB/s. This discrepancy in decay rate would produce an artificially high absorption coefficient, inflated by about 0.36 in the 100 and 125 Hz bands. During normal sound absorption testing, a fast decay rate such as 50 dB/s would result from the presence of a highly absorptive specimen in the chamber.

As a sanity check, perfect decays with rates of 30, 40, and 50 dB/s were generated in Matlab and analyzed by Spartan. The results are tabulated in Table 6. For these three rates, Spartan measured decay rates within 0.08 dB/s.

It can be concluded that the IAL reverberation chamber reproduced measurements of slow and moderate decay rates; for fast decay rates, results were contradictory. The decay rates of the prerecorded decays measured with Spartan did not match well with Lab A at frequencies below 400 Hz. However, Spartan accurately measured the decay rate of the perfect decays generated in

Matlab. Thus, the discrepancies at low frequencies can be attributed to the inherent variability with fewer data points in the linear regression calculation and the non-uniformity of the prerecorded decays.

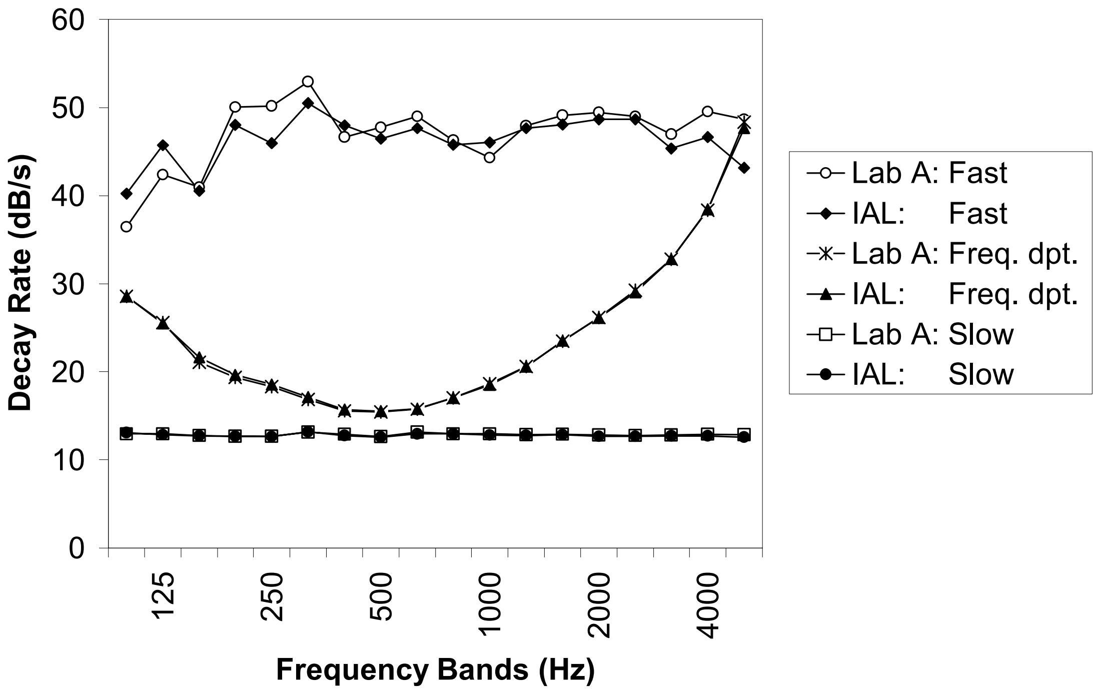

Figure 13. Measurements of Recorded Decays in IAL and Lab A

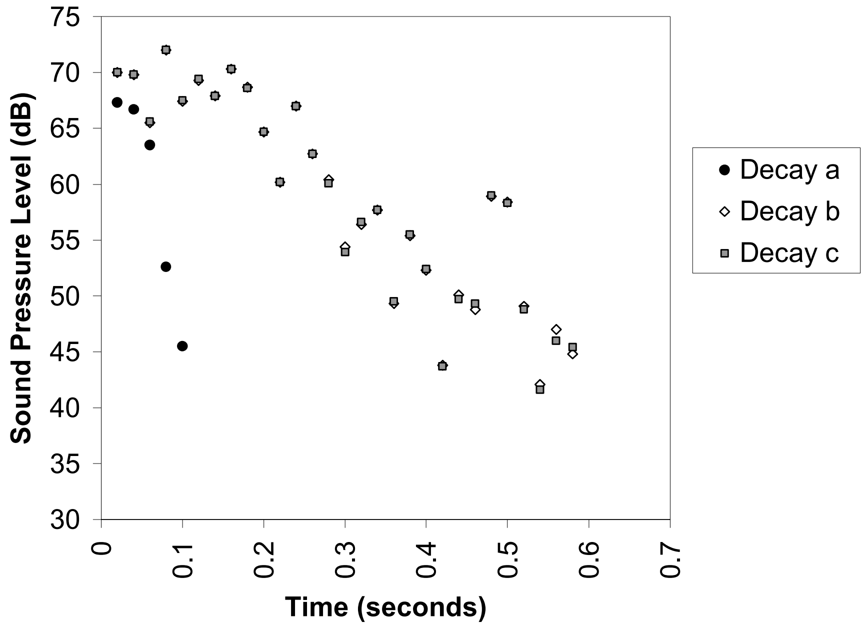

Figure 14. Representative Prerecorded Decays at 100 Hz

Table 6. Measured Decay Rates of Perfect Decays with 100 Hz Signal

Actual dB/s	Measured dB/s
20	19.92
30	30.05
40	39.97
50	50.04

5.4. MICROPHONE TRAVERSING RATE

It was speculated that increasing the microphone traversing rate would result in a more accurate sampling of the sound field in the reverberation chamber. It was thought that if a 20 ms sample of the sound pressure included the average along a longer arc length, it would be a better estimate of the sound pressure in the chamber; this would help to minimize the effect of spatial pressure fluctuations. This hypothesis was tested.

5.4.1. Procedure

The decay rate of the chamber with the reference specimen was tested with the microphone traversing at a rate of 4 revolutions per minute. The variance of this decay rate was compared with the variance of the decay rate with the microphone traversing at 1 revolution per minute, the default rate for all testing in this thesis. Ten sets of forty decays were collected with the microphone traversing at the two rates.

5.4.2. Results

Figure 15 contains the relative standard deviations between the ten decay rates for each traversing rate. The variances between the 10 data points were compared using Levene's test of variance. The resulting p-values are shown in Figure 16. Assuming an α_{risk} of 0.05, there is possibly a statistical difference in the variances in frequency bands centered on the 8000 Hz. If a more lenient α_{risk} value of 0.1 is used, there may be a statistical difference in the 100, 200, and 8000 Hz bands. Based on these findings, there is no clear advantage to the faster traversing rate, and thus, the default rate of 1 rpm was retained.

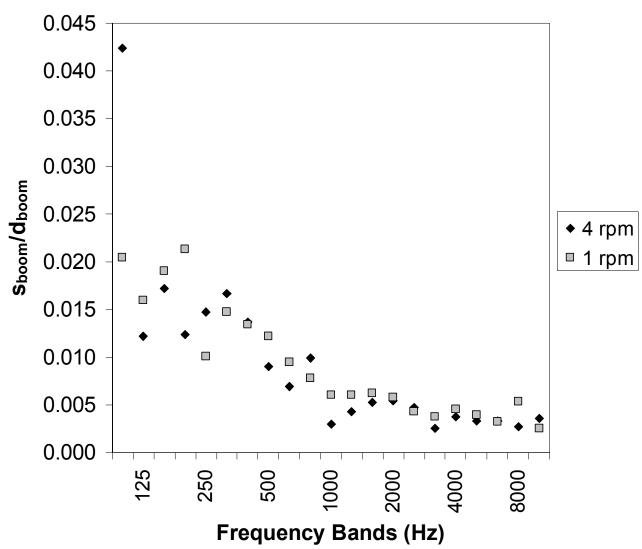

Figure 15. Relative Standard Deviation of Decay Rate for Boom Rates of 1 and 4 rpm

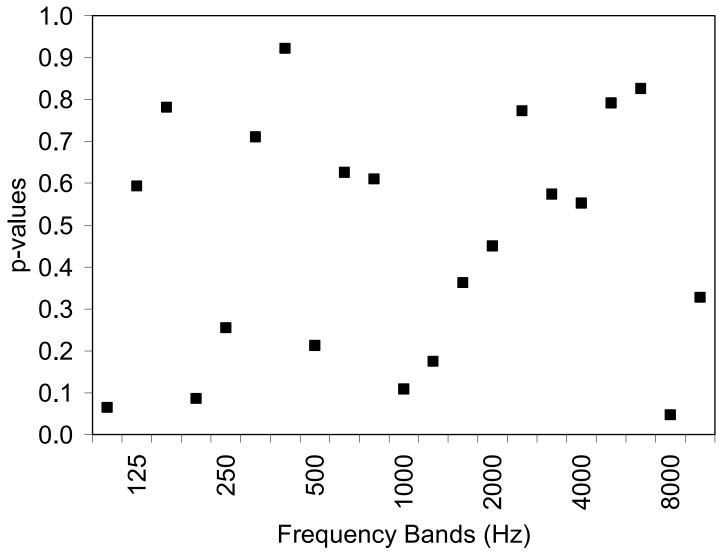

Figure 16. Comparison of Variance in Decay Rate for Boom Rates of 1 and 4 rpm

5.5. Conclusions

Testing the data acquisition system and analysis procedure showed that they were accurate and appropriate for sound absorption testing. The latency and decay rate of the IAL instrumentation chain did not interfere with decay rate measurements. Comparison of absorption measurements with a sound level meter showed that the coefficients calculated using the IAL reverberation chamber technique were within the limits of repeatability except in 4 of the 21 frequency bands. When analyzing recorded decays, the IAL instrument and analysis chain reproduced measurements of slow and moderate decay rates; measurements of fast decays were less repeatable and reproducible. The decay rates measured with Spartan did not match well with Lab A at frequencies below 400 Hz. However, Spartan accurately measured the decay rate of perfect decays to within 0.08 dB/s. These discrepancies at low frequencies can be attributed to the inherent variability with fewer data points in the linear regression calculation and the non-uniformity of the prerecorded decays. The traversing rate of the microphone did not affect the standard deviation of decay rate when varied from 1 to 4 rpm. All instrumentation requirements of ASTM C423 and verification checking of the instrumentation chain indicated that it performed sufficiently well. Thus, the IAL instrument chain and data acquisition techniques were acceptable for testing and it was appropriate to proceed with qualification attempts.

6. ASTM C423 ABSORPTION TESTING

Preparation for sound absorption testing per ASTM C423-02a included determining the appropriate number of lightweight diffusers and quantifying the dependence of the chamber's sound field on the position of the loudspeakers, the test specimen and the microphone position.

6.1. APPENDIX X1 –EXPLORATION OF PERFORMANCE WITH STATIONARY LIGHTWEIGHT DIFFUSERS

The recommendations of ASTM C423 Appendix X1 were outlined in the introduction to this thesis. Briefly, they include testing the absorption of a reference specimen with incremental amounts of diffuser surface area, increasing the surface area of diffusers until the average absorption coefficient reaches a maximum. The configuration with the maximum coefficient should be used for absorption testing. Secondly, the relative standard deviation of decay rate with respect to loudspeaker position should be determined as an indication of the robustness of the reverberation chamber design. High standard deviations indicate that the decay rate is highly dependent on loudspeaker position, and thus, the chamber's sound field is not necessarily diffuse for all speaker locations. The underlying assumptions of the reverberation chamber method of measuring absorption may not be valid for such a chamber. These two tests and their results for the IAL chamber are described below.

6.1.1. Optimum Diffuser Area

6.1.1.1 Experimental Setup

To determine the optimum number of diffusers, the diffusers were added one at a time and the absorption of the reference specimen was measured for each configuration. The diffusers were suspended from the ceiling of the chamber at random orientations. All diffusers were stationary. The microphone boom was continually rotating while tests were conducted.

6.1.1.2 Results

Figure 17 and Figure 18 show the measured absorption coefficient of the reference specimen for each diffuser configuration. Figure 19 indicates that the average absorption coefficient increased with the addition of each diffuser, reaching a maximum with 5 diffusers and thereafter remaining relatively constant. As outlined in C423.X1.2.2.4, the diffuser configuration with the first maximum average sound absorption coefficient is the optimum chamber configuration. Therefore, the chamber was optimized with 5 diffusers, which equates to a diffuser-to-chamber surface area ratio of 19%. For comparison with Davy's results, the diffuser-to-floor surface area ratio was 1.07 compared with his optimum value of 1.25±0.14 [19]. It should be noted that increasing the number of diffusers beyond this point did not affect the measured absorption; the mean coefficient settled at its maximum.

As discussed in the literature review, G.D. Plumb[24] found that above 500 Hz increasing the diffuser surface area increased the average absorption coefficient of a specimen. He also noticed that the diffusers impacted his measured absorption coefficient in the 80 Hz band; this impact was random and showed no trend of increasing absorption with the addition of diffusers. Similarly in the IAL chamber, there was this effect in the 160 and the 250 Hz bands, evident in Figure 17 and Figure 18. It is noteworthy that the diffuser dimensions are approximately 2.13 m x 1.52 m, and sound waves with these wavelengths have frequencies of 161 and 225 Hz. At frequencies greater than 400 Hz, the addition of each diffuser increased the absorption coefficient curve uniformly with respect to frequency until there were four diffusers. The effect of each additional diffuser was dependent on frequency.

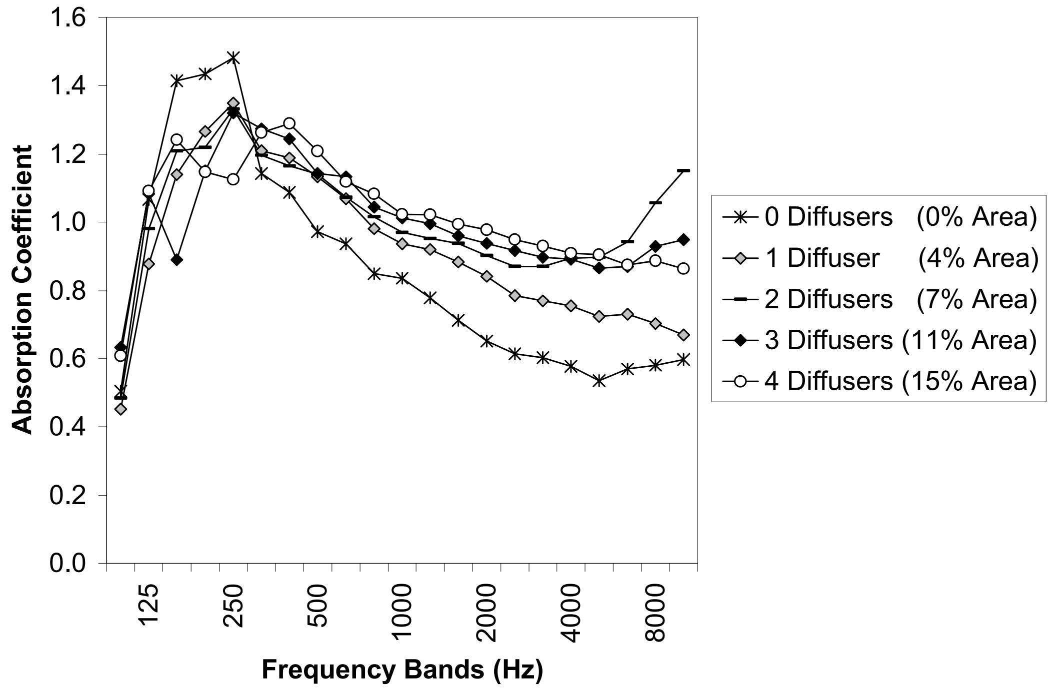

Figure 17. Absorption Coefficient of Reference Sample with Zero to Four Diffusers

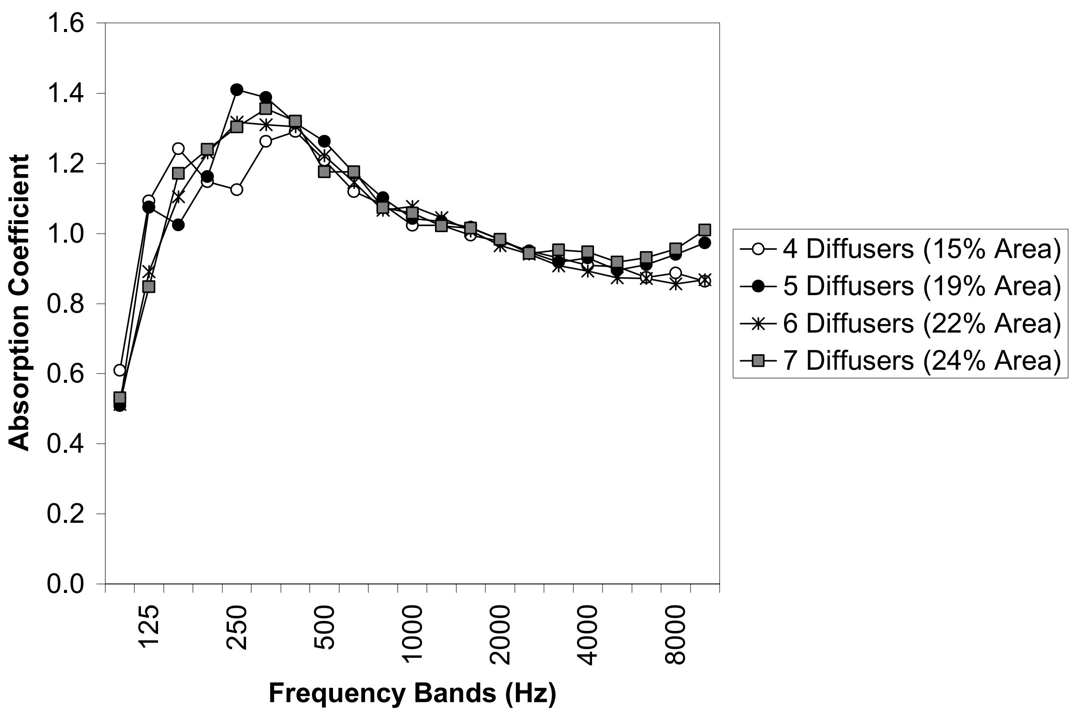

Figure 18. Absorption Coefficient of Reference Sample with Four to Seven Diffusers

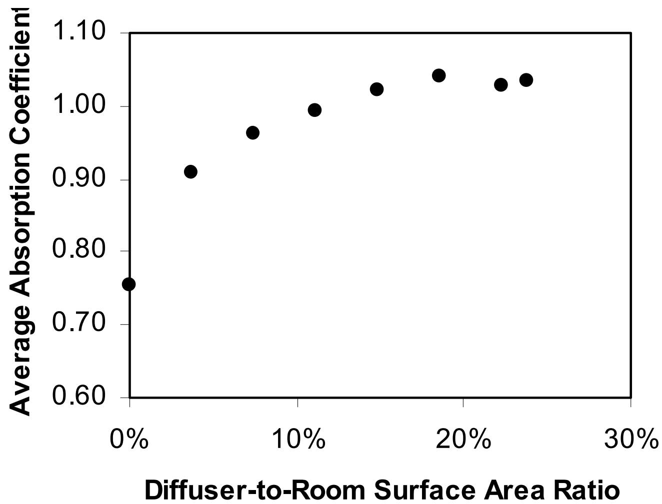

Figure 19. Average Absorption Coefficient for Various Diffuser Configurations

6.1.1.3 Conclusions

The lightweight diffusers had a measurable impact on the performance of the IAL chamber in that they affected the measured absorption coefficient of the reference specimen. Further, a diffuser-to-chamber surface area ratio of 19% was optimal according to ASTM C423.X1.2.2.4, and additional diffusers had little impact on the measured absorption.

6.1.2. Variation of Decay Rate with Loudspeaker Position

6.1.2.1 Experimental Setup

The dependence of the sound field on loudspeaker position was tested by altering the number and combination of loudspeakers. Figure 4 shows the location of the loudspeakers. While their positions were not changed, each combination of one or more loudspeakers gave a unique geometric center; with three speakers, there were seven combinations in all. For this testing, the reference specimen was in the chamber and five stationary diffuser panels were used, for a diffuser to room surface area ratio of 19%.

