BASIC DESIGN PARAMETERS OF ACOUSTICALLY TREATED SHIELDED ENCLOSURES

Acoustically treated shielded enclosures are ideally suited for a conference room required to provide a high degree of RF and acoustic isolation to the parent room. Parent room floor loading restraints, degree of isolation and cost become the primary factors in the design.

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HISTORICAL REVIEW

PURPOSE

Historically, the primary purpose of a shielded enclosure was to provide a sterile electromagnetic environment, free from radio frequency contamination caused by electromagnetic signals such as radio/TV broadcasting, and industrial RF signals (lights, switches, motors, or any other device that makes or breaks the flow of electric current). Enclosures providing such sterile electromagnetic environments were used as test chambers to measure the electromagnetic characteristics of equipment under test.

Although shielded enclosures date back to the 1930's, their popularity increased significantly in the 1940 to 1950 era. The concept of developing a sterile electromagnetic environment was expanded from a "Test Bed" usage to an "operation" usage, whereby equipment and systems were placed in shielded enclosures to protect them from the interference generated by signals emanating from commercial communications and industrial equipment. In other words, computers or sensitive electronics were placed in shielded enclosures for protection against interfering signals.

A secondary purpose of a shielded enclosure was to contain the electromagnetic energy radiated by a device within the boundaries of the enclosure, so that the electromagnetic radiation from the device would not adversely affect equipment outside the shielded enclosure.

SCREEN ROOMS

Initially, the intent and purpose of a shielded enclosure was satisfied by a simple Faraday screen design. The first commercially available shielded enclosures consisted of a series of panels constructed of copper screen wire mesh mounted on 2' x 4' wood frames. Each panel was approximately 4' x 8' in size and the panels were assembled as a room by bolting together the 2' x 4' frame. The floor was covered with plywood to protect the screen mesh.

The door consisted of a screened panel with beryllium copper fingerstock soldered to the perimeter of a brass-edged frame. A hinge system and a companion door buck completed the door assembly.

These enclosures were originally marketed as "screen rooms" and were available with an interior electrical package consisting of incandescent light fixtures, wall outlets, a light switch and power line filters. During the advent of the screen room, electronic laboratories were not necessarily air conditioned so that the screen room was heated and cooled by the air that circulated through the screen room from the parent room.

ATTENUATION CHARACTERISTICS

A typical screen room would be expected to have an electric field shielding effectiveness of 100 dB over the frequency of 100 kHz to 400 MHz. As technology progressed, the generation of signals in the higher frequency ranges became commonplace and the shielding effectiveness limits were raised to include these frequencies. The attenuation of electromagnetic energy generated by the magnetic field also became of interest.

In 1954 a measurement standard was issued for the purpose of establishing a method of measuring the attenuation characteristics of electromagnetic shielded enclosures for electronic test purposes. This standard was called MIL-STD-285 "Attenuation Measurements for Enclosures, Electromagnetic Shielding, for Electronic Test Purposes, Method of." The standard was superceded by a Bureau of Ships document referred to as MIL-A-18123. The 1954 version of MIL-STD-285 was revised in 1956 and redefined the specifications for the test setup requirements of shielded enclosure attenuation measurements.

MIL-STD-285 required the attenuation of shielded enclosures to conform with the specifications given in Table 1.

In 1964, the National Security Agency issued a specification addressing the attenuation of shielded enclosures. This document was called NSA No. 65-6 and specified magnetic field, electric field and plane wave attenuation covering the frequency range of 1 kHz to 10 GHz (Table 2).

	Attenuation (dB)		
Frequency	Magnetic Field	Electric Field	Plane Wave
One Frequency 150 kHz - 200 kHz	70		
200 kHz		100	
1 MHz		100	
18 MHz		100	
400 MHz			100

Table 1. MIL-STD-285.

	Attenuation (dB)		
Frequency	Magnetic Field	Electric Field	Plane Wave
1 kHz	20	70	
10 kHz	55	100	
100 kHz	90	100	
1 MHz	100	100	
10 MHz		100	
100 MHz			100
400 MHz			100
1 GHz			100
10 GHz			100

Table 2. NSA 65-6.

SINGLE SKIN AND DOUBLE SKIN DESIGNS

With the requirements of a magnetic field attenuation being levied on shielded enclosures, the copper screen construction was no longer applicable. Coincidentally, in the same time period, the price of copper rose sharply and a more cost effective method of providing a shielded enclosure type of sterile environment was needed.

Industry responded with the development of a modular shielded enclosure design that consisted of 3/4-inch thick plywood panels (nominally 4' x 8' with a sheet of 24-26 gauge galvanized steel bonded to each side (sandwich design). (It has been said by some industry experts that a single sheet of the galvanized steel would be sufficient to meet the shielding specifications, but it was less costly to cover both sides of the plywood with steel rather than to cover one side with steel and paint or finish the other side). The steel covered plywood sheets were clamped together by a heavy gauge galvanized steel frame assembly and the entire room was bolted together at the frame joints.

A sophisticated RF door was developed to match the shielding characteristics of the steel covered plywood panels. This design was introduced in the late 1950's, and by the mid-1960's was the primary shielded enclosure being offered for sale. In 1990 the modular wood-core/steel-clad shielded enclosure is still the undisputed leader in shielded enclosure sales. Steel welded enclosures and lightweight, single skin sheet metal enclosures are also in common use and both meet the electromagnetic attenuation requirements of NSA 65-6.

Since 1970 a buyer has had the option of comparing shielded enclosures in a competitive market and could expect a quality turn-key product that would meet the attenuation requirements of MIL-STD-285 or NSA 65-6.

The shielded enclosure industry had developed a standard product that could be used as a sterile electromagnetic test chamber or as an enclosure to restrict the radiation of electromagnetic energy of equipment being operated inside the enclosure.

