EXPERIMENTAL ANALYSIS OF NOISE REDUCTION PROPERTIES OF SOUND ABSORBING FOAM

by

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Abstract

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Abstract

Wood dust deposition had both positive and negative effects on the sound absorption properties of acoustical foam.

Three layers of wood dust were deposited on acoustical foam in a 2.44 meter by 2.44 meter by 2.44 meter Plexiglas test chamber. The amount of dust deposited ranged from 3.34 grams/m^2 to 30.95 grams/m^2.

The wood dust on the uncoated SONEX foam reduced the sound pressure levels in the chamber by 2 dB at 1000 Hz and by 6 dB at 4000 Hz. Similarly, the dust improved the sound absorption by Hypalon coated SONEX foam by 3 dB at 500 Hz and by 1 dB at 2000 Hz.

The wood dust on the uncoated SONEX foam increased the sound pressure levels in the chamber by 6 dB at 2000 Hz and by 1 dB at 1000 Hz and 7 dB at 4000 Hz for Hypalon coated SONEX.

Vacuuming removed all the wood particulates from the Hypalon coated foam and about 70% of the dust from the uncoated SONEX.

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Table of Contents

Chapter One: Statement of the Problem

Chapter 2: Review of Literature

Chapter 3: Methodology

Chapter 4: Results and Discussion

Chapter 5: Conclusions and Recommendations

Chapter 1: Statement of the Problem

1.1 Introduction

The Upper Midwestern United State has an abundance of wood and wood products industries. The area is noted for paper manufacturing, sawmills, furniture manufacturing, and raw building material companies. The processes used in these industries can create sound levels that exceed 90 dBA (Garcia, Garcia, Baixauli, Boix, & Marcos, 1997). The National Institute of Occupational Safety and Health states in the National Occupational Research Agenda (2000):

> Problems created by occupational hearing loss include the following: 1) reduced quality of life because of social isolation and unrelenting tinnitus (ringing in the ears), 2) impaired communication with family members, the public, and coworkers, 3) diminished ability to monitor the work environment (warning signals, equipment sounds, etc.), 4) loss of productivity and increased accidents resulting from impaired communication and isolation, and 5) expenses for worker's compensation and hearing aids.

Under OSHA's general industry standard, 29 CFR 1910.95, feasible administrative and engineering controls must be implemented whenever employee noise exposure equals or exceeds 90 dBA (8-hour time-weighted average (TWA)). In addition, an effective hearing conservation program including noise exposure monitoring, audiometric testing, audiogram evaluation, availability of personal hearing protection, training and education, and record keeping must be implemented whenever employee exposure equals or exceeds an 8-hour TWA sound level of 85 dBA.

Engineering controls are the preferred method for noise reduction. Engineering controls include sound barriers, which reduce the transmission of sound, and sound absorbing materials, which decrease reverberant sound. Noise can be reduced by suppressing audible kinetic energy in three ways: 1) containing noise with barrier materials and enclosures; 2) canceling noise by introducing sound energy which mirrors the offending sound, and 3) absorbing sound energy with panels, baffles, and other acoustic foam products (NIOSH, 1979).

Acoustical foam is one of the most popular materials available for absorbing noise. When used inside or around loud machinery, sound-absorbing acoustical foam reduces the build-up of noise, which in turn protects employee hearing, improves safety and enhances communication. Acoustical foam is commonly used for enclosing noisy machinery as well as in utility and maintenance rooms containing loud equipment where reflection of noise needs to be reduced (Industrial Noise Control, 1987).

Since the sound absorbance characteristics of acoustical foam are determined by its structure, changes in the surface of the foam may affect its sound absorption characteristics (Yang and Bolton, 1996). The deposition of particulate matter on the absorbing surface is a potential problem, however, the effects of particulate deposition have not been determined by acoustical foam manufacturers, Owens Corning or Illbruck Inc. (Murphy, personal interview, 20 February 2000 and Carlson & Hutmacher, personal interview 19 February 2000).

1.2 Problem Statement

This study examined the effect of surface deposition of wood particulates on the sound absorption properties of Hypalon coated and uncoated SONEX melomine foam panels.

1.3 Purpose of the Study

This study examined the sound absorption properties of two sound absorbing materials commonly used in the wood processing industry. Different levels of wood particulate accumulation were tested to determine how particulate buildup affects the sound absorption qualities.

This project provides the wood product manufacturers and acoustical foam manufacturers with sound absorption performance information of soiled acoustical foam and cleaned foam. This information may help wood products manufacturers select acoustical foams best suited for their specific noise control problem.

Recommendations regarding the use of foam acoustical materials in wood manufacturing processes were provided to participating companies.

1.4 Research Objectives

The objectives of this study were to:

1) Measure the particulate deposition effects on the sound absorption characteristics of uncoated and Hypalon coated melomine foam by determining if $\alpha_{\text{clean foam}} - \alpha_{\text{soiled foam}} = 0$, where α is the Noise Reduction Coefficient (NRC).
2) Determine the effectiveness of cleaning methods for both Hypalon coated and uncoated SONEX Willtec™ foam panels in terms of noise absorption effects.

1.5 Background and Significance

There are few published studies that determine the sound absorption characteristics of acoustical foam contaminated by wood dust. Leading acoustical foam producers acknowledge this lack of research, and hope to gain valuable insight into this potential problem (Murphy, personal interview, 20 February 2000 and Carlson & Hutmacher, personal interview 19 February 2000). The manufacturers of acoustical foams are the primary source of clean foam research and information. However, no studies of sound absorption characteristics of acoustical foam in environments with airborne wood dust were in the literature.

1.6 Limitations

The limitations to the research are as follows:

1.6.1 Type of particulates

Only wood dust was used in this study. The results may not be applicable to other types of particulate material.

1.6.2 Physical characteristics of wood particles

Wood types, moisture content, and generation method may affect wood particulate deposition and noise reduction coefficients of the acoustical foam. Chapter 3 outlines the type of wood used during this preliminary investigation and the physical characteristics of the wood particulate used during experimental testing.

1.6.3 Size of particulates

The research focused on a limited range of wood particulate size. The relationship between particulate size and sound absorption was not tested. Also, the effect of particulate size on wood dust's affinity for attachment to the acoustical foam was not examined.

1.7 Definition of Terms

The following definition section will assist the reader with terminology used in the areas of noise and acoustical foam research.

A-Weighted Sound Level – The ear does not respond equally to frequencies, but is less efficient at low and high frequencies than it is a medium or speech range frequencies. A-weighted sound level is used to obtain a single number representing the sound level of a noise contained within a wide range of frequencies which is representative of the ear's response. In order to do this it is necessary to reduce, or weigh, the effects of the low and high frequencies with respect to the medium frequencies. The resultant sound level is said to be A-weighted, the units are decibel. A popular method of indicating the units is dBA. The A-weighted sound level is also called the noise level. Sound level meters have an A-weighted network for measuring A-weighted sound level. (Chereminoff, 1996)

Action Level – An 8-hour time-weighted average of 85 decibels measured on the A-scale, slow response, or equivalently, a dose of fifty percent. (OSHA: Definitions, 2000)

Criterion Sound Level – A sound level of 90 decibels. (OSHA: Definitions, 2000)

Decibel (dB) – Unit of measurement of sound level. (OSHA: Definitions, 2000)

Free Sound Field (Free Field) – An isotropic, homogeneous sound field free from bounding surfaces. (Chereminoff, 1996)

Hertz (Hz) – Unit of measurement of frequency, numerically equal to cycles per second. (OSHA: Definitions, 2000)

Interstices - simply a little space between two things (Beranek & Ver, 1992)

Noise Dose – The ratio, expressed as a percentage, of (1) the time integral, over a stated time or event, of the 0.6 power of the measured SLOW exponential time-averaged, squared A-weighted sound pressure and (2) the product of the criterion during (8 hours) and the 0.6 power of the squared sound pressure corresponding to the criterion sound level (90 dB). (OSHA: Definitions, 2000)

Noise Reduction Coefficient (NRC) - The average of the absorption coefficients at the most common frequencies (250, 500, 1000 and 2000 Hz). The NRC is used to compare the acoustical performance of various materials. (Illbruck: Industrial Noise Control Room Acoustics Anechoic Environments, 2000).

Sabin - A unit of sound absorption, which is equivalent to one square foot of a perfectly absorptive surface. Baffles are frequently described as providing X number of sabins of absorption based on the size of the baffle tested, through the standard range of frequencies 125-4000 Hz. (Illbruck: Industrial Noise Control Room Acoustics Anechoic Environments, 2000).

Sound Level – Ten times the common logarithm of the ratio of the square of the measured A-weighted sound pressure to the square of the standard reference pressure of 20 micropascals. Unit: decibels (dB). For use with

1910.95, SLOW time response, in accordance with ANSI S1.-1971 (OSHA: Definitions, 2000)

Sound Level Meter – An instrument for the measurement of sound level. (OSHA: Definitions, 2000)

Time-Weighted Average Sound Level – That sound level, which if constant over an 8-hour exposure, would result in the same noise dose if measured. (OSHA: Definitions, 2000)

Chapter 2: Review of Literature

Noise often can be traced to specific devices such as industrial machines, pumps, blowers, loudspeakers and generators. Overall, noise is unwanted sound. Noise is a byproduct of many industrial processes, which include noise from conversation, tools, and machines located throughout a plant (Sataloff and Sataloff, 1993).

2.1 Health Effects of Noise Exposure

Under the Occupational Safety and Health Act (OSHA), every employer is legally responsible for providing a workplace free of recognized hazards, such as excessive noise. It has been estimated that 14 million U.S. workers are exposed to hazardous noise (Ghereminіnoff, 1996). In the Code of Federal Regulations (CFR), OSHA states their: “hearing conservation program is designed to protect workers with significant occupational noise exposures from suffering material hearing impairment even if they are subject to such noise exposures over their entire working lifetimes” (OSHA Hearing Conservation, 1995).

Occupational exposure to noise levels in excess of the current OSHA standards places hundreds of thousands of workers at risk of developing hearing impairment, hypertension, and elevated blood pressure levels (NIOSH Survey, 1990). According to the Morbidity and Mortality Weekly Reports, “occupationally induced hearing loss continues to be one of the leading occupational illnesses in the United States” (MMWR, 1986, p. 185). In following, hearing loss is the most studied effect of noise on health (Sataloff and Sataloff, 1993).

2.1.1 Hearing loss

Sound consists of pressure changes in a medium (usually air) caused by vibration or turbulence. These pressure changes produce waves emanating away from the turbulent or vibrating source (Crocker, 1998). Exposure to high levels of these waves can result in hearing loss and may induce other health effects as well. The severity of damage depends primarily on the intensity of noise and the duration of exposure. Noise-induced hearing loss can be temporary or permanent. Temporary hearing loss results from short-term exposures to high levels of noise, with normal hearing returning after a period of rest from noise exposure. Generally, prolonged exposure to high noise levels over a period of time gradually causes permanent damage (OSHA Hearing Conservation, 1995).

2.2 Noise in the Wood Products Industry

The United States is the world's leading consumer and producer of wood products. While home to only five percent of the world's population, the US consumes more than 17 percent of the world's wood (Bahouth, 1995).

Most woodworking machinery creates high noise levels requiring that employers establish and maintain effective hearing conservation programs (National Safety Council, 2000).

Garcia et al. (1997) investigated the hearing loss experienced by wood and furniture workers, reporting that one in five examined workers suffered "advanced acoustic trauma". The analysis showed a relationship between noise exposure and hearing capacity in homogeneous age groups, especially for frequencies of 4,000 to 6,000 Hz. Mean values of hearing losses ranged from 13 dB to 36 dB at frequencies of 1,000 Hz and 6,000 Hz, respectively.

2.2.1 Wood industry noise exposures

Garcia et al. (1997) evaluated workers' noise exposure at nine typical small to medium size wood and furniture industries in Valencia, Spain. They reported that 86% of the 150 workplaces had daily noise levels over 80 dBA-TWA and 23% of them were over 90 dBA. The workstations with higher sound levels involved the use of ordinary saws (4 cases), moulding machines (3 cases), multiple circular saws (2 cases), polishing machines (2 cases), and drilling machines (2 cases). In one sector evaluated, the presence of huge quantities of raw and manufactured wood products produced an unintentional and significant sound absorption, reducing reverberation time from the typical 2.3 seconds to 0.9 seconds decay time (Garcia et al., 1997).

Although the study by Garcia et al. (1997) was based on a limited sample of factories, the research shows some interesting results regarding occupational noise in raw wood and furniture manufacturing. The study showed 1) very high noise levels (frequently exceeding Spanish regulations), 2) evidences of health damage effects (as manifested in losses of hearing capacity), and 3) multiple contradicting attitudes from employers and workers.

