A Quiet Success – Caterpillar's Noise Control Research Lab

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Caterpillar recently completed a new noise control research laboratory. Through careful planning and coordination, the lab was designed and constructed in about a year and, most importantly, the lab's sound chambers – a reverberation chamber and a hemi-anechoic chamber – met all functional acoustical performance design goals. This article is an overview of the lab and its construction, covering the steps taken to achieve success and the measured performance of the sound chambers.

Recognizing a growing need for noise control research and development, Caterpillar has completed a new noise control laboratory at its Technical Center in Mossville, IL. The new facility includes two sound chambers – a reverberation chamber and a hemi-anechoic chamber – state-of-the-art instrumentation and a spacious analysis/control room.

It is noted that, with respect to the efforts outlined here, an article by Kolano and Traub[1] appearing in the September 1999 issue of *Sound and Vibration* proved to be a valuable and almost prophetic resource.

Planning, Design and Construction

Once the need for a new noise control laboratory was identified at Caterpillar, extensive planning commenced to establish the functional requirements and budget. It was decided early in the concept development phase that the laboratory would be constructed as part of a new building construction project using prefabricated test chambers, and not housed within an existing building. This was desirable from a noise control standpoint, as it afforded the opportunity to design all aspects of the lab literally from the ground up, without being subject to inherent challenges experienced by labs built within existing structures. However, because it was not feasible to build an entirely new and separate building complex, it was decided that the lab would be built adjacent to an existing complex. This decision posed some interesting challenges, as the designated site had some unique noise and vibration characteristics of its own.

Concurrent with the conceptual design phase, Caterpillar noise engineers conducted literature reviews, visited similar laboratories and reviewed requirements from others within the company who would potentially use the lab. Exploratory meetings were held with potential sound chamber suppliers to better understand the state of the art and potential costs involved. Campanella Associates was hired as a third party acoustical consultant and added to the planning team to provide expertise, objective input and help with areas of noise control vital to the project that were not as familiar to Caterpillar noise engineers (building HVAC systems, floor isolation systems, etc.). Also, during this fact-finding phase, cost estimates were generated, updated and reviewed against realistic budget forecasts.

One of the critical requirements was for a hemi-anechoic chamber large enough to test a variety of machine components, including some that would require exhaust ventilation. Low-frequency measurement capability was identified early on as a requirement, thus it was set that both chambers would qualify to industry standards (i.e., ISO 3744, ISO 3745) down to 80 Hz. Due to the variety of anticipated research, a very low noise floor was required and set to be no greater than NC-20 with the HVAC system operating. In addition, a transmission loss aperture was desired between the two chambers in order to conduct noise industry standard noise barrier performance tests (i.e., SAE J1400) on specimens with STC ratings into the mid 40 range.

After establishing the requirements for the chambers, an assessment of potential external noise sources at the designated construction site was made. Two primary sources were identified: 1) mid-frequency tones originating from several hydraulic power units (HPUs) in the existing building and traveling through exterior wall and, more significantly, through the ground (60 dB re: 1 μg at 275 Hz); and 2) a large helper fan for a large wind tunnel, to be installed in the room adjacent to the chamber that generates airborne sound pressure levels of approximately 85 dBA (90 dB in the 63 Hz band). To a lesser extent, noise and vibration sources from lift truck traffic and nearby machinery were considered. Through measurement and analysis, it was determined that the presence of these kinds of noise and vibration sources necessitated specifying isolated floor and high STC wall systems.

Using the data from the site survey of external noise sources and the design criteria for the chamber noise floor, standard power flow calculations were made to estimate the vibration isolation requirements and required sound transmission loss for the test facility. The groundborne transmissions from the HPUs necessitated that the chambers be installed on independently isolated concrete slabs with a natural frequency of 10 Hz. This includes the stiffness of the trapped air layer as well as that of the isolator medium. An additional requirement was that this treatment would provide the requisite sound isolation against flanking sound transmission along this floor path during noise barrier isolation tests. The airborne sound pressure levels from the wind tunnel helper fan necessitated a double wall construction for the facility, with 8 in. thick concrete block walls and a 12 in. insulated airspace between the block wall and the prefabricated 11-gauge steel panels that form the test chamber shells.

