Low-noise chambers for auditory research*

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The experimental work of the Eaton–Peabody Laboratory of Auditory Physiology requires chambers unusually free of ambient acoustic, vibratory, and electric noise, so that small mechanical or electric signals in response to low-level sounds can be measured. This paper deals with the problems that arose in setting of criteria, the design, and the construction of such chambers, and reports on the evaluation of their performance. The ambient acoustic noise is well below the human threshold of hearing even with the ventilation system operating. The noise reduction between the control rooms and the chambers is almost 80 dB at 250 Hz and more than 90 dB above 500 Hz. The octave-band ambient vibration acceleration level at the experimental tables in the chambers is below -120 dB *re* 1 g.

Subject Classification: 55.40; 65.10.

INTRODUCTION

When plans to enlarge the Massachusetts Eye and Ear Infirmary called for the demolition of the building that housed the Eaton–Peabody Laboratory of Auditory Physiology, an opportunity arose not only to increase the number of "sound-proofed" experimental chambers but also to improve their performance characteristics. The research of the laboratory involves the systematic and quantitative descriptions of events in vertebrate auditory systems following sound stimulation. The sensitivity of the systems and the low levels of the signals to be studied require an environment that is unusually free from uncontrolled vibration, acoustic noise, and electric fields.

Since the design of such specialized facilities is beyond the experience of most architects and mechanical engineers, an acoustical consultant[1] with an interest and competence in designing special acoustical facilities was required. The three authors worked closely together in supplying the architect[2] and mechanical engineer[3] with detailed sketches of all the features of the plan. These ideas were incorporated into the working drawings and specifications. The authors supervised every stage of the construction and made the performance evaluation of the completed chambers.

I. DESIGN GOALS

The future user[4] of a specialized facility must first determine the performance that is required and the reasons why. His input and approval are essential to assure that the facility will incorporate all essential features at a reasonable cost.

Table I summarizes the (1) main performance requirements for the new experimental chambers of the Eaton–Peabody Laboratory, (2) reasons for these requirements, and (3) types of construction needed to meet these requirements.

The chambers do not need to be anechoic as no free-field work is contemplated. To provide sufficient room for experimental subjects and equipment, the inside dimensions of the chamber were chosen to be 10 ft × 8.5 ft × 7 ft high. With normal activity in the surrounding control room, the octave-band sound pressure level in the chambers—with or without the ventilation system running—had to be below the threshold of hearing, because previous findings had established that spontaneous activity in the auditory nerve differs from activity generated in response to low-level acoustic noise.[5]

II. DESIGN

The infirmary building is on filled land so that a basement floor would be partially below the water table where accumulation of water, entering through small cracks in the foundation, could not be avoided with certainty even at prohibitive expense. Eventually the fourth floor of the building was chosen as the site of the new laboratory.

As listed in Table I, the design must simultaneously fulfil strict functional, acoustical, vibrational, and shielding requirements which can be met if the test chambers consist of three concentric boxes which are structurally separated from each other by resilient mounts on the floor and by airspaces at other partitions, as shown schematically in Fig. 1. Information pertinent to the design of such vibration isolating "floating floor" constructions is found in Refs. 6–9. The relevant details of the experimental chambers are identified in Fig. 2, which is an actual cross section of a chamber as depicted in the architectural drawings.[10] These details are discussed below.

A. Enclosure

The walls of the outer box rest rigidly on the structural floor slab. The middle box is carried on a 10-in.-thick precast dense concrete slab **1**[11] which also provides

TABLE I. Performance requirements influencing major design decisions.

