NATIONAL BUREAU OF STANDARDS

NBS BUILDING SCIENCE SERIES 77

Acoustical and Thermal Performance of Exterior Residential Walls, Doors and Windows

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

The Building Science Series

The Building Science Series disseminates technical information developed at the National Bureau of Standards on building materials, components, systems, and whole structures. The Series presents research results, test methods, and performance criteria related to the structural and environmental functions and the durability and safety characteristics of building elements and systems.

These publications, similar in style and content to the NBS Building Materials and Structures Reports (1938-59), are directed toward the manufacturing, design, construction, and research segments of the building industry, standards organizations, and officials responsible for building codes.

The material for this Series originates principally in the Center for Building Technology of the NBS Institute for Applied Technology. The publications are divided into three general groups: Building Systems and Processes; Health, Safety and Comfort; and Structures and Materials. For further information regarding these publications please contact the Scientific and Professional Liaison Section, Center for Building Technology, Institute for Applied Technology, National Bureau of Standards, Washington, D.C. 20234.

[See mailing list announcement on last page]

Acoustical and Thermal Performance of Exterior Residential Walls, Doors and Windows

Hale J. Sabine and Myron B. Lacher

Owens-Corning Fiberglass Corporation
Granville, Ohio 43023

Daniel R. Flynn and Thomas L. Quindry

Institute for Basic Standards
National Bureau of Standards
Washington, D.C. 20234

U.S. DEPARTMENT OF COMMERCE, Rogers C. B. Morton, *Secretary*

James A. Baker, III, *Under Secretary*

Dr. Betsy Ancker-Johnson, *Assistant Secretary for Science and Technology*

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Acting Director*

Issued November 1975

Library of Congress Catalog Card Number: **75–600084**

Nat. Bur. Stand. (U.S.), Bldg. Sci. Ser. 77, 170 pages (Nov. 1975)
CODEN: BSSNBV

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1975

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
(Order by SD Catalog No. C13.29/2:77). Price $2.35 (Add 25 percent additional for other than U.S. mailing).

Abstract

Laboratory tests of sound transmission loss, thermal transmittance, and rate of air leakage were conducted on full scale (9 feet high x 14 feet wide; 2.7 x 4.3 meters) specimens of typical residential exterior wall constructions, either unbroken or penetrated by a door or window. The walls were of wood frame construction with gypsum board drywall interior finish and exterior finishes of wood siding, stucco, or brick veneer. Additional acoustical tests were run on a number of individual doors and windows. A total of 109 acoustical tests and 48 thermal tests are reported. The resultant data are compared with literature data on similar constructions. Correlations developed among the several quantities measured will assist more rational design where both energy conservation and noise isolation must be considered.

Key Words: Acoustics, air infiltration, air leakage, architectural acoustics, building acoustics, doors, energy conservation, heat loss from buildings, heat transfer, sound transmission loss, thermal resistance, thermal transmittance, windows.

Table of Contents

List of Figures

List of Tables

1. Introduction and Scope

There are many considerations which affect the final design of the exterior shell of a residential building. Esthetics and economics are, of course, major concerns but two factors which are increasing in importance in the design decision are factors emphasized by the energy "crisis" and environmental considerations.

These two increasing concerns are for conserving heating and cooling energy through improved thermal performance and for achieving a sufficiently quiet interior environment in which to live comfortably by providing isolation from exterior noise.

Quite often a good acoustical design for an exterior wall is also a good thermal design since some of the same general principles are followed. The elimination of paths for excessive air leakage, for instance, can improve both the thermal and acoustical performance as can the use of wall insulation and storm windows.

The objective of the tests presented in this report was to obtain design information consisting of meaningful, representative data on the acoustical, thermal, and air infiltration performance of typical doors, windows, and exterior walls as used in residential construction.

Heat transmission and air infiltration data are useful for:

> Accurately estimating heat loss or gain for residences.
>
> Providing reference data on conventional constructions with which to compare performance of new types of construction designed to improve thermal energy utilization.

Similarly, sound transmission data are useful for:

> Estimating noise levels within residences due to outside sources such as aircraft and traffic.
>
> Providing reference data on conventional constructions and components against which to compare specified or measured performance of new types of construction.
>
> Designing combinations of walls with doors or windows to provide a given overall sound isolation.

Laboratory tests of sound transmission, heat transmission, air infiltration, and heat transmission in the presence of air infiltration were conducted on full-scale (9 x 14 ft) specimens of typical residential wall constructions, either unbroken or penetrated by doors or windows. The walls were of wood frame construction with gypsum board drywall interior finish. Three exterior finishes were used: wood siding, stucco, and brick veneer.

The test program on doors and windows was intended only to provide a representative data base on those types commonly used in residential construction. No attempt was made to obtain a statistical sampling of all available doors and windows nor to establish definitive averages and ranges of performance. Also, with one or two exceptions as noted, no tests were made on experimental constructions or variations designed to improve performance or to illustrate new departures in building practice. In accordance with the above method of selection, all units tested were purchased from the local lumber yard or supplied at no cost by a manufacturer from his standard product line.

The door tests included five exterior units, plus the addition of a storm door and a substitution of weather stripping in one of the exterior units.

Three general types of windows were tested, namely, wood, wood with exterior plastic coating, and aluminum. The window sizes ranged from 3 x 4 ft up to a 6 x 7 ft sliding glass door. Other window variables included type of glazing, number of lights (i.e., panes of glass in a given sash), and the addition of storm sash.

This report is organized as follows. Section 2 contains descriptions of the test specimens. In Sections 3, 4, and 5, which have parallel structures to facilitate cross-comparisons, the sound transmission loss, thermal transmittance, and air infiltration tests, respectively, are discussed. In each of these three sections, an introductory sub-section provides background information and references to related literature. Chapter 6 presents correlations among the sound transmission, thermal transmittance, and air leakage test results.

In order to make the test results more immediately useful to American architects and designers, customary engineering units are used rather than the (metric) International System of Units (SI) normally used in NBS publications. A table of conversion factors is given in Appendix A.

2. Description of Test Specimens

The program covered tests on three types of specimens:

(a) Continuous unbroken exterior walls
(b) Individual doors or windows
(c) Combinations of doors or windows set in exterior walls

The tests on continuous walls were conducted by building the wall construction into the entire 9 x 14 ft test opening of the sound or thermal test facility. These walls were built in strict conformity with normally good field practice except that, in addition, they were thoroughly caulked into the test opening around the entire perimeter.

For tests on combinations of doors or windows set into exterior walls, field practice was again followed. The doors and windows were installed, with their frames, as complete units into rough openings framed to the required nominal dimensions. The outer perimeters of all door and window frames were thoroughly sealed to the exterior side of the wall opening in accordance with good field practice.

For sound transmission tests on individual doors or windows, the same installation procedure was followed except that a "filler wall" construction surrounding the unit under test was specially built to eliminate errors due to flanking transmission. Details of this construction are discussed in Section 3 and in Appendix B. In some cases, auxiliary construction was added to an existing exterior wall construction, and in other cases a complete filler wall was built.

In all cases, the exterior side of the test construction faced the sound source room or the thermal cold chamber (which was also the pressurized side for infiltration tests).

2. 1. Walls

The sound transmission test program included all of the walls, doors, and windows listed below. To avoid duplication, a complete tabulation of the test specimens is not given in this chapter but rather is included in Appendix C, where all of the sound transmission test results are presented. The thermal transmittance test program covered only a limited selection of the test specimens.

Three types of wood frame exterior walls were tested having outside facings of painted wood siding, unpainted stucco, and brick veneer, respectively. The interior surfaces were unpainted 1/2 in. gypsum board drywall. The framing throughout was 2 x 4 in. wood studs,[1/] 16 in. on centers (o.c.).

The basic constructions[2/] are described as follows:

Wood Siding (Figure 1)

Framing -	2 x 4 in. wood studs, 16 in. o.c.
Sheathing -	1/2 in. wood fiberboard insulation nailed to studs
Siding -	5/8 by 10 in. redwood nailed through sheathing into studs
Interior -	1/2 in. gypsum board screwed to studs or to metal resilient channels which were attached to the studs.

[1/] 2 x 4 in. wood stud dimensions were 1 5/8 by 3 5/8 in.

[2/] The purchase of specific brands of building materials used in the fabrication of test specimens was based on availability. Brand names and company names which appear in the text or photographs of this publication do not imply endorsement by the National Bureau of Standards.

Figure 1. Application of wood siding to frame wall installed in sound transmission facility.

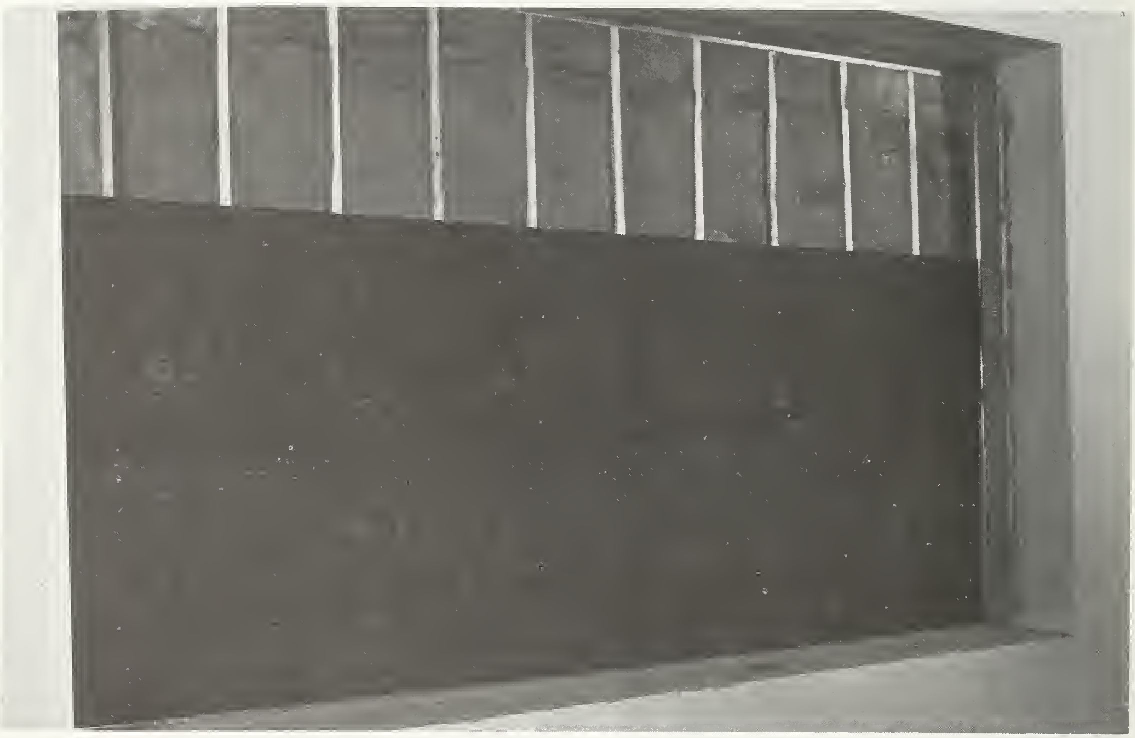


Figure 2. Application of building felt and wire mesh prior to stucco application.

Stucco (Figure 2)

Framing -	2 x 4 in. wood studs, 16 in. o.c.
Sheathing -	none
Stucco -	No. 15 felt building paper and 1 in. wire mesh nailed to studs. Stucco applied in 3 coats to 7/8 in. total thickness. Dry weight of stucco 7.9 lb/sq ft.
Interior -	1/2 in. gypsum board screwed to studs or resilient channel

Brick Veneer (Figure 3)

Framing -	2 x 4 in. wood studs, 16 in. o.c.
Sheathing -	3/4 in. wood fiberboard insulation
Brick -	standard face brick 3 1/2 in. wide, spaced 1/2 in. out from sheathing with metal ties nailed through sheathing into studs. Dry weight of brick and mortar 41 lb/sq ft.
Interior -	1/2 in. gypsum board screwed to studs or resilient channel

For each wall, variations involving cavity insulation and resilient drywall channels were tested.

The constructions without resilient channel would be more typical of residential exterior walls, and the tests with channel were included to show the improvement in sound isolation which might be expected.

The cavity insulation used in all of the walls was Fiberglas[3/] 3 1/2 in. R11 Kraft Faced Building Insulation. In addition, the wood siding wall with the gypsum board fastened directly to the studs was also tested with Fiberglas 3 1/2 in Friction Fit Building Insulation, with Alfol[3/] Type 2P R14 (inset stapled) reflective-type insulation and with 3 in R11 Premium Brand[3/] Paper Enclosed Rock Wool Building Insulation.

The resilient drywall channel, when used, was one of three makes of product which had been previously tested and found essentially equivalent for sound isolation. The channel was nailed horizontally to the studs on 2 ft spacing, and the gypsum board was screwed into the channels (see Figure 4). At the bottom, the gypsum board was screwed into the studs through a gypsum board base strip in accordance with standard field practice; this, however, reduces the potential sound isolating value of the resilient channel appreciably, as shown by earlier tests.

2. 2. Doors

Five types of residential exterior doors were obtained locally and tested. These included three wood doors of differing construction, a steel door, and a molded glass fiber reinforced plastic (FRP), foam filled panel door. The wood doors and the FRP door all fit interchangeably into a single wood door frame unit, and the metal door was furnished with its own wood frame unit. The frame for the three wood doors was furnished with a spring brass weather strip on three sides and an aluminum threshold with a half-round plastic closure strip. The weather strip was later replaced with an extruded plastic strip for the test on the FRP door and a repeat test on one of the wood doors.

The frame for the steel door was fitted with a magnetic weather strip similar to that on a refrigerator door. The bottom of the door carried three soft plastic fingers which closed against a flat aluminum threshold. All doors were nominally 3 x 7 ft and 1 3/4 in. thick with an actual area of 20.0 sq ft.

[3/] Registered Trademark. Building material brand names are included in this publication in order to adequately specify the materials used. Use of such names does not imply endorsement of these materials by the National Bureau of Standards. The "R-values" given in this paragraph are as stated by the manufacturer and may not agree with the data obtained under the conditions of the present investigation.

Figure 3. Brick veneer wall with opening cut for picture window.

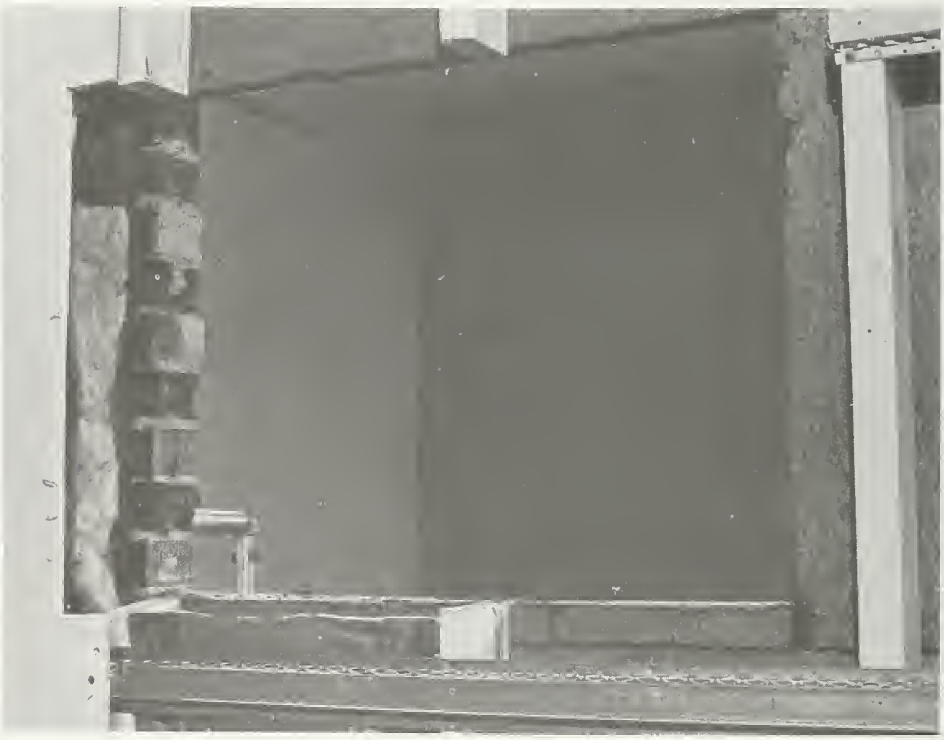


Figure 4. Detail of brick veneer wall construction with resilient channel and cavity insulation.

One of the wood doors was retested with the addition of an aluminum combination screen and storm door. The removable storm panes were clamped against soft plastic gaskets, and the aluminum frame for the door was fitted with thin plastic weather stripping on three sides. The bottom of the door carried a single plastic strip which wiped against the wood sill of the main door frame.

The doors are further described as follows:

Flush Solid Core Wood Door (Figure 5)

3 x 7 ft by 1 3/4 in.
Weight - 78 lb, 3.9 lb/sq ft

Flush Hollow Core Wood Door

3 x 7 ft by 1 3/4 in.
Weight - 25 lb, 1.25 lb/sq ft

Wood French Door (Figure 6)

3 x 7 ft by 1 3/4 in.
12 lights glazed single strength
Glass area 8.0 sq ft
Weight - 57 lb, 2.85 lb/sq ft

Flush Steel Door

3 x 7 ft by 1 3/4 in.
Faces - 0.028 in. steel, separated by plastic perimeter strip
Core - rigid polyurethane, 2 to 2 1/2 lb/cubic ft, foamed in place
Weight - 64 lb, 3.2 lb/sq ft

FRP Panel Door

3 x 7 ft by 1 3/4 in.
Faces and edges - fiberglass-reinforced plastic
Core - rigid polyurethane, 3 lb/cubic ft, foamed in place
Weight - 47 lb, 2.35 lb/sq ft

Aluminum Storm Door

3 x 7 ft by 1 in.
Glazed single strength, glass area 12 sq ft

2. 3. Windows

Three sets of typical residential windows were purchased locally or supplied at no cost by the manufacturer, as follows:

All wood
Wood with plastic coating
Aluminum

Various types of windows were included in each of the above material categories. In the following descriptions, the dimensions are given as width by height and are approximate.

Double Hung (Figure 7)

3 x 5 ft. Vertically sliding upper and lower sashes, interchangeable in a single frame unit supplied as part of the complete window assembly.

Figure 5. Solid core flush wood door mounted in wood siding wall for thermal test.

Figure 6. Wood french door mounted in wood siding wall for sound transmission and air infiltration test. Auxiliary construction on opposite side eliminates significant flanking sound transmission.

Figure 7. Wood double-hung window installed in filler wall.

Single Hung (Figure 8)

3 x 4 ft. Lower sash vertically sliding, upper sash fixed.

Picture Window (Figure 9)

6 x 5 ft. Fixed large single sash, normally sealed when installed into frame unit. For tests, various sashes were sealed directly into rough opening.

Awning (Figure 10)

3 x 4 ft. Upper and lower sashes swing outward from upper hinge on each. Interchangeable sashes were tested in frame unit supplied.

Fixed Casement

3 x 5 ft. Sealed integrally into frame unit as received.

Operable Casement (Figure 11)

4 x 5 ft wood and 3 x 4 ft aluminum. Right and left half of window swing outward from hinges on outer edges, operated by cranks.

Sliding (Figure 12)

3 x 4 ft. Half of window slides horizontally, other half fixed.

Jalousie

3 x 4 ft. Horizontal glass louvers operable together. Louvers 4 1/2 in. wide with 1/2 in. overlap.

Sliding Glass Door (Figure 13)

6 x 7 ft. Half of door rolls on track, other half fixed.

Storm Sash

A separate window unit added to the corresponding main window unit for test.

Variations in glazing for the above window types included single strength, double strength, safety glass, and insulating glass. The safety glass tested consisted of a double layer laminated to a transparent inner septum. Insulating glass consists of two layers separated by an air space, usually with a mastic perimeter seal. Insulating glass varies in overall thickness and weight depending on the type and size of window in which it is used. The types of glazing included in the test program are as follows:

Single Strength

Nominal thickness 3/32 in.
Nominal weight 1.30 lb/sq ft

Double Strength

Nominal thickness 1/8 in.
Nominal weight 1.63 lb/sq ft

3/16 in. Safety Glass

3/32 in. layers laminated
Nominal weight 2.60 lb/sq ft

Figure 8. Aluminum single hung window.

Figure 9. 6 x 5 ft picture window installed in wood siding wall.

Figure 10. Auxiliary construction erected on interior side of wood siding wall for sound transmission testing of window.

Figure 11. Plastic coated wood operable casement window.

Figure 12. Aluminum Sliding window.

Figure 13. Plastic coated wood sliding glass door.

3/8 in. Insulating Glass

3/32 in. layers, 3/16 in. air space
Nominal weight 2.60 lb/sq ft

7/16 in. Insulating Glass

1/8 in. layers, 3/16 in. air space
Nominal weight 3.3 lb/sq ft

1 in. Insulating Glass

3/16 in. layers, 5/8 in. air space
Nominal weight 5.2 lb/sq ft

1/4 in. Louvers (in jalousie window)

Nominal weight 3.3 lb/sq ft

For additional information, a test was run on a single 3 x 4 ft sheet of 1/4 in. laminated glass. This is a special product designed for high transmission loss consisting of two sheets of 1/8 in. glass laminated to a transparent inner damping layer. The measured areal density was 3.0 lb/sq ft.

The windows are further characterized as to whether each sash, or the entire unit in the case of a picture window, contains single or multiple panes.

Single light - one pane in each sash, or each half of a storm window

Divided lights - multiple panes in each sash

2. 4. Combinations

Sound transmission tests were run on four combinations of a wall penetrated by a window as follows:

Wood siding wall with 6 x 5 ft picture window, glazed single strength

Same, except picture window glazed insulating glass

Brick veneer wall with each of the above windows

The two walls represent the extremes of transmission loss to be expected in wood frame exterior constructions. Except for the sliding glass patio door, the picture window had the largest area of any window tested and would be expected to cause the largest change in overall transmission loss on the basis of relative areas of window and wall. The two glazings in the picture window represented extremes in transmission loss as a function of glazing.

Thermal transmission tests on walls penetrated by doors or windows were run only on the wood siding wall with gypsum board fastened directly to the studs and with Fiberglas 3-1/2 in. Friction Fit Building Insulation in the cavities, for each of the following penetrations:

Doors

Flush solid core wood door, brass weather strip
Same, plus aluminum storm door
Flush steel door, magnetic weather strip
Molded plastic panel door, extruded plastic weather strip

Windows

Wood double-hung 3 x 5 ft glazed single strength, single light
Same, plus wood storm sash, glazed single strength, single light
Wood double-hung 3 x 5 ft glazed insulating glass, single light
Wood picture window 6 x 5 ft glazed single strength, divided lights
Same, except insulating glass, single light

2. 5. Cracks and Openings

Sound transmission tests of the doors and windows were made under varying conditions of sound leakage. In every case, a test was made with the door or window completely sealed with tape or caulking. This established the maximum transmission loss of which the unit under test is capable. A special series was run on the 6 x 5 ft picture window in which accurately measured cracks of varying width and length were provided around the perimeter. All of the other doors and windows were tested as normally closed, in addition to the completely sealed condition. Further tests were made on some of the windows to compare the locked with the unlocked condition and to show the effects of slight amounts of opening.

Thermal transmission tests and the accompanying air infiltration tests on the doors and windows were made only on the normally closed condition. All tests on the double-hung window were made with the window locked and unlocked.

Air infiltration tests in the two-room sound transmission facility were run for the same leakage and crack conditions as stated above for the sound transmission tests, except for complete sealing.

3. Sound Transmission Loss Tests

3. 1. Background

There are many useful texts and summary articles for the reader who is not familiar with acoustics. The books by Harris [1] and Beranek [2] contain chapters by experts in different areas of acoustics. Young [3], Franken [4], and Beranek [5] discuss the fundamental concepts and the use of decibels. Rudnick [6] and Kurze and Beranek [7] describe outdoor sound propagation. Beranek [8] and Embleton [9] summarize the theory of sound propagation in small and large rooms, respectively. Ingerslev and Harris [10] and Cook and Chrzanowski [11] discuss solid-borne and air-borne noise respectively, while Vér and Holmer [12] summarize related analytical findings. The chapter by Sabine [13] provides a discussion of acoustical materials.[4/]

Beranek [14] describes different criteria for human response to noise in buildings. Three recent publications [15-17] of the U. S. Environmental Protection Agency provide an overview of human response to noise.

In the following brief discussion, only those concepts needed for understanding and use of sound transmission loss data are addressed. For additional definitions of acoustical terms, see [18,19].

The spatially-averaged mean-square sound pressure in a room is, within the limitations of certain simplifying assumptions, proportional to the total sound power entering the room and inversely proportional to the total sound absorption in the room. In a typical building this sound power can enter a room from sources within the room, from sources elsewhere in the building, or from sources exterior to the building. In the present report, only sound due to exterior sources is of concern.[5/] Furthermore, attention is confined to sounds transmitted through the exterior facade, as opposed to roofs, chimneys, crawl spaces, etc.

Sound transmission through a partition can be described in terms of the <u>sound transmission coefficient</u>, τ, of the partition. The sound transmission coefficient in a specified frequency band is the fraction of the airborne sound incident on the partition that is transmitted by the partition and radiated on the other side.

For an infinitely large panel in free space with a plane wave incident on one side,

$$\tau = \frac{p_2^2}{p_1^2}, \tag{1}$$

where p_1^2 is the mean-square sound pressure characterizing the incident wave and p_2^2 is the mean-square sound pressure characterizing the transmitted wave. The mean-square sound pressure is related to the normally-measured sound level, L, by the expression, $L = 10 \log_{10} (p^2/p_o^2)$, where p_o = 20 micropascals is the reference pressure.

4/ Figures in square brackets refer to the literature references at the end of this report.

5/ Of course sound can leave a building and then re-enter it elsewhere (e.g., open windows across a courtyard). This can be treated as noise of exterior origin.

Usually the effectiveness of a partition is described in terms of the sound transmission loss,

$$TL = 10 \log \left(\frac{1}{\tau}\right), \quad (2)$$

where the logarithm is to the base ten. Combining equations (1) and (2), it is seen that, in free space,

$$TL = L_1 - L_2, \quad (3)$$

where L_1 and L_2 are the sound pressure levels of the incident and transmitted waves, respectively.

The transmission coefficient and the transmission loss are functions of the direction from which the incident wave impinges upon the partition. At sufficiently low frequencies, where a simple partition behaves approximately as a limp mass which is vibrated by the sound field and the partition is thin compared to the wavelength of sound, the limp-wall mass law [12,20] is approximately valid. As shown in Figure 14, for a given angle of incidence, the sound transmission loss increases as a function of the product of frequency (of the sound wave) and the areal density (mass per unit area) of the partition. The transmission loss is a maximum for a normally incident sound wave and decreases as the sound approaches grazing incidence.

The exterior facade of a building needs to provide adequate attenuation of sound arriving from a number of directions. Thus, it seems appropriate, for design purposes, to utilize a sound transmission loss corresponding to an average over many angles of incidence. For some situations, such as the upper floors of a high-rise building near a highway, the sound will typically arrive at near-grazing incidence and the design value for sound transmission loss should be selected accordingly. However, for residential constructions such as are considered in the present report, sound could be expected to arrive from essentially all angles. Thus for this report, "random incidence" sound transmission loss was measured by placing the partition under test in an opening between two reverberation chambers -- acoustically hard rooms that cause the sound to be reflected many times so there is essentially equal probability of sound striking the test partition from any direction. The dashed curve in Figure 14 shows the theoretical "field-incident mass law", which is derived from the discrete-angle mass law by averaging over all angles of incidence from normal (0°) to 78°.[6/] It is seen that the use of "random-incidence data" for design purposes would be conservative for sound striking the partition at angles from 0° (normal) to beyond 45°. Unless it is known that sound will usually impinge at near-grazing incidence, the use of data obtained under random-incidence conditions should be suitable for exterior walls.

Since real walls do not behave as ideal limp masses, the rather simplistic curves shown in Figure 14 cannot be taken too seriously. However, they show two features which are important to remember -- sound transmission loss generally increases as the mass of the partition increases and also increases as the frequency of sound increases. The actual frequency dependence of the sound transmission loss can be complicated by resonance phenomena and "coincidence effects" [12,20] which depend upon, among other things, the bending stiffness and internal damping of the partition. For constructions which are more complex, such as a double partition separated by structural elements, the transmission loss also depends upon how well the several components are vibration isolated from one another,

---

[6/] The integration is only taken up to 78° rather than 90° so as to obtain better agreement with experimental data. The finite size of the partition, the effect of the test facility, and possible damping effects in the wall for near-grazing incidence are probably responsible for the observed deviations between experiment and the simple mass-law theory [12, 20-21].

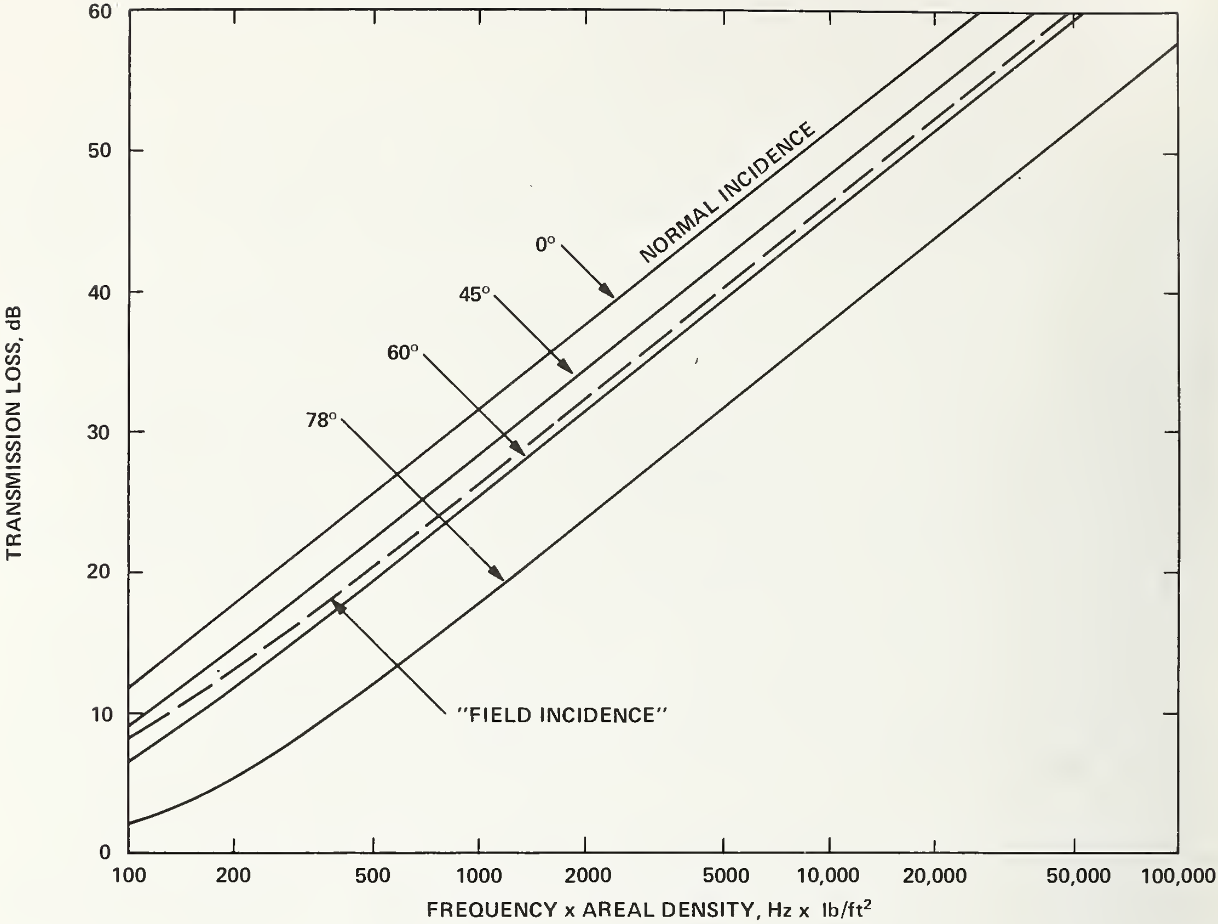


Figure 14. Limp-wall mass law transmission loss. The solid curves correspond to a plane wave arriving at a discrete angle of incidence. The dashed curve corresponds to "field-incidence mass law", a sum over all angles of incidence up to 78°.

the thickness of any air spaces, and the amount of acoustically absorptive material in these air spaces [12,21]. For many partitions, it is possible to calculate approximately the sound transmission loss as a function of frequency but, in general, empirical data are required.

When a partition is composed of several elements (i.e., wall, door, window, cracks) which provide parallel paths through which the sound can be transmitted, the overall sound transmission coefficient is obtained from [11, 12]

$$\tau_o = \frac{\tau_1 S_1 + \tau_2 S_2 + \tau_2 S_3 + \ldots}{S_1 + S_2 + S_3 + \ldots} \tag{4}$$

where τ_1 is the transmission coefficient for the element of area S_1, etc., and the summation is over all areas of the partition. As an example of the use of equation (4), consider a 14 ft by 9 ft wall having a transmission loss of 48 dB and being penetrated by a 3 ft by 4 ft window having a transmission loss of 32 dB. Solving equation (2) for τ in terms of TL yields

$$\tau_1 = 10^{-TL_1/10} = 10^{-4.8} = 1.6 \times 10^{-5}$$

and

$$\tau_2 = 10^{-TL_2/10} = 10^{-3.2} = 6.3 \times 10^{-4}.$$

Substituting these values into eq. (4),

$$\tau_o = \frac{(1.6 \times 10^{-5}) \times (126-12) + (6.3 \times 10^{-4}) \times (12)}{126} = 7.4 \times 10^{-5}$$

so that, again using eq. (2), the effective transmission loss of the composite wall is

$$TL_o = 10 \log \left(\frac{1}{\tau_o}\right) = 41 \text{ dB}.$$

A chart derived from equation (4) for estimating the overall transmission loss of any combination of a wall and a single penetration such as a door or window, knowing the area and transmission loss of each component, is shown in Figure 15. The linear portions of the curves in Figure 15 correspond to situations where nearly all of the sound energy comes through the portion of the wall having the lower transmission loss so that $TL_o \approx TL_2 + 10 \log (100/k)$, where k is the percent of the total wall area occupied by the door, window, crack or other path of low sound transmission loss. Consideration of eq. (2) and Figure 15 reveals that even a small area having a low transmission loss can greatly reduce the overall transmission loss below that of the basic wall structure. Since cracks may have a transmission loss that is near zero, "leaky" doors, windows, and louvers can vitiate an otherwise good construction. The effect of cracks is discussed in some detail in Sections 3.6 and 6.1.

Neglecting interior sources of noise, the average sound pressure level in a room having an exterior wall on which sound is incident from a large range of directions is given approximately by

$$L_2 = L_1 - TL_o + 10 \log S/A, \tag{5}$$

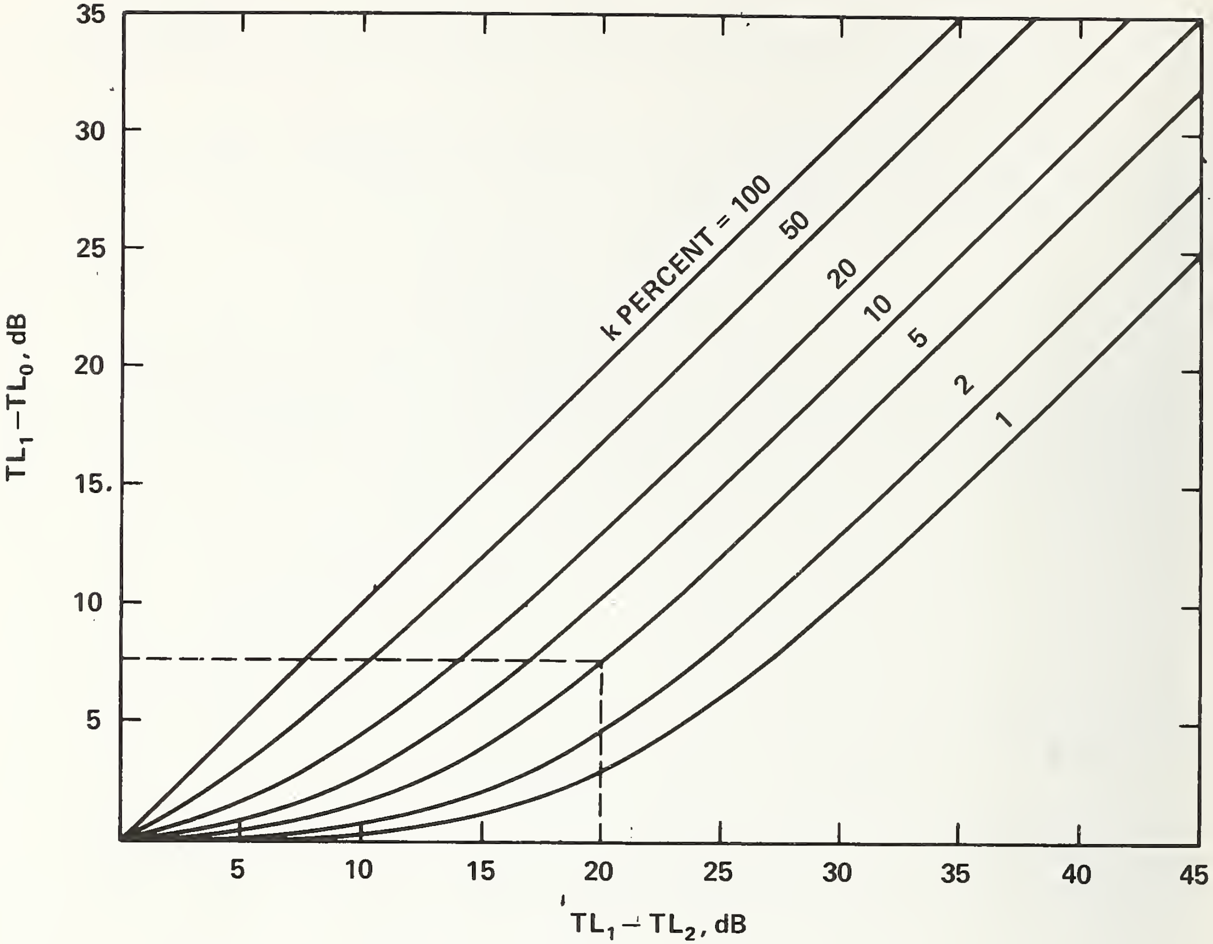


Figure 15. Chart for determining the overall sound transmission loss, TL_o, of a wall with a penetration (e.g., door or window) having a transmission loss, TL_2, less than the transmission loss, TL_1, of the basic wall construction. The penetration occupies "k percent" of the total wall area. The transmission loss of the combination is shown in relation to that of the wall as $TL_1 - TL_o$. Example: A window with TL_2 = 30 dB occupies 5 percent of the area of a wall with TL_1 = 50 dB. Then,

$TL_1 - TL_2 = 20$ dB

$TL_1 - TL_o = 8$ dB

$TL_o = 50 - 8 = 42$ dB

where L_1 is the exterior sound pressure level[7/], TL_o is the effective sound transmission loss of the wall, S is the area of the wall, and A is the total sound absorption (equivalent area of a perfect absorber, in the same units as S) in the room. Equation (5) may be used in applications of the experimental sound transmission loss data presented in this report.

As discussed previously, sound transmission loss varies markedly with the sound frequency. The room absorption, A, is also a function, albeit a much weaker one, of frequency. Thus the sound attenuation in a particular application will depend on the frequency spectrum of the noise. The need to provide a "single-figure rating that can be used for comparing partitions for general building design purposes" has led to the development, by the American Society for Testing and Materials (ASTM), of the Sound Transmission Class [22] and, by the International Organization for Standardization, of a quite similar rating scheme [23]. The Sound Transmission Class "is designed to correlate with subjective impressions of the sound insulation provided against the sounds of speech, radio, television, music, and similar sources of noise in offices and dwellings." [22]

"Excluded from the scope of this classification system are applications involving noise spectra that differ markedly from those described above....A particular exclusion would be the exterior walls of buildings, for which noise problems are most likely to involve motor vehicles or aircraft. In all such problems it is best to use the detailed sound transmission loss values, in conjunction with actual spectra of intrusive and ambient noise." [22]

Since there are, at present, no generally accepted single-figure ratings for exterior walls, the Sound Transmission Class has been included in this report to provide a quick way of easily comparing different partitions. The above-quoted caution should be observed in applying these data.

Figure 16 illustrates the concept of the Sound Transmission Class. The solid data points represent the measured 1/3-octave band sound transmission loss over the frequency range 125 to 4000 Hz. "The STC contour is shifted vertically relative to the test curve until some of the measured TL values for the test specimen fall below those of the STC contour and the following conditions are fulfilled: The sum of the deficiencies (that is, the deviations below the contour) shall not be greater than 32 dB and the maximum deficiency at a single test point shall not exceed 8 dB. When the contour is adjusted to the highest value (in integral decibels) that meets the above requirements, the sound transmission class for the specimen is the TL value corresponding to the intersection of the contour and the 500-Hz ordinate..."[22]. The cross-hatched region in Figure 16 indicates the frequencies at which deficiencies occur. For the example shown, the sum of the deficiencies is 29 dB and the largest single deficiencies occurring are 5 dB, so the "-8 dB rule" need not be applied.

NBS has in the past prepared several compilations of sound transmission loss, chiefly for interior walls, doors, and floor-ceiling assemblies [24-26]. The most comprehensive of these is the large report of Berendt, Winzer, and Burroughs [26] which has recently been reprinted. In 1960, the British Building Research Station published a large compilation of field data [27]. This is now being updated and expanded. The Experimental Building Station of Australia has recently published a compilation of laboratory transmission loss data [28]. Jain and Mulholland [29] and Gillam [30] have described a databank of sound insulation measurements which is being developed at the University of Liverpool (Great Britain). A recent study [31] for the U. S. Department of Housing and Urban Development includes data on a number of constructions having fairly high sound transmission losses.

7/ Specifically, L_1 is the sound pressure level corresponding to the sound energy incident on the wall. Unless the sound source is very close, L_1 is nearly equal to the sound pressure level measured, say, 5 to 10 ft from the exterior surface of the wall. Levels measured very close to the wall need to be adjusted to correct for the effect of sound reflected back from the wall.