6.1.2.2 Data Analysis

The decay rates were calculated according to Equation 10 and adjusted for atmospheric conditions per ANSI S1.26. The standard deviation over the seven positions was calculated using Equation 12.

6.1.2.3 Results

Figure 20 shows that the variation of decay rate with loudspeaker position is small. In the lowest four one-third octave bands, the relative standard deviation is approximately 0.035. There is a significant change in variation between the 200 and 250 Hz bands, which is below the Schroeder frequency of the chamber; the low standard deviation in the 250 Hz band is surprising, but not unreasonable. The increase in relative standard deviation at frequencies greater than 2000 Hz can be attributed to atmospheric effects. While the decay rates were adjusted for atmospheric absorption, this adjustment significantly decreases the average decay rate which is the devisor in the relative standard deviation calculation. Because of this adjustment, the relative standard deviation is high in frequency bands above 2000 Hz. Overall, the variation of decay rate with loudspeaker position is small.

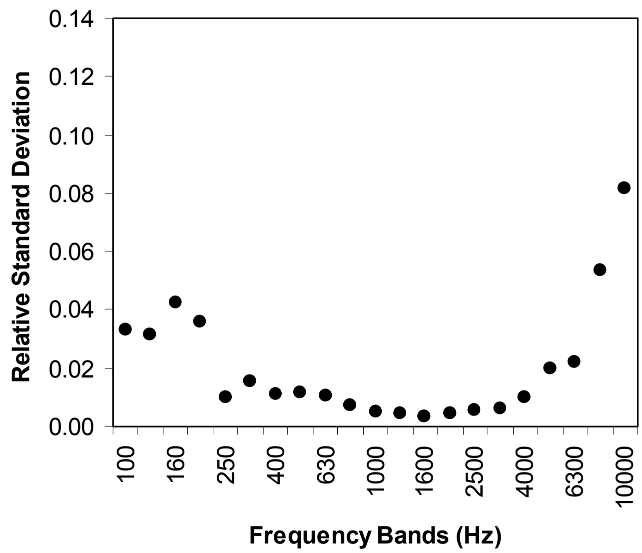

Figure 20. Relative Standard Deviation of Decay Rate with Respect to Speaker Location

6.2. ANNEX A3-QUALIFICATION OF REVERBERATION CHAMBER WITH VARIOUS DIFFUSER CONFIGURATIONS

Qualifying the reverberation chamber per ASTM C423 required demonstration that the decay rate did not vary significantly with microphone position or with specimen position. Qualification testing with respect to microphone position was performed for configurations with: no diffusers, stationary diffusers, stationary and one rotating diffuser, and stationary and two rotating diffusers. A diffuser configuration that yielded sufficiently low relative standard deviation with respect to microphone position was found and used during the qualification testing with respect to specimen position. The setup, analysis procedure, and results are presented below.

6.2.1. Experimental Setups

For the determination of the relative standard deviation of decay rate with microphone position, the microphone was moved to ten discrete positions throughout the chamber, six of which were equally spaced on the original boom path; the additional four positions were randomly spaced throughout the chamber, at least 1.5 m from any other microphone position and at least 0.75 m from any surface of the chamber. The coordinates of the ten microphone positions are tabulated in Table 7. The decay rates were measured at each microphone position for four diffuser configurations; the layout of each configuration is shown in Figure 21. The first configuration, labeled “None”, had no diffusers in the chamber. The second configuration, “Stationary”, had 5 stationary fiberglass diffusers distributed throughout the chamber. The third configuration, “Rotating”, had 6 diffusers in the chamber with the diffuser in the SE corner rotating. Finally, the fourth configuration, “Two Rotating”, had rotating diffusers in the SE and NW corners and the 4 remaining diffusers stationary.

To determine the relative standard deviation of decay rate with respect to specimen position, s_s/d_s, the specimen was tested in three different locations, shown in Figure 22, none of which overlapped by more than 30%. Diffuser configurations, “Stationary” and “Two Rotating” were tested.

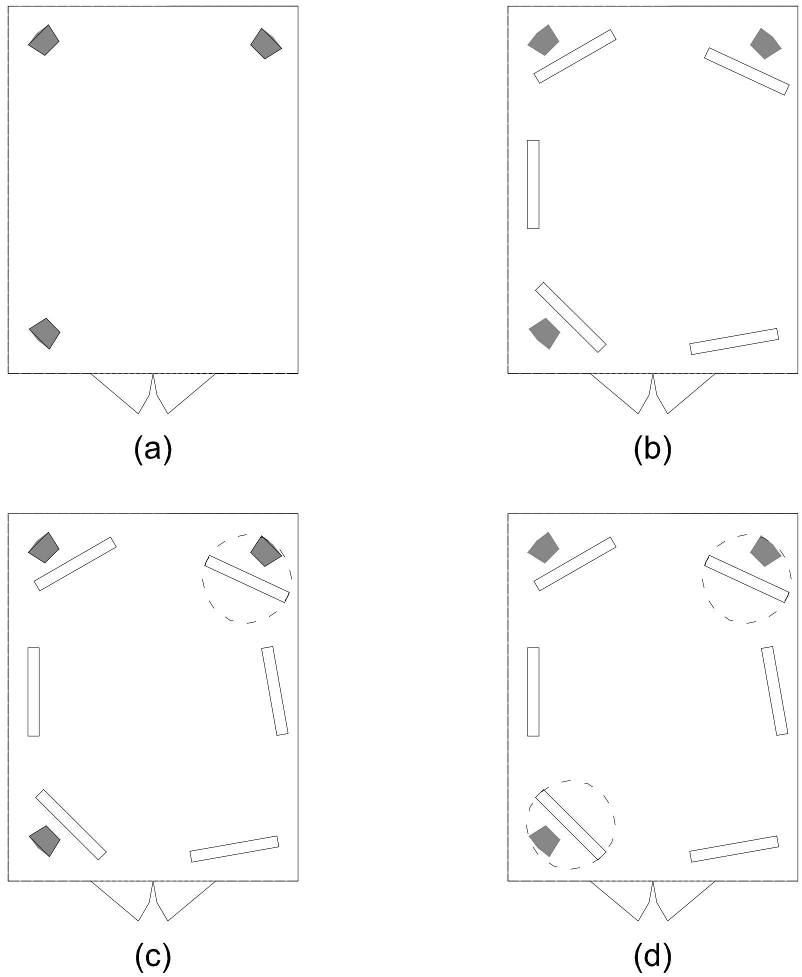

Figure 21. Diffuser Configurations
(a) None; (b) Stationary; (c) One Rotating; (d) Two Rotating

Table 7. Positions of Microphone for C423-A3 Qualification (meters)

	Mic Position Label									
Coordinate	1	2	3	4	5	6	7	8	9	10
x	2.16	1.65	2.67	4.14	4.70	3.68	3.15	3.05	1.22	1.73
y	4.80	3.68	2.67	2.84	4.11	5.18	4.09	2.44	2.39	1.30
z	1.78	2.54	3.10	2.84	2.13	1.60	1.63	0.91	0.89	0.89

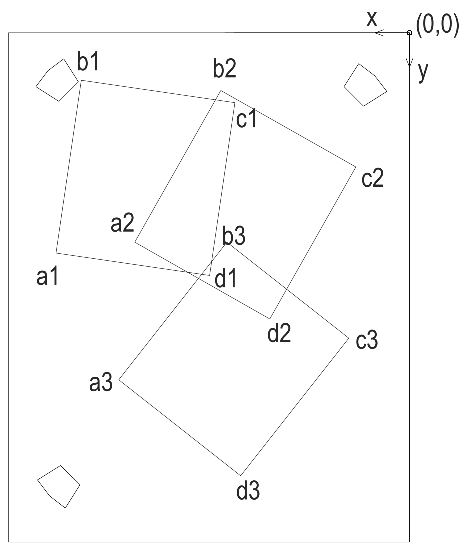

Figure 22. Location of Specimen for C423-A3 Qualification

Table 8. Positions of Specimen for C423-A3 Qualification (meters)

Position Number	Specimen Corner a	b	c	d
1	(5.54, 3.46)	(5.15, 0.75)	(2.74, 1.1)	(3.14, 3.81)
2	(4.32, 3.29)	(2.96, 0.91)	(0.84, 2.11)	(2.19, 4.5)
3	(4.57, 5.45)	(2.87, 3.29)	(0.95, 4.86)	(2.65, 6.96)

(x,y) meters

6.2.2. Analysis

The relative standard deviation of decay rate with respect to microphone position and specimen position were calculated, the decay rates according to Equation 10 and the standard deviations according to Equation 12.

To verify that the diffusers have a statistically significant impact on the standard deviation of decay rate with respect to microphone position, Levene's test was used to compare the variance of decay rate for each diffuser configuration to the variance for the "None" configuration. Levene's test was used instead of an F-test for two reasons. Since it uses the distance of a data point from the median instead of the mean, Levene's test is more robust for smaller samples.

Also, the F-test is based on the assumption that the data is normally distributed, while Levene's test is not [25].

6.2.3. Results

The results show that stationary lightweight diffusers do not significantly affect the standard deviation of decay rate with microphone position. Figure 23 contains the relative standard deviation of decay rate with respect to microphone position for diffuser configurations "None" and "Stationary". With no diffusers in the chamber, the relative standard deviation of decay rate was higher than allowed in ASTM C423 Appendix A3 in frequency bands with center frequencies of 125, 160, 200, 500, and 6300 Hz, the severest violation being in the 160 Hz band. The addition of stationary diffusers decreased the standard deviation of the decay rate in the 160 Hz band significantly, and decreased the standard deviation in the 125 Hz and 200 Hz bands modestly. Above 200 Hz, no definite improvement in the diffusion was noted with the addition of the diffusers. The diffusion with stationary diffusers was not sufficient to meet the requirements of the standard in the 200, 315, 400, 500, and 800 Hz frequency bands. Aside from eliminating the spike in the 160 Hz band, the stationary lightweight diffusers did not have a significant impact on the chamber diffusion. As a side note, the figures in this section have lines connecting the data points for clarity; the lines do not indicate continuous data.

Conversely, rotating lightweight diffusers had significant impact on diffusion. Figure 24 contains the relative standard deviations of decay rate for diffuser configurations "None", "Rotating", and "Two Rotating". The "Rotating" configuration had lower relative standard deviations that "None" in all bands except the 100 Hz band. With the careful selection of five microphone positions, the chamber easily passed the ASTM C423 qualification requirements in all bands. As can be seen in Figure 24, the "Two Rotating" configuration produced relative standard deviations that were lower still in nearly all bands from 125 to 2500 Hz. With the careful selection of five microphone positions, s_m/d_m for each frequency band was well below the allowable. Figure 25 shows that the IAL chamber, equipped with four stationary and two rotating lightweight diffusers, easily meets the diffusion qualification requirements of ASTM C423-02a with respect to microphone position.

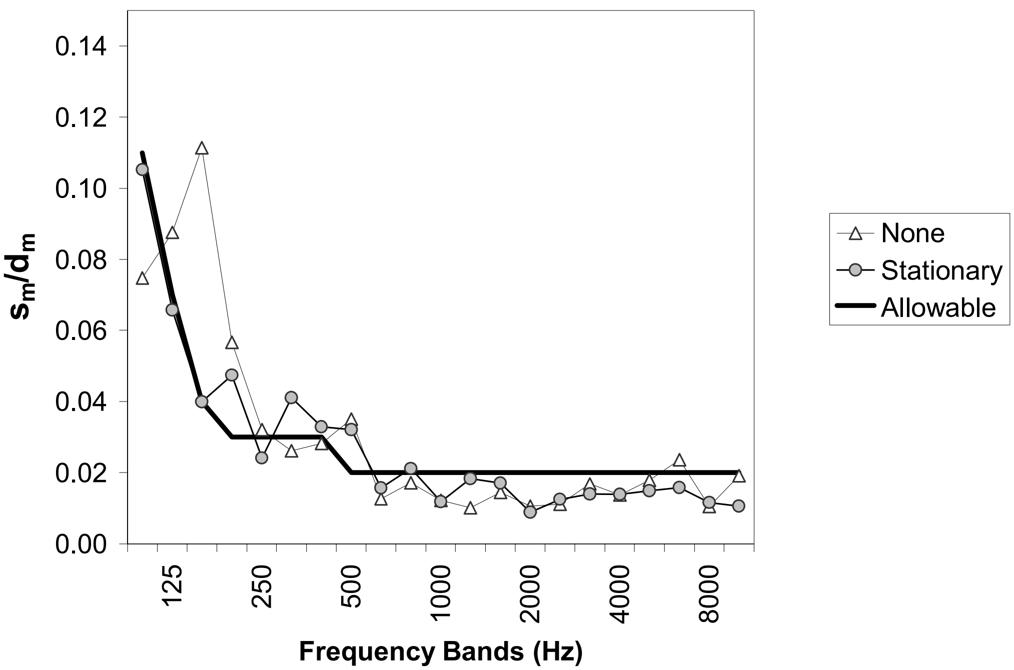

Figure 23. Relative Standard Deviation of Decay Rate with Microphone Position for “None” and “Stationary” Diffuser Configurations

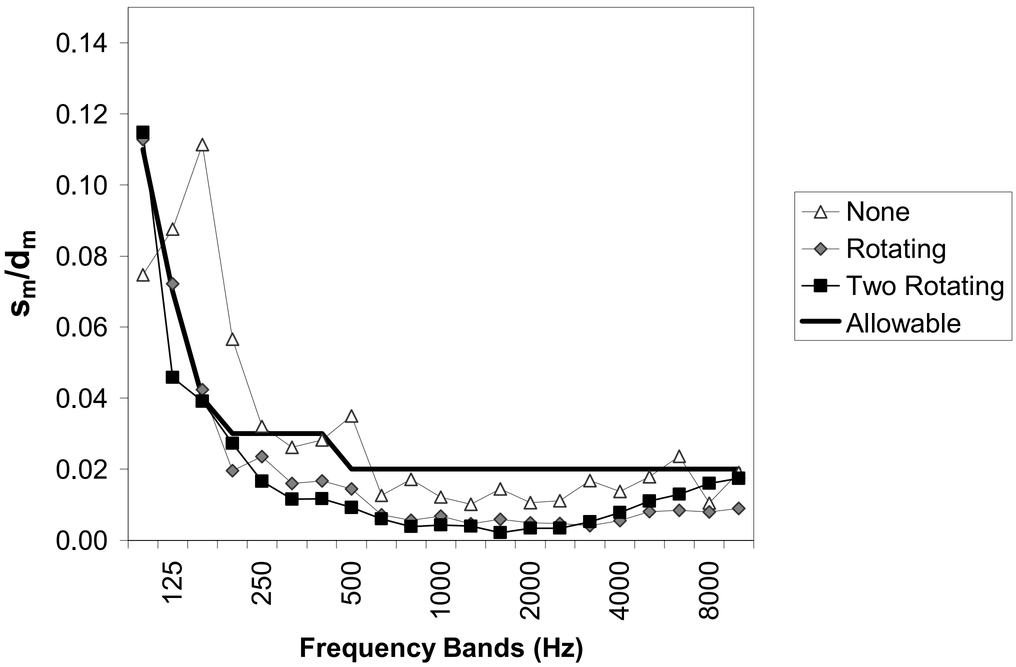

Figure 24. Relative Standard Deviation of Decay Rate with Microphone Position for “None”, “Rotating” and “Two Rotating” Diffuser Configurations

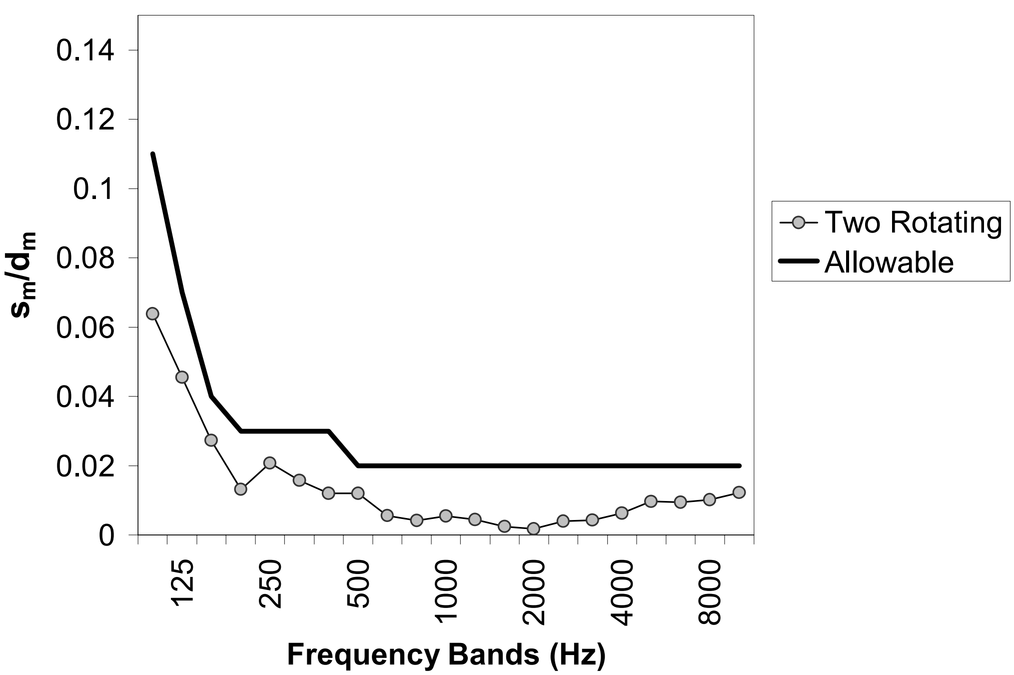

Figure 25. Optimized Relative Standard Deviation of Decay Rate with Microphone Position

Examining Figure 23 and Figure 24, it seems clear that stationary lightweight diffusers had minimal impact on diffusion while rotating lightweight diffusers significantly improved diffusion. This was verified statistically by applying Levene's equality of variance test. The resulting p-values are plotted in Figure 26. Assuming $p<0.05$ was statistically significant, the two rotating diffusers were effective in certain bands, including the 160, 315, 1600, 2000, 2500 Hz bands. However in Figure 26, there is a clear trend of lower p-values for the comparison of "None" with "Rotating" and "Two Rotating" and higher p-values for the comparison of "None" with "Stationary", indicating that the rotating diffusers had a greater effect on diffusion. The p-values for the "None" and "Stationary" comparison were generally around 0.75; only in the 160 Hz band was the p-value less than 0.10, where it was 0.02. For the "None" and "Rotating" comparison, the p-values were less than 0.10 in 8 of 21 bands, and for the "None" and "Two Rotating" comparison, the p-values were less than 0.10 in 14 of 21 bands. Note the large p-values above 2500 Hz; this was due to atmospheric absorption.