	Uses and requirements	Specifications to meet requirements	Design decision
(1)	Planned experiments include Mössbauer techniques, lasers, pressure probes, and microelectrodes.	Vibration-free platform to support experimental setup.	Three concentric boxes with the experimental table mounted on the floor of the middle box. The two inner boxes and the experimental table are all resiliently mounted.
(2)	User must frequently enter chamber during experiments (i.e., recording from a single cell should not be interrupted by entry.)	Access to chamber without introducing vibration into the experimental setup.	Special doors, hung on outer and inner boxes, to minimize impact of opening and closing.
(3)	User must record low-level electric signals without contamination by broadcast signals, paging system, and mechanical equipment.	Electrostatic shielding.	Light door carrying both electrostatic shields is attached to the middle box. Shield must cover all surfaces, including doors, windows, duct terminals and penetration boxes. To avoid ground loops, the inner and outer shield must not be connected, except at a single point.
(4)	Measurements near threshold are required. Chambers serve for human and animal experiments of long duration. Barbituate anesthetized mammals require a room temperature around 90 °F, human subjects prefer 70 °F, and cold-blooded animals require much lower temperatures.	Low ambient noise level even with ventilation and rapid control of temperature.	Control of duct-borne noise by silencers and duct lining. Control of self-generated aerodynamic noise by appropriate choice of the terminal velocities. Sound-absorbing treatment of the walls of the inner box.
(5)	Chamber should be usable even in the presence of high-level noise in the control room such as voices, walking, teletypes, printers, plotters, fans, amplified signals for monitoring experiments, paging system, etc.	High noise reduction between control room and chamber.	High sound transmission loss of all partitions including walls, doors, windows, and penetration boxes. Wrapping of ventilation ducts. Structural separation between the boxes. (Flexible connections at all duct and pipe penetrations.) Sound-absorbing wall treatment of the inner box.
(6)	Experimental setup requires connection between the chamber proper and control room for vacuum, compressed air, hydraulic lines, and electric wires.	Penetrations	No rigid connection is permitted between the boxes. Airtight seal of penetration pipes and heavy gauge internally lined penetration box is required on both interior and exterior walls.
(7)	Observation of experimental subjects is required (i.e., checking for movement of animals.)	Windows	Structurally separated triple-paned window.

a foundation for the experimental table. This slab is carried along its perimeter by 14 sets of elastic mounts, each consisting of two stacked 6 in. × 6 in. × 1 in.-high 60 durometer neoprene bridge-bearing pads **2**. The hot-dip galvanized screen ($\frac{1}{8}$-in.-square mesh) constituting the outer electrostatic shield **3**, is sandwiched between

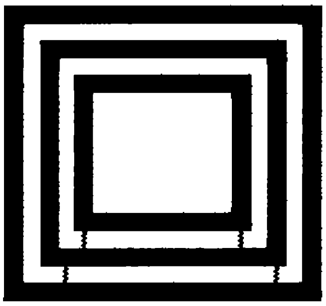

FIG. 1. Design concept of the chambers.

the two pads. To avoid any accidental structural or electric bridging, the airspace above and below the electrostatic shield is filled with glass fiber. A 6-in. concrete slab **4**, carries the inside box and is supported on 63 elastic mounts,[12] each consisting of two 2-in.-thick 6-in.-diameter elastomeric floor mounts **5**. Here again, the inside electrostatic shield **6** is sandwiched between the vibration isolation mounts, and the airspace is filled with glass fiber. The supports for the experimental table protrude through holes in the 6-in. slab into the inside box. Thus, the 500-lb experimental table **7** which rests on four elastic mounts, each made up of eight ribbed neoprene pads providing 0.4-in. static deflection, is dynamically isolated in two stages from the inside box, the outside box, and the structural floor. Because of the permanent nature of the facility, it was found most practical to use solid concrete block for the walls **8** and precast concrete planks **9** for the ceilings of the boxes. The total weight of each chamber is approximately 70 tons.