A cross-sectional noise survey was carried out in 200 Danish wood and furniture factories. Overall TWA exposure to noise was 90.5 dBA, which exceeds both Dutch and OSHA noise regulations (Vinzents and Laursen, 1993).

For woodworking in sawmills, both Garcia et al. (1997) and Vinzents & Laursen (1993) showed noise levels had a tendency to increase with factory size. In addition, the TWA noise levels at sawmills were higher compared with the means for other factories. For non-sawmill industries, which include wood products manufacturing the means were at a sound level of approximately 90 dBA (Vinzents and Laursen, 1993). Investigators reported usage of noise reduction controls, including noise shields or acoustic absorbers, in production areas varied from 31% in small factories to 47% in large factories (Vinzents and Laursen, 1993).

In contrast to Garcia's finding of several sources of noise, Miller, Montone, and Oviatt (1980) concluded that any acoustical study of the wood products industry would immediately reveal two major sources of noise, saws and planers. Furthermore, they state that while defining effective noise problems is fairly simple, finding engineering solutions is much more difficult (Miller, Montone, & Oviatt, 1980).

Noise levels during wood working was the only exposure in the Garcia et al. (1997) study which was at the same level of or exceeding the Spanish OEL (Occupational Exposure Limits) of 90 dBA, 8- hour TWA. Garcia et al (1997) found that 90% of the employees were exposed to noise levels of 85 dBA or more and thus were exposed to risk of hearing damage. Until approximately ten years ago, the principles of noise reduction were not well established, both in working areas and at the wood processes (Garcia et al, 1997). Vinzents and Laursen (1993) and their fellow researchers feel that in many wood industries the seriousness of noise as an occupational hazard has been underestimated.

One of the unique features of the noise associated with wood product plants is its intermittent nature. While the OSHA regulation stipulates a limit of 90 dBA for 8 hours, higher sound levels are allowed if employee exposure is less than 8 hours. For example, a saw operator may be exposed to sound levels of 95 dBA, but not exceed the OSHA limits if the cumulative daily exposure is 4 hours or less. In most cases, the noise produced by conventional saws and planers may be reduced significantly using engineering controls and maintenance practices; however, it is often not technically feasible to reduce sound levels to within the OSHA limits (Miller, Montone, & Oviatt, 1980). Sound absorbing materials, such as polyurethane foam, are one technically feasible engineering control that is often used. The performance of these materials is affected by environmental conditions, such as, dusty environments, humidity, and temperature (Illbruck brochure, 1998; Acoustical Solutions, 2000).

2.3 Dust Particulate in the Wood Products Industry

Vinzents and Laursen's (1993) cross sectional study of 200 Dutch wood and furniture factories determined that the overall average exposure to wood dust was 0.90 mg/m^3. The study determined that the concentration of wood dust was slightly decreased at larger factories (>20 employees) compared to the smaller size organizations. The exposure at furniture factories and other wood products factories was significantly elevated, compared to sawmills and manufacturers of doors and windows.

Vinzents and Laursen's (1993) determined that the mean concentration of total dust vs. concentration of respirable dust was 0.33 mg/m^3 with a standard deviation of 0.24 with a total of 148 measurements. No significant differences in respirable dust were seen by type of industry or size of factory. Furthermore, no significant differences were identified relative to work task, ventilation, or local exhaust. The geometric mean (GM) for the concentration of inhalable dust was 1.11 mg/m^3 and was elevated compared to the GM of total dust concentration, which was 0.71mg/m^3 for 40 simultaneous samples collected at the 32 large factories.

In the Vinzents and Laursen (1993) study of factories producing doors and windows, woodworking was carried out on rectangular pieces of wood at stationary machines that did not sand the wood. The researchers indicate in this kind of wood working, it is easy to establish effective ventilation in order to reduce employee exposure to high particulate. The ease of establishing effective ventilation may be the reason for the low estimate wood dust concentration of 0.63 mg/m^3. A full-shift of manual sanding was the work task resulting in the highest level of dust exposure, which requires better dust control systems (Vinzents and Laursen, 1993).

2.4 Noise Control

In Preventing Occupational Hearing Loss: A Practical Guide, the National Institute for Occupational Safety and Health (NIOSH, 1990) discusses several strategies for reducing with workplace noise exposure. These strategies include; 1) prevent or contain the escape of the hazardous workplace agent (in this case, noise) at its source, and 2) control the exposure with barriers between the worker and the hazard (Illbruck brochure: Industrial Noise Control, Room Acoustics, Anechoic Environments, 1998).

There are a variety of control techniques documented in noise control literature to reduce the overall worker exposure to noise. Such controls reduce the amount of sound energy released by the noise source, divert the flow of sound energy away from the receiver, or protect the receiver from the sound energy reaching the worker. Noise control examples include proper maintenance of equipment, revised operating procedures, equipment replacements, acoustical shields and/or barriers, equipment redesign, enclosures, administrative controls, and use of personal protective equipment (NIOSH 79-117, 1979).

Absorbers are designed to reduce the amount of reflected sound energy (Beranek, 1992). When sound hits any surface, it takes three paths: 1)some goes through the surface (noise transmission), 2) some dissipates within the surface (causing vibration), and 3) some reflects back off the surface (noise reflection).

2.4.1 Sound absorption

In Everest's Master Handbook of Acoustics (1981) it states, "The law of conservation of energy states that energy can neither be created nor destroyed but that it can be changed from one form to another." Acoustical foam is one method of changing sound energy from the form of vibratory energy of air particles to heat energy through dissipation (Everest, 1997).

Each time sound waves meet the boundary surfaces of the room; some energy is absorbed while the remainder is represented by the waves reflected from the surface. These reflected waves eventually meet a boundary and again, some energy is absorbed, some is re-reflected, and so on. In the lack of continuous replacement of the original sound energy one would expect sound produced in a room to die away slowly to an inaudibility signature, rather than to cease abruptly when the supplying energy is turned off. The length of time this process will take depends on two factors 1) how much absorption occurs when the waves meet the boundaries and 2) how often they do so (Parkin & Humphreys, 1958). If the boundary surfaces of a room are highly reflective the reverberation time is long. When certain sound of energy is introduced because of the constant reflection of sound, the loudness is expected to be greater than if the same sound were made in a free field. Constant reflection of sound is typical around large manufacturing sites where steel/aluminum construction serves as the boundaries and the noise generating wood-working machines continually reintroduce sound enhancing reverberation.

Two phenomena account for most of the energy losses at high sound frequencies, which change the sound energy to thermal energy (Beranek & Ver, 1992). According to Beranek and Ver, (1992) sound pressures of air molecules (in addition to their random thermal motion) oscillate in the interstices of a porous material with the frequency of the excited sound wave. Porous sound absorbers use the properties of interstices to alter the energy form of noise. The oscillations result in frictional losses. Changes in flow direction, expansions, and contractions of the flow through irregular pores result in losses of momentum in the direction of wave propagation.

At low frequencies the conduction of sound waves is another source of energy loss. Because of the excited sound, the air in the pores undergoes periodic compression and decompression and an accompanying change of temperature. Due to the length of time during each half-period of oscillation, the large surface-to-volume ratio, and the relatively high heat conduction of the fibers, the efficient exchange of heat means that the compressions are essentially isothermal. At high frequencies the compression process is adiabatic (occurring without loss or gain of heat). In the frequency range between isothermal and adiabatic compression, the heat exchange process results in further loss of sound energy. In a fibrous material this loss is especially high if the sound propagates parallel to the plane of the fibers and may account for up to 40% if sound attenuation occurs (energy lost per meter of propagation) (Beranek, 1992).

When sound energy is absorbed it is converted into a very small amount of heat energy. As the pressure of the air momentarily increases or decreases at the surface of a porous material, due to the arrival of sound waves, air flows out of the pores. The friction produced between individual molecules of air moving within the restricted space of the pores has the ability to change some of the sound energy into heat. Alternatively, the vibration type absorbed will set the surface in motion by alternating air pressure. The friction between the molecules of the vibrating material creates heat (Parkin & Humphreys, 1958).

Everest (1997) describes the process of sound waves striking a wad of cotton batting. The description illustrates the transfer of sound energy to mechanical energy through the vibration of cotton fibers. The fiber amplitude is never as great as the air particle amplitudes of the sound wave due to frictional resistance. Some sound energy is changed to frictional heat as the cotton fibers are set in motion. The sound continues to penetrate further into the interstices of the cotton, losing more energy as increased numbers of fibers are vibrated (Everest, 1997).

Absorptivity of a material varies with sound frequency. The noise reduction coefficient for a given material may easily be eight or nine times greater at one part of the frequency scale compared to another. The amount of effective absorption is not only dependent on the absorption coefficient, but also the position of absorbent material in the room and its relation to other surfaces. The complete picture of the behavior of a decaying sound in a room comprises a complicated pattern of waves traveling the room being reflected on various surfaces. Each reflection reduces the intensity of the wave and alters it at one part of the frequency scale more than at another. Combined with this reflective motion, there may be very long standing waves set up between the various parallel surfaces, particularly if the room is small (Parkin & Humphreys, 1958).

2.4.2 Absorption and barriers

Absorptive materials are most effective when used in conjunction with barriers or barrier material. If barriers do not already exist in the form of walls, machine guards, cabinets, ceilings, etc., they may need to be introduced into the treated area. (Industrial Noise Control, Inc., Products and Systems for Workplace Noise Control. 4th Edition Planning Guide and Catalog, 1987).

2.4.3 Reverberation

Overall noise levels and reverberation are the two most common problems found in large interior spaces. When sound is introduced into a room, the reverberant field level will increase until the sound energy introduction is just equal to the sound energy absorption. If the sound source is abruptly shut off, the reverberant field will decay at a rate determined by the rate of sound energy absorption. The reverberant field is the single most important parameter describing the acoustical properties of a room (Crocker, 1998). Reverberation, which is caused by the reflection of sound waves from hard surfaces, can hamper communications and contribute to higher noise levels. Sound absorbing foams have been developed as an engineering control to reduce reverberation and overall sound levels.

2.5 Introduction into Foam Absorbers

Sound absorbing foams first appeared in the mid 1970’s (Crocker, 1998). Flexible polyurethane foams are widely used in automobiles, machinery, aircraft, and various industrial applications. To reduce the affects of noise, foams are finding application as sound absorbers in architectural and industrial applications, including machine areas, HVAC systems, recording studios and test laboratories (Illbruck brochure, 1998).

2.5.1 Benefits of acoustical foam

According to Chereminoff (1996), some benefits of acoustical polyurethane foam are:

- Its effectiveness to absorb noise in mid-to-high frequencies
- Can create cost effective enclosures around machinery
- Low susceptibility to material degradation (if faced and edges are sealed)
- Non-toxic and vibration resistant
- Made from self-fire extinguishing material (generally suitable for architectural purposes).

2.5.2 Cons for acoustical foam

Some of the negatives of acoustical polyurethane foam as, determined by Chereminoff (1996), are:

- Selection of foam type is dependent on the factors of exposure, moisture, solvents, vibration, dirt, oil and grease, temperature, corrosive materials, and erosive conditions.
- Can become damaged, torn, cut, and ripped by abrasion
- Do not meet regulatory restrictions for disinfecting/cleaning materials in and contacting food and drug products
- Fire requirements – materials of construction
- Restrictions on shedding fibers
- Machine guarding restrictions
- Deteriorates at high temperature.

2.5.3 Types of absorbers

Porous sound-absorbing materials are available in the form of mates, boards, and preformed elements. They are manufactured of glass, mineral or organic fibers, wood chips, coco fibers, felted textile, or open cell foam (usually polyurethane). These materials have open pores with typical dimensions less than 1 mm. These open pores are significantly smaller than the wavelength of sound. Open pore foam can be treated as a poor homogeneous medium with uniform structure or composition. The goal of acoustical foam characterization is the prediction of the characteristic impedance and propagation constant (Beranek, 1992).

Noise absorbers are designed to reduce reflected noise and dissipate noise energy. The open cell structure of acoustical foam dissipates noise energy to control harsh reflected noise and reverberations in enclosed surroundings. Baffles, which are typically hung from ceilings, are 2-sided acoustical foam panels with an integral wire support frame (Netwell: Noise Control Solutions, 2000)

2.6 How Acoustical Foam Absorbers Work

Noise absorbers allow most of the incident noise to be transmitted, but also dissipate some energy during the process. Very little noise is reflected from the surface of the acoustical foam (Industrial Noise Control, 1987).

