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Acoustical Benefits Resulting from Insulation and Air-Leakage-Control Retrofits in Family Housing Units

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ABSTRACT

In an investigation sponsored by the Navy Family Housing Office, a series of tests was conducted to determine the improvement in acoustical sound transmission loss resulting from housing envelope energy conservation retrofits involving increased insulation level and/or control of air-leakage.

Three wall and two roof/ceiling test structures were constructed to be representative of present-day Navy family housing units. The sound transmission loss and air-leakage rate were determined for each basic construction. Subsequently, various retrofit measures were performed. Following the retrofit, the improvements in air-leakage rate and sound transmission loss were again determined. The thermal transmittance (U value) of the base constructions and the retrofits was calculated or measured.

Data are presented on the sound transmission loss, overall sound transmission class (STC), air-leakage rate, and thermal transmittance of the constructions tested. Typical (1982) retrofit costs are also estimated, along with estimates of the seasonal average heat loss, so that benefit-to-cost performance can be analyzed.

INTRODUCTION

Energy conservation retrofits in buildings through the addition of insulation, the installation of storm windows and doors, and the general "tightening up" of the building envelope have been and will continue to be the subject of much attention. Several studies have suggested that retrofit measures intended principally for energy conservation purposes often are remarkably similar to those used for the reduction of noise transmission from the exterior of a building to the occupants inside.[1-3]

The complementary relationship between thermal and acoustical retrofit measures was of interest to the U.S. Navy Family Housing Office, especially the acoustical benefits resulting from energy conservation measures implemented in existing housing units near naval air operations. This interest led to the contracting of an extensive laboratory investigation of the thermal and acoustical benefits of various retrofit measures, the results of which were compiled in a comprehensive 180-page report.[4] This paper is a condensation of that formal report and presents the most pertinent findings, which are applicable to public as well as to military housing units.

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PROGRAM OBJECTIVES

The major objectives of the investigation were as follows:

1. Identify typical wall and roof/ceiling construction elements representative of those found in naval base family housing units.
2. Develop several retrofit measures for each wall and floor/ceiling element (identified above) having the potential for significant improvement in thermal and/or acoustical performance.
3. Construct full-scale replications of each building element in the laboratory, and test to determine the sound transmission and air-leakage performance for each panel before and after the installation of retrofit measures.
4. Calculate or measure the thermal transmittance of each basic assembly and retrofit.
5. Provide a compilation of the acoustical and air-leakage test results along with estimates of the installed cost and the estimated annual energy loss for the basic construction and each retrofit, normalized to a panel gross area of 100 ft^2 (9.3 m^2).

CHARACTERIZATION OF THERMAL/ACOUSTICAL PERFORMANCE

For the purposes of this investigation, the thermal and acoustical performances of a building envelope element (wall or roof/ceiling) are considered to be characterized by the following measurements:

Thermal

--Thermal transmittance or U factor, $Btu/h{\cdot}ft^2{\cdot}{}^{o}F (W/m^2K)$

--Air leakage rate, ft^3/min (m^3/s)

Acoustical

--Random incidence sound transmission loss (TL)

--Sound transmission class (STC)

The thermal transmittance or U value for each basic panel design and each retrofit was calculated in accordance with the procedures and data given in the ASHRAE Handbook--1981 Fundamentals. In two cases, the panel geometries were felt to be sufficiently complex to prohibit the precise calculation of heat loss. Actual measurements of the thermal transmittance of these panels were made using the guarded hot box method for these constructions.

The air-infiltration rate for each of the assembly designs was measured at several points over a pressure differential range of -0.3 to +0.3 in. H_2O (-75 to +75 Pa).

Both the thermal transmittance values and air-leakage rates were used to estimate the annual heat loss in Btu (kWh) based on a heating season of 5000(°F) degree-days (2778 [°C] degree-days) as described in the "Test Procedure" section of this report.

The sound transmission properties were measured over the frequency range of 100 to 5000 Hz and are expressed as TL values in decibel units. The TL values for the frequency range of 125 to 4000 Hz were used to calculate a single-number measure of acoustical performance identified as the Sound Transmission Class (STC).

SELECTION OF BASIC CONSTRUCTION ELEMENT DESIGNS

A field survey was conducted in cooperation with the Navy in which 18 individual housing units from 8 different projects at a major base were examined in detail. The original construction of these units spanned the time interval from 1940 to 1977. From the survey, three exterior wall and two roof/ceiling panel designs were selected for evaluation.
The general construction details for each of the five basic panels were as follows:

Panel Designation	Type	Description
A	Wall	Wood frame with plywood siding on exterior, gypsum-board interior, R-5 mineral-fiber insulation, two metal electric outlet boxes, 12-ft^2 (1.1-m^2) single-glazed, fixed wood sash window. This panel represented a slab-on-grade construction.
B	Wall	Wood frame with stucco on fiberboard sheathing on exterior, gypsum-board interior, R-5 mineral-fiber insulation, two metal electrical outlet boxes, 12-ft^2 (1.1 m^2), single-glazed horizontal slider window. Built over 1.0-ft (0.3-m)-deep simulated crawlspace with screened vent.
C	Wall	Eight-inch concrete (masonry) block with stucco exterior, furred, uninsulated, gypsum-board interior, two metal electrical outlet boxes, 12-ft^2 (1.1-m^2) single-glazed, double-vent, steel casement window.
D	Roof/ Ceiling	Plywood-sheathed, wood truss roof (3/12 pitch) with asphalt shingles and 0.5-ft (0.15-m) diameter roof vent, plywood soffit with 3/4-in. (19-mm) continuous eave vent, R-7 mineral-fiber insulation, 4.6-ft^2 (0.43-m^2) attic scuttle and recessed ceiling-light fixture.
E	Roof/ Ceiling	Built-up, three-ply roof with 400-lb/sq (100 sq. ft.) (19.5 kg/m^2) gravel surface over nominal 2- by 6- in. (50- by 150- mm) tongue-and-groove wood decking supported by exposed nominal 2- by 12-in. (50- by 300- mm) wood beams installed at a 1/12 pitch.

Details of the basic panel constructions are shown in Figures 1 through 5. Note that in these figures, only inch-pound units are used to aid in the identification of common building material sizes.

IDENTIFICATION OF RETROFIT MEASURES

A literature search, which was included as part of the investigation, revealed that two prime sources of noise transmission into residential buildings were windows and other openings. These were, of course, also major heat-flow paths and were thus considered to be high-priority areas for retrofit measures.

Sealing of openings such as cracks was a particularly attractive starting point, because the cost of this measure was considerably lower than the costs of the more extensive treatments. Caulking of each basic construction was thus established as the initial retrofit.

For the wall panels, the treatment of window areas, which has an immediate appeal from an intuitive standpoint, was identified as the second order of priority. It will be demonstrated analytically in the "Discussion" section that windows, as well as other low TL paths, must be treated before improving the acoustical performance of panel areas that already have moderate to high TL properties. Other retrofit measures employed as part of this investigation were aimed at enhancing the acoustical and/or thermal performance of the panels after the more obvious sound and heat-flow paths were treated.