B. Doors

The inside box is accessible through a triple door (not shown in Fig. 2). The outside and inside doors are 2.5-in. acoustical doors with a sound transmission class of STC 42. These doors [13] are equipped with special cam-type hinges and double magnetic seals, permitting the operation of the doors with a minimum of impact. In a sense, the need for tight acoustic seals at the doors conflicts with the need to carry the shielding across the doors and the jamb. Since three doors

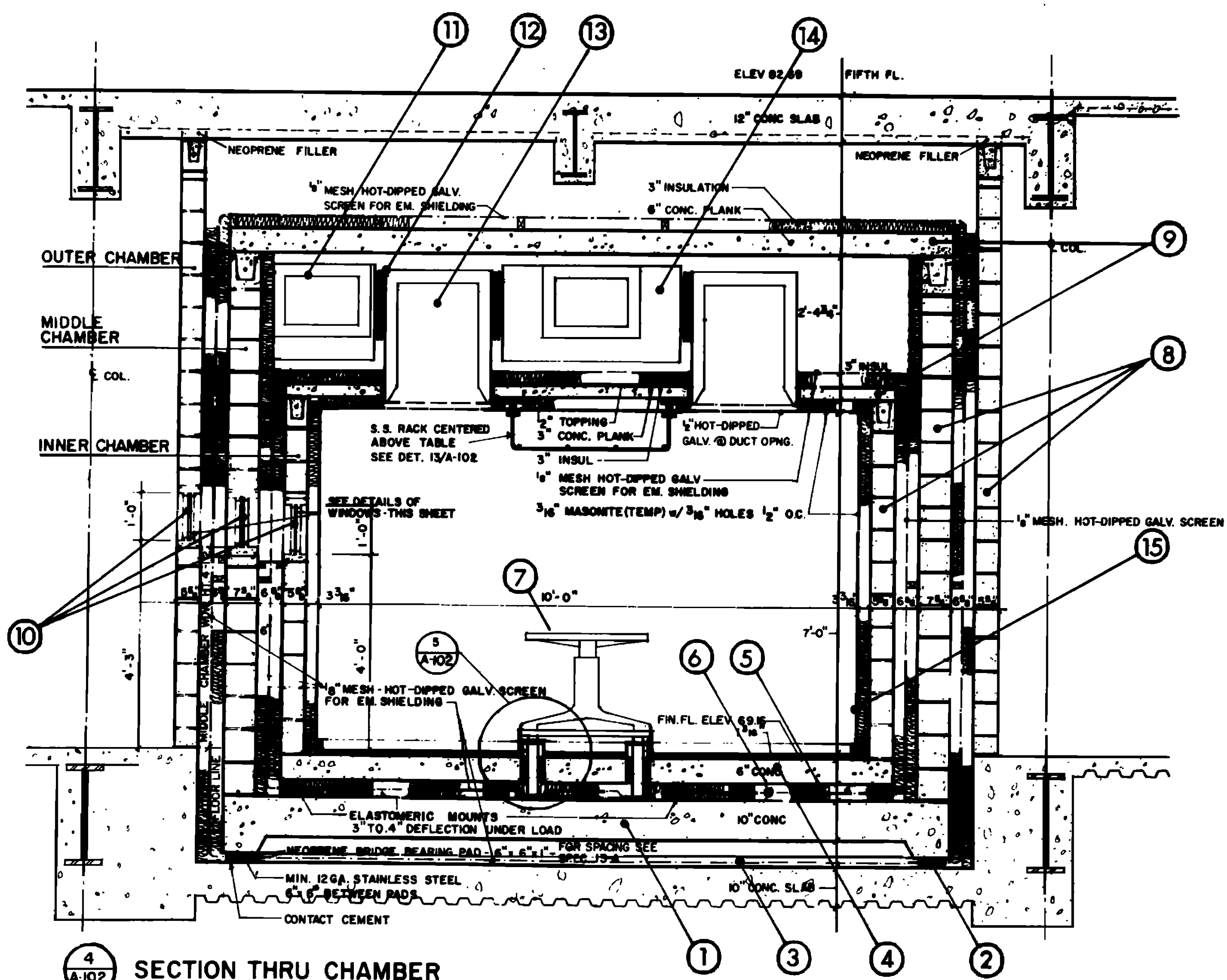

FIG. 2. Cross section of the chamber (details identified by numbers are described in the text).

were available here, it was convenient to use the inner and outer doors for acoustic seals and the middle door to carry both electrostatic shields.