A SHIELDED ENCLOSURE AS A SECURE ROOM

RF SECURITY

From the concept that a shielded enclosure was very effective in containing electromagnetic energy being generated inside the enclosure to the confines of the shielded enclosure's interior, grew the requirement to prohibit an unauthorized person from recovering the electromagnetic energy being emitted by equipment placed inside the shielded enclosure.

Since it had long been deemed feasible that intelligence could sometimes be extracted from a radiated electromagnetic signal, industry and government engineers realized that a shielded enclosure could be a very economical security measure. The enclosure could be used to significantly reduce the risk of an unauthorized person accessing information from equipment placed inside the enclosure that was processing proprietary, sensitive, or classified data. This concept was so successful that currently, the majority of shielded enclosures are purchased as test chambers or as a means to safeguard against the possible loss of sensitive or classified data through electromagnetic recovery techniques.

Users of shielded enclosures have come to depend on the electromagnetic attenuation characteristics of the enclosure to provide the necessary protection against electronic surveillance techniques that can be used in an attempt to recover information that is being processed by electronic equipment placed inside the enclosure.

In the past, the attenuation of *acoustic* signals emanating from equipment and personnel inside the enclosure had been considered only for special applications.

ACOUSTIC SECURITY

In recent years, the acoustic attenuation characteristics of a shielded enclosure has become an important design requirement. More and more users of shielded enclosures are requiring a shielded enclosure to meet an acoustic attenuation specification as well as an electromagnetic attenuation specification.

Specification NSA 65-5 was issued in 1964 and established an acoustic attenuation limit over a range of frequencies. This document is a companion to the NSA 65-6 electromagnetic attenuation specification with the exception that NSA 65-5 does not give a user any specifics on how to perform the measurements. An acoustic attenuation specification comparable to the MIL-STD-285 electromagnetic attenuation specification has never been prepared in the past simply for the lack of a need for such a document.

ACOUSTIC MEASUREMENT GUIDELINES

ACOUSTIC MEASUREMENT RECOMMENDATION

To effectively attenuate sound transmission, both modes of sound transmission (airborne and structure-borne) can be considered in the same manner that the electric field and magnetic field modes of radiation are considered in the procurement of an enclosure designed to attenuate electromagnetic energy.

NSA 65-6 addresses acoustic airborne transmission only. Structure-borne transmission measurements require a different instrumentation setup and different technical expertise. U.S. Government guidance in the form of a standard for performing shielded enclosure structure-borne attenuation of acoustic signals is not readily available.

The subject of a complete specification for acoustic attenuation measurements of a shielded enclosure (airborne and structure-borne) is expected to be addressed by concerned professionals in the very near future. The American Society for Testing Materials (ASTM), has issued a number of standards for measurements of airborne sound energy. In the meantime, users and manufacturers are working together on a best-effort basis to provide a shielded enclosure that offers an acceptable degree of RF and AF attenuation.

BASIC PRINCIPLES OF ACOUSTIC MEASUREMENTS

Basic acoustic engineering principles can quickly be learned by a competent electromagnetic compatibility (EMC) engineer, so that the EMC engineer can make a meaningful contribution in the design or evaluation of an RF/AF shielded enclosure.

Acoustic attenuation measurements are basically made in much the same way as RF attenuation measurements, and require an audio signal source that covers the audio spectrum of interest and an audio detection system. The audio source should be capable of covering the frequency range of approximately 100 Hz to 4,000 Hz and can be in the form of a broadband audio signal source such as a white noise generator which has constant energy output per unit of frequency.

The sound source can also be in the form of a centrifugal fan driven by an induction motor to produce a constant level white noise output.

MEASUREMENTS OF ACOUSTIC ATTENUATION

ACOUSTIC ATTENUATION OF A BARRIER

If a barrier is to be tested for acoustic isolation (sound transmission loss), a random sound field is established on one side of the barrier (source side) and the average sound pressure levels are measured in the source side with a sound level meter (detector). The measurements are repeated on the opposite side of the barrier (receiving side). From this data and the absorption in the receiving room, the sound transmission loss of the barrier may be determined. When cursory sound level measurements are performed in the field, the transmission loss is sometimes given as the difference of the average sound pressure level reading taken on each side of the barrier; however, this procedure is not recommended.

The transmission loss of a barrier is sometimes stated as a single number that represents the overall value of transmission losses measured at nine frequencies: 125; 175; 250; 350; 500; 700; 1,000; 2,000; and 4,000 Hz. In Europe 16 test frequencies (125 to 4,000 Hz) are used.

It is becoming more common to separate the transmission loss measurements into 6 frequencies: 125; 250; 500; 1,000; 2,000; and 4,000 Hz.

The theoretical relationship describing the sound transmission loss of a limp, non-porous, homogeneous barrier in terms of weight per square foot of surface area and frequency is expressed as:

$$TL = 20 \log w + 20 \log f - 33.5 \text{ dB}$$

where

w = weight of barrier in lbs/ft^2
f = frequency of interest in Hz

This equation is called the "Mass Law" equation, and states that the transmission loss of a homogeneous barrier increases by 6 dB with each doubling of weight and increases by 6 dB with each doubling of frequency. The "Mass Law" equation asserts that the heavier the barrier in lbs/ft^2, the higher the transmission loss.

No lightweight material is available (space age included) which exhibits a high degree of acoustic energy attenuation over the frequency range of 100 Hz to 4,000 Hz; users should beware of the merchant selling "lightweight acoustically secure enclosures."

ACOUSTIC DESIGN PARAMETERS

Propagation of Sound Energy. Airborne sound is transmitted through a barrier in much the same manner as a radio frequency signal. When a sound wave traveling through air strikes the barrier surface, some of the energy is reflected back into the source room, some is absorbed in the barrier and dissipated as heat, and some of the energy penetrates the barrier and is detectable in the receiving room.