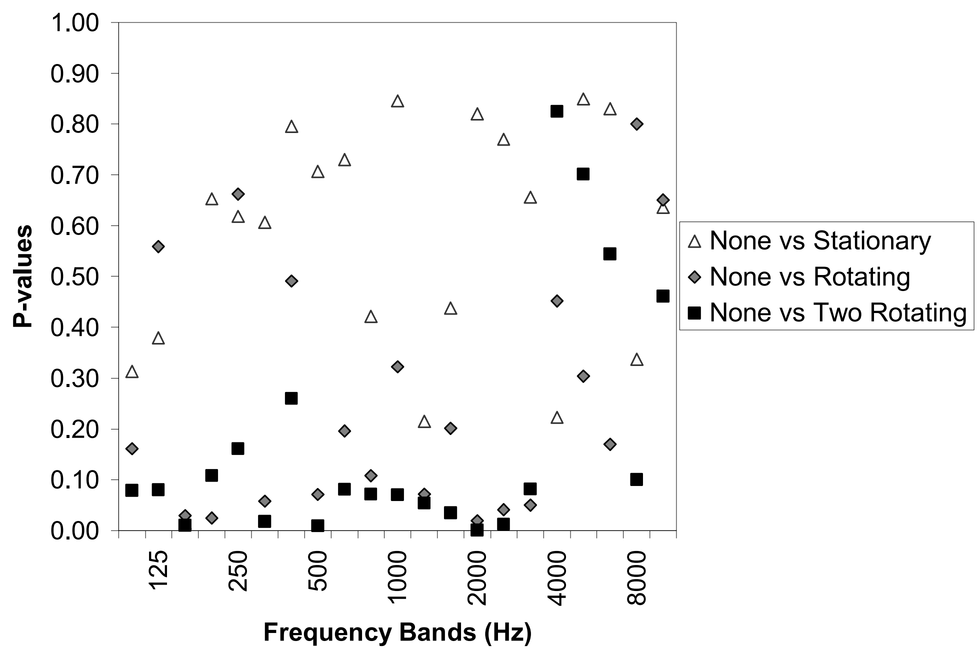

Figure 26. P-values from Levene's Test for Equal Variance

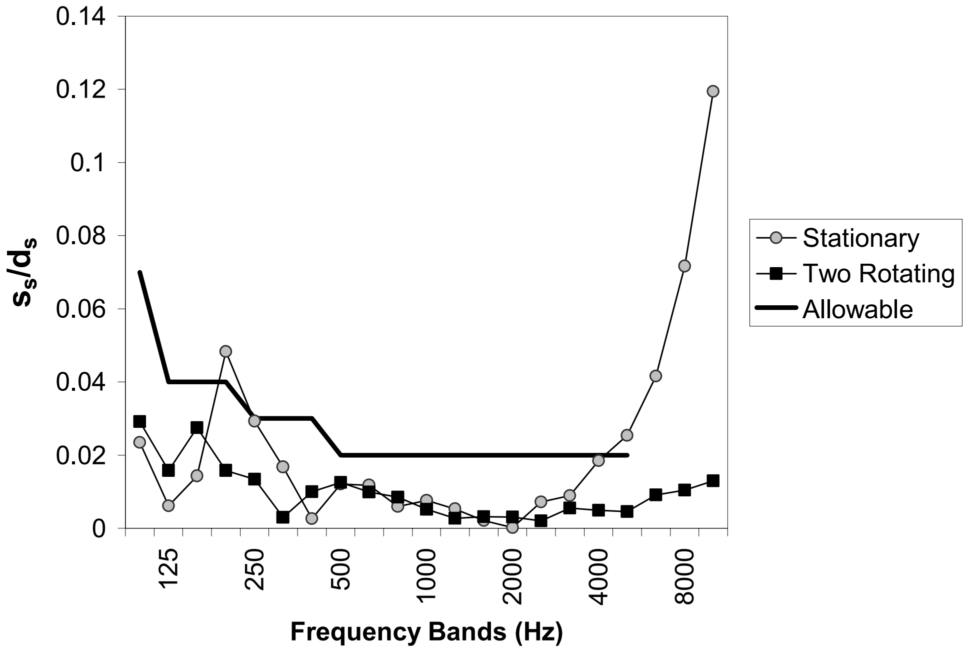

Figure 27. Relative Standard Deviation of Decay Rate with Specimen Position for "Stationary" and "Two Rotating" Diffuser Configurations

Figure 27 depicts the variation of decay rate with sample position, along with the maximum permissible values in C423. Although close to meeting the requirements of the standard with the "Stationary" diffuser configuration, the variation exceeded the permissible levels at frequencies of 200 and 5000 Hz. With the "Two Rotating" diffuser configuration, the variation was less than the allowable in all bands. The variation was noticeably reduced in the 200, 250, and 315 bands, along with bands greater than 4000 Hz. The difference at high frequency is most probably a function of the uniformity of environmental conditions during testing and not the diffusers.

Given the satisfactory qualification of the chamber and test methodology in accordance with C423, results from the IAL chamber can be reported with the expected limits of repeatability and reproducibility of Table 2 of the standard. This is interesting, since the standard requires that the average decay curve include a minimum of 50 decays while a convergence study in the IAL chamber, discussed in Section 6.3.3, showed that for the IAL chamber the average decay curve must include significantly more decays.

As an aside, diffusers are meant to diffuse--but not absorb--sound. The "empty room" (without specimen) decay rates with each of the four diffuser configurations were compared to determine the diffusers' effect on the "empty room" decay. Figure 28 contains the absorption coefficients of the chamber for each diffuser configuration, where the absorption coefficient was the ratio of the absorption area to the total surface area. The total surface area includes the chamber and both sides of the diffusers. Clearly, the diffusers absorbed sound at frequencies of 160 Hz and greater. The addition of the diffusers increased the absorption coefficient on average by about 0.005, less at low frequencies and more at high frequencies. It is noteworthy that the addition of diffusers increased the absorption coefficient of the "empty room" by the same amount, whether rotating or stationary.

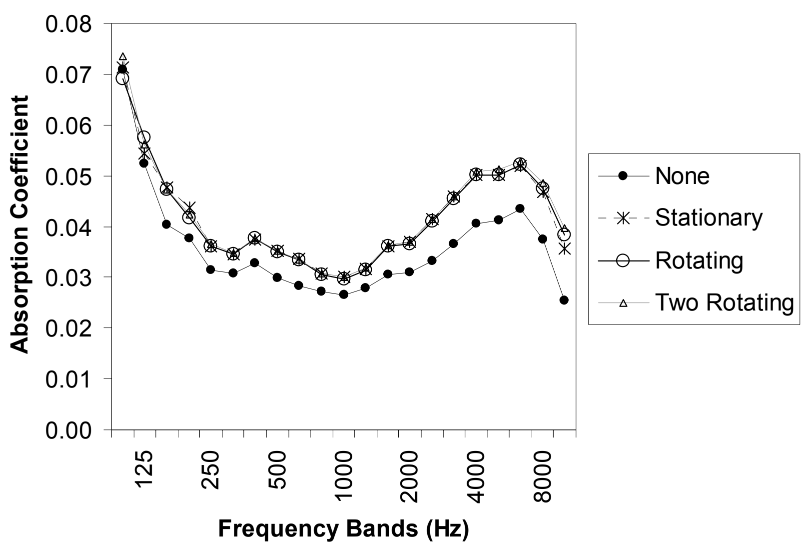

Figure 28. Absorption Coefficient of "Empty Room" for Various Diffuser Configurations

6.2.4. Conclusions

From the C423-A3 qualification testing, the following general conclusions can be drawn. With respect to variation with microphone position, the diffuser configuration with two rotating and four stationary lightweight diffusers produced the most diffuse sound field in the chamber and easily met the requirements of ASTM C423-A3. Further investigation showed that the stationary diffusers only had a statistically significant impact on diffusion in the 160 Hz band, where a p-value of 0.10 was considered significant; two rotating diffusers had a statistically significant impact in 14 of the 21 one-third octave bands. With respect to specimen position, the chamber met the qualification requirements when equipped with the "Two Rotating" diffuser configuration. The absorption coefficient of the "empty room" increased with the addition of the diffusers by about 0.005, whether stationary or rotating.

6.3. SOUND ABSORPTION TESTING METHODS

During the qualification process, the testing methods for sound absorption tests were optimized. Optimization testing included varying the specimen area, and the empty room absorption of the chamber. Also, the precision of the decay rate measurement was determined and optimized by conducting a convergence study; this yielded an appropriate number of decays to be included in the average decay curve to optimize the repeatability of sound absorption coefficient measurements. These tests were performed with the stationary diffuser configuration.

6.3.1. Specimen Area

To observe the effect of specimen area on the absorption coefficient of a specimen, specimen area was varied between 3.34 m^2 and 8.18 m^2 (36 ft^2 to 88 ft^2). Since the absorption coefficient is normalized with respect to the specimen area, Sabine's equation would indicate that the coefficient would not change. However, according to the work by Northwood[9], diffraction effects are highly dependent on the dimensions of the specimen. Therefore, as the dimensions of the specimen change, the severity of the diffraction effects change. So, there may be observable differences in α for different specimen sizes.

6.3.1.1 Setup and Procedure

The reference sample, comprised of four sections with dimensions of 1.22 x 1.37 x 0.10 m, was tested in three configurations, as shown in Figure 29. The surface areas were 3.34 m^2, 4.51m^2, and 6.69 m^2. An insulation board sample was also tested in three configurations, shown in Figure 30; its areas were 6.69 m^2, 7.43 m^2, and 8.18 m^2.

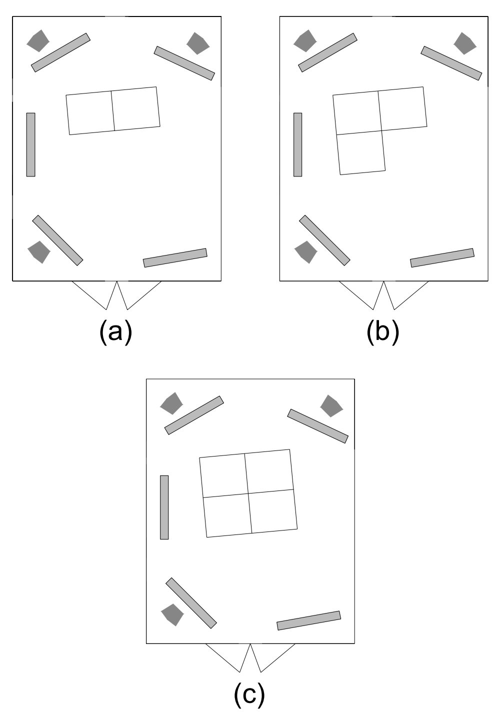

Figure 29. Reference Specimen Positions for Areas of 3.34, 4.51, and 6.69 m^2

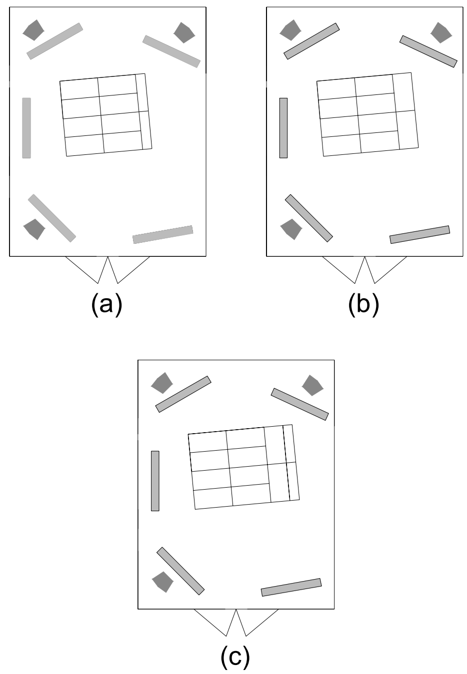

Figure 30. Insulation Board Specimen Layout for Areas of 6.69, 7.43, and 8.18 m^2

6.3.1.2 Results

Figure 31 contains the results of sample area tests on the reference sample. The absorption coefficient varied with the specimen area, especially in the frequency bands from 200 to 400 Hz. Also, there were some differences at high frequencies. Overall, the smaller specimens had higher absorption coefficients than the larger specimens. This is predicted by Northwood, et al. in their work from 1959[9], due to diffraction effects.

Increasing the area of the insulation board specimen had minimal effect on the measured absorption, as can be seen in Figure 32. The variation in the absorption coefficient was within the repeatability interval of a typical reverberation chamber, provided in ASTM C423 Table 2. It can be concluded that sample size does not significantly affect absorption measurements in the IAL chamber if the area is between 6.7 and 8.2 m^2 and the specimen absorption coefficient at frequencies less than 250 Hz is significantly less than 1. Also, absorption measurements are biased if the specimen is smaller than 6.7 m^2 and highly absorptive, i.e. α greater than 1 at frequencies greater than 160 Hz.

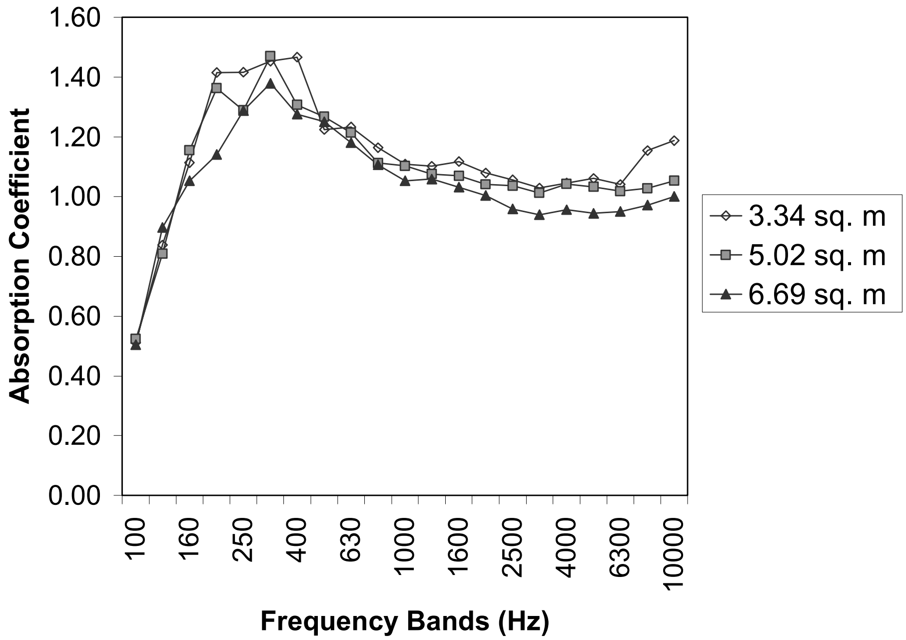

Figure 31. Absorption Coefficients of Reference Specimen for Different Sample Areas

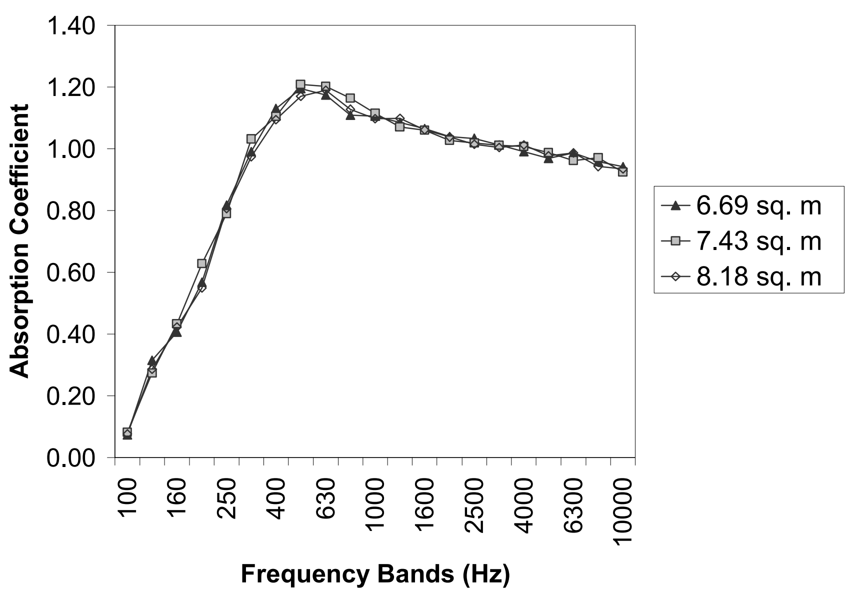

Figure 32. Absorption Coefficients for Round Robin Insulation Board Specimen for Different Sample Areas

6.3.2. Added Absorption

Another optimization test involved adding absorption to the IAL chamber to access its effect on the measured absorption of a specimen. The IAL reverberation chamber is acoustically harder than the reverberation chamber in Lab A and harder than most reverberation chambers at low frequencies. A highly absorptive specimen placed in a hard room would greatly disrupt the diffuseness in the sound field, making it non-uniform. It was thought that the impact of a highly absorptive specimen on the sound field in the IAL chamber would be more severe than in other softer chambers. Thus, the assumptions upon which Sabine's equation is based, namely that the specimen does not significantly affect the diffuseness of the sound field, would be less valid for the IAL chamber. If the "empty room" absorption of the chamber were increased, the change in the room's absorption would be less severe with the addition of the specimen. Thus, it was hypothesized that increasing the absorption of the chamber would change the results of sound absorption tests.

6.3.2.1 Procedure

To test this hypothesis, loose pieces of fiberglass insulation was placed in the chamber to increase the empty room absorption. Each piece was about 1m x 0.3m x 0.1m, although the thickness varied. The pieces were distributed randomly throughout the chamber, close to the chamber surfaces. For one test, labeled "2 PILES", piles of fiberglass insulation pieces were placed on the floor in the SW and NE corners of the chamber, to act as bass traps. Absorption tests were conducted on the reference sample with the loose insulation present for both the specimen in and specimen out measurements.

6.3.2.2 Results

Loose insulation dispersed throughout the chamber increased the absorption area of the room across all frequency bands. Figure 33 shows the “empty room” absorption areas for the various configurations. The addition of 2, 4, and 8 pieces of insulation caused a uniform increase in the absorption area with respect to frequency bands. All curves in Figure 33 follow the same trend as the empty room; they have a slight increase at 400 Hz, the slight dip around 1000 Hz and the second maximum around 5000 Hz. With 22 pieces of insulation, the absorption curve follows the same general trend, but the increase at 400 Hz is pronounced and the dip at 1000 Hz is small in comparison. With two piles of insulation in two corners of the chamber, the low frequency absorption of the chamber increases significantly; at frequencies above 500 Hz, the effect is similar to the configuration with 4 pieces of insulation.

Figure 34 and Figure 35 contain data that show how the absorption coefficient of the reference specimen changed with the absorption of the room. The addition of 2, 4, and 8 ply of insulation affected the low frequency absorption of the reference specimen but not in a systematic manner. Below 250 Hz, there was random variation in the coefficient, presumably due to the anomalies below the Schroeder frequency. Additionally, at frequency between 400 and 630 Hz, the configuration with 8 pieces of insulation yielded high values for the specimen’s absorption coefficient. The addition of 22 pieces increased the absorption of the reference specimen in the mid bands significantly, and may have decreased the absorption in the 100 and 160 Hz bands. When piles of insulation were placed in chamber corners, the absorption of the specimen in the 100 Hz band was actually reported to be negative and the absorption in the 160 Hz band was greater than with no added insulation. Based on this information, adding insulation did not have a consistent effect on the absorption values with respect to frequency. If there was an impact at low frequency, it was immeasurable due to the great uncertainty in absorption measurements at low frequency.