The middle door consists of a light wooden frame carrying, on opposite sides, the two electrostatic shields and the beryllium brass strips that contact conductive strips placed around the door frame. The shields are held away from the concrete, which is a good electrical conductor, by wood framing strips.

C. Windows

The 2 ft×1 ft viewing window **10** provides a direct line of sight from the control room to the experimental table. It is a triple window with pane thicknesses of $\frac{5}{8}$ in., $\frac{1}{2}$ in., and $\frac{3}{8}$ in., respectively. The panes are set into a soft rubber gasket. The galvanized electrostatic screens are transparent enough so that they do not block the view but are, nevertheless, tight enough to provide the needed electrostatic shielding. The perimeter of the airspace between the panes is filled with low-density glass fiber. This is to decrease the sound transmission of the window at low frequencies by providing a lateral relief for the air volume trapped between the panes, and at high frequencies by eliminating standing waves with components in the plane of the window panes.

D. Penetrations

To bring in the various electrical wiring, flexible piping, etc., needed in the chamber without degrading the acoustical, vibration, and electrostatic shielding performance of the chambers, each of the three walls contains a set of axially aligned copper pipes. These penetration pipes, which are bonded to the electrostatic shielding, provide shielded channels for a large number of wires and pipes to enter the chamber proper, without creating a rigid contact between the chamber walls. With all the wires, conduits, and pipes in place, the penetration pipes are closed from both the control room side and the chamber side by duct seal; the heavy-gauge penetration boxes, which cover the pipe openings from both sides, are filled with sound-absorbing material and closed. These precautions are necessary to assure that the penetration holes do not degrade the high sound transmission loss of the triple box enclosure.

E. Ventilation and temperature control

To dissipate the heat produced by the subjects, the dc light fixtures, and the electronic equipment in the chamber, and to maintain desired temperature required for a given experiment, each chamber has its own air conditioning system capable of supplying air at a volume flow of 560 ft^3/min. The driving fan is inside the supply duct and is situated in the control room more than 15 ft upstream from the chamber to permit the insertion of duct lining and silencers **11** into both the supply and return ducts, so as to reduce duct-borne fan noise. To keep noise from the control room from entering the air conditioning ducts, the ducts are wrapped with glass fiber and lagged with sheet lead. Flexible connections **12** are inserted wherever the ducts penetrate partitions to reduce the intensity of sound reaching the chamber proper via structural paths. The air passages are so designed that the air speed gradually decreases as the air approaches the supply and return air terminals **13** which are connected to large, heavily lined acoustical plenums **14**. The lowest air velocity of 4.5 ft/sec occurs at the duct terminals, where the flow passes through the $\frac{1}{2}$-in. mesh electrostatic shields. The homogeneous inflow and the low terminal velocity insures that the sound pressure level of the aerodynamic noise remains low.

F. Sound-absorbing treatment

All interior wall and ceiling surfaces are lined with 3-in.-thick porous sound-absorbing lining, protected by a perforated pegboard facing **15**, to minimize the reverberant buildup of sound in the room and thereby to reduce the ambient noise.

III. CONSTRUCTION

The 10-in. (19 000 lb) dense concrete slab was cast in a form resting directly on the building slab on which it would eventually be supported. The 6-in. (10 000 lb) slab was cast in a form resting on the 10-in. slab. Appropriate openings were left in the floor above to facilitate chamber construction. Because of the complex nature of the chambers, a step-by-step construction sequence was worked out, specifying where to start, how to proceed, and what to check at each stage.