When the sound waves strike the source side of the barrier, they exert fluctuating pressure on it. The wall will then vibrate like a diaphragm and radiate sound to the receiving side of the barrier. This will occur to some extent on any shielded enclosure wall. For most purposes encountered in shielded enclosure construction, the heavier the barrier and the less the vibration, the greater the sound attenuation.

Only a small portion of the sound wave, incident to the barrier on the source side, is detected as sound energy on the receiving side. The greatest portion of the sound energy is either reflected or absorbed at the surface of the barrier on the source side. Most of the remainder is dissipated within the material of the barrier and a fraction of the initial sound energy incident to the source side of the barrier is radiated to the receiving space. However a large difference is required between the levels on the opposite sides of the barrier to provide good sound isolation. Even a difference as great as 40 to 50 dB will allow a listener on the receiving side to hear loud speech from the source side.

Reverberation. The acoustic treatment of RF enclosures for the purpose of attenuating airborne transmission of sound must be accomplished in such a manner that the effects of sound reflections inside of the enclosure are unobjectionable to the occupants.

When sound radiated in an enclosure reaches the surface -- walls, floors, and ceilings -- some of the incident energy will be reflected back into the room, some will be absorbed by the surface structure and some will be transmitted through the surface. A room treated with hard reflective surfaces will cause much of the sound energy to be reflected back into the enclosure. Hard reflecting surfaces are used to create a diffuse field with sound energy uniformly distributed throughout the room. When these conditions exist, the room is called a reverberant room. Reverberation prolongs sound during the intervals in which no sound is being emitted. (This effect is measured in terms of reverberation time.) Reverberation can be defined in simple terms as the time, in seconds, required for the sound pressure level of reflected sound to diminish by 60 dB *after* the sound source has been turned off. A reverberant room becomes uncomfortable and annoying to the occupants because of a disagreeable "ringing" quality of sounds produced by such a room design.

Acoustical Absorption. To relieve the annoying effects of a reverberant room, the interior surfaces are treated with a material that will absorb the acoustical energy and minimize the sound being reflected back into the room. A room whose interior surface area is highly absorbent to sound energy, whereby the sound energy radiates away from the source as if the source were in a free unrestricted field, is called an anechoic room.

The practical "sound conditioning" design considerations of an acoustically treated RF shielded enclosure should consider a compromise in selecting the material for an acoustic treatment design. For security concerns, the more absorbent, the better. While prime consideration should be given to a material that will prevent the sound frequencies being generated inside of the enclosure from being recovered on the outside, a secondary consideration must be given to the physical and psychological comfort of the occupants. To reduce the annoyance caused by reflected sounds, the interior design of an acoustically treated RF enclosure should specify some acoustically absorbent surface areas. To design a room with a noticeable reverberation improvement, the total absorption of the room after treatment should be approximately *six* times the absorption before treatment.

Absorption Coefficient. Most building materials manufactured for the purpose of acoustic treatment are assigned to a measured sound absorption coefficient which represents the fraction of the sound energy absorbed by the material when a sound wave strikes its surface. The absorption coefficient of a material will vary from 0.01 to 1.0 and is sometimes referred to as its "acoustic absorptivity." The absorptive coefficient of a material is a function of the material itself, the frequency of the sound energy, the angle of incidence when the sound wave strikes the acoustic barrier and the mounting configuration.

It is a common practice for manufacturers of acoustic building materials to publish data relative to the sound absorption qualities of their products. Since the absorption coefficient of a material is a function of frequency, it has become common practice to publish the sound absorption coefficients of the material at six frequencies; 125; 250; 500; 1,000; 2,000; and 4,000 Hz.

Noise Reduction Coefficient. For the purposes of quickly comparing materials for their ability to quiet noise, a noise reduction coefficient is used (NRC). The noise reduction coefficient of a material represents the average of the absorption coefficients (to the nearest multiple of 0.05) at the four frequencies of 125, 500, 1,000 and 2,000 Hz. While the NRC does not totally represent a truly scientific evaluation of the acoustic properties of a material, it is an excellent method of determining an approximate rating of the relative effectiveness of different materials to reduce noise.

Sound Transmission Class. For comparing the transmission loss qualities of one material to another, a sound transmission class (STC) has been accorded to various building materials. The STC is a single number rating for describing the sound transmission loss (attenuation) of a building material.

To determine the STC of a material, the material is subjected to transmission loss measurements over a series of 16 bands (125 Hz to 4,000 Hz). The tests are conducted by qualified independent acoustical laboratories. The tests are performed by placing a test sample between two rooms that are constructed in such a manner that sound originating in a source room must pass through the test sample to reach the receiving room. All other transmission paths are insignificant. Readings are taken at sixteen 1/3 octave frequency band intervals.

After adjustments are made for room absorption and test sample size, the average sound levels measured in the receiving room are subtracted from the corresponding sound levels in the source room and are recorded as transmission loss (dB) levels versus the sixteen 1/3 octave frequency band intervals.

These measured transmission loss levels are plotted on graph paper (preferably transparent) and compared to an ASTM "Criterion" or reference curve. The reference curve is adjusted vertically over the test data curve until the total of the test data points that are below the reference curve does not exceed 32 dB, and at the same time, no test data point extends below the reference curve by more than 9 dB. (Refer to ASTM E413-70T.)

The sound transmission class (STC) of the sample under test is read at 500 Hz. This STC number is generally published in manufacturers' data sheets of building materials commonly used for the construction of interior walls.