Details of the various retrofit measures employed with each basic panel construction are given in Tabs 1 to 5 and are listed in the originally established order of priority.

TEST PROCEDURES

All acoustical, air-leakage-rate, and thermal transmittance tests were performed within the facilities of a research and development center in Denver, CO. The acoustical and air-leakage tests were performed on specimens installed within the reverberation room suite of the acoustical test facility, as shown in Figs. 6 and 7. In all cases, the exterior side of the test panel faced the sound source in the smaller room.

Sound Transmission Test Procedure

The sound transmission properties of the panels were measured in accordance with ASTM E90-75, "Standard Method of Laboratory Measurement of Airborne Sound Transmission Loss of Building Materials". The wall test specimens were constructed within the 9-ft-high by 14-ft-wide (2.7-m by 4.3-m) opening formed between the smaller and larger reverberation chambers as shown in Fig. 7.

Testing of the roof/ceiling designs presented a logistics problem in that the constructions (particularly the gravel-surfaced built-up roof panel E), normally oriented horizontally, could not be installed in the vertical test opening. This was solved by constructing a temporary supporting wall approximately 9-ft-high (2.7m) in the smaller room at a distance approximately 8-ft (2.4m) from the normal test opening. The temporary wall was known by earlier tests to have very high sound attenuation properties. The roof/ceiling panels were then installed within the smaller test chamber and were supported along one long edge by the temporary wall and along the edge adjacent to the vertical test opening by a beam installed for this purpose (Fig. 7).

Sound transmission loss (TL) is the ratio (expressed on a decibel scale) of the airborne sound power incident on a partition to the sound power radiated on the other side. It can be expressed as

$$TL = 10 \log_{10} \left(\frac{1}{\tau}\right), \text{ dB} \qquad (1)$$

where

TL = Transmission loss

τ = Transmission coefficient = the fraction of airborne sound power incident on the panel that is radiated on the other side

Sound transmission loss normally varies as a function of the frequency of the incident sound. As a result, measurements of TL are normally made over a wide range of frequencies in one-third octave bandwidths. As suggested in ASTM E-90, measurements of TL made under this investigation were performed over the one-third octave band center frequency range of 100 to 5000 Hz.

A single-number rating of overall TL performance, known as the STC, was calculated for each panel using the TL values covering the frequency range of 125 to 4000 Hz (ASTM E-413-73, "Standard Classification for Determination of Sound Transmission Class"). The STC was designed to correlate with subjective impressions of sound isolation in offices and dwellings. Although the STC was not intended for use in applications where sound spectra differing from human speech are involved, the single-number measure of partition performance is widely recognized by those working in building acoustics and has been provided as a simple means of ranking the acoustical effectiveness of various panels and retrofits.

Air-Leakage Rate Test Procedure

Measurements of panel air-leakage rates were performed on the same constructions tested for TL. The procedure followed in these measurements was ASTM E-283-73, "Standard Method for Rate of Air Leakage Through Exterior Windows, Curtain Walls and Doors".

The leakage rates were determined by either pressurizing or evacuating the "source" room through a plastic pipe, which was fitted with a square-edged orifice plate metering station. Air-leakage rates were determined at five values of differential pressure across the test panel over the range of 0.1 to 0.3 in. H_2O (25 to 75 Pa) for both positive and negative pressures on the interior side of the panel. All panel air-leakage rates were corrected to standard atmospheric conditions and were adjusted for the facility leakage determined by covering the test specimen with plastic film.

A computer program was written that transformed the pressure differential/leakage rate data pairs to log pressure-log flow data pairs, calculated a least squares equation of best fit to the transformed data, and interpolated leakage rates at evenly spaced increments of pressure differential.

Thermal Transmittance Determinations

The thermal transmittance of most of the basic constructions and retrofits was calculated using the procedures and data given in the ASHRAE Handbook--1981 Fundamentals, chapter 23. In the case of retrofits A5 and E2, these procedures were not felt to be sufficiently precise, and actual measurements of the basic panel and retrofit constructions were made. The thermal transmittance tests were performed on panels 5.3 by 6.7-ft (1.6 by 2.0 m) using ASTM C-236, "Standard Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box". The tests were performed at a mean temperature of 45°F (7°C), representing a typical winter temperature range of 20 to 70°F (-7 to 21°C).

TEST RESULTS

The results of the acoustical and air-leakage tests are given in Tabs. 6 and 7. Figures 8 through 16 show the individual TL values measured at various frequencies.

The acoustical test results shown in the tables are expressed in the form of the single-number STC rating for each panel.

The air-leakage rates are given in terms of the average of the volumetric flow rate in ft^3/min (m^3/s) for positive and negative pressure differentials of 0.3 in. H_2O (75 Pa) which is equivalent to the static pressure developed across a specimen subjected to a 25-mph (40-km/h) wind.

(Thermal transmittance test results have not been included in this paper, but both the calculated and measured transmittance values have been included in the original report to the Navy.)

PERFORMANCE SUMMARY

The acoustical and air-leakage data that were reported reflect the performance for a panel with a gross area of approximately 112 ft^2 (10.4 m^2) with a window area (for walls) of approximately 12 ft^2 (1.1 m^2) or 11% of the gross area.

The reported TL and STC values for these panels are directly applicable to panels with larger or smaller gross areas having ratios of window area to total wall area on the order of 11%.

The estimated cost of each retrofit and the estimates of the annual heat loss for each construction were determined and normalized to a basis of 100 ft^2 (9.3 m^2) of panel area with an assumed ratio of window area to total wall area (in the case of walls) of 0.11 (11%).

Cost data for the various retrofits were estimated on the basis of costs for various tasks tabulated in Repair and Remodeling Cost Data - 1982 and Building Construction Cost Data - 1982.[5-6]

The averaged air-leakage rate at a pressure differential of 0.3 in H_2O (75 Pa) was converted to an estimated seasonal average leakage. The conversion of steady-state airflow to a seasonal average value is subject to many variables. For the purpose of this investigation, the measured average air leakage at 0.3 in H_2O (75 Pa) was divided by a constant of 27 to obtain the seasonal average leakage rate.

This constant is consistent with others that were suggested, such as a value of 4 at 0.016 in. H_2O (4 Pa) and 20 at 0.2 in. H_2O (50 Pa). The seasonal average leakage rates were then converted to seasonal average heat loss in Btu (kWh) based on a heating season of 5000 ($^{\circ}F$) degree-days (2778 [$^{\circ}C$] degree-days.

The conductive and convective heat losses were determined on the basis of a 5000 ($^{\circ}F$) degree-days (2778 [$^{\circ}C$] degree-days) heating season, an outside wind velocity of 15 mph (24 km/h), and a mean temperature of 45$^{\circ}F$ (7$^{\circ}C$).

The estimated cost and performance for each base construction and each retrofit procedure normalized to a panel area of 100 ft^2 (9.3 m^2) are given in Tabs. 6 and 7. These data can be used to evaluate the attractiveness of a particular retrofit measure in light of individual needs and budget.