During the critical phases of construction, the owner, the acoustical consultant, and the architect's representative[14] monitored the progress continuously. This was necessary because few contractors have had experience with projects where small mistakes such as leaving a tool or debris in a hidden place or connecting the electrostatic shields by an improperly placed nail can seriously compromise the facility. Indeed, this continuous inspection did detect many errors, such as improper orientation of silencers—which would have resulted in excessively high airflow noise, short circuits in the electrostatic shielding, and improperly sealed portions in the partitions.

IV. PERFORMANCE EVALUATION

After completion of the building the experimental chambers were evaluated. The purpose of the tests was to (1) determine whether or not they met the performance goals, (2) discover and, if possible, correct any mistakes made during the construction, and (3) document the acoustical and vibration conditions before occupancy. The tests included the measurement of the ambient noise in the chambers with and without the ventilation system running, the documentation of the noise reduction between the control room and the test chambers, and the measurement of the vibration level on the experimental table under normal and extreme conditions.

A. Ambient noise

A preliminary experiment was performed to determine whether or not the most sensitive sound level meter

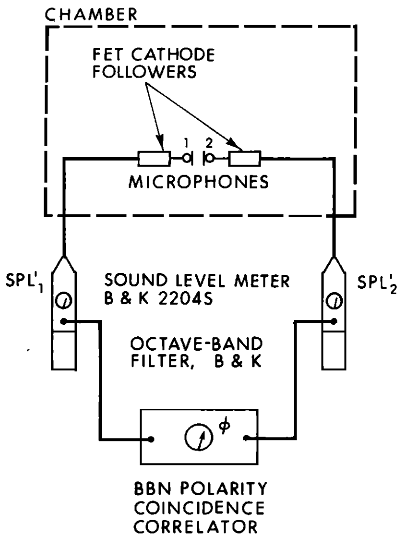

FIG. 3. Block diagram of the experimental setup to measure ambient acoustic noise.

(Brüel & Kjaer type 2204S with a 1-in. microphone) is capable of measuring the low ambient noise in the chambers. The two sets of octave-band spectra obtained with the microphone enclosed in an airtight cavity of high sound transmission loss and with the microphone free yielded identical results, indicating that the instrument did not have sufficient signal/noise ratio to measure the lower-than-threshold ambient noise levels found in the completed chambers.

Consequently, a more sophisticated measurement system (Fig. 3) had to be used which could measure acoustic signals well below the electronic noise floor of the sound level meter. The ambient noise in the chamber is picked up by two closely spaced microphones. Electric signals, containing both the voltage proportional to the acoustic signal and the electronic noise of the cathode follower, reach the input of the respective sound level meters. The amplified and filtered contaminated signals SPL_1' and SPL_2' are read on the scale of the respective sound level meters and are also connected to the inputs of a special polarity coincidence correlator[15,16] which indirectly measures the normalized correlation coefficient of the two contaminated signals. The meter reading $\phi = 0$ corresponds to total correlation and $\phi = 90°$ to total lack of correlation. Since the signal proportional to the ambient acoustic noise in both channels is fully correlated while the respective electronic noises lack any correlation, the true ambient acoustic noise in the chambers, SPL, is obtained as

$$SPL = 0.5(SPL_1' + SPL_2') + 10\log_{10}\cos\phi ,$$

where SPL_1' and SPL_2' are sound level meter readings due to the contaminated signals in the respective channels and ϕ is the phase angle reading on the meter of the polarity coincidence correlator.