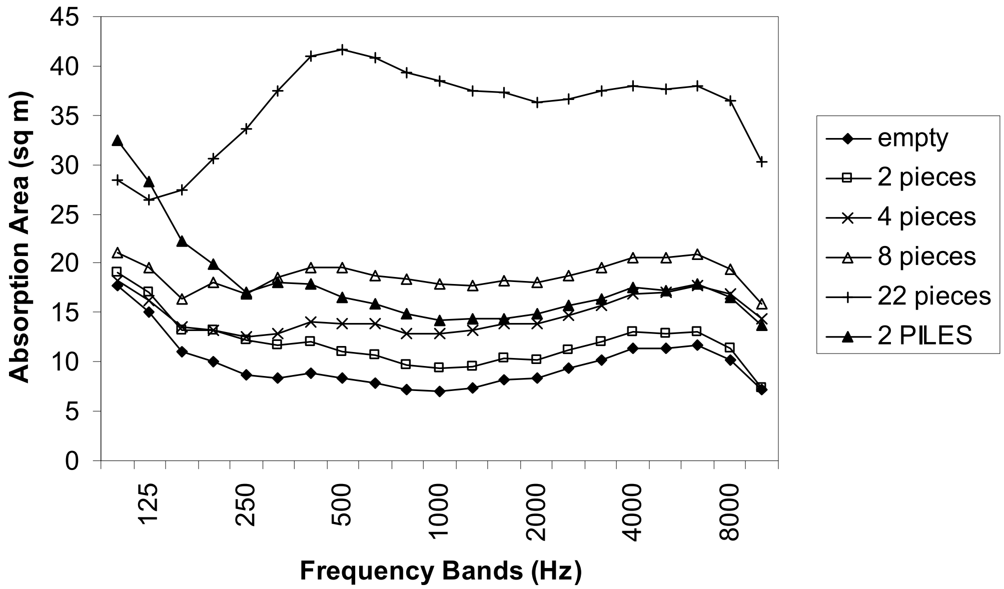

Figure 33. Absorption Area of "Empty Room" with Added Absorption

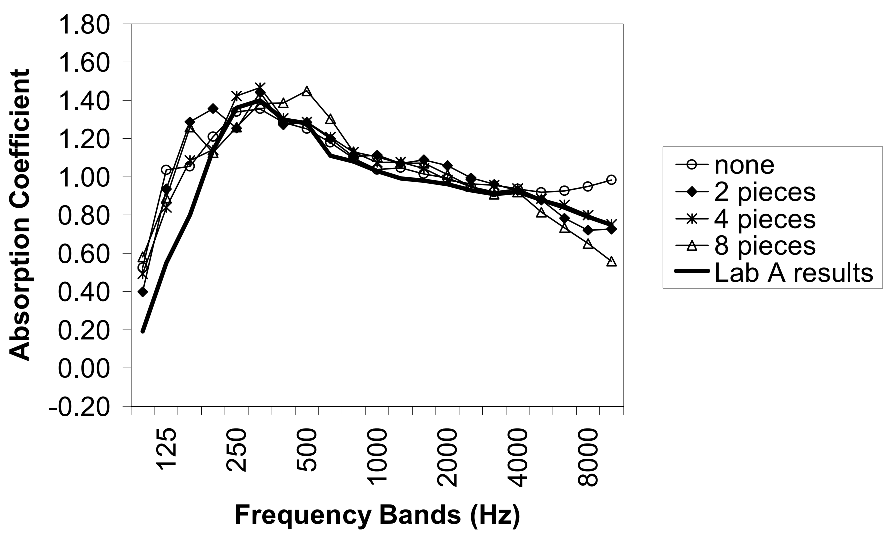

Figure 34. Sound Absorption Coefficient of Reference Sample with Loose Insulation

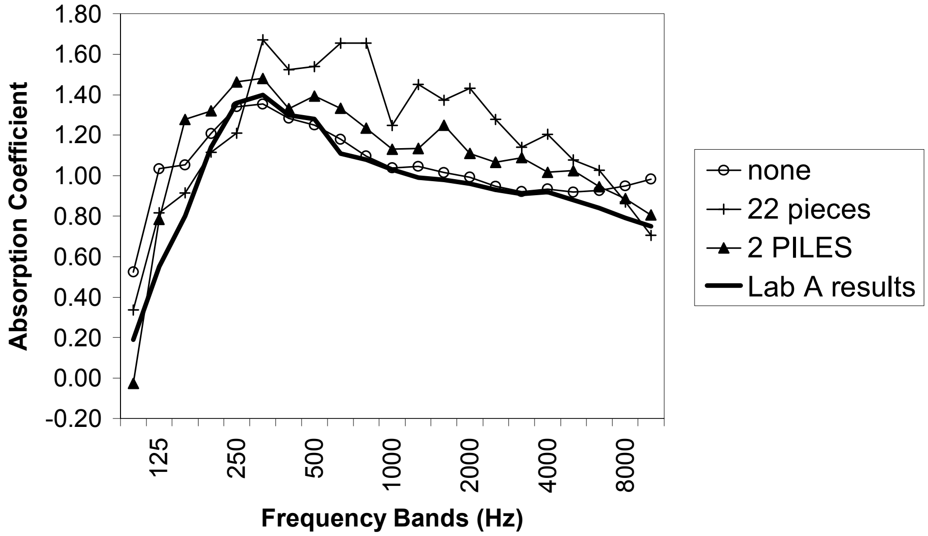

Figure 35. Sound Absorption Coefficient of Reference Sample with Loose Insulation

6.3.3. Absorption Coefficient Convergence Study

The convergence study was conducted to determine the number of decays needed to be included in the average decay curves in order to obtain repeatable measurements of sound absorption, where repeatability is defined as "the value below which the absolute difference between two single test results obtained with the same method on identical test material, under the same conditions may be expected to lie with a probability of 95%" (ASTM C423-02a.13.1.1). ASTM C423 requires that the average decay curves include at least 50 decays. It also provides typical values for the repeatability of absorption measurements conducted per the standard, tabulated in Table 2 of the standard. This repeatability interval includes variation due to imprecision in the measurement of the decay rate, in addition to extraneous variations like: variations due to specimen installation and re-installation, variations in the chamber and specimen over time, transient background noise effects, etc. It is demonstrated below that, for the IAL chamber equipped with lightweight diffusers, significantly more than 50 decays must be averaged to sufficiently reduce the imprecision in the measurement of decay rate. To determine the optimum number, a study was conducted, yielding a relation between the tolerable imprecision in the absorption coefficient and the required number of decays in the average decay curve.

For much of the work in this thesis, the number of decays, i, was 160, collected as 5 ensembles of 32. These were averaged to produce a single average decay curve and from this average curve, linear regression yielded a decay rate. The question under test is whether i can be reduced without adverse consequences or if the repeatability of absorption tests can be significantly improved by increasing i.

In optimizing the number of decays in the average decay curve, length of test is an important factor to consider. It can be approximated as

$$t = t_{test} \cdot i + t_{delay} \cdot \left(\frac{i}{5}\right) + t_{set\ delay} \cdot sets \tag{18}$$

where t= length of test in seconds
t_{test} = 8 seconds
t_{delay} = 5 seconds
$t_{set\ delay}$ = 10 seconds
i = total number of decays in test
$sets$ = number of sets into which the decays are divided

As a reference point, collecting 5 sets of 32 decays, for a total of 160 decays, takes approximately 25 minutes.

When optimizing i, only imprecision in the measurement of decay rate was considered. Extraneous variations, like those listed above, were not considered in this convergence study. It was the aim to reduce the imprecision in the absorption coefficient such that its repeatability interval was at least as tight as that in Table 2 of ASTM C423, as these repeatability limits are meant to encompass extraneous variations as well. The following is a description of the procedure and results of the convergence study conducted on this premise.

6.3.3.1 Procedure

A group of n=1000 individual decays was recorded with the reference specimen in and out of the chamber. Then, average decay curves were calculated from random groups of i individual decays, for i=1…n. Thus, for each frequency band, 1000 decay rates were calculated; the first was the decay rate of one decay, randomly selected from the 1000. The 300th was the decay rate of an average decay curve which was generated from a random group of 300 of the 1000 decays. This procedure was repeated ten times to generate ten average decay curves for every value of i. As i approached 1000, the uniqueness of random combinations of i decays became questionable. It was assumed that for i less than 30% of n, the combinations were random. Data for i greater than 300 was considered insufficiently independent.

The standard deviation of the absorption coefficient was approximated two ways, here after referred to as Method 1 and Method 2. Method 1 involved calculating ten α values, α_{ij}, for each value of i=1…0.3n and j=1…10 by pairing the j^{th} specimen out decay and the j^{th} specimen in decay for a certain value of i, and finding the standard deviation of α_i as the standard deviation between the ten α_{ij}.

Method 2 involved calculating the standard deviation of the ten decay rates for each value of i=1…0.3n and then applying propagation of error to determine the resulting imprecision in the absorption coefficient

$$s_a^2 = \left(g \cdot \frac{s_{SI_i}}{m}\right)^2 + \left(h \cdot \frac{s_{SO_j}}{n}\right)^2 \tag{19}$$

$$a = t \cdot s_a$$

where s_{SIi} = standard deviation of average "specimen in" decay rates
s_{SOj} = standard deviation of average "specimen out" decay rates
$g = h = 0.921*V/Sc$
m = number of average "specimen in" decay rates
n = number of average "specimen out" decay rates
a = imprecision in decay rate measurement with 95% confidence
t = Student's distribution factor: 2.26 for m=n=10

Implicit in this equation is the assumption that the volume of the room and the speed of sound are constants, known to infinite precision. Also, for this study the number of decays included in the average for specimen out and specimen in was the same, i.e. i=j.

Methods 1 and 2 of approximating the imprecision in α were verified by performing ten absorption tests with i=160 and i=200. This verification procedure is Method 3. It was assumed that if the imprecisions were similar for these two values of i, the results were reliable. Ten sets of 160 decays were collected with the reference specimen in and specimen out. From this, ten absorption coefficients were calculated. This was repeated for i=200 decays. The imprecision in α for these values of i were compared with those found using Methods 1 and 2.

6.3.3.2 Results

The results of the analysis show that the repeatability values of C423 Table 2 (or Table 2 of this thesis) are attainable in the IAL chamber for frequencies above 200 Hz. The number of decays required to obtain the repeatabilities of C423 Table 2 are plotted in Figure 36 versus frequency. Frequencies for which there is no data had imprecisions greater than the repeatabilities of C423 for i=300. There is good agreement between Methods 1 and 2, matching within about 8 decays in most frequency bands. The imprecision in α for values of i = 1 to 1000 are tabulated in the appendix in Table and

Table, Methods 1 and 2 respectively.

From Figure 36, it can be concluded that more than 300 decays must be averaged to have the repeatability of the absorption coefficient be comparable to ASTM C423 Table 2 values in all frequency bands. If only frequency bands from 315 to 5000 Hz are considered, the average decay curve must include 225 decays. If only frequency bands from 400 to 5000 Hz are considered, the average decay curve need only include 150 decays.

Figure 37 and Figure 38 show that for *i*=160 and *i*=200 respectively, there is good agreement between Methods 1, 2 and 3. This verified that the analysis techniques of Method 1 and 2 were valid. Note that the lines connecting data are not intended to indicate continuous data, but are used for clarity.

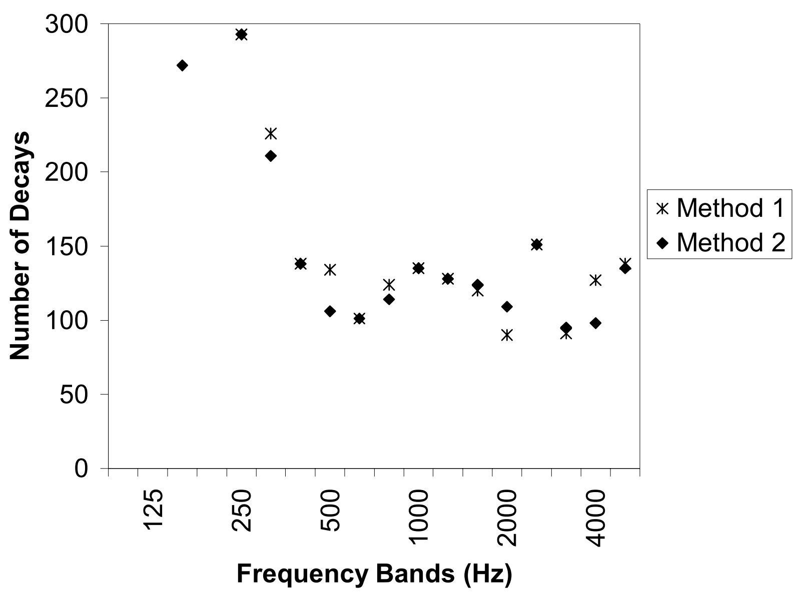

Figure 36. Number of Decays in Average Curve to Attain Repeatability of C423 Table 2

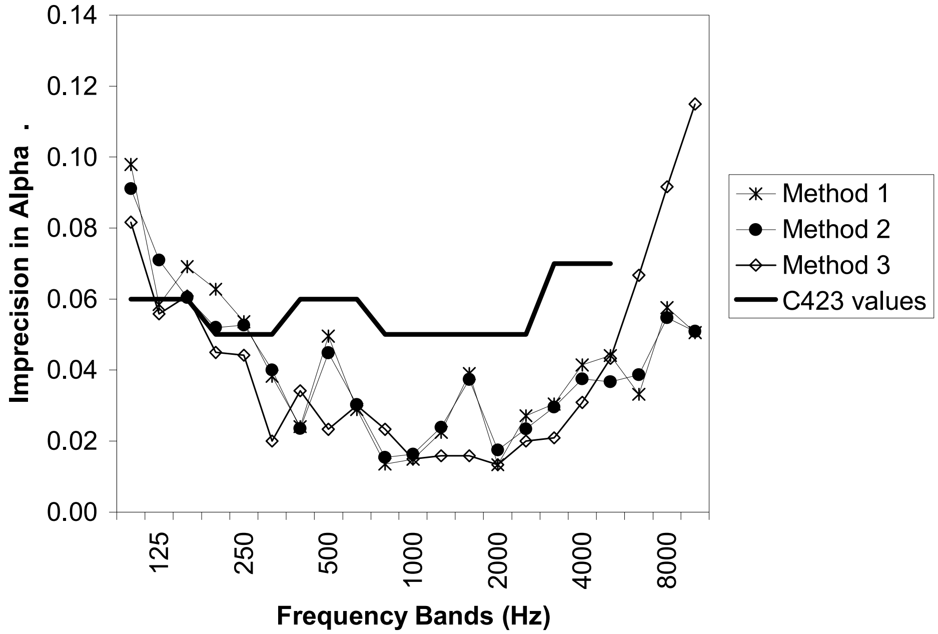

Figure 37. Imprecision in α for Methods 1, 2 and 3 for i=160

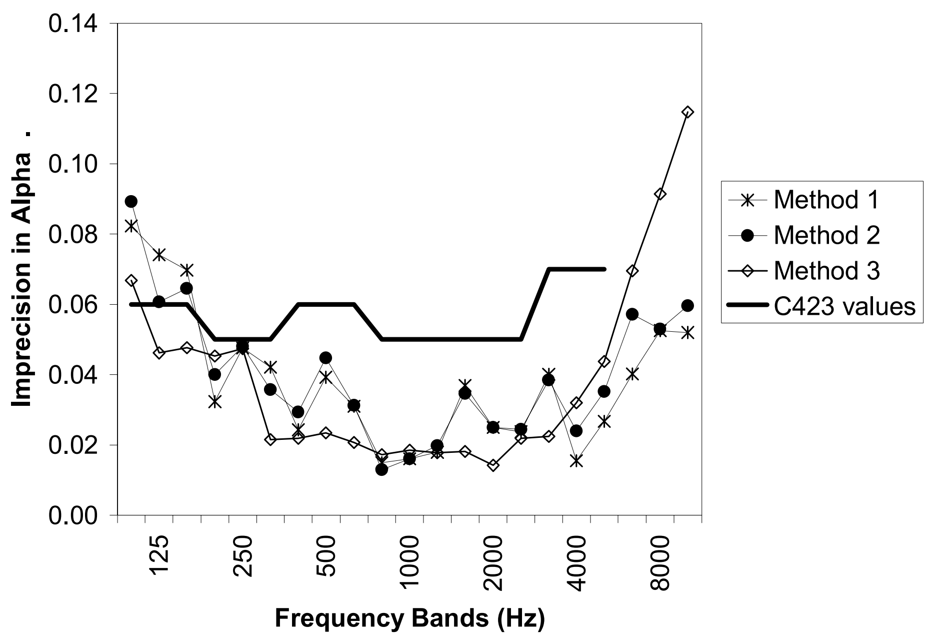

Figure 38. Imprecision in α for Methods 1, 2 and 3 for i =200

6.3.3.3 Conclusions

Based on this data, , the averaging of 300 decays was not sufficient for obtaining repeatabilities comparable to those in ASTM C423 in all frequency bands. It is recommended that the standard procedure for absorption tests in the IAL chamber include 225 decays in its average decay curve; this test would last 35 minutes. Further investigation should be conducted to determine the reason for such large variability at frequencies lower than 315 Hz. Most pertinent is whether more dense diffusers would remedy this problem.

6.4. SOUND ABSORPTION TESTING

Throughout the exploratory testing in the IAL chamber, sound absorption tests were performed to monitor the chamber's performance and compare it with other qualified laboratories. The following are results from absorption testing of the reference specimen and two round robin specimens tested in the IAL chamber. Also included are the results from tests on denim specimens of varying thickness which were tested in two similar facilities.

6.4.1. Reference Specimen

The absorption coefficient of the reference specimen and its repeatability were assessed with two diffuser configurations: "Stationary" and "One Rotating" (Figure 21c). The IAL reference specimen was previously tested in Lab A for comparison. To assess the repeatability of IAL absorption measurements, the reference specimen's absorption was measured four times within a 20 day period; the specimen was removed and reinstalled between each test.

As can be seen from Figure 39, when compared with measurements in Lab A, the absorption coefficients of the reference specimen were within the reproducibility limits from ASTM C423 Table 2, except in the 100, 125 and 160 Hz one-third octave bands. In these bands, the coefficients measured in the IAL were significantly higher than those measured in Lab A.

As for the standard deviations for the four tests, they are summarized in Figure 40. The figure also includes the imprecision in α due to the imprecise measure of decay rate found during the convergence study discussed in Section 6.3.3. The data series “Stationary” and “Two Rotating” represent overall repeatability data from the four absorption tests for the stationary and rotating diffuser configurations, respectively. “Rot-no reinstall” is the variation between ten tests run consecutively with no specimen removal, or equally, the standard deviation in absorption solely due to imprecision in decay rate measurement. As expected, the overall repeatability of α, labeled “Two Rotating”, is greater than the variation due to imprecision in decay rate, “Rot-no reinstall”. The imprecision contributes significantly to the repeatability. Its contribution depends on frequency; it accounts for about 40% at frequencies in the 125 and 250 Hz octave bands, 90% in the 500 and 1000 Hz bands, and 20% in the 4000 Hz band. So in the mid frequencies, 500 and 1000 Hz, the imprecision in decay rate accounts for nearly all of the variation in α. At low frequencies, the variation was due partially to imprecision in decay rate and partially to the inconsistency of the measurements day-to-day at low frequencies. Changes in environmental conditions caused the variation at frequencies greater than 2000 Hz. This data shows that variation in α can be attributed to the imprecision in the measurement of decay rate, almost exclusively in the mid frequencies, but only partially at low and high frequencies.

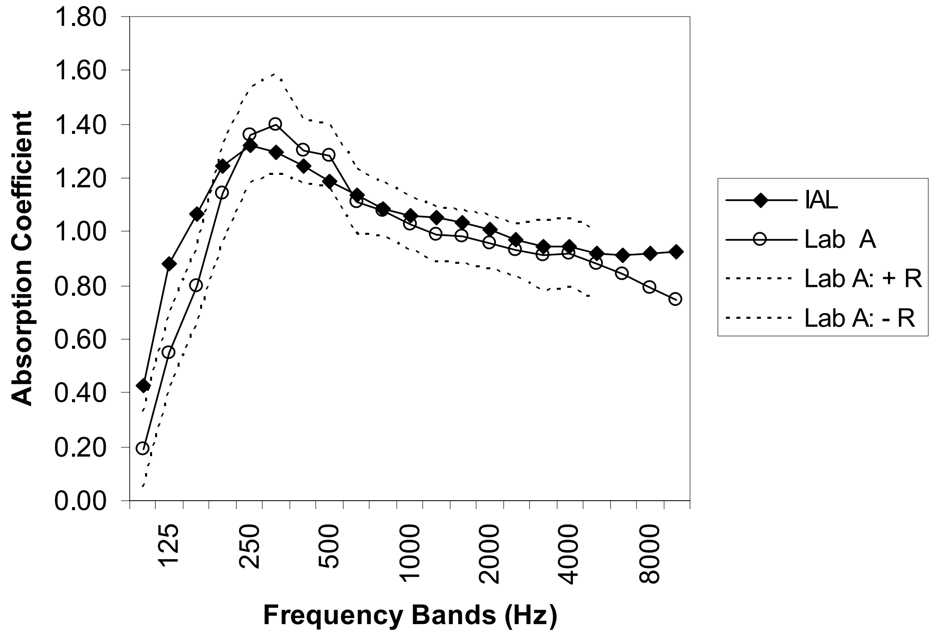

Figure 39. Measured Absorption Coefficient of Reference Specimen: IAL and Lab A

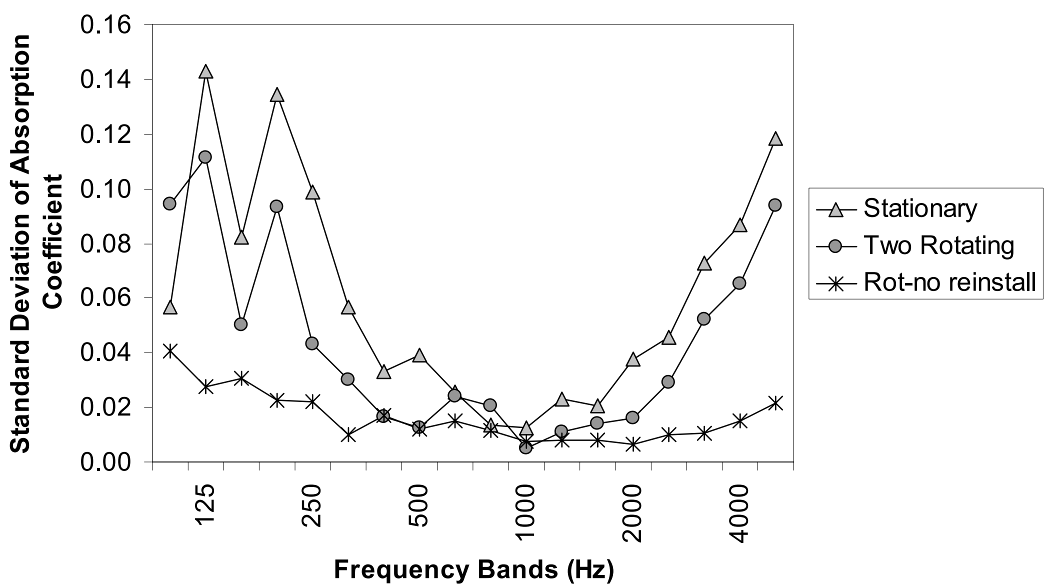

Figure 40. Standard Deviation of Reference Specimen α with "Stationary" and "Two Rotating" Diffuser Configurations and with "Two Rotating" without Reinstalling Specimen Between Tests

6.4.2. ASTM C423 Unpublished Round Robin Testing of Insulation Board

The round robin test on the CertaPro fiberglass insulation board (product number 906583) was reproduced in the IAL chamber to test the chamber's ability to measure sound absorption values within the inter-laboratory reproducibility interval. This test was also used to quantify the repeatability of absorption measurements in the chamber and compare this to the inter-laboratory average.