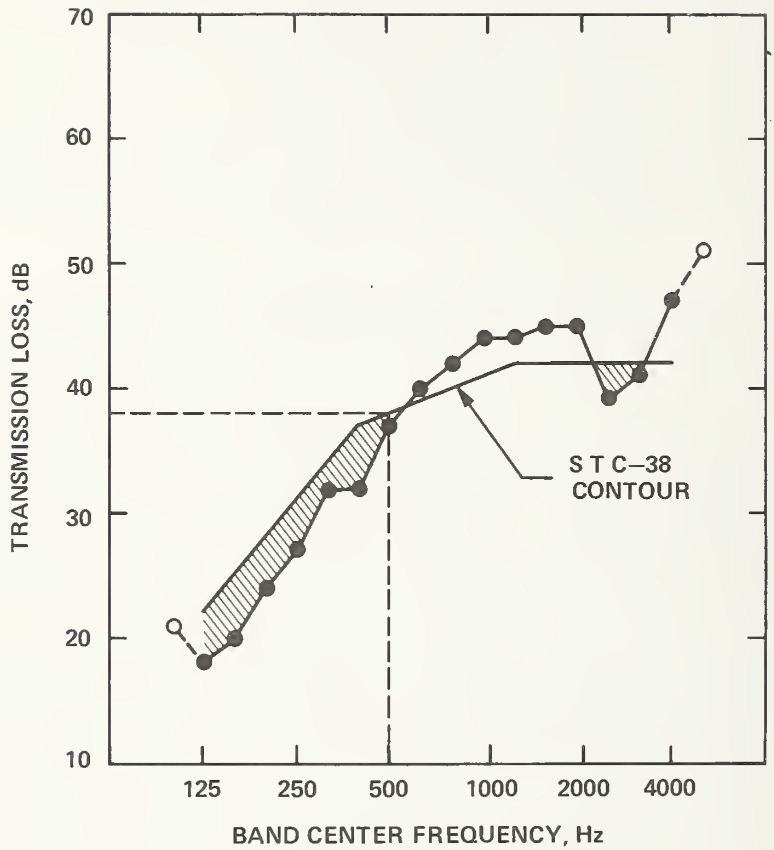


Figure 16. An example of a Sound Transmission Class contour fitted to a sound transmission loss curve. The fitting procedure is described in the text.

Although the above-referenced compilations contain a few data on exterior walls, doors, or windows, the vast majority of the data are for interior partitions. There have been some studies [32-36] of the overall attenuation of exterior noise that is provided by a typical complete building. NBS has published a translation [37] of a French study on the sound transmission loss of exterior walls. Section 3.5 includes some references to previous work on the sound transmission loss of windows.

3. 2. Experimental Procedure

Current standard procedures for measuring the airborne sound transmission loss of a partition between two reverberant spaces are based on the theory developed at NBS many years ago by Buckingham [38]. Early experimental work at NBS [39,40] contributed to the development of the ASTM Standard Recommended Practice for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions [41] and to the later ASTM standard for field measurements [42]. The current international test method, ISO R140-60 [43], is similar to these but the procedures are not so completely described. ASTM E90-70 and ISO R140-60 describe the laboratory procedure for determining the airborne sound transmission loss of walls of all kinds, floor-ceiling assemblies, doors, and other space-dividing elements. The procedure is to mount the test specimen as a partition between two reverberation rooms arranged and constructed so that the only significant sound transmission between them is through the test specimen. A random incidence sound field is used for the test and, as discussed previously, the results are most directly applicable to similar sound fields, but provide a useful general measure of performance for the variety of sound fields to which an exterior partition may typically be exposed.

Sound transmission tests were run in essential conformity with ASTM E90-70. The facility used for the tests is comprised of a 4400 cubic foot source room and a 10,000 cubic foot receiving room, both reverberant. The room volumes are large enough to qualify the facility under E90-70 recommendations for tests down to a lower frequency limit of 110 Hz. Both dimensions of the 9 x 14 ft test opening exceed the minimum dimensions specified in E90-70.

The wall in which the test opening was located was of poured concrete 13 in. thick, and common to both rooms, with an area of 13 x 22 ft on the source room side. This wall was mechanically isolated by separate footings and by mastic joints from the side walls and floor and ceiling of both the source and the receiving rooms. Since many of the test specimens had areas which were quite small compared to the common wall between the source and the receiving rooms, special provisions, described in Appendix B, were made to minimize flanking sound transmission.

The source room was rectangular and contained no fixed or moving diffusing elements. Previous tests had shown that the introduction of these elements produced no significant change in the measurement of room-average sound pressure levels or of transmission loss values.

The receiving room was also rectangular but contained an 8 x 16 ft rotating vane and a number of fixed diffusing panels. These had been permanently installed for other types of test, so that their effect on transmission loss measurements was not directly established.

Space-time averages of sound pressure level were obtained by a continuously moving microphone in each room. In the source room the microphone traversed an 8 ft long arc along a room diagonal, and in the receiving room the microphone was attached to the moving vane and traversed a 16 ft diameter circle. The time interval for each complete traverse and for the corresponding period of measurement at each 1/3-octave frequency was about 15 seconds.

The test signal was a broad band noise generated by a Brüel & Kjaer Type 1402 Random Noise Generator.[8/] The signal was shaped for maximum utilization of sound power and was

---

[8/] Instrumentation brand names and model numbers are included in this publication in order to adequately specify the equipment used. Use of such names does not imply endorsement of this equipment by the National Bureau of Standards.

divided into a high and low frequency channel, each of which was fed into a 60-watt power amplifier. The high frequency channel drove a horn loudspeaker and the low frequency channel a 15 in. cone speaker in an enclosure. The loudspeakers were placed in a room corner opposite to the test wall.

The maximum sound pressure level developed in the source room was about 115 dB (re 20 micropascals). This level was high enough that no corrections for acoustical or electrical background noise were needed for the highest values of transmission loss measured throughout the program.

Sound pressure levels in each room were measured with separate Brüel & Kjaer Type 4132 condenser microphones, fed alternately into a Brüel & Kjaer Type 2112 Audio-Frequency Spectrometer. The two microphone channels had equal overall sensitivity within 0.1 dB at the input to the spectrometer, as measured by a pistonphone at 250 Hz on each microphone. The difference was less than 1/2 dB at all frequencies up to 6300 Hz, as measured with both microphones exposed to 1/3-octave noise bands in a reverberant field. The source room microphone was approximately 1/2 dB more sensitive at 6300 Hz and 1 dB at 8000 Hz.

The 1/3-octave band frequency levels measured by the spectrometer were recorded on a Brüel & Kjaer Type 2305 Level Recorder. Sound pressure levels were read to the nearest 1 dB from the average of the fluctuating recorder trace at each frequency. Measurements were made over a frequency range of 80 to 6300 Hz, although the range only from 125 to 4000 Hz is commonly reported in standard transmission tests in the United States.

The calculation of transmission loss from measurements of sound pressure level differences involved the measurement of 10 log A_2, where A_2 is the absorption of the receiving room in sabins. This measurement was made for each test by means of a calibrated sound power source. The source used was an ILG fan, which is widely used for this purpose. To calibrate the power of the source, the room average sound pressure level was measured with the source operating in a room of known room absorption, which was measured by the decay method.

3. 3. Calibration Procedures and Uncertainties

The overall sound transmission loss of each specimen was computed from the expression

$$TL = L_1 - L_2 + 10 \log S/A_2, \tag{6}$$

where L_1 is the average sound pressure level in the source room, L_2 is the average sound pressure level in the receiving room, S is the projected area of sound transmitting surface of the test specimen, and A_2 is the total absorption of the receiving room, expressed in units consistent with S. This equation generally is considered to be valid provided the total flow of acoustic energy between the source and receiving room is not too large [44,45].

A number of papers [44-60] in recent years have addressed the question of how well sound transmission loss measurements made in different laboratory or field situations can be expected to agree with one another or with theoretical predictions. It is known that the size of the source and receive rooms, the nature of the opening in which the specimen is placed, and the size and method of mounting of the specimen all can influence the test results. At the present time there are no generally accepted procedures for quantitative evaluation of the effect of these factors in a given testing facility. Comparative tests have shown that measurements of sound transmission loss in the facility used for the tests in this report are in good agreement with tests on nominally identical specimens in other good facilities in North America.

The precision of reading of space-time average sound pressure levels in the two rooms, including levels for the calibrated power source, ranged from about 2 dB at 80 Hz to 1/2 dB at 6300 Hz. All measured levels were recorded only to the nearest 1 dB. Calculated values of transmission loss were also stated to the nearest 1 dB. The calibration of the power source was checked periodically and found to be constant within the measurement precision of the sound pressure levels. The measurement of 10 log A was therefore of the same order of precision as the measurement of level difference between the rooms.

The overall accuracy of a transmission loss test can be stated in various ways. The immediate repeatability of a test without removing the test specimen or knowingly changing the receiving room absorption typically is within 1 dB from 80 to 6300 Hz.

The repeatability of a test on two different installations of the same nominal construction in the Owens-Corning Fiberglas Sound Laboratory, using different lots of materials, is shown in Figure 17. The tests were made four months apart on a standard wood stud exterior wall with wood siding and insulating sheathing on the outside and gypsum board drywall on the inside. The maximum difference between the curves at any frequency from 80 to 6300 Hz is 4 dB, and the difference between the averages for the two curves is 1.2 dB.

The accuracy of a transmission loss test can be affected by flanking transmission through the wall surrounding the test specimen. This can be of special importance when the test specimen has a very high transmission loss or has a comparatively small area, such as a door or window, in relation to that of the surrounding wall. Significant errors due to flanking were minimized by the auxiliary constructions detailed in Appendix B.

3. 4. Results

Sound transmission loss data were obtained on all of the specimens described in Section 2. Data were obtained, in many cases, on both individual elements and on combinations. To determine the effect of sound leakage through cracks, tests of doors and windows were made with the unit sealed in place to establish maximum capability and with the unit as normally mounted. In addition, a number of tests were carried out on windows with large controlled cracks around them.

Complete data for all specimens tested are listed in Table C-6 of Appendix C in the form of 1/3-octave band sound transmission loss versus frequency for each test. Each set of data is assigned a Sound Transmission Class (STC) rating in accordance with ASTM E413-73 [22]. Tables C-1 through C-5 list the tests which were carried out on (C-1) walls, (C-2) doors, (C-3) windows, (C-4) walls containing windows, and (C-5) windows with cracks and openings. These five tables are cross-referenced to the detailed test results given in Table C-6.

Section 3.4.1., below, gives a summary of the test results and certain of the more important conclusions. Section 3.4.2. contains a more detailed discussion of the test results

3. 4. 1. Summary and Conclusions

The summarized test data given below are those obtained only for the specific tests in this program and do not necessarily apply to general types or classes of construction or products.

The single number performance ratings for sound transmission loss are given as Sound Transmission Class (STC) as defined in ASTM E413-70. In general, a high STC rating corresponds to a high resistance to sound transmission.

1. Wood stud exterior walls with the drywall secured directly to the studs, with insulation board sheathing (except for stucco) and glass fiber cavity insulation, had STC values as follows:

Wood siding	39
Stucco	46
Brick veneer	56

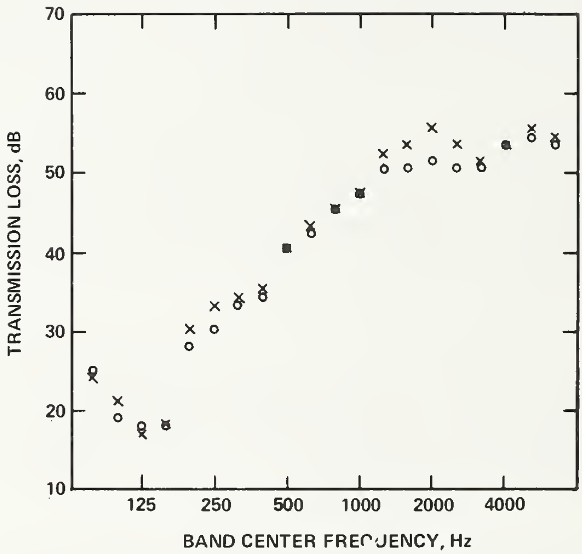


Figure 17. Sound transmission loss vs frequency data for wood-siding, wood-stud exterior wall with cavity insulation. Repeat tests (W-54-71 and W-3-72) on same nominal construction using different lots of materials.

The presence of insulating material in the stud cavities, with the drywall secured directly to the studs, made a negligible difference of less than about 3 dB.

2. If the drywall was attached to resilient channel, the cavity insulation was much more effective, giving the following STC values:

Wood siding	47
Stucco	57
Brick veneer	58

3. The measured transmission loss of a wall containing a door or window agreed very closely with the calculated value based on the measured transmission loss and area of each component. The transmission loss of the combination of two components will always have a value between the respective transmission loss values of each component. A chart for determining the transmission loss of the combination was given in Figure 15.

4. Cracks can greatly reduce the effective sound transmission loss of wall/window combinations (see Sections 3.5.4. and 6.1. for discussions of means to estimate the sound transmission loss of cracks).

5. Five exterior doors sealed into the frame had STC values ranging from 21 to 31. These values were governed largely by door weight, rather than materials or construction, and corresponded to an areal density range of 1.2 to 3.9 lb/sq ft.

6. The same five doors as normally closed against a weather stripped frame ranged from 20 to 28 STC.

7. A solid core flush wood door having an STC of 30 sealed was reduced to STC 27 when normally closed against either a spring brass or a plastic weather strip. A steel-faced door had an STC of 28 whether sealed or normally closed against a magnetic weather strip. The latter was considerably more effective at high frequencies than the brass or plastic weather strip.

8. The tests on all of the windows when completely sealed showed an overall range of 26 to 39 STC, subdivided as follows:

Single glass (single strength, double strength, 3/16 in. safety)	28 - 32
Insulating glass (3/8 to 1 in.)	26 - 34
Windows plus storm sash (windows up to 7/16 in. insulating glass, storm sash single and double strength glass)	29 - 39

9. There were no significant differences due to single versus divided panes or to the sash and frame material.

10. The insulating glass up to 7/16 in. thickness was on the whole no better than single glass in single or double strength.

11. A test on a special 1/4 in. laminated glass having an inner damping layer designed for high transmission loss showed an STC of 34. The high frequency performance of this glass was better than standard glass, but the higher STC value was due to its greater weight.

12. The effectiveness of double glazing, either with insulating glass or with an added storm sash, depended mainly on the width of separation between the panes.

13. The use of standard storm sash with single glazed windows with as wide a spacing as possible is probably the most effective and economical means of obtaining high sound insulation.

14. Windows installed with weather stripping as furnished showed values averaging about 4 STC lower than those measured with complete sealing.

3.4.2. Discussion

a. Walls

The tests conducted on the three exterior wall constructions are listed in Table C-1. Complete data are shown in Figures 18 to 20. For each wall, the use of cavity insulation but not resilient channel was considered as "standard" construction as commonly used for thermal requirements. This is shown by the left-hand side of each diagram. For the wood siding wall, an additional test was made on this standard construction, but omitting the Fiberglas Kraft Faced cavity insulation. This showed a slight reduction in transmission loss of from zero to 6 dB over the frequency range with a reduction in STC from 39 to 37. The other three types of cavity insulation in the same construction showed similar results with STC values of 37 to 39. The relative ineffectiveness of cavity insulation is commonly observed in single wood stud construction and is due to the transmission of sound by vibration through the rigid coupling of both sides to the studs.

The combination of resilient channel and cavity insulation effects a substantial improvement in transmission loss over the standard wall for most of the frequency range. For the wood siding wall the increase in STC was 8, from 39 to 47, and for the stucco wall, 11, from 46 to 57. The improvement in the brick veneer wall, however, was only 2, from 56 to 58 STC. This might be explained by the fact that the brick was already partially isolated from the wood stud portion by the air space and the metal ties.

The tests with resilient channel but without insulation show a lesser improvement over the standard wall. The test series as a whole indicated that with the inner surface decoupled by the resilient channel, transmission took place largely through the air cavity rather than through the studs, thus allowing the sound absorbing action of the cavity insulation to become fully effective.

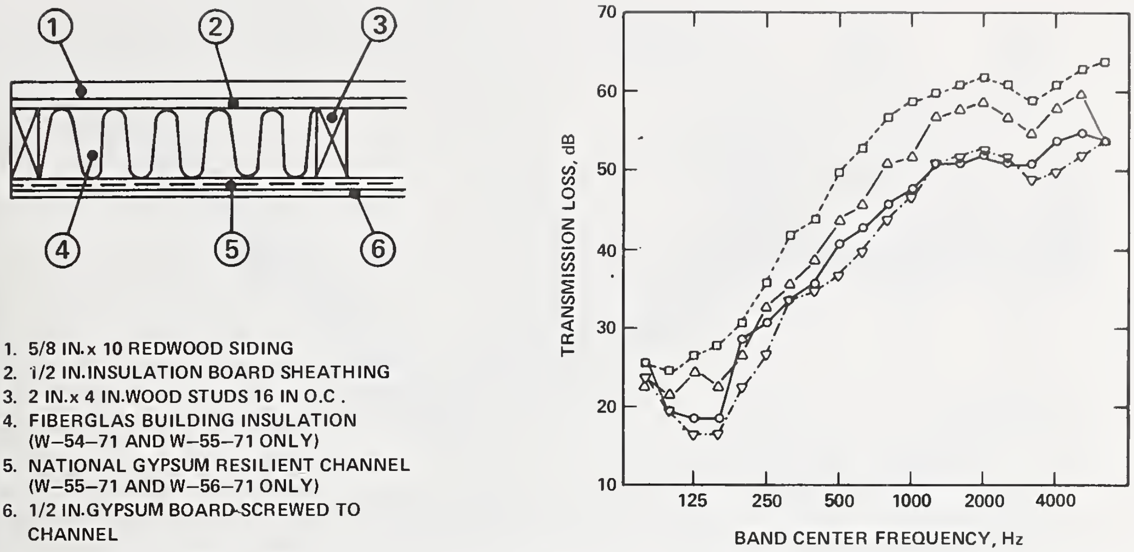
b. Doors

The tests conducted on exterior doors are listed in Table C-2. Figure 21 shows the envelope of frequency curves for the five doors sealed into the frame, with an STC range of 21 to 31. Also shown are theoretical "mass law" lines corresponding to the range of areal densities of 1.2 to 3.9 lb/sq ft. The ranges of measured and theoretical data agreed quite well at the lower frequencies. At the higher frequencies, the lower measured values were due to stiffness effects which acted oppositely to those of mass.

Frequency curves for the three wood doors sealed in place are shown in Figure 22 and for the doors with foamed plastic cores in Figure 23. The aforementioned stiffness effects are shown quite clearly for the foamed plastic doors in the form of sharp dips in the curve around 2000 Hz. The wood hollow core door also shows a similar dip at 800 Hz. These "wave coincidence dips" are further discussed in the following section on windows.

A comparison of sealed versus normally closed doors is shown in Figure 24 for the three wood doors mounted in the same frame with the spring brass weather strip originally furnished with the unit. The TL values were significantly lowered only at the higher frequencies by about 6 dB, with a corresponding change in STC values of 1 to 4.

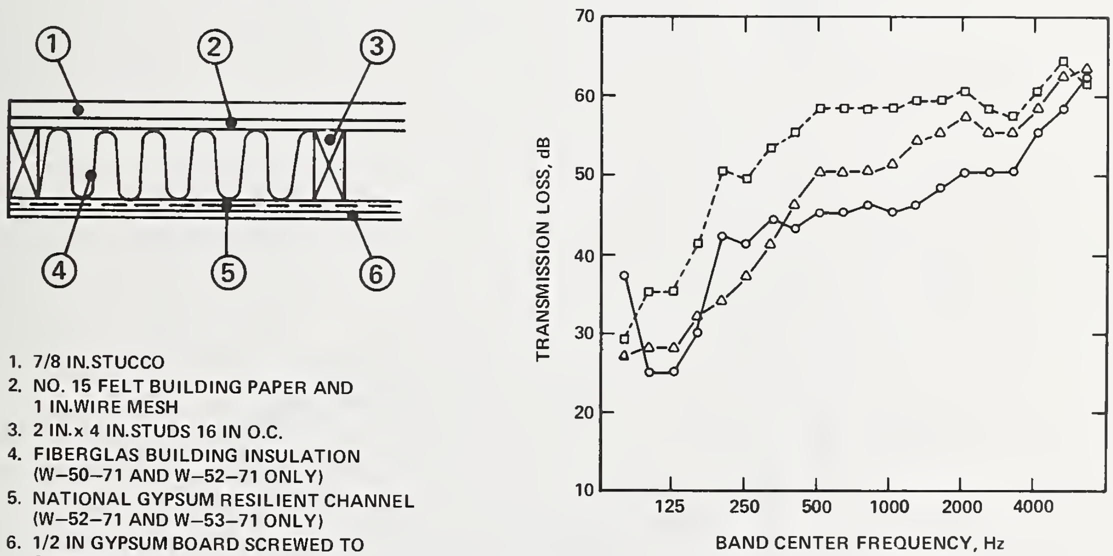
Figure 25 shows a comparison of three weather strips. Two of these were spring brass and extruded plastic, the latter being substituted for the former in the same door frame and with the same solid core wood door. The threshold was a half-round plastic strip. By referring to the sealed door in Figure 22, it is seen that both weather strips reduced the TL by about the same amount; namely 3 to 8 dB at the higher frequencies and from 30 to 27 STC.



1. 5/8 IN.x 10 REDWOOD SIDING
2. 1/2 IN.INSULATION BOARD SHEATHING
3. 2 IN.x 4 IN.WOOD STUDS 16 IN O.C.
4. FIBERGLAS BUILDING INSULATION (W–54–71 AND W–55–71 ONLY)
5. NATIONAL GYPSUM RESILIENT CHANNEL (W–55–71 AND W–56–71 ONLY)
6. 1/2 IN.GYPSUM BOARD SCREWED TO CHANNEL

Figure 18. Sound transmission loss vs frequency data for wood-siding, wood-stud exterior walls of four different constructions (with or without resilient channels and with or without cavity insulation).

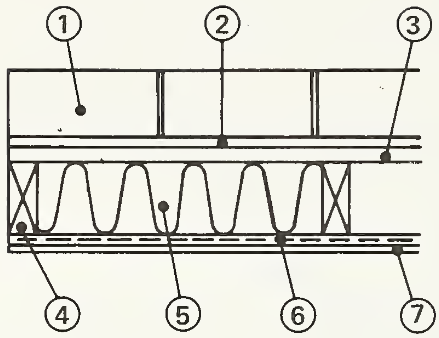
Symbol	Test No.	Cavity Insulation	Resilient Channel	STC
○	W-54-71	yes	no	39
△	W-56-71	no	yes	43
□	W-55-71	yes	yes	47
▽	W-4-72	no	no	37



1. 7/8 IN.STUCCO
2. NO. 15 FELT BUILDING PAPER AND 1 IN.WIRE MESH
3. 2 IN.x 4 IN.STUDS 16 IN O.C.
4. FIBERGLAS BUILDING INSULATION (W–50–71 AND W–52–71 ONLY)
5. NATIONAL GYPSUM RESILIENT CHANNEL (W–52–71 AND W–53–71 ONLY)
6. 1/2 IN GYPSUM BOARD SCREWED TO CHANNEL

Figure 19. Sound transmission loss vs frequency data for stucco, wood stud exterior walls of three different constructions (with or without resilient channel and with or without cavity insulation).

Symbol	Test No.	Cavity Insulation	Resilient Channel	STC
○	W-50-71	yes	no	46
△	W-53-71	no	yes	49
□	W-52-71	yes	yes	57



1. FACE BRICK
2. 1/2—IN. AIR SPACE, WITH METAL TIES
3. 3/4—IN. INSULATION BOARD SHEATHING
4. 2 IN. x 4 IN. STUDS 16 IN. O.C.
5. FIBERGLAS BUILDING INSULATION (W—44—71) AND W—45—71 ONLY)
6. NATIONAL GYPSUM RESILIENT CHANNEL (W—45—71 AND W—46—71 ONLY)
7. 1/2 IN. GYPSUM BOARD SCREWED TO CHANNEL

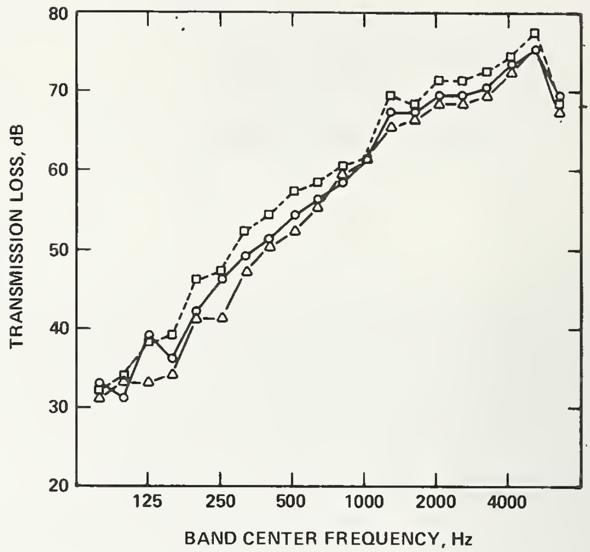


Figure 20. Sound transmission loss vs frequency data for brick veneer, wood stud exterior walls of three different constructions (with or without resilient channel and with or without cavity insulation).

Symbol	Test No.	Cavity Insulation	Resilient Channel	STC
○	W-44-71	yes	no	56
△	W-46-71	no	yes	54
□	W-45-71	yes	yes	58

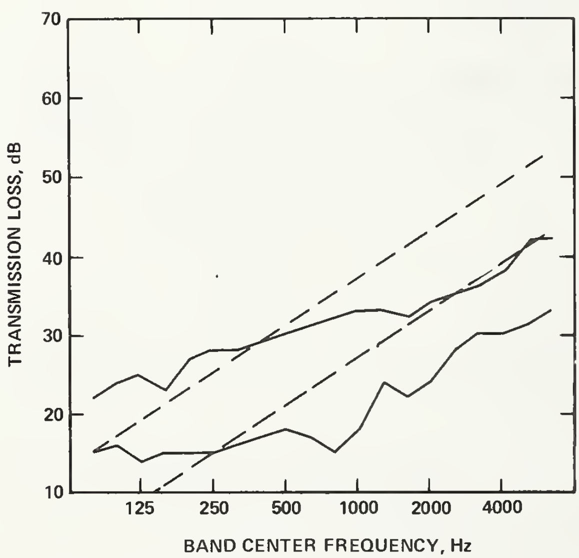


Figure 21. Envelope of sound transmission loss vs frequency data for five doors sealed into the frame. The corresponding Sound Transmission Class range is STC 21-31. The dashed lines correspond to the field incidence mass law (see Figure 14 and accompanying text) for the range of areal densities (1.2 to 3.9 lb/sq ft) of the five doors.

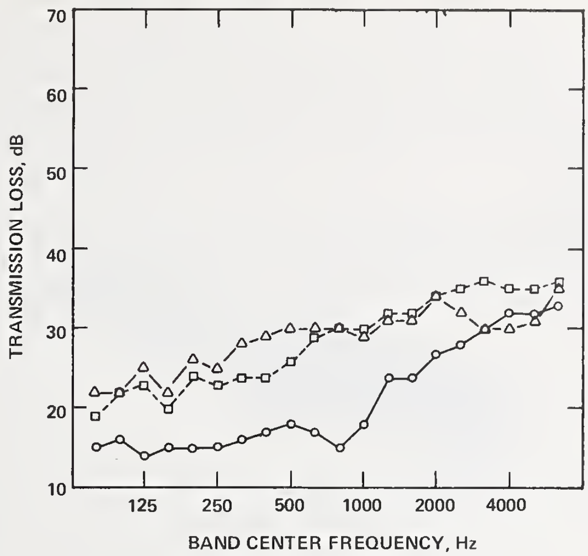


Figure 22. Sound transmission loss vs frequency data for the three wood doors sealed into the frame.

Symbol	Test No.	Specimen	STC
○	W-93-71	Wood flush hollow core	21
△	W-91-71	Wood flush solid core	30
□	W-95-71	Wood french door	31

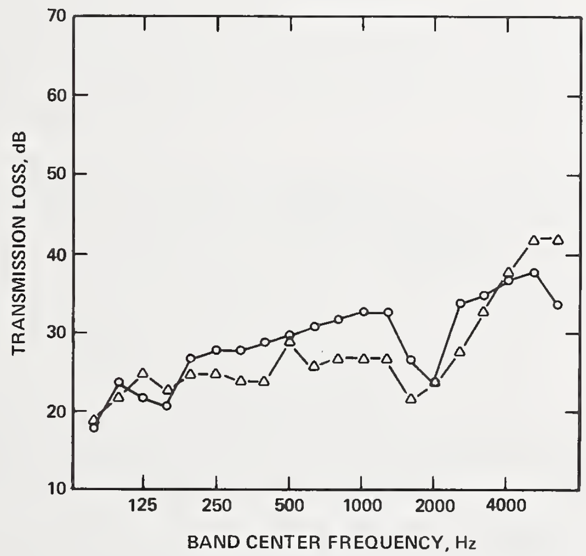


Figure 23. Sound transmission loss vs frequency data for the two urethane foam core doors sealed into the frame.

Symbol	Test No.	Specimen	STC
○	W-3-72	Steel faces	28
△	W-44-72	Fiberglas reinforced plastic faces	26

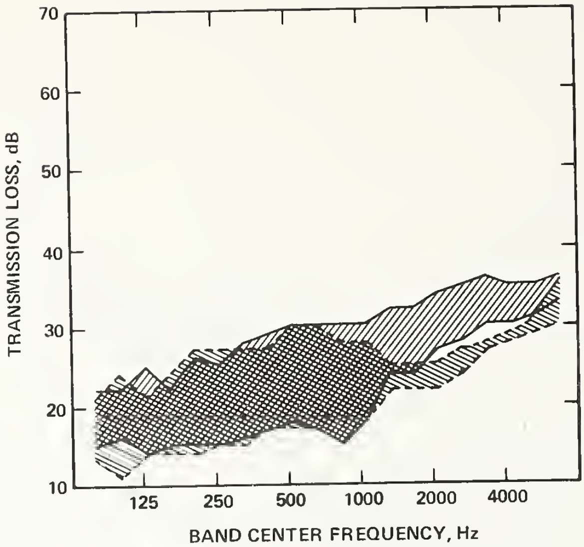


Figure 24. Sound transmission loss vs frequency data (STC 21-31) for three wooden doors unsealed with weather stripping, compared with data for the same doors when sealed (STC 20-27).

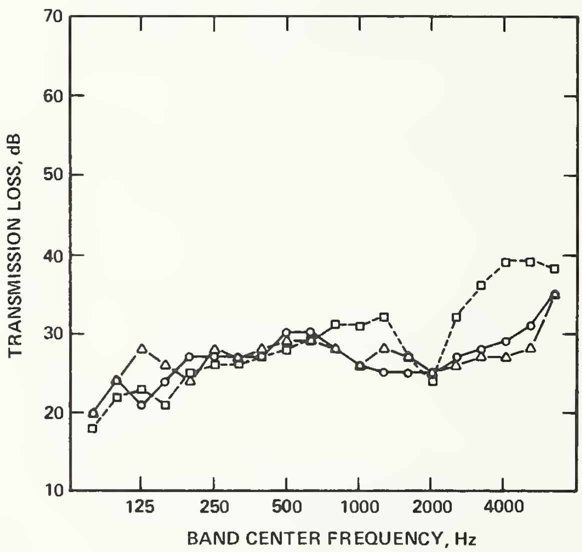


Figure 25. Comparison of effect of three types of weather stripping on sound transmission loss vs frequency data for doors.

Symbol	Test No.	Specimen	STC
○	W-90-71	Spring brass on 3 sides of solid core wood door; plastic half-round threshold strip	27
△	W-42-72	Same except extruded plastic 3 sides	27
□	W-2-72	Magnetic strip on 3 sides of steel door, plastic fingers on bottom	28

For the steel door with magnetic weather strip, there was no significant difference between the sealed and the normally closed door. The fact that in both cases the TL was substantially higher at most frequencies than that of the wood solid core door, either sealed or normally closed, indicated that the magnetic weather strip provides a 5 to 10 dB better sound seal than the other two weather strips in the upper frequencies. The sharp dip at 2000 Hz is due to direct transmission through the steel door and therefore could not be controlled by the perimeter seal.

The effect of adding a storm door to the solid core wood door is shown in Figure 26. For both doors normally closed, the STC was raised from 27 to 34, and with both sealed there was a further improvement to 42 STC. This indicates the need for a drastic improvement in the weather stripping of the storm door in order to approach its full capability when added to the wood door.

c. Sealed Windows

<u>Sealed Single Glazing</u>

The tests conducted on windows with complete perimeter seals are listed in Table C-3. The data for single glazed windows are summarized in Figures 27 to 31. The overall range of STC values for sealed windows without storm sash was 28 to 34. For sealed windows with storm sash, the range was 29 to 39 STC.

The average characteristics for single glazed windows are shown in the curves of Figure 27. The STC values are as follows:

Single Strength	28 - 29
Double Strength	29-32
3/16 in. safety glass	31
1/4 in. laminated with damping layer	34

The envelope of all data for five windows with single strength glazing is shown in Figure 28. This showed a remarkably low spread of 1 to 3 dB over most of the frequency range in spite of wide variations in window style including single and divided lights, wood and aluminum frames, and a wide range of sash and pane area. The conclusion is that the glass rather than the window material and construction was the governing factor in sound transmission of sealed windows.

Comparison of the curves for the four types of glazing in Figure 27 shows that the transmission loss in the middle and lower frequencies was controlled essentially by the surface weight of the glass. For a given frequency, the mass law for single layer materials states that their difference in transmission loss is equal to 20 times the log of their areal density ratio. For an overall range of 1.3 to 3.0 lb/sq ft for the four types of glass, the predicted spread in TL value was 7 dB, a value which is very closely matched by the data from 160 to 1000 Hz.

The mass law further states that for a perfectly limp, single layer material of a given weight, the TL increases with frequency at 6 dB per octave. The data curves, however, show, due to stiffness effects, a much lower rate of increase. At the high frequencies, the observed dips are due to wave coincidence and occur at a critical frequency which depends on the ratio of surface weight to bending stiffness. For a given material, the bending stiffness increases with thickness at a more rapid rate than does the surface weight so that the coincidence dip occurs at lower frequencies with increasing thickness. The frequencies of the observed dips for three of the glazings from 2500 to 6300 Hz agreed well with the calculated frequencies based on nominal surface weights and stiffness for the various thicknesses.

The depth of the coincidence dip is governed by the damping properties of the glass and its mounting. The dip for the 1/4 in. laminated glass should have occurred around 2000 Hz, but the large amount of damping provided by the inner layer almost completely filled in the dip, resulting in a large improvement above 2000 Hz over the 3/16 in. laminated glass

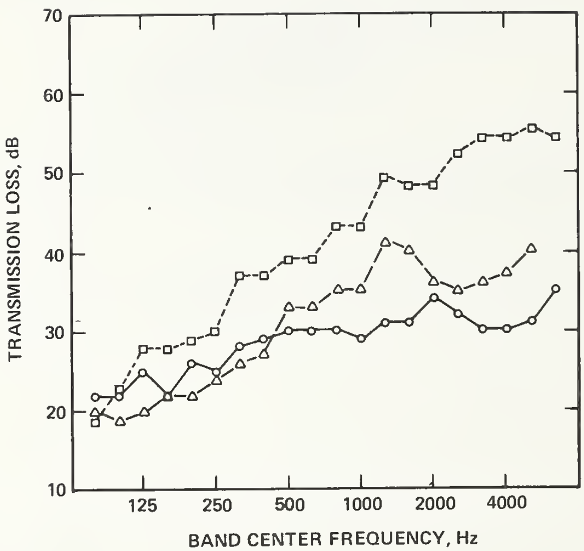


Figure 26. Comparison showing the effect of adding a storm door on the sound transmission loss vs frequency of a solid core wood door.

Symbol	Test No.	Specimen	STC
○	W-91-71	Door alone, sealed into frame	30
△	W-40-72	Door unsealed, extruded plastic weather strip, plus aluminum storm door, unsealed.	34
□	W-41-72	As above, both doors sealed	42

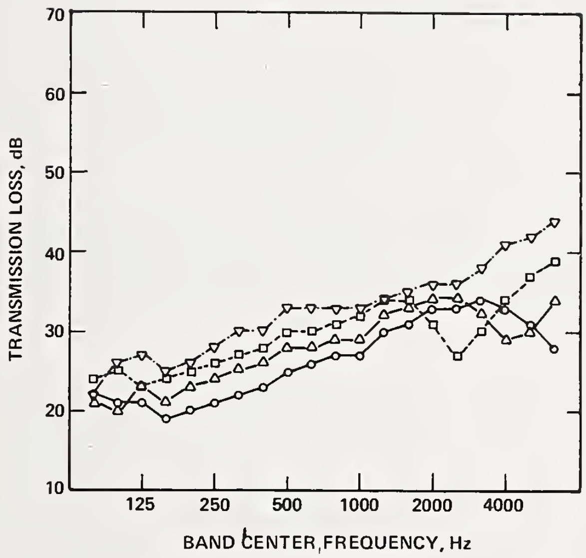


Figure 27. Comparison of sound transmission loss vs frequency data for different types of sealed glazing.

Symbol	Test No.	Specimen	STC
○	W-8-71 W-33-71 W-41-71 W-76-71 W-26-72	single strength (average of 5 tests)	28-29
△	W-7-71 W-32-71 W-34-71 W-64-71 W-66-71 W-21-72	double strength (average of 6 tests)	29-32
□	W-18-72	3/16 in. safety glass	31
▽	W-22-72	1/4 in. laminated glass with inner damping layer	34

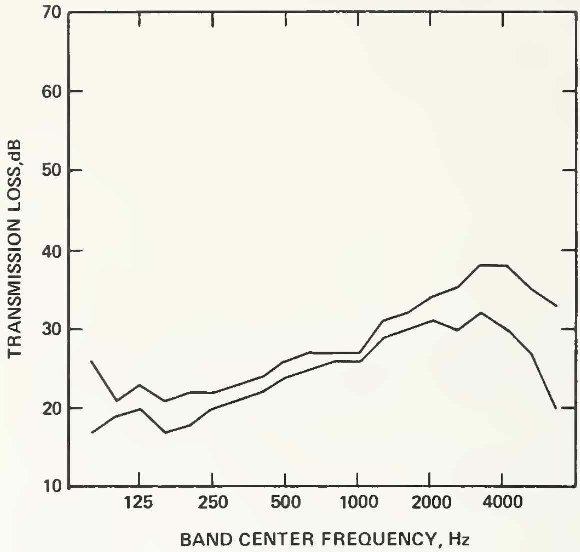


Figure 28. Envelope of sound transmission loss vs frequency data for five sealed windows with single-strength glazing (Tests W-8-71, W-33-71, W-41-71, W-76-71, and W-26-72). Windows include: wood and aluminum sash, single and divided lights, sash areas from 6 to 30 sq ft. The corresponding Sound Transmission Class range is STC 28-29.

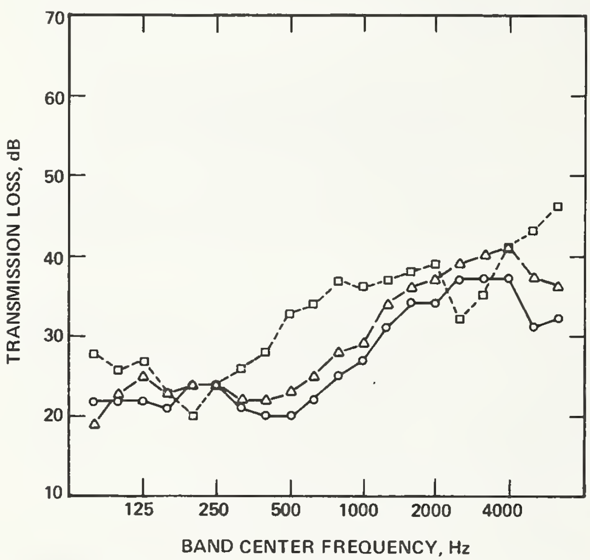


Figure 29. Sound transmission loss vs frequency data for three types of insulating glass.

Symbol	Test No.	Specimen	STC
○	W-68-71 W-82-71	3/8 in. insulating glass (average of 2 tests)	26-28
△	W-31-71 W-29-72	7/16 in. insulating glass (average of 2 tests)	28-30
□	W-10-71	1 in. insulating glass	34

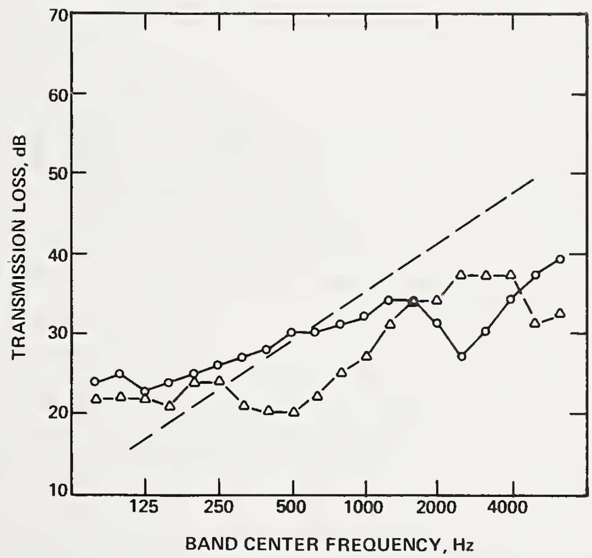


Figure 30. Comparison of sound transmission loss vs frequency data for insulating glass with data for single glazing of the same surface density (nominally 2.6 lb/ft^2). The dashed curve represents field incidence mass law (see Figure 14 and accompanying text).

Symbol	Test No.	Specimen	STC
○	W-18-72	3/16 in. safety glass	31
△	W-68-71 W-82-71	3/8 in. insulating glass (average of 2 tests).	26-28

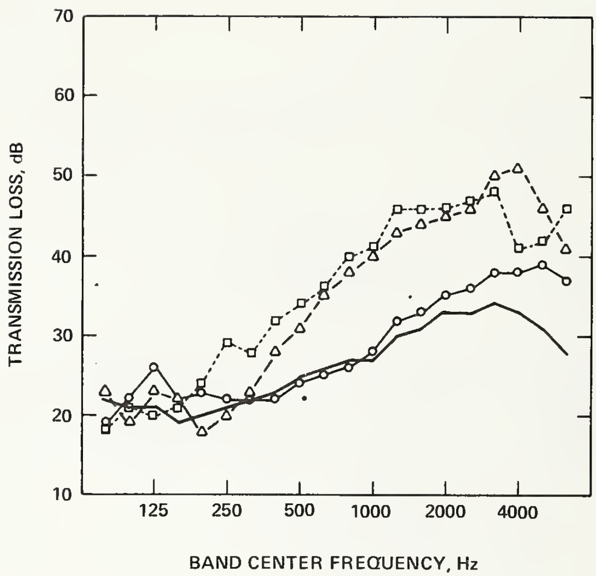


Figure 31. Comparison of sound transmission loss vs frequency data for sealed single-strength windows with storm sash (at various spacings from primary glazing) with data for sealed windows, glazed single-strength with storm sash. In the following table the spacing is the average between panes for upper and lower sash.