DESIGN CONSIDERATIONS OF AN RF/AF ENCLOSURE

FLOOR LOADING CONSIDERATIONS

Greater sound isolation can easily be achieved by designing a more massive shielded enclosure. This concept can lead to the design of a masonry structure lined with sheet metal. Since the requirements of RF/AF enclosures very often specify a demountable structure that can be moved to other locations, only modular bolt-together structures are being addressed in this article.

Many RF/AF enclosures are designed around the floor load limitation that the parent room can accept. If the RF/AF enclosure is located on a building floor plan where weight becomes a critical factor, the design emphasizes the maximum RF/AF attenuation per pound of enclosure weight. If the enclosure is positioned on a basement or ground floor where floor loading is not a factor, the enclosure can then be designed to maximize the RF/AF attenuation characteristics with less regard to weight.

The fact that very acceptable AF/RF attenuation characteristics of a shielded enclosure are readily available if weight and cost are not too restrictive has been stated. However, the designer should limit the extent of AF/RF treatment to practical good engineering concepts and sound economic considerations. If the AF/RF designer accepts a standard RF shielded enclosure as the base structure, then the acoustic treatment becomes the driving force of the design.

RESTRICTED FLOOR LOAD DESIGN - LIGHTWEIGHT RF ENCLOSURE WITH ACOUSTIC TREATMENT

When AF/RF requirements locate

the room on a floor area that has a limited floor loading capacity, the acoustically treated shielded enclosure design should begin with a single-skin sheet metal RF enclosure. The overall weight of a single-skin sheet metal enclosure is approximately 1/2 the weight per surface square foot (SSF) as the weight of a double-skin, wood core/sandwich-type enclosure (approximately 3 1/2 lbs/SSF to 6 1/4 lbs/SSF).

ACOUSTIC DESIGN CONSIDERATIONS OF LIGHTWEIGHT ENCLOSURES (SINGLE-SKIN)

For a lightweight acoustically treated shielded enclosure, an RF enclosure that meets the RF shielding requirements should be selected. The choice should give strong consideration to the simplicity of adding an acoustical barrier to the structure of the basic enclosure.

Walls. A technique that has proven to yield excellent results is to design an internal acoustic barrier that is essentially a second room erected inside the RF shield. The acoustic barrier should be positioned away from the RF skin and should be acoustically isolated at each and every point of contact with the RF structure. A practical means of isolating the acoustic structure from the RF structure is to place an elastic material (such as neoprene) between the two structures at each point where they come into contact with each other (floor to walls to ceiling). The acoustic barrier should be selected to offer the maximum sound transmission loss per square foot of weight as the floor load requirement will stand. A single or double layer of standard gypsum wallboard spaced away from the RF skin is a good starting point in the initial design.

Additional sound transmission loss is obtained if a blanket of sound absorbing material is laid in the open space between the RF skin and the acoustic barrier. The improvement attributed to the sound absorbing blanket is based on the fact that some of the sound energy is absorbed in the acoustic blanket as the sound is transmitted through the open space between the acoustic barrier and the RF barrier.

To provide a soft and warm acoustic environment within the acoustically treated enclosures, the hard reflective surface of the gypsum wallboard should be finished with an acoustic absorbing material with a noise reduction coefficient of between 0.6 to 0.8. A number of commercially available products manufactured in sheets and produced in various colors and textures are available.

Ceiling. A popular ceiling design is a modified acoustic tile drop ceiling matrix suspended by hanger wires which are isolated from the RF structure by neoprene pads. Added sound transmission loss in the ceiling is obtained by adding a sound absorbing blanket above the acoustic tiles.

Floor. The floor design must consider the weight of equipment and occupants, and a simple solution is a double layer of plywood laid in opposite directions over a wood frame laid on the RF skin. A neoprene strip should be placed between the frame and the RF skin. An alternate solution is to lay a layer of plywood directly on the RF skin and then construct the floor frame over it. Neoprene isolation on the bottom of the frame is still recommended. The space between the floor frame should be filled with a sound absorbent blanket to enhance the transmission loss. A wall-to-wall rug with a rubber pad will serve very well as a floor sound absorbing treatment.

Acoustic Leaks. To ensure that the AF treatment is acoustically "tight," all joining points that may serve as a passageway for air between the interior side of the acoustic room and the RF skin should be caulked with a pliable acoustic compound (between panels, drop ceiling, around electrical outlet boxes, around light fixtures, etc.).

An excellent acoustic room design can be compromised by a very small opening that allows an air passage beyond the acoustic boundary. Small slits or cracks caused by loose fitting assemblies can cause a significant reduction in overall system transmission loss of the enclosure.

In the construction of an acoustically secure room, a slit is an opening where the length is large in comparison to the wavelength of sound and in comparison to the width of the slit. For example: If a 3' x 7' door does not have a tight acoustic seal, the slit opening can be on the order of 3' or 7' long, 5" in depth and 1/16" in width.

The wavelength in inches as a function of the frequency is expressed as:

$$\lambda = \text{Speed of Sound} / \text{Frequency (Hz)}$$

at 1,000 Hz,

$$\lambda = 1.13 \text{ ft.}$$

This equation illustrates that any slit on either side or top and bottom of the door can greatly reduce the attenuation of the door assembly. In such cases more sound energy will be transmitted through the slits than through the barrier.

Sealing all possible air passages with acoustic caulking becomes very important when trying to achieve acoustic isolation.

ACOUSTIC DESIGN CONSIDERATIONS OF A HEAVY WEIGHT ENCLOSURE (DOUBLE-SKIN SANDWICH)

Heavy Weight Enclosures: A Description. The heavyweight, acoustically treated shielded enclosures encompass the same design principles as the lightweight design. In applications where floor loading allows a heavier AF/RF enclosure, the acoustic design can accommodate a greater mass and hence a greater acoustic attenuation. The heavyweight shielded enclosure panels are constructed of 3/4-inch plywood or particle board, with a sheet of galvanized steel glued to each side. The additional mass of the plywood plus the additional hard surface of the galvanized sheet of a sandwich-style enclosure enhances the acoustic attenuation from the start.