6.4.2.1 Experimental Setup, Procedure, and Analysis

These tests used the common configuration, instrumentation, and procedures expect for the modifications that are described below. The round-robin test specimen was made of nine pieces of CertaPro fiberglass insulation board. The pieces were laid side-by-side to form a 2.44 m x 2.74 m rectangular specimen (8 x 9 ft), A-mounted according to ASTM E795-00 with flashing and duct tape around its edges. Two diffuser configurations were tested: "Stationary" and "One Rotating".

The specimen was installed, tested, removed, and reinstalled for a total of four complete repetitions. The average absorption coefficient was calculated for each frequency band and test, in addition to the standard deviation of the four test results.

6.4.2.2 Results

As depicted in Figure 41 and Figure 42, the IAL chamber was able to reproduce the absorption values obtained for the specimen during round robin testing; the results exhibited comparable repeatability, as well. Figure 41 contains the mean absorption values from the ASTM round robin test data set, with upper and lower bounds representing a two-standard-deviation confidence interval about the mean. Also shown are the average absorption values obtained in the IAL chamber for both diffuser configurations. The IAL-obtained absorption values fell within the confidence interval in all frequency bands, and did so for each of the four individual tests as well (not shown). Interestingly, only six of the seventeen chambers that participated in the round robin test performed equally as well. The tests in the IAL yielded results fully consistent with those obtained by the other laboratories that participated in the round robin testing, even though the IAL chamber with the "Stationary" diffuser configuration did not conform to C423 diffusion requirements. The standard deviations for the IAL data sets are plotted in Figure 42, with the control bounds from the ASTM round robin tests. The standard deviations of the IAL's measurements were within the control bounds from the round robin test with both diffuser configurations, indicating that the IAL measurements were as repeatable as those obtained in the participating laboratories. Note that with respect to diffuser configuration, the repeatability improved with the rotating diffusers in the 250, 315, and 400 Hz bands and worsened in the 100 and 125 Hz bands.

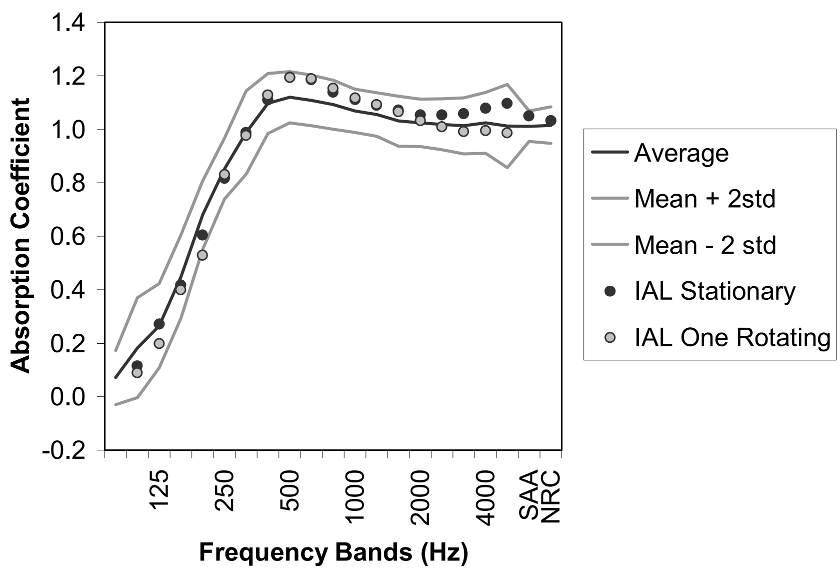

Figure 41. Absorption Coefficient of Insulation Board: Round Robin Results and Results from IAL

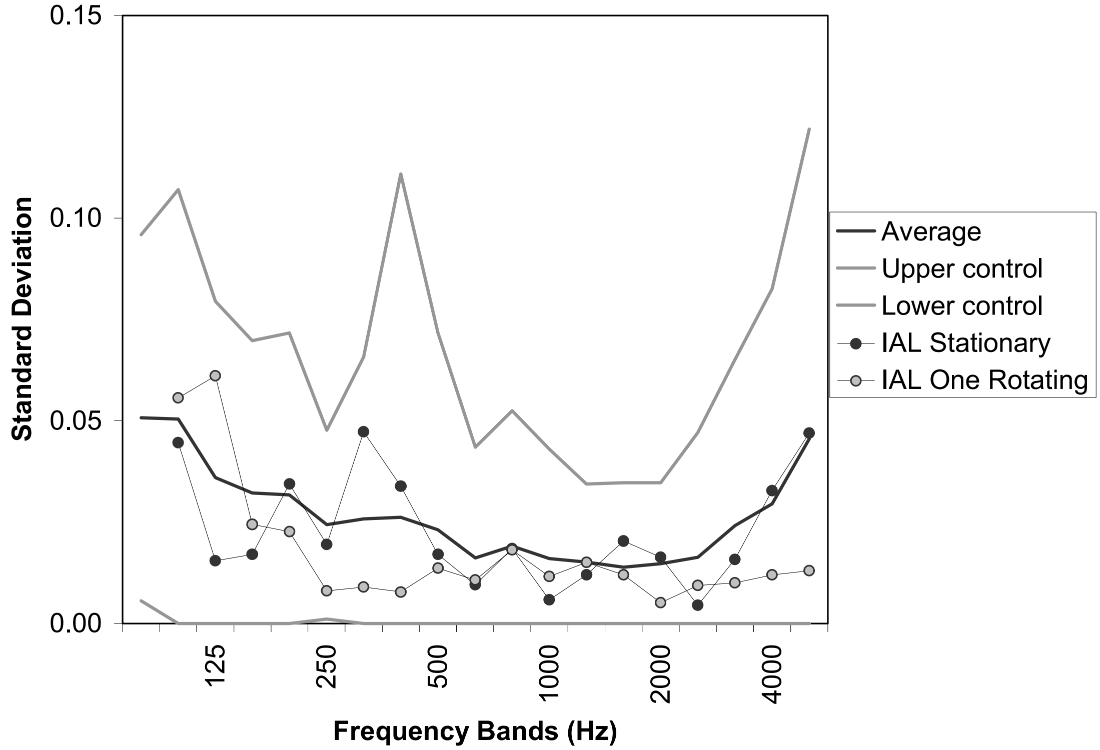

Figure 42. Standard Deviation of α for Insulation Board: Round Robin and IAL results

6.4.2.3 Conclusions

Reproduction of the 2003 ASTM C423 round robin absorption test in the IAL showed that the IAL chamber performed as well as laboratories that participated in the round robin, even when equipped with only stationary diffusers and not yet qualified per ASTM C423. When qualified, equipped with the "One Rotating" diffuser configuration, the performance changed marginally becoming more repeatable in the 250, 315, and 400 Hz frequency bands and less repeatable in the 100 and 125 Hz bands. Thus, qualification per ASTM C423, which requires demonstration of a sound field independent of microphone or specimen position, was not necessary for repeatable and reproducible measurement of a specimen's sound absorption. Also, the use of a rotating diffuser did not have a great effect on the measured absorption coefficient or its repeatability.

6.4.3. NVLAP 1999 Round Robin Absorption Testing of Ceiling Tiles

A second round robin test was repeated in the IAL chamber to compare its performance to the compiled results of the round robin tests. NVLAP organized a round robin test in the summer of 1999 to evaluate the procedures of ASTM C423-90A. Thirteen NVLAP accredited laboratories participated in the study, each testing a specimen of Armstrong World Industries ceiling tiles (product number 1910) with a nominal area of 6.69 m^2.

To repeat the test in the IAL chamber, a newly manufactured specimen of ceiling tile was acquired from Armstrong Industries. An absorption test performed on this material was compared with the results of the NVLAP round robin test to further evaluate the repeatability and reproducibility of the IAL chamber.

6.4.3.1 Experimental Setup

Armstrong performed an ASTM C423 test on a newly-manufactured batch of ceiling tile before sending it to the IAL. Figure 43 contains this data and the average absorption coefficient for the material under test for the NVLAP round robin. Clearly, the absorption of the new material was significantly different from the round robin material in frequency bands from 400 to 800 Hz.

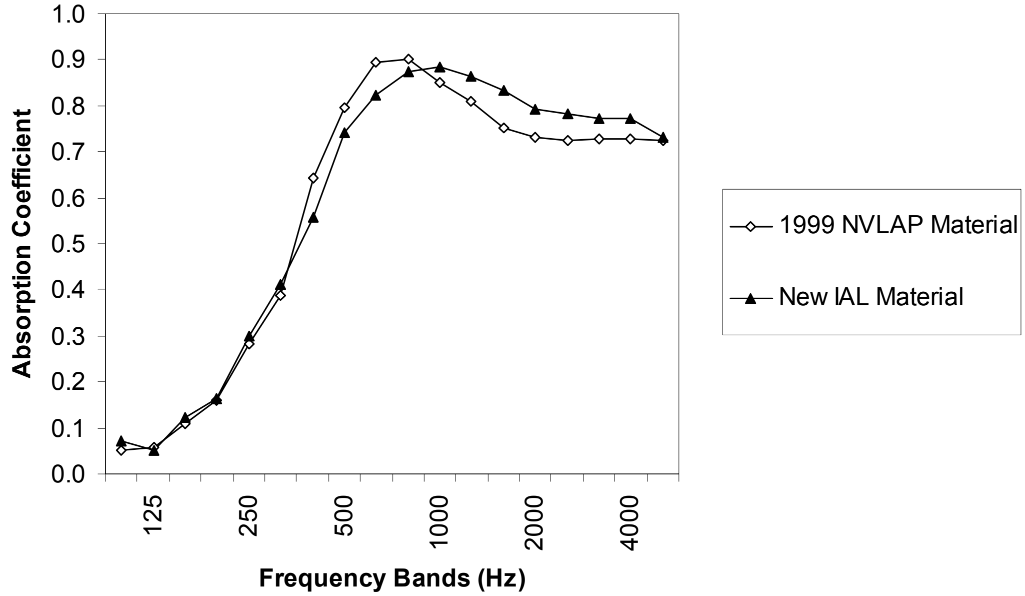

Figure 43. Absorption Coefficients Measured by Armstrong Industries for 1999 NVLAP Material and the New Material to Be Tested in IAL

Twenty pieces of ceiling tile were arranged as shown in Figure 44 to make a specimen with an area of 6.69 m^2. The ceiling tiles were laid out to mate as closely as possible. Lightweight ½" aluminum angle served as the flashing around the perimeter of the specimen, sealed against the ceiling tile surface with masking tape and against the floor of the chamber with duct tape. C423 absorption tests were then conducted. The specimen was tested, removed and reinstalled four times.

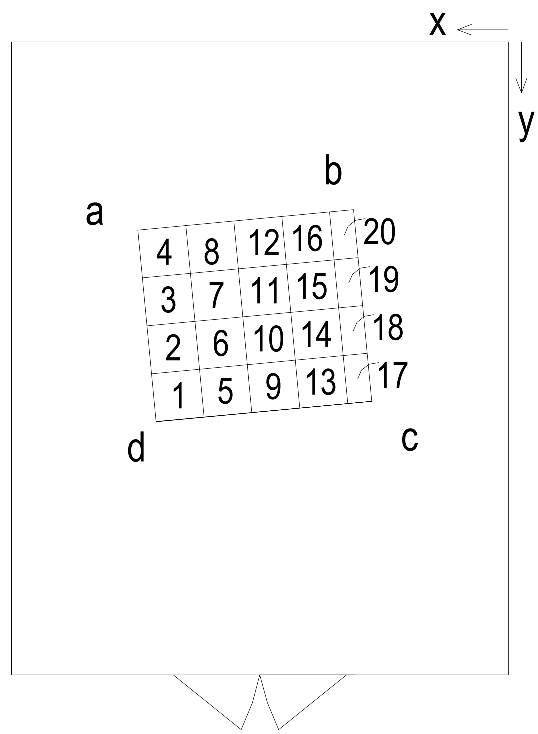

Figure 44. Layout of NVLAP Round Robin Specimen
Note position of *a, b, c*, and *d* were the same as for reference specimen. See Table 4

6.4.3.2 Data Analysis

Average absorption coefficients were taken to be the average of the four tests; these were then compared to those measured by Armstrong Industries. The confidence intervals from the NVLAP round robin results were centered about the absorption values measured by Armstrong for the newly manufactured specimen. The standard deviations of the four tests conducted in the IAL were compared with the average standard deviations from the round robin tests.

6.4.3.3 Results

Figure 45 contains the absorption coefficients of the specimen measured in the IAL and at Armstrong Industries, with the 95% confidence intervals, the width of which was determined during the round robin testing of 1999. The values labeled IAL are the average of the four tests.

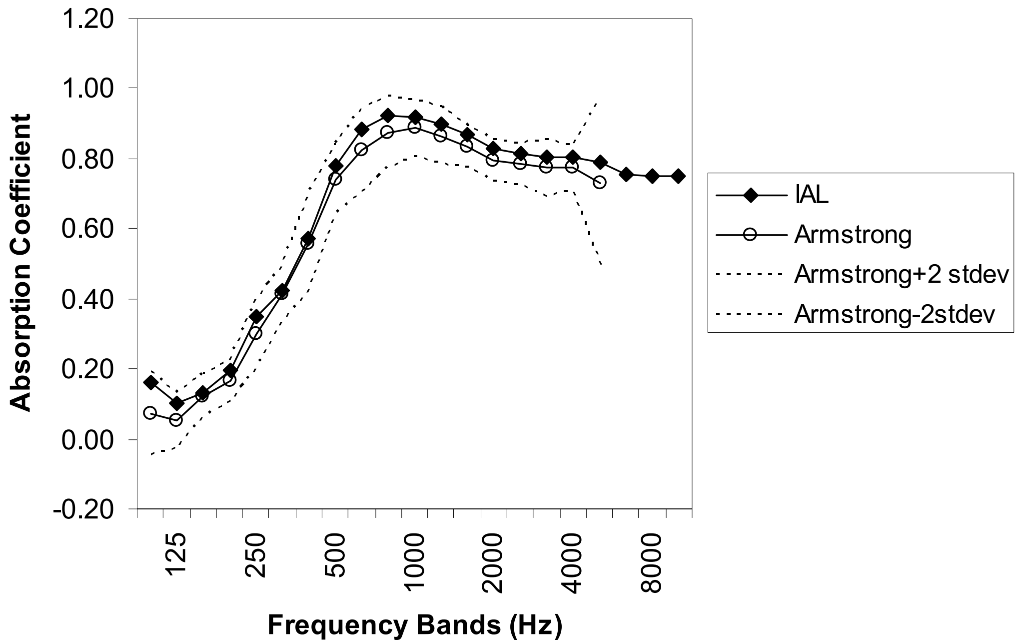

Figure 45. Measured Absorption of New IAL Material at Armstrong Industries and the IAL, with 95% Confidence Intervals from 1999 NVLAP Results

6.4.3.4 Conclusions

All measurements fell within the 95% confidence interval. This shows that the IAL was able to reproduce sound absorption measurements with accuracy comparable to other qualified laboratories. It is noteworthy that the absorption coefficients measured in the IAL were consistently greater than those measured by Armstrong, approximately 0.05 greater.

6.4.4. Denim Specimens

It was observed that measurements of the low frequency absorption of the round robin specimens were repeatable and reproducible in the IAL chamber, but the low frequency absorption of the reference specimen was not repeatable in the 100, 125, 160 Hz bands and was not comparable to Lab A's test results. To further investigate the low frequency, high absorptivity issues in the IAL chamber, specimens of denim batting of varying thickness were tested in the IAL chamber, and two other accredited facilities. Lab A measured the sound absorption coefficient of denim batting of various thicknesses. Note that Lab A has the same dimensions, instrumentation, and microphone traverse system as the IAL but uses heavy diffusers. Also note that Lab A has trouble qualifying for sound absorption measurements at frequencies between 315 and 630 Hz. A second laboratory, referred to as Lab B, is a qualified industrial acoustic laboratory that voluntarily performed absorption tests on the denim specimens for comparison.

6.4.4.1 Experimental Setup

Denim batting specimen thicknesses included 0.0254, 0.0508, 0.0762, 0.1016, and 0.127 m (1", 2", 3", 4", 5"), each with an area of 5.95 m^2 (64 ft^2). Their layout and corresponding test name are defined in Table 9. The layers of denim batting were tested as loose specimens with no flashing or duct tape.

Table 9. Thicknesses for Tests on Denim Batting Specimen
s

Top Layer						2"
↑				1"	1"	1"
			1"	1"	1"	1"
Bottom Layer		1"	1"	1"	2"	1"
Test Names	IAL	IAL-001	IAL-002	IAL-003	IAL-004	IAL-005
	Lab A	A-001	A-002	A-003		A-005
	Lab B			B-003	B-004	B-005

6.4.4.2 Results

As shown in Figure 46, the measured absorption coefficients for the 001 test specimen were very comparable for the IAL chamber and Lab A. In frequency bands greater than 200 Hz, the difference between the α values was less than 0.03. Likewise, for the 002 specimen in Figure 47, the difference between the two measurements was less than 0.06 for frequencies greater than 200 Hz. In the lowest frequency bands (100-200 Hz), the difference was significantly higher, again related to the irregular sound field at frequencies below the Schroeder frequencies of the chambers. At low frequencies, not only was the measure of absorption highly non-repeatable at a facility, it was also hard to produce comparable results in other facilities. It was expected that the variability would be progressively more evident as the thickness, or equivalently the absorption of the denim specimens was increased. This was observable with the 001 and 002 specimens. For the 003 specimen in Figure 48, the difference in measured α between labs increased. The difference was as high as 0.16 at 315 Hz. Also, the variation in the high frequency bands, such as 8 and 10 kHz, was significant, with differences of 0.15. The 004 specimen was very well behaved in frequency bands between 200 and 2500 Hz as can be seen in Figure 49. Below 200 Hz, the IAL absorption values were higher than those obtained at Lab B. At frequencies greater than 2500 Hz, the IAL values were lower than those from Lab B. The variation in absorption is the greatest in Figure 50 for the 005 specimen. The difference between the IAL and Lab A was as high as 0.27 at low frequencies and 0.20 at 400 Hz.

ASTM C423 provides limits of reproducibility for sound absorption tests performed per the standard in different laboratories. These limits are to be used as a guide only. When applied to the IAL results for the denim specimens, the results of Lab A and Lab B lie within these limits except at low frequencies with the thicker specimens. With the 004 specimen, absorptions in the 125 Hz band were too different. Likewise, with the 005 specimen, the measured absorption at

Lab A and Lab B in several frequency bands below 500 Hz differed more than the limits of reproducibility. For reference, Table 9 in the appendix highlights those tests and frequency bands that do not lie within these limits. Although there is inherently more variability in tests at low frequencies, the C423 limits take this into account. So it was reasonable to expect the reproducibility of the absorption coefficients to fall within the band. Notice that the limits of reproducibility allowed the absolute difference between the absorption coefficients in the lowest octave band to be 0.14. The differences in this testing were larger than this.