Figure 4 shows the octave-band ambient noise level spectra obtained with the ventilation system off and on, respectively, and compares these data with the threshold of hearing for octave band in a diffuse sound field as determined by Ref. 17. Figure 4 indicates that ambient noise, even with the ventilation system on and normal activity in the control room, remains approximately 10 dB below the threshold of human hearing. Above 125 Hz, the ambient noise in the chamber can be further reduced by shutting off the ventilation system. These values indicate that the chambers would be acoustically satisfactory for studying human or cat auditory systems.[18]

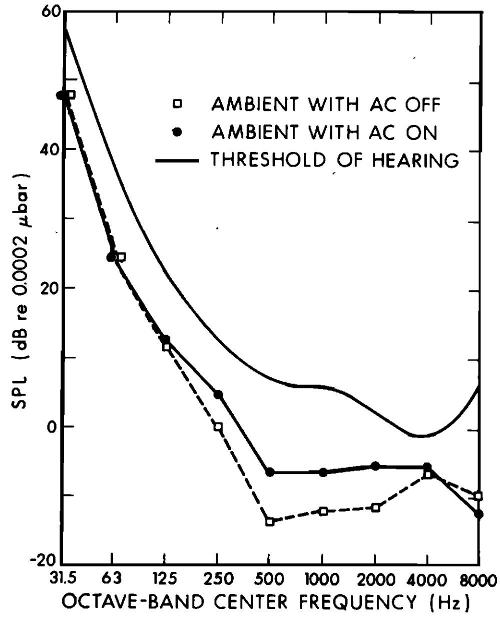

FIG. 4. Measured ambient noise in one of the chambers.

B. Noise reduction between control rooms and chambers

The noise reduction between the individual experimental chambers and their respective control rooms was evaluated by creating a high-intensity, quasidiffuse sound field in the control room surrounding the chamber and measuring simultaneously the noise in both the control room and in the chamber. The curves of measured noise reduction, defined as the difference in the space average octave-band sound pressure levels obtained in the control room and in the chamber, are given in Fig. 5. The noise reduction, which is most

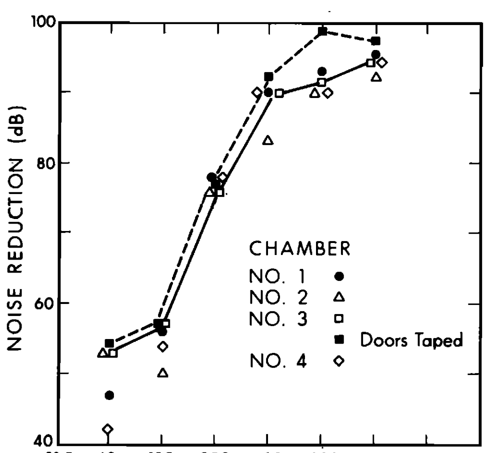

FIG. 5. Measured noise reduction of the chambers.

probably limited by the sound transmission loss of the doors and windows, increases from 50 dB at 63 Hz to 90 dB at 500 Hz, and is higher than 90 dB above 800 Hz. The solid and empty squares in Fig. 5 represent the noise reduction of chamber 3 with and without taping of the doors. The increased noise reduction above 500 Hz, resulting from the taping of both the exterior and interior doors along their entire perimeter, indicates that, if needed, the noise reduction in this frequency region could be improved by better gasketing.

C. Ambient acceleration levels on the experimental table

The octave-band spectrum of the ambient vibration level on the experimental table was measured by a special accelerometer of high sensitivity. The resonance frequency of this accelerometer is 5 kHz, so that the flat portion of its curve of sensitivity versus frequency does not extend above 2 kHz. Since small acceleration levels at high frequencies result in very small displacements, they are of no practical concern and were not recorded. The acceleration levels plotted in Fig. 6 result from operation of machinery in the main mechanical equipment room of the hospital, situated two floors above the laboratory, from the operation of heavy construction equipment adjacent to the building foundation, and from normal use of the building. The solid and empty trapezoids in Fig. 6 represent the ambient acceleration levels measured on the experimental table of chamber 4, both before the discovery of a short circuit in one of the vibration isolation mounts of the table and after corrective realignment. This large improvement in performance emphasizes the vital necessity of attention to detail during construction and the practical value of thorough final performance evaluation. As shown in Fig. 6, the ambient acceleration level of the properly aligned experimental tables is -100 dB *re* 1 g in the 31.5-Hz band, is well below -120 dB (i.e., smaller than 10^{-5} m/sec^2) in all higher octave bands, and could not be determined exactly because of instrumentation limitations.