2.6.1 Noise reduction coefficient

The amount of noise dissipated or absorbed is a fraction of the total noise. The amount absorbed is stated as absorption coefficients for each frequency. The Noise Reduction Coefficient (NRC) is a simple average of the performance at four frequency bands: 250, 500, 1000, and 2000 hertz and is a convenient way to classify absorption performance (Industrial Noise Control, 1987).

Sound absorption coefficients of acoustical materials will range from 0.01 to greater than 1.00. The higher number indicates a better absorber of sound. For example, a material having a sound absorption coefficient of 0.85 will absorb 85% of the incident sound energy striking its surface. A sound absorption coefficient greater than 1.00 cannot occur in theory but can be measured for materials that are highly sound absorptive. However, the sound absorption coefficient should always be rounded to 1.00 when calculating sabins of absorption (Industrial Noise Control, 1987). The amount of noise reduction obtained in an area when sound absorption material is added depends on several factors, these factors include the size and geometry of the area, the sound absorbing properties of existing materials in the area, the location of the noise source or sources, the amount of sound absorbing material added in the area, and the placement of such material (Owens/Corning, 2000).

The sabin absorption coefficient of a material is measured using a reverberation chamber, in which reverberation decay times are determined. This is accomplished in one-third-octave bands, with and without the material under test. The differences in measured decay times with the absorbent material in place allows determination of the absorption due to the presence of the test material using the total area of all room surfaces, including the sample when in place, and the area of material (usually between 10 and 12 m^2 exposed to the sound field) (Crocker, 1998).

2.6.2 Installation of acoustical foam

At its most basic level, correction of room acoustics involves using sound-absorbing materials on three non-parallel surfaces. This technique suppresses unwanted reverberation by keeping sound waves from bouncing back and forth between parallel surfaces. It also reduces the overall noise level by preventing noise from building up (Everest 1997).

Polyurethane foam tiles may be installed using panel or contact adhesive, or mechanical fasteners. It can be glued to standard drywall construction, plaster, paneling, concrete, cinder block walls, or stapled to stud walls (Acoustical Solutions, 2000). Illustration 1 shows the use of SPA-02 adhesive, which is applied along all four edges and so that each diagonal corner is connected in an X-pattern (Figure 2.1).

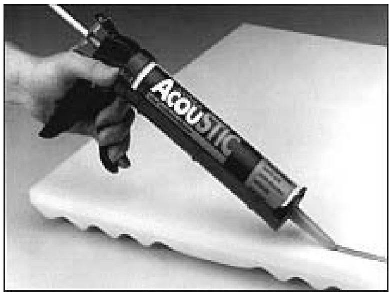

Figure 2.1. Application of acoustical foam using SPA-02 adhesive (Illbruck, 1998).

2.7 Physical Properties of Absorbers

Polyester fibre products are generally known as non-woven or bonded fibre fabrics. This industry has grown substantially during this century due to the development of several synthetic polymer fibers including polyester. A number of parameters can be varied in the polyester fibre web (held together by the binding fibers) to produce a final product with specific properties and appearance. According to Narang (1995) these properties include:

- Length of polyester fibre
- Length of binding fibre
- Mass/area of the final product
- Thickness of the batt or blanket manufactured
- Diameter of the regular polyester fibers

- Type of fibers – hollow or solid
- Percentage of binding fibers in the total as a ratio
- Type of fibre crimp – spiral or saw tooth
- Web arrangement – parallel or randomized.

The two most important properties for acoustic applications are sound insulation and sound absorption, which for fibrous material is a function of the material flow resistance (Narang, 1995).

One of the most important differences between fiberglass and partially reticulated foam is the large structure factor. The larger structure factor of partially reticulated foam has two consequences. First, a large structure factor reduces the phase speed of airborne wave propagation within the foam. This has the effect of shifting layer resonance effects to correspondingly lower frequencies. In foam, this effect is controlled primarily by the degree of reticulation, which may be increased or decreased as desired without significantly affecting the treatment weight. Second, viscous and inertial effects associated with a large structure factor cause the motion of the solid phase of the foam (frame) and the interstitial air to be coupled (Bonton & Green, 1993).

2.7.1 Density

Glass fiber and other materials come in densities ranging from flimsy thermal insulation batts to semi rigid and rigid boards. According to Everest (1981), density shows relatively little difference in absorption coefficients as the density is varied. In very low densities, the fibers are widely spaced which affects the absorption of the material. For extremely dense rigid boards the surface reflection is high and sound penetration is decreased, therefore, absorption is low.

Fibrous, porous, low-density materials are often good sound absorbers. Because absorbers generally exhibit less mechanical strength than barrier materials, their selection requires some additional consideration. Facings are applied to many sound absorbing materials to protect them from the physical environment (Industrial Noise Control Inc, 1987). For example, glass fiber blanket is a good absorber but lacks strength in lower densities. Adding a glass fabric facing and fabricating the layers into a quilted blanket creates a strong material with excellent absorption performance. Urethane foams are excellent absorbers and are strong with or without facing.

2.7.2 Flow resistivity

Flow resistivity (specific flow resistance per unit thickness) is the most important physical characteristic of a porous material. Since resistivity depends on the sound wave velocity, it is customary to extrapolate measured resistivity versus velocity to v=0.05 cm/s. Below this particle velocity the flow resistivity of most fibrous materials does not depend any more on the velocity.

2.7.3 Wedges

According to SONEX manufacturer, Illbruck Inc., (2000) to enhance dissipation, the optimum surface geometry for sonic deflection is the standard "anechoic-wedge". This is widely used in sound laboratories. The SONEX contour is based on this anechoic-wedge principle, which presents a surface area 450% greater than flat surfaces. (SONEX, "The Beautiful Way to Kill Noise" brochure).

One polyurethane foam, SONEX, is contoured to simulate the wedges used in anechoic rooms. They are shaped in male and female molds and come in meshed pairs (Everest 1997).

Pyramids are attractive acoustical foam panels that effectively trap and absorb sound energy. Wedges feature a special, contoured profile that helps trap airborne industrial noise (Netwell, 2000). It has been found that by making the wedges sharper and longer, while keeping the total volume of foam material constant, the absorption characteristics of forward wedges can be improved at the high frequency range, while at the same time the absorption of inverse wedges is improved in the low frequency range. Hybrid foam treatments that have wedge shapes at both their front and rear surfaces were found to increase the frequency-averaged absorption coefficient to 0.9 (Kang & Bolton, 1996). Figures 2.2 and 2.3, by Illbruck 1998, show various wedge shaped acoustical foams.

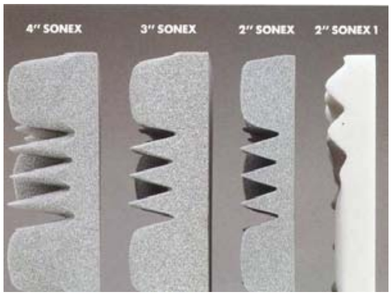

Figure 2.2. SONEX acoustical foam wedge-shaped form of various thickness.

Figure 2.3. SONEX Super fiber-free deep wedge foam.

2.7.4 Fiber arrangement

Most fibrous materials are anisotropic, because the fibers lie preferentially in the planar directions (Allard, et al., 1993). In dealing with sound absorption the goal is usually to determine the absorbed versus reflected portion of a sound wave. This is easiest when the surface of the absorber is flat and sufficiently large so sound waves scattered at the edges of the absorber can be neglected. Then, for the special case of a plane incident sound wave, it is possible to assign a sound energy absorption coefficient α = (absorbed energy/incident energy) = $1 - |R^2|$ where R is the reflection factor, which is defined as the ratio of the reflected and incident sound pressure at the interface. At high sound absorption coefficient ($\alpha \rightarrow 1$) requires that $|R| \rightarrow 0$. Edge effects manifest themselves in increased sound absorption with increasing perimeter-surface area ratio of the absorber (Beranek, 1992).

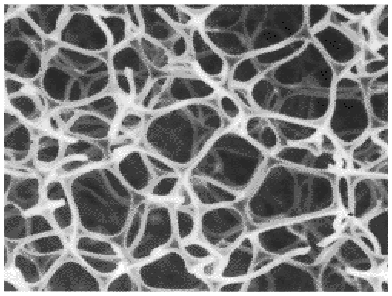

Figure 2.4. Close up of polyurethane foam fiber arrangement (Illbruck, 1998).

2.7.5 Current products

The following acoustical foam information is a representative sample of the materials available for sound absorption. PROSPEC foams by Illbruck feature elevated sound-absorbing qualities. Two material options to accommodate varying needs are Willtec™ and polyurethane. Foam in Willtec™ comes standard with a convoluted surface coated with gray Hypalon™ facing for easy clean-up and resistance to dust and fluids. This product is also available with a tougher Tedlar™ facing or aluminized Mylar™ for special applications. Prospec foam, in polyurethane, is a more economical option that provides high sound absorption. It comes standard with a Tuftane™ facing that resists water, oil and solvents. Aluminized Mylar™ is also available to provide increased protection against fluids or other special applications.

PROSPEC™ products contain and/or absorb sound at its source and are ideal for insolating noisy equipment and minimizing sound transmission through walls and ceilings. Materials by other manufacturers are comparable in their sound absorbing qualities.

2.8 Effect of Particulate Deposition on Foam Noise Absorption

Owens-Corning research representative, Patricia Murphy (personal interview, 20 February 2000) indicates the Owens-Corning company has not performed any studies on soiled acoustical polyurethane foam sound absorption. However, Owens-Corning did report that specialized acoustical tile protective layers can be used to protect their absorptive materials from wood particulate accumulation (Murphy, 2000).

According to Illbruck representative, Joerg Hatmacher (personal interview, 19 February 2000), Illbruck a manufacturer of SONEX™, has not done any tests on the performance of soiled acoustical foam in either their United States or Germany facilities. When Illbruck materials become soiled with wood dust particulate it is common practice to encourage cleaning of the product or removal of current product and subsequent replacement with environmentally resistant materials. Illbruck makes a product line which includes a Hypalon™ coating which has been found to protect against many environmental conditions (Hatmacher, 2000). Hypalon coating repels oil, acid, or solvents and can be hosed or wiped clean.

2.9 Summary of Literature

Manufacturers of polyurethane acoustical foam have recognized the need for acoustical foam to perform under variable physical environments. Protective coatings have been developed to protect the physical structure of the foam, which is responsible for sound absorption with minimal reflection. The wedge-shaped face surfaces of these products have proven to enhance the sound absorbency of foams, but create surfaces where particulates can deposit. Studies by Vinzents and Laursen (1993) and Garcia et al. (1997) have shown that wood particulate generation in wood products industries can be significant and possibly affect absorption of acoustical foam. The studies by Garcia et al. confirm that noise within wood products factories must be controlled using engineering controls such as acoustical foam. The need for sound absorption, and therefore acoustical foam, within an environment producing airborne particulate matter has created the need for research on the effect of wood particulate deposition on acoustical foam performance.

Chapter 3: Methodology

3.1 Research Strategy

The effect of wood particulates on the sound absorption properties of SONEX uncoated and Hypalon™ coated acoustical foam were examined in a controlled test chamber. The sound absorption properties of new, soiled, and cleaned acoustical foam were measured using the acoustical foam manufacturers, and foam users in the wood products industry, standard test methods (ASTM, 126). At each stage of testing the acoustical foam was weighed to determine the amount of wood particulate gain or loss.

Testing was performed for each of the two types of foam in the following order:

A. Empty Plexiglas chamber
    1. Sound level readings
B. Clean SONEX
    1. Sound level readings
    2. Foam column weighing
C. Particulate layer 1 SONEX
    1. Wood particulate soiling
    2. Chamber cleaning
    3. Sound level readings
    4. Foam column weighing
D. Particulate layer 2 SONEX
    1. Wood particulate soiling
    2. Chamber cleaning
    3. Sound level readings
    4. Foam column weighing
E. Particulate layer 3 SONEX
    1. Wood particulate soiling
    2. Chamber cleaning
    3. Sound level readings
    4. Foam column weighing

3.2 Facility

3.2.1 Experimental Chamber.

A cube chamber with side lengths of 2.44 meters was constructed of 0.635 centimeter-thick construction grade Plexiglas (Figure 3.1, 3.2 and 3.3). This provided a total surface are of 35.7 m^3. Two, 1.22 meters by 2.44 meters sheets were used to create each of the four walls, ceiling and floor. One-half sheet of Plexiglas served as the door on the front of the chamber measuring 1.22 meters by 1.22 meters. Clear silicone caulk was used to seal all of the joints between Plexiglas panels to minimize wood particulate losses, control vibration of the panels, and control air leaks. The panels were fastened every twelve inches along the edges of the Plexiglas with screws to the wood framing.