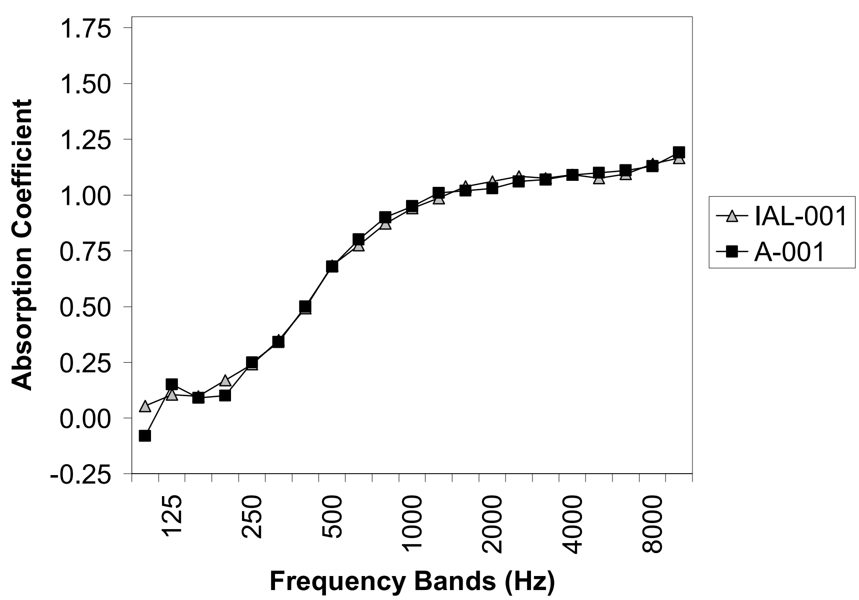

Figure 46. Absorption Coefficient for Denim Specimen with Thickness of 1”

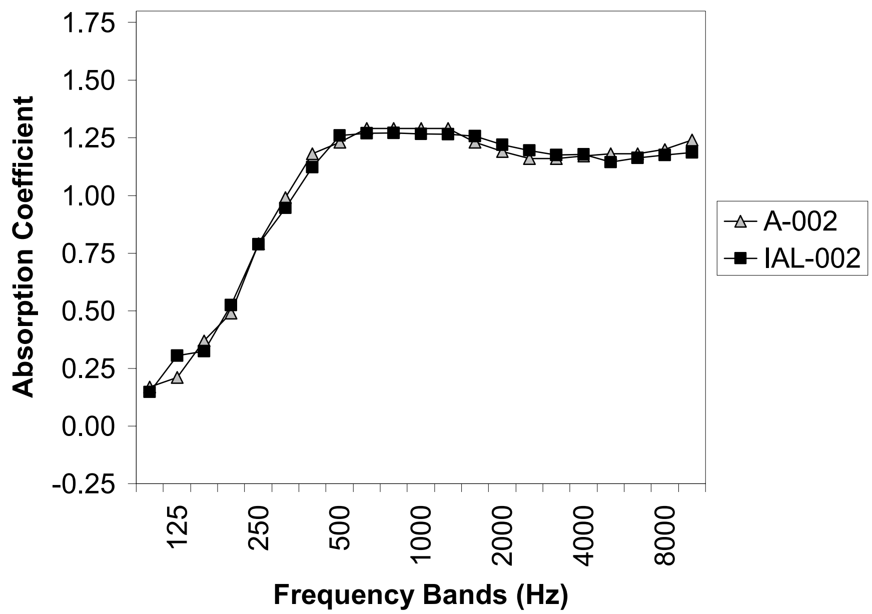

Figure 47. Absorption Coefficient for Denim Specimen with Thickness of 2”

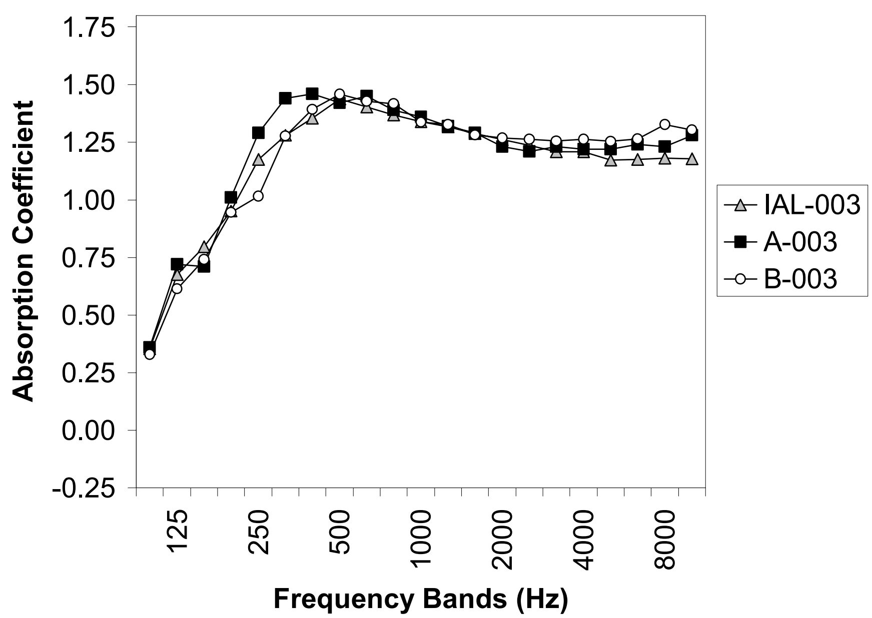

Figure 48. Absorption Coefficient for Denim Specimen with Thickness of 3”

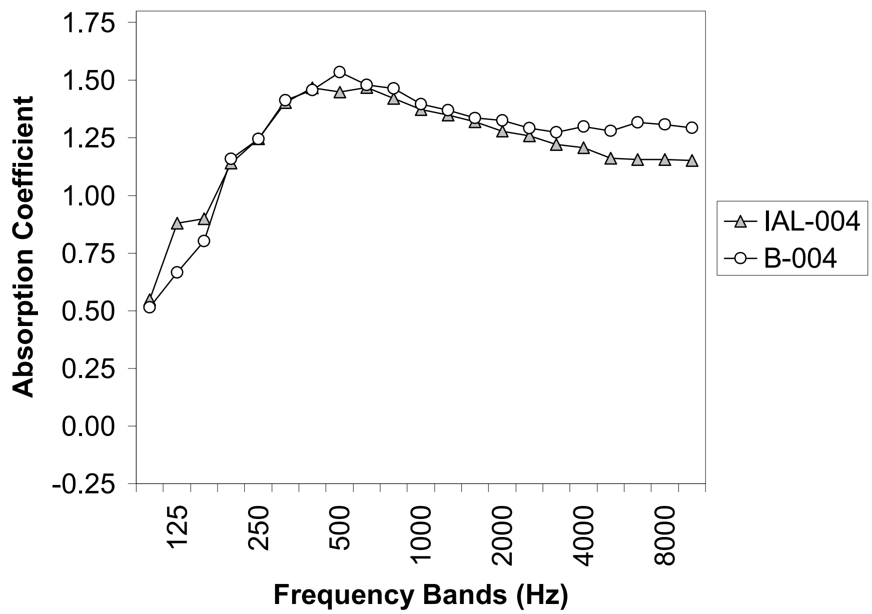

Figure 49. Absorption Coefficient for Denim Specimen with Thickness of 4”

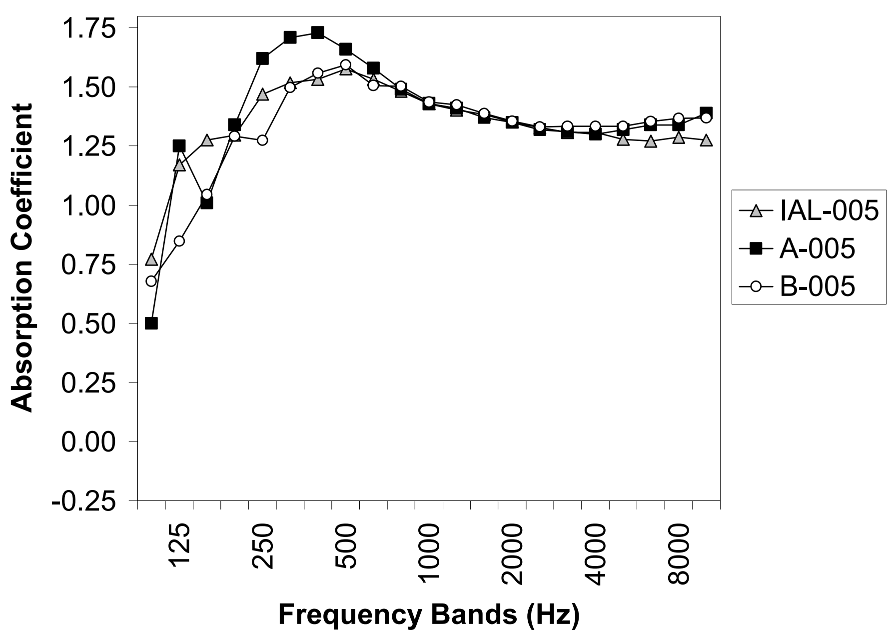

Figure 50. Absorption Coefficient for Denim Specimen with Thickness of 5”

6.4.4.3 Conclusions

This testing was very conclusive, in that absorption measurements on specimens with low absorption were reproducible in the IAL chamber; the results compare well with both Lab A and Lab B. As the specimen's absorption increased, variability in the low frequency absorption coefficients increased. As seen with the reference specimen, the measured absorption in the IAL chamber was consistently higher than Lab A and B for highly absorptive samples. The absorption coefficients from the IAL chamber did not fall within the reproducibility limits when compared to Labs A and B.

This comparison test concluded the investigative absorption testing in the IAL chamber. Results showed that the chamber qualified for testing per the applicable standard and performed tests with acceptable repeatability and reproducibility, except at low frequencies with highly absorptive specimens.

7. ISO 3741 SOUND POWER TESTING: COMPARISON TESTING OF REFERENCE SOUND SOURCE

The second major application of the IAL reverberation chamber is sound power testing. Thus, testing was performed in the IAL reverberation chamber to determine if it qualified for sound power measurements per ISO 3741 and to test its ability to reproduce sound power results obtained in Lab A. Lab A measured the sound power of a reference sound source using the direct method of ISO 3741. Recall that the dimensions, instrumentation, and microphone traverse system are the same for Lab A and the IAL. The main difference between the two facilities is the surface density of the diffusers used.

7.1. EXPERIMENTAL SETUP

The sound source used for the sound power test was an Acculab Reference Sound Source, manufactured by Campanella Associates of Columbus, Ohio, model number 101. The nominal sound power of the Acculab Reference Sound Source was 86 dBA.

The absorption of the IAL chamber equipped with lightweight diffusers was measured to compare with the requirements of ISO 3741.5.3 for qualification. Also, the qualification procedure of ISO 3741 Annex E was carried out to document the chamber's performance. The six source positions used for testing are shown in Figure 51; positions *a-d* were common positions tested in both Lab A and the IAL. Additionally, positions *e* and *f* were tested in the IAL chamber to qualify it per Annex E. For this testing, the IAL chamber was equipped with five stationary lightweight diffusers.

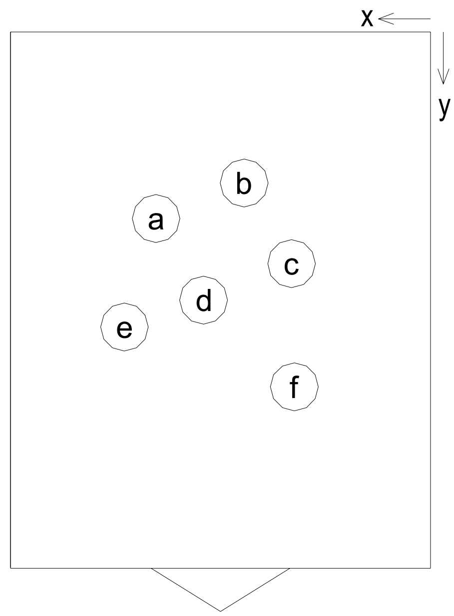

Figure 51. Positions of Sound Source for Sound Power Qualification

Table 10. Positions of Sound Source for ISO 3741 Annex E Qualification (meters)

	Source Position					
Coordinate	a	b	c	d	e	f
x	4.11	2.79	2.08	3.40	4.47	2.59
y	2.79	2.26	3.48	4.01	4.62	4.75

7.2. DATA ACQUISITION AND ANALYSIS

Sound power measurements require measurement of the empty room absorption and also the spatial average sound pressure level while the source of interest is in operation. The empty room absorption values were determined as discussed in Section 3.1.1. The same data acquisition as was used to obtain the decay curves was used to acquire the spatial average sound power levels with the microphone on the rotating boom. In the course of performing the sound power test, the measurements were also analyzed for qualification purposes per Annex E of 3741.

At each of the six source positions, the source was operated continuously while five thirty-second L_{eq}'s were acquired. The average sound pressure level at each source position was calculated using the energy averaging method, according to Equation 14. For qualification, the standard deviation of the average sound pressure level was calculated over the six source positions. To determine the sound power levels of the source, the average sound pressure levels over source positions 1-4, with the absorption area of the chamber, were used to calculate the sound power level within each band using Equation 13.

7.3. RESULTS

The absorption of the empty chamber, plotted in Figure 28, qualified it for sound power testing, per ISO 3741.5.3 since the absorption is less than 0.16 in all frequency bands. For documentation, the Annex E qualification was carried out as well. Figure 52 displays these results. The standard deviation of the sound pressure level at the six source positions for each frequency band is shown, as well as the maximum standard deviation allowed for qualification per ISO 3741. The measured standard deviation was less than the allowable value for each one-third octave band between 100 and 10,000 Hz; therefore, the chamber is qualified for sound power measurements when equipped with five stationary lightweight diffusers.

Figure 53 depicts the sound power measurements obtained for the reference sound source in the IAL. Figure 53 also displays the values of the sound power levels measured in Lab A. The upper and lower limits shown in Figure 53 represent the upper and lower limits of reproducibility specified in ISO 3741, Table 3.

The values of sound power measured in the IAL chamber fell well within the limits of reproducibility. The measured sound power differed from the values from Lab A by at most 1.2

dB. The overall A-weighted sound power of the source was 85.1 dBA measured in the IAL, compared with 85.5 dBA measured at Lab A, and the nominal manufacturer value of 86 dBA.

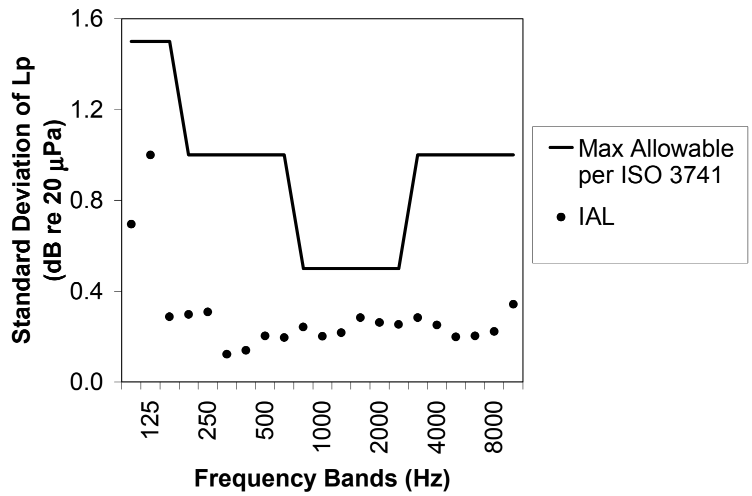

Figure 52. Qualification for Sound Power Testing per ISO 3741

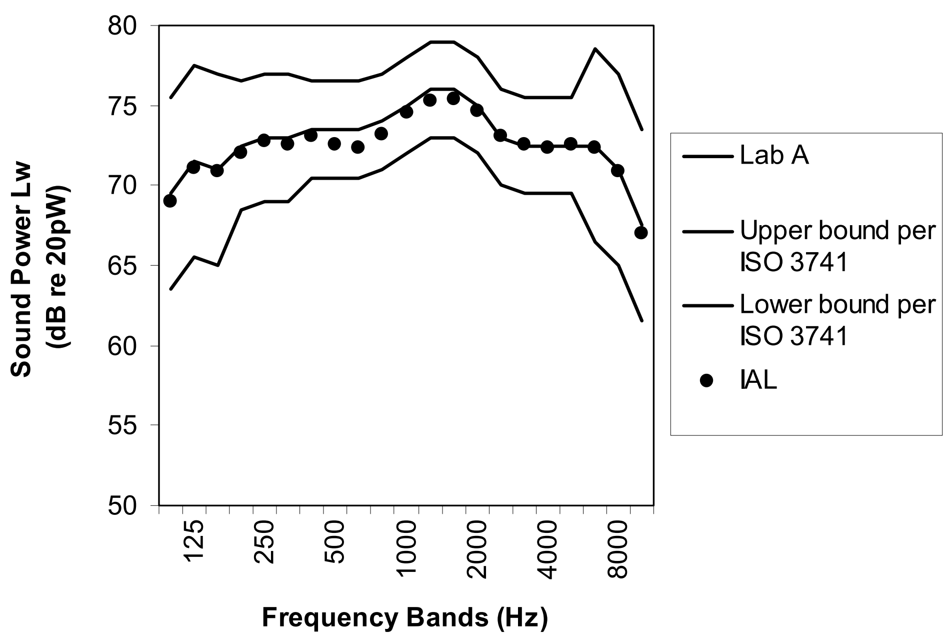

Figure 53. Sound Power Results from Lab A and IAL

7.4. CONCLUSION

Based on qualification per ISO 3741, comparable power measurements with Lab A and a satisfactory measure of the overall A-weighted sound power, the IAL chamber was suitable for sound power testing per ISO 3741, even though its sound field was not considered diffuse by C423 standards when equipped with five stationary lightweight diffusers.

8. OVERALL CONCLUSIONS

From the work of this thesis, the IAL reverberation chamber equipped with lightweight diffusers has been characterized and qualified for sound absorption and sound power testing.

Testing showed that the data acquisition and analysis procedures were accurate and appropriate for sound absorption testing. The latency and decay rate of the IAL instrumentation chain were sufficiently small that they did not interfere with decay rate measurements. Comparison of absorption measurements with a sound level meter showed that the coefficients calculated using the IAL reverberation chamber technique were within the limits of repeatability except in 4 of the 21 frequency bands. Considering the limited sample size of the sound level meter measurement, this was acceptable. When analyzing recorded decays, the IAL instrument and analysis chain reproduced measurements of slow and moderate decay rates; measurements of fast decays were less repeatable and reproducible. The decay rates measured with Spartan did not match well with Lab A at frequencies below 400 Hz. However, Spartan accurately measured the decay rate of perfect decays to within 0.08 dB/s. These discrepancies at low frequencies can be attributed to the inherent variability with fewer data points in the linear regression calculation and the non-uniformity of the prerecorded decays. The traversing rate of the microphone did not affect the standard deviation of decay rate when varied from 1 to 4 rpm. All instrumentation requirements of ASTM C423 and verification checking of the instrumentation chain indicated that it performed sufficiently well.

With regard to diffusers, an optimal configuration was found for the IAL chamber. According to the method suggested in ASTM C423-X1, five 2.1 x 2.1 m stationary fiberglass diffusers optimized the chamber's ability to perform sound absorption testing. This equates to a diffuser-to-chamber surface area ratio of 19%. However, with this diffuser configuration, the variation in decay rate with microphone and specimen position was greater than what is allowable per ASTM C423-A3. When the diffusers were arranged such that there were four stationary diffusers and two rotating diffusers, the variation with respect to microphone position and specimen position decreased and the chamber qualified per ASTM C423-02a.A3.

With the chamber qualified, an optimized test procedure for sound absorption tests was developed specifically for the IAL chamber. With regard to specimen size, the absorption coefficient of a thin, less absorptive specimen was less sensitive to specimen size. With thicker samples, the variation was much more significant, especially at low frequencies. Increasing the "empty room" absorption of the chamber did not improve the reproducibility of low frequency absorption measurements. The convergence study showed that 225 decays must be included in the average decay curve for repeatable measurements of decay rate in frequency bands from 315 to 5000 Hz. The diffusers did not significantly affect the precision of the measurement of decay rate.