Symbol	Test No.	Specimen	STC
——	W-8-71 W-33-71 W-41-71 W-76-71 W-26-72	single strength (average of 5 tests)	28-29
○	W-25-72	storm sash glazed single strength spaced 1/8 in.	29
△	W-37-71	storm sash glazed single single strength, spaced 2 1/8 in.	34
□	W-11-71	storm sash glazed double strength, spaced 3 3/4 in.	38

which was undamped. Below 2000 Hz, however, the small improvement was due only to its slightly higher weight.

Sealed Insulating Glass

Averaged data curves for the three thicknesses of insulating glass are shown in Figure 29, with STC values as follows:

3/8 in.	26 - 28
7/16 in.	28 - 30
1 in.	34

The first two of these were formed of double layers of single strength and double strength glass, respectively, but for most of the frequency range they had TL values equal to or lower than the single layer alone. The 1 in. insulating glass was formed of 3/16 in. safety glass on each side.

According to sound transmission theory, a double wall generally has a higher TL than a single wall of the same total surface weight. This, however, occurs only above a resonance frequency which is determined by the weight of each layer and their separation. The greater the weight and the wider the separation, the lower is the resonance frequency. At or near the resonance frequency, the TL is actually lower for the double wall than for the single wall. Also, the improvement in TL above the resonance frequency for the double wall may in practice be limited by mechanical coupling between the two sides.

These effects are clearly shown in Figure 30, where the TL curve of the single-layer 3/16 in. safety glass is compared with that of the 3/8 in. insulating glass having the same total areal density of 2.6 lb/sq ft. Also shown is the theoretical mass law curve for a limp, single layer material of that weight. The calculated resonance frequency for the insulating glass is approximately 500 Hz, and the data curves show a wide dip around this frequency which is 10 dB below the curve for the single layer. In well-isolated double wall structures with wide separation, the TL curve generally rises steeply beyond the mass law line above the resonance frequency, but for the insulating glass this did not occur. This was due largely to the high compressive stiffness of the shallow air cavity and to the influence of coincidence effects at the highest frequencies. There was also rigid mechanical coupling around the perimeter of the glass due to the "welded" structure which may have contributed to flanking sound transmission.

For the 1 in. insulating glass shown in Figure 29 both the calculated and observed resonance frequencies are around 200 Hz, and the rise in TL above resonance is effective over a larger part of the frequency range. This rise, however, was again severely limited by the coincidence dip at 2500 Hz.

Sealed Windows with Storm Sash

The data for sealed windows with added storm sash may be grouped as follows:

Window Glazing	Storm Glazing	STC
Single and double strength	Single and double strength	29 - 38
3/8 in. and 7/16 in. insulating	Single and double strength	35 - 39

The wide spreads in the above groupings were due, not to the variations in glazing, but to the wide range of spacings between the window and the storm sash. These varied from 1/8 in. for the aluminum sliding window to 3 3/4 in. for the picture window. The effect of spacing is shown in Figure 31, where curves are plotted for three single or double strength storm sashes added to the average of five single strength windows.

These curves agreed well with the predictions of double wall theory. The curve for 1/8 in. spacing was quite similar to those for the insulating glass in Figure 29 and showed no improvement over the window alone except above 1000 Hz. The calculated resonance frequency for this spacing was 600 Hz, which was too high for effective double wall performance. The calculated resonance frequencies for the 2 1/8 in. and 3 3/4 in. spacings were 145 and 105 Hz, respectively, which agreed fairly well with the observed dips in the TL curves. In both cases, the TL curves rose rapidly with frequency above the resonance frequency, resulting in a 10 to 20 dB improvement over the window alone at all frequencies above about 500 Hz. The STC values were 34 and 38, respectively, as compared to 28 to 29 for the window alone.

The highest STC value obtained in the entire window program was 39 for a combination of a double hung wood window with 7/16 in. insulating glass and a storm sash glazed double strength at 2 1/8 in. spacing. Although not tested, a considerably higher value could probably have been obtained by adding a storm sash to the 1 in. insulating glass in the picture window at 3 3/4 in. spacing. The insulating glass alone had an STC of 34. However, it was assumed that the use of storm sash or insulating glass is dictated by thermal insulation requirements in common building practice, rather than sound insulation, and that it would be unlikely that a storm sash would be added to a 1 in. thick insulating glass.

d. Unsealed Windows

The foregoing data on sealed windows represent their maximum sound insulating capability. Under normal conditions, of course, this performance is more or less compromised by sound leakage through perimeter cracks and openings. In all tests of unsealed windows, the outer frame of the window unit was thoroughly sealed into the wall, it being assumed that this degree of sealing could reasonably be expected in field practice. The measured sound leakage, therefore, was attributable only to that which occurred around the perimeters of movable sashes in various conditions of opening, closing, and locking.

To provide a reference for interpreting such data, a series was run on accurately gauged perimeter cracks around the 6 x 5 ft picture window, as shown in Figure 32. The series was repeated for two picture window sashes having double strength glazing and 1 in. insulating glass, respectively, in order to show more clearly the relative transmission through the cracks and the glass.

The transmission loss data curves for gauged perimeter cracks around the picture window are shown in Figure 33 for double strength glazing and Figure 34 for insulating glass. Each curve represents the combined transmission through the parallel sound paths of open crack and glass, the transmission being governed essentially by the weaker of the two paths. The curves show that over most of the frequency range, the transmission is governed by the crack area. At low frequencies, the glass transmission tended to govern, and there was less difference in transmission due to the various crack areas. In accordance with theory, the transmission loss should decrease 3 dB with each doubling of transmitting area, and the curves agreed quite well with this prediction. The curves also showed that the transmission through the crack was almost independent of frequency.

The transmission loss of a window with a perimeter crack of known dimensions can be estimated by assuming that: (1) the transmission loss of the sealed window is much higher than the window with the crack, (2) the transmission loss of the crack is zero at all frequencies, and (3) the sound energy transmitted by either the crack or the glass is directly proportional to the corresponding area. On this basis, the theoretical transmission loss of the window with crack is:

$$TL = 10 \log (1/k) \qquad (7)$$

where: k = ratio of crack area to window area.

In general, for each of the gauged cracks in Appendix C (Test Nos. W-12-71 to W-21-71), the measured values were lower than equation (7) would predict. This point is discussed in Section 3.5.

As a further check on the above estimating procedure, the transmission loss curves of the picture window with two cracks of equal area but different lengths and widths are

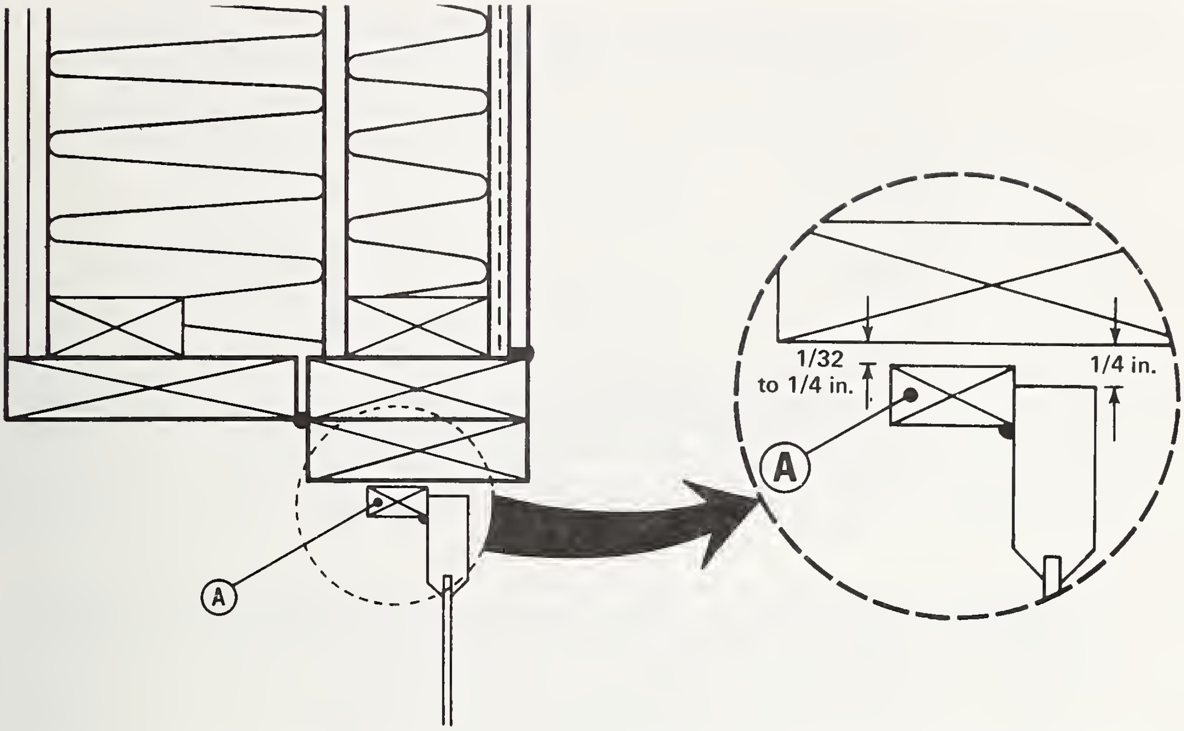


Figure 32. Detail of framing in filler wall to receive picture window sashes. Strip A was shimmed out to provide perimeter cracks ranging from 1/32 to 1/4 in.

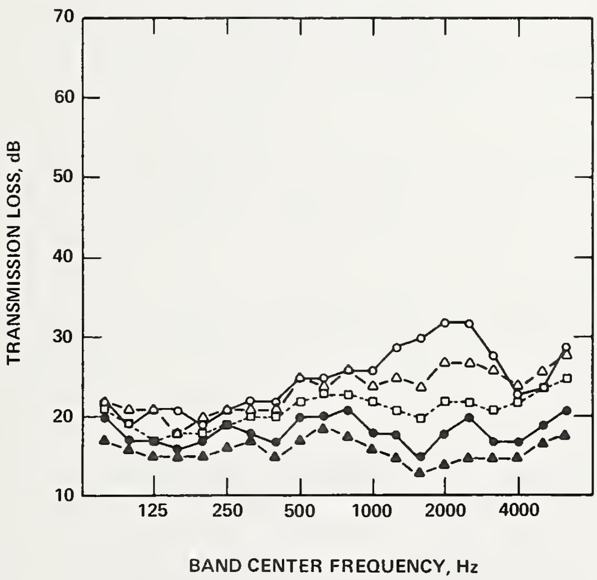


Figure 33. Sound transmission loss vs frequency data for 6 x 5 ft picture window, double-strength glazing, with perimeter cracks of controlled size.

Symbol	Test No.	Crack Width	STC
○	W-7-71	None, complete seal	29
△	W-21-71	1/32 in.	25
□	W-17-71	1/16 in.	21
●	W-15-71	1/8 in.	18
▲	W-16-71	1/4 in.	15

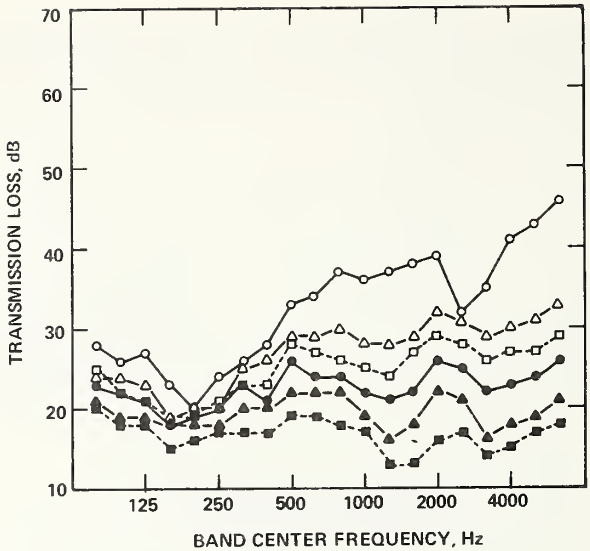


Figure 34. Sound transmission loss vs frequency data for 6 x 5 ft picture window, glazed with 1 in. insulating glass, with perimeter cracks of controlled size.

Symbol	Test No.	Crack Size	STC
○	W-10-71	None, complete seal	34
△	W-20-71	1/32 in., half perimeter	29
□	W-19-71	1/32 in., full perimeter	26
●	W-18-71	1/16 in., full perimeter	23
▲	W-14-71	1/8 in., full perimeter	19
■	W-12-71	1/4 in., full perimeter	15

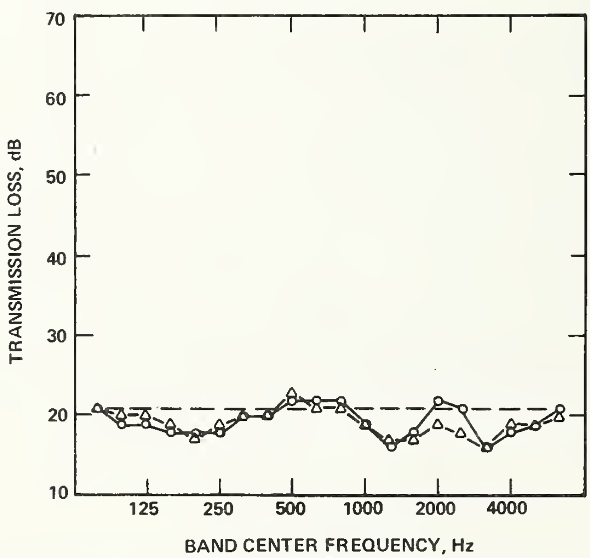


Figure 35. Comparison of effect of perimeter cracks of the same area, but different widths, on the sound transmission loss vs frequency for a 6 x 5 ft picture window, glazed with 1 in. insulating glass. The dashed horizontal line corresponds to the theoretical transmission loss, based on the ratio of crack area to window area, assuming the transmission loss of the crack is 0 dB.

Symbol	Test No.	Crack Size	STC
○	W-14-71	1/8 in., full perimeter	19
△	W-13-71	1/4 in., half perimeter	18

compared in Figure 35. It is shown that there is no significant difference between the two tests and generally good agreement with the theoretical transmission loss.

The above equation for the transmission loss of a window with perimeter cracks can be put in the form:

$$TL = 10 \log \frac{12}{d} \frac{A}{L} \tag{8}$$

where: d = crack width, in.

A = window area, sq ft

L = total crack length, ft

This is plotted in Figure 36 which can be used either to estimate an equivalent crack width from measurements of transmission loss or to estimate the transmission loss from a known crack width, knowing in either case the window area and sash perimeter. The latter would be the total crack length for double hung or multiple sash units. It must also be known that the measured transmission loss is much lower than that of the sealed window. As noted above, this would generally be true at the higher frequencies.

As an example, compare the data in Appendix C for the 3 x 5 ft wood double hung window, glazed insulating glass, sealed (Test No. W-31-71) versus normally closed and unlocked (Test No. W-25-71). Above 1000 Hz, the transmission loss of the sealed window ranged from 27 to 40 dB, and for the normally closed window 21 to 29 dB with an average of about 24 dB. The ratio A/L for total sash area to total crack length of both sashes (counting the joint between sashes only once) was calculated at about 0.7. Referring to Figure 36, a transmission loss of 24 dB at A/L = 0.7 would result from an equivalent crack width at all sash perimeter joints of .037 in. or slightly over 1/32 in.

Illustrative data on the effect of sealing only the horizontal joints of this window are given in Test Nos. W-23-71 and W-35-71 in Appendix C. Summarized test data and test number references for gauged openings in the other windows are listed in Table C-5.

Probably a more typical condition in practice would be a fully closed window either locked or unlocked rather than one partially open by a slight amount. Accordingly, all windows in the program were tested both locked and unlocked as well as fully sealed. In some types of operable window, closing and locking or latching were accomplished together so that an unlocked condition could not be tested separately.

An overall comparison of all of the test data for sealed versus unsealed windows is shown by the envelopes of data in Figure 37. The unsealed windows were all closed tight and either locked or unlocked. The lower limit of the envelope for the unsealed windows corresponded almost entirely to the data for the aluminum casement window unlocked, having an STC of 17 (Test No. W-20-72). This window had no weatherstripping of any kind. The same window locked showed a 21 STC (Test No. W-21-72). Omitting the envelope data for the unlocked window, there was an average difference of about 4 STC between the two envelopes, with slightly more difference at the high frequencies and less at the low frequencies.

Illustrative data for a few windows are shown in Figures 38 and 39. The differences between sealed and unsealed units were most pronounced at the high frequencies, especially for the insulating glass which has higher transmission loss at high frequencies than single or double strength. There were no consistently large differences between the locked and the unlocked condition, although there was quite an erratic spread of data in the highest frequencies. The large dip at 4000 Hz for the unlocked window in Test No. W-25-71 could be due to resonance phenomena as are discussed in Section 3.5.

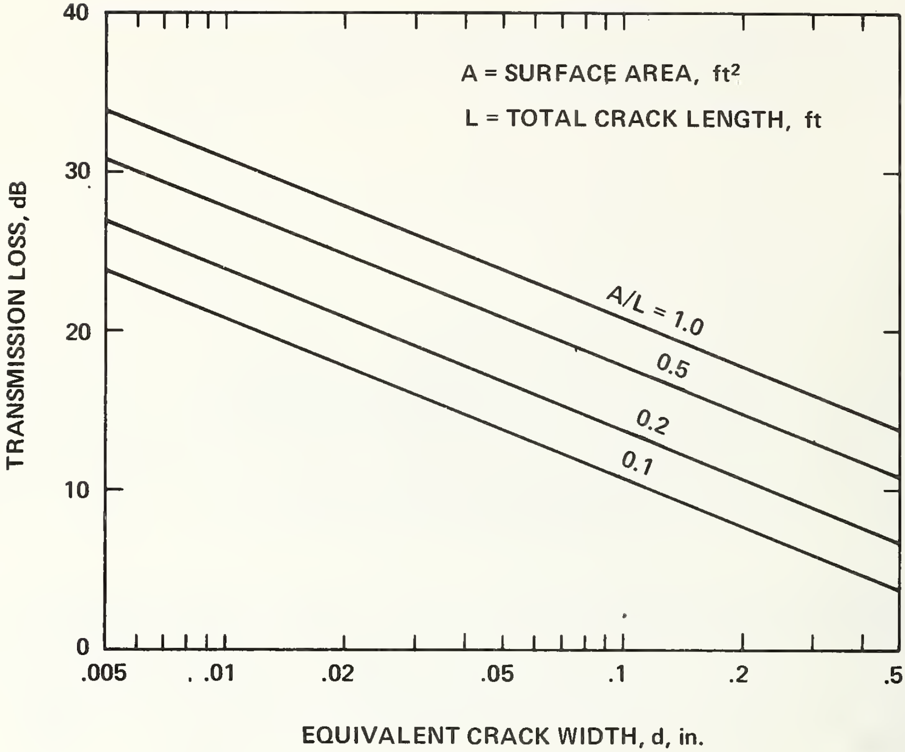


Figure 36. Theoretical sound transmission loss of surface with cracks, assuming the sound transmission loss of the sealed surface is at least 10 dB higher than that of the surface with cracks (see text).

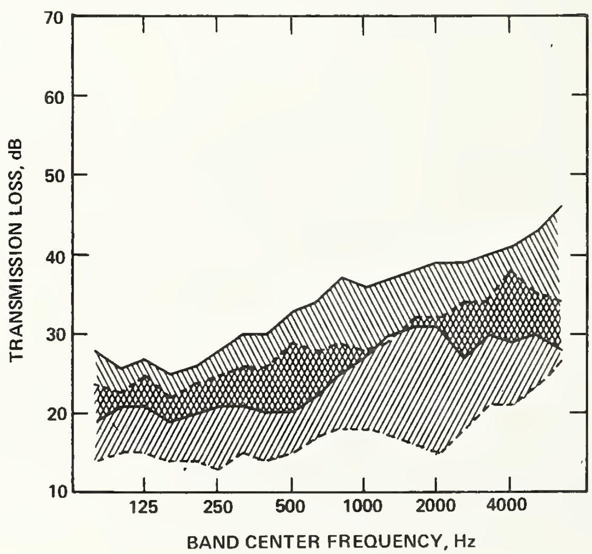


Figure 37. Comparison of the envelope (corresponding to STC 26-34) of sound transmission loss vs frequency data for all sealed windows with the envelope (STC 17-30) of data for all unsealed windows, locked and unlocked.

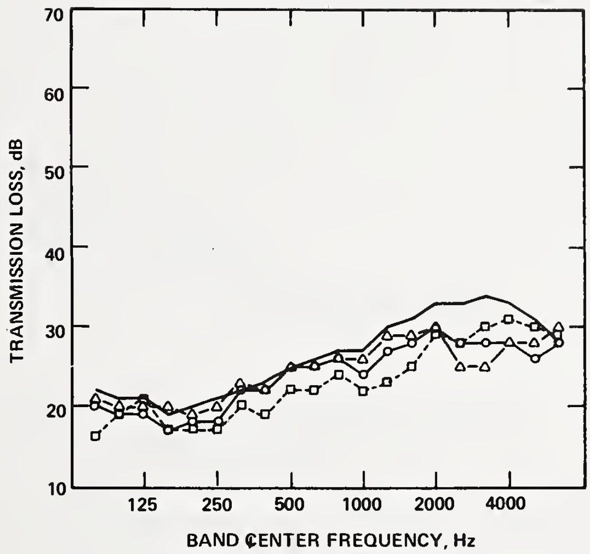


Figure 38. Comparison of sound transmission loss vs frequency data for sealed and unsealed windows, glazed single-strength.

Symbol	Test No.	Specimen	STC
———	same as in Figure 31	sealed (average of 5 tests)	28-29
○	W-74-71	wood double-hung, locked	26
△	W-75-71	wood double-hung, unlocked	26
□	W-23-72	aluminum sliding, latched	24

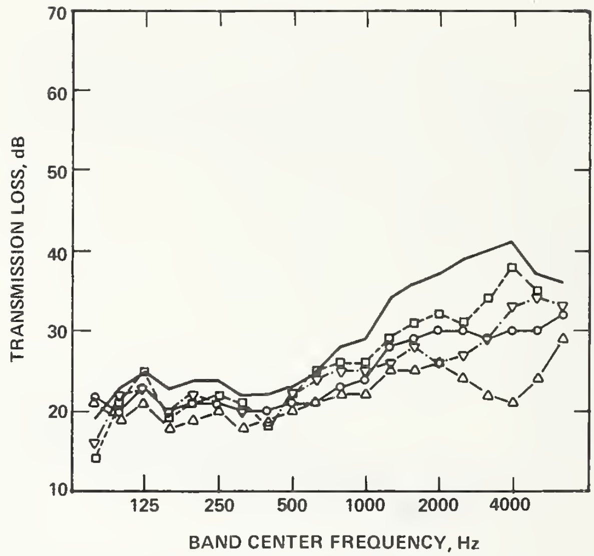


Figure 39. Comparison of sound transmission loss vs frequency data for sealed and unsealed windows, glazed 7/16 in. insulating glass.

Symbol	Test No.	Specimen	STC
———	W-31-71 W-29-72	sealed (average of 2 tests)	28-30
○	W-24-71	wood double-hung, locked	26
△	W-25-71	wood double-hung, unlocked	22
□	W-27-72	aluminum single hung, locked	27
▽	W-28-72	aluminum single hung, unlocked	25

e. Combinations of Windows in Walls

Complete test data for the four combinations of the 6 x 5 ft picture window in two walls are shown in Figure 40 to 43. For each combination of wall and window, the measured transmission loss data curve for each component is shown on the charts. Also, on each chart is shown the calculated transmission loss of the combination, this calculation being made using equation (4) with only two areas, that of the wall and that of the window, being used.

An example of the application of this approximation is shown in the curves of Figure 42 where the window having the minimum transmission loss was placed in the wall having maximum transmission loss. Even though the window area S_1 was much less than the remaining wall area S_2, the transmission coefficient of the window was so much greater than that of the wall that the ratio $(\tau_1 S_1)/(\tau_2 S_2)$ was greater than 10 at almost all frequencies. As discussed in Section 3.1., in such a case the transmission loss of the combination should exceed the transmission loss of the window by the amount 10 log (S/S_1). For corresponding areas of 126 and 25.6 sq ft, respectively, the excess is 7 dB. It will be seen in Figure 42 that the calculated curve of the combination lies 7 dB above the measured curve of the window over nearly all of the frequency range. For the other combinations where there was less difference between the transmission loss of the window, and that of the wall, the complete formula in equation (4) was used. In every case, the transmission loss of the combination fell between the transmission loss values of each component.

3. 5. Comparison of Results with Those of Other Investigations

3. 5. 1. Walls

No data were found in the literature on exterior walls similar in construction to those tested during the present investigation. However, it was felt to be useful to compare the effects of resilient channels and cavity insulation with corresponding data on interior walls. Figure 44 repeats the data shown in Figure 18 for the wood-siding wood-stud, exterior wall, with and without cavity insulation and with and without resilient channels. Figure 45 presents the data of Northwood [61] on two-leaf walls with 1/2 in. plasterboard on either side of nominal 4 in. studs; curves 1 and 2 correspond to 2 x 4 in. wood studs on 24 in. centers while curves 3 and 4 correspond to 3 5/8 in. steel channel studs on 24 in. centers (the steel channel studs should have provided roughly equivalent vibration isolation to that provided by the resilient channels in the case of the wood siding, wood stud exterior wall). Several similarities and differences between Figures 44 and 45 can be pointed out. Since both sides of the plasterboard walls were of identical construction, the high frequency coincidence dips for these walls are much more pronounced than are those for the exterior walls. The improvement due to resilient channels plus cavity insulation is about the same for the interior and the exterior walls. Since both sides of the plasterboard walls are identical, they are very efficiently coupled by the stiffness of the air in the cavity so that resilient channels, without cavity insulation, do not produce as much improvement for the interior walls as they do for exterior walls. Since the inner and outer surfaces of the exterior walls are of different construction, the coupling through the air cavity is not very efficient so that addition of cavity insulation alone does not provide much improvement for the exterior walls. Vér and Holmer [12] give procedures for estimating the effectiveness of different procedures for vibration isolation between the two sides of double walls.

3. 5. 2. Doors

The data presented here are restricted to sealed or tightly gasketed doors. The effects of cracks are discussed in Sections 3.5.4. and 6.1.

Figures 46 and 47 present data on a total of eight solid core wood doors having areal densities ranging between 3.3 and 7.0 lb/sq ft. The data (Test W-91-71) from the present investigation are shown in both figures to facilitate comparisons. Although the sound transmission loss curves from the several investigations differ somewhat at low and high frequencies, the STC values are all within a range of ± 3 around the value obtained in the present investigation.

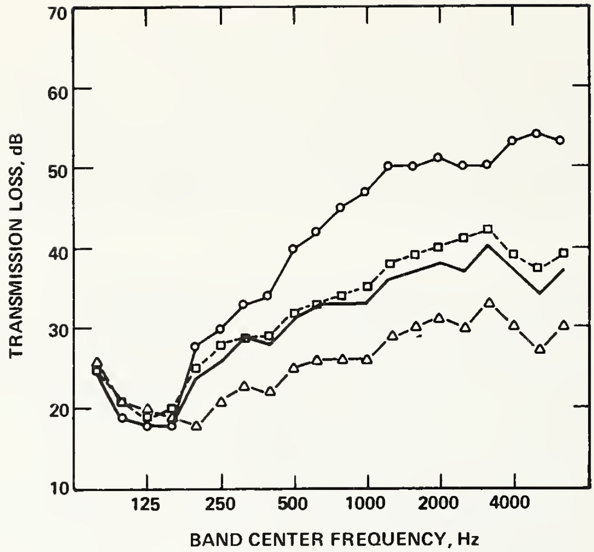


Figure 40. Comparison of measured sound transmission loss vs frequency data for a 6 x 5 ft picture window, glazed single strength, in a wood siding wall with that predicted from the transmission losses and areas of the wall and window (window area = 25.6 sq ft, wall plus window area = 126 sq ft).

Symbol	Test No.	Specimen	STC
○	W-54-71	wall alone	39
△	W-8-71	window alone	28
□	W-57-71	combination, measured	35
———	---	combination, calculated	34

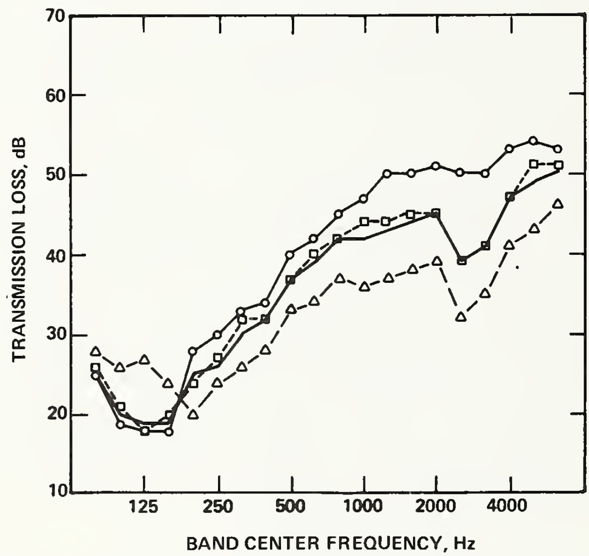
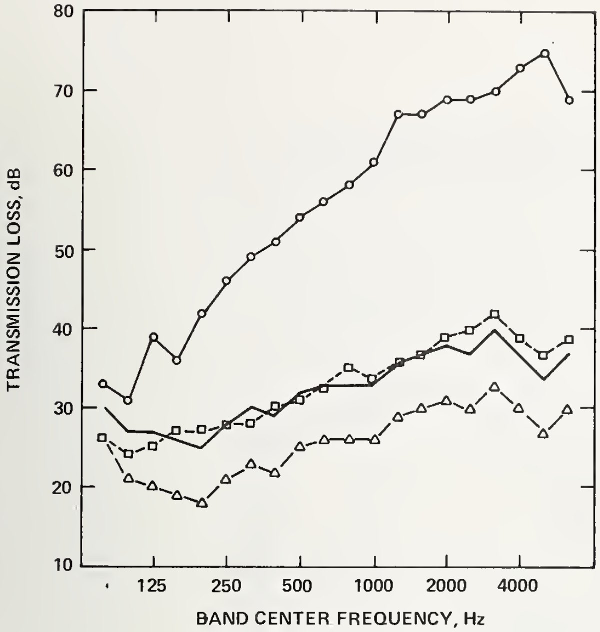


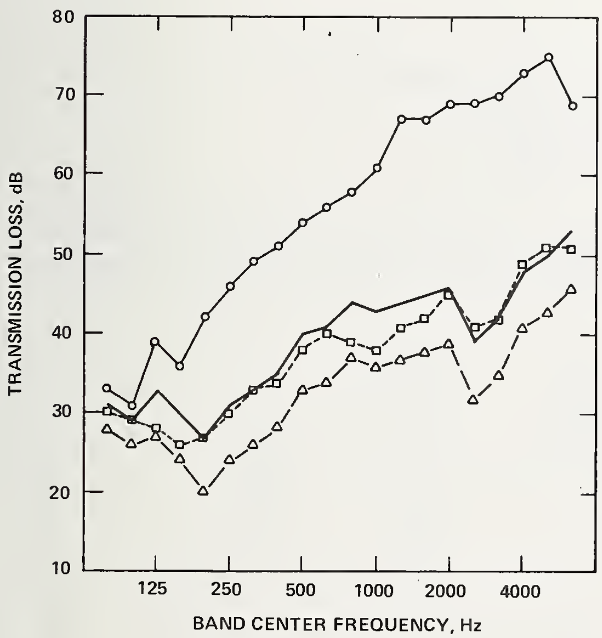
Figure 41. Comparison of measured sound transmission loss vs frequency data for a 6 x 5 ft picture window, glazed 1 in. insulating glass, in a wood siding wall with that predicted from the transmission losses and areas of the wall and window (window area = 25.6 sq ft, wall plus window area = 126 sq ft).

Symbol	Test No.	Specimen	STC
○	W-54-71	wall alone	39
△	W-10-71	window alone	34
□	W-58-71	combination, measured	38
———	---	combination, calculated	38



Symbol	Test No.	Specimen	STC
○	W-44-71	wall alone	56
△	W-8-71	window alone	28
□	W-49-71	combination, measured	35
———	---	combination, calculated	35

Figure 42. Comparison of measured sound transmission loss vs frequency data for a 6 x 5 ft picture window, glazed single strength, in a brick veneer wall with that predicted from the transmission losses and areas of the wall and window (window area = 25.6 sq ft, wall plus window area = 126 sq ft).



Symbol	Test No.	Specimen	STC
○	W-44-71	wall alone	56
△	W-10-71	window alone	34
□	W-48-71	combination, measured	39
———	---	combination, calculated	41

Figure 43. Comparison of measured sound transmission loss vs frequency data for a 6 x 5 ft picture window, glazed 1 in insulating glass, in a brick veneer wall with that predicted from the transmission losses and areas of the wall and window (window area = 25.6 sq ft, wall plus window area = 126 sq ft).

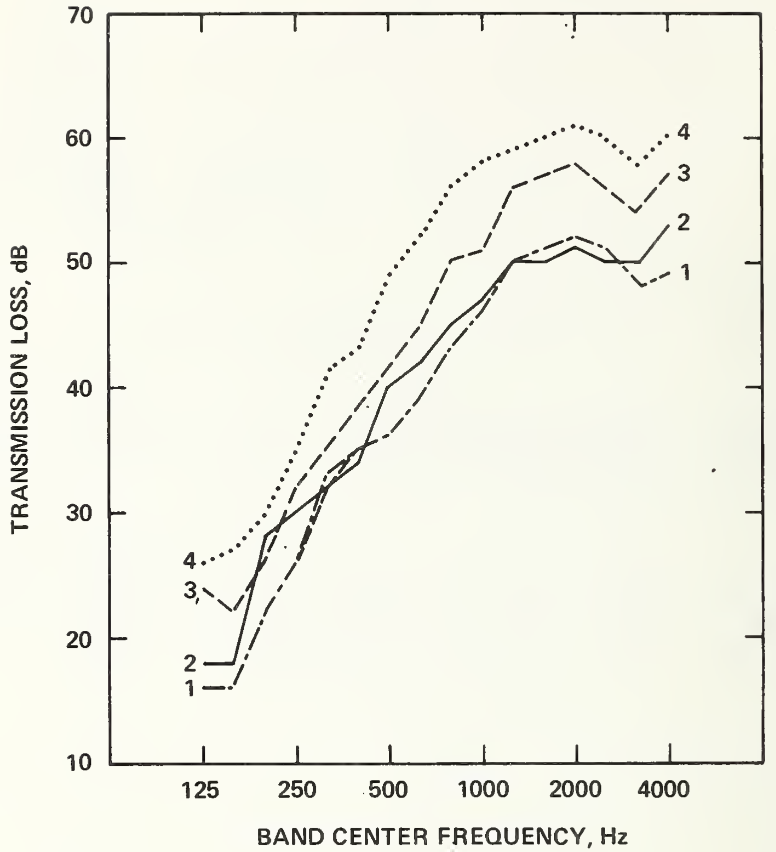


Figure 44. Sound transmission loss vs frequdncy data for wood-siding, wood-stud, exterior walls. The data are from the present investigation and correspond to walls with or without resilient channels and with or without cavity insulation.

Curve	Test No.	Cavity Insulation	Resilient Channel	STC
1	W-4-72	no	no	37
2	W-54-71	yes	no	39
3	W-56-71	no	yes	43
4	W-55-71	yes	yes	47

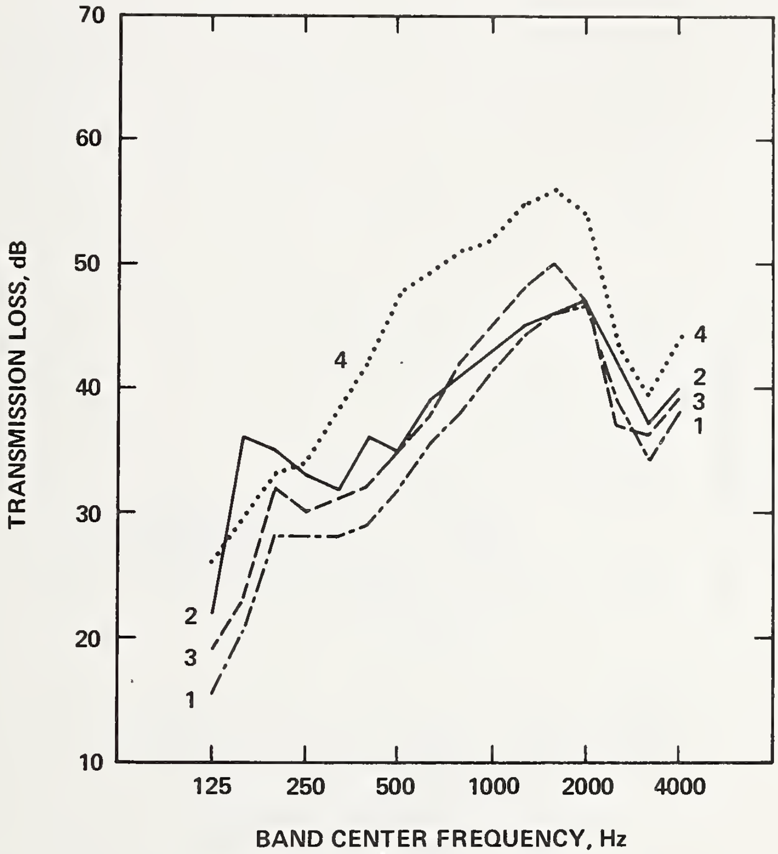


Figure 45. Sound transmission loss vs frequency data for plasterboard interior walls. The data are from Northwood [61] and correspond to walls with wood or metal studs and with or without cavity insulation.

Curve	Wall No.	Cavity Insulation	Metal Channel Stud	STC
1	2.03	no	no	35
2	2.13	yes	no	40
3	2.04	no	yes	36
4	2.14	yes	yes	44

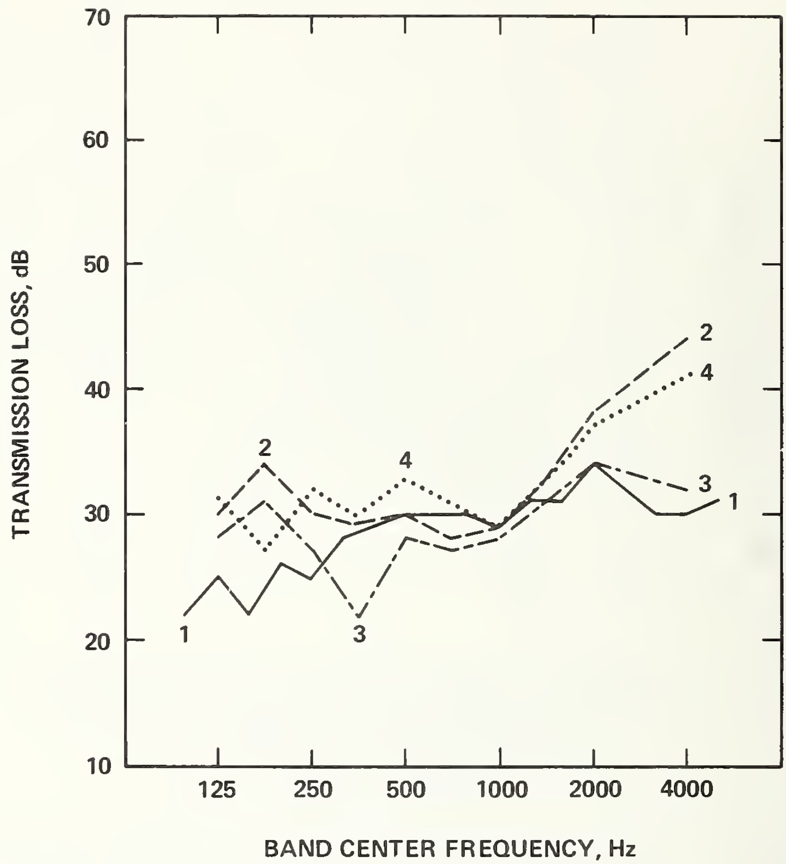


Figure 46. Sound transmission loss vs frequency data for solid core wood doors.

Curve	Reference	Test or Specimen No.	STC	Areal Density
				lb ft^{-2}
1	present investigation	W-91-71	30	3.91
2	[25]	632	30	4.6
3	[25]	617	28	5.6
4	[25]	616	30	7.0

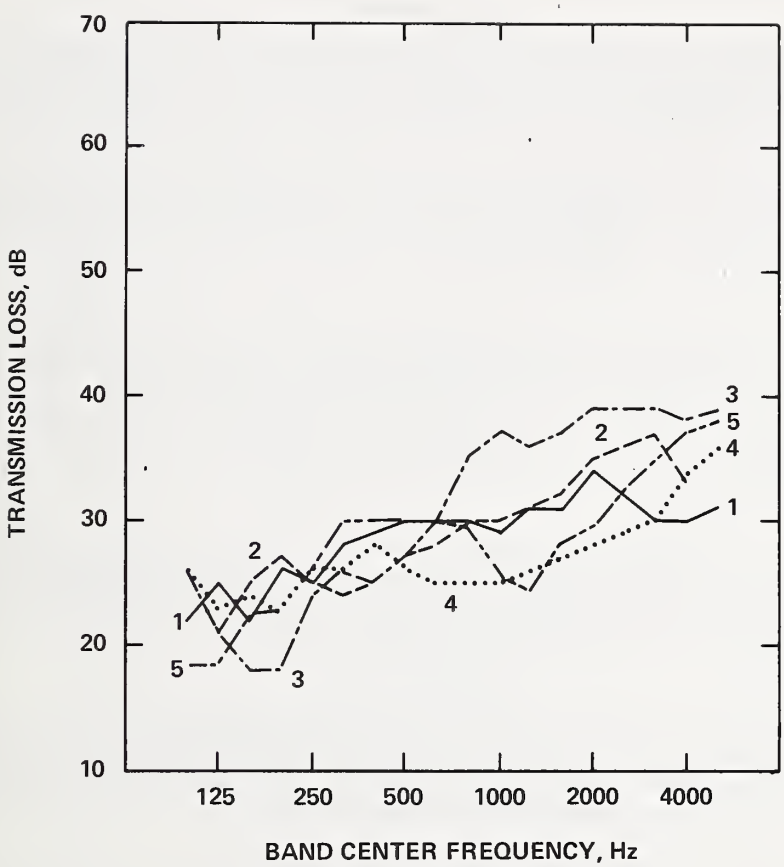


Figure 47. Sound transmission loss vs frequency data for solid core wood doors. Curve 1 is the same as in Figure 46.