The heat loss data can be converted to dollars per season by simply multiplying the heat loss per season by the cost of fuel in dollars per Btu (kWh) adjusted for the expected heating plant efficiency. Dividing the energy saved resulting from a retrofit measure by the seasonal heating cost provides the simple payback period in years.

DISCUSSION OF RESULTS

An assessment of the improvement in performance provided by a particular retrofit scheme must include many factors. From an energy savings standpoint alone, the benefit can be evaluated in terms of the payback time and is thus relatively easily quantified.

The acoustical benefits on the other hand are subject to the psychological as well as to the physiological response of human inhabitants and thus require a qualitative as well as a quantitative analysis, which is beyond the scope of this paper. However, some general guidelines for judging the effectiveness of the various retrofits can be stated to serve as a preliminary screening tool.

Small differences in TL ($\leq$ 3 dB) and STC are generally indistinguishable and may be considered insignificant. Changes on the order of 4 to 9 dB are easily distinguishable and may be considered significant. A change of 10 dB is perceived as about twice (or half) as loud, and a change of 20 dB is perceived as being four times (or one-fourth) as loud. In the case of retrofitted buildings, evidence indicates that reductions of 10 dB or more are required before occupants will acknowledge a definite improvement in their environment.

In the acoustical treatment of the building envelope, one must be aware of the strong influence a small area of high acoustical transmission (low TL) can have on the total amount of sound passing through a composite panel, such as a wall containing a door and windows. For example, a wall constructed of a material having a TL of 50 dB with a gross area of 129-ft^2 (12-m^2) containing a 10.8-ft^2 (1-m^2) window having a TL of 10 dB will provide an _effective_ TL of only 21 dB.

The reason for this can be appreciated more easily if one expresses the transmission properties of the elements making up a composite panel in terms of transmission coefficients, τ, rather than the TL.

The transmission coefficient can be obtained from the TL as follows:

$$\tau = 10^{-(TL/10)} \qquad (2)$$

where

τ = Transmission coefficient
TL = Transmission loss

The total amount of sound power transmitted by the composite wall or roof/ceiling is proportional to the sum of the products of the individual element transmission coefficients and their respective areas as follows:

$$\tau_c S_c = \tau_1 S_1 + \tau_2 S_2 + \tau_n S_n \qquad (3)$$

where

τc = Transmission coefficient of composite panel

τ_1, τ_2, τ_n = Transmission coefficient of component areas making up composite panel

S_c = Total area of composite panel

S_1, S_2, S_n = Area of components making up composite panels

Observing that the τ varies exponentially with TL (Eq 2), it can be seen that a small area with a very low TL located in the field of a panel formed of very high TL construction can cause the small component τS product to virtually dictate the total amount of power transmitted by the composite panel.

If one divides the right side of Eq 3 by the gross area of the composite panel, S_c, and substitutes the resulting composite panel transmission coefficient, τc, in Eq 1, one will find that the effective TL of the panel as a whole can be severely limited by the low TL of a small area (such as a window, door, or through penetration). This should really come as no surprise to anyone who has ever experienced the effect in a room where there is a large gap between the door and the floor.

If one acoustically treats a composite panel area that already has a low τS product, it can be seen that the overall TL of the panel changes very little so long as the low TL path exists.

When two or more such paths exist, they can interact in a synergistic fashion to result in a very significant improvement in overall TL. A particularly good example of this phenomenon occurred in the testing of panel design A. When a storm window was added, thus increasing the TL of the window area alone, the STC increased by only 3 dB from 35 to 38. When the opaque wall area was treated (but not the window), the increase was again 3 dB from 35 to

38. When both transmission paths were improved, the composite panel TL increased 12 points from 35 to 47.

This concept also comes into play for the entire building envelope, where the individual wall and roof/ceiling areas may be considered components of a larger, gross envelope area. Under these circumstances, it is of little benefit to improve the effective TL of a roof/ceiling, for instance to 50 dB, while a wall area with an effective TL of 20 or 30 dB serves as a boundary of the same occupied space. As a general rule, the product of the transmission coefficient, τ, and area, S, should be no greater than twice the τS product for any other panel enclosing the same occupied space.

As in any other noise control application, a final judgement regarding the suitability of a particular retrofit should include consideration of the spectral nature of the exterior sound field and the TL-versus-frequency relationship for the retrofit under consideration.

Tests of the assemblies considered under this program demonstrated that the effective STC values for the roof/ceiling designs are from 9 to 18 STC points better than for the walls. When a window is opened, the roof/ceiling STC becomes as much as 30 points higher than that of the wall. Considering the relative areas of roof/ceiling and walls in a typical housing unit, it becomes clear that the acoustical treatment of exterior walls should generally be done before that of the roof/ceiling. The installation of storm windows has been shown to significantly improve the effective TL of composite wall assemblies, particularly in cases where the surrounding opaque wall is of relatively massive construction. In lightweight wood-frame construction (such as panel A), the TL of both the opaque wall areas and windows may need to be treated before significant increases in the composite panel STC are obtained through the addition of storm windows. The addition of storm windows in conjunction with thorough caulking also demonstrated large reductions (approximately 30 percent) in estimated annual heat loss for walls at relatively low cost, suggesting that this retrofit should be given primary consideration.

Caulking and sealing alone were not shown to be of significant benefit from an acoustical standpoint unless very large gaps occurred in the construction, such as in panel C with the steel casement window.

In the case of wood frame construction over vented crawl-spaces (panel B), it was shown that a marginal improvement in overall sound isolation can be realized through treatment of the vents and insulation of the floor joist space. Reductions in heat loss due to this retrofit were, however, very substantial (approximately 40 percent), even without storm windows, making this an attractive and relatively inexpensive retrofit.

The installation of furred, supplementary interior or exterior walls with additional insulation has been demonstrated to provide large increases in STC ratings but only if window areas are also treated through the use of supplementary glazing.

In the case of roof/ceiling D, it has been shown that the acoustical baffling of the attic vent does not result in improvements in sound isolation, at least when the attic space is insulated to provide some measure of sound absorption. In the case of both roof/ceilings D and E, it was shown that the addition of a dropped and supplementary insulated ceiling can add approximately 10 STC points to the acoustical performance.

CONCLUSIONS

1. For the wall assemblies examined under this study, it was found that single-glazed windows severely limited the effective TL of the overall panel.

2. Improvements in sound transmission class of from 6 to 12 units were achieved through the use of supplementary or replacement storm windows in conjunction with caulking and sealing. At the same time, overall heat loss was reduced by approximately 30 percent.

3. Caulking and sealing were found to provide moderate increases in STC, with the most pronounced improvement at high frequencies. Although this retrofit does not appear to be justified solely on the basis of acoustical benefits, the combined thermal and acoustical performance improvements do appear attractive, particularly if done by the building resident or owner.

4. Caulking and sealing of the exterior walls can be accomplished by sealing either the exterior or interior surface; the choice of exterior or interior depends on accessibility and cost. Only slight improvement was found when both surfaces were sealed.