After the concept and budget were approved, the design phase began in earnest. A multi-disciplinary team was formed that included individuals from many departments within the company (i.e., facilities management, purchasing, research, etc.) as well as the architectural firm selected to design the addition in which the sound chambers would be contained. Acoustic Systems of Austin, TX, was chosen as the chamber supplier and became intimately involved in the design process.

As the design of the facility progressed, consistent and thorough reviews were conducted to ensure the best practices in architectural acoustics construction design were considered. It was important that no shortcuts were taken that might compromise the acoustic performance of the chambers. For instance, numerous construction breaks were specified in the concrete foundations. Air handling equipment was located remote from the test facility complex and was connected to the test chambers via lined sheet metal ductwork, packaged HVAC silencers and turning vanes to minimize both flanking and self noise in the HVAC systems. To provide double wall noise isolation for the chambers, concrete block was extended all the way around the two adjoining chambers and the analysis/control room.

As the design solidified and cost estimates were refined,

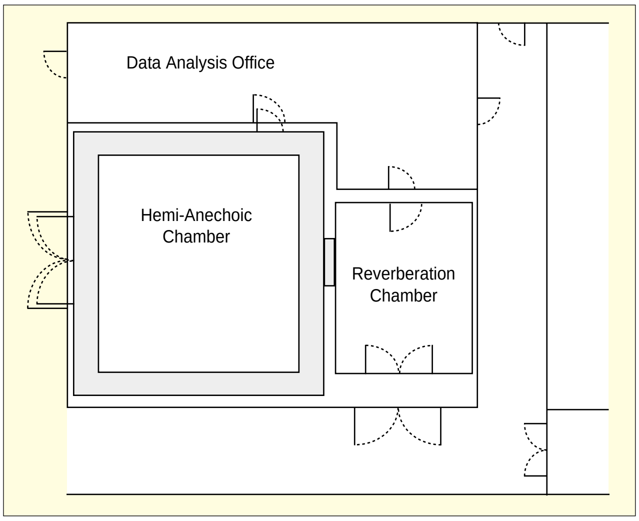

Figure 1. General layout of the noise control research lab.

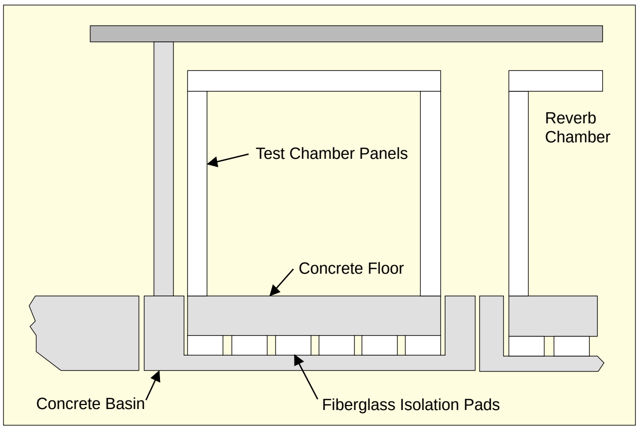

Figure 2. Representation of the isolated floor and double wall systems for two chambers. Drawing not to scale.

some design elements from the total project had to be removed to stay within budget. However, due to management's commitment to build a world-class acoustics lab and due to the attention paid by all, no major concessions were made against the acoustic performance of the chambers. Rather, sacrifices were made in less important areas such as the office environment in the analysis/control room.

Once the designs were finalized and approved, a general contractor was selected, ground was broken and construction commenced. An aggressive time schedule had been set and the lab seemed to grow overnight. Within six months after ground breaking, most of the work was done and the sound lab portion was nearing completion. At this stage – about the same time the chamber shells were in place – plumbing, electrical conduits and the HVAC system were being connected to the chambers. This work was monitored and inspected regularly to be sure careful attention was given to each penetration and joint so that gaps were sealed and structural flanking paths were avoided.

Thus, through close cooperation between all parties involved, the lab was designed and built in about one year. Sound tests supporting research programs began on schedule.