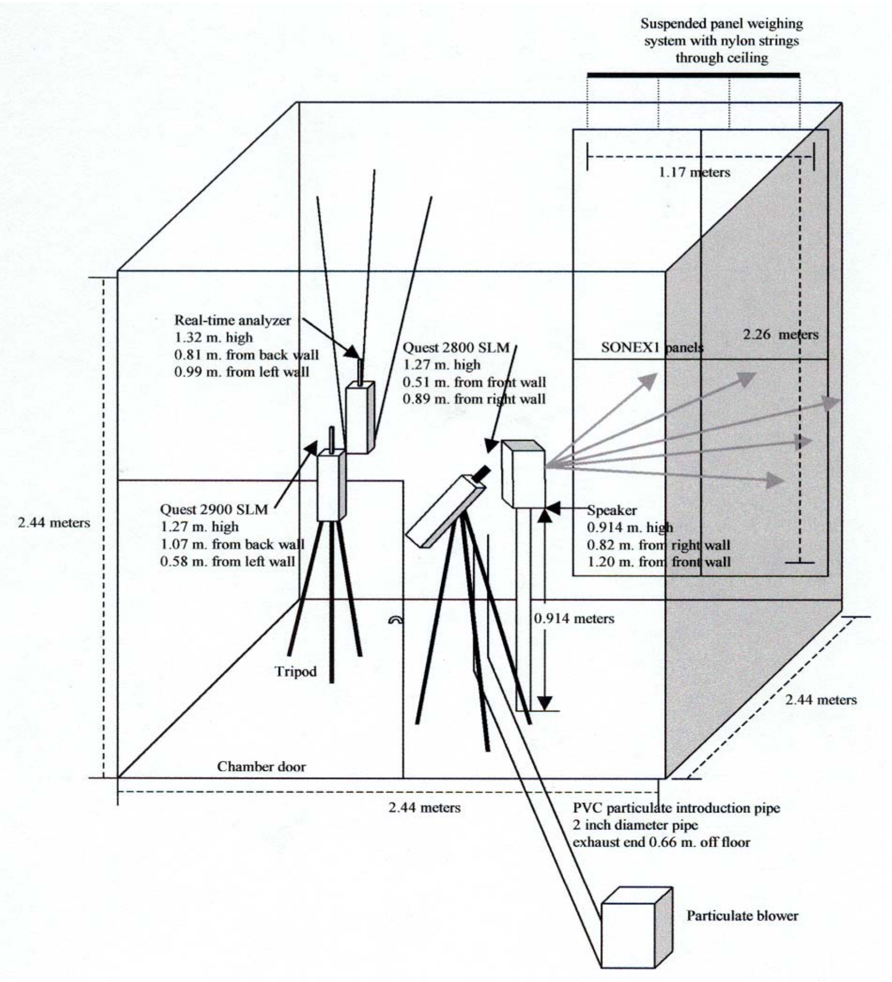

Figure 3.1. Experimental chamber with positions of RTA, sound level meters, and particulate distribution equipment.

Figure 3.2. Chamber construction with Plexiglas sides, front access door, and particulate introduction pipe.

Figure 3.3. Corner of experimental chamber with fastening screws and silicone adhesion corner seal.

3.2.2 Acoustical Foam Panels.

Four of the SONEX foam panels, 0.61 meter by 1.22 meters, were trimmed, glued, using construction adhesive (SP-200), and duct taped together to create panels measuring approximately 1.18 meters by 2.26 meters (Figure 3.4 and 3.5). Two columns of SONEX panels were suspended from the ceiling on the back, right, and left walls. One column of panels was also suspended from the ceiling on the non-door front panel of Plexiglas and a half column was suspended over the door (0.79 meter by 1.14 meters). The total surface treatment provided by the 7 1/2 columns was 20.0 m^3. Columns were suspended by four removable hooks on nylon strings through the chamber ceiling where they connected to the weighing system (Figures 3.6 and 3.7). The panels were pressed against the walls, using nylon string, to simulate a glued adhesive installation, as recommended by the manufacturer for acoustical foam installation (Figure 3.8).

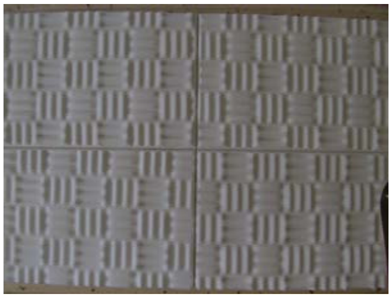

Figure 3.4. Front of four SONEX panels trimmed, glued and taped together.

Figure 3.5. Back of four SONEX panels trimmed, glued and taped together.

Figure 3.6. SONEX panel weighing system consisting of scale and cross member that was attached to four strings affixed to removable hooks.

Figure 3.7. Cross member of the weighing system with hooks on nylon strings through the ceiling of the chamber.

Figure 3.8. SONEX panels pressed to the wall of the chamber by nylon string.

3.3 Apparatus

3.3.1 Sound Generation.

The audio oscillator, an HP model 200AB sound generator, was run for five minutes at each frequency evaluated: 125, 250, 500, 1000, 2000, and 4000 hertz. During all sound level test procedures, one standard stereo speaker, Pyramid 4080, 250 watt, 8 ohm impedance, 92 dB sensitivity, frequency response 60 to 20,000 hertz, was placed on a 0.91 meter high speaker stand directed at the left trihedral corner of the room. The sound generator was operated from outside the chamber. Throughout testing, the generator was operated at maximum amplitude generating sound at 125, 250, 500, 1000, 2000, and 4000 hertz (Figures 3.9, 3.10. and 3.11).

Figure 3.9. Stereo speaker placement directed to the back right corner of the chamber 0.91 meter high.

Figure 3.10. Top view photograph through the ceiling of the chamber showing the position of the speaker, particulate dispersal pipe and real-time analyzer locations.

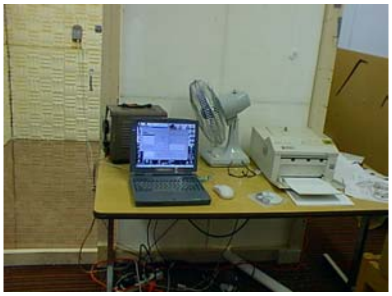

Figure 3.11. Front photograph of the outside of the experimental chamber with sound generator equipment and real-time analyzer control by means of the laptop.

3.3.2 Sound Pressure Level Measurement.

The Quest 2800 and 2900 SLMs were placed on tripods in the opposite corner of the chamber as the speaker. The Quest 2800 SLM was 1.27 meters high, 0.508 meters from the front wall, and 0.895 meters from the left wall. The Quest 2900 SLM was 1.27 meters high, 1.067 meters from the back wall, and 0.578 meters from the right wall. The three legs of both tripods were marked on the floor to ensure that both meters were placed consistently in the same location. The RTA was mounted on a wood platform that was suspended from the ceiling at a height of 1.32 meters, 0.81 meters from the back wall, and 0.99 meters from the right wall.

The sound absorption characteristics of the chamber without acoustical foam were determined using the Quest 2800, the Quest 2900 SLM, and Larson Davis 824 RTA to determine the NRC for 0.635 centimeter Plexiglas. The manufacturer's published values for SONEX were used to calculate the NRC for Plexiglas.

3.3.3.1 Sound level meter.

Calibration of the Quest 2800 and 2900 sound level meters were performed as outlined by the manufacturer. In addition, the Quest QC-10 Calibrator, 114 dB SPL at 1000 hertz, calibration date 4/2000, was used to check and/or calibrate the sound level meters at the beginning of testing each day. A post-calibration was performed at the end of each day and differences in calibration levels were noted. Sound pressure levels were measured at 1/1 octave bands.

3.3.3.2 Real-time analyzer.

Calibration of the Larson-Davis 824 real-time analyzer was performed as outlined by the manufacturer. The LD Precision Acoustic Calibrator CA250, 114.0 dB SPL at 250 hertz, calibration date 02/18/99, was used to check and/or calibrate the RTA at the beginning of testing each day. A post-calibration was performed at the end of each day and differences in calibration levels were noted. The RTA measured the sound pressure level at 1/3 octave band intervals.

3.3.3 Balance.

An OHAUS Dial-O-Gram triple-beam balance was used to weigh each of the acoustical foam columns during the study. The balance used suspended, balanced wood dowels to hold the foam columns with nylon string off the floor and away from the walls. This method of weighing the panels minimized the loss of the wood particulate from the acoustical foam after its deposition (Figure 3.12). The OHAUS Dial-O-Gram triple-beam balance was calibrated using a precise calibration weight of 500 mg +/- 0.002 mg. The balance was calibrated at the beginning of each test day and checked at the completion of each day.

Figure 3.12. Space between the SONEX panels and the chamber wall during particulate weighing.

3.3.4 Wood Particulate.

Baled wood dust generated during the milling process of part profile molders, tenoners, and jump saw cutting processes of white pine wood was purchased from a wood products manufacturer.

3.3.5. Hygrometer.

A Taylor Comfortguide® Hygrometer was used to measure the relative humidity level in the test chamber several times each day.

3.4 Test Process

3.4.1 Baseline Measurement of Sound Pressure Level.

The Quest 2800 SLM, Quest 2900 SLM and Larson-Davis RTA 824 were used to measure the baseline sound levels in the empty Plexiglas chamber at each of the 8 octave bands.

3.4.2 SONEX Testing.

For SONEX uncoated and Hypalon coated, clean and particulate soiled foams, the real-time analyzer was placed on its suspended platform within the chamber and was connected to a laptop computer located outside the chamber. The RTA timer was set for 5 minute intervals with a delay start and stop which allowed time between frequencies to setup the RTA, exit the chamber, turn on the signal generator, collect the data, download the data, and setup the instrument for the next frequency. The Hewlett Packard Audio Oscillator, model 200AB, operated from outside the chamber at 125, 250, 500, 1000, 2000, and 4000 hertz while the RTA collected sound level data.

Initial sound absorbance tests were performed in the clean chamber on the SONEX uncoated and Hypalon coated acoustical foam. After each set of measurements the strings holding the acoustical foam against the walls of the chamber were released allowing the columns to hang freely. Each foam panel was weighed individually on the triple-beam balance system. While one researcher weighed the columns from atop the chamber, the other ensured that the panels hung freely for precise measurements. A set of sound pressure level measurements were taken after the introduction of each particulate layer and after cleaning the acoustical foam.

3.4.3 Wood Dust Deposition.

Three levels of wood particulate deposition were examined on two types of acoustical foam, SONEX uncoated and Hypalon coated. The wood dust was dispensed in the chamber using a vertical blast of air generated by a Paramount PB150 single-speed leaf blower through 2” diameter PVC pipe. The air stream was directed upward in the center of the floor using a 90^0 elbow in the PVC 0.66 meters off the chamber floor with a funnel secured to the top to facilitate the dispersal of particulate (Figures 3.13 and 3.14).

With the leaf blower running, wood particulate was introduced into the input box at approximately one cup per second. Roughly twelve cubic feet of wood particulate in one compressed bale was introduced into the chamber for each layer of particulate on the foam. Two standard household box fans were used to suspend and distribute the particulates in the chamber during deposition. After the completion of the wood dust introduction, the leaf blower ran for an additional 2 minutes. After the dust was allowed to settle, the chamber floor was cleared of the many inches of particulate on the floor using dustpans and a ShopVac™. The ceiling and walls above the foam columns were wiped clean with antistatic wipes. All cleaning was performed carefully so not to disturb the soiled acoustical foam.

Figure 3.13. A standard single speed leaf blower introduced wood particulate into the chamber by means of a PVC pipe delivery apparatus.

Figure 3.14. A funnel and household box fans were used to facilitate dispersal of wood particulate within the chamber.

3.4.4 Foam Cleaning.

After testing with the three layers of wood dust, the acoustical foam was cleaned according to the manufacturers recommendations. The absorbing surface of each panel was vacuumed with a standard household ShopVac™ vacuum unit equipped with a plastic or brush attachment. The five inch long attachment was carefully pulled down the face of the panels to avoid tearing the foam (Figure 3.15).

Figure 3.15. Cleaning of SONEX was performed using a standard vacuum and attachment.

3.5 Data Analysis Methologies

3.5.1 Sound Absorption Coefficient Calculation.

The sound absorption coefficient, α, is a decimal fraction of the sound energy incident to the surface of a material that is absorbed by the material and varies with frequency. Sound absorption coefficients for the surface treatment materials can be calculated from changes in sound pressure levels caused by changes in the surface treatment, equation 3.1.

$$\text{SPL change in dB} = 10 \bullet \log(((\alpha_p(A_{total} - A_{foam})) + (\alpha_f \bullet A_{foam}))/(\alpha_p \bullet A_{total})) \qquad (3.1)$$

When α_p = sound absorption coefficient for Plexiglas

α_f = sound absorption coefficient for acoustical foam.