The reproduction of sound absorption tests showed that the IAL chamber was able to reproduce absorption measurements well. For thin specimens, the reproducibility was very good in all frequency bands. For the thicker, more absorptive specimens, the low frequency measurements were consistently slightly higher than those measured in Lab A and Lab B. The important question yet unanswered is whether heavy diffusers would remedy this problem.

For broadband sound power testing, the IAL chamber performed well. Its absorption was sufficiently low and the sound pressure level was sufficiently independent of the sound source's location to qualify per ISO 3741. Sound power results were repeatable and reproducible, well within the limits of ISO 3741.

In short, the lightweight diffusers performed better than expected, considering the repeated recommendations of heavy diffusers by all applicable standards. Their flexibility, simplicity and economy make them ideal; their performance proves that they are functional. Thus, it can be concluded from this thesis that lightweight diffusers are suitable for the IAL reverberation chamber.

APPENDIX A
DENIM SPECIMENS

Table A-1. Absorption Coefficients of Denim Specimens

Test Number:	IAL-001	A-001	IAL-002	A-002	IAL-003	A-003	B-003	IAL-004	B-004	IAL-005	A-005	B-005
	0.05	-0.08	0.15	0.17	0.35	0.36	0.33	0.55	0.51	0.77	0.50	0.68
125	0.10	0.15	0.31	0.21	0.68	0.72	0.61	0.88	0.67	1.17	1.25	0.85
	0.10	0.09	0.32	0.37	0.80	0.71	0.74	0.90	0.80	1.28	1.01	1.04
	0.17	0.10	0.52	0.49	0.95	1.01	0.95	1.14	1.16	1.30	1.34	1.29
250	0.24	0.25	0.79	0.79	1.17	1.29	1.02	1.25	1.25	1.47	1.62	1.27
	0.35	0.34	0.95	0.99	1.28	1.44	1.28	1.40	1.41	1.52	1.71	1.50
	0.49	0.50	1.12	1.18	1.35	1.46	1.39	1.47	1.46	1.53	1.73	1.56
500	0.68	0.68	1.26	1.23	1.44	1.42	1.46	1.45	1.53	1.58	1.66	1.59
	0.77	0.80	1.27	1.29	1.40	1.45	1.43	1.47	1.48	1.53	1.58	1.51
	0.87	0.90	1.27	1.29	1.37	1.39	1.42	1.42	1.46	1.48	1.49	1.50
1000	0.94	0.95	1.27	1.29	1.34	1.36	1.34	1.37	1.39	1.43	1.43	1.44
	0.99	1.01	1.27	1.29	1.32	1.32	1.33	1.35	1.37	1.40	1.41	1.42
	1.04	1.02	1.26	1.23	1.29	1.29	1.28	1.32	1.33	1.38	1.37	1.39
2000	1.06	1.03	1.22	1.19	1.26	1.23	1.27	1.28	1.32	1.35	1.35	1.36
	1.08	1.06	1.20	1.16	1.24	1.21	1.26	1.26	1.29	1.33	1.32	1.33
	1.07	1.07	1.17	1.16	1.21	1.23	1.25	1.22	1.27	1.31	1.31	1.33
4000	1.09	1.09	1.18	1.17	1.21	1.22	1.26	1.21	1.30	1.31	1.30	1.33
	1.08	1.10	1.14	1.18	1.17	1.22	1.25	1.16	1.28	1.28	1.32	1.33
	1.09	1.11	1.16	1.18	1.17	1.24	1.26	1.16	1.32	1.27	1.34	1.35
8000	1.14	1.13	1.18	1.20	1.18	1.23	1.33	1.16	1.31	1.29	1.34	1.37
	1.17	1.19	1.19	1.24	1.18	1.28	1.30	1.15	1.29	1.28	1.39	1.37
SAA	0.73	0.72	1.12	1.12	1.29	1.32		1.35		1.45	1.50	
	0.74	0.75	1.14	1.15	1.31	1.35		1.33		1.46	1.50	

APPENDIX B
CONVERGENCE STUDY

Table B-1. Imprecision in Absorption Coefficient vs. Number of Decays Method 1

	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
5	0.819	0.680	0.325	0.493	0.637	0.265	0.277	0.145	0.122	0.157	0.146	0.084	0.101	0.091	0.050	0.095	0.438	0.122	0.120	0.136	0.177
10	0.669	0.273	0.353	0.371	0.202	0.141	0.168	0.348	0.208	0.139	0.108	0.053	0.239	0.055	0.207	0.051	0.058	0.102	0.117	0.104	0.132
15	0.315	0.275	0.183	0.237	0.148	0.188	0.154	0.125	0.183	0.144	0.059	0.086	0.066	0.159	0.068	0.214	0.151	0.055	0.203	0.086	0.087
20	0.327	0.282	0.156	0.117	0.183	0.062	0.083	0.162	0.060	0.065	0.069	0.045	0.055	0.161	0.153	0.057	0.110	0.137	0.082	0.204	0.080
25	0.281	0.226	0.145	0.190	0.173	0.101	0.132	0.105	0.044	0.064	0.064	0.041	0.034	0.087	0.039	0.095	0.049	0.149	0.046	0.235	0.068
30	0.278	0.203	0.147	0.200	0.174	0.110	0.111	0.125	0.083	0.051	0.043	0.079	0.023	0.032	0.059	0.095	0.171	0.065	0.069	0.063	0.231
35	0.211	0.184	0.170	0.093	0.125	0.070	0.144	0.132	0.077	0.077	0.020	0.059	0.053	0.063	0.066	0.024	0.071	0.168	0.145	0.185	0.206
40	0.212	0.116	0.116	0.137	0.062	0.076	0.048	0.083	0.056	0.070	0.083	0.038	0.068	0.071	0.031	0.079	0.119	0.082	0.138	0.115	0.167
45	0.200	0.142	0.133	0.098	0.139	0.108	0.115	0.108	0.036	0.053	0.083	0.041	0.029	0.061	0.035	0.082	0.143	0.067	0.157	0.082	0.202
50	0.182	0.127	0.107	0.134	0.070	0.095	0.096	0.100	0.060	0.039	0.055	0.049	0.089	0.071	0.073	0.068	0.054	0.125	0.121	0.145	0.138
55	0.267	0.109	0.143	0.148	0.066	0.113	0.076	0.059	0.059	0.046	0.039	0.042	0.069	0.057	0.023	0.081	0.049	0.041	0.061	0.156	0.093
60	0.236	0.156	0.130	0.144	0.113	0.047	0.086	0.074	0.048	0.020	0.053	0.068	0.020	0.030	0.029	0.065	0.062	0.077	0.064	0.138	0.128
65	0.160	0.106	0.127	0.096	0.070	0.079	0.064	0.062	0.044	0.059	0.052	0.023	0.027	0.042	0.048	0.072	0.024	0.059	0.098	0.097	0.102
70	0.137	0.064	0.127	0.084	0.076	0.069	0.066	0.052	0.050	0.031	0.022	0.027	0.020	0.020	0.050	0.022	0.031	0.060	0.076	0.077	0.187
75	0.159	0.145	0.123	0.094	0.119	0.076	0.107	0.045	0.076	0.052	0.048	0.049	0.039	0.030	0.045	0.060	0.053	0.046	0.075	0.112	0.058
80	0.162	0.100	0.098	0.107	0.090	0.067	0.061	0.033	0.065	0.045	0.035	0.033	0.030	0.061	0.040	0.031	0.106	0.070	0.110	0.086	0.096
85	0.095	0.109	0.117	0.090	0.078	0.047	0.073	0.060	0.058	0.039	0.047	0.020	0.044	0.040	0.035	0.047	0.063	0.071	0.085	0.086	0.091
90	0.148	0.118	0.063	0.084	0.094	0.056	0.051	0.058	0.044	0.030	0.029	0.030	0.064	0.048	0.056	0.076	0.047	0.062	0.051	0.118	0.109
95	0.188	0.097	0.089	0.113	0.074	0.048	0.037	0.033	0.057	0.053	0.031	0.025	0.043	0.033	0.055	0.044	0.046	0.041	0.067	0.104	0.129
100	0.116	0.095	0.059	0.083	0.081	0.070	0.059	0.041	0.067	0.049	0.039	0.024	0.064	0.017	0.033	0.043	0.066	0.043	0.042	0.097	0.114
105	0.156	0.075	0.074	0.086	0.048	0.047	0.058	0.062	0.053	0.035	0.019	0.023	0.039	0.042	0.044	0.052	0.049	0.050	0.068	0.090	0.100
110	0.096	0.121	0.074	0.070	0.059	0.037	0.034	0.035	0.040	0.053	0.052	0.026	0.022	0.031	0.027	0.038	0.043	0.095	0.051	0.093	0.138
115	0.090	0.123	0.100	0.065	0.114	0.069	0.042	0.048	0.047	0.033	0.040	0.031	0.037	0.038	0.037	0.061	0.031	0.062	0.065	0.087	0.076
120	0.112	0.082	0.081	0.077	0.036	0.034	0.041	0.046	0.043	0.037	0.027	0.034	0.023	0.033	0.040	0.039	0.052	0.059	0.091	0.100	0.049
125	0.164	0.089	0.064	0.069	0.066	0.040	0.032	0.026	0.037	0.043	0.033	0.032	0.030	0.042	0.033	0.034	0.060	0.059	0.088	0.095	0.059
130	0.127	0.080	0.072	0.041	0.058	0.060	0.071	0.042	0.024	0.034	0.031	0.027	0.018	0.036	0.031	0.031	0.069	0.035	0.075	0.052	0.088
135	0.125	0.102	0.032	0.054	0.058	0.057	0.042	0.051	0.051	0.028	0.029	0.023	0.018	0.028	0.039	0.031	0.058	0.054	0.070	0.063	0.064
140	0.122	0.068	0.069	0.053	0.077	0.047	0.029	0.038	0.041	0.013	0.022	0.025	0.033	0.038	0.044	0.032	0.034	0.052	0.047	0.058	0.085
145	0.110	0.104	0.062	0.060	0.060	0.034	0.034	0.046	0.030	0.039	0.033	0.048	0.032	0.029	0.039	0.058	0.043	0.044	0.073	0.057	0.090
150	0.161	0.114	0.062	0.060	0.029	0.046	0.044	0.054	0.029	0.023	0.019	0.023	0.033	0.026	0.055	0.027	0.048	0.036	0.061	0.063	0.070
155	0.134	0.076	0.038	0.063	0.042	0.066	0.026	0.031	0.048	0.038	0.038	0.035	0.020	0.026	0.038	0.057	0.054	0.051	0.071	0.075	0.081
160	0.113	0.067	0.080	0.072	0.062	0.044	0.028	0.057	0.033	0.016	0.017	0.026	0.045	0.015	0.031	0.035	0.048	0.051	0.038	0.066	0.058
165	0.092	0.067	0.075	0.061	0.074	0.057	0.051	0.056	0.039	0.031	0.027	0.021	0.031	0.018	0.017	0.032	0.026	0.027	0.082	0.097	0.063
170	0.119	0.106	0.071	0.061	0.058	0.049	0.033	0.024	0.032	0.028	0.025	0.030	0.038	0.033	0.027	0.030	0.037	0.041	0.049	0.073	0.066
175	0.128	0.062	0.066	0.058	0.059	0.036	0.029	0.046	0.038	0.028	0.021	0.024	0.016	0.027	0.028	0.024	0.050	0.031	0.051	0.052	0.062
180	0.135	0.075	0.074	0.043	0.058	0.036	0.016	0.043	0.032	0.025	0.032	0.019	0.026	0.043	0.035	0.032	0.047	0.034	0.072	0.075	0.051
185	0.117	0.114	0.054	0.067	0.072	0.052	0.030	0.042	0.041	0.029	0.028	0.023	0.025	0.026	0.033	0.040	0.037	0.039	0.049	0.054	0.063
190	0.068	0.092	0.045	0.069	0.037	0.040	0.031	0.033	0.017	0.020	0.025	0.013	0.018	0.024	0.032	0.030	0.049	0.029	0.024	0.083	0.053
195	0.104	0.090	0.057	0.045	0.065	0.039	0.024	0.029	0.020	0.043	0.029	0.020	0.020	0.018	0.035	0.038	0.039	0.039	0.068	0.077	0.064
200	0.095	0.085	0.080	0.037	0.055	0.048	0.028	0.045	0.036	0.017	0.018	0.021	0.043	0.029	0.027	0.046	0.018	0.031	0.046	0.061	0.060
205	0.094	0.062	0.056	0.043	0.031	0.036	0.028	0.032	0.017	0.025	0.020	0.025	0.029	0.023	0.026	0.029	0.042	0.037	0.043	0.056	0.075
210	0.135	0.054	0.065	0.045	0.042	0.053	0.043	0.022	0.031	0.015	0.024	0.023	0.038	0.018	0.029	0.025	0.020	0.030	0.038	0.047	0.053
215	0.087	0.068	0.031	0.067	0.036	0.027	0.033	0.029	0.029	0.016	0.020	0.028	0.024	0.035	0.021	0.029	0.022	0.038	0.048	0.050	0.051
220	0.090	0.060	0.072	0.035	0.047	0.045	0.032	0.024	0.024	0.027	0.024	0.026	0.026	0.029	0.019	0.017	0.031	0.029	0.065	0.045	0.106
225	0.092	0.060	0.044	0.032	0.066	0.053	0.032	0.035	0.026	0.015	0.029	0.028	0.021	0.029	0.029	0.041	0.026	0.045	0.044	0.052	0.084
230	0.144	0.064	0.050	0.047	0.036	0.041	0.028	0.034	0.023	0.025	0.028	0.025	0.016	0.026	0.025	0.017	0.032	0.034	0.050	0.076	0.076
235	0.087	0.057	0.064	0.055	0.054	0.023	0.032	0.030	0.020	0.032	0.025	0.019	0.031	0.023	0.025	0.028	0.033	0.036	0.039	0.041	0.072
240	0.063	0.058	0.054	0.044	0.051	0.034	0.027	0.027	0.023	0.026	0.024	0.025	0.025	0.029	0.024	0.025	0.034	0.037	0.028	0.048	0.067
245	0.084	0.058	0.048	0.040	0.058	0.030	0.044	0.023	0.024	0.017	0.019	0.020	0.028	0.033	0.031	0.027	0.029	0.033	0.039	0.045	0.049
250	0.084	0.064	0.046	0.036	0.041	0.036	0.027	0.026	0.031	0.021	0.023	0.014	0.016	0.016	0.030	0.028	0.034	0.035	0.055	0.052	0.061
255	0.065	0.040	0.047	0.045	0.042	0.027	0.025	0.030	0.019	0.019	0.025	0.023	0.018	0.025	0.017	0.022	0.021	0.022	0.043	0.057	0.084
260	0.065	0.031	0.047	0.044	0.047	0.036	0.015	0.031	0.028	0.019	0.019	0.018	0.026	0.028	0.020	0.017	0.041	0.019	0.033	0.056	0.040
265	0.082	0.048	0.039	0.049	0.038	0.032	0.036	0.029	0.024	0.015	0.018	0.023	0.021	0.011	0.015	0.028	0.039	0.032	0.043	0.046	0.056
270	0.072	0.041	0.044	0.036	0.025	0.026	0.009	0.023	0.025	0.012	0.018	0.017	0.026	0.018	0.022	0.030	0.023	0.044	0.055	0.047	0.073
275	0.117	0.049	0.045	0.050	0.051	0.020	0.034	0.033	0.018	0.017	0.018	0.020	0.020	0.023	0.019	0.018	0.020	0.028	0.034	0.062	0.027
280	0.052	0.049	0.036	0.023	0.056	0.036	0.017	0.029	0.022	0.025	0.021	0.023	0.024	0.019	0.013	0.024	0.022	0.028	0.031	0.049	0.047
285	0.072	0.056	0.059	0.044	0.038	0.033	0.020	0.026	0.022	0.026	0.018	0.016	0.016	0.025	0.015	0.028	0.030	0.022	0.045	0.052	0.044
290	0.081	0.061	0.054	0.047	0.048	0.028	0.028	0.026	0.022	0.027	0.023	0.018	0.016	0.015	0.024	0.031	0.018	0.033	0.043	0.034	0.060
295	0.115	0.044	0.042	0.049	0.048	0.022	0.035	0.028	0.021	0.014	0.016	0.017	0.016	0.023	0.020	0.015	0.021	0.031	0.038	0.059	0.036
300	0.090	0.056	0.022	0.022	0.028	0.030	0.022	0.034	0.019	0.019	0.016	0.022	0.015	0.023	0.025	0.035	0.034	0.030	0.038	0.050	0.058
305	0.066	0.074	0.045	0.050	0.034	0.029	0.025	0.022	0.022	0.012	0.023	0.019	0.025	0.014	0.019	0.020	0.035	0.028	0.037	0.046	0.042
310	0.054	0.072	0.042	0.054	0.033	0.027	0.020	0.023	0.023	0.017	0.019	0.017	0.019	0.019	0.021	0.028	0.026	0.032	0.034	0.047	0.061
315	0.057	0.050	0.062	0.033	0.034	0.023	0.020	0.023	0.035	0.024	0.013	0.016	0.024	0.017	0.014	0.022	0.025	0.031	0.049	0.024	0.053
320	0.029	0.058	0.048	0.041	0.024	0.021	0.034	0.021	0.024	0.014	0.016	0.019	0.017	0.020	0.026	0.019	0.023	0.032	0.024	0.043	0.055
325	0.075	0.048	0.045	0.024	0.043	0.034	0.021	0.013	0.020	0.011	0.029	0.016	0.018	0.023	0.029	0.034	0.024	0.019	0.029	0.037	0.059
330	0.042	0.042	0.039	0.041	0.026	0.021	0.039	0.030	0.031	0.021	0.021	0.014	0.015	0.023	0.022	0.016	0.026	0.023	0.027	0.025	0.037
335	0.056	0.084	0.023	0.038	0.032	0.022	0.021	0.038	0.015	0.025	0.018	0.017	0.017	0.014	0.018	0.017	0.016	0.044	0.030	0.035	0.048
340	0.104	0.070	0.050	0.025	0.036	0.024	0.027	0.023	0.024	0.019	0.014	0.014	0.013	0.014	0.017	0.023	0.014	0.026	0.031	0.052	0.046
345	0.074	0.046	0.043	0.031	0.034	0.024	0.021	0.023	0.030	0.017	0.015	0.011	0.015	0.018	0.017	0.024	0.024	0.022	0.035	0.036	0.038
350	0.055	0.053	0.034	0.031	0.028	0.024	0.028	0.018	0.021	0.021	0.014	0.016	0.011	0.018	0.016	0.013	0.022	0.023	0.020	0.040	0.040
355	0.068	0.043	0.042	0.035	0.034	0.023	0.015	0.016	0.016	0.022	0.016	0.020	0.023	0.018	0.029	0.017	0.021	0.025	0.027	0.029	0.054
360	0.079	0.044	0.043	0.028	0.029	0.032	0.022	0.025	0.021	0.015	0.014	0.017	0.021	0.022	0.023	0.026	0.023	0.030	0.025	0.033	0.047
365	0.055	0.051	0.039	0.040	0.020	0.012	0.017	0.021	0.018	0.015	0.016	0.013	0.013	0.017	0.019	0.032	0.028	0.030	0.035	0.042	0.046
370	0.096	0.041	0.035	0.032	0.033	0.029	0.019	0.023	0.018	0.017	0.015	0.018	0.018	0.019	0.021	0.019	0.020	0.025	0.030	0.038	0.043
375	0.052	0.051	0.027	0.033	0.029	0.037	0.022	0.016	0.027	0.013	0.013	0.016	0.014	0.016	0.016	0.018	0.022	0.021	0.023	0.045	0.032
380	0.057	0.054	0.040	0.041	0.036	0.021	0.024	0.012	0.015	0.020	0.015	0.020	0.009	0.015	0.017	0.024	0.025	0.020	0.030	0.043	0.028
385	0.057	0.039	0.049	0.037	0.021	0.027	0.018	0.023	0.022	0.017	0.024	0.016	0.016	0.018	0.016	0.020	0.020	0.031	0.018	0.046	0.045
390	0.036	0.037	0.033	0.031	0.034	0.017	0.023	0.028	0.013	0.018	0.018	0.016	0.019	0.022	0.020	0.022	0.013	0.016	0.024	0.040	0.032
395	0.064	0.030	0.039	0.032	0.027	0.021	0.017	0.024	0.015	0.022	0.010	0.010	0.017	0.014	0.015	0.020	0.030	0.022	0.035	0.035	0.037
400	0.063	0.049	0.037	0.029	0.029	0.026	0.021	0.016	0.016	0.013	0.014	0.015	0.019	0.016	0.015	0.026	0.026	0.027	0.032	0.033	0.041
405	0.053	0.038	0.026	0.040	0.024	0.015	0.022	0.019	0.021	0.013	0.012	0.016	0.014	0.015	0.016	0.024	0.020	0.022	0.021	0.031	0.044
410	0.067	0.049	0.024	0.050	0.032	0.028	0.019	0.023	0.018	0.017	0.018	0.012	0.017	0.014	0.025	0.024	0.022	0.024	0.026	0.030	0.044
415	0.077	0.045	0.035	0.029	0.021	0.015	0.010	0.025	0.020	0.015	0.012	0.017	0.012	0.020	0.015	0.022	0.020	0.027	0.035	0.035	0.036
420	0.023	0.031	0.039	0.026	0.034	0.021	0.020	0.022	0.015	0.012	0.017	0.010	0.015	0.017	0.017	0.018	0.021	0.020	0.023	0.044	0.031
425	0.062	0.038	0.044	0.027	0.028	0.017	0.021	0.018	0.012	0.020	0.023	0.014	0.011	0.011	0.019	0.030	0.025	0.017	0.026	0.023	0.054
430	0.041	0.051	0.022	0.020	0.026	0.027	0.016	0.014	0.023	0.019	0.012	0.013	0.013	0.015	0.017	0.026	0.019	0.023	0.026	0.038	0.036
435	0.057	0.029	0.032	0.025	0.016	0.022	0.017	0.016	0.022	0.012	0.011	0.018	0.012	0.011	0.018	0.016	0.017	0.023	0.031	0.026	0.036