Curve	Reference	Test or Specimen No.	STC	Areal Density
				lb ft^{-2}
1	present investigation	W-91-71	30	3.91
2	[62]	27	31	4.52
3	[28]	7031	33	3.28
4	[28]	7111-3	27	3.69
5	[31]	p.100	29	?

Figure 48 presents data on four hollow core doors having areal densities from 1.2 to 2.3 lb/sq ft. Again there are significant differences at low and high frequencies but the STC values are essentially identical.

3. 5. 3. Windows

Marsh [63] has given a comprehensive review of the literature on the sound transmission loss of glass, including a compilation of tabulated data. Wherever possible, data in this section were taken from her review rather than from the original source.

Probably because most measurements of the sound transmission loss of glass presumably have been taken in support of engineering solutions for situations where better-than-usual sound isolation was required, most of the data reported by Marsh are for glass much thicker than the single- and double-strength glass used for most of the windows examined in the present investigation.

Figure 49 shows a comparison of the envelope of sound transmission loss data, from the present investigation, for sealed windows having double-strength glazing (nominally 1/8 in.) with the envelope of data for sealed windows having 3 mm glazing as reported in Table A1 of Marsh [63]. The agreement is not good at low frequencies, where it is difficult to make accurate sound transmission loss measurements. Insofar as overall performance is concerned, the present data fall in the upper end (STC 29-31) of the range of data cited by Marsh (STC 26-31).

Figure 50 shows a comparison of the envelope of sound transmission loss data, from the present investigation, for sealed windows having single-strength glazing (nominally 3/32 in) with the envelope of data for three sealed windows of similar thickness as reported in the literature [62,63]. The present data correspond to STC 28-29 while the literature data correspond to STC 26-28.

Marsh [63] found that the solid line shown in Figure 51 represented the mean sound transmission loss (<u>not</u> the Sound Transmission Class) for sealed windows over the frequency range from 100 to 3150 Hz as a function of glass thickness. The dashed lines 3 dB above and below the solid line encompass about 95 percent of the literature data which she used. The solid circles indicate the average and range of the data from the present investigation.

Patil [64] reported a number of recent STC determinations made at Riverbank Acoustical Laboratories on glass of various thicknesses. These results are compared, in Figure 52, with the average and range of data on single- and double-strength glass from the present investigation. The present data lie from 1 to 3 STC-units above a mean curve through the Riverbank data.

In the present investigation it was found that the Sound Transmission Class for a given glass thickness was essentially independent of the size of the individual panes and of the type of window. Since glass has very low internal damping, one would expect that resilient mounting of the glass, which was not examined in the present investigation, would improve the sound transmission loss, especially near the coincidence region. Marsh [63] discusses this point briefly. The work of Utley and Fletcher [65-66] and Cops, Myncke, and Lambert [67] provides considerable useful information on the influence of edge damping.

Figure 53 compares the results from the present investigation on 1/4 in. laminated glass, having an internal damping layer, with data on nominally identical glazing as reported by Marsh [63]. The data are seen to be very similar. In the present investigation an STC of 34 was found while the data reported by Marsh correspond to approximately STC 32-33. Patil [64] reports a value for similar glazing of STC 34.

Of the pre-fabricated insulating glass units tested in the present investigation, literature data on comparable units were found only for the 7/16 in. insulating glass (two 1/8 in. panes with a 3/16 in. air space). In Figure 54, the solid curves represent the envelope for the two units tested (STC 28 and 30) while the dotted curves represent the envelope of three windows reported by Marsh [63].

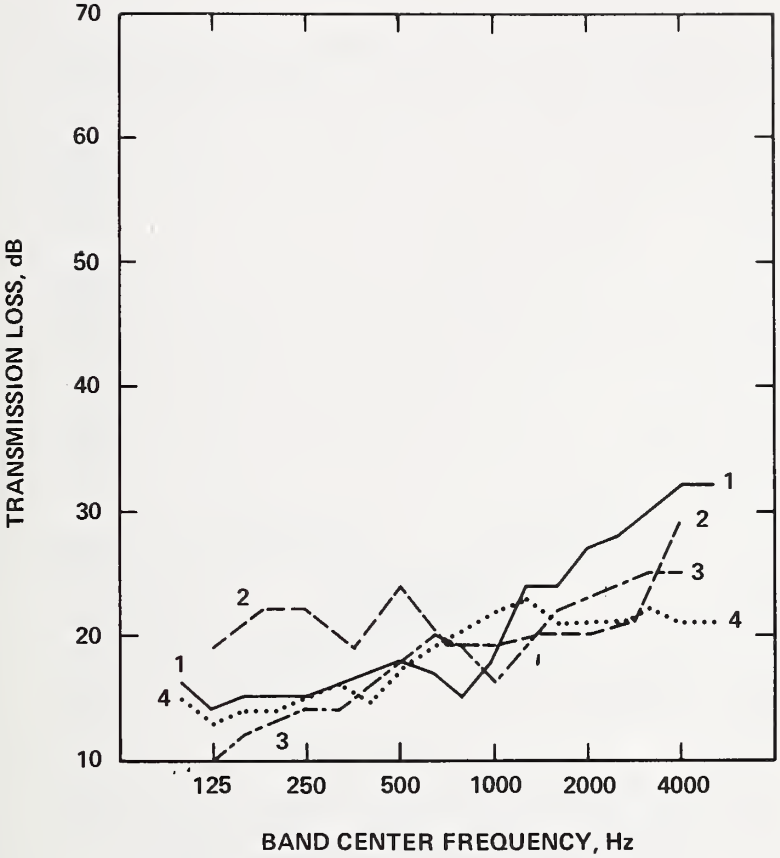


Figure 48. Sound transmission loss vs frequency data for hollow core wood cores.

Curve	Reference	Test or Specimen No.	STC	Areal Density
				lb ft^{-2}
1	present investigation	W-93-71	21	1.23
2	[25]	634	20	1.9
3	[62]	26	20	1.43
4	[28]	7083-1	20	2.25

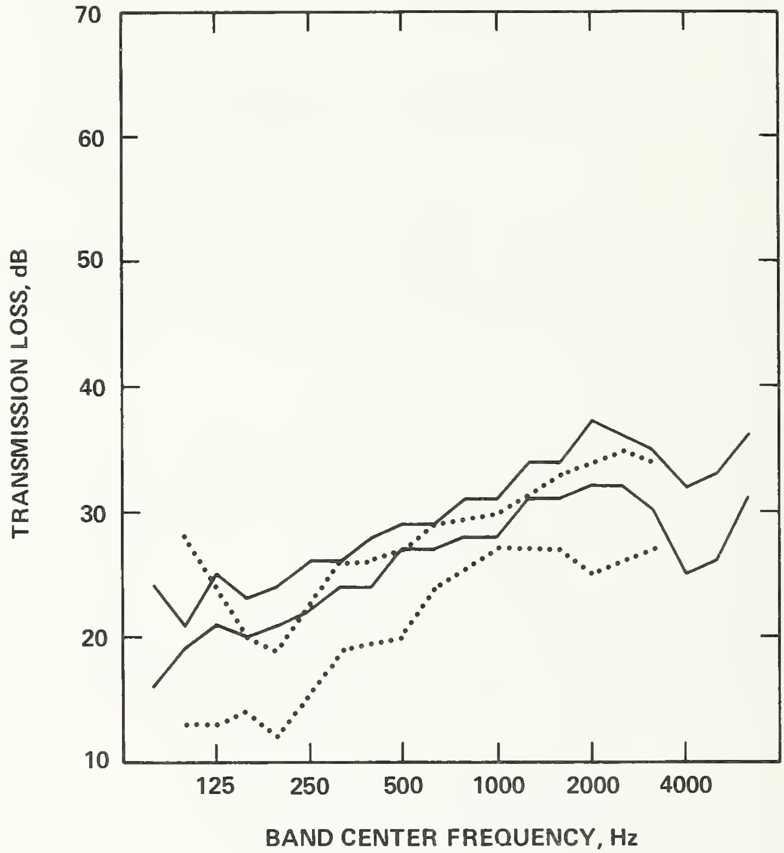


Figure 49. Sound transmission loss vs frequency data for sealed windows, of various types and sizes, with double-strength (3 mm) glazing. The solid curves represent the envelope of data obtained in the present investigation (Tests W-7-71, W-32-71, W-34-71, W-64-71, W-66-71, and W-21-72). The dotted curves represent the envelope of data, on sealed windows only, from Table A5 of Marsh [63] (the sets of data included are the 2nd and 3rd of Aston, the 1st of Wooley, and the 1st, 2nd and 4th of Saint-Gobain).

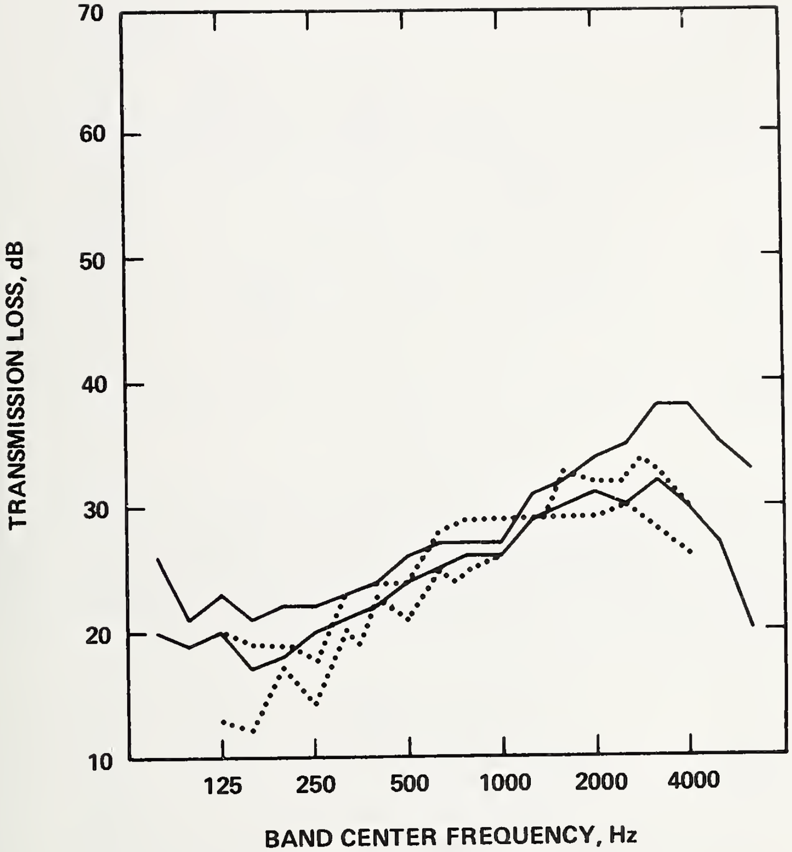


Figure 50. Sound transmission loss vs frequency data for sealed windows, of various types and sizes, with single-strength glazing. The solid curves represent the envelope of data obtained in the present investigation (Tests W-8-71, W-33-71, W-41-71, W-76-71, and W-26-72). The dotted curves represent the envelope of the following data: Brandt (2 mm glass) and Libbey-Owens-Ford (3/32 in. glass) from Table A6 of Marsh [63]; caulked steel frame casement window (3/32 in. glass) from Bishop and Hirtle [62].

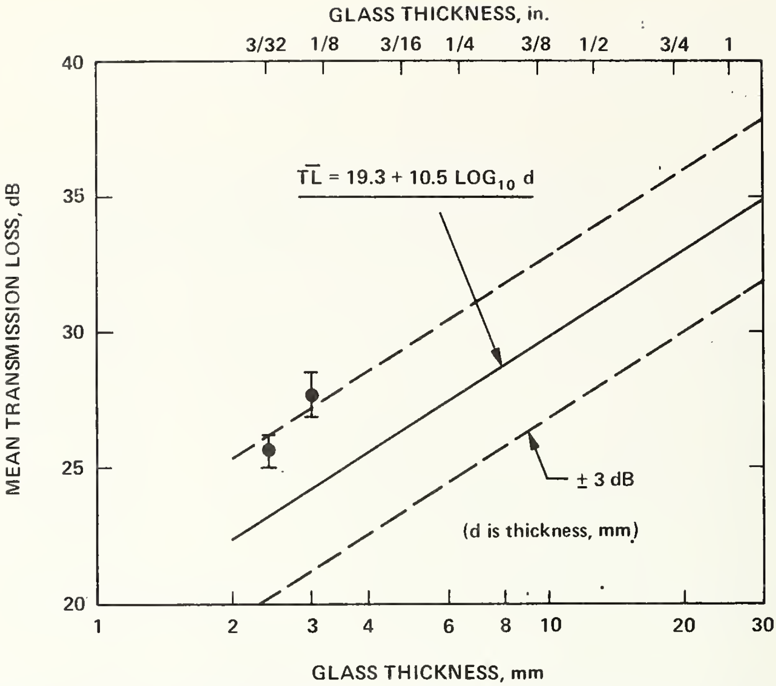


Figure 51. Mean sound transmission loss (arithmetic average of the values over the range 100 to 3150 Hz) of sealed windows vs glass thickness. The solid line is that which was fitted to literature data by Marsh [63]. The dashed lines enclose all but two of the data points she used to derive the solid line. The solid circles represent the average and range of data on single- and double-strength glazing from the present investigation.

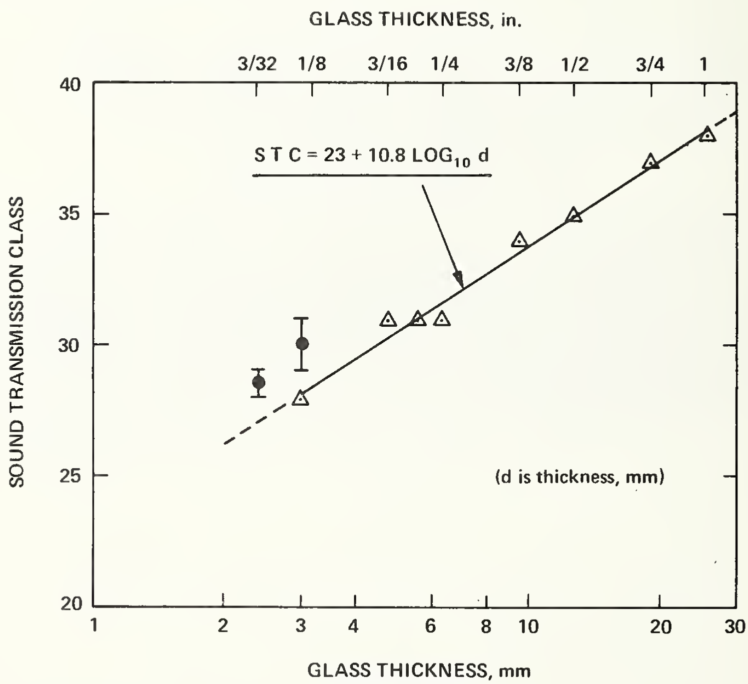


Figure 52. Sound Transmission Class of sealed windows vs glass thickness. The triangles and the line fitted through them represent the data reported by Patil [64]. The solid circles represent the average and range of data on single- and double-strength glazing from the present investigation.

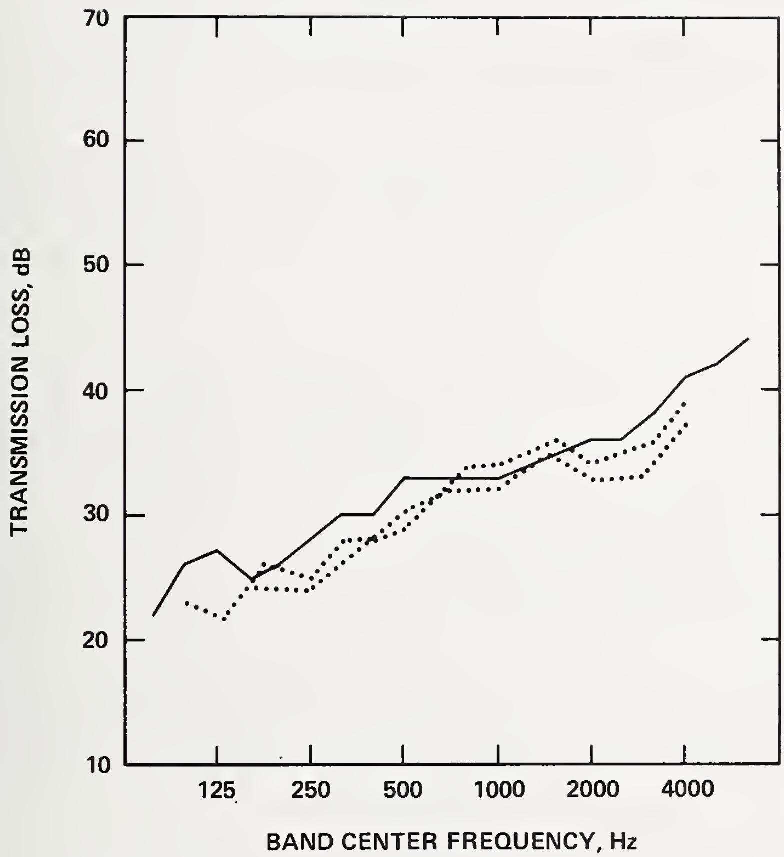


Figure 53. Sound transmission loss vs frequency data for 1/4 in. laminated glass with an internal damping layer. The solid curve represents the data from the present investigation (Test No. W-22-72) while the dotted curves represent the envelope of data from Table A8 of Marsh [63] (the two sets of data are that of Pilkington Bros. and the 1st of Libbey-Owens-Ford).

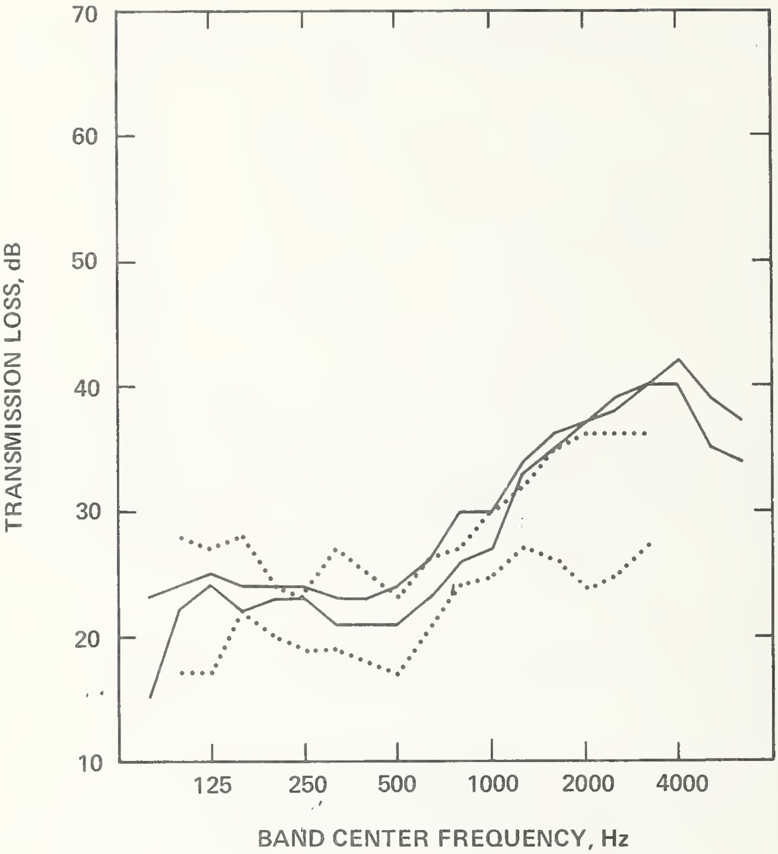


Figure 54. Sound transmission loss vs frequency data for 7/16 in. insulating glass units consisting, nominally, of two 1/8 in. panes of glass separated by a 3/16 in. air space. The solid curves represent the envelope of data obtained in the present investigation (Tests W-31-71 and W-29-72). The dotted curves represent the envelope of data from Table B1 of Marsh [63]. (the sets of data included are the 2nd of Wooley and the two of Saint-Gobain).

The solid curve in Figure 55 represents the data for the single-strength picture window with a double-strength storm sash spaced 3 3/4 in. away. The dotted curves represent the envelope of data for three windows reported by Marsh [63]. All four windows had an STC of 38.

Curve No. 1 in Figure 56 represents the average sound transmission loss for three double-hung windows with storm sashes an average distance of either 2 1/8 or 2 3/4 in. (54 or 70 mm) away. Since the upper and lower window sashes were not the same distance from the storm sash, comparisons with literature data are not very meaningful. Curves 2 and 3 correspond to literature data with spacings of 32 and 75 mm, respectively. Curve 4 corresponds to literature data with a spacing of 51 mm. Curve 5 is for a double-hung window with the upper and lower sashes spaced different distances from the storm sash. These spacings were very similar to those in the present investigation. However, the poor high frequency performance indicates that this window may not have been tightly sealed.

Marsh [63] tabulates data on a large number of double-glazing situations and discusses these data in some detail. DeLange [68] gives data (measured under conditions wherein the sound impinged on the windows from discrete directions) on a variety of constructions and discusses the use of such data. Sharp [31] gives data on a few windows having high sound transmission loss.

3. 5. 4. Cracks and Openings

Data reported by Marsh [63], Bishop and Hirtle [62], and others are in qualitative agreement with the results of the present investigation as regards the influence of cracks and openings on the effective sound transmission loss of doors and windows. These data all indicate that such leaks can seriously reduce the sound isolation at medium to high frequencies. In the absence of quantitative information on the size of such leaks, there is little or no point in quantitative comparisons of sound transmission loss data since different windows or doors of nominally the same construction may differ considerably in the size of cracks and openings. For this reason, further discussion of the effect of normally occurring cracks is deferred until Section 6.1, where correlations are made with the results of air leakage tests. The remainder of the discussion in the present section is limited to those tests where controlled-width cracks were intentionally introduced.

There are many papers in the literature which address the problem of wave propagation through openings in very thin walls. Papers which are directly relevant to sound transmission through finite thickness walls include [69-82]. The work of Gomperts [76,77] and Gomperts and Kihlman [78] is most directly applicable to the tests, in the present investigation, on windows with cracks of known size.

Figure 57 displays the sound transmission loss, computed from equation (69) of Gomperts [76], for slits in the middle of a wall separating two reverberation chambers. The lower figure shows the results for 1/32 in. and 1/4 in. slits in a 2 in. thick wall while the upper figure corresponds to slits of the same widths in a 4 in. thick wall. (The abcissa in this figure represents continuous frequency rather than discrete 1/3-octave frequency bands as used in previous figures). For a given slit, the sound transmission loss increases monotonically with frequency until the wavelength of sound decreases to a value approaching twice the wall thickness. The resonances occur when the frequency is such that the wall thickness is approximately equal to an odd number of half-wavelengths of the sound.

For measurements made in 1/3-octave frequency bands, as was done in the present investigation, the sharp resonances shown in Figure 57 could not be observed. Figure 58 compares the curve (from Figure 57) for a 1/32 in. wide, 2 in. deep slit with the corresponding curve averaged over a 1/3-octave frequency band by numerical integration of Gomperts' equation (69). It is seen that the resonance dips are neither so sharp nor so deep as in the pure tone case.

Gomperts' equation (69) does not include the effects of energy loss due to viscous flow in the slit. As shown in his later paper [77], this will further increase the measured sound transmission loss at frequencies near to the resonances.

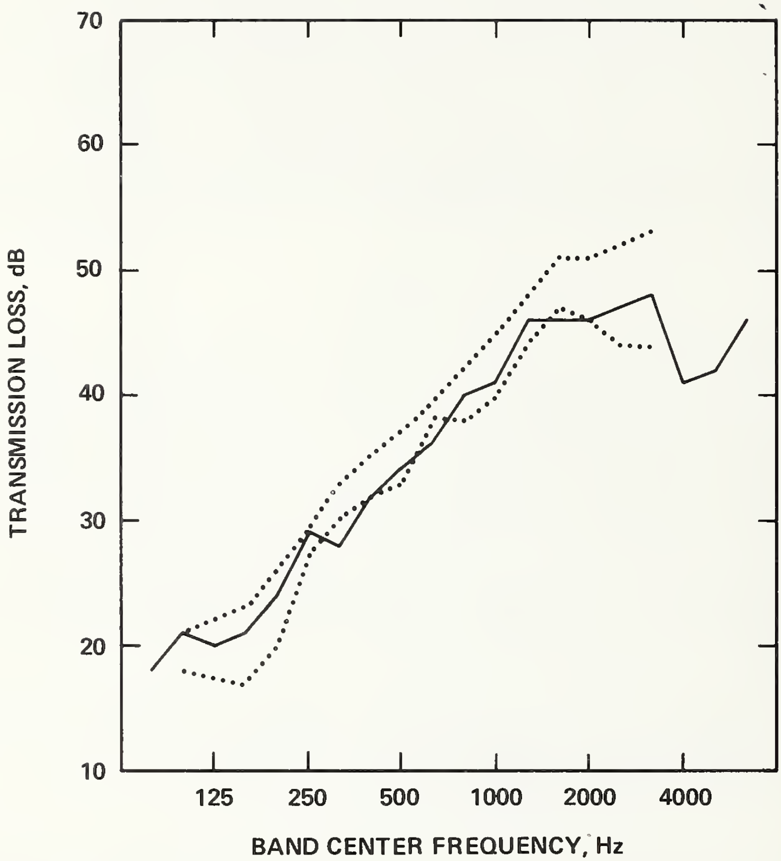


Figure 55. Sound transmission loss vs frequency data for double glazing with a nominal 4 in. separation between the two panes. The solid curve represents a 6 x 5 ft picture window glazed single strength (2.4 mm) with a double strength (3mm) storm window spaced 95 mm (3 3/4 in.) away (Test W-11-71). The dotted curves represent the envelope of data, from Table C2 of Marsh [63], for 3 mm panes separated by 100 to 102 mm (the sets of data are the first listed for each of the following: Aston, Ingemansson, and Woolley).

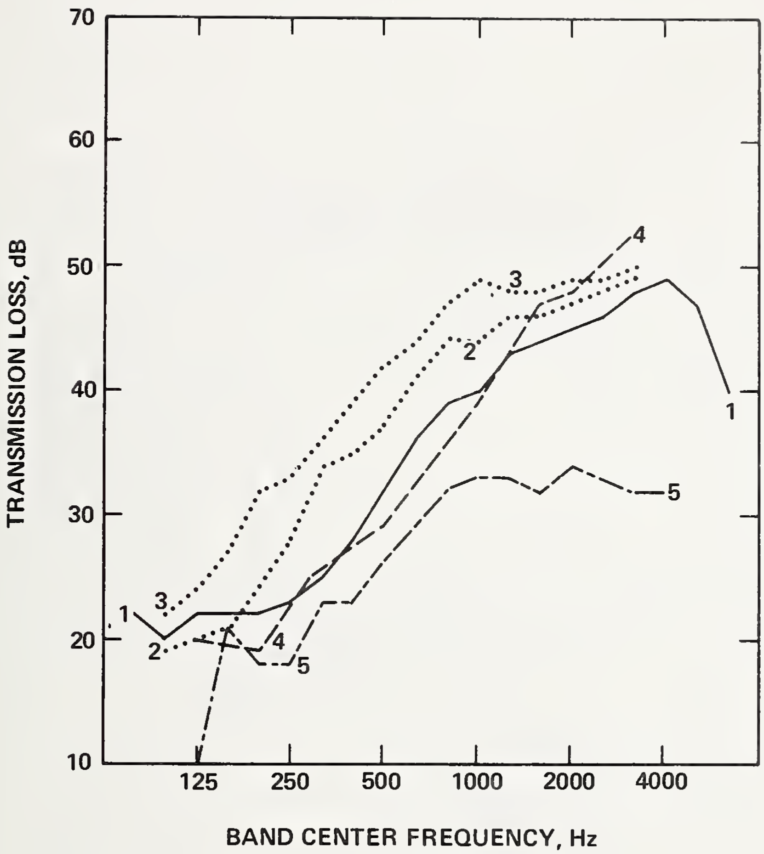


Figure 56. Sound transmission loss vs frequency data for double glazing with an average nominal spacing of about 2 to 3 in. between the two panes.

Curve	Reference	Comments	STC
1	present investigation	average of Tests W-36-71, W-37-71, and W-79-71 (54 or 70 mm air space)	36,34,36
2	[63, Table B2] Fasold	3 mm glazing with 32 mm air space	40
3	[63, Table C1] Fasold	3 mm glazing with 75 mm air space	44
4	[63, Table C1] Aston	3 mm glazing with 51 mm air space	34
5	[62]	Test 15, 3/32 in. glass with 51 mm air space at top, 95 mm air space at bottom	29

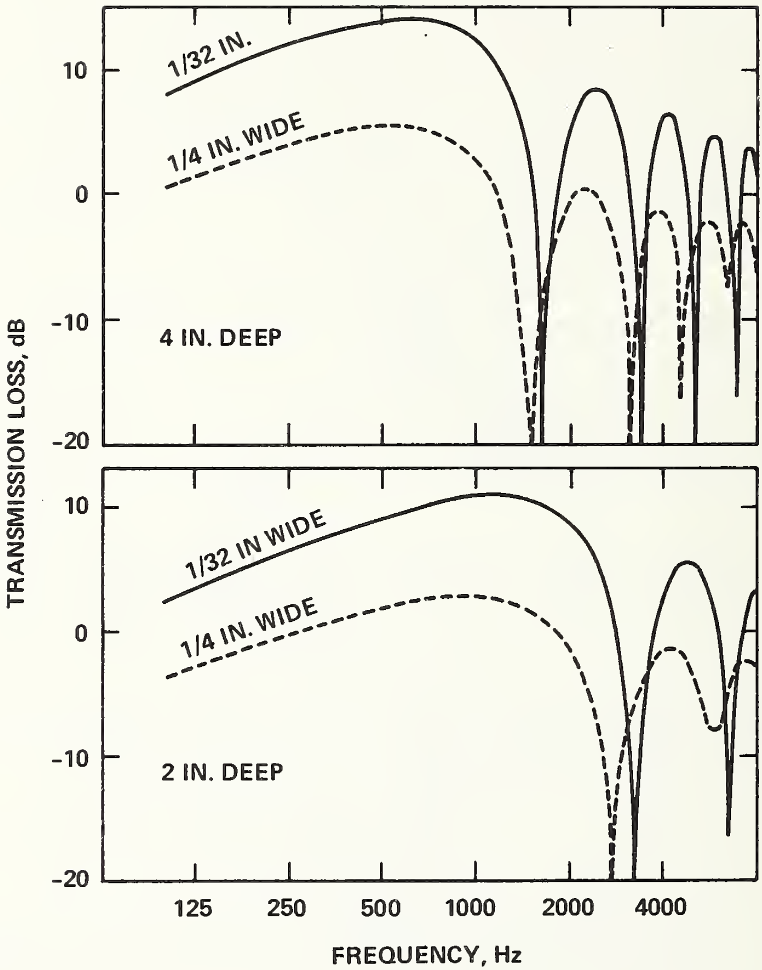


Figure 57. Theoretical sound transmission loss vs frequency data for slits in the middle of a wall between two reverberant rooms, as computed from eq. (69) of Gomperts [76].

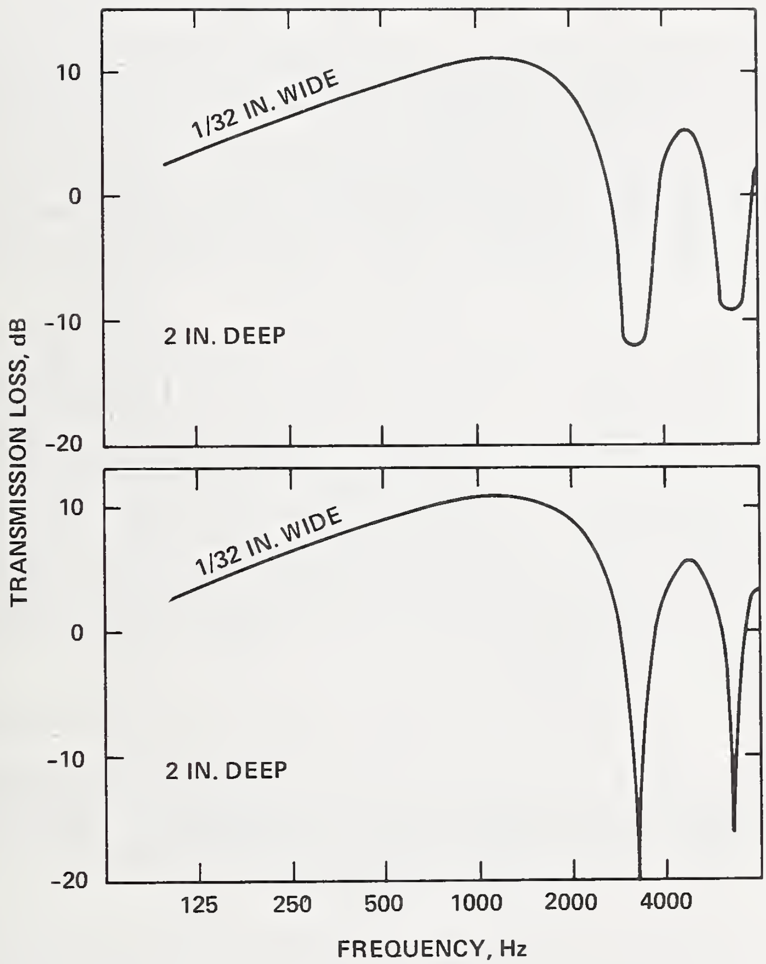


Figure 58. Theoretical sound transmission loss vs frequency data for slits in the middle of a wall between two reverberant rooms. The lower curve represents pure tone behavior while the upper curve corresponds to values averaged over a frequency band that is 1/3 octave in width. The lower curve was computed from eq. (69) of Gomperts [76] while the upper curve was derived by numerical integration of the transmission coefficient corresponding to the lower curve.

Figures 59 through 62 compare the experimental data for the sound transmission loss of cracks of known width around picture windows with the predictions of equation (69) of Gomperts [76]. The experimental data were calculated, using equation (4) of the present report, from two tests -- one with the crack present and one with the window sealed. As shown in Figure 32, for cracks smaller than 1/4 in. in width, the actual crack consisted of two cracks in series -- a 1/4 in. wide crack between the sash and the framing and a 1/8, 1/16, or 1/32 in. crack between strip A and the framing. For calculation of both the data points and the theoretical curves in Figures 59-62, an effective crack width was used, namely, the width of a uniform crack that would contain the same volume of air as the actual crack.

Further reference to Figure 32 indicates that the proper values for the effective depths of the cracks are not obvious. Since it was found empirically that effective crack depths about 25 percent greater than the combined thickness of the sash and of strip A gave theoretical resonance frequencies in good agreement with the experimental data, those were the depths used for the two theoretical curves in Figures 59-62. The dotted curves in these four figures were computed in the same manner as the upper curve in Figure 58; they correspond to the transmission coefficient, averaged over a 1/3-octave band, for a slit in the middle of a wall between two reverberant rooms. Since the window was located in a recess in an otherwise thick wall, the solid curves were also generated; they correspond to a slit at the edge of a wall between two reverberant rooms.

Considering the rather complex geometry of the slit, framing, and filler wall, the agreement between the experimental data and the theoretical curves in Figure 59 is perhaps better than might have been expected. At very low frequencies, the geometry irregularities were small compared to the wavelength of sound so the slit behaved as if it were in the middle of a smooth wall between the two reverberant rooms (corresponding to the dotted curves). As frequency increased, the wavelength decreased so that the recesses on either side became effective in making the slit behave as if it were at the edge of the wall (corresponding to the solid curves). At high frequencies, the irregular geometry leads to much less pronounced resonances that are calculated for a slit in a smooth wall. As the slit width decreases, the experimental data at very low and very high frequencies lie further and further above the theoretical curves. Preliminary analysis indicates that this is at least partially due to energy loss by viscous flow through the narrow slit between strip A and the framing (see Figure 32).

Discussion of other experimental data on leaky windows is deferred until Section 6.1.

In general, openings severely reduce the sound isolation otherwise provided by windows. However, when no other means of ventilation is available, the work of Ford and Kerry [83] and Kerry and Ford [84] is of particular interest since it shows that double glazing with staggered openings can be rather effective even for fairly large openings.

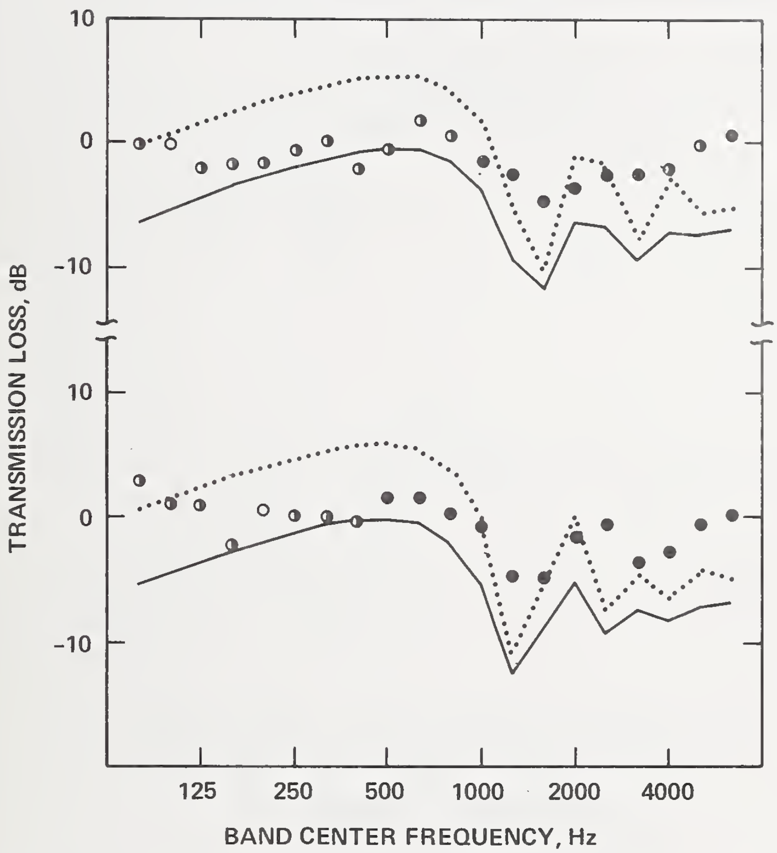


Figure 59. Comparison of experimental results and theoretical predictions for the sound transmission loss of 1/4 in. cracks around picture windows. The data points in the upper portion of the figure are from Test W-16-71 and the average of Tests W-7-71 and W-9-71; those in the lower portion are from Tests W-12-71 and W-10-71. Solid symbols indicate that the transmission loss of the sealed window was at least 9 dB greater than that of the leaky window, while half-filled symbols indicate a 6 to 9 dB difference and open symbols a 3 to 6 dB difference. If the effect of the crack was less than 3 dB for a given frequency band, the data are not plotted. The dotted curves were calculated from equation (69) of Gomperts [76] averaged over a 1/3 octave band, for a slit in the middle of a wall; the solid curves were calculated in a similar manner but correspond to a slit at the edge of a wall between two reverberant rooms. The effective depth of the slit was taken as 4.5 in. for the theoretical calculations in the lower figure and as 4.0 in. for those in the upper figure.

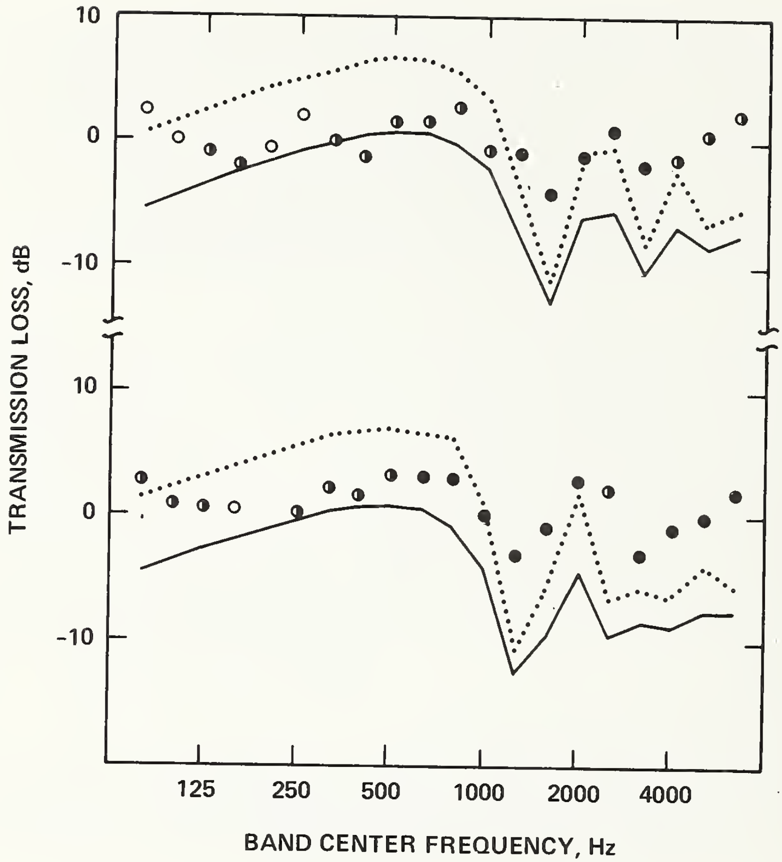


Figure 60. Comparison of experimental results and theoretical predictions for the sound transmission loss of 1/8 in. cracks around picture windows. The data points in the upper portion of the figure are from Test W-15-71 and the average of Tests W-7-71 and W-9-71; those in the lower portion are from Tests W-18-71 and W-10-71. The effective width of the slit was taken as the uniform width which would contain the same mass of air as the actual slit (which consisted of two segments of different widths. (Otherwise, as in Figure 59).