5. Acoustical treatment of a roof-mounted attic vent does not appear to offer any increase in acoustical performance for roof/ceiling designs similar to panel D.

6. The addition of a dropped ceiling provided substantial improvements in acoustical and thermal performance. However, it is doubtful that the acoustical improvement would be noticed unless exterior walls and windows were treated to bring the effective TL to approximately the same level as the roof/ceiling.

REFERENCES

1. "Home Soundproofing Pilot Project for The Los Angeles Department of Airports", Wyle Laboratories Report WCR70-1, 1970.

2. "Guide to the Soundproofing of Existing Homes Against Noise", Wyle Laboratories Report WCR 70-2, 1970.

3. "Design Guide-Methods For Improving the Noise Insulation of Houses with Respect to Aircraft Noise", Bolt, Beranek and Newman, Inc., Report 1390, Los Angeles, CA, 1966.

4. The report should subsequently be available to the public through the National Technical Information Service, Springfield, VA.

5. "Repair and Remodeling Cost Data-1982 (Commercial-Residential)", Robert Snow Means Company, Inc., 1982.

6. "Building Construction Cost Data-1982", Robert Snow Means Company, Inc., 1982.

TABLE 1

Retrofit Measures for Panel A

Retrofit no.	Description of retrofit
A1	Caulk and seal interior including window frame perimeter, baseboard, perimeter of wall, and add foam gaskets under cover plates of two electrical outlets.
A2	Same as A1 but with exterior also caulked
A3	Same as A2 but with 0.25-in. (6.4-mm) float-glass storm window installed.
A4	Same as A2 but with interior surface of opaque wall furred out with 1.5-in. (38-mm)-deep steel "Z" girts covered with 0.5-in. (13-mm) gypsum board. Space between existing and added gypsum board filled with R-5 mineral fiber insulation (no storm window installed).
A5	Same as A4 but with 0.25-in. (6.4-mm) storm window installed.

TABLE 2

Retrofit Measures for Panel B

Retrofit no.	Description of retrofit
B1	Caulk and seal perimeter of window frame, lower plate, baseboard, sill plate and entire perimeter of wall on interior side.
B2	As in B1 but with an aluminum framed, double-strength, 0.125-in. (3.2-mm) glazing (storm window) installed.
B3	As in B2 with window area blocked using high sound attenuation plug.
B4	As in B3 but with crawlspace vent sealed off.
B5	As in B4 but with crawlspace vent opened and fitted with an acoustic baffle. Also, R-11 mineral fiber insulation added to space between floor joists.

TABLE 3

Retrofit Measures for Panel C

Retrofit no.	Description of retrofit
C1	Install foam gasketing on movable sash units.
C2	As in C1 but with perimeter of stationary frame caulked, perimeter of panel caulked (interior only).
C3	As in C2 but with steel sash window replaced with single-hung, double-glazed, aluminum-framed, thermal-break window with double strength 0.125-in. (3.2-mm) panes separated by 0.25-in. (6.4-mm) airspace.
	As in C3 but with exterior of wall furred out with a 1.5-in. (38-mm) square wood strips spaced 25.5-in. (0.65-m) o.c. The space between the strips was insulated with 1.5-in. (38-mm) polystyrene board. A new layer of 0.75-in. (19-mm)-thick stucco with chicken wire mesh was then applied directly over the insulation.
C5	As in C4 but with window blocked closed with high sound attenuation plug.

TABLE 4

Retrofit Measures for Panel D

Retrofit no.	Description of retrofit
D1	Install lens in recessed light fixture.
D2	As in D1 but with roof vent blocked off from inside attic.
D3	As in D2 but with light fixture removed and attic insulation increased from R7 to R19 with blown-in, mineral-fiber insulation.
D4	As in D3 but with eave vent blocked off.
D5	As in D1 but with light fixture removed and dropped ceiling added consisting of nominal 2- by 6-in. (50- by 150-mm) wood joists spaced 1-in. (25-mm) below existing ceiling, 0.5-in. (13-mm) gypsum board attached to bottom of new joists and space between existing and new ceilings fitted with R-11 mineral-fiber insulation blankets. New attic scuttle installed in dropped ceiling and fitted with open-cell foam tape weather-strip seal. Note that the roof vent was reopened for this test and the original attic insulation (R-7) was in place.
D6	As in D5 but with open cell foam weatherstrip on scuttle replaced with closed cell foam.
D7	As in D6 but with attic insulation increased to R-19.

TABLE 5

Retrofit Measures for Panel E

Retrofit no.	Description of retrofit
E1	Caulk and seal beam closures at supporting "stub wall" inside and out.
E2	As in E1 but with dropped ceiling added below existing exposed tongue-and-groove wood decking between supporting beams. The dropped ceiling consisted of nominal 2- by 4-in. (50- by 100-mm) joists spaced 1-in. (25-mm) below the tongue-and-groove decking with a layer of 0.5-in. (13-mm) gypsum board attached to the bottom of the joists. R-19 mineral-fiber insulation was installed in the space between the decking and new ceiling.

TABLE 6

Test Results and Estimates of Installed Cost and Thermal Performance

Panel No.	Retrofit No.	STC	Air-leakage rate in ft^3/min ($m^3/s \times 10^3$) at pressure differential of 0.3 in. H_2O (75 Pa)		Est. Cost, ($)	Estimated annual heat loss per heating Season[a] in MBtu (mWh) due to air-leakage		thermal transmit.		total	
A	B/C[b]	32	66.4	(31.33)		0.32	(0.094)	2.81	(0.823)	3.11	(0.911)
	A1	35[c]	6.0	(2.83)	71	0.03	(0.009)	2.81	(0.823)	2.842	(0.832)
	A2	38	4.0	(1.89)	83	0.02	(0.006)	2.04	(0.597)	2.06	(0.603)
	A3	38	4.0	(1.89)	168	0.02	(0.006)	2.22	(0.650)	2.24	(0.656)
	A4	47	2.0	(0.94)	251	0.01	(0.003)	1.47	(0.430)	1.48	(0.433)
B	B/C[b]	13[d]	No Test								
	B/C[b]	29	39.0	(18.41)		0.17	(0.050)	2.69	(0.788)	2.86	(0.837)
	B1	30	26.0	(12.27)	71	0.12	(0.035)	2.69	(0.798)	2.81	(0.823)
	B2	38	22.7	(10.71)	53	0.10	(0.029)	1.92	(0.562)	2.02	(0.591)
	B3	46	7.0	(3.30)		0.03	(0.008)	2.06	(0.603)	2.09	(0.612)
	B4	49	No Test								
	B5	49	7.9	(3.73)	53	0.03	(0.009)	0.85	(0.249)	0.88	(0.258)

(a) Basis is 100-ft^2 (9.3-m^2) gross projected area, 5000 (°F) degree-days (2778 [°C] degree-days), wind velocity of 15 mph (24 km/h).

(b) Basic construction prior to retrofitting.

(c) No test was conducted on this retrofit. However, tests of minor panel changes immediately before and after installation of retrofit A1 both resulted in STC values of 35 and it is assumed panel A1 would also provide an STC of 35.