Laboratory Construction

A plan view of the Caterpillar Noise Control Research Lab is shown in Figure 1. The chambers are built on separate isolated concrete slabs, each resting on fiberglass pads, in turn resting in separate concrete basins. The basins are structurally isolated from the building's concrete foundation, which in turn is structurally isolated from the preexisting building. This arrangement is depicted in Figure 2.

Hemi-Anechoic Chamber. The hemi-anechoic chamber walls are constructed of 12 in. thick panels, fabricated from 11-gauge steel outer surfaces backed up with gypsum board, filled with fiberglass and a 22 gauge perforated steel inner surface. The sound transmission loss of the chamber panels is STC 50.

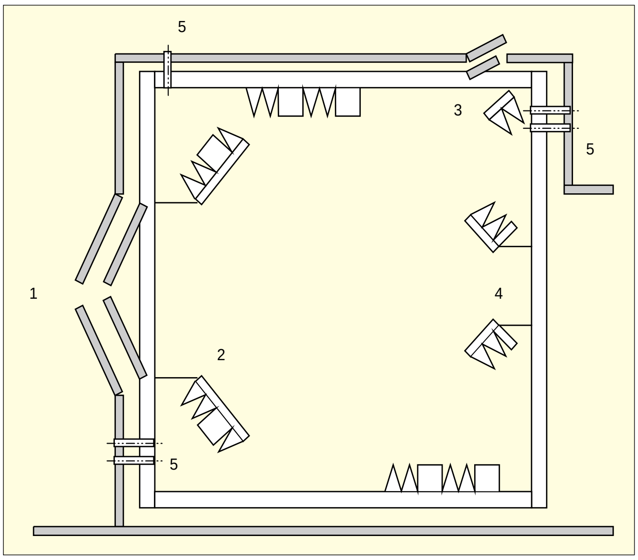

Figure 3. General layout of the hemi-anechoic chamber.

Figure 4. Looking into the hemi-anechoic chamber through the large double doors.

The interior of the hemi-anechoic chamber is lined with over 1500 melamine foam wedges. The wedges have a 12 in. × 24 in. base section, are 24 in. deep and are mounted to the acoustical wall panels using a clip assembly on a 4 in. airspace to achieve maximum sound absorption down to 80 Hz. Melamine resin is the basis for Formica and being quite inert, does not deteriorate with exposure to acids and alkalies. Also, melamine foam does not burn under normal atmospheric conditions and has a high flash point. One drawback of the melamine foam wedges is that they are brittle and somewhat fragile. However, because this facility is primarily used for research purposes and wedge replacement cost is not too prohibitive, it was decided that the benefits of superior acoustic performance outweigh the risks of their fragility.

To meet access requirements, the hemi-anechoic chamber contains a set of large, high STC double doors (Figure 3, number 1 and Figure 4) with wedge-basket doors (Figure 3, number 2) and a personnel door with accompanying wedge basket door (Figure 3, number 3). The sound transmission loss aperture and wall plugs are also covered by wedge basket doors (Figure 3, number 4). To facilitate instrumentation and services for test equipment there are several 3 in. diameter cable pass-throughs located around the chamber (Figure 3, number 5). To accommodate engine and vehicle testing, there is a removable ceiling plug, a telescoping vent and a high-volume fan to remove exhaust gasses from the chamber. The inside of the hemi-anechoic chamber is shown in Figure 5.

The doors and plugs are all high Sound Transmission Class (STC) design and are magnetically sealed. Door frames are

Figure 5. Inside the hemi-anechoic chamber.