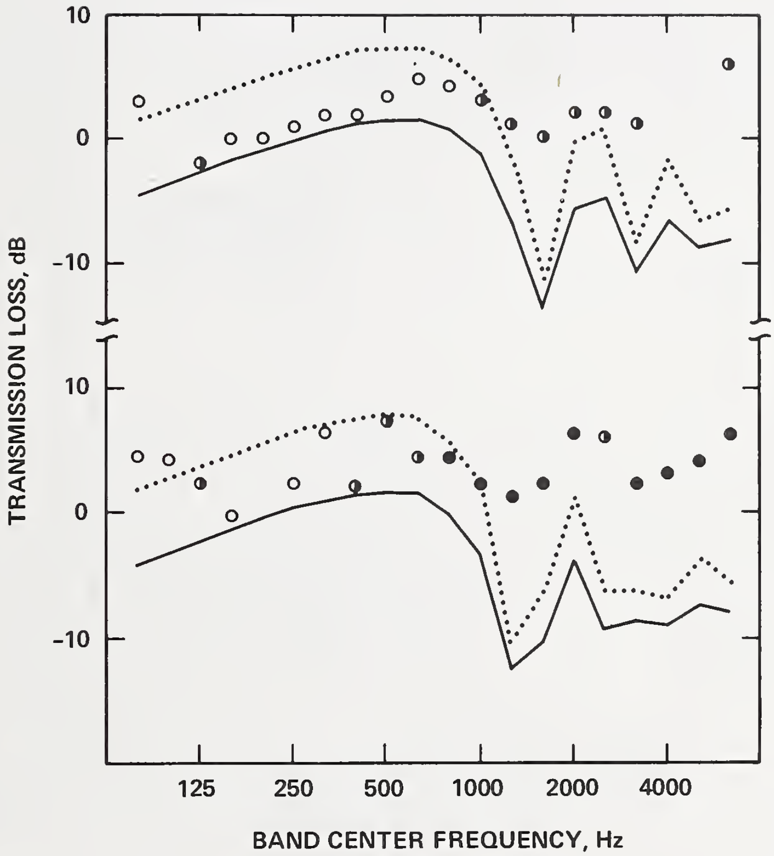


Figure 61. Comparison of experimental results and theoretical predictions for the sound transmission loss of 1/16 in. cracks around picture windows. The data points in the upper portion of the figure are from Test W-17-71 and the average of Tests W-7-71 and W-9-71; those in the lower portion are from Tests W-18-71 and W-10-71 (Otherwise, as in Figure 60).

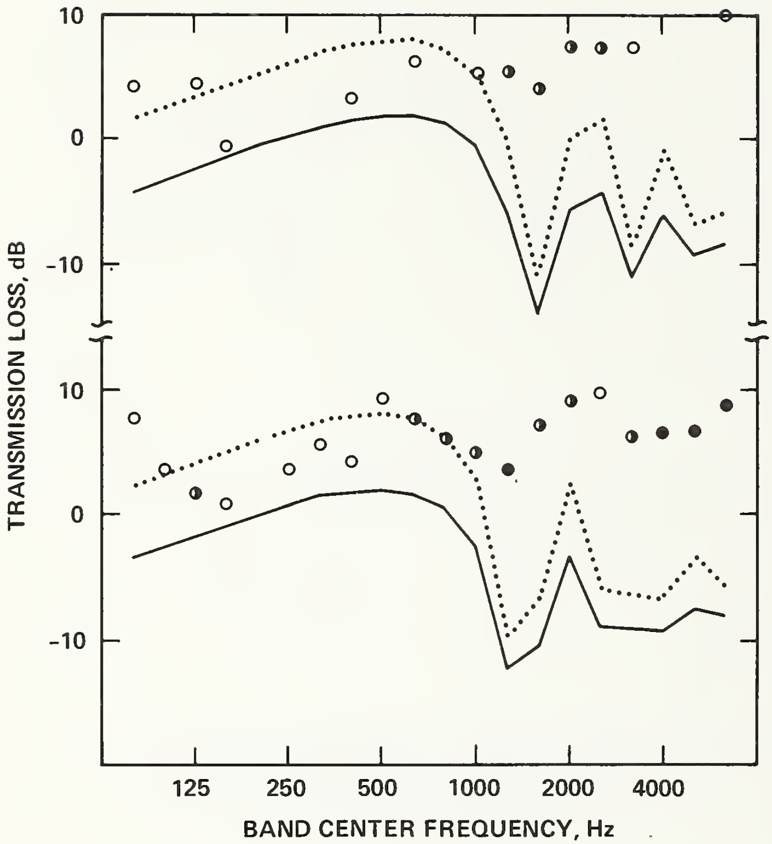


Figure 62. Comparison of experimental results and theoretical predictions for the sound transmission loss of 1/32 in. cracks around picture windows. The data points in the upper portion of the figure are from Test W-21-71 and the average of Tests W-7-71 and W-9-71; those in the lower portion are from Tests W-19-71 and W-10-71. (Otherwise, as in Figure 60).

4. Thermal Transmittance and Resistance Tests

4. 1. Background

In general, architects, engineers, builders and others who might use the data and information in this report have a more thorough background in heat transfer than they do in acoustics. Accordingly, less background information is given here than in the preceding chapter. References are given, however, for those who seek additional material concerning the concepts of thermal insulation of buildings.

The general concepts and procedures for estimating heat transmission through building elements are covered in the ASHRAE Handbook of Fundamentals[85]; additional information is given in the ASHRAE Handbook and Product Directory -- Systems[86]. Other useful references include[87-97]. The National Bureau of Standards has published a number of technical papers and reports[98-112] and consumer-oriented publications[113-114] relative to heat gain or loss from buildings.

The following discussion is intended to briefly define those terms used in this section of the report. For additional definitions, see [115].

The total heat flow through a wall from an air space on one side of the wall to the air space on the other side of the wall is usually computed from

$$Q = SU(T_h - T_c), \tag{9}$$

where S is the total area (ft^2 = sq ft)[9/] of the wall, T_h and T_c are the average air temperatures (°F) on the hot and cold sides, respectively, and U is the <u>thermal transmittance</u> or over-all coefficient of heat transfer (Btu hr^{-1} ft^{-2} $°F^{-1}$ = Btu/(hr sq ft °F). Note that for a non-homogeneous wall, U is an average value (per unit area) for that particular wall. The thermal transmittance can, in principle, be computed from the <u>thermal conductance</u>, C, (Btu/(hr sq ft °F)) or the <u>thermal resistance</u>, R, (Btu^{-1} hr ft^2 °F = hr sq ft °F/Btu))[10/] of the wall and the <u>surface coefficients</u> (f_h, f_c) on either side of the wall:

$$\frac{1}{U} = \frac{1}{C} + \frac{1}{f_h} + \frac{1}{f_c} = R + \frac{1}{f_h} + \frac{1}{f_c}. \tag{10}$$

The total temperature difference between the air spaces on either side of the wall is the sum of three components:

9/ The units given in parenthesis are customary U. S. Engineering units. Metric equivalents are given in Appendix A.

10/ "Terms ending in "-ance" generally designate properties of a particular object and thus may depend not only on its component elements, but also on its size, shape, or surface conditions. Strictly speaking, the terms "conductance", "transmittance," and "resistance" apply to an object having a particular and individual total or whole area of cross section through which the heat flows. However, in general practice and usage, it is convenient to refer to unit area conductance or resistance where the unit area is considered to be representative of the whole area of cross section. "Conductance (or Resistance) per Unit Area" could be used, but in ordinary usage, this is shortened to "Conductance" or "Resistance" with the unit area concept understood." [115].

$$T_h - T_h' = \frac{Q}{S} \cdot \frac{1}{f_h} \tag{11a}$$

$$T_h' - T_c' = \frac{Q}{S} \cdot \frac{1}{C} = \frac{Q}{S} \cdot R \tag{11b}$$

$$T_c' - T_c = \frac{Q}{S} \cdot \frac{1}{f_c}\ , \tag{11c}$$

where T_h' and T_c' are the average temperatures of the hot and cold sides of the wall, respectively. These three equations may be thought of as the defining equations for R, C, f_h, and f_c. As defined above, R is the "surface-to-surface resistance" in that it does not include the resistance of the "air films" on either side of the wall. The "air-to-air resistance", which does include these "films", is simply the reciprocal of the thermal transmittance, U.

When a wall is penetrated by windows, doors, or other parallel heat paths, the effective thermal transmittance of the composite wall is related to the transmittances of the several components by

$$U = \frac{U_1S_1 + U_2S_2 + U_3S_3 + \ldots}{S_1 + S_2 + S_3 + \ldots}\ , \tag{12}$$

where U_1 is the transmittance for the element of area S_1, etc., and the summation is over all areas of the partition.[11/] Equation (12) may be written in terms of resistances as

$$\frac{1}{R} = \frac{S_1/R_1 + S_2/R_2 + S_3/R_3 + \ldots}{S}\ , \tag{13}$$

where $S = S_1 + S_2 + S_3 + \ldots$ is the total wall area corresponding to R. Equations (12) and (13) assume independent parallel heat flow along the several paths and ignore exchanges of heat among the several paths. Furthermore, it is important to note that <u>equations (12 and (13) correspond to heat flow between isothermal surfaces</u>. Since "U-values" typically correspond to heat transfer from one essentially isothermal body of air to another essentially isothermal body of air, equation (12) usually may be used with some confidence. However, <u>caution must be used in applying equation (13)</u>. When a well-insulated wall is penetrated by a door or window whose thermal resistance is much less than that of the wall, the surface-to-surface temperature difference through the penetration can be much less than that through the wall so that use of equation (12) to calculate surface-to-surface resistances can lead to very large errors.

Pressure differences between the inside and outside of a building can result in a flow of air through cracks and openings. The heat flow associated with this air flow is equal to the product of the mass flow rate of air, the specific heat of air, and the temperature difference through which the air must be heated or cooled. In the customary engineering units being used in this report, this heat flow is given by

$$Q_a = 1.08\ \dot{V}\ (T_h - T_c)\ \text{Btu hr}^{-1}, \tag{14}$$

where $\dot{V}$ is the volumetric flow rate at standard conditions (standard $ft^3\ min^{-1}$ = scfm); see Section 6.2 for further discussion. The apparent thermal transmittance of a wall either can be computed from the total heat flow or from the difference between the total heat flow and that associated with the mass flow of air through leaks. Care must be taken to avoid confusion between these alternative approaches.

11/ cf. equation (4).

4. 2. Experimental Procedure

The thermal resistance of walls and other structures may be calculated with some success from values of the thermal conductivity of the component materials as measured according to standard methods [116,117]. However, for non-homogeneous walls, it is preferable to make direct measurements on the construction of interest, using, for example, a guarded hot box [118]. Earlier NBS publications relevant to this type of measurement include [98-100].

ASTM C236-66 (1971) covers the measurement of the thermal transmittance and thermal resistance of non-homogeneous panels representative of such constructions as the walls, roofs, and floors of buildings. The essential principles and the general arrangement are given but the final details of the apparatus and test procedures are the responsibility of the tester so as not to restrict the configuration of the specimen to be tested. The method determines the total flow of heat from the warmer to the cooler side through the test area demarcated by the metering box and may be applied to any construction for which it is possible to build a reasonably representative panel.

Thermal transmission testing was performed using a facility,[12/] previously described by Mumaw [119], which was designed especially for evaluation of heat transmission, air infiltration, and heat transmission in the presence of air infiltration through full-size building wall sections. The equipment was patterned after the ASTM C236 Guarded Hot Box but modified to operate on a calibrated box principle. It was operated within a controlled environment maintained at 75 °F, 50% relative humidity, and consisted of two massively insulated chambers, one controlled at reduced temperatures down to -30 °F and the other normally controlled at room temperature (75 °F) in which metered power consumption was measured. The 9 x 14 ft specimen, constructed on a movable test frame, was positioned and clamped between the two chambers for a test. See Figure 63.

With the specimen in this position, conditioned, temperature-controlled air was circulated past the exposed wall surfaces using small blowers and an air handling system designed to provide even flow across the specimen. The air, circulated in the direction of natural convection, moved at a rate of 40 to 50 ft/min.

The rate of heat flow through the wall is equal to the net energy input to the hot side, after correcting for wall losses of the hot box. Electrical input energy was measured using a precision watt-hour-meter. The heat losses by conduction through the box side walls were determined using a heat meter technique. Subtracting the wall correction from the electrical energy yielded the net heat flow through the test wall. Temperature measurements for the various surfaces were obtained using copper-constantan thermocouples referenced through a constant temperature reference system.

Auxiliary equipment (see Section 5.2) was used to provide a constant air flow (from cold side to hot side) rate through the specimen during some of the thermal tests.

After completion of selected thermal tests, the heated metering side of the thermal test apparatus (normally maintained at 75 °F for testing) was removed, exposing the test wall to the ambient room conditions which were controlled at 75 °F, 50% relative humidity. The test wall was then observed with a Barnes/Bofors Model T-101 (modified by supplier to T-102) real-time infrared camera[13/] to obtain additional information regarding principal heat flow paths.

[12/] The facility was designed and built by Owens-Corning Fiberglas Corporation prior to performance of the contract work described in this publication.

[13/] The equipment used is commercially available. The techniques used, however, were developed by Owens-Corning Fiberglas Corporation prior to performance of the contract work described in this publication.

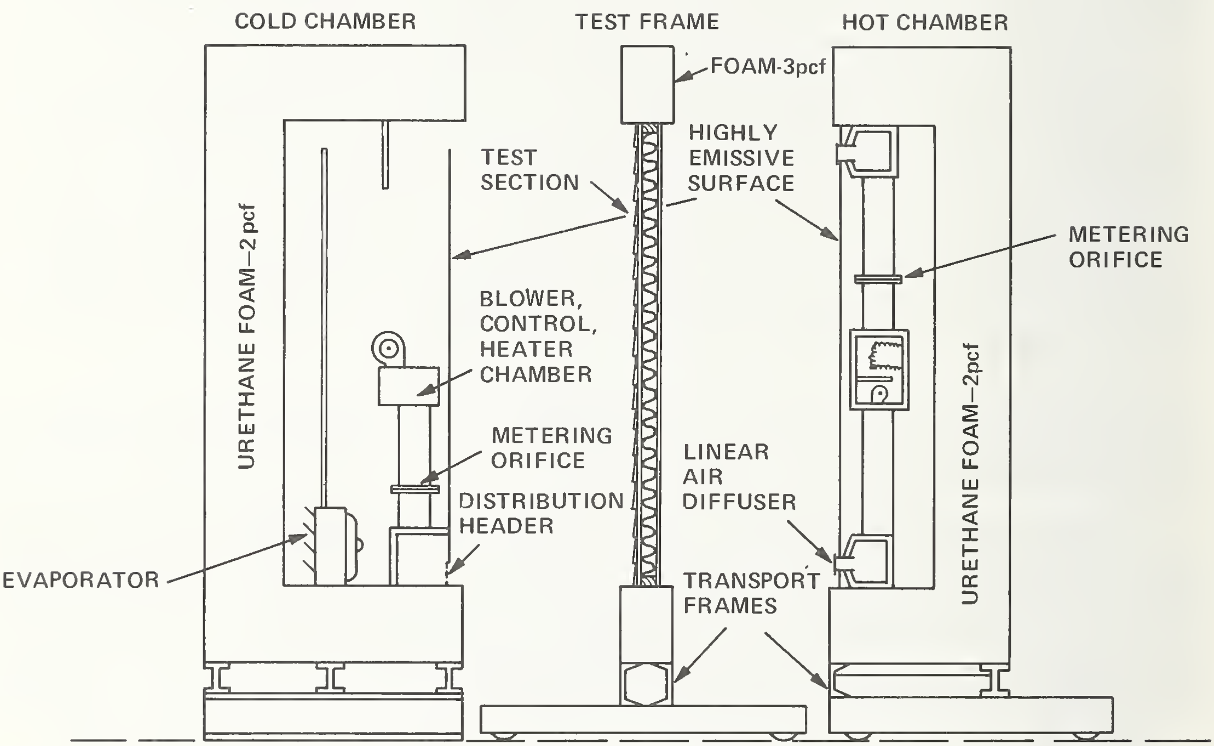


Figure 63. Schematic section of calibrated hot box facility used for thermal tests. Components are described in the text and by Mumaw [119].

The infrared camera normally operates with 12.5° vertical by 25° horizontal field of view. This particular high resolution camera has a scanning rate of two frames per second, with each frame presenting 225 bits of information on each of 160 lines. The data are presented on the cathode ray tube of an oscilloscope as a gray scale picture with higher intensities representing higher temperatures and lower intensities representing lower temperatures. In addition, the camera is equipped with a single line scan option. This permits selecting one scan line and presenting a temperature profile on the y-axis with temperature proportional to pulse height.

To provide more accurate temperature measurement with the single line scan, a comparator is used. It has two 8 x 8 in. by 1/2-in. thick aluminum plates which are painted to match the emittance of the test wall. They are equipped with thermocouples so that their surface temperatures can be measured. The plates are thermoelectrically cooled and controlled to maintain a selectable temperature of approximately 2 °F between them. The comparator can be placed in the field of view of the infrared camera and used as a calibration. The camera is capable of a resolution of approximately 0.2 °F.

4. 3. Calculation Procedures and Uncertainties

The thermal transmittance between the hot box and the cold box and the thermal resistance (surface-to-surface) of the wall were computed using equations (9) and (11b), respectively.

Mumaw [119] has reported on the estimated measurement uncertainties associated with this apparatus. He estimates that the overall uncertainty is typically less than 1 percent. As in the case of sound transmission, additional uncertainties arise in computing the performance of a window or door from data obtained in two tests, one on the composite structure with the penetration in place and one on the basic wall. No estimate has been made of the additional uncertainties that may be introduced due to a large air flow through the test specimen.

4. 4. Results

The thermal transmission tests were limited to wall constructions with the wood siding and brick veneer exterior finishes. The thermal tests included wooden frame windows in two sizes and three of the five doors. The doors and windows were tested only as normally installed without special sealing. In all cases, tests were run both with and without an imposed pressure difference (either 0.25 or 0.50 in. water, corresponding to a wind speed of approximately 20-25 or 30-35 mph, respectively) across the test specimen.

Selected data in condensed form listing nominal test conditions and thermal transmittance values are given in Section 4.4.2 below. Complete test data are given in Table D-1, Appendix D. Section 4.4.1, below gives a very brief summary of the test data along with certain of the more important conclusions.

4. 4. 1. Summary and Conclusions

The summarized test data given below are those obtained only for the specific tests in this program and do not necessarily apply to general types or classes of construction or products.

1. Installation of 3-1/2 in. R11 insulation between the studs of a wood-siding wood-stud exterior wall raised the thermal resistance of the wall by approximately a factor of three.

2. Attaching the interior drywall to resilient channel raised the thermal resistance of the wall by about five percent above that obtained with the drywall attached directly to the studs (cavity insulation in both cases).

3. Installation of a nominal 3 x 7 ft door in a 9 x 14 ft insulated wall decreased the effective (average) air-to-air thermal resistance by 2.1 to 4.4 hr sq ft °F/Btu in the absence of an imposed air flow and by 5.4 to 9.1 hr sq ft °F/Btu with an imposed pressure differential of 0.25 in. water. A normally installed (i.e., leaky) storm door did not provide much improvement.

4. Installation of a window in a 9 x 14 ft insulated wall decreased the effective (average) air-to-air thermal resistance of the combination by the following amounts:

Description of Window	Nominal Window Area, %	Decrease in Effective Air-to-Air Thermal Resistance, hr sq ft °F/Btu	
		without imposed pressure differential	with imposed pressure differential of 0.25 in. water
3 x 5 ft wood double-hung single glazed window, locked	12	5.5	9.2
same window as above, locked, plus single glazed wood storm windows	12	3.9	9.7
3 x 5 ft wood double-hung window, glazed 7/16 in. insulating glass, locked	12	4.4	10.2
6 x 5 ft wood picture window, single glazed, divided light	24	7.5	7.6
6 x 5 ft wood picture window, glazed 1 in. insulating glass, single light	24	5.6	6.6

5. In the presence of an imposed pressure difference corresponding to a 20-25 mph wind speed, heat transfer through walls with normally installed openable doors and windows was due chiefly to air leakage.

4. 4. 2. Discussion

a. Walls

The results of the nine pairs (i.e., with and without imposed air flow) of tests conducted on two basic exterior wall constructions are given in Table 1. Seven of the test pairs correspond to wood siding walls with differences in sheathing, cavity insulation, and use of resilient channel. The other two test pairs were on brick veneer walls with and without cavity insulation. For two of the constructions, the test at 0.0 in. water pressure difference was repeated.

Table 1 includes values for both the air-to-air thermal transmittance and the surface-to-surface thermal resistance. Both quantities correspond to the total heat flow through the wall, i.e., no correction has been made for the heat transferred by the mass flow of air. The thermal transmittance values include the surface film coefficients given in Table D-1 (1.2 to 1.8 Btu/(hr sq ft °F) on the hot side and 1.4 to 3.1 Btu/(hr sq ft °F) on the cold side).

Inspection of Table 1 clearly shows the importance of cavity insulation. In the absence of cavity insulation, the use of 3/4 in. foamed polystyrene sheathing resulted in significantly higher thermal resistance than did the use of 1/2 in. wood fiber sheathing (the improvement would have been proportionately much less if the foamed polystyrene sheathing had been used in combination with cavity insulation). The use of resilient channel on the interior side resulted in a small improvement (this would have been larger for reflective faced insulation). Brick veneer increased the thermal resistance slightly in the absence of an imposed air pressure difference across the wall but did not lead to as good performance as wood siding when an air pressure difference was present (note, in Appendix D, the difference in air leakage).

Table 1. Thermal transmittance and thermal resistance of various 2 x 4 in. wood stud walls with 1/2 in. gypsum board on the interior surface. The nominal mean temperature was 27.5 °F. 75 °F hotside, -20 °F cold side.

Description of Exterior Surface	Description of Cavity Insulation	Test No.	Pressure Differential	Effective* Thermal Transmittance (air-to-air)	Effective* Thermal Resistance (surface to-surface)
			in. water	$Btu\,hr^{-1}\,ft^{-2}\,{}^{o}F^{-1}$	$Btu^{-1}\,hr\,ft^{2}\,{}^{o}F$
Redwood siding over 1/2 inch wood fiber sheathing	None	TT-001-71	0.	0.195	3.75
		TT-018-71	0.	0.194	3.77
		TT-019-71	0.50	0.196	3.76
Same as above	Alfol Type 2B inset stapled	TT-014-71	0.	0.125	6.58
		TT-015-7	0.50	0.126	6.49
Same as above	Premium Brand 3 in. Paper Enclosed Rock Wool Bldg. Insul.	TT-030-72	0.	0.091	9.62
		TT-031-72	0.25	0.093	9.43
Same as above	3 1/2 in. Fiberglas Friction Fit Bldg Insul. polyethylene vapor barrier	TT-002-71	0.	0.076	11.76
		TT-022-71	0.	0.078	11.49
		TT-023-71	0.50	0.080	11.11
Same as above	3 1/2 in. Fiberglas Kraft Faced Bldg. Insul.	TT-038-72	0.	0.074	12.05
		TT-039-72	0.25	0.076	11.90
Same as above	3 1/2 in. Fiberglas Kraft Faced Bldg. Insul. Gypsum Board mounted on DG-8 resilient channel	TT-042-72	0.	0.073	12.66
		TT-043-72	0.25	0.074	12.20
Redwood siding over 3/4 in. Styrofoam TG sheathing	None	TT-036-72	0.	0.124	6.62
		TT-037-72	0.25	0.131	6.25
Four-inch brick veneer over 1/2 in. wood fiber sheathing	None	TT-065-72	0.	0.153	5.10
		TT-066-72	0.25	0.160	4.88
Same	3 1/2 in. Fiberglas Friction Fit Bldg. Insul., polyethylene vapor barrier	TT-069-72	0.	0.075	11.90
		TT-070-72	0.25	0.085	10.53

* Effective thermal transmittance and resistance are the values calculated from measured heat flow. In pressure tests, this value includes energy consumed in heating the leakage air from cold side to warm side temperature. See Table D-1 for complete data including air leakage.

The wood siding wall with Fiberglas 3-1/2 in. R11 Friction Fit Building Insulation was tested at three mean temperatures; the results are plotted in Figure 64. In the absence of an imposed air pressure differential across the wall, the thermal resistance, which is controlled by the resistance of the cavity insulation, decreases smoothly with increasing temperature as would be expected. With an air pressure differential of 0.5 in. water, the thermal resistance dropped much faster with temperature. Inspection of the detailed data in Table D-1, Appendix D, reveals that this decrease in thermal resistance is primarily due to increased air leakage at higher mean temperatures, probably due to warping of the wall.

Figure 65 shows an infrared thermograph of the inside surface of a wood siding wall with cavity insulation. In these thermographs, light areas are warmer than dark areas. The comparator plates described at the end of Section 4.2 can be seen in the lower center of the figure. The superimposed graph of temperature corresponds to the scan position indicated by the white bar across the entire lower portion of the figure. The irregular dark vertical bars correspond to cold regions caused by heat flow through the studs.

b. Doors

The results of the tests on three doors and on a door plus storm door are given in Table 2. In all cases, the wall in which the door was installed was a 2 x 4 in. stud wall with 1/2 in. gypsum board on the interior surface, 10 in. wide redwood lap siding over 1/2 in. thick wood fiber sheathing on the exterior surface, and Fiberglas 3-1/2 in. Friction Fit Building Insulation and polyethylene vapor barrier in the cavity.

The next-to-last column in Table 2 gives the effective thermal transmittance of the wall/door combination -- i.e., computed from the total heat flow, including that associated with air leakage. The last column gives the effective thermal transmittance of the door, computed using equation (12) rearranged as follows

$$U_p = \frac{US - U_w S_w}{S_p} , \qquad (15)$$

where S and U correspond to the combination wall plus door, S_w and U_w correspond to the basic wall construction and S_p and U_p correspond to the penetration (door) above. The thermal transmittance of the basic wall construction was assumed to be 0.077 Btu/(hr sq ft °F) at 0.0 in. water (average of Tests TT-002-71 and TT-022-71) and 0.079 Btu/(hr sq ft °F) at 0.25 in. water (interpolation between Test TT-023-71 and TT-022-71). The area of each door was taken as 20.0 sq ft (this corresponds to the door only, not the door plus frame).

Looking at the effective thermal transmittance (i.e., including effects of air leakage) of the doors only, it is seen that in the absence of an imposed air pressure difference, the addition of a storm door to a solid wood flush door decreases the thermal transmittance by about thirty percent. The doors with urethane foam cores have about one-half the thermal transmittance of the solid wood door. With an air pressure differential of 0.25 in. water, the FRP door with a foam core was much better than the other doors, in large part due to the smaller air leakage.

c. Windows

The results of the tests on windows are given in Table 3. The wall in which the windows were installed was of the same construction as that in which the doors were installed. The thermal transmittance of the windows was computed using equation (15) and the same values for the thermal transmittance of the basic wall construction as were used in the calculations for doors. The sash area of the windows was used in computing their effective thermal resistance -- 12.7 sq ft for the nominal 3 x 5 ft windows and 25.6 sq ft for the nominal 6 x 5 ft windows.

There were no large differences between the performance of locked and unlocked windows. In the absence of an imposed air pressure difference, the addition of a storm sash or the use of insulating glass offered about the same improvement over conventional single glazing. The imposed air pressure drastically increased the effective thermal transmittance of the openable windows.

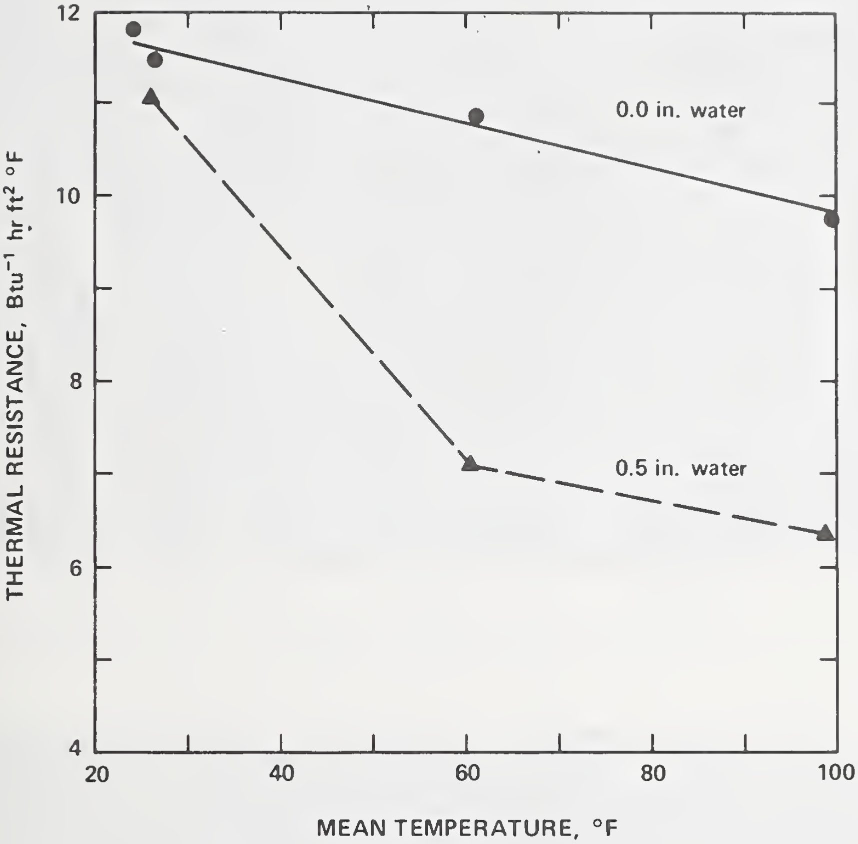


Figure 64. Thermal resistance vs mean temperature data for a 2 x 4 in. stud wall with 1/2 in. gypsum board on the interior surface, redwood lap siding over 1/2 in. wood fiber sheathing on the exterior surface, and 3 1/2 in. Fiberglas Friction Fit Building Insulation plus a polyethylene vapor barrier in the cavity.

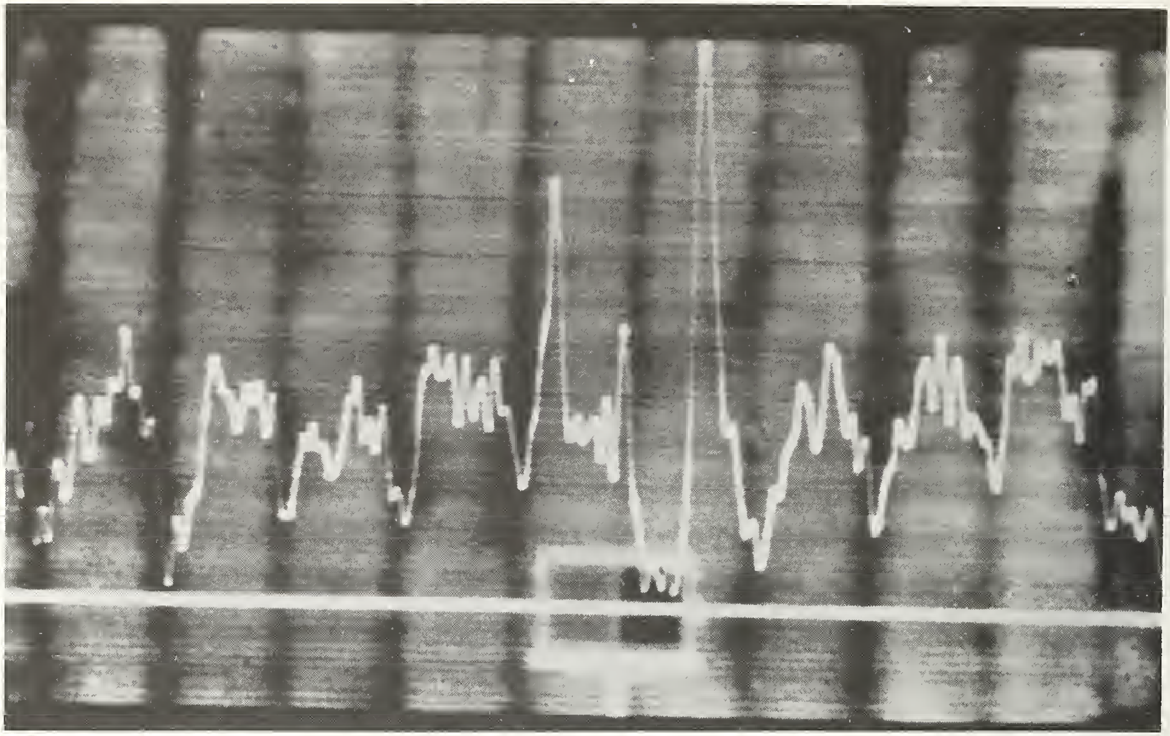


Figure 65. Infrared thermograph of warm side of wall insulated with 3 1/2 in. Fiberglas Friction Fit Insulation. Comparator temperature difference: 2.1 °F.

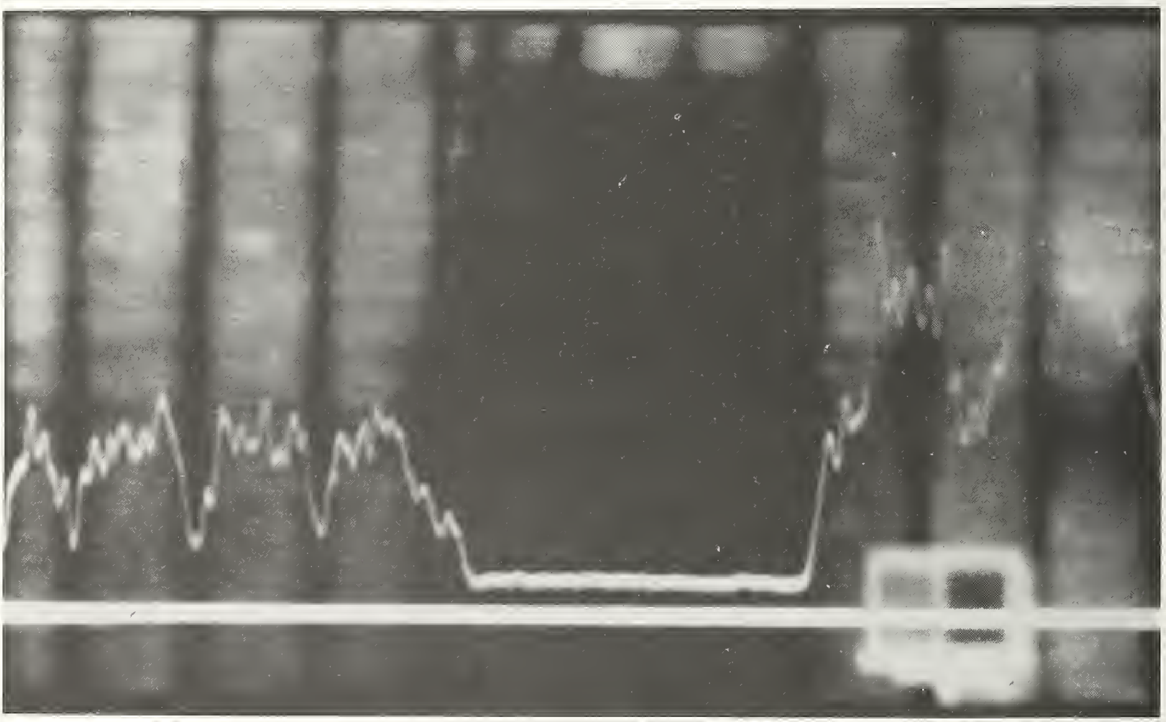


Figure 66. Infrared thermograph of warm side of wall insulated with 3 1/2 in. Fiberglas Friction Fit Insulation, penetrated by a double-hung wood window, 3 x 5 ft, single-glazed, locked. Comparator temperature difference: 2.0 °F.

Table 2. Thermal transmittance of doors and wall/door combinations. The wall was a 2 x 4 in. stud wall with 1/2 in. gypsum board on the interior surface, redwood siding over 1/2 in. wood fiber sheathing on the exterior surface, and Fiberglas 3 1/2 in. Friction Fit Building Insulation and polyethylene vapor barrier in the cavity. The doors were not sealed. All doors were 1 3/4 in. thick, 3 ft wide, and 6 ft, 8 in. high. The nominal mean temperature was 27.5 °F.

Description of Door	Test No.	Pressure Differential	Effective* Thermal Transmittance (air-to-air) Wall/Door Combination	Door Only
		in. water	Btu hr^{-1} ft^{-2} $°F^{-1}$	Btu hr^{-1} ft^{-2} $°F^{-1}$
Solid wood flush door, brass weatherstrip	TT-049-72	0.	0.117	0.33
	TT-050-72	0.25	0.279	1.33
Same as above plus aluminum storm door	TT-055-72	0.	0.100	0.22
	TT-056-72	0.25	0.236	1.06
Steel flush door with urethane foam core, magnetic gasket	TT-059-72	0.	0.092	0.17
	TT-060-72	0.25	0.202	0.85
Fiberglas Reinforced Plastic panel door with urethane foam core, plastic extended weatherstrip	TT-063-72	0.	0.093	.18
	TT-064-72	0.25	0.138	.45

*Effective thermal transmittance is the value calculated from measured heat flow. In pressure tests, this value includes energy consumed in heating the leakage air from cold side to warm side temperature. See Table D-1 for complete data including air leakage.

Note: Care should be taken in using these experimentally-determined values for design purposes since the film coefficients were significantly different than for most tabulated design data.

Table 3. Thermal transmittance of windows and wall/window combinations. The wall was a 2 x 4 in. stud wall with 1/2 in. gypsum board on the interior surface, redwood siding over 1/2 in. wood fiber sheathing on the exterior surface, and Fiberglas 3 1/2 in. Friction Fit Building Insulation and polyethylene vapor barrier in the cavity. The windows were not sealed. The nominal mean temperature was 27.5 °F.

Window Description	Test No.	Pressure Differential	Effective* Thermal Transmittance (air-to-air)	
			Wall/Window Combination	Window Only
		in. water	Btu hr^{-1} ft^{-2} $°F^{-1}$	Btu hr^{-1} ft^{-2} $°F^{-1}$
3 x 5 ft wood double-hung single glazed window, locked	TT-020-71 TT-021-71	0. 0.25	0.133 0.293	0.64 2.22
Same as above, but unlocked	TT-024-71 TT-025-71	0. 0.25	0.136 0.340	0.67 2.69
Same window as above, locked, plus single glazed wood storm window	TT-026-72 TT-027-72	0. 0.25	0.110 0.343	0.41 2.72
Same as above, but unlocked	TT-028-72 TT-029-72	0. 0.25	0.114 0.401	0.45 3.30
3 x 5 ft wood double-hung window, glazed 7/16 in. insulating glass, locked	TT-032-72 TT-033-72	0. 0.25	0.116 0.405	0.45 3.34
Same as above, but unlocked	TT-034-72 TT-035-72	0. 0.25	0.117 0.501	0.48 4.30
6 x 5 ft wood picture window, single glazed, divided light	TT-040-72 TT-046-72	0. 0.25	0.183 0.198	0.61 0.67
6 x 5 ft wood picture window, glazed 1 in. insulating glass, single light	TT-044-72 TT-045-72	0. 0.25	0.135 0.165	0.37 0.51

* Effective thermal transmittance is the value calculated from measured heat flow. In pressure tests, this value includes energy consumed in hearing the leakage air from cold side to warm side temperature. See Table D-1 for complete data including air leakage.

<u>Note:</u> Care should be taken in using these experimentally-determined values for design purposes since the film coefficients were significantly different than for most tabulated design data.

Figure 66 shows an infrared thermograph of the inside surface of a wood siding wall penetrated by a single-glazed 3 x 5 ft double-hung window.

4. 5. Comparison of Results with Those of Other Investigations

Rather than attempt to compare the above data with literature data, as was done in the case of sound transmission loss, selected data will be compared with values calculated using the tables and procedures in the 1972 ASHRAE Handbook of Fundamentals [85]. These design heat transfer coefficients and procedures represent a consensus of many experts and thus implicitly include carefully evaluated experimental data, both published and unpublished. For the walls without penetrations, the comparison will be done on the basis of surface-to-surface thermal resistance. For doors and windows, the comparison will be done on the basis of air-to-air thermal transmittance with an adjustment for surface film coefficients.

4. 5. 1. Walls

The ASHRAE calculation procedure involves adding up the series thermal resistances along two parallel heat flow paths (through the studs and through the cavity) and then combining these parallel resistances using equation (13).

For the uninsulated stud wall, this calculation proceeds as follows:

Path through Stud		Path through Cavity	
Material	Thermal Resistance	Material	Thermal Resistance
	Btu^{-1} hr ft^2 °F		Btu^{-1} hr ft^2 °F
1/2 in. gypsum board	0.45	1/2 in. gypsum board	0.45
2 x 4 in. stud	4.35	3 1/2 in. air space	1.0 (approx.)
1/2 in. sheathing	1.32	1/2 in. sheathing	1.32
5/8 in. wood siding	0.93	5/8 in. wood siding	0.93
Total	7.05	Total	3.7

Assuming the studs occupy 10 percent of the total wall area, equation (13) yields

$$\frac{1}{R} = \frac{S_1}{S} \cdot \frac{1}{R_1} + \frac{S_2}{S} \cdot \frac{1}{R_2} = \frac{0.10}{7.05} + \frac{0.90}{3.7}$$

so that R = 3.9 hr sq ft °F/Btu. The average measured value (see Table 1) was 3.77 hr sq ft °F/Btu The agreement is better than might have been expected since the values for the resistance of the air space [85,99] are not well known for temperature differences as large as were used in the present investigation.

In order to predict the thermal resistance when the cavity is filled with "R-11 insulation", the thermal resistance of the air space is replaced with a value of 11.0 hr sq ft °F/Btu and the above calculation repeated, yielding an overall thermal resistance of 12.5 hr sq ft °F/Btu which is in good agreement with the range of values (11.46 - 11.94 hr sq ft °F/Btu) measured for 3-1/2 in. Fiberglas insulation in the absence of an imposed air pressure difference. (Still better agreement was obtained when measured values [116,117] were used for the thermal resistance of the cavity insulation.)

4. 5. 2. Doors

Table 9 in Chapter 20 of the ASHRAE Handbook of Fundamentals [85] tabulates overall air-to-air thermal transmittances for several kinds of doors. These design values correspond to "still air" inside but a 15 mph wind outside while the experimental values in the present investigation had slowly moving air on both sides. Accordingly, for comparison, the data from Table 2 have been adjusted[14/] to correspond to the ASHRAE conditions. Table 4 shows the comparison. It is seen that the agreement is quite good for a wooden door, with and without a storm door. The steel door with a urethane foam core in the present investigation is seen to be much better than the ASHRAE design value.

4. 5. 3. Windows

Table 8 in Chapter 20 of [85] tabulates overall air-to-air thermal transmittances for several kinds of windows. These values are compared with adjusted (see Section 4.5.2) values from the present investigation in Table 5. The agreement is seen to be quite good.