To evaluate the effect of the worst type of vibration excitation that may occur in the control room area (e.g., impacts produced by dropping solid objects on the floor), we operated an ISO Standard Tapping Machine[19] on the floor of the control room approximately 5 ft from the chamber wall and measured the octave-band acceleration level on the operating table. The results of these tests, plotted in Fig. 7, indicate that even under extremely unfavorable conditions the octave-band acceleration levels on the experimental operating table remain below -100 dB *re* 1 g at frequencies below 500 Hz and below -110 dB above 500 Hz. The noise in the experimental chambers produced by the operation of the tapping machine is only slightly above the threshold of hearing and is barely noticeable by human subjects in the chamber.

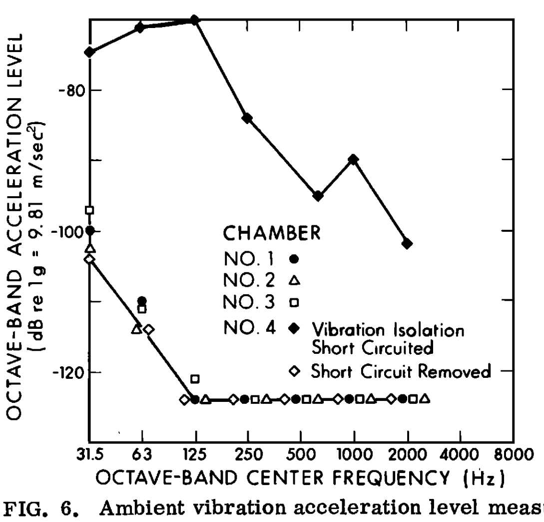

FIG. 6. Ambient vibration acceleration level measured on the experimental tables.

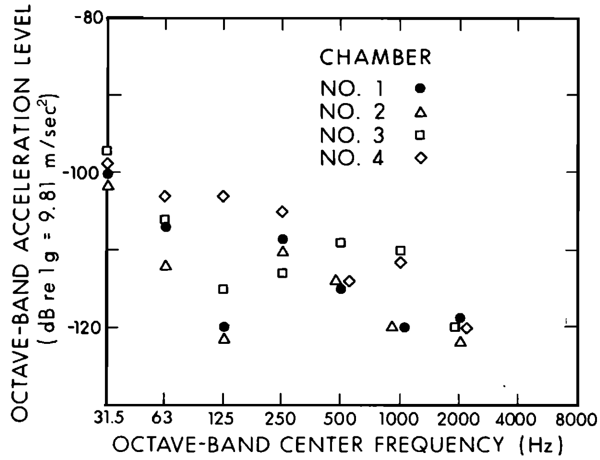

FIG. 7. Vibration acceleration level of the experimental tables for tapping machine excitation of the control room floor.

V. CONCLUSIONS

The results of the performance evaluation have confirmed that the completed experimental chambers have met the performance goals. Close cooperation of the user and a specialist in the technical areas where major difficulties are expected can result in the meeting of highly demanding performance criteria if careful attention to the design and execution of details is paid. In the present example, there would have been no inexpensive way to correct for minor errors that would have had major consequences for performance, so that the prototype had to be the final version.

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[1]Represented by the first listed author.
[2]Walk Jones and Francis Mah Architects, Inc., Memphis, TN.
[3]Griffith C. Burr, Inc., Consulting Engineers, Memphis, TN.
[4]Represented by the authors listed second and third.
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[10]Courtesy of Walk Jones and Francis Mah, Inc.
[11]The numbers in boldface refer to details in Fig. 2.
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