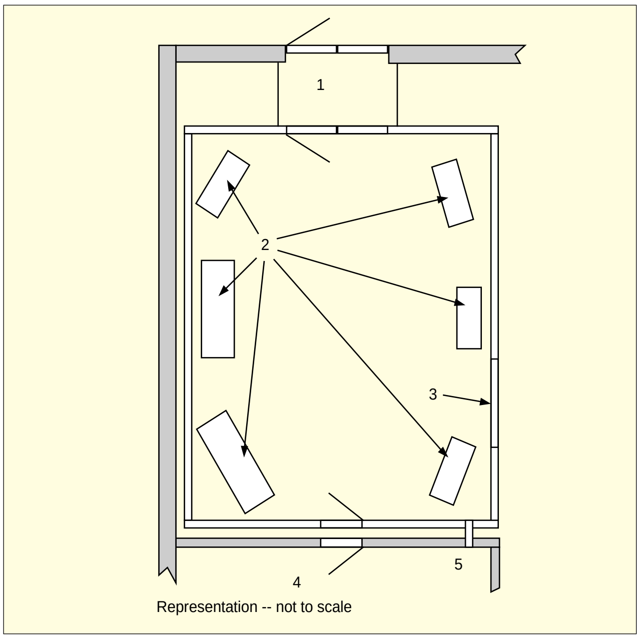

Figure 6. Layout of the reverberation chamber.

caulked or otherwise sealed to the chamber structure. The passive leaf of the large exterior door is equipped with a cane and chain bolt assembly to ensure a good seal when both leaves are shut. The large exterior doors have an innovative, adjustable drag seal that ensures a very tight acoustic seal to the floor and door threshold.

All airspaces between the concrete outer shell and the prefabricated chambers were insulated with fiberglass insulation material to improve sound transmission characteristics. In the region above the large doors, a pressure-relief channel through the fiberglass layer was necessary to permit the doors to open and close due to the tight seal between the chamber shells.

Reverberation Chamber. The reverberation chamber walls are 4 in. thick prefabricated steel panels constructed of 11-gauge steel outer skin backed up with gypsum board and 16-gauge inner skins. The panels are filled with fiberglass insulation materials and provide acoustic performance equal to STC 58. The chamber was designed by Acoustic Systems to qualify for sound power level evaluations in accordance with ANSI S12.31 from 80 Hz to 10 kHz and for sound absorption measurements in accordance with ASTM C-423 from 100 Hz to 5 kHz. Six stationary metal panel diffusers (Figure 6, number 2), suspended by adjustable chains, are crucial to establishing a diffuse acoustic field at low frequencies. Their sizes, locations and orientations were based on the supplier's experience with the diffusing elements in their reverberation chamber.

Figure 7. Analysis/Control station.

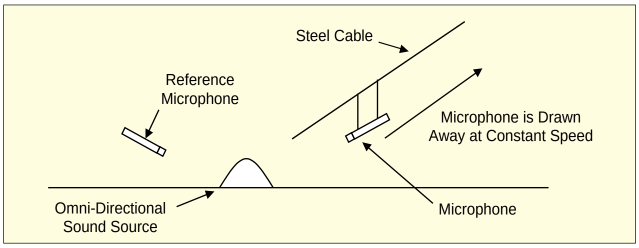

Figure 8. Illustration of traverse line draw-away test aparatus.

To meet access requirements, the reverberation chamber contains a large double-leaf access door (Figure 6, number 1) and a personnel door (Figure 6, number 4). A transmission loss aperture (Figure 6, number 3) couples the reverberation chamber to the hemi-anechoic chamber for sound transmission loss measurements. Instrumentation cabling and test device services are facilitated by 3 in. diameter pass-throughs in the chamber wall (Figure 6, number 5).

Interior lighting is provided by five fluorescent light fixtures. The ballasts were mounted remotely above and away from the chamber in order to minimize buzzing noises. Sprinklers and emergency lighting are provided per building requirement codes.

HVAC Systems. The hemi-anechoic chamber has two independent HVAC systems, one used for environmental or personnel comfort air, the other used to ventilate the chamber during engine operation. The reverberation chamber has its own independent HVAC system to avoid sound transmission between chambers through ductwork.

To minimize HVAC noise, several key noise control techniques were employed, including:

- Remote placement of air handling units (100+ ft away in a different part of building).
- Long runs of acoustically lined sheetmetal ducts for low-frequency insertion loss.
- Ducts with large cross-sectional area to maintain low flow velocities.
- Multiple parallel baffle silencer units located where ducts penetrated the concrete shell.
- Guide vanes at turns.
- Caulk around wall penetrations (vents, conduit, pipes, lighting fixtures, etc.).

Analysis/Control Room and Equipment. A spacious analysis/control room provides work space for primary and secondary instrument control stations, two data analysis stations and a conference table. In addition, there is ample room for supply cabinets and resource materials. Two Brüel & Kjær PULSE systems provide primary data acquisition and signal control for the chambers. Video cameras are mounted in each chamber allowing the test engineer to monitor test activity. A view of the Analysis/Control Room is shown in Figure 7.