[14/] By using equation (10), subtracting a film resistance corresponding to a still-air film coefficient of 1.46 Btu/(hr sq ft °F) and adding a film resistance corresponding to a surface film coefficient of 6.00 Btu/(hr sq ft °F).

Table 4. Comparison of ASHRAE design values [85] for thermal transmittances of doors with the results of the present investigation (without an imposed air pressure difference).

Description of Door	Effective Thermal Transmittance	
	ASHRAE [85]	Present Investigation [adjusted from Table 2]
	Btu hr^{-1} ft^{-2} $°F^{-1}$	Btu hr^{-1} ft^{-2} $°F^{-1}$
Solid wood, 1 3/4 in.	0.46 [a]	0.40 [b]
Solid wood, 1 3/4 in. plus metal storm door	0.31 [a]	0.25 [b]
Steel, 1 3/4 in. with urethane foam core	0.40	0.19 [b]

[a] Interpolated

[b] Adjusted (see text) to an outdoor surface film coefficient of 6.00 Btu hr^{-1} ft^{-2} $°F^{-1}$.

Table 5. Comparison of ASHRAE design values [85] for thermal transmittance of windows with results of present investigation (for locked windows without an imposed air pressure difference). The designation "80% glass" or "100% glass" corresponds to ASHRAE adjustments based on portion of sash area which is glazed.

Description of Window	Effective Thermal Transmittance	
	ASHRAE [89]	Present Investigation [adjusted from Table 3]
	$Btu\ hr^{-1}\ ft^{-2}\ {}^{o}F^{-1}$	$Btu\ hr^{-1}\ ft^{-2}\ {}^{o}F^{-1}$
Single glazing, 80% glass	1.02 1.02	0.96 [a,b] 0.89 [a,c]
7/16 in. insulating glazing, 80% glass	0.66	0.62 [a]
1 in. insulating glazing, 100% glass	0.56	0.46[a]
Single glazing plus wood storm window, 80% glass	0.50	0.52[a]

[a] Adjusted (see text) to an outdoor surface film coefficient of 6.00 $Btu\ hr^{-1}\ ft^{-2}\ {}^{o}F^{-1}$.

[b] 3 x 5 ft double-hung window

[c] 6 x 5 ft picture window

5. Air Leakage Tests

5. 1. Background

Air leakage into (infiltration) and out of (exfiltration) buildings is of concern because it increases the cost of winter heating and summer cooling, creates drafts, and makes difficult the maintainance of a controlled relative humidity. Condensation within walls and between panes of double windows, resulting from exfiltration during cold weather, can damage the building. Air leakage also determines the entrance and exit of smoke and odors and is important with respect to rain leakage and dust penetration. The sound insulation provided by exterior walls is greatly influenced by the existence of paths large enough to allow significant air leakage.

Chapter 19 of the ASHRAE Handbook of Fundamentals [85] discusses air infiltration and gives numerous references to the literature. Other references of interest include [103, 120-124].

Air infiltration and exfiltration result from air pressure differences between the inside and outside of a building. Such pressure differences result from air flow around and over buildings and from air density differences caused by temperature differences between the inside and outside air. For air at standard density, the stagnation pressure is related to wind speed by

$$p_v = 0.000482\ v^2, \qquad (16)$$

where v is the wind velocity and p_v is the stagnation pressure, or velocity head (in. water). Values of the stagnation pressure for winds from 5 to 25 mph are given below:

Wind Speed	Stagnation Pressure
mph	in. water
5	0.012
10	0.048
15	0.104
20	0.193
25	0.301

According to [85], pressure may vary from +0.5 p_v to +0.9 p_v on the windward side and from -0.3 p_v to -0.6 p_v on the leeward side for simple square or rectangular buildings, depending on the angle of the wind. Pressures on the other sides, parallel to, or at slight angles to the wind direction, may range from -0.1 p_v to -0.9 p_v.

The "stack effect", or air flow due to indoor-to-outdoor temperature differences, can be very important in tall buildings but, compared to wind effects, is of little consequence for air flow through walls and windows in residences which are only a few stories high.

The air leakage due to a given pressure difference may be expressed as

$$\dot{V} = C(\Delta p)^n, \qquad (17)$$

where V is the volumetric flow rate (e.g., cfm), C is a proportionality constant, Δp is the indoor-to-outdoor pressure difference and n is an exponent between 1/2 and 1. In the United States and Canada, air leakage characteristics of windows are usually expressed as flow rate per foot of sash crack.

5. 2. Experimental Procedure

ASTM E283-73, Standard Method of Test for Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors [125], covers the determination of the resistance of exterior windows, curtain walls, and doors to air infiltration resulting from air pressure differences. This test is applicable to any curtain wall area, or to windows or doors alone, and consists of sealing a test specimen into or against one face of an air chamber, supplying air to or exhausting air from the chamber at the rate required to maintain the specified test pressure difference across the apecimen, and measuring the resultant air flow through the specimen.

The following describes the procedure used in carrying out air leakage tests in the sound transmission facility. An essentially similar setup was used in the thermal test facility.

The facility for air infiltration measurement is patterned after ASTM E-283. The pressurized airtight chamber specified in the Method consisted of the entire source room used normally for sound transmission tests as described in Section 3.2. This room is normally well sealed for sound leakage and was made more airtight by caulking and taping all openings and installing new gasketing on the double doors.

Air was fed into the test chamber as illustrated in Figure 67. A Dayton 2-C- 820, 9 in. wheel blower, with a rated delivery at 3450 rpm of 160 cfm at 5 in. water static pressure, driven by a Dayton 6-K-011.1/2 HP variable speed motor with speed continuously variable from 500 to 5000 rpm was used. Air flow into the room was measured by a calibrated orifice plate and a pair of flanges with pressure taps, manufactured by Foxboro Company. The pressure difference across the orifice plate was measured by a Dwyer Model 424-10 inclined manometer, having a slant range of 0-2 in. water gauge in a scale length of 20 in., plus a vertical range of 2.1 to 10 in. The air flow metering section was based on standard 3 in. pipe (3.068 in. ID) and was designed strictly as specified in [126].

The air was delivered to the room through a 3 in. elbow which was imbedded in the concrete wall during building construction. This elbow was connected to the metering section by the intermediate pipe connections and duct work. The interior side of the elbow was fitted with a threaded plug which could be used to test for any leakage between the metering section and the room. For air delivery, the plug was removed.

Static pressure in the room was measured with a Dwyer Model 200.5 slant manometer having a range of 0-1 in. and a scale length of 8 in. The manometer was connected to the room interior through a small pipe opening previously existing in the concrete wall. This opening was about 30 in. away from the air delivery point.

In conducting a test, the fan speed was set to pressurize the room over a range of 0.1 to 0.7 in. water above atmospheric pressure in steps of approximately 0.1 in. water. Points of air flow in cfm versus pressure were plotted and a smooth curve drawn through the points. The intersections of this curve with the exact pressure points of 0.1, 0.3 and 0.7 in. water were then tabulated and presented as the final data.

In the course of the program, three different wall constructions surrounded the test specimen; namely, the gypsum board filler wall used for the early tests and later two separate constructions of the wood siding exterior wall. In all cases, the walls were thoroughly sealed with two coats of shellac or paint. When windows of various sizes were tested in a given wall, an opening was cut for the largest, and the excess area for the smaller units was filled in with gypsum board which was shellacked. Care was taken to seal the joints at all surface discontinuities as thoroughly as possible. Measurements of residual leakage for the entire room, over the pressure range from 0.1 to 0.7 in. water for the three unbroken walls showed the following:

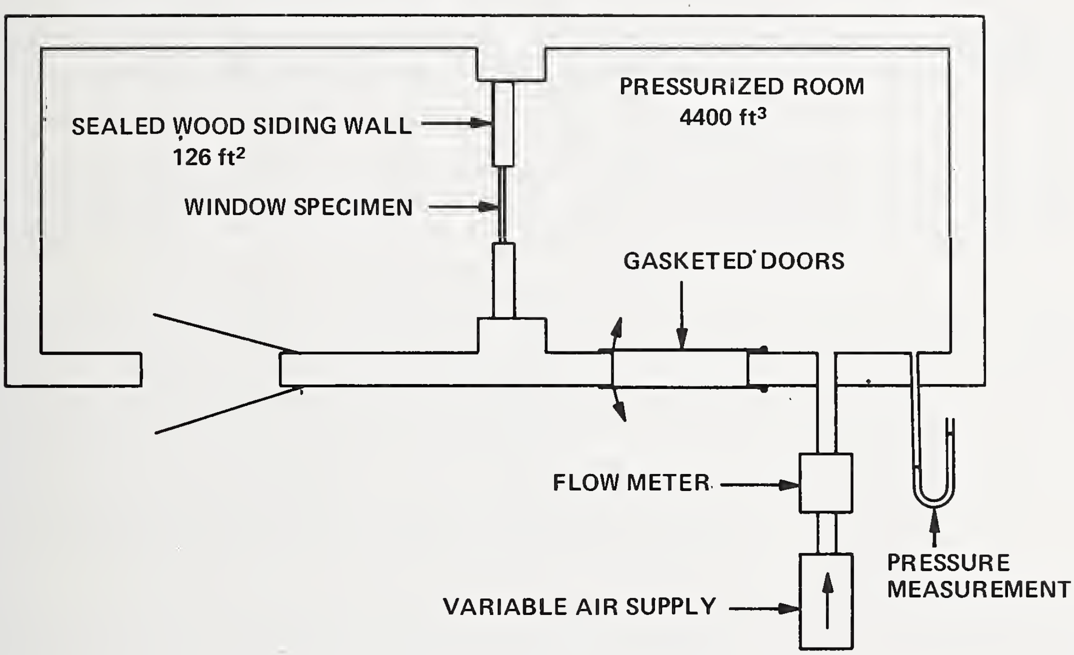


Figure 67. Experimental setup for measuring air filtration of doors and windows in the sound transmission facility.

Wall	Air Flow $ft^3\ min^{-1}$		
	0.1 in. water	0.3 in. water	0.7 in. water
Gypsum board, shellacked and painted	2.4	4.7	7.9
Wood siding wall No. 1, painted	2.4	5.1	9.0
Wood siding wall No. 2, painted	2.1	3.4	5.3

For each test of a window, interpolated values of residual leakage were subtracted from the overall measured air flow, it being assumed that the residual leakage was not changed by the use of gypsum board filler areas or by any of the resulting joints.

5. 3. Calculation Procedures and Uncertainties

Air flow rates were determined from the calibration of the orifice plate (see below); pressure differences across the orifice plate and between the source and receive rooms were read directly from the manometers. Thus no special calculation procedures were required.

The Foxboro orifice plate was supplied with a calculated calibration point of 50 cfm at standard conditions[15/] at a pressure drop of 2.0 in. water. A calibration curve was drawn from this point with a logarithmic slope (cfm versus in. water) of 0.5. This curve was then compared with readings of a Meriam Laminar Flow Element, Model 50MW20, which was placed upstream of the orifice plate, having a nominal range of 20 cfm at standard conditions. These readings agreed with the Foxboro calibration curve within plus or minus 2 percent between 7 and 20 cfm. Below this range, the logarithmic slope of the orifice curve became nonlinear, and the Meriam readings were used to extend the calibration curve down to 2 cfm. Above 20 cfm, the calibration curve of the orifice plate was used as supplied. The accuracy of the overall calibration curve of cfm at standard conditions versus pressure drop across the orifice plate was taken as plus or minus 2 percent.

The laboratory environment during the test program was maintained at 74 ± 2 °F and 50 ± 5 percent relative humidity. At standard barometric pressure (29.92 in. Hg), these conditions, if not corrected to standard conditions, correspond to an error of -0.7 percent in air flow measurement. Extremes of barometric pressure from 29.0 to 31.0 in. Hg superimposed on the above change would cause a total error of from -2.2 to +1.2 percent. In view of considerably larger uncertainties in the test measurements, no corrections were made in the actual tests from room air to standard air.

Inaccuracies in the test procedure arose from several causes and were observed chiefly at low flow rates and low pressure drops across the specimen. Contributing causes were:

(1) Fluctuation of pressure difference across the specimen due to gusts of wind outdoors, causing poor readability of both air flow and room pressure.

(2) Uncertainties in the exact value of residual air flow. At low overall flows not much larger than the net flow being measured, the net flow would be subject to considerable error due to an unknown change in the residual leakage.

As a rough estimate, the accuracy of the method can be placed at about 0.5 cfm, or 5 percent, whichever is larger. In view of wide variability of test specimens themselves, this accuracy appeared acceptable for the purposes of the program.

[15/] Denotes dry air at standard conditions: pressure -- 29.92 in. Hg.; Temperature -- 69.4 °F; Density -- 0.075 lb/cubic ft.

5. 4. Results

Separate tests for air infiltration[16/] were run in the sound transmission and thermal transmission facilities, respectively. For the former, one of the two rooms comprising the facility was pressurized over a range of 0.1 to 0.7 in. water, and air flow measured at normal room temperatures, 75 °F. These tests were run only on the doors and windows.

Early air infiltration tests in the thermal transmission facility were run at a pressure of 0.5 in. water. They were run at the same hot and cold side temperatures used for heat transmission measurements, 75 °F and -20 °F, except for two tests at higher mean temperatures. Air pressure was lowered to 0.25 in. water when it was discovered that some of the window units required greater volumes of dry air than the equipment could supply. Infiltration tests were run both on unbroken walls and on combinations of a wall with door or window. The doors and windows were normally mounted without special sealing.

Air infiltration data measured in the sound transmission facility are given in Appendix E in the form of tables of air flow versus pressure drop. The air flows at 0.1, 0.3, and 0.7 in. water pressure are listed in Table E-1 for doors and Tables E-2 and E-3 for windows.

Air infiltrations measured in conjunction with thermal transmission at pressures of 0.25 and 0.5 in. water are listed with the thermal data for each test construction in Appendix D.

5. 4. 1. Summary and Conclusions

The following observations relate to data taken in the sound transmission facility:

a. Air flow measured through accurately gauged cracks around a window was found to be closely proportional to crack width and length and to a power of the room pressure ranging from 0.54 to 0.72.

In the following, the single-number ratings for air infiltration through doors and windows tested in the sound transmission facility are given as net air flow in cfm for a room pressure of 0.3 in. water on the exterior side.

b. A 3 x 7 ft wood door unit with spring brass weather strip supplied with the frame, and half-round plastic threshold strip, showed an average of 10 cfm. This was the lowest value obtained for a normally fitting door. A lower value was obtained for a slightly oversize door which made a forcing fit with the frame.

c. A steel-faced door with magnetic weather strip supplied with the frame and three soft plastic threshold wiping strips, tested at 15.4 cfm.

d. Addition of an aluminum storm door with minimal weather stripping lowered the air flow by only about 2.5 cfm.

e. All of the operable windows, including the sliding glass door but not the jalousie window, covered a range of approximately 5 to 25 cfm locked and 5 to 70 cfm unlocked. The jalousie window tested at 83 cfm.

f. Addition of storm sash made only a negligible reduction in air flow for the windows tested.

g. In some cases, locking the window increased the air flow, due to twisting or displacement of the sash.

[16/] Measurements were made only with air flow in the direction corresponding to infiltration as opposed to exfiltration (see [124,125]).

5. 4. 2. Discussion

a. Doors

All of the air infiltration tests on doors were made with the doors normally closed. The tests involved three types of weather strip and two threshold seals. The data for pressure differences of 0.1, 0.3, and 0.7 in. water are given in Table E-1 in Appendix E.

For three wood doors in the same frame and against the same spring brass weather strip and half-round plastic threshold seal, the air flow at 0.3 in. water ranged from 8.9 to 11.4 cfm. This amounted to a test for repeatability of interchanged doors and normal closings.

Replacing the brass weather strip with the extruded plastic strip in the same frame and with the same wood door raised the air flow to 19.8 cfm. The plastic strip, however, could not be installed exactly in accordance with its design, and this may account for the higher air flow. On the other hand, replacing the wood door with an FRP panel door in the same frame and against the plastic weather strip lowered the air flow to 4.0 cfm. As noted in Table E-1, the FRP door was somewhat oversize and made a very tight fit against the weather strip.

The steel door in its own frame with magnetic weather strip and soft plastic fingers closing the threshold showed somewhat higher air flow (15.4 cfm) than the wood door in its own frame with brass weather strip and half-round threshold seal.

The addition of the aluminum storm door to the wood door with plastic weather strip lowered the air flow only from 19.8 to 17.2 cfm. The storm door had only minimal weather stripping, consisting of a thin plastic strip on three sides and a single soft plastic finger at the threshold.

b. Windows

Airflow tests were run on the same set of perimeter cracks around the picture window on which sound transmission was measured. The results are plotted in Figure 68, showing airflow in cfm per foot length of crack as a function of room pressure for each crack width and length. The data were corrected for residual flow. For each crack width, the airflow was very closely proportional to a power of the pressure which ranged from approximately 0.72 for a 1/32 in. crack to 0.54 for the 1/8 in. and 1/4 in. cracks. Where data corresponding to two crack lengths are shown for the same crack width, there is good agreement between the corresponding airflows per unit length.

The same data are shown in Figure 69 for a constant room pressure of 0.3 in. water, as a function of crack width. The airflow was roughly proportional to crack width over the range measured, the deviation from strict proportionality being indicated by the departures from the straight line drawn through the data points. Taking the straight line as an average, and assuming an average logarithmic slope of airflow versus pressure of 0.56, the following empirical equation may be used as an approximation to the data;

$$(\mathrm{ft}^3\ \mathrm{min}^{-1}) \text{ per foot length of crack} = 284\ W\ p^{0.56}$$

where: W = crack width, in.

p = room pressure, in. water

As shown in Table E-2, the air flow at 0.3 in. water pressure for all of the windows tested, as normally closed and/or locked, covered a very large range -- from 1.8 cfm for the fixed casement window to 82.6 cfm for the jalousie window. Since the latter had no provision in its design for air sealing, it should probably be considered only as an extreme end point in the test series. Omitting this window, the highest airflow for locked or latched windows was approximately 25 cfm for the wood double hung window locked and 70 cfm for the same window unlocked. This was a typical low-cost window purchased at the local lumberyard.

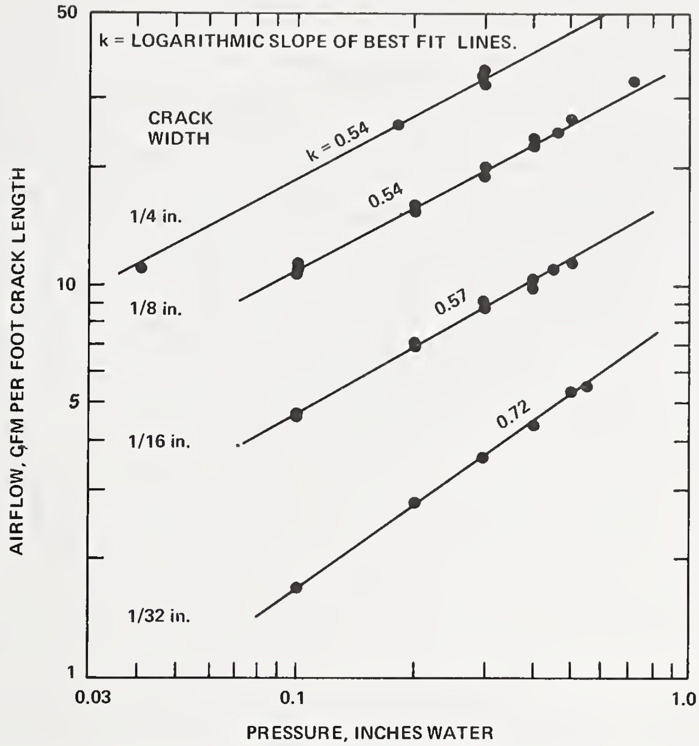


Figure 68. Air infiltration through gauged cracks around picture window. Multiple points at the same pressure and crack width represent crack lengths varying from 2 to 20 ft.

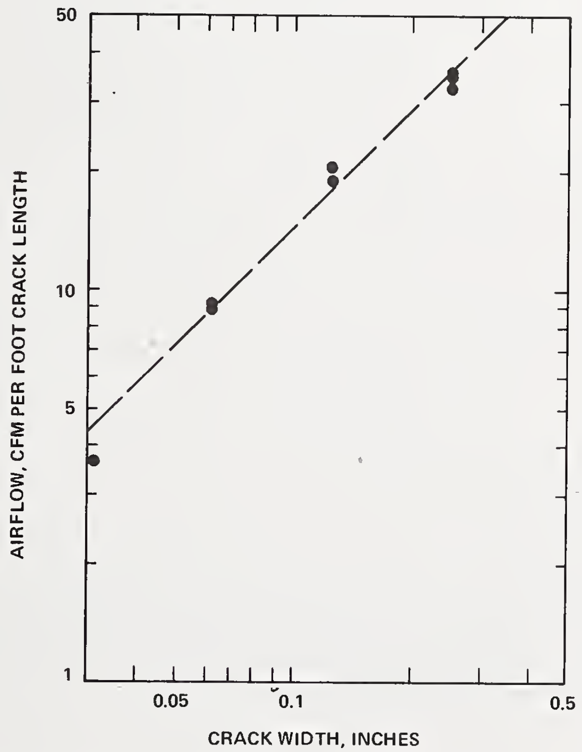


Figure 69. Air infiltration, as a function of crack width, through gauged cracks around picture window at 0.3 in. water pressure.

The wood-plastic windows were much better, showing 5 to 6 cfm both locked and unlocked. The awning and operable casement windows of the wood-plastic type ranged up to 10 cfm for the locked or tightly closed condition, and the sliding glass door measured 16 and 17 cfm, locked and unlocked, respectively.

The aluminum windows covered a wide range from 5.6 cfm for the single hung window, locked, to 44.6 for the operable casement window, unlocked. Although not enough samples were tested to make generalizations, it appeared that as a group the aluminum windows were roughly between the plain wood and the plastic-wood windows.

In some cases, the unlocked windows showed slightly lower air flow than the same windows locked. This was apparently due to the fact that the locking tended to twist or displace the sashes enough to cause a larger leak around each sash perimeter.

For awning and casement windows, which open outward on hinges, it was noted that increasing room pressure on the exterior side sometimes tended to close the windows more tightly. This is shown clearly in Table E-2 in Appendix E.

Table E-3 in Appendix E shows data obtained on the effect of opening an awning window by gauged amounts. The opening was gauged by inserting shims at the bottom of each sash. The data were not reproducible, however, since a repeat with different sashes in the same frame showed much less change in air flow for the same openings.

In general, all of the air infiltration data, because of the limited and more or less random sampling of windows, should be considered as illustrative rather than definitive.

Direct comparisons of air flows measured in the sound transmission facility at room temperature with those measured in the thermal facility were made for one window and three doors. The results, with the sound-transmission-facility data corrected to a common basis of 0.25 in. water pressure, are as follows:

Test No.	Unit Tested	Thermal Facility	Two-Room Facility
		$ft^3\ min^{-1}$	$ft^3\ min^{-1}$
TT-033-72	Wood double-hung window, glazed insulating glass, locked	40	22
TT-035-72	Same, unlocked	50	62
TT-050-72	Solid core wood door, brass weather strip	22	9
TT-060-72	Steel door, urethane foam core, magnetic weather strip	15	14
TT-064-72	FRP panel door, urethane foam core plastic weather strip	7	3

There is only very rough agreement, the values for the thermal facility being generally higher. The best agreement appears for the steel door. It should be noted that close agreement should not necessarily be expected. The 95 °F temperature differential for the thermal tests should be expected to cause dimensional distortions which could greatly alter perimeter leakage characteristics [122].

5. 5. Comparison of Results with Those of Other Investigations

Because of the large variation in leakage rates among windows, depending upon design, fabrication and installation, there is little point in a detailed comparison of the present data with that of previous investigations.

The ASHRAE Handbook of Fundamentals [85] gives the design values, for double- hung wood windows, shown in Figure 70. The ranges of values shown correspond to "average fit" to "loose fit". ASHRAE also gives rough equivalences between other types of windows and the wood double-hung windows. Figure 70 also shows, for comparison, data from the present investigation for locked wood and wood-plastic double-hung windows as measured in the sound transmission facility. The reader interested in more detailed comparisons should consult [120-124] and the references therein and in [85]. In addition, comparisons can be made with industry specifications put out by the Architectural Aluminum Manufacturers Association, the National Woodwork Manufacturers Association, and the Mobile Homes Manufacturers Association.

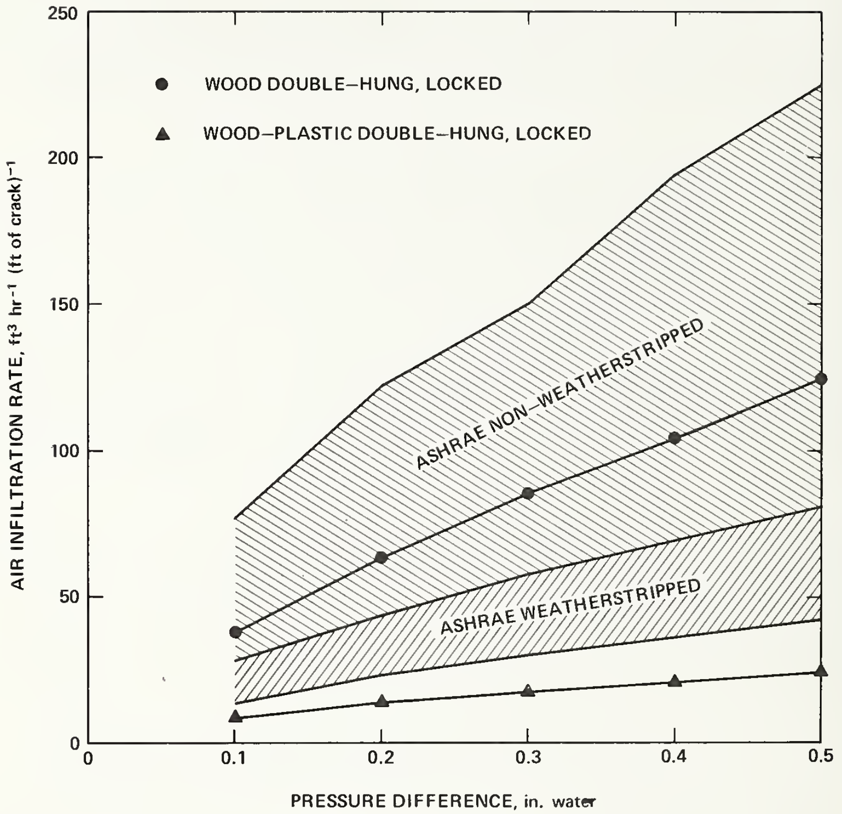


Figure 70. Air infiltration, per foot of crack, for locked wood (Test W-24-71) and wood-plastic (Test W-74-71) double-hung windows compared with ASHRAE design values.

6. Correlations among Sound Transmission Loss, Thermal Transmittance, and Air Leakage Test Results

6. 1. Sound Transmission Loss and Air Leakage

Section 3.5.4 includes a brief discussion of sound transmission through cracks of known geometry. In general, however, cracks around doors and windows and leaks in walls will be of unknown geometry and some means is needed to estimate the effective size of the cracks. This need was a prime motivating factor in conducting the air leakage tests in the sound transmission loss facility.

The following rather simplistic approach was found to lead to an adequate correlation between sound transmission loss data and air leakage data.

> Assumption 1 Design calculations on the effects of cracks and openings on the effective sound transmission loss can be based on a single-figure rating, e.g., Sound Transmission Class, and detailed effects at different frequencies can be ignored.

From equation (4), one can write

$$\tau_2^* S_2 = \tau^* S - \tau_1^* S, \tag{18}$$

where τ^* is the effective sound transmission coefficient of the leaky window of area S, τ_1^* is the effective transmission coefficient of the sealed window, also of area S, and τ_2^* is the effective transmission coefficient of the crack of area S_2. The asterisk on each τ indicates that the transmission coefficient is that corresponding to the sound transmission class, i.e., STC = 10 log $(1/\tau^*)$.

Taking logarithms,

$$STC_2 - 10 \log S_2/S_o = -10 \log \left[10^{-STC/10} - 10^{-STC_1/10} \right] -10 \log S/S_o \tag{19}$$

where the reference area is $S_o = 1\ ft^2$ and where STC, STC_1, and STC_2 are the Sound Transmission Classes of the leaky window, the sealed window, and the leak, respectively. Since S_2, the leak area, is not known, one cannot compute STC_2 but one can obtain, using equation (19) the quantity $(STC_2 - 10 \log S_2/S_o)$.

> Assumption 2 The Sound Transmission Class of an opening is approximately independent of the size of the opening; thus the sound power (in an "STC-sense") transmitted through an opening is proportional to the area of the opening.

> Assumption 3 Typical leaks are sufficiently alike (e.g., in terms of depth) that, at a given pressure difference, the air leakage rate is proportional to the area of the opening.

Assumptions 2 and 3 lead to

$$\tau_2^* S_2 = K\dot{V}, \tag{20}$$

where $\dot{V}$ is the air leakage rate at some particular pressure difference and K is a constant relating the leakage rate to the (unknown) crack size. Again taking logarithms

$$STC_2 - 10 \log S_2/S_o = -10 \log K - 10 \log \dot{V}/\dot{V}_o, \tag{21}$$

where $\dot{V}_o$ = 1 cfm.

Figure 71 shows the quantity $(\dot{S}TC_2 - 10 \log S_2)$, as computed from equation (19), plotted vs $-10 \log \dot{V}/\dot{V}_o$, where $\dot{V}$ is the air leakage rate (cfm) at a pressure difference of 0.3 in. water. The data points plotted include all tests on doors or windows without storm sashes where the effect of the leak was sufficiently severe as to lower the Sound Transmission Class[17/] by at least 3 (it was felt that the experimental precision did not allow reliable determinations of $STC_2 - 10 \log S_2$ for smaller differences). As will be seen below, some of the data with a storm window or door in place did not lie close to the line in Figure 71 so no data corresponding to storm windows or doors were included. (These data are shown in Figure 72, below.) The solid data points represent "normal" leaks which occurred for closed (locked or unlocked) windows. The open data points correspond to the artificial cracks around the 6 x 5 ft picture window and the 3 x 4 ft wood-plastic awning window.

The solid line in Figure 71, which was fitted to the solid data points, corresponds to (cf. equation (21))

$$STC_2 - 10 \log S_2/S_o = 26.4 - 10 \log \dot{V}/\dot{V}_o. \tag{22}$$

The dashed lines are 3 dB above and below the solid line. Substituting equation (22) into (19) and rearranging,

$$STC_1 - STC = 10 \log \left[1 + \frac{.00229 \dot{V}/S}{10^{-STC_1/10}} \right], \tag{23}$$

where, as before, $\dot{V}$ is expressed in cfm at 0.3 in. water and S in sq ft.

Figure 72 shows the predicted change in Sound Transmission Class, as computed from equation (23) plotted vs the actual observed change. The agreement for experimental changes greater than 3 is to be expected, of course, at least in the absence of storm windows or doors, since these are the same data as were used in deriving equations (22) and (23). As stated previously, experimental values less than about 3 are subject to considerable uncertainty. Ignoring these small values, which are of little practical concern anyway, almost all of the experimental data lie within ± 3 of the prediction. The most notable departure from agreement corresponds to the solid core wood door plus aluminum storm door (Tests W-40-72 (unsealed) and W-41-72 (sealed)) where the experimental value was about 7 less than that predicted (i.e., the prediction erred on the conservative side).

The data in Figure 72 indicate that equation (23) may be used with some confidence in predicting the effect of cracks on the Sound Transmission Class of doors and windows from a simple measure of the air leakage rate. A family of curves, generated using equation (23), is shown in Figure 73. These curves clearly show the large influence of air leakage on elements which otherwise have a high sound transmission loss.

As an example of the use of Figure 73, consider a window of area 15 ft^2 having an inherent (i.e., when sealed) Sound Transmission Class of 30. If the measured air leakage rate was 30 cfm at 0.3 in. water, $\dot{V}/S$ would be 2.0 ft/min. Entering Figure 73, this is seen to correspond to a decrease of 7.5 in STC so the predicted value would be 22.5 (or, rounded down, 22).

Seifert [127] has published a nomogram for estimating the effect of air leakage of the sound transmission loss of windows. Since his procedure is based on a pressure difference of 1 mm water (lower than was examined in the present investigation) and he is interested in the average sound transmission loss from 100 to 3150 Hz (rather than the Sound Transmission Class) a direct comparison is not easy to make.

[17/] The Sound Transmission Class was computed "exactly" rather than to the nearest 1 dB and the "-8 dB rule" was ignored in order to avoid introducing spurious scatter into the data.

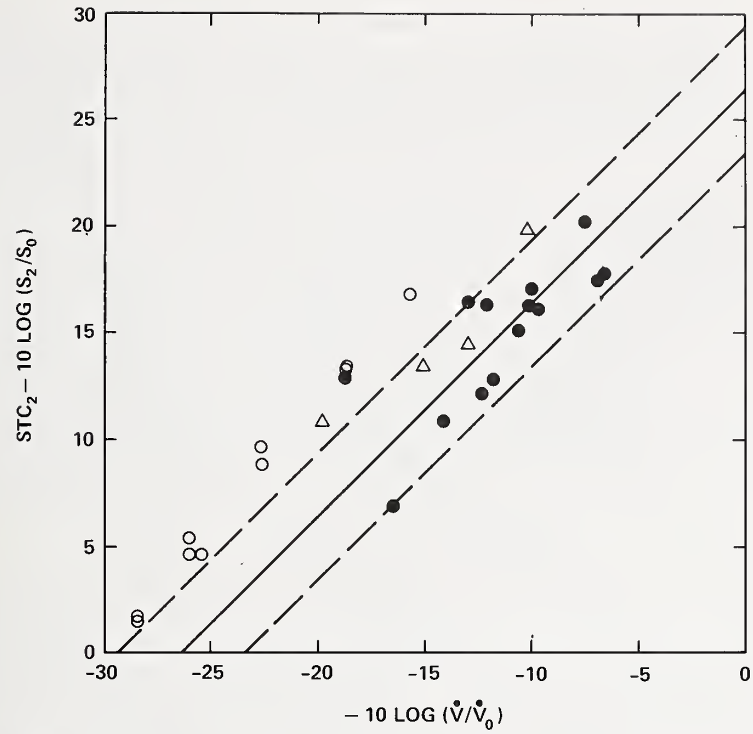


Figure 71. Experimentally determined values for STC_2 - 10 log (S_2/S_o) plotted vs experimentally determined values for -10 log $(\dot{V}/\dot{V}_o)$; see text.

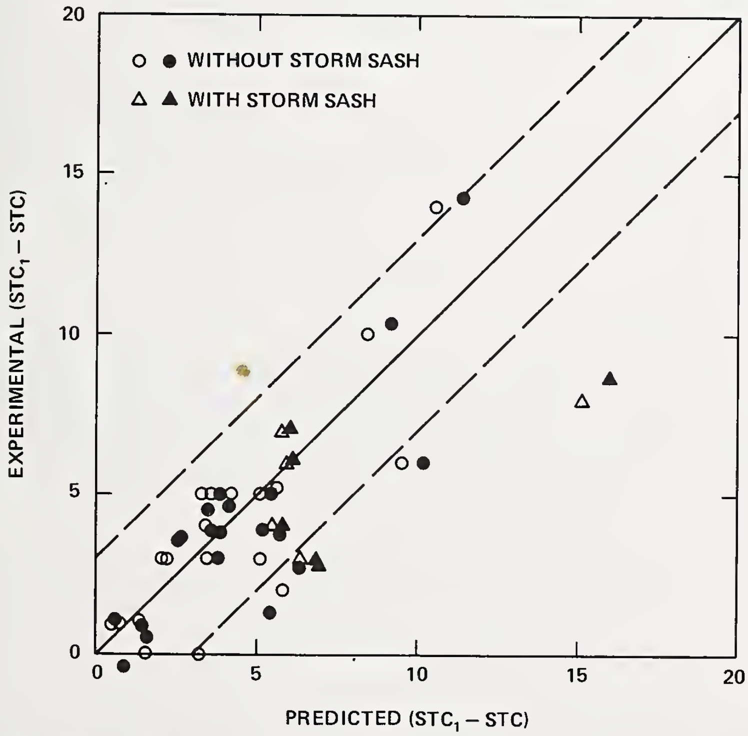


Figure 72. Experimental values for the decrease in sound transmission loss due to leaks around windows or doors versus values predicted using equation (22). The open symbols represent conventional calculations [22] of the Sound Transmission Class. Closed symbols correspond to STC-values computed exactly (rather than to the next lowest decibel) and without invoking the "-8 dB rule".

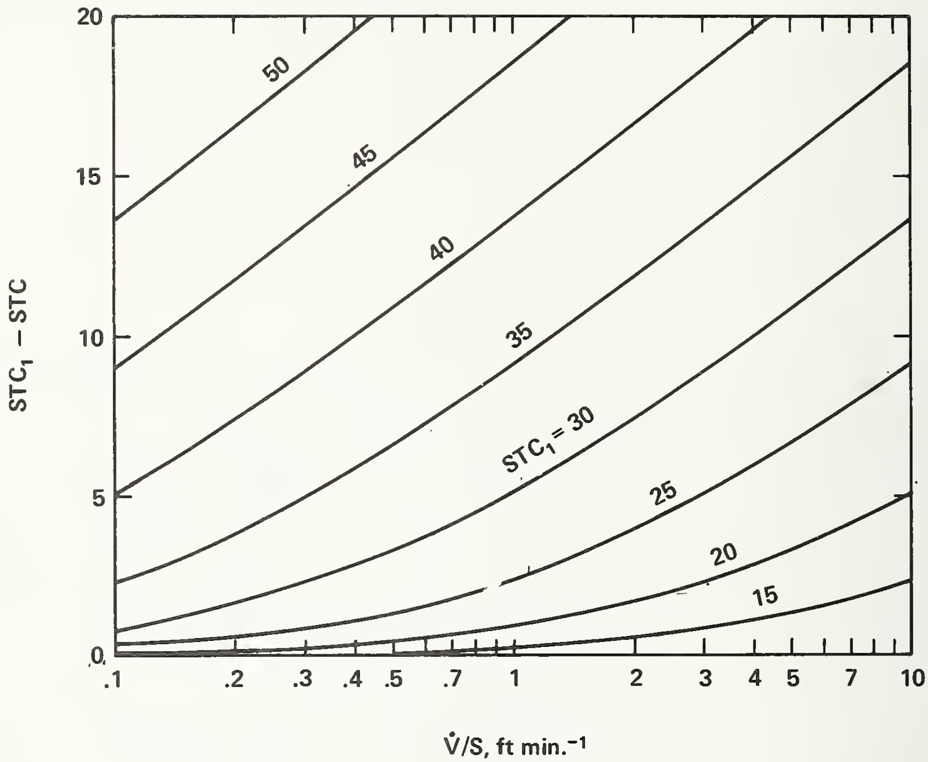


Figure 73. Expected decrease in Sound Transmission Class as a function of air leakage rate divided by area. The air leakage rate, $\dot{V}$, measured according to ASTM E283-73 [125] is expressed in scfm at a pressure difference of 0.3 in. water. The window or door area, S, is in sq ft. The parameter on the curves is the Sound Transmission Class of the sealed unit (window or door).

Parenthetically, there might be an advantage to using, as Seifert did, a much smaller pressure difference in the air leakage tests since there would then be less chance of the pressure difference opening or closing cracks so as to change the effective crack size from what would be present during sound transmission loss tests. However, air leakage at a pressure difference of 0.3 in. water is a commonly cited value in the United States and Canada so it was used in the present correlation.

6. 2. Thermal Transmittance and Air Leakage

Table D-1, in Appendix D, includes values of the apparent amount of net heat flow due to air leakage, as computed from equation (14). It is seen that for many of the tests on walls with penetrating doors and windows, the heat flow associated with leakage is much larger than that due to thermal conduction. Thus it is important to accurately assess the influence of air leakage on the effective thermal transmittance.

Let U and U' designate the effective thermal transmittance of a wall (including any penetrations) in the absence and presence, respectively, of air flow through the wall. Then, from equations (9) and (14) it follows that

$$U' - U = 1.08 \frac{\dot{V}}{S} \quad \text{Btu hr}^{-1} \text{ ft}^{-2} \text{ °F}^{-1}, \tag{24}$$

where $\dot{V}/S$ is the volumetric flow rate (scfm) per unit area (sq ft) of wall. Figure 74 shows the experimentally-determined increase in thermal transmittance, for all the pairs of tests (with and without an imposed pressure difference) in Table D-1, plotted vs the increase predicted by equation (24). Log-log paper was used so as to make the fractional error in the prediction more evident. It is seen that the experimental values fall well below the predicted values for very low flow rates but that the agreement becomes asymptotically better (as regards fractional, not absolute, error) for large flow rates. It is not apparent whether the behavior exhibited in Figure 74 is correct or is due to experimental error (e.g., undetected air leaks or systematic errors in air flow measurement). Bursey and Green [122] have observed rather similar behavior in their measurements on double- glazed windows. They attribute it to partial heating of the air as it passes through the space between the windows but their arguments are not very convincing.

The following equation was modified empirically from equation (24) to account for the observed behavior in Figure 74:

$$U' - U = 0.93 \frac{\dot{V}-0.7}{S} \quad \text{Btu hr}^{-1} \text{ ft}^{-2} \text{ °F}^{-1}. \tag{25}$$

The value, 0.7 cfm, which is subtracted from $\dot{V}$ in equation 25 is consistent with a measured value of cold box air leakage of 0.6 cfm for the one test setup for which this measurement was made. This leakage probably varies from test to test but is believed to have always been less than 1 cfm. Although, as shown in Figure 75, equation (25) more accurately conforms to the results of the present investigation than does equation (24), it should not be used for predictive purposes pending a better understanding as to why the proportionality constant (0.93) is less than would be expected (1.08).

6. 3. Sound Transmission Loss and Thermal Transmittance

Acoustical and thermal energy transfer through walls, doors, and windows obey very different physical principles so one should not expect very good correlation between sound transmission loss and thermal transmittance. However, in considering alternative constructions, it is useful to compare these two properties.

Table 6 lists Sound Transmission Class and thermal transmittance at 25 °F for those basic walls, doors, and windows (no combinations) for which comparable data were obtained. These same data are plotted in Figure 76. Although, as expected, there is considerable scatter, the overall trend of the data is important to remember -- good acoustical performance (high STC) usually implies good thermal performance (low thermal transmittance).