A_{total} = total Area of chamber

A_{foam} = total Area of foam

SPL change in dB = difference in sound pressure level between treatments, with and without foam.

3.5.2 Noise Reduction Coefficient.

The noise reduction coefficient, NRC, is the arithmetic average of a material's sound absorption coefficients at 250, 500, 1000 and 2000 hertz. The NRC was used to compare the acoustical performance of the coated and uncoated materials and between the different particulate level absorptions.

Chapter 4: Results and Discussion

4.1 Sound Pressure Levels

The 1/3-octave band sound pressure level measurements are presented in Appendix A. The 1/3-octave band SPL measurements demonstrated a harmonic at the next higher octave band (Figure 4.1 and Appendix A).

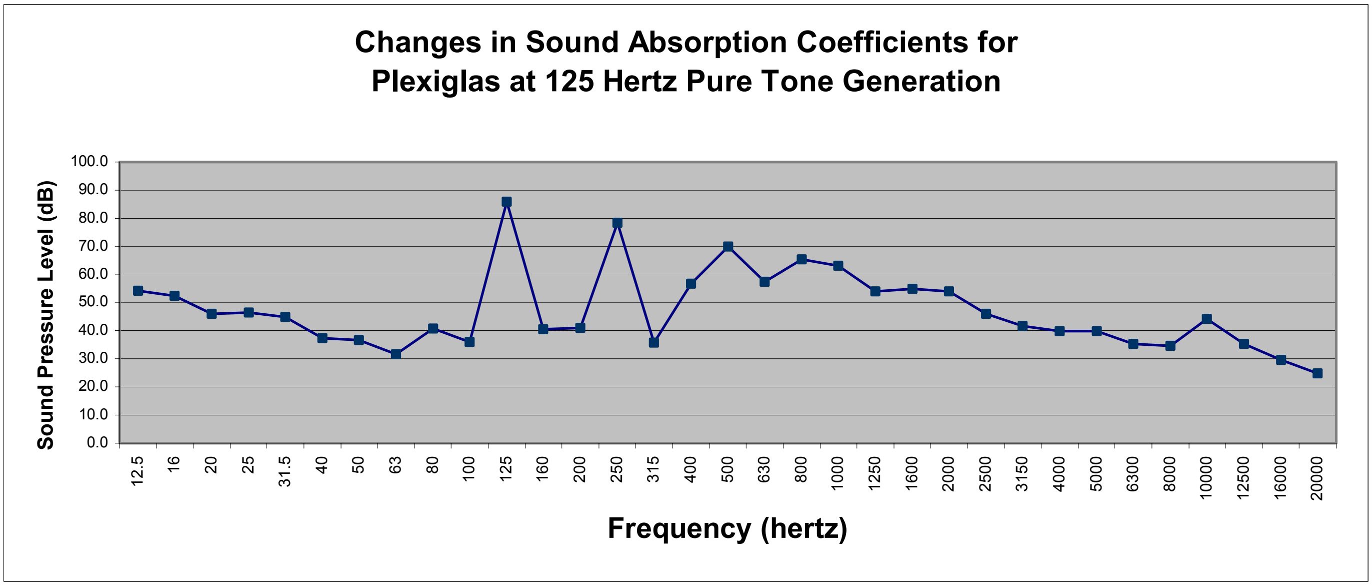

Figure 4.1. Plexiglas Sound Pressure Level at each 1/3 Octave Band.

4.2 Sound Absorption by the Acoustical Foam.

The presence of acoustical foam in the test chamber provided substantial decreases in sound pressure level at frequencies 500 hertz and greater, but increased the SPL at 125 Hz and 250 Hz (Table 4.1).

Table 4.1. Sound Pressure Levels in the Test Chamber (dB).

	Frequency (hertz)					
	125	250	500	1000	2000	4000
Plexiglas[1]	84.9	80.1	92.4	95.1	93.5	94.2
Uncoated SONEX (clean)	88.4	91.2	70.9	71.4	65.8	76.9
Uncoated SONEX (layer 1)	88.6	91.4	71.3	68.5	70.2	71.3
Uncoated SONEX (layer 2)	88.5	91.3	71.1	70.0	71.4	74.5
Uncoated SONEX (layer 3)	86.3	90.1	71.9	69.3	73.7	69.0
Uncoated SONEX (cleaned)	85.2	89.6	72.0	72.2	70.9	75.1
Hypalon coated SONEX (clean)	86.5	89.3	64.9	71.6	69.1	66.6
Hypalon coated SONEX (layer 1)	86.5	89.2	62.1	73.2	69.1	69.6
Hypalon coated SONEX (layer 2)	86.8	88.9	62.5	70.0	68.5	75.1
Hypalon coated SONEX (layer 3)	87.0	89.5	60.9	75.7	65.7	59.8
Hypalon coated SONEX (cleaned)	87.1	89.1	64.3	71.9	69.9	71.9

1. Average of 3 trials.

4.3 Wood Dust Deposition and Cleaning.

Three layers of wood dust were deposited on the foam. Each application increased the mass of dust on the foam, Table 4.2, Figures 4.2 – 4.4.

Table 4.2. Mass of Wood Dust on Surface of Foam.

	Uncoated Foam		Hypalon Coated Foam	
Dust Application				
1	66.8 (g)	3.34 (g/m^2)	135.4 (g)	6.77 (g/m^2)
2	157.8 (g)	7.89 (g/m^2)	347.3 (g)	17.365 (g/m^2)
3	619.0 (g)	30.95 (g/m^2)	453.9 (g)	22.695 (g/m^2)
After Cleaning	189.7 (g)	9.485 (g/m^2)	-22.6 (g)	-1.13 (g/m^2)

Figure 4.2. Photograph demonstrating the amount of wood particulate on the SONEX Hypalon coated acoustical panels during layer 1 deposition.

Figure 4.3. Photograph of the particulate level on Hypalon coated SONEX for particulate layer 2.

Figure 4.4. Close up photograph of particulate layer 3 on Hypalon coated SONEX.

The cleaning removed some of the particulates from the uncoated foam and virtually all the dust from the coated foam, Figure 4.5.

Figure 4.5. Photograph of cleaning SONEX foam with standard vacuum and attachment demonstrates level of cleanliness.

4.4 Effect of Wood Particulate on the Sound Absorption of Acoustical Foam

The change in sound pressure level measured after application of wood dust varied with frequency, foam type, and level of particulate deposition (Table 4.3). The wood dust improved the sound absorption for uncoated SONEX at 1000 and

4000 hertz and for the Hypalon coated SONEX at 500 and 2000 hertz. The sound absorption decreased with dust deposition on the uncoated SONEX at 2000 hertz and Hypalon coated SONEX at 1000 and 4000 hertz.

Table 4.3. Changes in Sound Pressure Level after Deposition of Wood Dust on the Acoustical Foam (dB).

	Frequency (hertz)					
	125	250	500	1000	2000	4000
Uncoated SONEX (clean)	**88.4 dB**	**91.2 dB**	**70.9 dB**	**71.4 dB**	**65.8 dB**	**76.9 dB**
Uncoated SONEX, layer 1 (0.33 g/ft^2)	-0.2	-0.2	-0.4	2.9	-4.4	5.6
Uncoated SONEX, layer 2 (0.77 g/ft^2)	-0.1	-0.1	-0.2	1.4	-5.6	2.4
Uncoated SONEX, layer 3 (3.01 g/ft^2)	2.1	1.1	-1.0	2.1	-7.9	7.9
Uncoated SONEX (cleaned)	3.2	1.6	-1.1	-0.8	-5.1	1.8
Hypalon coated SONEX (clean)	**86.5 dB**	**89.3 dB**	**64.9 dB**	**71.6 dB**	**69.1 dB**	**66.6 dB**
Hypalon coated SONEX, layer 1 (0.654 g/ft^2)	0.0	0.1	2.8	-1.6	0.0	-3.0
Hypalon coated SONEX, layer 2 (1.68 g/ft^2)	-0.3	0.4	2.4	1.6	0.6	-8.5
Hypalon coated SONEX, layer 3 (2.48 g/ft^2)	-0.5	-0.2	4.0	-4.1	3.4	6.8[1]
Hypalon coated SONEX (cleaned)	-0.6	0.2	0.6	-0.3	-0.8	-5.3

Note: A negative change in SPL indicates an increase in SPL with deposition of wood dust while a positive change in SPL indicates a decrease in SPL.

1. Appears to be a measurement anomaly. See Appendix A-6.

4.5 Sound Absorption Coefficients.

Sound absorption coefficients provide an estimate of a noise control treatment's reduction of reverberant sound. A surface absorbing all energy incident on its surface has a sound absorption coefficient of one, while a totally reflective surface has a sound absorption coefficient of zero. Sound absorption coefficients are calculated from the change in sound pressure level (SPL) after changing the acoustical materials or their surface. The published sound absorption coefficients for the SONEX foams are presented in Table 4.4.

Table 4.4. Sound Absorption Coefficients for SONEX1.

	Frequency (hertz)					
	125	250	500	1000	2000	4000
Uncoated SONEX1	0.11	0.33	0.85	1.05	1.09	1.06
Hypalon coated SONEX1	0.13	0.41	1.002	1.18	1.18	1.13

Note: From SONEXone Panels, 2000 available at www.illbruck-sonex.com.

4.51 Plexiglas Sound Absorption Coefficients.

Since there are no published sound absorption coefficients for Plexiglas, these values, Table 4.5, were calculated using the SONEX coefficients and the changes in SPL, equation 4.1.

Changes in dB =

$$10\bullet\log\left[\left(\left(\alpha_{\mathrm{SONEX}}\bullet 20\ \mathrm{m}^3\right)+\left(\alpha_{\mathrm{Plexiglas}}\bullet 15.7\ \mathrm{m}^3\right)\right)/\left(\alpha_{\mathrm{Plexiglas}}\bullet 35.7\ \mathrm{m}^3\right)\right] \quad (4.1)$$

Coefficients could not be calculated when there was an increase in SPL and the difference exceeded the maximum theoretical difference, 3.6 dB.

Table 4.5. Calculated Sound Absorption Coefficients for Plexiglas.

	Frequency (hertz)					
	125	250	500	1000	2000	4000
Plexiglas (using Hypalon coated data)	0.29	N/A[1]	0.00102	0.00296	0.00240	0.0011
Plexiglas (using uncoated data)	N/A[1]	N/A[1]	0.00340	0.00250	0.00104	0.0111

1. Change in SPL exceeded the maximum theoretical difference.

4.52 Sound Absorption Coefficients for Treated Foam.

Sound absorption coefficients were calculated for particulate laden foam and clean foam, Table 4.6.

Table 4.6. Sound Absorption Coefficients for Particulate Laden and Clean Foam.

	Frequency (hertz)					
	125	250	500	1000	2000	4000
Clean Hypalon Coated SONEX	0.130	[1]	1.023	1.181	1.178	1.129
Layer 1 (0.654 g/ft^2)	0.130	[1]	1.95	0.816	1.178	0.565
Layer 2 (1.68 g/ft^2)	0.107	[1]	1.778	1.707	1.353	0.159
Layer 3 (2.48 g/ft^2)	0.092	[1]	2.571	0.458	2.579	5.407
Post cleaning	0.084	[1]	1.175	1.102	0.980	0.333
Clean Uncoated SONEX	[1]	[1]	0.855	1.044	1.092	1.055
Layer 1 (0.33 g/ft^2)	[1]	[1]	0.779	2.038	0.396	3.855
Layer 2 (0.77 g/ft^2)	[1]	[1]	0.816	1.442	0.300	1.840
Layer 3 (3.01 g/ft^2)	[1]	[1]	0.678	1.695	0.176	6.552
Post cleaning	[1]	[1]	0.663	0.868	0.337	1.602

1. Sound absorption coefficients for the foam were not calculated because Plexiglas sound absorption coefficients were not able to be calculated (see section 4.41).

The values for the sound absorption coefficients vary widely. Many are much greater than the theoretical maximum of 1. This limits their usefulness for predicting the effect of wood dust on SPL.

Chapter 5: Conclusions and Recommendations

5.1 Conclusion to Objective One

Objective one for the experimental study was to measure the particulate deposition affects on the sound absorption characteristics of uncoated and Hypalon coated melomine foam by determining if $\alpha_{\text{clean foam}} - \alpha_{\text{soiled foam}} = 0$, where α is the Noise Reduction Coefficient (NRC).