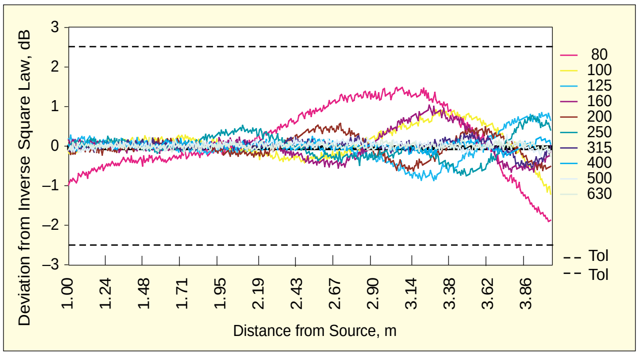

Figure 9. Side wall microphone traverse for frequency bands 80-630 Hz with a pink noise sound source. While exhibiting increasing deviation with distance, the 80 Hz curve is still well within the tolerance bands.

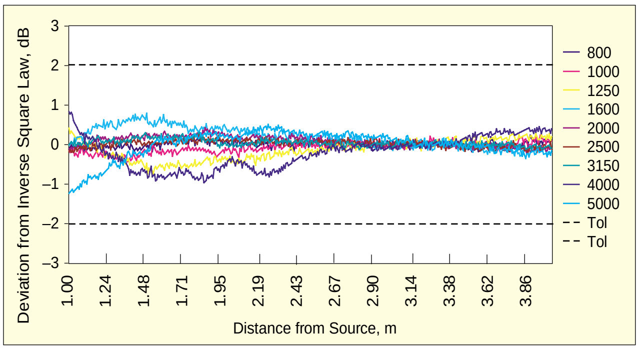

Figure 10. Side wall microphone traverse results for frequency bands 800-5000 Hz.

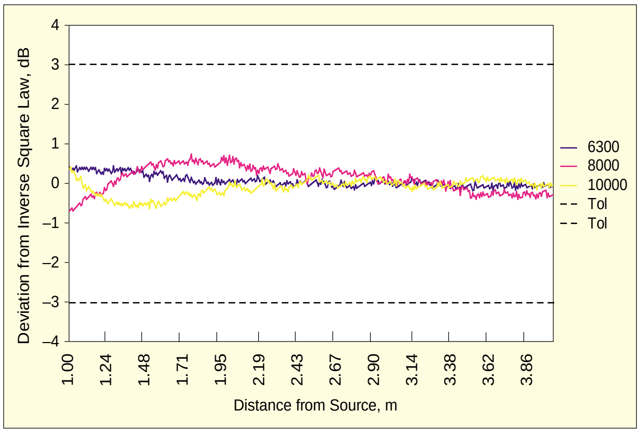

Figure 11. Side wall microphone traverse results for frequency bands 6.3-10 kHz.

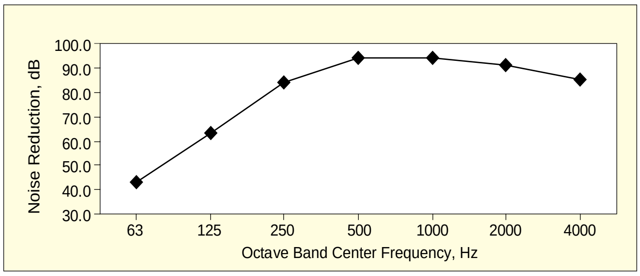

Figure 12. Noise reduction between chambers.

Performance Specifications via Qualification Testing

Before placing the facility in use, the acoustical performance of each chamber was tested for compliance with the original specifications. A third party acoustical consultant (JGS Consulting) was contracted to oversee the supplier's on-site qualification testing of both chambers. Selected results are presented below.