--	=	CI > r
--	=	r > CI > r/2
--	=	r/2 > CI > 0.005
--		CI < 0.005

Table B-2. Imprecision in Absorption Coefficient vs. Number of Decays: Method 2

	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
5	1.094	0.573	0.396	0.551	0.600	0.296	0.299	0.170	0.122	0.148	0.143	0.102	0.092	0.099	0.051	0.089	0.402	0.106	0.101	0.154	0.173
10	0.578	0.332	0.357	0.364	0.193	0.135	0.165	0.306	0.229	0.123	0.096	0.057	0.233	0.050	0.204	0.051	0.076	0.093	0.099	0.116	0.114
15	0.326	0.263	0.178	0.219	0.172	0.175	0.132	0.139	0.183	0.113	0.063	0.078	0.066	0.154	0.069	0.206	0.155	0.061	0.194	0.082	0.080
20	0.386	0.270	0.187	0.120	0.171	0.069	0.088	0.147	0.061	0.061	0.061	0.043	0.048	0.135	0.139	0.059	0.117	0.128	0.076	0.192	0.081
25	0.269	0.235	0.167	0.167	0.161	0.129	0.113	0.110	0.047	0.061	0.060	0.053	0.030	0.082	0.036	0.100	0.040	0.152	0.038	0.242	0.072
30	0.285	0.236	0.129	0.164	0.168	0.124	0.098	0.122	0.075	0.073	0.042	0.076	0.026	0.030	0.057	0.090	0.147	0.085	0.055	0.061	0.225
35	0.204	0.155	0.148	0.098	0.114	0.076	0.128	0.117	0.074	0.066	0.024	0.071	0.056	0.082	0.057	0.033	0.063	0.165	0.135	0.223	0.203
40	0.218	0.123	0.124	0.123	0.090	0.088	0.067	0.079	0.054	0.060	0.088	0.043	0.064	0.067	0.028	0.066	0.138	0.087	0.140	0.116	0.170
45	0.191	0.161	0.128	0.102	0.137	0.095	0.106	0.102	0.048	0.054	0.075	0.042	0.029	0.055	0.036	0.083	0.133	0.068	0.140	0.083	0.188
50	0.159	0.122	0.106	0.140	0.077	0.109	0.082	0.092	0.058	0.039	0.053	0.043	0.082	0.071	0.073	0.072	0.061	0.111	0.107	0.123	0.138
55	0.252	0.169	0.130	0.129	0.065	0.107	0.061	0.068	0.053	0.054	0.044	0.034	0.072	0.059	0.029	0.073	0.058	0.065	0.098	0.141	0.089
60	0.259	0.154	0.136	0.123	0.092	0.058	0.079	0.075	0.042	0.032	0.056	0.065	0.027	0.038	0.052	0.092	0.065	0.076	0.061	0.134	0.141
65	0.146	0.108	0.112	0.098	0.085	0.081	0.063	0.072	0.051	0.060	0.058	0.028	0.032	0.044	0.046	0.066	0.026	0.066	0.109	0.082	0.111
70	0.143	0.136	0.140	0.100	0.075	0.071	0.062	0.052	0.058	0.031	0.027	0.027	0.025	0.023	0.043	0.054	0.050	0.060	0.076	0.073	0.188
75	0.181	0.118	0.119	0.099	0.106	0.090	0.091	0.039	0.067	0.050	0.041	0.049	0.044	0.050	0.056	0.057	0.052	0.054	0.077	0.105	0.070
80	0.187	0.128	0.097	0.112	0.091	0.062	0.072	0.043	0.064	0.046	0.037	0.043	0.031	0.053	0.042	0.033	0.109	0.065	0.113	0.078	0.104
85	0.137	0.133	0.108	0.113	0.069	0.047	0.063	0.071	0.050	0.038	0.048	0.031	0.041	0.041	0.032	0.042	0.055	0.068	0.074	0.091	0.100
90	0.156	0.124	0.086	0.102	0.086	0.057	0.056	0.052	0.040	0.032	0.039	0.033	0.057	0.047	0.052	0.070	0.041	0.054	0.070	0.122	0.128
95	0.190	0.110	0.093	0.102	0.064	0.058	0.037	0.033	0.049	0.049	0.028	0.025	0.043	0.033	0.057	0.046	0.047	0.041	0.071	0.100	0.108
100	0.138	0.091	0.070	0.071	0.074	0.063	0.060	0.049	0.063	0.047	0.038	0.021	0.052	0.022	0.034	0.050	0.062	0.042	0.050	0.092	0.100
105	0.132	0.099	0.060	0.087	0.058	0.067	0.057	0.066	0.047	0.032	0.023	0.027	0.036	0.039	0.048	0.044	0.048	0.052	0.063	0.091	0.086
110	0.146	0.114	0.065	0.078	0.071	0.045	0.034	0.040	0.043	0.046	0.050	0.031	0.023	0.036	0.034	0.046	0.038	0.082	0.053	0.096	0.124
115	0.142	0.109	0.102	0.069	0.100	0.066	0.040	0.047	0.051	0.035	0.042	0.032	0.039	0.036	0.045	0.049	0.032	0.061	0.052	0.071	0.073
120	0.111	0.074	0.069	0.084	0.040	0.032	0.041	0.052	0.040	0.036	0.026	0.034	0.022	0.032	0.034	0.051	0.051	0.064	0.076	0.089	0.049
125	0.143	0.082	0.064	0.057	0.062	0.044	0.032	0.031	0.035	0.040	0.031	0.029	0.030	0.038	0.035	0.031	0.053	0.070	0.076	0.084	0.057
130	0.117	0.075	0.072	0.052	0.051	0.053	0.064	0.040	0.034	0.035	0.026	0.027	0.019	0.033	0.033	0.028	0.060	0.047	0.066	0.062	0.081
135	0.130	0.084	0.049	0.058	0.070	0.059	0.043	0.048	0.050	0.025	0.027	0.025	0.023	0.031	0.035	0.038	0.054	0.059	0.069	0.069	0.080
140	0.125	0.104	0.069	0.054	0.079	0.054	0.032	0.037	0.038	0.027	0.022	0.023	0.031	0.036	0.036	0.033	0.037	0.054	0.048	0.060	0.108
145	0.121	0.098	0.080	0.056	0.058	0.037	0.043	0.041	0.039	0.033	0.031	0.046	0.027	0.032	0.036	0.047	0.035	0.041	0.067	0.084	0.087
150	0.164	0.098	0.053	0.058	0.039	0.052	0.049	0.049	0.029	0.030	0.018	0.026	0.033	0.026	0.052	0.031	0.042	0.032	0.071	0.062	0.074
155	0.111	0.080	0.051	0.057	0.038	0.053	0.031	0.030	0.048	0.033	0.031	0.031	0.027	0.026	0.036	0.049	0.051	0.047	0.064	0.061	0.085
160	0.105	0.082	0.070	0.060	0.061	0.046	0.027	0.052	0.035	0.018	0.019	0.027	0.043	0.020	0.027	0.034	0.043	0.042	0.045	0.063	0.059
165	0.091	0.052	0.066	0.054	0.068	0.048	0.051	0.053	0.041	0.033	0.028	0.022	0.029	0.021	0.018	0.033	0.030	0.041	0.075	0.093	0.071
170	0.118	0.086	0.083	0.058	0.058	0.043	0.036	0.023	0.037	0.024	0.022	0.034	0.033	0.026	0.038	0.034	0.033	0.040	0.042	0.068	0.065
175	0.119	0.058	0.065	0.061	0.052	0.035	0.036	0.047	0.035	0.027	0.021	0.021	0.024	0.030	0.035	0.026	0.046	0.043	0.045	0.054	0.061
180	0.118	0.081	0.073	0.052	0.057	0.035	0.019	0.048	0.027	0.024	0.027	0.020	0.025	0.037	0.034	0.036	0.036	0.037	0.060	0.071	0.059
185	0.106	0.099	0.050	0.060	0.075	0.051	0.033	0.038	0.035	0.025	0.026	0.022	0.022	0.031	0.035	0.039	0.038	0.045	0.067	0.056	0.063
190	0.091	0.077	0.049	0.071	0.035	0.042	0.028	0.037	0.019	0.020	0.027	0.015	0.018	0.025	0.031	0.031	0.039	0.037	0.050	0.079	0.057
195	0.104	0.078	0.050	0.047	0.058	0.037	0.021	0.033	0.020	0.039	0.025	0.021	0.022	0.015	0.030	0.046	0.037	0.041	0.060	0.073	0.071
200	0.103	0.070	0.074	0.046	0.055	0.041	0.034	0.052	0.036	0.015	0.019	0.023	0.040	0.029	0.028	0.044	0.028	0.041	0.066	0.061	0.069
205	0.088	0.071	0.050	0.047	0.033	0.037	0.026	0.029	0.021	0.022	0.017	0.026	0.027	0.020	0.025	0.028	0.036	0.036	0.046	0.049	0.067
210	0.118	0.075	0.058	0.059	0.041	0.050	0.041	0.018	0.028	0.017	0.025	0.021	0.031	0.022	0.030	0.024	0.022	0.027	0.041	0.047	0.064
215	0.086	0.060	0.035	0.068	0.041	0.029	0.031	0.039	0.025	0.020	0.020	0.025	0.021	0.028	0.026	0.031	0.019	0.040	0.052	0.055	0.054
220	0.077	0.061	0.064	0.052	0.047	0.039	0.033	0.028	0.025	0.026	0.023	0.025	0.022	0.026	0.018	0.025	0.032	0.027	0.059	0.051	0.089
225	0.086	0.053	0.046	0.044	0.062	0.047	0.036	0.041	0.026	0.022	0.029	0.025	0.022	0.024	0.031	0.040	0.027	0.042	0.040	0.064	0.073
230	0.131	0.056	0.053	0.053	0.043	0.033	0.025	0.036	0.023	0.024	0.027	0.022	0.018	0.020	0.024	0.025	0.029	0.034	0.044	0.068	0.068
235	0.101	0.050	0.067	0.054	0.054	0.033	0.029	0.030	0.026	0.030	0.023	0.016	0.027	0.025	0.024	0.030	0.032	0.035	0.047	0.044	0.069
240	0.073	0.052	0.059	0.052	0.048	0.031	0.031	0.028	0.022	0.023	0.026	0.022	0.021	0.024	0.022	0.033	0.032	0.040	0.038	0.051	0.057
245	0.076	0.058	0.048	0.047	0.052	0.035	0.040	0.020	0.024	0.022	0.021	0.018	0.024	0.030	0.034	0.029	0.028	0.034	0.037	0.041	0.064
250	0.074	0.052	0.043	0.039	0.039	0.035	0.027	0.028	0.027	0.019	0.024	0.017	0.016	0.023	0.030	0.030	0.032	0.035	0.056	0.061	0.056
255	0.076	0.049	0.037	0.049	0.042	0.029	0.023	0.031	0.021	0.018	0.023	0.023	0.017	0.024	0.022	0.020	0.022	0.031	0.043	0.054	0.094
260	0.073	0.054	0.056	0.045	0.052	0.033	0.017	0.029	0.026	0.020	0.022	0.019	0.023	0.026	0.018	0.018	0.033	0.024	0.033	0.050	0.063
265	0.086	0.057	0.046	0.049	0.036	0.034	0.037	0.031	0.025	0.017	0.020	0.023	0.020	0.017	0.019	0.024	0.035	0.029	0.043	0.043	0.071
270	0.070	0.047	0.042	0.037	0.027	0.024	0.019	0.020	0.024	0.017	0.017	0.018	0.025	0.017	0.019	0.026	0.029	0.038	0.049	0.053	0.070
275	0.101	0.059	0.044	0.053	0.046	0.018	0.031	0.027	0.015	0.018	0.016	0.016	0.019	0.021	0.019	0.020	0.026	0.025	0.044	0.055	0.040
280	0.061	0.060	0.046	0.026	0.054	0.039	0.019	0.029	0.022	0.025	0.020	0.021	0.026	0.020	0.018	0.021	0.026	0.028	0.035	0.050	0.046
285	0.080	0.068	0.054	0.047	0.036	0.030	0.023	0.032	0.020	0.025	0.019	0.016	0.017	0.023	0.024	0.028	0.028	0.027	0.043	0.047	0.053
290	0.081	0.061	0.051	0.044	0.038	0.027	0.027	0.025	0.025	0.025	0.019	0.022	0.019	0.017	0.022	0.028	0.020	0.036	0.036	0.034	0.063
295	0.104	0.047	0.042	0.046	0.045	0.023	0.033	0.026	0.024	0.017	0.015	0.016	0.018	0.028	0.022	0.016	0.028	0.036	0.036	0.051	0.040
300	0.081	0.045	0.027	0.029	0.033	0.026	0.022	0.035	0.019	0.020	0.015	0.017	0.014	0.024	0.025	0.032	0.032	0.026	0.032	0.046	0.060
305	0.056	0.067	0.045	0.050	0.040	0.031	0.022	0.023	0.019	0.013	0.021	0.017	0.021	0.016	0.019	0.018	0.032	0.030	0.036	0.048	0.056
310	0.054	0.057	0.037	0.053	0.044	0.030	0.023	0.023	0.025	0.019	0.022	0.020	0.019	0.017	0.020	0.025	0.028	0.027	0.030	0.042	0.051
315	0.072	0.058	0.058	0.039	0.034	0.028	0.019	0.021	0.032	0.021	0.014	0.016	0.023	0.014	0.015	0.019	0.021	0.027	0.042	0.039	0.058
320	0.055	0.053	0.050	0.044	0.027	0.023	0.036	0.023	0.020	0.015	0.019	0.017	0.021	0.020	0.023	0.023	0.026	0.028	0.028	0.041	0.055
325	0.079	0.053	0.043	0.036	0.043	0.033	0.020	0.016	0.019	0.014	0.028	0.017	0.020	0.018	0.024	0.029	0.026	0.021	0.026	0.043	0.061
330	0.060	0.048	0.035	0.039	0.026	0.026	0.038	0.026	0.029	0.019	0.019	0.014	0.014	0.020	0.021	0.020	0.027	0.029	0.037	0.030	0.056
335	0.048	0.065	0.030	0.035	0.031	0.021	0.020	0.036	0.020	0.023	0.016	0.016	0.018	0.012	0.019	0.017	0.020	0.035	0.032	0.042	0.050
340	0.090	0.054	0.053	0.025	0.041	0.025	0.028	0.019	0.023	0.021	0.012	0.016	0.011	0.014	0.017	0.024	0.012	0.024	0.034	0.043	0.053
345	0.056	0.045	0.042	0.043	0.032	0.031	0.025	0.022	0.028	0.019	0.014	0.015	0.018	0.020	0.015	0.023	0.021	0.021	0.042	0.039	0.036
350	0.056	0.053	0.041	0.032	0.027	0.026	0.031	0.022	0.024	0.019	0.013	0.014	0.012	0.018	0.018	0.019	0.026	0.023	0.022	0.037	0.040
355	0.062	0.042	0.039	0.040	0.037	0.025	0.020	0.022	0.017	0.019	0.014	0.021	0.020	0.020	0.029	0.021	0.021	0.024	0.032	0.029	0.046
360	0.075	0.042	0.038	0.030	0.029	0.034	0.024	0.028	0.023	0.017	0.018	0.017	0.020	0.018	0.021	0.022	0.022	0.025	0.027	0.041	0.048
365	0.050	0.045	0.035	0.036	0.022	0.022	0.016	0.020	0.016	0.016	0.018	0.014	0.016	0.019	0.018	0.027	0.028	0.026	0.037	0.046	0.045
370	0.078	0.038	0.040	0.031	0.032	0.025	0.022	0.021	0.020	0.018	0.013	0.018	0.017	0.019	0.022	0.021	0.019	0.025	0.031	0.041	0.041
375	0.062	0.051	0.025	0.029	0.028	0.031	0.025	0.020	0.028	0.014	0.012	0.016	0.017	0.017	0.017	0.019	0.022	0.020	0.033	0.048	0.038
380	0.064	0.055	0.040	0.035	0.037	0.023	0.020	0.011	0.013	0.017	0.018	0.017	0.010	0.014	0.020	0.021	0.023	0.022	0.026	0.037	0.041
385	0.058	0.036	0.039	0.033	0.020	0.027	0.025	0.020	0.021	0.016	0.021	0.016	0.020	0.018	0.017	0.018	0.021	0.028	0.026	0.036	0.036
390	0.063	0.036	0.032	0.033	0.035	0.020	0.025	0.025	0.012	0.017	0.015	0.015	0.016	0.017	0.021	0.019	0.018	0.022	0.032	0.037	0.045
395	0.059	0.047	0.035	0.031	0.023	0.022	0.018	0.025	0.018	0.020	0.012	0.012	0.015	0.015	0.017	0.017	0.031	0.026	0.030	0.038	0.037
400	0.048	0.049	0.030	0.024	0.027	0.028	0.022	0.013	0.014	0.013	0.018	0.014	0.017	0.018	0.021	0.022	0.022	0.021	0.027	0.032	0.046
405	0.065	0.034	0.025	0.043	0.031	0.016	0.019	0.017	0.019	0.013	0.014	0.018	0.015	0.016	0.017	0.024	0.019	0.028	0.023	0.039	0.049
410	0.060	0.052	0.028	0.042	0.035	0.027	0.018	0.027	0.016	0.016	0.016	0.011	0.018	0.017	0.024	0.022	0.023	0.026	0.027	0.038	0.037
415	0.061	0.041	0.035	0.025	0.027	0.018	0.014	0.023	0.021	0.014	0.013	0.017	0.014	0.016	0.014	0.022	0.025	0.028	0.031	0.043	0.028
420	0.032	0.036	0.037	0.026	0.028	0.024	0.016	0.018	0.017	0.016	0.017	0.012	0.017	0.017	0.017	0.019	0.020	0.018	0.025	0.036	0.043
425	0.069	0.046	0.040	0.032	0.030	0.018	0.019	0.019	0.012	0.019	0.020	0.016	0.011	0.011	0.019	0.028	0.022	0.020	0.025	0.034	0.053
430	0.042	0.044	0.031	0.023	0.029	0.027	0.018	0.018	0.024	0.020	0.012	0.015	0.011	0.013	0.016	0.022	0.019	0.019	0.027	0.034	0.041
435	0.064	0.032	0.026	0.028	0.014	0.023	0.015	0.016	0.021	0.015	0.013	0.014	0.012	0.012	0.015	0.018	0.018	0.021	0.029	0.030	0.031

--	=	CI > r
--	=	r > CI > r/2
--	=	r/2 > CI > 0.005
--		CI < 0.005

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