The variations in the calculated sound absorption coefficients prevent this evaluation. In general, however, the sound absorption by the two types of SONEX foam were affected by the presence of wood particulate. A decrease in sound absorption was observed with an increase in particulate deposition for uncoated SONEX at 2000 Hz and Hypalon coated SONEX at 1000 Hz and 4000 Hz. Wood dust deposition appeared to increase the sound absorption for uncoated SONEX at 1000 and 4000 Hz and for Hypalon Coated SONEX at 500 and 2000 Hz.

5.2 Conclusion to Objective Two

Objective two for the experimental study was to determine the effectiveness of cleaning methods for both Hypalon coated and uncoated SONEX Willtec™ foam panels in terms of noise absorption effects.

The cleaning methods recommended by the manufacturer of SONEX are effective for removing the wood dust. Vacuuming removed substantial quantities of wood dust.

The sound absorption coefficients after cleaning were nearly equal to the clean foam for the Hypalon coated foam. The uncoated SONEX experienced larger differences in coefficients and had residual particulate mass equal to two applications. This was due to difficulties in removing particulates from the pore spaces. The Hypalon coating effectively blocked the particles from entering sound absorbing pore spaces and made the foam easier to clean.

5.3 Positive Attributes of the Study Recommended for Future Investigation

The experimental study had many affective attributes that are recommended in future studies in this area. The recommendations include the areas of chamber construction, particulate dispersal, weighing systems and recording sound levels.

5.3.1 Chamber construction

The 0.25-inch Plexiglas construction was beneficial during the study. The clear chamber allowed a clear line of vision into the chamber to observe particulate dispersal, column movement from air turbulence, chamber cleanliness before and after cleaning, and allow photographing opportunities. While observing the particulate dispersal, the flow-rate and direction of particulate projection could be adjusted to accommodate physical conditions within the chamber without continuously interrupting the procedures to check the conditions. The ability to see behind the foam columns, which were pressed against the chamber walls, allowed any particulate forced behind the panels to be accounted for during the weighing process without moving the panels. One drawback to 0.635 cm thick Plexiglas is the unavailability of published sound absorption coefficients.

5.3.2 Particulate dispersal

The modified leaf-blower particulate dispersal system described in chapter three was an affective means of introducing the particulate into the chamber in a manner representative of industry occurrences. The system allowed small particulate matter to remain airborne for longer periods and settle on the acoustical foam and allowed larger particles to settle to the bottom of the chamber. Additional vertically positioned box fans were used to assist the dispersal system in directing smaller particulate matter back toward the acoustical foam until the desired particulate levels were achieved.

5.3.3 Weighing system

The triple-beam balance weighing system performed beyond the expectations anticipated in the study. The free-hanging acoustical foam columns were weighed to the nearest 1/100th of a gram with ease and accuracy. The triple-beam balance was easy to use, calibrate, and presented a moveable device for measurement. The “fish-hook” hangers used to hold the foam columns from the wooden dowel crossbar made foam changing timely, were lightweight, and added adjustability to balance the acoustical columns.

5.3.4 Sound level recording

The real-time analyzer used to record sound levels allowed for timely and accurate measurements. The ability to analyze the needed frequencies during the same time frame added accuracy to sound level recording and decreased the likelihood of sound level generation variation. The computer interface allowed for data transfer and equipment setup without disturbing the particulate in the chamber.

5.4 Recognized Errors in Study

5.4.1 Effects of humidity on sound absorption

During the study, the humidity within the room was not controlled with either dehumidifiers or humidifiers. Each day of testing, the humidity was measured with a humidistat and recorded. It is unknown what, if any, effect the humidity within the room and within the foam had on its sound absorption coefficient. The humidity did have affects on the sum of the foam column weights, which affected the perceived amount of wood particulate on the foam. For this reason, the sound absorption coefficients were not used within a ratio to the amount of wood particulate on the foam.

5.4.2 Equality of wood particulate levels on both foams

During the introduction of wood dust into the chamber for application on the two types of foam, the particulate was added to each level by visual equality, not measured weight equality. For example, layer one particulate on the uncoated foam was 66.8 grams, which was visually comparable to 135.4 grams on the Hypalon coated foam. The goal during particulate deposition was to obtain three distinct levels of particulate significantly different from the previous layer, but visually comparable between foam types.

5.4.3 Validity from repeated trials

Each of the two foams was measured with the real-time analyzer for a five-minute interval for each layer of wood particulate. During the study, a repeated sound analysis was not performed which would be used to validate the first. This resulted in the inability to make valid conclusions as to the performance of acoustical foam under wood particulate soiled conditions. With three measurements to determine the sound absorption coefficient of Plexiglas, two types of foam, three layers of particulate, a pre-soiled measurement, and a post-clean sound analysis, the tasks of sound analysis, acoustical foam weighing and chamber cleaning became cumbersome. Continued research should focus on study repeatability and a narrowed scope of evaluation. The study sampled over a significant amount of time to collect sound levels for specific layers on the day of testing. Because, temperature and humidity levels were not controlled, questionability of the results arose when measurements were taken on days when the weather conditions had significant differences. Repeated trials would help to clarify some of the concerns regarding the effects of environmental conditions.

5.4.4. Unavailability of Plexiglas Sound Absorption Coefficient

Because published values for the sound absorption coefficient of 6.38 mm thick Plexiglas could not be found, the coefficients used for Plexiglas in the calculation of soiled acoustical foam sound absorption coefficients were based on manufacturer published values for foam to calculate those of Plexiglas. This oversight and the lack of replicate sampling precluded calculating sound reduction coefficients which could be applied to other situations.

5.5 Recommended Continued Work in Areas Not Addressed in Study

5.5.1 Environmental conditions

As mentioned in the “Recognized Errors in the Study” section, continued studies should control the environmental conditions during the study of acoustical foam. A simple humidifier/dehumidifier would accommodate this factor.

One area for continued work is to determine the effects of temperature and humidity on the performance of acoustical foam. The American Conference for Governmental Industrial Hygienists has created a noise reduction coefficient for air at 50% relative humidity only.

5.5.2 Particulate Type and Size

Wood particulate from one manufacturing process within a wood-processing manufacturer was used during the study. The particulate varied in size from fine dust to course wood shavings. During the application of wood particulate on the sound-absorbing surface of the foam, the fine dust particles settled more predominately on the foam while the course particles either settled out before reaching the foam or bounced off the foam. The settling out of large particles is consistent with conditions found within wood manufacturing settings.

Continued studies should focus on a specific size of wood particulate. Studies should also pre-determine wood differences, wood moisture content, and additional types of dust.

5.5.3 Sound Intensity

The voltage of the signal applied to the speaker was not evaluated in this study. It should be consistent and recorded.

5.5.4 Decay Times

Sound absorption coefficients can be measured using reverberation decay times. Future studies should consider using standard methods, ASTM C423-66 (Standard Method of Test for Sound Absorption of Acoustical Materials in Reverberation Room) and ISO R354 (Measurement of Absorption Coefficients in a Reverberation Room).

Appendix A:
1/3-Octave Band Sound Pressure Levels Measured in the Test Chamber

Appendix A, Table 1.0

125 Hertz Pure Tone Generation Sound Level Results (dB)

		Plexiglas			Uncoated SONEX1					Hypalon Coated SONEX1				
		Plexiglas (1)	Plexiglas (2)	Plexiglas (3)	Uncoated Clean	Uncoated Layer 1	Uncoated Layer 2	Uncoated Layer 3	Uncoated Cleaned	Hypalon Clean	Hypalon Layer 1	Hypalon Layer 2	Hypalon Layer 3	Hypalon Cleaned
Frequency (hertz)	**12.5**	54.3	56.4	55.1	58.9	53.5	55.9	52.2	55.8	54.4	52.7	56.9	55.9	60.6
	16	52.5	53.6	55.2	55.3	56.6	52.6	55.0	53.8	55.0	57.5	54.6	55.5	57.7
	20	45.9	49.9	53.9	48.4	56.4	47.6	53.7	49.4	53.7	55.5	52.2	53.5	56.8
	25	46.4	48.9	51.0	45.6	52.6	49.6	48.9	46.2	49.7	46.4	50.4	50.9	59.0
	31.5	44.8	42.4	41.6	43.4	46.4	40.2	40.9	40.4	40.5	41.9	42.0	48.0	52.0
	40	37.3	40.4	38.5	34.1	39.7	35.1	35.0	35.5	36.2	37.6	36.6	42.0	50.6
	50	36.7	43.7	38.7	35.7	40.2	35.1	32.1	36.8	35.6	38.0	36.6	41.2	42.0
	63	31.6	38.8	35.5	33.8	36.9	33.9	31.9	33.8	33.5	33.9	35.4	36.9	39.8
	80	40.7	50.7	43.8	43.2	39.3	37.0	30.4	37.6	40.7	38.8	36.9	44.5	42.4
	100	36.1	40.1	36.5	34.7	37.1	35.4	27.5	34.7	33.8	31.9	34.2	37.1	38.2
	125	**85.9**	**83.9**	**84.6**	**88.4**	**88.6**	**88.5**	**86.3**	**85.2**	**86.5**	**86.5**	**86.8**	**87.0**	**87.1**
	160	40.6	43.6	45.6	42.2	40.5	40.3	42.7	41.0	43.2	43.3	43.1	43.9	44.2
	200	40.9	41.7	40.8	36.5	34.7	36.0	31.3	32.1	31.8	29.9	31.6	39.2	36.5
	250	78.4	68.3	74.9	81.8	81.0	81.1	80.3	78.5	80.3	80.1	80.2	80.7	79.8
	315	35.7	41.0	39.6	35.3	32.7	33.4	39.9	42.4	37.1	37.0	36.2	38.8	36.3
	400	56.8	55.1	56.8	50.3	51.0	51.7	56.6	57.9	50.4	50.7	50.4	47.9	48.5
	500	70.0	66.1	64.8	53.9	55.2	56.1	62.3	64.3	53.8	55.7	54.2	51.6	52.1
	630	57.4	62.0	71.1	59.5	58.1	58.8	60.8	59.4	59.2	59.4	59.1	59.3	59.3
	800	65.3	62.5	59.7	52.2	52.0	53.0	50.2	51.7	48.3	45.0	50.5	49.9	50.1
	1000	63.2	53.5	55.4	49.6	49.7	50.6	39.6	42.6	43.3	40.7	46.1	45.9	46.0
	1250	53.9	55.0	59.1	38.4	37.8	38.5	38.6	38.4	41.1	40.8	41.2	40.4	40.2
	1600	54.9	53.5	60.2	42.8	41.9	41.1	40.0	41.1	37.0	36.9	39.1	37.9	38.3
	2000	53.9	51.5	51.9	37.6	39.4	38.1	36.5	39.3	35.1	34.9	37.3	38.4	38.6
	2500	46.0	44.1	47.1	29.6	30.5	30.3	28.5	25.4	29.1	28.9	28.4	32.3	30.5
	3150	41.6	41.0	41.5	25.7	24.9	24.5	25.0	25.0	25.2	24.5	25.4	27.3	25.7
	4000	39.9	40.8	40.2	26.0	26.2	26.7	26.4	26.1	25.6	25.6	25.6	27.5	26.0
	5000	39.9	40.7	40.4	27.1	27.6	27.4	27.3	27.0	26.5	27.2	27.3	28.6	27.8
	6300	35.4	36.4	35.5	25.3	24.7	25.3	25.0	25.2	25.2	24.8	25.0	26.6	25.2
	8000	34.6	35.7	35.8	25.8	25.5	25.9	25.8	25.4	25.2	25.7	25.8	26.7	26.1
	10000	44.1	45.2	44.8	35.1	35.2	35.2	34.8	35.0	34.7	35.3	35.1	35.7	35.1
	12500	35.4	38.2	36.9	27.9	28.3	29.2	28.6	29.3	28.6	29.0	29.0	28.7	28.6
	16000	29.6	31.7	30.5	24.8	24.8	24.8	24.7	24.8	24.5	25.3	26.1	27.0	25.7
	20000	24.8	25.8	25.2	23.8	23.9	23.9	23.9	23.9	23.9	24.0	23.9	24.0	24.0