(d) Test conducted with slider window open.

TABLE 7

Test Results and Estimates of Installed Cost and Thermal Performance

Panel No.	Retro-fit No.	STC	Air-Leakage Rate in ft^3/min ($m^3/sec \times 10^3$) at pressure differential of 0.3 in. H_2O (75 Pa)		Est. Cost ($)	Estimated annual heat loss per heating season[a] in MBtu (mWh) due to air-leakage		thermal transmit.		total	
C	B/C[b]	24	144.1	(68.00)		0.65	(0.190)	3.80	(1.113)	4.45	(1.303)
	C1	30	34.9	(16.47)	15	0.16	(0.047)	3.80	(1.113)	3.96	(1.159)
	C2	30	14.8	(6.98)	71	0.017	(0.020)	3.80	(1.113)	3.87	(1.133)
	C3	37	1.2	(0.57)	263	0.01	(0.003)	3.10	(0.908)	3.11	(0.911)
	C4	39	No Test		538	0.01[c]	(0.003)	1.73	(0.507)	1.74	(0.509)
	C5	52	No Test								
D	B/C[b]	43	70.2	(33.13)		0.32	(0.094)	1.29	(0.378)	1.61	(0.471)
	D1	43	30.6	(14.44)	11	0.02	(0.006)	1.29	(0.378)	1.31	(0.384)
	D2	43	No Test			0.02[c]	(0.006)	1.29	(0.378)	1.31	(0.384)
	D3	47	No Test		53	0.02[c]	(0.006)	0.56	(0.164)	0.58	(0.170)
	D4	49	30.5	(14.39)		0.02	(0.006)	0.56	(0.164)	0.58	(0.170)
	D5	57	15.5	(7.32)	57	0.01	(0.003)	0.56	(0.164)	0.58	(0.170)
	D6	59	2.9	(1.37)	320	0.01	(0.003)	0.35	(0.102)	0.37	(0.108)
	D7	60	No Test		Not Est.						
E	B/C[b]	41	33.1	(15.62)		0.15	(0.044)	1.80	(0.527)	1.95	(0.571)
	E1	46	1.1	(0.52)	189	0	(0)	1.80	(0.527)	1.80	(0.527)
	E2	51	0.2	(0.09)	253	0	(0)	0.56	(0.164)	0.56	(0.164)

(a) Basis is 100-ft^2 (9.3-m^2) gross projected area, 5000 (°F) degree-days (2778 [°C] degree-days), wind velocity of 15 mph (24 km/h).

(b) Basic construction before retrofitting.

(c) Estimated value.