Measurement of the sound isolation of the chambers and qualification of the free field environment in the hemi-anechoic chamber are relatively straightforward procedures and were conducted by the chamber manufacturer at the completion of the project. Qualification of a reverberation chamber is considerably more complex and time-consuming. As such, the consultant conducted an initial study of the reverberation chamber acoustical properties and instructed Caterpillar acoustical engineers on how to complete the remainder of the required qualification measurements and adjustments. The following discussion on the reverberation chamber integrates results from both the initial round of tests by the consultant and the more comprehensive tests conducted by Caterpillar.

Isolated Floor Performance – Hemi-Anechoic and Reverberation Chambers. A highly sensitive seismometer was used to measure the isolation characteristics of the isolated floor systems before and after installation of the chamber. With chambers resting on their respective isolated floors, the installed resonance frequency was found to be near 10 Hz for each chamber/floor system. Such a low resonance frequency ensures excellent structural isolation for audible frequencies and helps achieve the required low ambient levels even when nearby test equipment and machinery are running.

Hemi-Anechoic Chamber – Anechoic Field Quantification. To discover the region of anechoic behavior inside the hemi-anechoic chamber, traverse lines were mounted from the chamber floor center to various positions on the chamber walls and corners (Figure 8). A traverse line consists of the following equipment and procedure: A steel cable is affixed at the endpoints and a microphone is drawn upon this cable at constant velocity from a sound source near the bottom of the traverse line. A reference microphone, kept at a fixed position near the sound source, is used to compensate for minor source amplitude fluctuations. By sampling the sound pressure levels at both microphones as the traverse microphone moves up the line, a time history of sound pressure levels is created. This time history is then compared to the predicted sound pressure level decay governed by the inverse square law.

Typical results for one of the draw-away tests are presented in Figures 9-11. Deviations from the predicted inverse square pressure level decay are given. The dashed black lines indicate the tolerance bands per ISO 3745.

The following conclusions were made after analyzing the draw-away results:

- The chamber qualifies for precision grade sound power level measurements in accordance with ISO 3745 for measurement surfaces with a radius of up to 4 m down to a lower limiting frequency of 80 Hz.
- The chamber qualifies for engineering grade sound power level measurements on large sources in accordance with ISO 3744 down to a lower limiting frequency of 80 Hz.

Hemi-Anechoic Chamber – Noise Reduction. Before the contractor left the premises, noise reduction tests were conducted to evaluate the sound isolation characteristics of the hemi-anechoic chamber. These tests were accomplished by placing three high-powered sound sources (JBL speakers) in the spaces outside the chamber. As a result of preliminary tests, residual leaks where caulking was incomplete were identified in intermediate spaces (e.g., in the plenum over the chambers) and sealed.

With the sound sources producing pink noise with band levels in excess of 100 dB from 63 Hz to 4 kHz, octave band sound pressure levels were measured both in the space outside the chamber and within the useful test volume of the chamber. The noise reduction was calculated as the difference between the two sound pressure level measurements.

Hemi-Anechoic Chamber to Reverberation Chamber – Noise Reduction. The sound isolation between the hemi-anechoic and reverberation chambers was of particular importance since it contains the transmission loss test aperture. The noise reduction of this wall governs the upper limit of the sound transmission loss that can be measured in the facility. Figure 12 shows

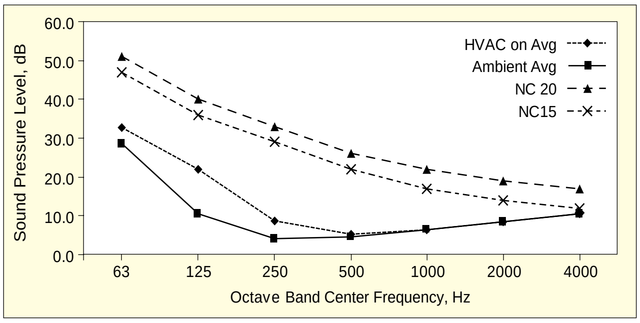

Figure 13. Ambient sound pressure levels in the hemi-anechoic chamber, with and without the HVAC system.

Figure 14. Rotating microphone setup inside the reverberation chamber.

that the noise reduction between these spaces is exceptional. This level of sound isolation is sufficient to allow Caterpillar to evaluate the sound transmission loss of panels and structures with STC ratings into the high 40s to low 50s, which meets and exceeds the design goals for the project.