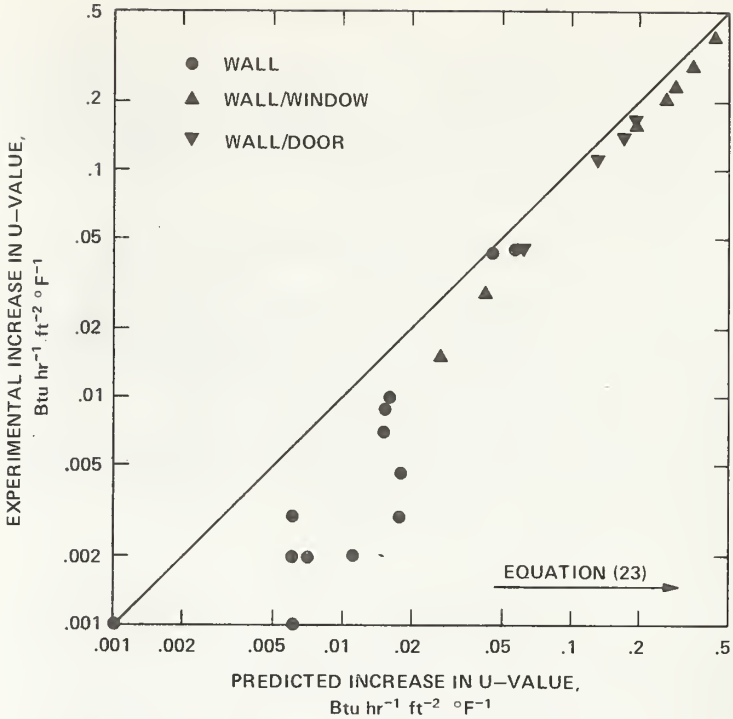


Figure 74. Experimentally observed increase in effective thermal transmittance of 9 x 14 ft walls, with and without penetrating doors or windows, vs the increase predicted by equation (23). The scatter for small values of thermal transmittance arises from imprecisions in both the thermal transmittance data and the air flow rate data (used in equation (23)).

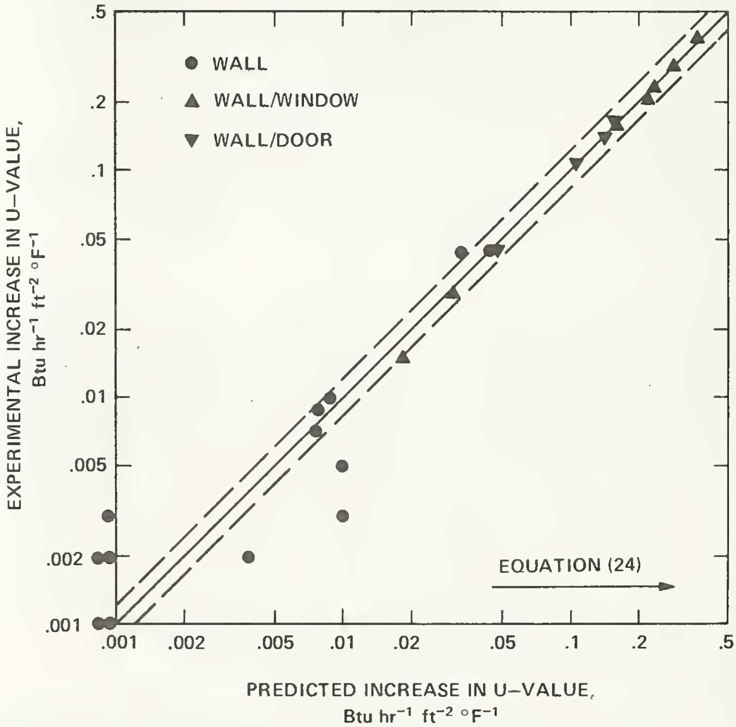


Figure 75. Experimentally observed increase in effective thermal transmittance of 9 x 14 ft walls, with and without penetrating doors or windows, vs the increase predicted by equation (24). The data points shown just to the left of the left-hand ordinate correspond to predicted values below the range of the abcissa (cf. corresponding points in Figure (74)). The dashed lines bound the region ±20 percent around the line of perfect concordance.

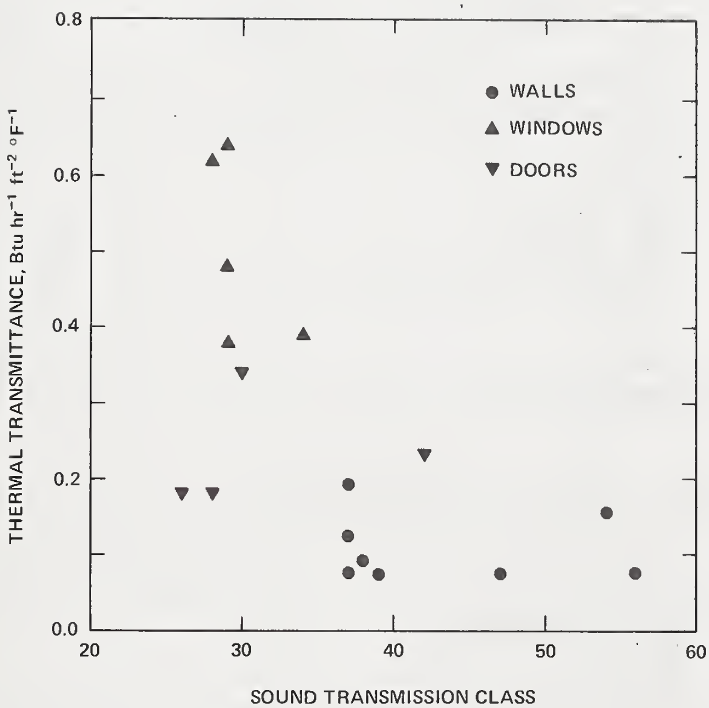


Figure 76. Comparison of Sound Transmission Class and thermal transmittance for basic walls, doors, and windows. The data plotted are listed in Table 6.

Table 6. Comparison of sound transmission loss data and thermal transmittance data for walls, doors, and windows. The sound transmission loss tests correspond to the sealed condition. The thermal transmittance tests correspond to the locked condition, with no imposed air pressure difference, at a nominal mean temperature of 27.5° F

	Sound Transmission Loss		Thermal Transmittance	
Specimen	Test No.	STC	Test No.	U-Value (air-to-air)
				Btu hr^{-1} ft^{-2} $°F^{-1}$
Walls				
Wood siding with no cavity insulation	W-4-72	37	TT-001-71 TT-018-71	.195 .194
Wood siding with 3 1/2 in. Fiberglas Friction Fit Bldg. Insul.	W-7-72	37	TT-002-71 TT-022-71	.076 .078
Wood siding with Alfol Type 2B insulation	W-6-72	37	TT-014-71	.125
Wood siding with Premium Rock Wool	W-5-72	38	TT-030-72	.091
Wood siding with 3 1/2 in. Fiberglas Kraft Faced Bldg. Insul.	W-54-71	39	TT-038-72	.074
Same as above but gypsum board on resilient channel	W-55-71	47	TT-042-72	.072
Brick veneer with no cavity insulation (resilient channel for acoustic test only)	W-46-71	54	TT-065-72	.153
Brick veneer with 3 1/2 in. Fiberglas Friction Fit Bldg. Insul.	W-44-71	56	TT-069-72	0.075
Doors				
Solid wood flush door	W-91-71	30	TT-049-72	0.33
Same as above plus aluminum storm door	W-41-71	42	TT-055-72	0.22
Steel flush door with urethane foam core	W-3-72	28	TT-059-72	0.17
Fiberglas Reinforced Plastic panel door with urethane foam core	W-44-72	26	TT-063-72	0.18

Table 6 (Con'd)

	Sound Transmission Loss		Thermal Transmittance	
Specimen	Test No.	STC	Test No.	U-Value (air-to-air)
Windows				
3 x 5 ft wood double hung window single strength glazing	W-41-71	29	TT-020-71	0.64
Same as above plus single glazed wood storm window	W-37-71	34	TT-026-71	0.41
3 x 5 ft wood double hung window, 7/16 in. insulating glass	W-32-71	29	TT-032-71	0.47
6 x 5 ft wood picture window, single glazed	W-8-71	28	TT-040-72	0.61
6 x 5 ft wood picture window, 1 in. insulating glass	W-7-71	29	TT-044-72	0.37

7. References

[1] Harris, C. M. (Editor), Handbook of Noise Control (McGraw-Hill, New York, 1957).

[2] Beranek, L. L. (Editor), Noise and Vibration Control (McGraw-Hill, New York, 1971).

[3] Young, R. W., Physical properties of noise and their specification, Chapter 2 in Harris [1].

[4] Franken, P. A., The behavior of sound waves, Chapter 1 in Beranek [2].

[5] Beranek, L. L., Levels, decibels, and spectra, Chapter 2 in Beranek [2].

[6] Rudnick, I., Propagation of sound in the open air, Chapter 3 in Harris [1].

[7] Kurze, U., and Beranek, L. L., Sound propagation outdoors, Chapter 7 in Beranek [2].

[8] Beranek, L. L., Sound in small spaces, Chapter 8 in Beranek [2].

[9] Embleton, T. F. W., Sound in large rooms, Chapter 9 in Beranek [2].

[10] Ingerslev, F., and Harris, C. M., Control of solid-borne noise in buildings, Chapter 19 in Harris [1].

[11] Cook, R. K., and Chrzanowski, P., Transmission of air-borne noise through walls and floors, Chapter 20 in Harris [1].

[12] Vér, I. L., and Holmer, C. I., Interaction of sound waves with solid structures, Chapter 11 in Beranek [2].

[13] Sabine, H. J., Acoustical materials, Chapter 18 in Harris [1].

[14] Beranek, L. L., Criteria for noise and vibration in communities, buildings and vehicles, Chapter 18 in Beranek [2].

[15] Effects of Noise on People, EPA Report No. NTID300.7 (U. S. Environmental Protection Agency, Washington, D. C., December, 1971). Available from U. S. Government Printing Office, Washington, D. C. 20402, as GPO Stock No. 5500-0050, Catalog No. EP1.2:N69/10. Also available from National Technical Information Service, Springfield, Va. 22151, as Accession No. PB-206723.

[16] Public Health and Welfare Criteria for Noise, EPA Report No. 550/9-73-002 (U. S. Environmental Protection Agency, Washington, D C., July 1973). Available from U. S. Government Printing Office, Washington, D. C. 20402, as GPO Stock No. 5500-00103, Catalog No. EP1.2:N69/23/973.

[17] Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety, EPA Report No. 550/9-74-004 (U. S. Environmental Protection Agency, Washington, D. C., March 1974). Available from U. S. Government Printing Office, Washington, D. C. 20402, as GPO Stock No. 5500-00120, Catalog No. EP1.2:N69/26.

[18] Standard Definitions of Terms Relating to Acoustical Tests of Building Constructions and Materials, C634-73, pp 278-284, Part 18, 1974 Annual Book of ASTM Standards (American Society for Testing and Materials, Philadelphia, 1974).

[19] American Standard Acoustical Terminology, S1.1-1960 (American Standards Association (now American National Standards Institute), New York, 1960).

[20] London, A., Transmission of reverberant sound through single walls, J. Research NBS 42, 605-615 (1949).

[21] London, A., Transmission of reverberant sound through double walls, J. Research NBS 44, 77-88 (1950).

[22] Standard Classification for Determination of Sound Transmission Class, E413-73, pp 728-730, Part 18, 1974 Annual Book of ASTM Standards (American Society for Testing and Materials, Philadelphia, 1974).

[23] Rating of Sound Insulation for Dwellings, ISO/R717-1968 (International Organization for Standardization, Switzerland, 1968).

[24] Sound Insulation of Wall and Floor Constructions, Building Materials and Structures Report 144 (National Bureau of Standards, Washington, D. C., 1955).

[25] Berendt, R. D., and Winzer, G. E., Sound Insulation of Wall, Floor, and Door Constructions, NBS Monograph 77 (1964).

[26] Berendt, R. D., Winzer, G. E., and Burroughs, C. B., A Guide to Airborne Impact, and Structureborne Noise Control in Multifamily Dwellings, Report No. HUD-TS-24 (U. S. Department of Housing and Urban Development, Washington, D. C., 1967).

[27] Parkin, P. H., Purkis, H. J., and Scholes, W. E., Field Measurements of Sound Insulation between Dwellings, National Building Studies Research Paper No. 33 (Her Majesty's Stationery Office, London, 1960).

[28] Weston, E. T., Burgess, M. A., and Whitlock, J. A., Airborne Sound Transmission through Elements of Buildings, EBS Technical Study 48, Experimental Building Station, Department of Housing and Construction (Australian Government Publishing Service, Canberra, 1973).

[29] Jain, R. K., and Mulholland, K. A., A databank of sound insulation measurements, Appl. Acous. 6, 133-141 (1973).

[30] Gillam, A. J., An interactive access system for an acoustics databank, Appl. Acous. 7, 35-45 (1974).

[31] Sharp, B. H., A Study of Techniques to Increase the Sound Insulation of Building Elements, Report No. WR73-5 (U. S. Department of Housing and Urban Development, 1973). Available from National Technical Information Service, Springfield, Va. 22151, as Accession No. PB-222829.

[32] Bishop, D. E., Reduction of aircraft noise measured in several school, motel, and residential rooms, J. Acous. Soc. Amer. 39, 907-913(1966).

[33] A Study -- Insulating Houses from Aircraft Noise, Report No. HUD TS-19 (U. S. Department of Housing and Urban Development, Washington, D. C. 1967).

[34] Young, J. R., Attenuation of Aircraft Noise by Wood-Sided and Brick- Veneered Frame Houses, Report No. NASA CR-1637 (National Aeronautics and Space Administration, Washington, D. C., 1970).

[35] Final Report on the Home Soundproofing Pilot Project for the Los Angeles Department of Airports, Report No. WCR 70-1 (Wyle Laboratories, El Segundo, Calif., 1970).

[36] House Noise-Reduction Measurements for Use in Studies of Aircraft Flyover Noise, SAE Information Report AIR 1081 (Society of Automotive Engineers, New York, 1971).

[37] Gilbert, P., Building Research Translation: An Investigation of the Protection of Dwellings from External Noise Through Facade Walls, NBS Technical Note 710-2 (1972). This is a translation of: Une etude sur la protection des habituations contre les bruits exterieurs penetrant par les facades, Cahiers du CSTB (Centre Scientifique et Technique du Batiment) No. 103 (1969).

[38] Buckingham, E., Theory and interpretation of experiments on the transmission of sound through partition walls, Nat. Bur. Standards (U. S.) Scientific Papers 20, 193-219 (1925).

[39] Chrisler, V. L., and Snyder, W. F., Recent sound-transmission measurements at the National Bureau of Standards, J. Research NBS 14, 749-764 (1935).

[40] London, A., Methods for determining sound transmission loss in the field, J. Research NBS 26, 419-453 (1941).

[41] Standard Recommended Practice for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions, E90-70, pp 583-592, Part 18, 1974 Annual Book of ASTM Standards (American Society for Testing and Materials, Philadelphia, 1974).

[42] Standard Recommended Practice for Measurement of Airborne Sound Insulation in Buildings, E336-71, pp 705-723, Part 18, 1974 Annual Book of ASTM Standards (American Society for Testing and Materials, Philadelphia, 1974).

[43] Field and Laboratory Measurements of Airborne and Impact Sound Transmission, ISO Recommendation R140-1960 (International Organization for Standardization, Geneva, Switzerland, 1960).

[44] Mariner, T., Critique of the reverberant room method of measuring air-borne sound transmission loss, J. Acous. Soc. Amer. 33, 1131-1139 (1961).

[45] Mulholland, K. A., and Parbrook, H. D., The measurement of sound transmission loss, J. Sound Vib. 2, 502-509 (1965).

[46] Kihlman, T., On the precision and accuracy of measurements of airborne sound transmission, paper F51, Proc. Fifth International Congress on Acoustics (Liege, 1965).

[47] Mulholland, K. A., and Parbrook, H. D., The measurement of transmission loss, J. Sound Vib. 5, 391-394 (1967).

[48] Kihlman, T., Sound radiation into a rectangular room. Applications to airborne sound transmission in buildings, Acustica 18, 11-20 (1967).

[49] Utley, W. A., Single leaf transmission loss at low frequencies, J. Sound Vib. 8, 256-261 (1968).

[50] de Bruijn, A., Influence of diffusivity on the transmission loss of a single wall, J. Acous. Soc. Amer. 47, 667-675 (1970).

[51] Sewell, E. C., Transmission of reverberant sound through a single-leaf partition surrounded by an infinite rigid baffle, J. Sound Vib. 12, 21-32 (1970).

[52] Holmer, C. I., Factors affecting the comparison of theoretical and experimental sound transmission loss of panels (abstract), J. Acous. Soc. Amer. 49, 88-89 (1971).

[53] Utley, W. A., The accuracy of laboratory measurements of transmission loss, J. Sound Vib. 16, 643-644 (1971).

[54] Schultz, T. J., Diffusion in reverberation rooms, J. Sound Vib. 16, 17-28 (1971).

[55] Nilsson, A., and Kihlman, T., Influence of boundary conditions upon the reduction index of a wall between two rectangular rooms, paper 20A1, Proc. Seventh International Congress on Acoustics (Budapest, 1971).

[56] Kihlman, T., and Nilsson, A. C., The effects of some laboratory designs and mounting conditions on reduction index measurements, J. Sound Vib. 24, 349-364 (1972).

[57] Lang, J., Differences between acoustical insulation properties measured in the laboratory and results of measurements in situ, Appl. Acous. 5, 21-37 (1972).

[58] Higginson, R. F., A study of measuring techniques for airborne sound insulation in buildings, J. Sound Vib. 21, 405-429 (1972).

[59] Bhattacharya, M. C., and Guy, R. W., The influence of the measuring facility on the measured sound insulating property of a panel, Acustica 26, 344-348 (1972).

[60] Sewell, E. C., Errors in the measurement of the sound reduction index of masonry walls in the BRE laboratory facility, CP 47/74 (Building Research Establishment, Garston, Watford, England, 1974).

[61] Northwood,.T. D., Transmission loss of plasterboard walls, Building Research Note No. 66 (National Research Council, Ottawa, Canada, October 1968 (revised December 1968 and July 1970)).

[62] Bishop, D. E., and Hirtle, P. W., Notes on the sound-transmission loss of residential-type windows and doors, J. Acous. Soc. Amer. 43, 880-882 (1968). This paper only presents, in graphical form, part of the data originally tabulated in Bolt Beranek and Newman Report 1387, Methods for Improving the Noise Insulation of Houses with Respect to Aircraft Noise, prepared for the Fed. Housing Admin. under FHA Contract FH-941 (1966). The tabular data are reproduced in Bolt Beranek and Newman Rept. 1460, Literature Survey for the FHA Contract on Urban Noise, prepared under FHA Contract FH-954 (1967). Neither of these BBN reports are generally available.

[63] Marsh, J. A., The airborne sound insulation of glass, Part 1, Appl. Acous. 4, 55-70 (1971); Part 2, Appl. Acous. 4, 131-154 (1971); and Part 3, Appl. Acous. 4, 175-191 (1971). Also available, in a single report, as Environmental Advisory Service 4 (Pilkington Bros. Ltd., St. Helena, Lancs., England, 1970).

[64] Patil, P. G., Designing glass units for sound reduction, Sound and Vibration 7 (9), 38-39 (Sept. 1973).

[65] Utley, W. A., and Fletcher, B. L., Influence of edge conditions on the sound insulation of windows, Appl. Acous. 2, 131-136 (1969).

[66] Utley, W. A., and Fletcher, B. L., The effect of edge conditions on the sound insulation of double windows, J. Sound Vib. 26, 63-72 (1973).

[67] Cops, A., Myncke, H., and Lambert, E., Sound insulation of glass by means of scale models, Acustica 31, 143-149 (1974).

[68] de Lange, P. A., Sound insulation of glazing with respect to traffic noise, Appl. Acous. 2, 215-236 (1969).

[69] Ingerslev, F., and Nielsen, A. K., On the transmission of sound through small apertures and narrow slits, Ingeniorvidenskabelige Skrifter, Nr. 5 (Köbenhavn 1944).

[70] Nomura, Y., and Inawashiro, S., On the transmission of acoustic waves through a circular channel of a thick wall, Sci. Rept. Tohoku Univ. 12B, 57-71 (1960).

[71] Sabine, H. J., Measurement of sound transmission through door seals (abstract), J. Acous. Soc. Amer. 33, 834 (1961).

[72] Bolt, R. H., Labate, S., and Ingard, U., The acoustic reactance of small circular orifices, J. Acous. Soc. Amer. 21, 94-97 (1949).

[73] Thurston, G. B., Periodic fluid flow through circular tubes, J. Acous Soc. Amer. 24, 653-656 (1952).

[74] Wood, J. K., and Thurston, G. B., Acoustic impedance of rectangular tubes, J. Acous. Soc. Amer. 25, 858-860 (1953).

[75] Smits, J. M. A., and Kosten, C. W., Sound absorption by slit resonators, Acustica 1, 114-122 (1951).

[76] Gomperts, M. D., The "sound insulation" of circular and slit-shaped apertures, Acustica 14, 1-16 (1964).

[77] Gomperts, M. C., The influence of viscosity on sound transmission through small circular apertures in walls of finite thickness, Acustica 15, 191- 198 (1965).

[78] Gomperts, M. C., and Kihlman, T., The sound transmission loss of circular and slit-shaped apertures in walls, Acustica 18, 144-150 (1967).

[79] Wilson, G. P., and Soroka, W. W., Approximation to the diffraction of sound by a circular aperture in a rigid wall of finite thickness, J. Acous. Soc. Amer. 37, 286-297 (1965).

[80] Wilson, G. P., Measurement of the transmission loss of a finite-depth aperture, J. Acous. Soc. Amer. 37, 298-307 (1965).

[81] Sauter, A., and Soroka, W. W., Sound transmission through rectangular slots of finite depth between reverberant rooms, J. Acous. Soc. Amer. 47, 5-11 (1970).

[82] Westerberg, G., On the sealing of circular holes in a thick wall for the purpose of sound insulation, Appl. Acous. 4, 115-129 (1971).

[83] Ford, R. D., and Kerry, G., The sound insulation of partially open double glazing, Appl. Acous. 6, 57-71 (1973).

[84] Kerry, G., and Ford, R. D., The field performance of partially open dual glazing, Appl. Acous. 7, 213-227 (1974).

[85] ASHRAE Handbook of Fundamentals (Amer. Soc. Heating, Refrigerating, and Air Conditioning Engineers, New York, N. Y., 1972).

[86] ASHRAE Handbook and Product Directory -- Systems (Amer. Soc. Heating, Refrigerating, and Air Conditioning Engineers, N. Y., 1973).

[87] Strock, C., and Koral, R. L., (editors), Handbook of Air Conditioning, Heating, and Ventilating, 2nd Ed. (Industrial Press, New York, 1965).

[88] Threlkeld, J. L., Thermal Environmental Engineering, 2nd Ed. (Prentice- Hall, Englewood Cliffs, N. J., 1970).

[89] Jennings, B. H., Environmental Engineering, 6th Ed. (International Textbook Co., Scranton, Pa., 1970).

[90] McGuinness, W. I., and Stein, B., Mechanical and Electrical Equipment for Buildings, 5th Ed. (John Wiley and Sons, New York, 1971).

[91] Wood, B. D., Applications of Thermodynamics (Addison-Wesley, Reading, Mass., 1969).

[92] Fanger, P. O., Thermal Comfort (Danish Technical Press, Copenhagen, 1970).

[93] Jones, W. P., Air Conditioning Engineering (Edward Arnold, London, 1973).

[94] Down, P. G., Heating and Cooling Load Calculations (Pergamon Press, London, 1969).

[95] Givohi, B., Man, Climate, and Architecture (Elsevier, Amsterdam, 1969).

[96] Van Straaten, J. F., Thermal Performance of Buildings (Elsevier, Amsterdam, 1967).

[97] Callendar, J. H., (editor-in-chief), Time-Saver Standards for Architectural Design Data, 5th Ed. (McGraw-Hill, New York, 1974).

[98] Van Dusen, M. S., and Finck, J. L., Heat transfer through building walls, Bur. Stds. J. Research 6, 493-522 (1931). RP 291.

[99] Robinson, H. E., Powlitch, F. J., and Dill, R. S., The Thermal Insulating Value of Airspaces, Housing Research Paper 32 (Housing and Home Finance Agency, 1957).

[100] Robinson, H. E., Cosgrove, L. A., and Powell, F. J., Thermal Resistance of Airspaces and Fibrous Insulations Bounded by Reflective Surfaces, NBS Building Materials and Structures Rept. 151 (1957).

[101] Kusuda, T., Proposed procedures for determining building heating and cooling loads for energy calculations, Amer. Soc. Heating, Refrigerating, and Air Conditioning Engrs. Spec. Bulletin, 1-10 (1968).

[102] Mulroy, W. J., Kusuda, T., and Phillips, C. W., Survey of digital computer programs for heating and cooling load calculations, SICCAPUS Bulletin 2(2), 4-8 (1968).

[103] Performance Criteria for Exterior Wall Systems -- Final Report, NBS Rept. 9817 to Federal Housing Administration (1968).

[104] Kusuda, T., Thermal response factors for multi-layer structures of various heat conditions systems, Amer. Soc. Heating, Refrigerating, and Air- Conditioning Engrs. Trans. 75, Part I, 246-271 (1969).

[105] Kusuda, T., Procedure for determining heating and cooling loads for computerized energy calculations, Amer. Soc. Heating, Refrigerating, and Air-Conditioning Engrs. Spec. Bulletin (1971).

[106] Kusuda, T., and Powell, F. J., Use of modern computer programs to evaluate dynamic heat transfer and energy use processes in buildings, pp 407-418 in Performance Concepts in Buildings, NBS Special Publication 361, Vol. 1 (1972).

[107] Powell, F. J., and Robinson, H. E., The Effect of Moisture on the Heat Transfer Performance of Insulated Flat-Roof Constructions, NBS Building Science Series 37 (1971).

[108] Kusuda, T., (editor), Use of Computers for Environmental Engineering Related to Buildings, NBS Building Science Series 39 (1971).

[109] Peavy, B. A., Powell, F. J., and Burch, D. M., Dynamic Thermal Performance of an Experimental Masonry Building, NBS Building Science Series 45 (1973).

[110] Berthier, J., Building Research Translation: Weak Thermal Points or Thermal Bridges, NBS Technical Note 710-7 (1973).

[111] Kusuda, T., NBSLD, Heating and cooling load calculation program, APEC Journal VIII (6) (Winter 1973/74).

[112] Petersen, S. R., Retrofitting Existing Housing for Energy Conservation: An Economic Analysis, NBS Building Science Series 64 (1974).

[113] 7 Ways to Reduce Fuel Consumption in Household Heating...Through Energy Conservation, prepared in cooperation with the Ad Hoc Committee on Fuel Conservation, Office of the Special Assistant to the President for Consumer Affairs and the U. S. Dept. of Commerce, National Bureau of Standards.

[114] 11 Ways to Reduce Energy Consumption and Increase Comfort in Household Cooling, prepared in cooperation with the Office of Consumer Affairs, by the U. S. Department of Commerce, National Bureau of Standards (1972).

[115] Standard Definitions of Terms Relating to Thermal Insulating Materials, C168-67, pp 11-14, Part 18, 1974 Annual Book of ASTM Standards (American Society for Testing and Materials, Philadelphia, 1974).

[116] Standard Method of Test for Thermal Conductivity of Materials by Means of the Guarded Hot Plate, C177-71, pp 15-28, Part 18, 1974 Annual Book of ASTM Standards (American Society for Testing and Materials, Philadelphia, 1974).

[117] Standard Method of Test for Thermal Conductivity of Materials by Means of the Heat Flow Meter, C518-70, pp 188-195, Part 18, 1974 Annual Book of ASTM Standards (American Society for Testing and Materials, Philadelphia, 1974).

[118] Standard Method of Test for Thermal Conductance and Transmittance of Built-Up Sections by Means of the Guarded Hot Box, C236-66 (1971), pp 56-67, Part 18, 1974 Annual Book of ASTM Standards (American Society for Testing and Materials, Philadelphia, 1974).

[119] Mumaw, J. R., Calibrated hot box: an effective means for measuring thermal conductance in large wall sections, pp 193-211, in Heat Transmission Measurements in Thermal Insulations (R. P. Tye, Ed.), ASTM Special Technical Publication 544 (American Society for Testing and Materials, Philadelphia, 1974).

[120] Coleman, E. F., and Heald, R. H., Air Infiltration through Windows, Natl. Bur. Stds. Building Materials and Structures Rept. 45 (1940).

[121] Sasaki, J. R., and Wilson, A. G., Air leakage values for residential windows, Amer. Soc. Heating, Refrigerating, and Air-Conditioning Engrs. Trans. 71, Part II, 81-88 (1965).

[122] Bursey, T., and Green, G. H., Combined thermal and air leakage performance of double windows, Amer. Soc. Heating, Refrigerating, and Air-Conditioning Engrs. Trans. 76, Part II, 215-226 (1970).

[123] Paulsen, E., Performance requirements for windows, pp 375-384 in Performance Concepts in Buildings, NBS Special Publication 361, Vol. 1 (1972).

[124] Wilson, A. G., and Sasaki, J. R., Evaluation of window performance, pp 385-394 in Performance Concepts in Buildings, Special Publication 361, Vol. 1 (1972).

[125] Standard Method of Test for Rate of Air Leakage through Exterior Windows, Curtain Walls, and Doors, E283-73, pp 683-687, Part 18, 1974 Annual Book of ASTM Standards (American Society for Testing and Materials, Philadelphia, 1974).

[126] Flow Measurement, Chapt. 4, PTC19.5;4-1959, Supplement to ASME Power Test Codes, Part 5-Measurement of Quantity of Materials (Amer. Soc. Mech. Engrs., New York, 1959).

[127] Seifert, E., Schallschutz im Fensterbau, Glaswelt 22, 92-100 (1969).

[128] The International System of Units (SI), NBS Special Publication 330, 1974 Edition.

[129] Some References on Metric Information, NBS Special Publication 389 (1973).

[130] Mechtly, E. A., The International System of Units -- Physical Constants and Conversion Factors (Revised), NASA SP-7012 (National Aeronautics and Space Administration, Washington, D. C., 1970).

Appendix A. Metric (SI) Conversion Factors

In view of the present accepted practice in this country for building technology, common U. S. units of measurements have been used throughout this paper. In recognition of the position of the United States as a signatory to the General Conference on Weights and Measures, which gave official status to the (metric) International System of Units (SI) in 1960, and in accordance with the policy of the National Bureau of Standards to promote familiarity with metric units, assistance is given to the reader interested in making use of the coherent system of SI units by giving conversion factors applicable to units used in this publication.

The International System of Units is described in NBS Special Publication 330 [128]; additional references concerning metrication are given in NBS Special Publication 389 [129]. An extensive compilation of factors for converting to SI units has been prepared by Mechtly [130].

Quantity	To convert from	To	Multiply by
Length	inch	meter	0.0254*
	foot	meter	0.3048*
Area	inch^2	meter^2	6.4516×10^{-4}*
	foot^2	meter^2	0.09290
Volume	foot^3	meter^3	0.02832
Volume flow rate	foot^3 min^{-1}	meter^3 sec^{-1}	4.719×10^{-4}
Speed	foot min^{-1}	meter sec^{-1}	5.08×10^{-3}*
	mile hr^{-1}	meter sec^{-1}	0.44704*
Mass	pound(avoirdupois)	kilogram	0.4536
Areal Density	pound(mass) foot^{-2}	kilogram meter^{-2}	4.881
Volumetric Density	pound(mass) foot^{-3}	kilogram meter^{-3}	16.02
Force	pound force (avoirdupois)	newton	4.448
Pressure	inch of water	pascal	249
	inch of mercury	pascal	3.38×10^3
Temperature	Fahrenheit	kelvin	$t_K = \frac{5}{9} (t_F + 459.67)$
	Fahrenheit	Celsius	$t_C = \frac{5}{9} (t_F - 32)$
Heat Flow	Btu (thermochemical) hour^{-1}	watt	0.2929
Specific Heat	Btu lb^{-1} deg F^{-1}	joule kilogram^{-1} kelvin^{-1}	1.000
Thermal Transmittance and Thermal Conductance	Btu hour^{-1} foot^{-2} deg F^{-1}	watt metre^{-2} kelvin^{-1}	5.68
Thermal Resistance	Btu^{-1} hour foot^2 deg F	watt^{-1} metre^2 kelvin	0.176

*Exactly, by definition.

Appendix B. Auxiliary and Filler Walls in Sound Transmission Loss Tests

The sound pressure level measured in the receiving room, from which the transmission loss of the test wall is derived, is determined by the combined transmission of the test wall and the concrete "surround," consisting of the concrete partition in which the test wall is installed. Due to the isolation of the concrete surround, however, transmission due to flanking into the side walls, floor and ceiling of the receiving room is eliminated. If it is known or assumed that the amount of sound energy transmitted by the surround is negligible compared to that transmitted by the test wall, the transmission loss (TL) of the test wall is determined by eq. (6).

If the transmission by the surround is not negligible in relation to that by the test wall, the apparent transmission loss of the test wall as determined by the above formula will be lower than its true value. The smaller the difference between the TL of the surround and that of the test wall, and the larger the area of the surround in relation to the test wall, the larger will be the error in measurement of the TL of the test wall.

Since much of the sound transmission test program involved the relatively small areas of windows in relation to the total transmitting (wall) area from the source room to the receiving room, it was necessary to provide as high a transmission loss as feasible for the wall area (between the two rooms) not occupied by the test item. This was done in two steps. The first step was to build a "filler wall" occupying the entire 9 x 14 ft opening. The construction of this wall is shown in Figure B-1, B-2, and B-3. One part of the construction, which happened to be already in place, was a conventional 2 x 4 in. wood stud drywall with Donn Products resilient channel and 5/8 in. gypsum board on one side and 5/8 in. gypsum board secured directly to the studs on the other side. The space between the studs was filled with 3 1/2 in. of Fiberglas building insulation. This wall had been previously tested and found to have an STC of 52. The curve of TL versus frequency is shown in Figure B-2. The side of the wall with the resilient channel was flush with the surround on the source room side.

To complete the filler wall, additional 2 x 4 in. studs were erected in the opening on separate plates spaced as far as possible from the original wall. The new studs were surfaced on the outer faces with two layers of gypsum board of 5/8 in. and 1/2 in. thickness respectively, and the entire cavity space between the two walls was filled with Fiberglas building insulation. The dissimilar thicknesses were used to reduce the depth of the coincidence dip characteristic of gypsum board.

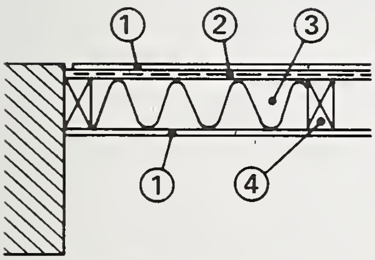
The entire filler wall was tested for sound transmission by the usual procedure, in which the area of the test wall, S = 126 sq ft, was used in eq. (6) to compute transmission loss. The results are shown in Figure B-3, indicating an STC of 63. It was suspected that the concrete surround, having an area of 160 sq ft, was providing significant flanking transmission which would make the apparent TL of the filler wall too low.

To check this possibility, auxiliary construction was added to the entire area of the concrete surround on the source room side. This consisted of 2 x 4 in. wood studs spaced out from the concrete, with one layer each of 5/8 in. and 1/2 in. gypsum board secured to the outer faces and the cavity completely filled with Fiberglas building insulation. The finished surface of the auxiliary wall was 16 in. from the concrete. The gypsum board was continued around the inner perimeter of the auxiliary wall to meet the filler wall, but a small gap was left at the joint which, in turn, was caulked and taped. The bottom side of the perimeter was faced with plywood instead of gypsum board to provide a step for access to the filler wall. The construction is detailed and illustrated in Figures B-4 and B-5.

The combination of the filler wall and the improved surround was again tested for sound transmission. Values of transmission loss can be computed and interpreted from the measured values of sound pressure level L_s and L_r in three different ways.

In the first case, the foregoing procedure is followed in which transmission by the surround is assumed negligible in relation to that by the filler wall, and the area of the filler wall, S = 126 sq ft, is used in eq. (6). This yields apparent values of TL for the filler wall as shown in Figure B-6, with an STC of 72. These values can be considered as

Figure B-1. Filler wall after cutting opening for picture window.



1. 5/8 IN. GYPSUM BOARD
2. DONN DG-8 RESILIENT CHANNEL
3. FIBERGLAS BUILDING INSULATION
4. 2 IN. x 4 IN. STUDS 16 IN. O.C.

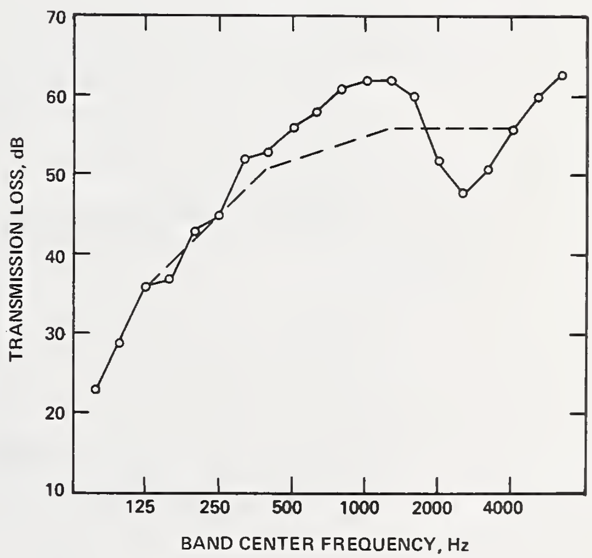


Figure B-2. Sound transmission loss vs frequency data for wood stud drywall with resilient channel and cavity insulation.

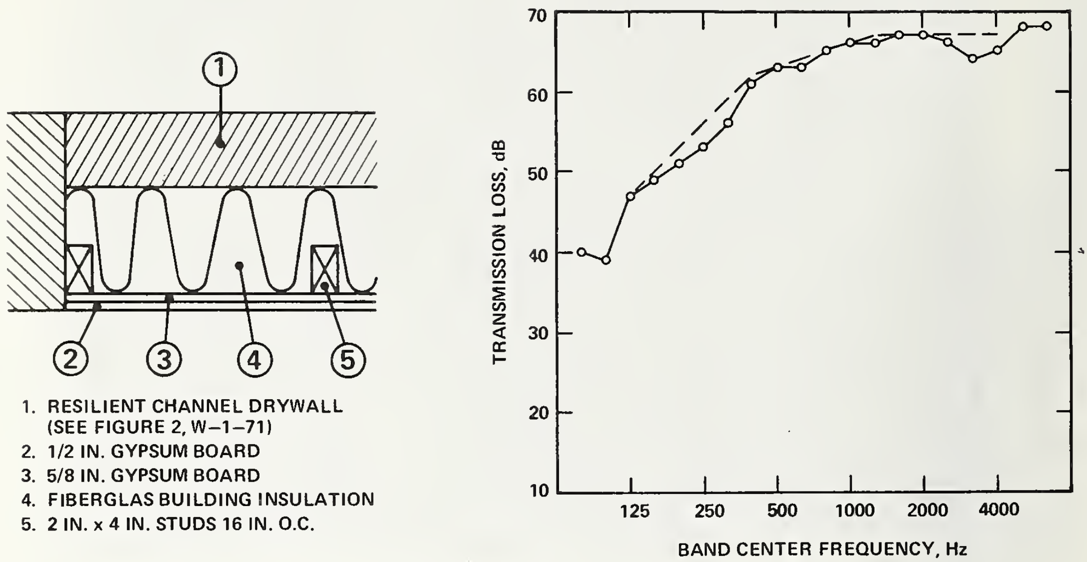


Figure B-3. Apparent sound transmission loss vs frequency data for complete filler wall, concrete surround not covered.

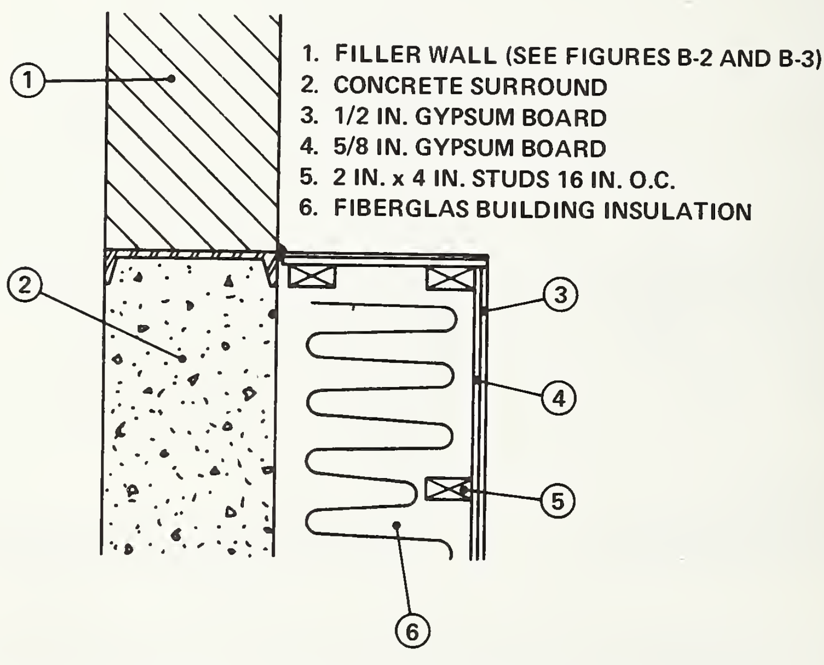


Figure B-4. Auxiliary construction added to concrete surround.

Figure B-5. Filler wall and auxiliary construction over concrete surround.

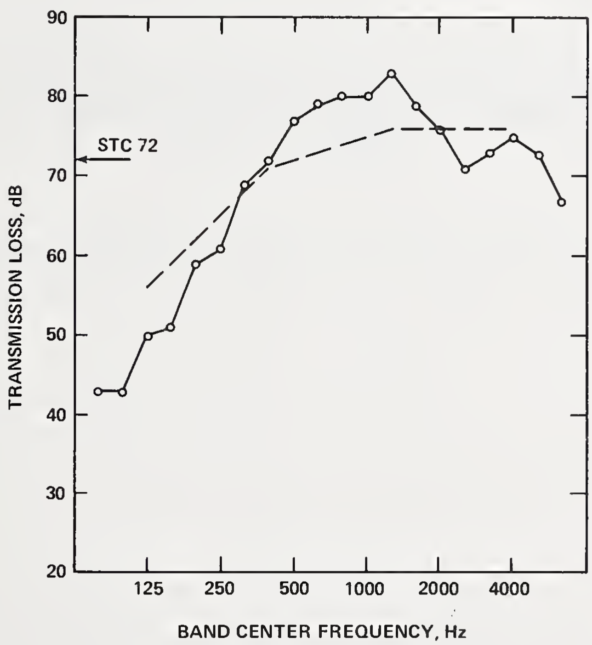


Figure B-6. Apparent sound transmission loss vs frequency data for complete filler wall with auxiliary construction added to concrete surround.

true values for the filler wall if transmission by the surround is assumed negligible. If transmission by the surround is not negligible, then the apparent TL values for the filler wall must be considered as minimum.