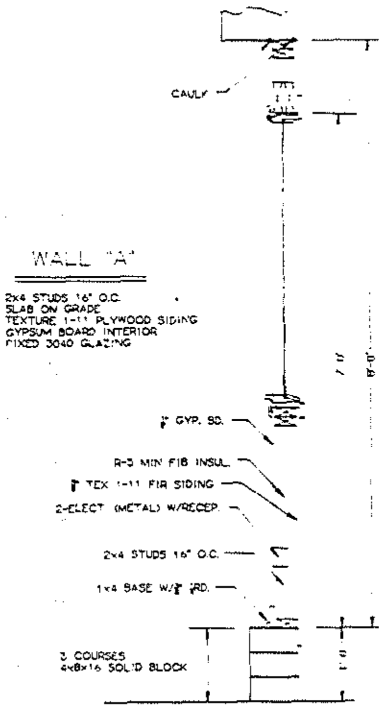

Figure 1. Vertical section through basic construction A

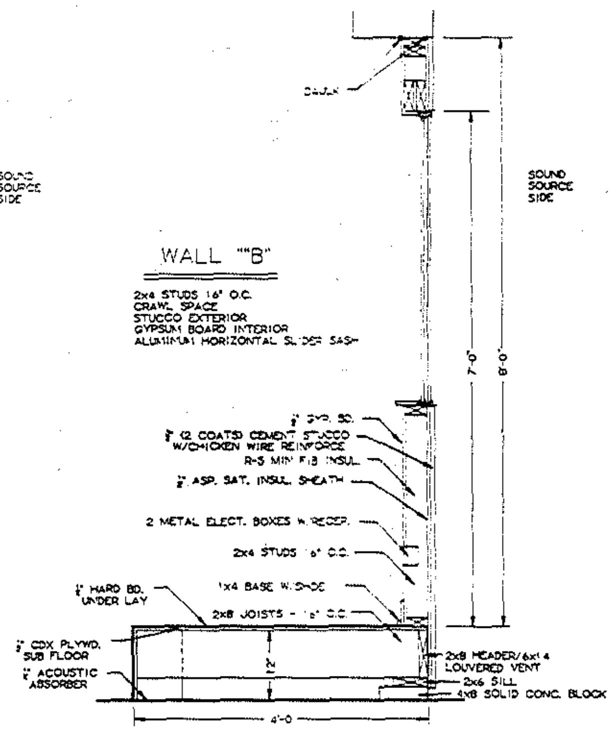

Figure 2. Vertical section through basic construction B

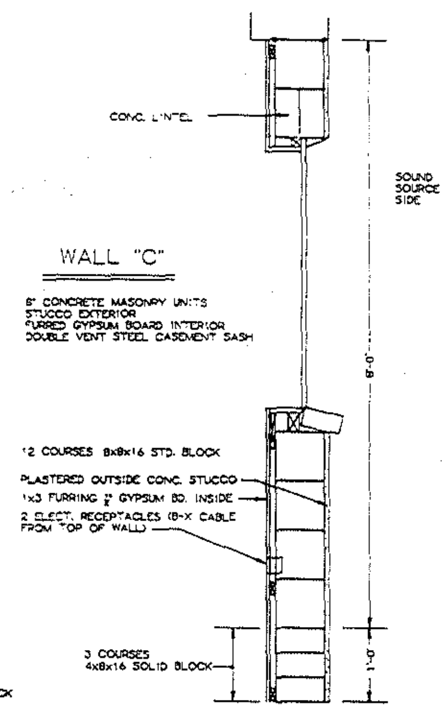

Figure 3. Vertical section through basic construction C

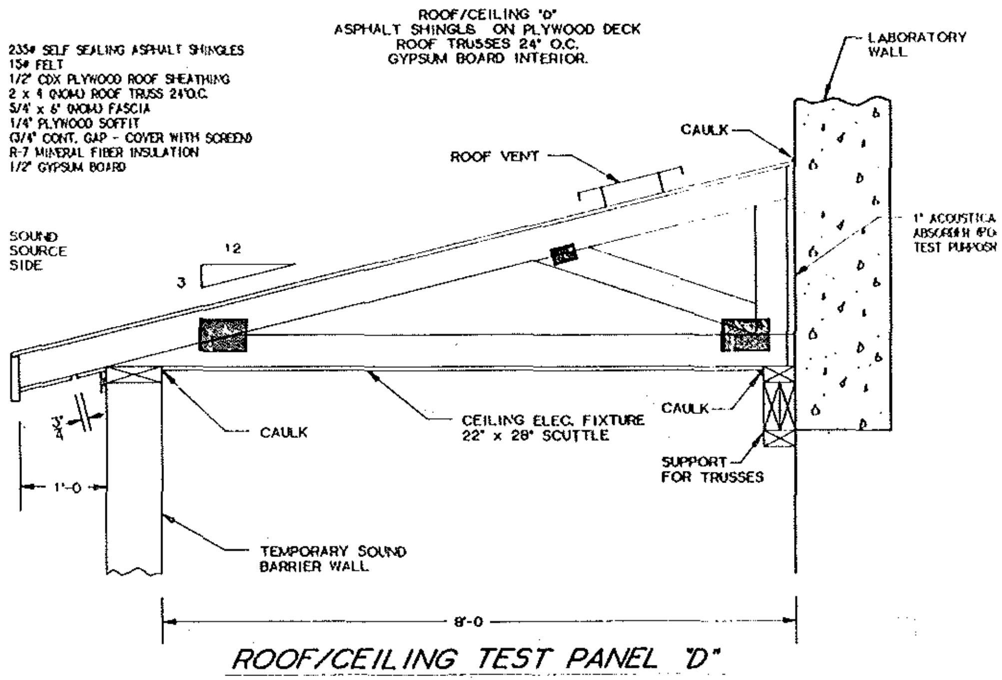

Figure 4. Vertical section through basic construction D

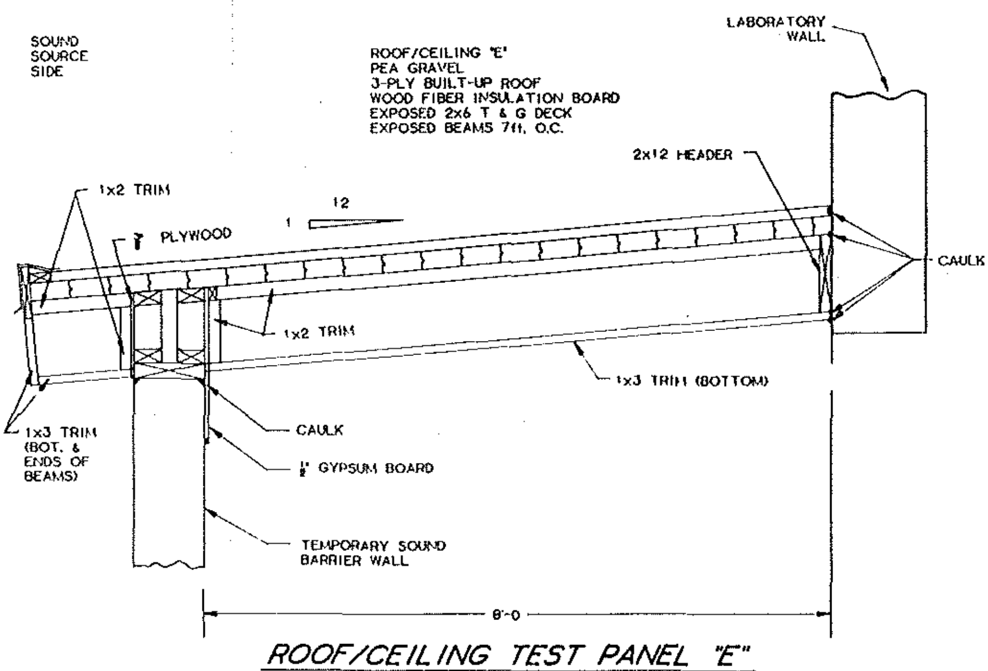

Figure 5. Vertical section through basic construction E

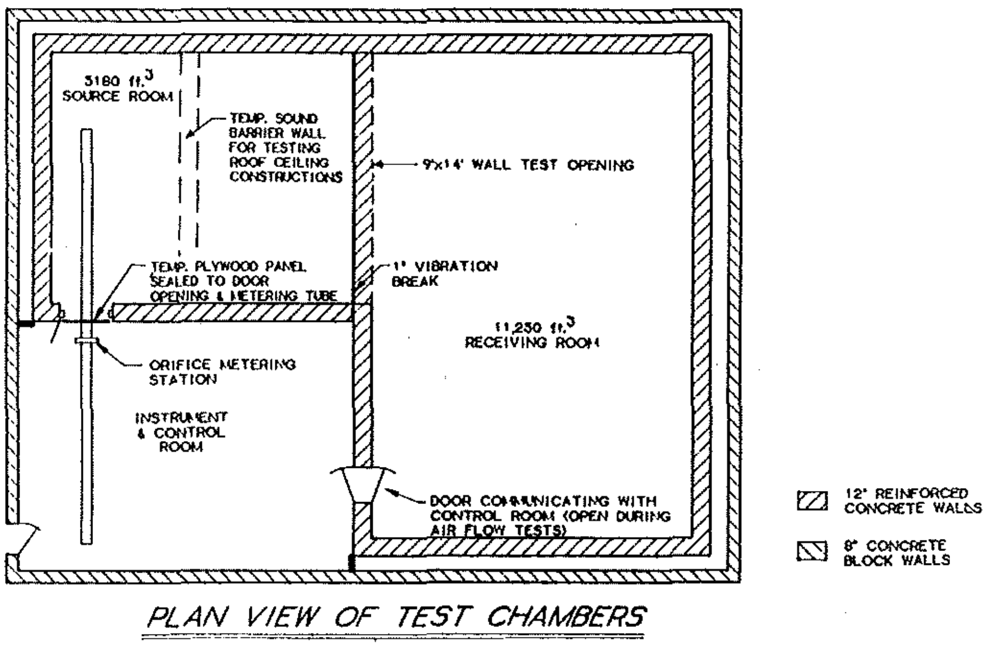

Figure 6. Plan view of acoustical/airflow measurement facilities

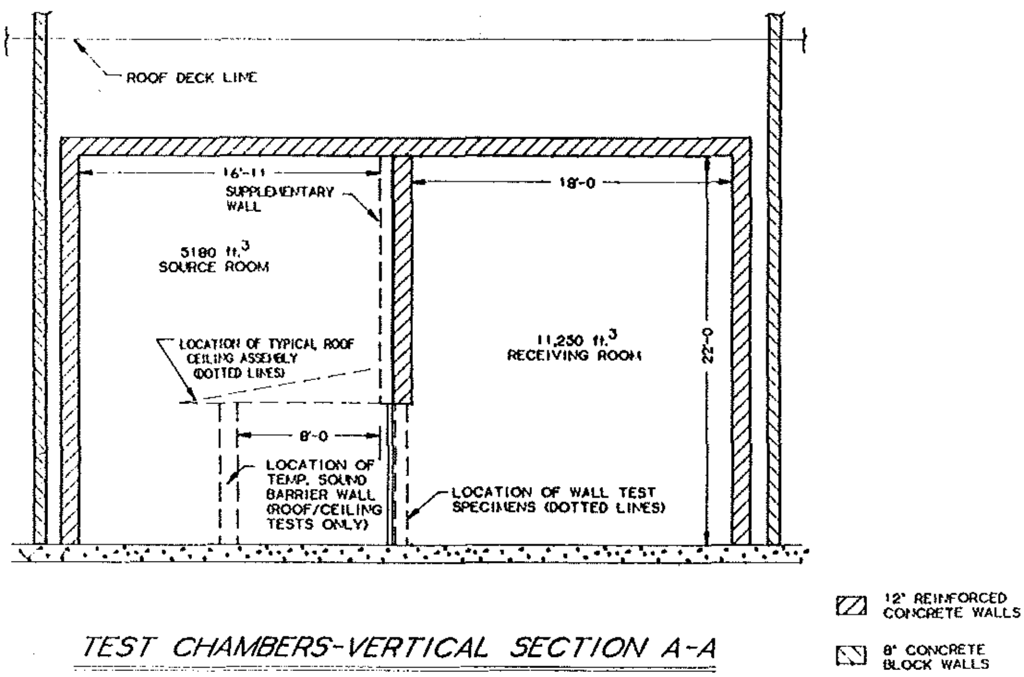

Figure 7. Vertical section through acoustical/airflow measurement facilities