Wherein the wall thickness of a lightweight acoustically treated shielded enclosure is recommended to be a few inches, the overall wall thickness of a heavyweight, acoustically treated shielded enclosure is recommended to be more than twice as thick for a high acoustic attenuation design. The design parameters for a lightweight or heavyweight, acoustically treated shielded enclosure are similar, in that the building floor load limitations and overall cost of the acoustic treatment become the deciding factors in selecting the particular design.

ACOUSTIC MEASUREMENTS

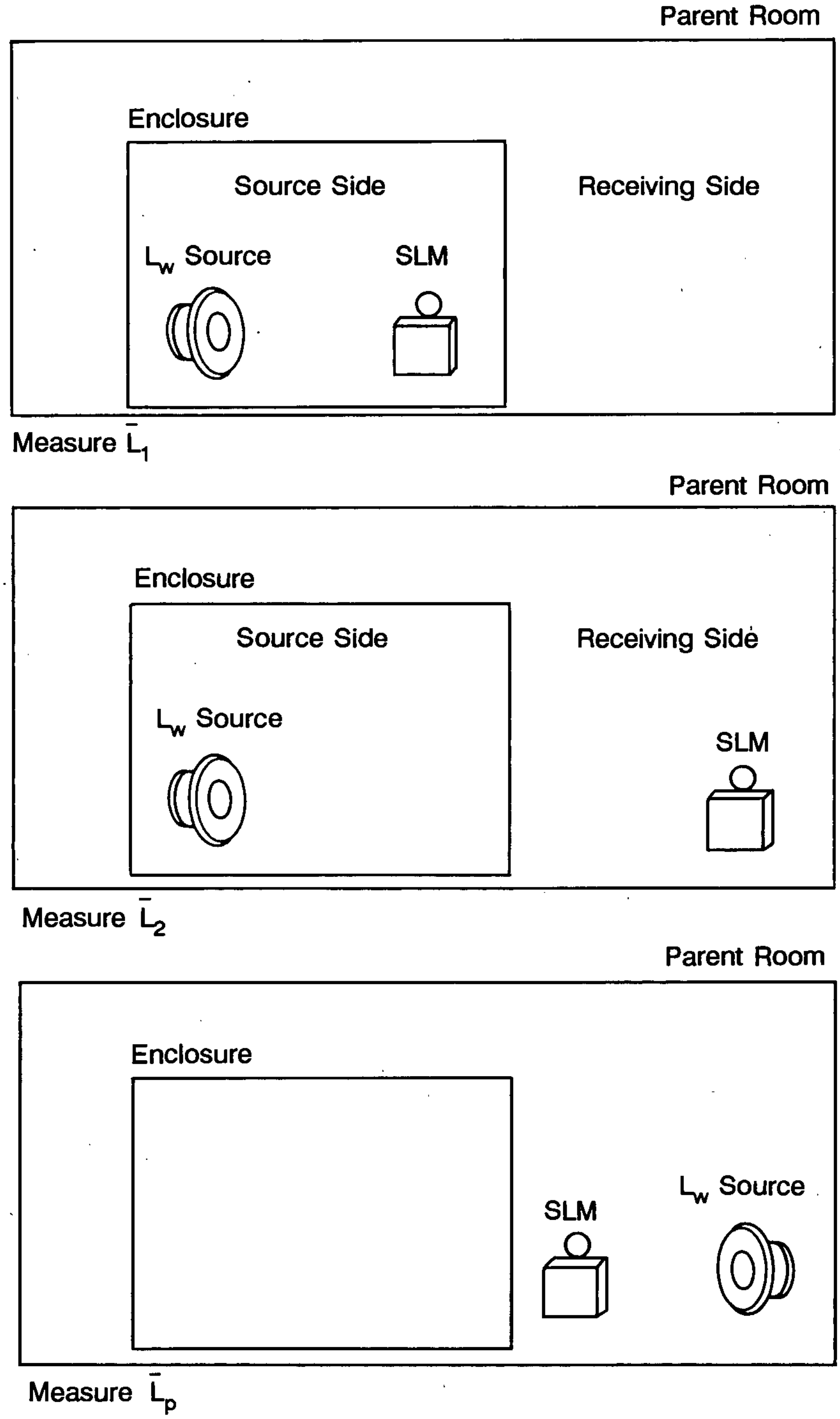
FIELD TRANSMISSION LOSS AND NORMALIZED NOISE REDUCTION MEASUREMENTS (FTL AND NNR)

A good indication of the transmission loss or the noise reduction of an acoustically treated shielded enclosure can be measured in the field with a sound level meter. Noise reduction (NR) in dB can be measured by taking the differences of the average sound pressure level measured in the source room and the receiving room with the sound source turned on. For field transmission loss (FTL) measurements, the sound absorption of the receiving room must be taken into consideration (See Figure 1).

$$NR = \bar{L}_1 - \bar{L}_2 \text{ dB}$$

where

$\bar{L}_1$ = Average sound pressure level in source room (dB)
$\bar{L}_2$ = Average sound pressure level in receiving room (dB)



$\bar{L}_1$ = Average sound level (dB) measured on source side when sound source is activated on the source side.

$\bar{L}_2$ = Average sound level (dB) measured on receiving side when sound source is activated on the source side.

$\bar{L}_p$ = Average sound level (dB) measured on receiving side when the sound source is activated on the receiving side.

$\bar{L}_w$ = Power output of sound source in (dB) referenced to one picowatt (10^{-12} watts).