Hemi-Anechoic Chamber – Ambient Noise Level (Background). Sound pressure levels were measured inside the hemi-anechoic chamber with and without its environmental HVAC system running. As shown in Figure 13, the spatial average ambient level is comfortably below the NC-15 curve, exceeding the NC-20 design criterion.

Reverberation Chamber – Diffuse Field Quantification Reverberation Time. Reverberation Time (RT) measurements provide the basis for many of the tests conducted in the chamber. The magnitude of the reverberation time at any frequency is a function of the chamber size (volume and surface area) and the total absorption contained within the chamber. The standard deviation of the spatial distribution of reverberation time measurement is a metric for chamber diffusion and is specified as a qualification parameter in standards such as ASTM C423. Many factors affect chamber diffusion including chamber size, dimension ratios, number and location of diffusing panels, number and location of sources and analysis procedures utilized to calculate reverberation times from level versus time decays. Optimization of diffusion within a chamber can be a tedious, trial-and-error process that can take months or even years to achieve.

Preliminary RT measurements were accomplished by driving two high-powered speakers independently with pink noise. A microphone was mounted at the end of a rotating boom adjusted so that its circular traverse was approximately 30° from the plane of the floor as shown in Figure 14. The boom was placed near the center of the room, such that the microphone would not come closer than 0.75 m from any surface at any point along its traverse. The length of the boom (radius of the circular traverse) was 1.7 m. RT measurements were conducted at six stationary points along the circular path of the microphone boom.

Figure 15 shows the results of the RT tests conducted with and without the six suspended diffusers. The RTs for the chamber without the diffusers are longer than those measured with the diffusers, suggesting that the diffusing panels absorb some

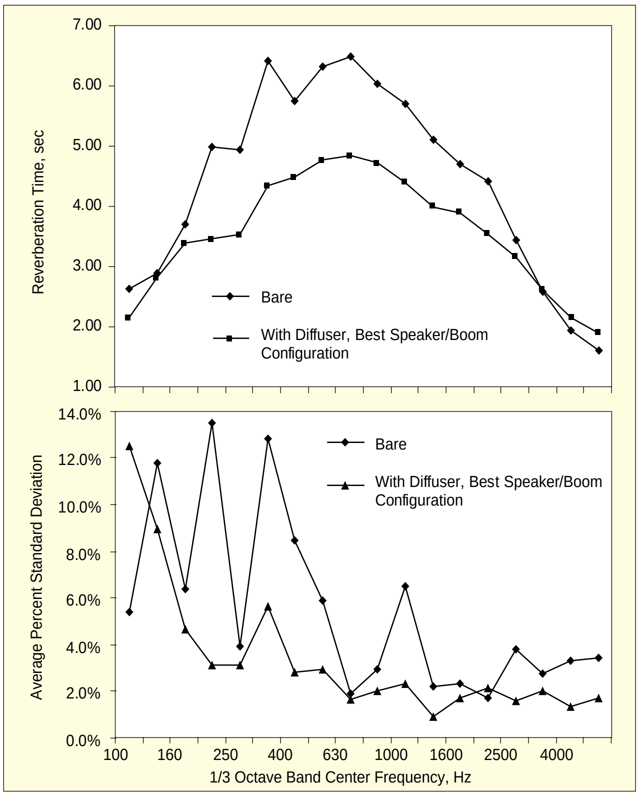

Figure 15. Spatial-average reverberation time and standard deviation with and without diffuser panels.

sound energy. However, the ratio of the standard deviation of the RTs is improved considerably with the diffusers. Not only is the standard deviation generally lower with the diffusing panels, it is also less erratic with respect to frequency. While it is desirable to have long RTs, the benefit of better chamber diffusion exceeds the decrease in the average RT.

Optimization of the diffusion in the 315 Hz band will require further study and may require modification of the diffuser positions, additional sound sources and/or modifications to the reverberation time analysis engine. Such studies and modifications are expected to involve a substantial amount of additional time. However, the chamber as currently configured is expected to meet the current needs of Caterpillar for the following reasons:

- Actual tests (for material testing, etc.) will be performed with the boom rotating, which has the effect of spatially averaging the pressure decay and provides the equivalent of 18 spatial samples at 315 Hz.
- The use of sound absorptive materials for engineering noise control solutions at 315 Hz on products and equipment such as those manufactured by Caterpillar is generally not a viable tactic. The small amount of uncertainty in the measurement due to chamber diffusion not being optimized in this band is not expected to be significant when compared to the time and effort required to achieve optimization.