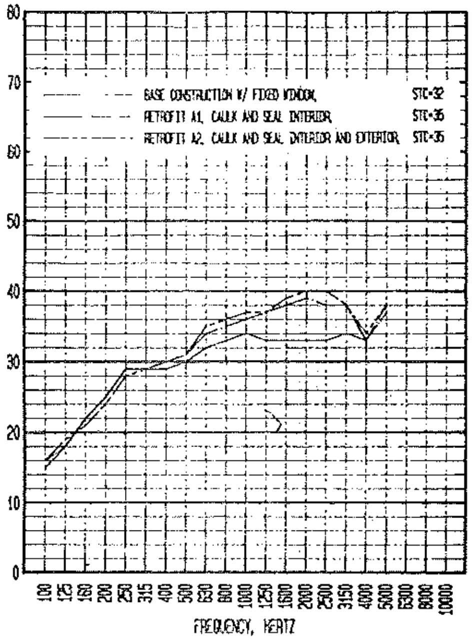

Figure 8. ASTM E-90 sound-transmission-loss values for basic construction A and retrofits A1 and A2

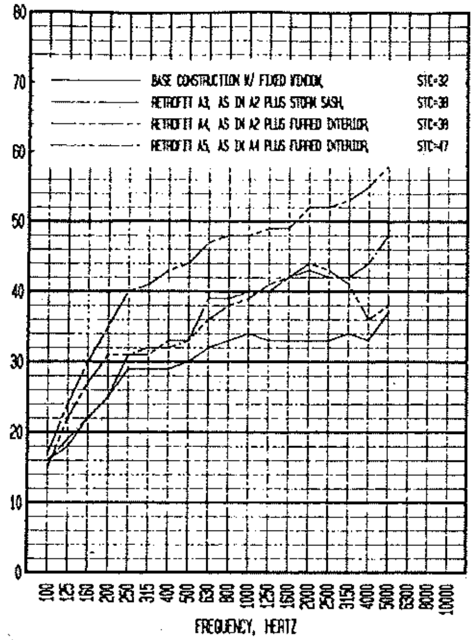

Figure 9. ASTM E-90 sound-transmission-loss values for basic construction A and retrofits A3, A4, and A5

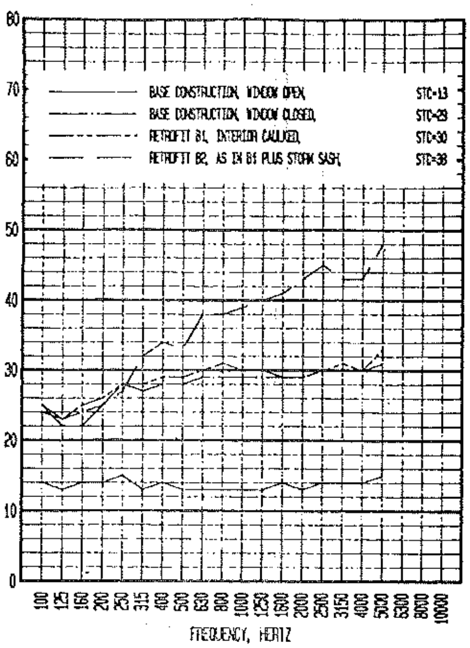

Figure 10. ASTM E-90 sound-transmission-loss values for basic construction B with and without window open and retrofits B1 and B2

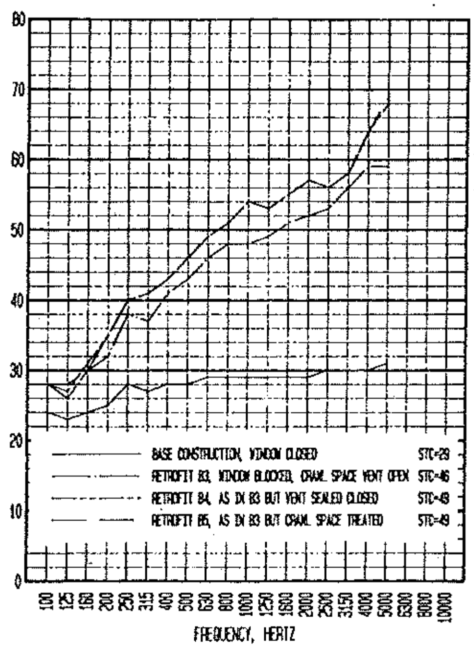

Figure 11. ASTM E-90 sound-transmission-loss values for basic construction B and retrofits B3, B4, and B5

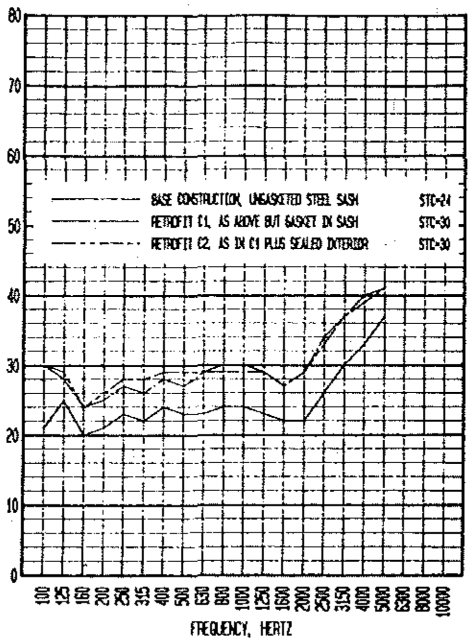

Figure 12. ASTM E-90 sound-transmission-loss values for basic construction C and retrofits C1 and C2