SLM = Sound level meter with octave band analyzer.

Figure 1. Field Transmission Loss Measurements.

The difference of sound pressure levels on two sides of a barrier may appear to be a measure of the transmission coefficient of the barrier. This is not so because the measurement on the source side includes some of the reflected energy as well as the incident energy.

Field sound transmission loss (FTL) of an acoustically treated shielded enclosure is made by using a sound source with a known power output relative to 1 picowatt (10^{-12}) for each octave band of frequencies with each band centered at 125, 250, 500, 1000, 2000, and 4000 Hz. The measurements are performed with a standard sound level meter equipped with octave band filtering.

The sound source can be positioned in the enclosure or the parent room. Whichever side (parent room or inside enclosure) the sound source is positioned in is referred to as the source room and the remaining room is called the receiving room.

In measuring a sound pressure level, inside the enclosure or outside, a series of measurements should be taken and then averaged ($\overline{L}$). It is suggested that six to eight readings be taken for each test frequency band to account for variations of measurement positions and microphone directivity.

Each of the measurements should be made at various locations and each reading is taken by slowly moving the sound level meter over a volume of space reachable at an arms length distance. Measurements should not be made in the close proximity of the enclosure walls or the sound source. The response of the meter should be set to "slow."

The sound source should be positioned to develop a diffuse sound field which is characterized by a uniform distribution of sound energy density throughout the sound field. A diffuse sound field is generated by sound waves reflecting from surfaces and arriving at any test point with equal probability.

When transmission loss measurements of a barrier are made under laboratory conditions, the barrier or partition is placed in an opening between two test rooms which are acoustically isolated from one another. Acoustic energy travels from one room to the other only through the partition under test.

The test procedure calls for generating a sound field in one room, and measuring the sound level in the source room and the receiving room with the sound source activated.

The transmission loss of the partition under test is determined by the equation:

$$\begin{aligned} TL &= \overline{L}_1 - \overline{L}_2 + 10 \log (S/a) \\ &= \overline{L}_1 - \overline{L}_2 + 10 \log S - 10 \log a \end{aligned}$$

where

$\overline{L}_1$ = Average sound pressure level in source room

$\overline{L}_2$ = Average sound pressure level in receiving room

S = Area of test partition (in square feet)

a = Number of sound absorptive units in the receiving room (SABINS)

ROOM ABSORPTION MEASUREMENTS

The sound absorption in the receiving room can be determined in two ways; (1) "decay rate method" in which (a) is determined by measuring the rate of decay of sound pressure level in the receiving room and (2) "reference sound source method."

In the first method, the room absorption expressed in SABINS is calculated from:

$$a = \frac{0.9210Vd}{C}$$

where

V = Volume of receiving room in ft^3

d = Rate of decay of sound pressure level in dB/sec

C = Speed of sound in ft/sec

$C = 49.022\sqrt{459.64 + T}$
T in degrees Fahrenheit

At T = 70°F, C = 1128 ft/sec

The measurement of rate of decay is made by turning on the sound source for a long enough period for the sound pressure level in the room to reach a steady state. When the sound source is turned off, the sound pressure level will decrease and the rate of decay can be determined by measuring the time it takes for the sound pressure level to decay 60 dB. This measurement is usually made with an acoustic analyzer or a high speed graphic recorder.

The second method for determining the sound absorption is the "reference sound source method." In this method a reference sound source is used that has a known constant power output (dB) relative to a picowatt for each of the 1/3 octave bands of interest (125 to 4000 Hz).

The manufacturer of the sound source should provide the data relating to power output versus 1/3 octave bands. Using a reference sound source with a known power output (Lw), the sound absorption (a) in the receiving room can be determined by measuring the average sound power level Lp in the receiving room with the sound power source placed in the receiving room.

The power output (Lw) of the sound source and the average sound power level (Lp) measured in the receiving room (with the sound receiver operating in the source room) are related to sound absorption (a) in the following manner:

$$10 \log a = Lw - \overline{L}p + 10 \log (PC/100)$$

The terms P and C are a function of the density of the medium, temperature and the speed of sound.

For average room temperature and humidity, the term 10 log (PC/100) is reduced to 16.4 when (a) is expressed in SABINS. The relationship is reduced to:

$$10 \log a = Lw - \overline{L}p + 16.4$$

Expanding the transmission loss equation $TL = \overline{L}_1 = -\overline{L}_2 + 10 \log (S/a)$ to $TL = \overline{L}_1 - \overline{L}_2 + 10 \log S - 10 \log a$, and substituting the last term (10 log a in the above), the equation for TL becomes:

$$TL = \overline{L}_1 - \overline{L}_2 + 10 \log S - Lw + \overline{L}p - 16.4 \text{ dB}$$

Because the parent rooms will all have different acoustic properties, the acoustic test results of the same acoustically treated shielded enclosure erected in different parent rooms may yield vastly different results in determining noise reduction.

NORMALIZED NOISE REDUCTION

The equation given above for transmission loss can be applied to acoustical enclosures if the surface area of the enclosure is used for S.

$$NNR = \overline{L}_1 - \overline{L}_2 + 10 \log S - Lw + \overline{L}p - 16.4 \text{ dB}$$

(This expression applies only when the average absorption of the receiving room is small.)

For measurements of an enclosure, S = the surface area of the enclosure boundaries through which sound waves will travel from the source room to the receiving room. The floor of the enclosure is considered an integral part of the parent room floor and is therefore not included in the calculations of the surface area of the acoustic barrier. The result of this computation is called "Normalized Noise Reduction" (NNR) and represents a property of the room construction that is independent of the size of the room and the absorption in the receiving room.