Caterpillar is participating in the ASTM C423 round robin tests currently being conducted by the ASTM E-33 committee and will utilize the results of this research to guide its future chamber qualification activities.

Reverberation Chamber – Noise Reduction. A Noise Reduction measurement through the reverberation chamber south wall was conducted. Three JBL Eon Power 15 loudspeakers were driven by a pink noise source in the corridor in front of the reverberation chamber doors. Estimates of the average sound pressure levels in the hallway and in the reverberation chamber were made using a Brüel & Kjær 2260 Investigator that was handheld and manually moved for spatial integration. Estimates of the sound pressure levels in the reverberation chamber were made by hand averaging with the Brüel & Kjær Inves-

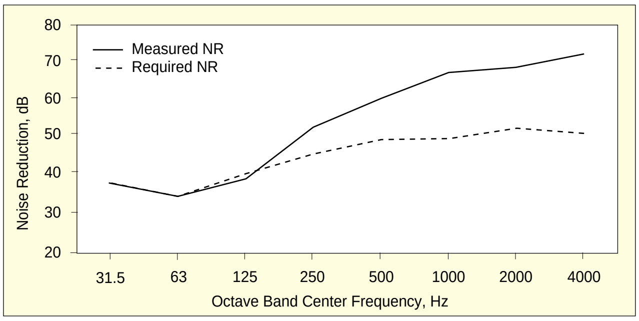

Figure 16. Noise reduction data for the south wall of the reverberation chamber.

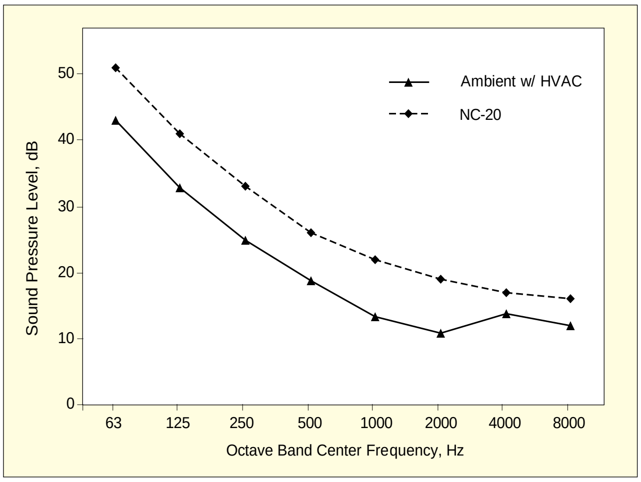

Figure 17. Background (ambient) sound pressure spectrum compared to NC-20 curve.

tigator on a path that approximates the boom path in the center of the chamber.

As shown in Figure 16, the required noise reduction was met and exceeded across the frequency range of interest. This confirmed the acoustical isolation of the room from exterior noise.

Reverberation Chamber – Ambient Level. Sound pressure levels were measured inside the reverberation chamber with its HVAC system operating. As shown in Figure 17, the spatial average ambient level is comfortably below the NC-20 curve, as required by the original design specification.

Summary

In summary, the new Caterpillar noise control research lab was designed, built and successfully qualified in a relatively short time frame considering the magnitude of the project. The keys to its success were many, including:

1. Realistic requirements set at the beginning of the project.
2. Commitment from the corporation to build a world-class facility with significant acoustical performance.
3. Cooperation between Caterpillar personnel, suppliers, architect, contractors, consultants, etc.
4. Attention to detail during design and construction.
5. Frequent reviews throughout the entire project.

Postscript. Caterpillar is opening the doors of this state-of-the-art lab for limited research and development work. Those interested in using these facilities should contact David Copley via email.

Reference

1. Kilano, R. A., and Traub, K., "Guidelines for the Design of Vehicle Acoustical Laboratories," *Sound and Vibration*, Sept. 1999, pp 30-33.

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