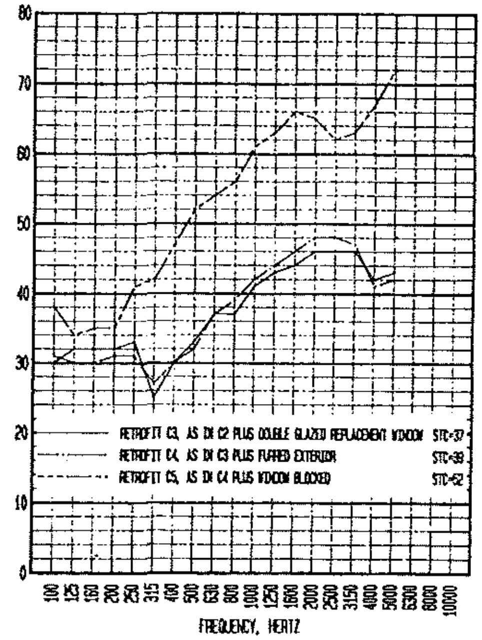

Figure 13. ASTM E-90 sound-transmission-loss values for basic construction C and retrofits C3, C4, and C5

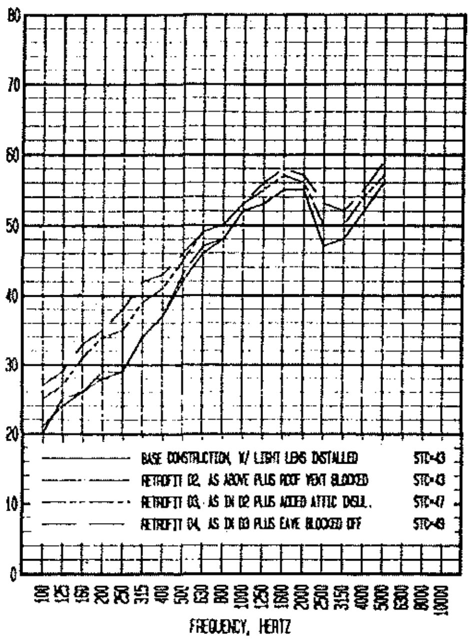

Figure 14. ASTM E-90 sound-transmission-loss values for basic construction D and retrofits D2, D3, and D4

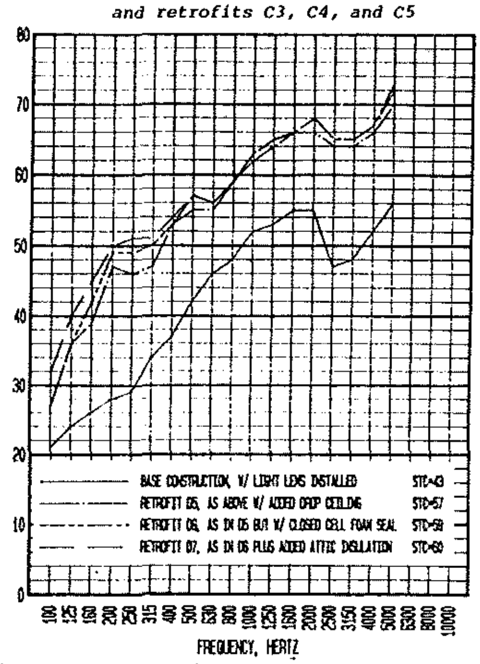

Figure 15. ASTM E-90 sound-transmission-loss values for basic construction D and retrofits D5, D6, and D7

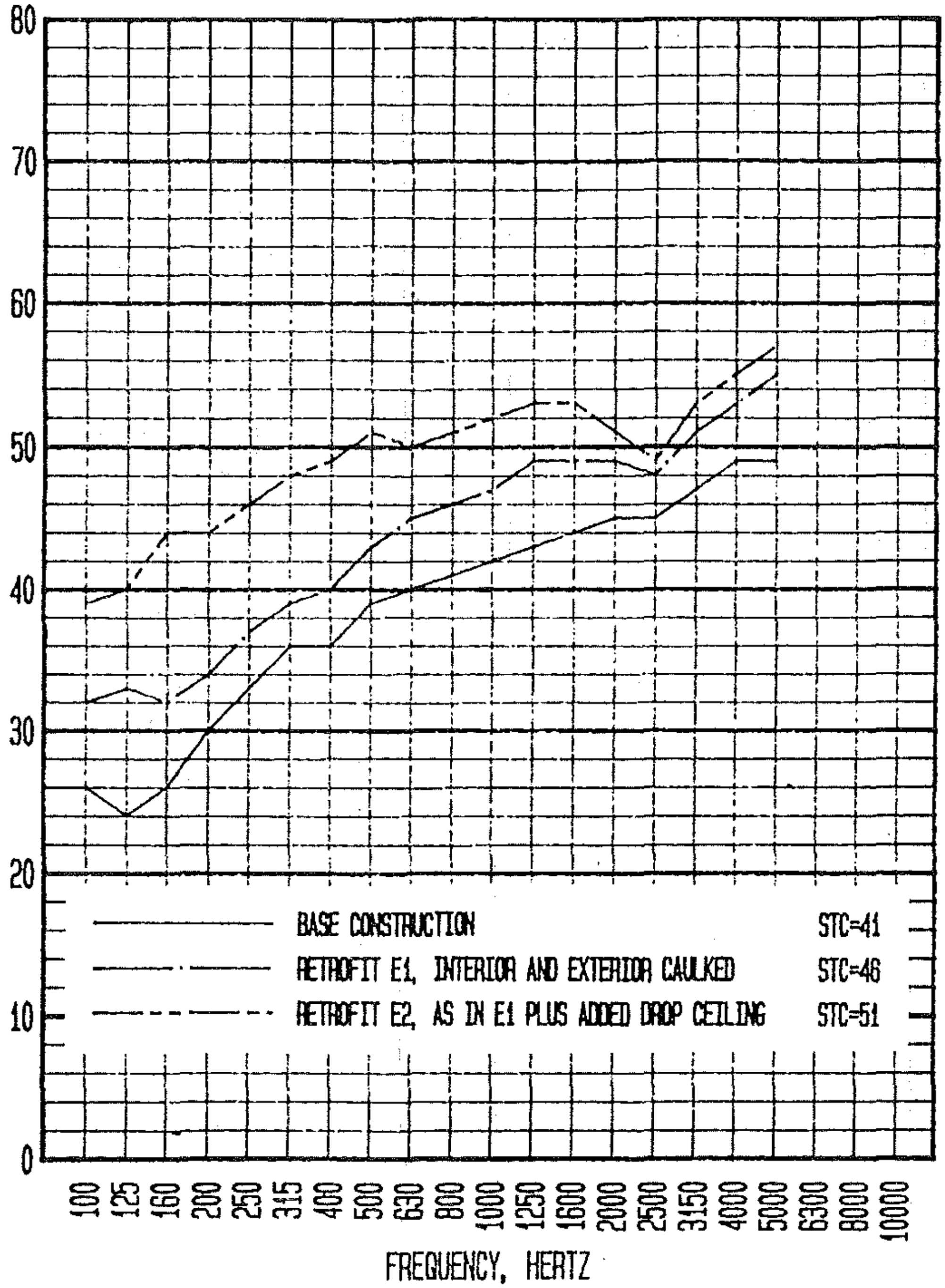

Figure 16. ASTM E-90 sound-transmission-loss values for basic construction E and retrofits E1 and E2