CALCULATIONS OF NNR

For a shielded enclosure the value of S is the sum of the areas of the 4 walls and the ceiling. Example:

Given:
Enclosure size is 12' x 24' x 8' H
S =
$2(8 \times 12) + 2(8 \times 24) + (12 \times 24) = 864 \text{ Ft}^2$

MEASUREMENT INSTRUMENTATION

Instrumentation required to perform the sound level pressure measurements for determining sound absorption by the reference sound source method are:

1. A sound level meter (SLM) with 1/3 octave band filters (IEC Type 1) and microphone calibrator.
2. A constant power white noise source with up to 110 dB output from 100 Hz to 4000 Hz with built-in filters.

Instrumentation required for determining the sound absorption coefficient by the rate of decay method: a white noise source as used in sound level pressure measurements and an Acoustic Analyzer (AA), complete with microphone and pre-amp or a sound level meter with a reverberation processor module.

TROUBLESHOOTING FOR RF/AF LEAKS

Once the RF and acoustic integrity of the acoustically treated shielded enclosure is established in the design stage, the penetrations of the RF/AF barrier must be treated to conform with the RF/AF system design goals.

RF AND AIRBORNE ACOUSTICS

Penetrations of the RF/AF barrier are the primary source of RF and acoustic leaks. Based on a number of field measurements, the sources of RF/AF leaks in their order of probable occurrence are:

1. Door and door gaskets
2. Air vents
3. Pipe penetrations - waveguide beyond cutoff
4. Pipe penetrations - water, air, power line filter leads
5. Panel joints

These five major sources of RF/AF leaks can easily be corrected for

RF/AF integrity by good engineering design and quality construction practices.

An acoustic treatment for a commercial recessed mechanism-style RF door has to be applied to the RF door to seal any air passages between the door and the door buck. Acoustic leakage associated with the air vent system is a different type of problem.

The air vents (intake and exhaust) can correct the RF leakage problems by utilizing a commercially available grill constructed of a matrix of waveguide beyond cutoff filters (commercially known as a honeycomb RF grill). The honeycomb RF grill is constructed of a number of waveguide beyond cutoff tubes electrically and mechanically connected together.

The waveguide tubes act as high pass filters and attenuate all frequencies below the cutoff frequency of the tubes. The waveguide tubes for the standard RF air vents are approximately 1/8- to 1/4-inch in diameter and are clear visual access openings to allow the passage of air. Obviously, any free flow of air through the acoustic barrier will allow the free flow of sound energy. Consequently the sound energy must be attenuated at the air intake/exhaust grills of the enclosure.

The vent openings must be treated to allow the passage of air while attenuating the sound energy generated inside the enclosure. A practical method of attenuating the acoustic energy at the enclosure vent openings is to place an acoustic filter or muffler over each of the openings. These acoustic filters are usually placed on the exterior of the enclosure in a specific order to provide filtering over the entire audible range extending from 125 Hz to 4000 Hz. The filter elements can be as long as 9 feet:

$$(\lambda \text{ ft} = C \text{ ft/sec} / f_{Hz} = 1128/125 = 9.02 \text{ ft})$$

It is beyond the scope of this article to discuss the design of acoustical filters. Users are advised to contact a reputable manufacturer of acoustical filters and have them suggest a unit that fits the vent opening and also offers the desired attenuation. Increased attenuation of a given acoustic filter design will normally require a longer length.

Since most acoustically treated shielded enclosures are 8' or 10' high, a 7' long acoustic attenuator may be the longest practical length for a vertical mount installation. The enclosure designer should consider a horizontal mount installation to allow a longer filter (greater attenuation) if one is required. Intake and exhaust air vent openings should be judiciously placed to accommodate the acoustical duct installation.

When including acoustical filters on the enclosure design, the designer should keep in mind that the commercial filters are made in a rectangular or circular tube form that is 5' to 9' long with an opening at each end.

To mount such a filter on the surface of a shielded enclosure (walls or roof), a right angle adapter of some type must be fabricated. The walls of the adapter must exhibit the same or better acoustic attenuation characteristics as the acoustic filter itself.

Field measurements have shown that the connecting point of the right angle elbow to the enclosure and to the filter is a common point of acoustic energy leakage.

The designer is cautioned to isolate the junction of the filter system and the enclosure with strips of neoprene. Acoustic caulking should be applied to all joints and seams of the acoustic filter system hardware.

STRUCTURE-BORNE TRANSMISSIONS

Up to this point, only the attenuation of the airborne transmission of sound energy originating inside of the enclosure was considered. The problems of structure-borne transmission of sound energy (vibration) must now be considered.

Structure-borne sound energy in an acoustically treated enclosure is caused by sound waves striking the interior surfaces of the enclosure. Some of the acoustic energy is absorbed by the acoustic treatment; and some is reflected back into the room, some of the energy passes through the acoustic treatment and travels through the enclosure structure itself. Some of the energy that penetrated the barrier becomes airborne.

That portion of the sound energy that travels through the structure of the barrier will eventually reach the point where the acoustically treated shielded enclosure makes contact with the parent room. Once the structure-borne energy reaches the parent room boundaries, it is free to travel throughout the building structure until it becomes dissipated.

For various reasons, it is desirable and in some cases mandatory, to prevent structure-borne acoustic energy generated inside of the enclosure from being coupled to the parent room structure. Since the acoustically treated shielded enclosure can be easily erected so that it does not make any physical contact with the walls or ceiling of the parent room, the isolation of structure-borne noise is concentrated at the floor level where the enclosure must make contact with the parent room.

The attenuation of structure-borne acoustic energy transmitted from the enclosure to the parent room floor can be remedied by the use of vibration isolation materials placed between the enclosure and the parent room floor. The vibration isolators reduce the transmitted structure-borne acoustic energy and the end result is the attenuation of the structure-borne energy. The attenuation of the structure-borne energy (vibrations) can be accomplished by the use of a rubber base isolator, a spring isolator, or a pneumatic isolator.