Appendix A, Table 2.0

250 Hertz Pure Tone Generation Sound Level Results (dB)

		Plexiglas			Uncoated SONEX1					Hypalon Coated SONEX1				
		Plexiglas (1)	Plexiglas (2)	Plexiglas (3)	Uncoated Clean	Uncoated Layer 1	Uncoated Layer 2	Uncoated Layer 3	Uncoated Cleaned	Hypalon Clean	Hypalon Layer 1	Hypalon Layer 2	Hypalon Layer 3	Hypalon Cleaned
Frequency (hertz)	**12.5**	55.1	56.0	55.3	59.4	53.9	55.9	52.4	56.2	55.9	52.8	55.4	51.0	61.5
	16	52.4	53.5	55.1	55.7	55.3	52.8	54.9	54.1	55.1	57.6	52.2	51.3	58.5
	20	46.3	49.0	53.5	49.3	55.9	47.5	53.6	50.9	53.8	55.9	49.8	50.6	57.7
	25	46.5	46.3	50.5	47.5	55.2	49.5	49.1	47.7	49.9	46.8	49.8	49.2	60.4
	31.5	44.8	40.4	42.5	44.9	46.0	41.0	41.4	40.8	40.7	42.0	42.8	42.9	63.3
	40	38.6	36.1	38.5	36.2	39.5	36.1	34.1	37.1	35.6	37.4	37.0	37.5	55.6
	50	41.6	37.6	36.9	39.6	38.6	45.1	31.2	36.5	35.7	37.7	36.6	36.6	46.1
	63	34.7	34.0	35.9	34.6	37.0	34.5	31.8	34.6	34.4	40.9	35.9	33.1	41.9
	80	40.9	35.8	40.4	39.0	37.5	34.3	32.1	36.5	41.5	38.3	42.8	37.0	48.5
	100	33.8	32.5	32.8	32.0	31.1	31.3	27.3	29.9	30.3	32.5	32.1	31.2	41.8
	125	37.0	35.8	36.8	38.4	38.9	39.4	37.9	37.1	37.5	41.3	37.4	37.0	40.1
	160	38.9	36.9	40.1	35.1	34.7	38.2	30.1	32.5	31.3	34.1	33.3	29.7	38.8
	200	39.4	34.8	37.3	32.4	31.4	38.9	35.2	36.2	33.8	40.3	33.3	31.8	36.1
	250	**81.9**	**78.9**	**78.8**	**91.2**	**91.4**	**91.3**	**90.1**	**89.6**	**89.3**	**89.2**	**88.9**	**89.5**	**89.1**
	315	40.3	36.0	40.0	46.9	47.3	47.5	45.0	44.5	44.2	44.3	44.3	44.6	44.1
	400	37.0	35.1	39.3	28.6	29.0	34.8	29.8	28.1	23.1	28.7	28.5	25.5	27.0
	500	82.7	77.2	77.8	73.4	73.6	73.3	74.7	75.7	69.4	70.1	70.6	69.5	70.2
	630	50.2	52.2	50.4	36.9	37.0	37.6	40.7	40.6	38.7	38.4	37.9	38.3	38.7
	800	70.2	69.7	66.6	54.7	55.4	54.9	57.3	57.3	56.0	55.8	56.0	55.9	55.8
	1000	63.6	72.2	63.9	51.6	51.9	51.6	52.4	53.1	49.8	51.0	51.8	50.8	52.5
	1250	73.6	72.4	70.3	56.8	59.1	58.7	55.4	48.1	53.6	50.8	49.4	50.0	49.8
	1600	56.7	59.1	67.0	36.5	33.1	33.3	37.2	42.5	40.5	40.2	44.3	40.6	43.2
	2000	66.4	59.2	62.1	39.8	39.3	39.9	39.5	39.5	33.6	33.9	36.3	31.7	35.7
	2500	52.9	54.5	57.2	32.1	32.5	31.8	31.4	30.3	35.0	33.1	28.7	35.2	33.9
	3150	54.5	53.6	53.7	34.9	37.0	36.5	30.7	27.4	31.9	33.1	32.1	31.6	31.9
	4000	47.4	44.5	47.3	27.7	28.5	27.5	28.0	27.0	25.7	26.4	28.2	27.1	27.8
	5000	43.9	47.0	46.3	22.7	22.7	23.7	28.5	27.9	23.9	24.8	26.2	24.9	26.7
	6300	37.1	36.3	35.2	22.0	22.8	23.2	22.6	23.5	21.9	21.5	23.6	23.4	23.7
	8000	29.4	27.8	29.0	20.5	20.7	20.8	20.8	21.0	20.8	20.8	20.7	20.9	21.2
	10000	26.7	25.2	27.3	21.6	21.6	21.5	21.5	21.9	21.9	21.6	21.3	21.9	21.4
	12500	22.5	22.6	23.2	21.3	21.5	21.5	21.3	21.3	21.7	21.3	21.3	21.3	21.3
	16000	24.4	24.2	24.8	23.5	23.5	23.4	23.7	24.0	23.2	23.9	25.3	25.9	24.6
	20000	23.7	23.7	23.8	23.8	23.9	23.9	23.9	23.8	23.9	23.9	23.8	23.9	23.9

Appendix A, Table 3.0

500 Hertz Pure Tone Generation Sound Level Results (dB)

		Plexiglas			Uncoated SONEX1					Hypalon Coated SONEX1				
		Plexiglas (1)	Plexiglas (2)	Plexiglas (3)	Uncoated Clean	Uncoated Layer 1	Uncoated Layer 2	Uncoated Layer 3	Uncoated Cleaned	Hypalon Clean	Hypalon Layer 1	Hypalon Layer 2	Hypalon Layer 3	Hypalon Cleaned
Frequency (hertz)	**12.5**	56.0	56.4	55.2	59.1	57.3	55.9	53.8	55.6	55.8	53.0	56.0	65.0	59.6
	16	52.9	53.6	55.3	55.4	54.0	52.6	55.6	53.6	55.1	57.8	52.6	65.3	56.2
	20	46.4	49.0	53.4	48.6	48.3	47.2	53.9	49.6	53.9	55.8	50.5	64.0	53.5
	25	46.3	46.2	50.3	46.2	49.4	49.6	49.2	45.9	49.8	46.8	49.9	63.0	53.7
	31.5	44.6	40.7	40.9	44.1	40.7	40.3	41.6	39.9	40.8	41.2	41.4	55.0	43.9
	40	37.5	37.1	36.8	36.8	36.6	35.5	39.0	34.8	36.5	37.8	37.5	50.1	41.2
	50	36.9	37.3	37.1	42.5	39.7	35.7	34.7	33.5	37.5	39.8	39.9	54.7	37.8
	63	32.0	33.5	34.2	34.6	35.6	34.8	32.5	34.5	35.9	36.8	35.0	48.0	38.0
	80	41.8	38.0	41.8	41.1	37.1	36.4	32.2	33.5	47.3	39.9	40.0	49.5	38.9
	100	34.0	31.8	30.3	33.2	31.8	28.9	26.3	30.4	34.6	36.0	31.1	44.4	30.9
	125	34.0	32.0	33.6	35.0	34.4	34.0	33.6	31.2	35.4	35.7	33.3	35.5	34.5
	160	43.1	37.3	36.5	36.9	34.3	38.1	32.4	35.1	37.9	39.0	33.0	35.5	31.9
	200	46.7	35.3	32.5	40.3	34.0	32.6	32.0	33.9	33.2	34.5	29.2	35.2	26.0
	250	44.6	37.4	33.0	36.1	31.0	34.5	31.0	33.4	29.7	32.9	31.5	31.5	27.2
	315	44.7	33.1	30.3	31.6	26.6	32.4	26.7	30.6	26.9	29.2	27.3	27.8	24.7
	400	42.7	41.8	39.1	32.8	28.3	31.6	29.6	28.1	26.8	28.5	27.7	26.8	26.1
	500	**94.4**	**90.9**	**91.1**	**70.9**	**71.3**	**71.1**	**71.9**	**72.0**	**64.9**	**62.1**	**62.5**	**60.9**	**64.3**
	630	54.4	43.3	40.9	32.6	31.2	34.1	31.0	32.8	27.6	29.8	28.2	26.9	27.3
	800	41.4	37.3	35.1	25.1	22.8	26.8	24.1	24.2	21.3	25.1	21.7	21.8	23.0
	1000	87.0	91.3	90.5	60.9	57.3	58.2	68.1	68.8	63.5	59.5	59.8	62.4	58.6
	1250	46.9	36.6	38.7	23.0	23.2	23.5	22.5	20.8	19.5	21.6	20.2	20.9	21.1
	1600	75.3	69.7	68.5	51.1	51.7	53.2	62.4	61.0	56.2	56.5	56.7	57.2	55.2
	2000	70.2	83.0	74.6	52.8	52.4	52.9	56.2	51.1	50.5	50.9	52.7	45.3	51.1
	2500	70.1	73.7	72.9	49.2	49.7	50.4	42.0	38.8	46.1	47.5	47.2	32.8	41.4
	3150	58.7	65.0	55.6	42.8	37.7	42.0	48.6	46.0	47.4	46.9	48.0	47.9	47.5
	4000	58.2	64.9	59.5	43.9	38.8	43.1	47.4	46.1	46.5	46.1	47.7	47.9	47.4
	5000	53.3	52.6	57.6	36.2	39.1	38.5	42.5	32.8	39.2	41.5	40.3	31.9	37.9
	6300	49.1	47.7	45.7	32.2	31.8	31.7	31.3	30.4	29.9	30.4	33.6	32.5	34.8
	8000	39.8	38.7	35.8	24.2	27.2	25.6	22.1	23.5	24.3	24.5	25.2	26.6	26.9
	10000	41.7	41.1	39.0	23.8	24.6	23.6	23.4	22.0	21.8	23.5	23.5	23.9	23.3
	12500	30.0	34.1	32.1	21.2	21.5	21.4	21.2	21.4	22.5	22.2	21.7	21.5	22.1
	16000	26.0	26.2	25.6	23.4	23.6	23.4	23.5	24.3	23.1	23.9	25.0	26.4	24.4
	20000	23.8	24.6	23.9	23.6	23.7	23.7	23.7	23.7		23.7	23.7	23.7	23.8

Appendix A, Table 4.0

1000 Hertz Pure Tone Generation Sound Level Results (dB)

		Plexiglas			Uncoated SONEX1					Hypalon Coated SONEX1				
		Plexiglas (1)	Plexiglas (2)	Plexiglas (3)	Uncoated Clean	Uncoated Layer 1	Uncoated Layer 2	Uncoated Layer 3	Uncoated Cleaned	Hypalon Clean	Hypalon Layer 1	Hypalon Layer 2	Hypalon Layer 3	Hypalon Cleaned
Frequency (hertz)	**12.5**	54.6	55.7	55.3	59.3	57.1	55.9	52.0	55.9	55.6	52.9	55.9	52.0	59.5
	16	52.6	53.4	55.4	55.6	54.0	52.6	55.1	53.8	55.2	57.6	52.6	52.4	56.5
	20	46.1	48.9	53.8	49.2	48.2	47.5	53.4	49.6	53.9	56.2	50.0	51.6	53.5
	25	47.0	45.6	50.7	47.2	49.6	49.7	49.1	45.7	49.8	46.7	50.3	49.7	53.8
	31.5	45.6	40.0	41.6	45.1	40.9	40.4	41.7	40.1	42.3	41.6	41.8	45.6	43.9
	40	37.3	35.7	38.3	36.4	36.0	34.9	34.8	36.1	38.0	36.5	38.2	39.0	39.2
	50	40.8	35.5	36.1	39.5	35.2	33.6	32.0	35.7	40.1	38.8	38.3	37.3	35.8
	63	31.6	33.6	36.4	35.4	34.8	35.2	31.8	33.5	38.0	35.5	35.0	36.4	38.3
	80	41.0	35.7	41.7	42.0	36.8	32.5	32.3	33.7	46.4	38.9	38.0	43.1	41.2
	100	34.2	31.6	32.6	34.6	32.4	29.4	28.1	31.3	33.7	36.2	29.1	37.9	32.2
	125	31.6	32.1	34.5	35.5	34.8	36.1	34.3	32.4	42.5	34.3	32.8	38.1	35.4
	160	34.6	35.5	36.0	35.8	33.3	37.0	31.9	33.7	48.8	34.8	33.9	43.7	32.7
	200	30.6	36.7	33.3	38.2	33.5	35.3	30.0	34.5	38.9	30.5	30.3	41.5	26.2
	250	30.6	38.5	33.0	34.5	31.9	36.7	33.5	34.8	35.7	36.0	30.8	45.0	29.5
	315	26.1	34.6	33.3	30.6	25.6	29.1	25.9	30.7	35.6	29.4	30.1	40.6	25.1
	400	24.5	38.2	30.8	31.7	26.5	33.0	25.4	29.1	32.1	29.8	27.0	29.5	23.1
	500	28.2	41.0	34.1	33.6	30.2	34.6	27.5	32.4	30.1	32.5	26.5	29.9	25.4
	630	30.1	40.3	33.9	31.0	27.7	31.5	23.7	29.4	25.6	29.8	21.8	28.1	24.1
	800	37.7	37.8	43.3	26.9	28.0	27.3	26.6	28.2	26.7	27.4	25.3	29.3	26.2
	1000	**94.4**	**97.1**	**92.5**	**71.4**	**68.5**	**70.0**	**69.3**	**72.2**	**71.6**	**73.2**	**70.0**	**75.7**	**71.9**
	1250	56.5	54.1	48.5	34.5	34.4	34.1	24.8	28.9	23.3	28.6	28.1	34.3	27.1
	1600	27.3	30.6	33.1	19.9	23.5	19.9	19.0	25.6	18.0	21.1	19.7	23.5	20.1
	2000	77.2	79.8	93.7	60.0	61.9	64.4	65.0	64.4	62.5	62.2	63.3	66.3	63.5
	2500	39.5	37.6	49.4	24.5	28.6	28.7	20.0	25.0	19.2	21.2	22.4	26.4	21.1
	3150	51.5	55.7	54.1	37.0	39.5	34.8	34.3	39.0	34.9	38.1	32.0	31.3	29.8
	4000	78.4	73.7	71.3	53.9	47.1	58.8	61.4	62.4	54.7	52.6	56.8	51.1	49.9
	5000	72.8	64.6	71.2	38.3	41.8	46.0	55.2	51.3	57.3	58.5	56.5	54.2	53.5
	6300	43.8	52.0	54.3	30.0	31.2	30.7	36.2	34.9	35.1	28.3	34.7	39.9	37.3
	8000	48.4	54.7	56.1	31.2	36.6	33.8	38.6	36.9	35.8	34.4	35.4	41.0	38.5
	10000	49.3	46.4	45.8	28.9	30.7	28.1	29.6	30.5	28.6	32.5	27.9	35.2	30.4
	12500	44.0	45.5	41.5	24.4	29.5	24.6	25.0	25.0	28.7	28.3	22.1	24.5	23.4
	16000	27.9	26.6	27.8	23.4	29.2	23.6	23.6	24.7	23.1	24.0	25.0	26.2	24.4
	20000	24.0	24.4	24.4	23.6	30.0	23.7	23.7	23.7	23.7	23.7	23.7	23.7	23.8