The amount of attenuation and the lowest frequency at which the structure-borne energy is attenuated will determine the type of vibration damping system required. A study of the various types of commercially available vibration mounts will assist the designer in choosing an appropriate vibration damping system.

Commercially available vibration isolators for this application have a contact surface area ranging from 4" square to 16" square. Practically, they cannot be placed directly between the bottom of the shielded enclosure and the parent room floor without some means of spreading the load over the entire floor surface of the enclosure.

A cost-effective and expedient method is to lay out the vibration absorbers in an appropriate pattern on the room floor where the enclosure will be erected. One or two layers (depending on the load) of 3/4-inch plywood are placed over the tops of the isolators. This effectively creates a raised floor on which the enclosure is erected. A thin layer (1/4-inch) of neoprene between the top of the vibration isolator and the plywood floor will be very effective in the overall design.

A better engineering approach is to design a metal framework (steel or aluminum) consisting of an "I" beam or "C" channel perimeter with interconnecting cross pieces at the seams of the floor panel. A 3" wide flange "I" beam or "C" channel has been found to be very effective in many applications. The vibration isolators are placed between the metal "undercarriage" framework and the parent room floor.

STRUCTURE-BORNE ACOUSTIC MEASUREMENTS

The testing of an acoustically treated shielded enclosure for vibration isolation requires a general purpose vibration meter with accelerometers to measure the vibration of either side of the isolators over the frequency range of interest. An accelerometer calibrator is also required as part of the test setup. A vibration analyzer or vibration meter with an appropriate 1/3 octave bandpass filter is required as a detector to measure the isolation of structure-borne transmissions of acoustical energy. An accelerometer of proper frequency response, gain and dynamic range is used as the input sensor to the vibration analyzer.

The vibration amplitudes measured inside the enclosure and on the floor of the parent room depend on a number of factors including the inertial and stiffness properties of the parent room floor. For example, all other things being equal, the vibration levels from acoustical excitation inside the enclosure, measured on a lightweight, wood parent room floor would be higher than the levels measured if the floor were concrete. Therefore, comparing vibration levels measured on the parent room floor would not necessarily give an indication of the attenuation properties of the vibration isolator.

If an indication of the attenuation properties of the isolator is desired, the "insertion loss" can be characterized by measuring the vibration levels on the parent room floor with the isolator in place, then making the same measurement with the isolator replaced with a rigid steel or aluminum rod. The insertion loss is the difference in the two measurements and can be reported in octave or 1/3 octave bands.

If an evaluation of the system performance of the enclosure structure plus isolators is desired, then vibration measurements made on the parent room floor while a calibrated sound source is operating inside the enclosure can be compared to vibration measurements made at the same location while a standard tapping source (used in evaluating the isolation provided by floor-to-ceiling systems in architectural structures) is operated on the parent room floor. This procedure makes the resulting isolation representation independent of the inertial and stiffness properties of the parent room. This representation can also be provided in octave or 1/3 octave bands.

MASKING

The primary purpose of applying an acoustic treatment to a room is to prevent an unauthorized listener outside of the room from hearing audible conversations that are taking place inside of the room. Taking advantage of the operational requirements of an acoustically treated shielded enclosure, the effective acoustic transmission loss of the enclosure can be augmented by raising the broadband noise environment outside of the enclosure, thereby lowering the signal-to-noise ratio at the observer's ear.

The process by which the threshold of audibility of one sound is raised by the presence of another sound is called "masking." If a white noise "masking" source of sufficient sound power level is placed outside of the acoustically treated shielded enclosure, the unauthorized listener would have a difficult time hearing or understanding any audible information being generated inside the enclosure.

The white noise "masking" technique does have its limitations; it is annoying to the occupants of the parent room, and it is easy prey to sophisticated electronic signal processing equipment. The vulnerability of a white noise masking generator against state-of-the-art signal processors renders the technique ineffective for high voice security situations.

The same signal processors that can defeat a white noise masker may have a more difficult time coping with a masking signal that is generated by a number of unrelated and constantly varying audio tones. While this type of masker provides a greater degree of voice security, it also is much more annoying to the occupants of the parent room.

If a high degree of voice security is a must, the installation of a multichannel audio frequency generator type of masker is recommended in a parent room that is only slightly larger than the acoustically treated enclosure (2' on all sides and top, 6" to 10" on bottom with an enclosure erected according to the pedestal system). In this scenario, there are no occupants in the parent room to be disturbed by the masker, and the volume of space between the enclosure and the parent room can be easily saturated with a masking signal. The output of the masker should simulate a number of discrete audio tones that are simultaneously all changing randomly in frequency and amplitude.

Of course, the same masking principles that apply to security in airborne signals apply to structure-borne signals as well. Vibration masking is needed so that any information transmitted to the parent room floor via the enclosure floor supports is immersed in masking vibration of suitable intensity so as to thwart attempts to obtain the information through vibration monitors on the parent room surfaces.

Vibration masking is provided through excitation of the parent room surfaces by the same source used to provide the masking sound. Additional vibration masking can be provided, if desired, through mechanical vibrators such as the tapping machine or electromagnetically driven shakers.

SUMMATION

The general practices for designing an acoustically treated shielded enclosure are based on both theory and practice. Much of the design methodology has been derived through field experience. Additional time and attention allotted for quality workmanship during the construction stage of an acoustically treated shielded enclosure consistently results in overall cost savings.

Acoustically treated shielded enclosures are ideally suited for a conference room required to provide a high degree of RF and acoustic isolation to the parent room. Parent room floor loading restraints, degree of isolation and cost become the primary factors in the design of an acoustically treated and electromagnetically shielded secure conference room. ■

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