Appendix A, Table 5.0

2000 Hertz Pure Tone Generation Sound Level Results (dB)

		Plexiglas			Uncoated SONEX1					Hypalon Coated SONEX1				
		Plexiglas (1)	**Plexiglas (2)**	**Plexiglas (3)**	**Uncoated Clean**	**Uncoated Layer 1**	**Uncoated Layer 2**	**Uncoated Layer 3**	**Uncoated Cleaned**	**Hypalon Clean**	**Hypalon Layer 1**	**Hypalon Layer 2**	**Hypalon Layer 3**	**Hypalon Cleaned**
Frequency (hertz)	**12.5**	55.5	55.7	55.5	59.3	57.2	55.8	53.0	55.7	53.0	53.0	55.9	51.3	59.9
	16	53.1	53.4	55.3	55.5	53.8	53.0	55.0	53.8	54.9	57.6	52.6	52.0	56.7
	20	48.0	49.0	53.5	48.7	48.9	47.2	53.9	49.6	54.5	55.9	50.6	50.8	54.0
	25	47.5	46.0	51.1	46.9	49.9	49.5	49.5	45.6	48.7	47.2	50.6	49.2	54.1
	31.5	45.7	39.9	41.5	43.8	41.0	40.4	42.1	39.9	41.2	41.4	41.8	46.4	45.1
	40	38.0	36.0	37.7	34.9	36.4	35.0	34.5	37.8	35.1	36.1	36.4	41.0	40.3
	50	41.7	36.6	38.5	39.7	35.4	35.7	31.6	40.6	34.0	37.3	37.5	38.5	43.7
	63	33.0	33.8	35.8	33.8	35.4	34.1	32.0	34.1	33.3	35.8	35.2	36.3	41.8
	80	39.2	34.8	42.3	36.6	37.1	36.1	30.9	34.6	37.1	45.4	39.0	42.2	45.5
	100	31.9	31.3	30.3	32.1	30.6	30.6	24.7	39.2	27.9	30.7	31.8	32.8	36.8
	125	30.8	31.3	33.6	33.1	34.8	33.8	33.5	33.9	34.1	32.6	34.3	33.8	35.5
	160	36.8	35.0	35.4	33.4	35.6	36.3	31.9	31.9	33.2	36.1	34.4	33.6	35.7
	200	33.3	37.8	35.6	34.7	35.6	35.0	30.9	36.3	29.2	36.7	29.9	32.0	31.1
	250	31.4	35.2	35.7	32.8	36.6	34.6	32.0	35.3	29.7	34.1	31.4	30.3	31.8
	315	27.6	31.2	30.4	29.2	29.1	30.3	28.1	29.5	24.5	30.8	27.3	31.0	28.6
	400	26.8	29.9	32.1	29.1	30.0	29.8	28.2	28.3	21.7	31.3	25.3	26.4	26.3
	500	28.8	34.5	30.6	31.3	32.7	31.8	29.7	32.5	23.5	33.5	26.1	26.0	29.5
	630	28.7	33.7	29.6	27.7	29.9	30.0	24.1	28.6	18.5	31.3	23.2	26.2	26.4
	800	29.2	28.5	37.1	22.9	23.9	25.1	19.6	25.1	17.1	24.4	20.9	24.3	22.5
	1000	26.1	26.6	38.4	20.0	18.6	20.7	17.1	21.5	16.4	19.9	18.3	22.0	20.4
	1250	25.1	28.4	32.9	18.8	18.3	21.3	17.6	20.3	17.1	19.9	19.4	25.2	20.3
	1600	30.2	36.2	41.3	19.4	20.5	20.8	20.8	24.1	18.7	21.1	20.9	21.8	20.4
	2000	**91.1**	**94.8**	**93.7**	**65.8**	**70.2**	**71.4**	**73.7**	**70.9**	**69.1**	**69.1**	**68.5**	**65.7**	**69.9**
	2500	50.7	43.7	51.1	27.8	30.9	32.1	19.6	22.6	19.0	19.6	20.8	22.0	19.9
	3150	23.9	26.7	25.3	18.7	18.4	18.6	19.1	21.3	18.6	19.4	19.8	19.6	19.4
	4000	85.5	82.9	80.8	70.3	70.0	68.5	68.9	68.1	68.1	64.0	67.7	67.1	70.3
	5000	45.0	32.5	38.2	31.9	30.8	29.4	19.5	21.9	19.6	19.3	20.2	20.9	20.2
	6300	62.2	56.4	59.0	49.3	47.7	44.7	38.2	36.5	39.8	32.3	41.8	35.8	46.7
	8000	63.1	66.9	68.5	44.1	50.7	48.9	48.9	41.8	47.4	38.1	49.7	42.0	52.9
	10000	68.6	63.8	63.0	45.0	40.5	32.9	43.7	39.6	35.4	47.5	39.0	46.8	36.1
	12500	44.2	42.7	45.2	29.1	26.4	26.5	23.6	26.8	30.0	26.3	26.5	30.2	26.8
	16000	42.6	40.3	44.4	27.9	29.5	26.2	27.5	28.6	24.3	25.2	30.0	30.7	26.6
	20000	25.9	28.9	27.4	23.6	23.8	23.8	23.8	26.6	23.7	24.0	23.7	23.9	24.1

Appendix A, Table 6.0

4000 Hertz Pure Tone Generation Sound Level Results (dB)

		Plexiglas			Uncoated SONEX1					Hypalon Coated SONEX1				
		Plexiglas (1)	**Plexiglas (2)**	**Plexiglas (3)**	**Uncoated Clean**	**Uncoated Layer 1**	**Uncoated Layer 2**	**Uncoated Layer 3**	**Uncoated Cleaned**	**Hypalon Clean**	**Hypalon Layer 1**	**Hypalon Layer 2**	**Hypalon Layer 3**	**Hypalon Cleaned**
Frequency (hertz)	**12.5**	55.5	55.7	55.3	59.4	56.9	55.7	51.6	55.7	53.4	52.5	55.6	52.1	57.6
	16	52.5	53.4	55.8	55.2	53.7	52.7	54.8	53.7	54.9	57.4	52.7	51.9	58.9
	20	46.8	48.9	53.9	48.5	47.7	47.8	53.5	49.8	54.0	56.1	50.2	51.1	59.0
	25	47.1	45.8	50.8	46.7	49.4	49.8	49.2	46.1	49.2	46.8	50.4	49.6	60.0
	31.5	45.3	40.2	41.6	45.2	40.9	40.3	41.8	39.8	40.8	41.1	41.5	41.6	55.1
	40	37.2	36.2	36.8	35.8	40.9	35.4	35.1	35.7	35.1	37.8	36.9	37.1	50.3
	50	38.8	39.0	34.7	39.9	39.6	39.9	32.4	36.3	35.0	36.3	37.7	35.8	45.5
	63	31.4	33.4	35.6	34.2	34.6	35.6	31.8	33.8	33.6	34.5	34.3	35.2	41.5
	80	41.5	34.1	40.0	39.5	36.1	35.4	32.2	34.0	47.8	40.9	36.5	41.6	48.3
	100	31.9	31.2	30.6	32.4	28.8	31.3	28.0	33.5	29.9	32.3	29.4	28.5	41.9
	125	29.2	30.6	34.2	34.3	33.9	35.2	35.0	33.5	33.8	33.9	31.2	31.8	40.6
	160	33.5	32.4	34.5	35.1	36.4	37.6	38.7	33.9	35.3	35.9	31.5	33.3	42.9
	200	30.5	32.1	31.8	34.7	27.2	32.0	36.9	38.9	28.9	35.4	27.3	26.0	35.7
	250	30.2	30.9	31.2	33.8	34.3	34.4	37.9	37.7	29.2	39.2	27.0	29.1	30.7
	315	26.5	29.1	29.2	29.6	31.9	32.7	34.7	30.9	26.1	32.1	25.7	26.6	28.0
	400	25.3	28.2	27.0	29.8	29.6	30.7	32.7	30.8	22.5	31.9	26.0	22.8	26.7
	500	27.0	30.1	31.4	33.7	30.0	34.2	36.1	35.4	21.9	35.8	24.8	23.9	24.3
	630	28.8	29.0	28.9	29.0	26.9	31.8	34.9	34.0	20.2	33.0	23.4	22.2	22.1
	800	31.1	26.3	28.0	26.6	23.7	27.3	26.9	26.9	21.9	24.7	21.0	19.4	20.8
	1000	26.7	28.0	27.3	23.8	19.1	25.4	21.6	21.2	19.5	20.5	18.5	18.3	19.1
	1250	27.1	28.4	27.0	21.7	19.8	23.6	22.5	21.4	20.9	19.6	19.8	19.2	19.8
	1600	24.1	26.6	28.2	21.4	20.6	27.5	23.5	22.2	21.5	21.3	20.6	19.9	20.0
	2000	24.5	25.4	28.3	22.2	20.5	27.7	21.0	22.1	21.2	20.1	20.3	20.4	20.0
	2500	24.9	26.7	28.3	22.5	21.0	26.6	20.2	22.5	22.7	20.4	19.8	21.0	20.4
	3150	29.2	29.4	34.7	24.1	22.0	25.7	19.2	23.3	22.7	19.5	19.9	21.5	21.6
	4000	**95.8**	**89.1**	**95.1**	**76.9**	**71.3**	**74.5**	**69.0**	**75.1**	**66.6**	**69.6**	**75.1**	**59.8**	**71.9**
	5000	57.0	41.8	47.9	36.0	29.6	35.9	24.4	26.5	25.0	24.8	30.8	23.7	25.8
	6300	23.9	23.8	25.3	25.3	23.9	27.9	19.8	24.1	23.9	19.6	19.9	23.7	23.1
	8000	78.4	80.8	77.2	60.9	60.1	60.8	62.9	63.1	53.5	64.6	53.9	61.1	65.6
	10000	39.8	33.8	30.8	27.8	26.3	27.2	22.4	25.9	25.8	23.1	21.3	26.3	25.3
	12500	64.8	63.3	61.3	44.9	38.2	43.5	36.1	37.3	46.4	47.7	36.9	40.0	36.2
	16000	45.8	52.2	49.5	34.7	41.5	34.0	33.9	34.4	33.5	38.6	33.8	38.3	32.8
	20000	37.2	33.2	34.0	30.1	28.6	28.0	25.3	29.1	28.9	24.4	23.7	29.5	28.4

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