In the second case, the TL of the surround can be established in the same way by inserting the area of the surround, S = 160 sq ft, in eq. (6). This will result in apparent TL values one dB higher at all frequencies than those for the filler wall, with an STC of 73. This difference results directly from the relative areas and is given by 10 log (160/126). The values for the surround can likewise be considered as minimum, or as true only if the TL of the filler wall is infinite (negligible transmission).

In the third case, the combined area of the filler wall and surround, S = 286 sq ft, is used to compute TL. This yields TL values 4 dB higher at all frequencies than the values computed for the filler wall alone, with an STC of 76. The TL values computed in this way represent the value which either the filler wall or the surround would have if their TL's were equal at all frequencies. In other words, the total sound energy transmitted by the entire surface of 286 square feet is that which would be accounted for by a single wall of this area having the computed TL value at each frequency. The minimum TL values of the filler wall and surround, respectively, and the equivalent TL value of the filler and surround combined are plotted together in Figure B-7. The latter set of data will be used to estimate the degree of flanking transmission when testing the windows, which will be inserted in the filler wall. The true value of TL for the window is given by the formula:

$$TL_w = 10 \log \left[\frac{1}{\tau_{wa} + \tau_o S_s / S_w} \right] \tag{B-1}$$

where: τ_{wa} = transmission coefficient of window

τ_o = equivalent transmission coefficient of filler wall and surround

S_s = total area of filler wall and surround, less window area

S_w = window area

If the transmittivity of the filler wall and surround, weighted by their combined area in relation to the window area, is much smaller than the transmittivity of the window, then the second term in the denominator of the above equation can be neglected, and the TL true value (TL_w) is essentially equal to the apparent value TL_{wa} and is given by eq. (6), using the window area for S.

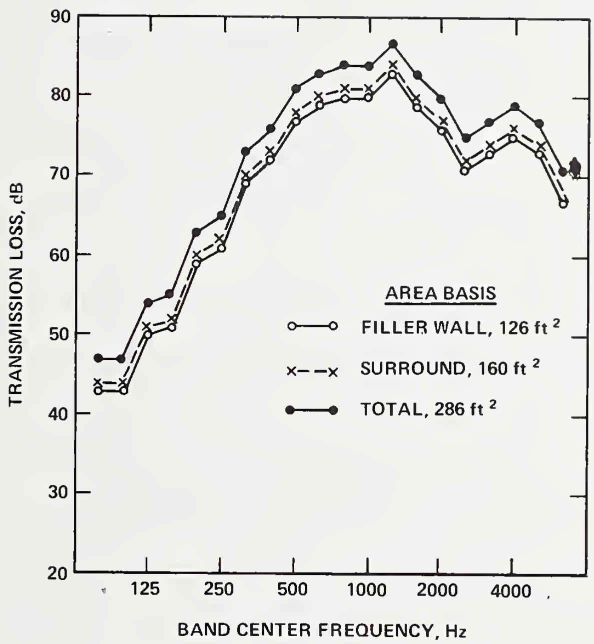


Figure B-7. Apparent sound transmission loss vs frequency data for complete filler wall with auxiliary construction added to concrete wall. The three curves represent computations based on three different values for the wall area.

Appendix C. Detailed Sound Transmission Loss Test Results

Table C-1

Sound Transmission Loss of Exterior Walls

Exterior Finish	Cavity Insulation	Resilient Channel	Test No.	STC
Wood Siding	No	No	W-4-72	37
	Fiberglas Kraft Faced	No	54-71	39
	Fiberglas Friction Fit	No	7-72	39
	Alfol Type 2P	No	6-72	37
	Premium Rock Wool	No	5-72	38
	No	Yes	56-71	43
	Fiberglas Kraft Faced	Yes	55-71	47
Stucco	Fiberglas Kraft Faced	No	50-71	46
	No	Yes	53-71	49
	Fiberglas Kraft Faced	Yes	52-71	57
Brick Veneer	Fiberglas Kraft Faced	No	44-71	56
	No	Yes	46-71	54
	Fiberglas Kraft Faced	Yes	45-71	58

Table C-2

Sound Transmission Loss of Exterior Doors

Door	Weather Strip	Normally Closed		Sealed	
		Test No.	STC	Test No.	STC
Wood, flush solid core	Brass	W-90-71	27	W-91-71	30
Same	Plastic	42-72	27		
Same, plus aluminum storm door	Plastic	40-72	34	41-72	42
Wood, flush hollow core	Brass	92-71	20	93-71	21
Wood, french door	Brass	94-71	26	95-71	31
FRP panel	Plastic	43-72	25	44-72	26
Steel, flush	Magnetic	2-72	28	3-72	28

Notes:

1. All doors were tested in the same frame except the steel door, which was prehung in a different frame.
2. The flush solid core wood door was prehung in frame with brass spring weather stripping supplied. Other wood doors were trimmed as needed to fit this frame.
3. Plastic weather stripping was substituted for the brass in the same frame.
4. The FRP panel door was slightly oversize and made a very tight fit against the plastic weather stripping.

Table C-3

Sound Transmission Loss of Windows

Material	Type	Glazing[1]	Storm Sash Glazing	Storm Sash Separation[2]	Sealed Test No.	Sealed STC	Locked[3] Test No.	Locked[3] STC	Unlocked Test No.	Unlocked STC
Wood	Double hung	ss			W-41-71	29			W-40-71	23
		ss-d			33-71	29				
		ds			32-71	29				
		ds-d			34-71	30				
		in-7/16 in.			31-71	28	24-71	26	25-71	22
		ss	ss	2 1/8 in.	37-71	34				
		ss	ds	2 1/8 in.	36-71	36				
		in-7/16 in.	ss	2 1/8 in.	28-71	35				
		in-7/16 in.	ds	2 1/8 in.	29-71	39				
	Picture	ss-d			8-71	28				
		ds			7-71	29				
		in-1 in.			10-71	34				
		ss-d	ds	3 3/4 in.	11-71	38				
Wood-plastic	Double hung	ss			76-71	29	74-71	26	75-71	26
		in-3/8 in.			82-71	26	81-71	26	80-71	25
		ss	ss	2 3/4 in.	79-71	36	78-71	32	77-71	30
		in-3/8 in.	ss	2 3/4 in.	85-71	36	84-71	33	83-71	33
	Awning	ds			64-71	30	59-71	27		
		in-3/8 in.			68-71	28	67-71	24		

Material	Type	Glazing[1]	Storm Sash Glazing	Storm Sash Separation[2]	Sealed Test No.	Sealed STC	Locked[3] Test No.	Locked[3] STC	Unlocked Test No.	Unlocked STC
	Fixed casement	ds			66-71	31				
	Operable casement	ds					88-71	30	89-71	22
	Sliding glass door	lam-3/16 in.			18-72	31	16-72	26	17-72	26
Aluminum	Sliding	ss			26-72	28	23-72	24		
		ss	ss	1/8 in.	25-72	29	24-72	22		
	Operable casement	ds			21-72	31	19-72	21	20-72	17
	Single hung	in-7/16 in.			29-72	30	27-72	27	28-72	25
Aluminum	Jalousie	1/4 in.			32-72	26	30-72	20		
Single pane 1/4 in. laminated glass					22-72	34				

1. ss = single strength; ds = double strength; d = divided lights; in = insulating glass of indicated overall thickness; lam = laminated safety glass of indicated overall thickness

2. Separation is between panes of main and storm window, averaged for upper and lower sashes

3. Applies also to operable windows mechanically tight shut without separate lock

Table C-4

Sound Transmission Loss of Walls Containing Windows

Wall area, 126 ft^2
Window area, 26 ft^2

Wall	Glazing	Wall alone Test No.	Wall alone STC	Window alone Test No.	Window alone STC	Combination Test No.	Combination STC
Wood siding	Single strength	W-54-71	39	W-8-71	28	W-57-71	35
	1 in. insul. glass		39	10-71	34	58-71	38
Brick veneer	Single strength	W-44-71	56	8-71	28	49-71	35
	1 in. insul. glass		56	10-71	34	48-71	39

Table C-5

Sound Transmission Loss of Windows with Cracks and Openings

A. 6 x 5 ft Picture Window, glazed double strength

Gauged crack around full perimeter = 20.3 ft

Crack Width	Test No.	STC
0 in. (sealed)	W-7-71	29
	9-71	27
1/32 in.	21-71	25
1/16 in.	17-71	21
1/8 in.	15-71	18
1/4 in.	16-71	15

B. 6 x 5 ft Picture Window, glazed 1 in. insulating glass

Gauged crack around half or full perimeter

Crack Width	Perimeter	Test No.	STC
0 in. (sealed)		W-10-71	34
1/32 in.	Half	20-71	29
1/32 in.	Full	19-71	26
1/16 in.	Full	18-71	23
1/8 in.	Full	14-71	19
1/4 in.	Half	13-71	18
1/4 in.	Full	12-71	15

C. 3 x 5 ft Wood Double-Hung, glazed 7/16 in. insulating glass.

Lower sash raised by gauged amounts

Condition	Test No.	STC
Sealed	W-31-71	28
Locked	24-71	26
Unlocked	25-71	22
Open 1/32 in.	26-71	20
Open 1/16 in.	27-71	20

D. 3 x 4 ft Wood-Plastic Awning Window, glazed double strength.

Both sashes cranked open by gauged amounts

Condition	Test No.	STC
Sealed	W-64-71	30
Cranked tight shut	59-71	27
Cranked open 1/32 in.	60-71	24
Cranked open 1/16 in.	61-71	23
Cranked open 1/8 in.	62-71	19
Cranked open 1/4 in.	63-71	17

Table C-5 (continued)

E. 3 x 4 ft Wood-Plastic Awning Window, glazed 3/8 in. insulating glass.

One or both sashes cranked open by gauged amounts

Condition	Test No.	STC
Sealed	W-68-71	28
Cranked tight shut	67-71	24
Upper cranked open 1/32 in.	69-71	24
Both cranked open 1/32 in.	70-71	24
Upper cranked open 1/16 in.	71-71	24
Both cranked open 1/16 in.	72-71	23
Upper cranked open 1/8 in.	73-71	22
Both cranked open 1/8 in.	73A-71	20

T A B L E C-6 S O U N D T R A N S M I S S I O N

TEST NO.	DESCRIPTION	STC	80	100	125
W- 7-71	6 x 5 ft picture window glazed double strength, single light.	29	24	21	23
W- 8-71	6 x 5 ft picture window glazed single strength, divided lights, 16 panes.	28	26	21	20
W- 9-71	Same as W-7-71	27	26	21	22
W-10-71	6 x 5 ft picture window, 1 in glazed insulating glass.	34	28	26	27
W-11-71	Same as W-8-71 plus storm sash, glazed double strength, single light, 3 3/4 in separation between panes.	38	18	21	20
W-12-71	Same as W-10-71 with 1/4 in crack around full sash perimeter (crack area/sash area = .0165) crack depth = 1 13/16 in.	15	20	18	18
W-13-71	Same as W-12-71 but 1/4 in crack around half sash perimeter (crack area/sash area = .00826).	18	21	20	20
W-14-71	Same as W-12-71 but 1/8 in crack (crack area/sash area = .00825).	19	21	19	19
W-15-71	Same as W-7-71 and W-9-71 with 1/8 in. crack around full sash perimeter (crack area/sash area = .00825); crack depth = 1 3/8 in.	18	20	17	17
W-16-71	Same as W-15-71 but 1/4 in. crack (crack area/sash area = .0165).	15	17	16	15
W-17-71	Same as W-15-71 but 1/16 in crack (crack area/sash area = .00413)	21	21	19	17

LOSS PERFORMANCE DATA

FREQUENCY, Hz

160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300
23	21	23	24	24	27	27	28	28	31	32	34	34	30	25	26	31
19	18	21	23	22	25	26	26	26	29	30	31	30	33	30	27	20
21	22	22	24	24	27	27	27	28	30	30	32	32	29	23	26	--
23	20	24	26	28	33	34	37	36	37	38	39	32	35	41	43	46
21	24	29	28	32	34	36	40	41	46	46	46	47	48	41	42	46
15	16	17	17	17	19	19	18	17	13	13	16	17	14	15	17	18
19	17	19	20	20	23	21	21	19	17	17	19	18	16	19	19	20
18	18	18	20	20	22	22	22	19	16	18	22	21	16	18	19	21
16	17	19	18	17	20	20	21	18	18	15	18	20	17	17	19	21
15	15	16	17	15	17	19	18	16	15	13	14	15	15	15	17	18
18	18	19	20	20	22	23	23	22	21	20	22	22	21	22	24	25

TABLE C-6 SOUND TRANSMISSION

TEST NO.	DESCRIPTION	STC	80	100	125
W-18-71	Same as W-12-71 but 1/16 in crack (crack area/sash area = .00413).	23	23	22	21
W-19-71	Same as W-12-71 but 1/32 in crack (crack area/sash area = .00206).	26	25	22	21
W-20-71	Same as W-13-71 but 1/32 in crack (crack area/sash area = .00103).	29	24	24	23
W-21-71	Same as W-15-71 but 1/32 in. crack (crack area/sash area = .00206).	25	22	21	21
W-23-71	3 x 5 ft double hung window, 7/16 in. glazed insulating glass, single light, partially sealed as shown in Fig. C-1.	26	23	22	22
W-24-71	Same as W-23-71 but not sealed	26	22	20	23
W-25-71	Same as W-24-71 but unlocked	22	21	19	21
W-26-71	Same as W-25-71 but lower sash raised 1/32 in.	20	21	19	21
W-27-71	Same as W-25-71 but lower sash raised 1/16 in.	20	20	18	20
W-28-71	3 x 5 ft double hung window, 7/16 in. glazed insulating glass, single light plus storm sash, glazed single strength, single sealed separation between panes: upper 1 1/2 in, lower 2 13/16 in.	35	23	19	26
W-29-71	Same as W-28-71 but storm sash glazed double strength.	39	22	22	27

L O S S   P E R F O R M A N C E   D A T A

F R E Q U E N C Y, Hz

160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300
18	19	20	23	21	26	24	24	22	21	22	26	25	22	23	24	26
19	19	21	23	23	28	27	26	25	24	27	29	28	26	27	27	29
19	20	20	25	26	29	29	30	28	28	29	32	31	29	30	31	33
18	20	21	22	21	25	24	26	24	25	24	27	27	26	24	26	28
20	22	22	20	20	21	22	25	24	28	31	32	33	34	34	32	34
20	21	21	20	20	21	21	23	24	28	29	30	30	29	30	30	32
18	19	20	18	19	20	21	22	22	25	25	26	24	22	21	24	29
17	17	18	18	18	19	20	21	20	23	23	22	20	19	18	19	24
16	18	19	18	17	18	19	21	20	22	22	22	20	19	19	21	24
20	19	22	24	28	33	36	38	39	43	43	45	48	50	53	50	47
23	25	28	30	31	35	38	40	40	45	46	47	48	50	49	50	45

TABLE C-6 SOUND TRANSMISSION

TEST NO.	DESCRIPTION	STC	80	100	125
W-31-71	Same as W-28-71 but no storm sash.	28	23	22	24
W-32-71	3 x 5 ft double hung window glazed double strength, single light, sealed.	29	23	21	25
W-33-71	3 x 5 ft double hung window, glazed single strength divided, 8 lights each sash, sealed.	29	20	20	21
W-34-71	Same as W-32-71 but divided, 8 lights each sash.	30	21	20	23
W-35-71	Same as W-33-71 but single light, unlocked partially sealed as shown in Fig. C-1.	25	21	18	20
W-36-71	Same as W-33-71 but single light plus storm sash, glazed double strength, single light, separation between panes: upper 1 7/8 in, lower 3 3/16 in.	36	24	20	26
W-37-71	Same as W-36-71 but storm sash glazed single strength.	34	23	19	23
W-38-71	Same as W-35-71 but not sealed, lower sash raised 1/16 in.	21	19	17	19
W-39-71	Same as W-38-71 but lower sash raised 1/32 in.	21	19	17	18
W-40-71	Same as W-35-71 but normally closed, not sealed.	23	21	18	20
W-41-71	Same as W-35-71 but completely sealed.	29	23	20	20

L O S S   P E R F O R M A N C E   D A T A

F R E Q U E N C Y, Hz

160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300
22	24	24	21	23	21	23	26	27	33	36	37	39	40	40	35	34
21	21	22	25	25	28	28	28	29	32	31	33	33	30	27	29	33
18	22	22	23	22	26	27	27	27	30	32	33	33	32	31	30	33
20	23	24	25	25	29	29	28	29	32	32	32	32	31	31	33	35
17	19	18	18	20	23	23	23	23	27	28	30	30	32	31	29	27
22	23	25	28	29	33	37	40	40	46	46	47	48	49	48	48	37
22	18	20	23	28	31	35	38	40	43	44	45	46	50	51	46	41
16	16	17	18	19	20	21	22	22	23	23	23	21	17	18	20	22
17	17	17	19	19	20	22	23	22	23	24	24	21	19	19	20	23
15	18	18	20	19	22	22	23	22	26	27	27	27	26	25	24	26
18	21	21	22	23	26	26	27	27	29	31	32	33	34	33	29	28

TABLE C-6 SOUND TRANSMISSION

TEST NO.	DESCRIPTION	STC	80	100	125
W-44-71	Brick veneer wood stud exterior wall, cavity insulation. See Fig. C-2.	56	33	31	39
W-45-71	Same as W-44-71 plus resilient channel. See Fig. C-2.	58	32	34	38
W-46-71	Same as W-45-71 but no insulation. See Fig. C-2.	54	31	33	33
W-48-71	Same as W-44-71 but penetrated by W-10-71.	39	30	29	28
W-49-71	Same as W-44-71 but penetrated by W-8-71.	35	26	24	25
W-50-71	Stucco wood stud exterior wall with cavity insulation. See Fig. C-3.	46	37	25	25
W-52-71	Same as W-50-71 plus resilient channel. See Fig. C-3.	57	29	35	35
W-53-71	Same as W-52-71 but no insulation. See Fig. C-3.	49	27	28	28
W-54-71	Wood siding wood stud exterior wall with cavity insulation. See Fig. C-4.	39	25	19	18
W-55-71	Same as W-54-71 plus resilient channel. See Fig. C-4.	47	22	24	26
W-56-71	Same as W-55-71 but no insulation. See Fig. C-4.	43	22	21	24

L O S S   P E R F O R M A N C E   D A T A

F R E Q U E N C Y, Hz

160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300
36	42	46	49	51	54	56	58	61	67	67	69	69	70	73	75	69
39	46	47	52	54	57	58	60	61	69	68	71	71	72	74	77	68
34	41	41	47	50	52	55	59	61	65	66	68	68	69	72	75	67
26	27	30	33	34	38	40	39	38	41	42	45	40	42	49	51	51
27	27	28	28	30	31	33	35	34	36	37	39	40	42	39	37	39
30	42	41	44	43	45	45	46	45	46	48	50	50	50	55	58	62
41	50	49	53	55	58	58	58	58	59	59	60	58	57	60	64	61
32	34	37	41	46	50	50	50	51	54	55	57	55	55	58	62	63
18	28	30	33	34	40	42	45	47	50	50	51	50	50	53	54	53
27	30	35	41	43	49	52	56	58	59	60	61	60	58	60	62	63
22	26	32	35	38	43	45	50	51	56	57	58	56	54	57	59	53

TABLE C-6 SOUND TRANSMISSION

TEST NO.	DESCRIPTION	STC	80	100	125
W-57-71	Same as W-54-71 but penetrated by W-8-71.	35	25	21	19
W-58-71	Same as W-54-71 but penetrated by W-10-71.	38	26	21	18
W-59-71	3 x 4 ft awning window, glazed double strength, both sashes cranked shut.	27	21	19	22
W-60-71	Same as W-59-71 but both sashes opened 1/32 in.	24	21	19	20
W-61-71	Same as W-59-71 but both sashes opened 1/16 in.	22	19	20	20
W-62-71	Same as W-59-71 but both sashes opened 1/8 in.	19	19	17	16
W-63-71	Same as W-59-71 but both sashes opened 1/4 in.	17	17	15	14
W-64-71	Same as W-59-71 but sealed.	30	16	20	21
W-65-71	3 x 5 ft fixed casement window, single light, glazed double strength.	32	23	21	24
W-66-71	Same as W-65-71 but sealed.	31	23	21	23
W-67-71	3 x 4 ft awning window, 3/8 in. glazed insulating glass, both sashes cranked shut.	24	21	22	21

L O S S   P E R F O R M A N C E   D A T A

F R E Q U E N C Y, Hz

160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300
20	25	28	29	29	32	33	34	35	38	39	40	41	42	39	37	39
20	24	27	32	32	37	40	42	44	44	45	45	39	41	47	51	51
19	23	25	26	26	28	28	27	26	24	23	27	30	32	31	31	34
18	21	22	23	24	25	24	23	22	20	20	23	26	29	29	31	32
17	20	22	22	23	24	23	23	21	18	19	23	26	27	28	29	31
18	19	19	21	21	22	22	21	18	16	15	22	23	25	25	27	28
13	16	18	18	18	20	19	18	15	13	13	18	20	23	23	23	25
21	23	25	26	26	28	28	28	28	31	32	35	36	35	32	31	36
21	22	25	26	27	29	30	30	32	33	34	36	37	35	30	32	35
20	24	23	26	26	29	29	30	30	33	35	37	36	35	30	31	35
20	24	24	22	20	19	22	25	24	23	23	25	28	33	33	30	31

TABLE C-6 SOUND TRANSMISSION

TEST NO.	DESCRIPTION	STC	80	100	125
W-68-71	Same as W-67-71 but sealed.	28	22	23	20
W-69-71	Same as W-67-71 but upper sash opened 1/32 in.	24	--	21	20
W-70-71	Same as W-67-71 but both sashes opened 1/32 in.	24	20	22	22
W-71-71	Same as W-67-71 but upper sash opened 1/16 in.	24	22	21	22
W-72-71	Same as W-67-71 but both sashes opened 1/16 in.	23	22	22	20
W-73-71	Same as W-67-71 but upper sash opened 1/8 in.	22	21	21	20
W-73A-71	Same as W-67-71 but both sashes opened 1/8 in.	20	20	20	18
W-74-71	3 x 5 ft double hung window, glazed single strength, single light, locked.	26	20	19	19
W-75-71	Same as W-74-71 but unlocked.	26	21	20	20
W-76-71	Same as W-74-71 but sealed.	29	22	19	21
W-77-71	Same as W-75-71 plus combination storm sash, glazed single strength, single light, separation between panes: upper 2 1/4 in., lower 3 3/8 in.	30	18	16	15

L O S S   P E R F O R M A N C E   D A T A

F R E Q U E N C Y, Hz

160	200	250	315	400	500	613	800	1000	1250	1630	2000	2500	3150	4000	5000	6300
20	25	25	21	19	20	23	26	30	32	33	34	36	37	34	29	31
21	23	22	22	19	18	22	24	23	24	23	25	28	32	34	29	31
21	24	24	22	19	20	22	25	25	22	23	25	27	31	32	30	31
21	25	22	21	19	19	22	25	23	22	23	25	28	32	33	30	31
20	25	24	22	18	19	22	23	23	21	22	23	27	31	32	29	30
18	22	22	21	19	18	21	23	22	18	19	24	26	30	30	29	29
20	22	21	20	19	19	21	22	20	16	17	22	26	28	30	28	28
17	18	18	22	22	25	25	26	24	27	28	30	28	28	28	26	28
20	19	20	23	22	25	25	26	26	29	29	30	25	25	28	28	30
17	19	21	23	24	25	26	27	27	31	32	33	33	35	36	32	30
15	16	18	20	21	26	30	32	34	37	37	37	36	37	38	37	37

TABLE C-6 SOUND TRANSMISSION

TEST NO.	DESCRIPTION	STC	80	100	125
W-78-71	Same as W-77-71 but locked.	32	19	15	14
W-79-71	Same as W-78-71 but storm sash sealed.	36	20	19	18
W-80-71	3 x 5 ft double hung window, 3/8 in. glazed insulating glass, single light, unlocked.	25	21	22	23
W-81-71	Same as W-80-71 but locked.	26	21	23	22
W-82-71	Same as W-80-71 but locked and sealed	26	21	21	23
W-83-71	Same as W-80-71 plus combination storm sash, glazed single strength, single light.	33	21	19	19
W-84-71	Same as W-83-71 but locked.	33	20	17	18
W-85-71	Same as W-84-71 but storm sash sealed.	36	20	19	21
W-88-71	4 x 5 ft casement window, both sashes operable, glazed double strength, both sashes locked.	30	24	23	24
W-89-71	Same as W-88-71 but both sashes unlocked.	22	17	22	21
W-90-71	3 x 7 ft solid core wood door, mounted in frame, brass weather strip.	27	20	24	21

L O S S   P E R F O R M A N C E   D A T A

F R E Q U E N C Y, Hz

160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300
16	19	20	22	23	30	33	36	37	40	40	41	40	40	43	43	40
19	24	25	25	28	33	37	40	40	41	41	42	44	45	48	46	43
21	21	23	18	21	19	22	24	23	29	32	31	28	28	30	29	31
21	21	22	19	20	19	21	24	24	29	30	32	33	34	32	30	30
21	23	23	20	21	20	21	24	24	29	33	34	37	37	39	33	32
16	21	24	24	25	30	32	35	37	41	41	42	40	41	45	43	40
17	21	22	24	25	30	32	35	37	41	42	42	42	45	46	44	40
19	25	25	27	29	33	36	39	37	42	43	42	43	47	49	46	43
22	24	24	26	26	29	28	29	28	28	28	32	34	34	31	32	34
19	21	21	23	21	25	23	23	22	21	20	20	23	25	28	28	31
24	27	27	27	27	30	30	28	26	25	25	25	27	28	29	31	35

TABLE C-6 SOUND TRANSMISSION

TEST NO.	DESCRIPTION	STC	80	100	125
W-91-71	Same as W-90-71 but sealed into frame.	30	22	22	25
W-92-71	3 x 7 ft hollow core wood door, mounted in frame, brass weather strip.	20	13	11	14
W-93-71	Same as W-92-71 but sealed into frame.	21	15	16	16
W-94-71	3 x 7 ft wood french door, 12 lights glazed single strength, mounted in frame, brass weather strip.	26	21	24	20
W-95-71	Same as W-94-71 but sealed into frame.	31	19	22	23
W- 2-72	3 x 7 ft hollow steel door, mounted in frame, magnetic weather strip.	28	18	22	23
W- 3-72	Same as W-2-72 but sealed into frame.	28	18	24	22
W- 4-72	Wood siding wood stud exterior wall. See Fig. C-4.	37	23	19	16
W- 5-72	Same as W-4-72 but with cavity insulation. See Fig. C-4.	38	23	17	16
W- 6-72	Same as W-5-72 but different cavity insulation. See Fig. C-4.	37	22	17	18
W- 7-72	Same as W-5-72 but different cavity insulation. See Fig. C-4.	37	24	16	13

L O S S   P E R F O R M A N C E   D A T A

F R E Q U E N C Y, Hz

160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300
22	26	25	28	29	30	30	30	29	31	31	34	32	30	30	31	35
14	14	15	15	17	17	17	15	18	22	22	22	24	27	29	29	30
15	15	15	16	17	18	17	15	18	24	24	27	28	30	32	32	33
20	24	25	23	24	28	29	28	28	25	25	23	25	27	28	30	32
20	24	23	24	24	26	29	30	30	32	32	34	35	36	35	35	36
21	25	26	26	27	28	29	31	31	32	27	24	32	36	39	39	38
21	27	28	28	29	30	31	32	33	33	27	24	34	35	37	38	34
16	22	26	33	35	36	39	43	46	50	51	52	51	48	49	51	53
17	27	31	34	35	38	42	45	46	49	51	53	53	50	52	51	54
16	22	26	32	34	38	39	43	46	51	52	55	53	52	52	53	54
16	26	31	36	36	39	41	46	46	49	50	52	51	49	49	50	51

T A B L E C-6 S O U N D T R A N S M I S S I O N

TEST NO.	DESCRIPTION	STC	80	100	125
W-16-72	6 x 7 ft sliding glass door, glazed 3/16 in. safety glass, locked.	26	20	24	25
W-17-72	Same as W-16-72 but unlocked.	26	25	25	25
W-18-72	Same as W-16-72 but completely sealed.	31	24	25	23
W-19-72	3 x 4 ft aluminum casement window, glazed double strength, 'locked.	21	21	19	20
W-20-72	Same as W-19-72 but unlocked.	17	16	15	15
W-21-72	Same as W-19-72 but sealed.	31	17	19	24
W-22-72	3 x 4 ft laminated glass, double sheets 1/8 in. glass laminated to inner clear damping layer, sealed in heavy wood frame.	34	22	26	27
W-23-72	3 x 4 ft aluminum sliding window, glazed single strength, closed and latched.	24	17	19	21
W-24-72	Same as W-23-72 plus storm sash, glazed single strength, separation between panes: one side 1/16 in., other side 3/16 in.	22	19	20	22
W-25-72	Same as W-24-72 but storm sash sealed.	29	19	22	26
W-26-72	Same as W-23-72 but sealed.	28	17	20	23

L O S S   P E R F O R M A N C E   D A T A

F R E Q U E N C Y, Hz

160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300
24	23	25	25	24	26	28	29	29	29	28	26	23	24	26	29	33
23	21	24	25	26	27	27	27	28	29	28	25	23	23	25	29	33
24	25	26	27	28	30	30	31	32	34	34	31	27	30	34	37	39
17	16	16	17	16	18	18	19	20	22	22	23	25	28	28	29	31
14	14	13	15	14	15	17	18	18	17	16	15	18	21	25	26	27
20	24	26	26	28	29	29	31	31	34	34	35	35	33	31	32	36
25	26	28	30	30	33	33	33	33	34	35	36	36	38	41	42	44
17	17	17	20	19	22	22	24	22	23	25	29	28	30	31	30	29
17	19	18	19	18	20	19	19	19	22	21	25	26	29	31	30	31
22	23	22	22	22	24	25	26	28	32	33	35	36	38	38	39	37
21	20	20	21	22	24	25	27	27	31	31	34	35	38	38	35	31

T A B L E C-6 S O U N D T R A N S M I S S I O N

TEST NO	DESCRIPTION	STC	80	100	125
W-27-72	3 x 4 ft aluminum single hung window, 7/16 in. glazed insulating glass, locked.	27	14	21	25
W-28-72	Same as W-27-72 but unlocked.	25	16	22	23
W-29-72	Same as W-27-72 but sealed.	30	15	24	25
W-30-72	3 x 4 ft jalousie window, glazed 1/4 in. glass, 4 1/2 in. wide louvers with 1/2 in overlap, cranked tight shut.	20	21	13	14
W-32-72	Same as W-30-72 but all horizontal and vertical joints sealed.	26	20	17	26
W-40-72	3 x 7 ft solid core wood door plus aluminum storm door, glazed single strength, main door normally closed in frame against extruded plastic weather strip.	34	20	19	20
W-41-72	Same as W-40-72 but both doors sealed.	42	19	23	28
W-42-72	Same as W-40-72 but without storm door.	27	20	24	28
W-43-72	3 x 7 ft fiberglass reinforced plastic panel door, mounted in frame, extruded plastic weather strip.	25	21	23	25
W-44-72	Same as W-43-72 but sealed.	26	19	22	25

L O S S P E R F O R M A N C E D A T A

F R E Q U E N C Y, Hz

160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300
19	21	22	21	18	22	25	26	26	29	31	32	31	34	38	35	--
20	22	21	21	18	22	24	25	25	26	28	26	27	29	33	34	33
24	23	23	23	21	24	26	30	30	34	35	37	38	40	42	39	37
13	14	13	16	17	20	18	19	17	19	20	20	21	24	23	25	25
26	26	26	29	29	28	27	26	26	25	25	25	25	27	29	30	33
22	22	24	26	27	33	33	35	35	41	40	36	35	36	37	40	--
28	29	30	37	37	39	39	43	43	49	48	48	52	54	54	55	54
26	24	28	27	28	29	29	28	26	28	27	25	26	27	27	28	34
23	24	23	25	27	28	27	28	27	27	21	24	28	33	37	40	41
23	25	25	24	24	29	26	27	27	27	22	24	28	33	38	42	42

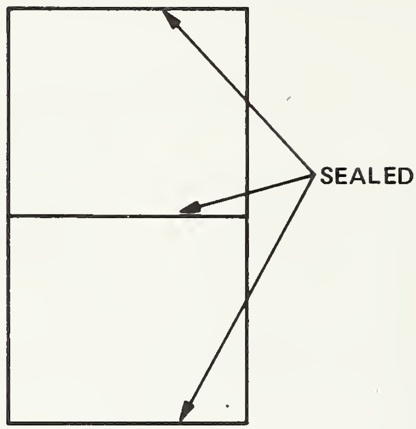
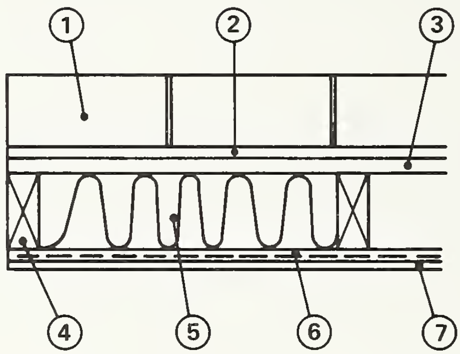
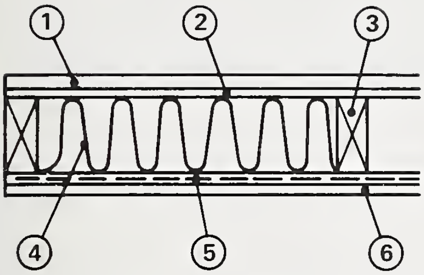


Figure C-1. Regions which were sealed for Test W-23-71.



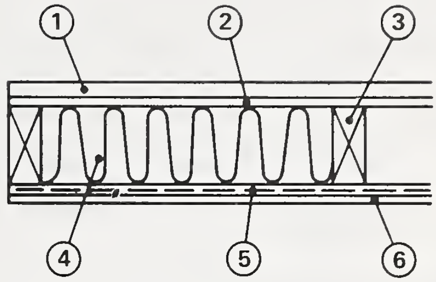
1. FACE BRICK
2. 1/2 IN. AIR SPACE, WITH METAL TIES
3. 3/4 IN. INSULATION BOARD SHEATHING
4. 2 IN. x 4 IN. STUDS 16 IN. O.C.
5. FIBERGLAS BUILDING INSULATION (W–44–71 AND W–45–71 ONLY)
6. NATIONAL GYPSUM RESILIENT CHANNEL (W–45–71 AND W–46–71 ONLY)
7. 1/2 IN. GYPSUM BOARD SCREWED TO CHANNEL

Figure C-2. Detail of brick-veneer, wood-stud exterior walls.



1. 7/8 IN. STUCCO
2. NO. 15 FELT BUILDING PAPER AND 1 IN. WIRE MESH
3. 2 IN. x 4 IN. STUDS 16 IN. O.C.
4. FIBERGLAS BUILDING INSULATION (W–50–71 AND W–52–71 ONLY)
5. NATIONAL GYPSUM RESILIENT CHANNEL (W–52–71 AND W–53–71 ONLY)
6. 1/2 IN. GYPSUM BOARD SCREWED TO CHANNEL

Figure C-3. Detail of stucco, wood-stud exterior walls.



1. 5/8 IN. x 10 IN. REDWOOD SIDING
2. 1/2 IN. INSULATION BOARD SHEATHING
3. 2 IN. x 4 IN. WOOD STUDS 16 IN. O.C.
4. FIBERGLAS BUILDING INSULATION (W–54–71 AND W–55–71 ONLY)

   3 IN. PREMIUM BRAND PAPER ENCLOSED BUILDING INSULATION (W–5–72 ONLY)

   ALFOL TYPE 2P REFLECTIVE-TYPE INSULATION (W–6–71 ONLY)

   3 1/2 IN. FIBERGLAS FRICTION FIT INSULATION (W–7–72 ONLY)
5. NATIONAL GYPSUM RESILIENT CHANNEL (W–55–71 AND W–56–71 ONLY)
6. 1/2 IN. GYPSUM BOARD SCREWED TO CHANNEL

Figure C-4. Detail of wood-siding, wood-stud exterior walls.

Appendix D. Detailed Thermal Test Results

Table D-1. Thermal test data for walls, doors and windows

Test No.	Wall Description	Pressure Differential	Air Leakage	Mean Wall Temp.	Hot Surface Temp.	Cold Surface Temp.	Mean Hot Air Temp.	Mean Cold Air Temp.
		in. water	$ft^3 min^{-1}$	°F	°F	°F	°F	°F
TT-001-71	2 x 4 in. studs on 16 in. centers, 1/2 in. gypsum board interior surface 1/2 in. wood fiber sheathing plus 10 in. wide redwood lap siding exterior surface. No insulation in cavities.	0	--	24.4	58.3	-9.4	71.2	-21.7
TT-018-71	Same as TT-001-71	0	--	27.6	63.2	-7.9	77.1	-20.1
TT-019-71	Same as TT-001-71	0.50	0.8	27.2	63.0	-8.4	76.3	-20.5
TT-002-71	Same construction as above but with Fiberglas 3-1/2 in. Friction Fit Building Insulation in cavities, polyethylene vapor barrier.	0	--	24.1	67.6	-19.2	73.7	-23.6
TT-022-71	Same as TT-002-71	0	--	26.6	72.2	-18.9	78.9	-23.8
TT-023-71	Same as TT-002-71	0.50	2.1	26.2	72.0	-19.4	78.8	-23.8
TT-003-71	Same as TT-002-71	0	--	61.0	105.0	17.0	111.4	12.0
TT-004-71	Same as TT-002-71	0.50	5.2	60.3	103.8	16.7	110.5	12.0
TT-005-71	Same as TT-002-71	0	--	99.5	138.9	60.0	144.7	55.7
TT-006-71	Same as TT-002-71	0.50	6.7	98.5	137.4	59.6	146.8	55.6
TT-014-71	Same construction as above but with Alfol Type 2P Insulation inset stapled in cavities.	0	--	27.9	66.9	-10.9	76.5	-18.3
TT-015-71	Same as TT-014-71	0.50	0.1	27.9	66.8	-11.0	76.5	-18.3
TT-030-72	Same as above but with Premium Brand 3 in. Paper Enclosed Rock Wool Bldg. Insul. in cavities.	0	--	26.0	67.9	-15.9	74.9	-20.0
TT-031-72	Same as TT-030-72	0.25	1.2	24.6	67.6	-18.2	74.7	-22.9
TT-038-72	Same as above but with Fiberglas 3-1/2 in. Kraft Faced Building Insulation in cavities.	0	--	25.7	68.5	-17.0	74.5	-21.1
TT-039-72	Same as TT-038-72	0.25	0.7	25.4	67.9	-16.9	73.9	-21.1
TT-042-72	Same as TT-038-72 but with gypsum board on Donn Products DG-8 resilient channel.	0	--	25.1	69.3	-19.1	74.4	-22.0
TT-043-72	Same as TT-042-72	0.25	0.8	24.8	68.7	-19.0	73.9	-22.4

Table D-1 (continued)

Test No.	Net Heat Flow	Apparent Amount of Net Heat Flow due to Air Leakage	Effective* Thermal Conductance (surface-to-surface)	Effective* Thermal Transmittance (air-to-air)	Effective* Hot Air Film Conductance	Effective* Cold Air Film Conductance	Effective* Thermal Resistance (surface-to-surface)
	$Btu\ hr^{-1}$	$Btu\ hr^{-1}$	$Btu\ hr^{-1}\ ft^{-2}\ {}^{\circ}F^{-1}$	$Btu\ hr^{-1}\ ft^{-2}\ {}^{\circ}F^{-1}$	$Btu\ hr^{-1}\ ft^{-2}\ {}^{\circ}F^{-1}$	$Btu\ hr^{-1}\ ft^{-2}\ {}^{\circ}F^{-1}$	$Btu^{-1}\ hr\ ft^{2}\ {}^{\circ}F$
TT-001-71	2280	--	0.267	0.195	1.4	1.5	3.75
TT-018-71	2370	--	0.265	0.194	1.3	1.5	3.77
TT-019-71	2390	85	0.266	0.196	1.4	1.6	3.76
TT-002-71	930	--	0.085	0.076	1.2	1.7	11.76
TT-022-71	1005	--	0.087	0.078	1.2	1.7	11.49
TT-023-71	1040	235	0.090	0.080	1.2	1.9	11.11
TT-003-71	1020	--	0.092	0.081	1.3	1.6	10.87
TT-004-71	1545	550	0.141	0.125	1.8	2.6	7.09
TT-005-71	1020	--	0.102	0.091	1.4	1.9	9.80
TT-006-71	1540	660	0.157	0.134	1.3	3.1	6.37
TT-014-71	1495	--	0.152	0.125	1.2	1.6	6.58
TT-015-71	1510	10	0.154	0.126	1.2	1.6	6.49
TT-030-72	1090	--	0.104	0.091	1.3	2.1	9.62
TT-031-72	1150	125	0.106	0.093	1.3	1.9	9.43
TT-038-72	900	--	0.083	0.074	1.2	1.7	12.05
TT-039-72	915	70	0.084	0.076	1.2	1.8	11.90
TT-042-72	880	--	0.079	0.072	1.4	2.4	12.66
TT-043-72	900	85	0.082	0.074	1.4	2.1	12.20

*Effective refers to the value calculated from measured heat flow. In tests with an imposed pressure difference, this value includes energy consumed in heating the leakage air from cold side to warm side temperature.

Table D-1. (continued)

Test No.	Wall Description	Pressure Differential	Air Leakage	Mean Wall Temp.	Hot Surface Temp.	Cold Surface Temp.	Mean Hot Air Temp.	Mean Cold Air Temp.
		in. water	$ft^3 min^{-1}$	°F	°F	°F	°F	°F
TT-020-71	Same as above but with Fiberglas 3-1/2 in. Friction Fit Building Insulation in cavities, polyethylene vapor barrier, and wood doublehung window, 3 x 5 ft., single glazed sashes, locked.	0	--	27.7	70.3	-14.8	78.1	-21.4
TT-021-71	Same as TT-020-71	0.25	22.5	27.1	68.7	-14.4	75.9	-20.5
TT-024-71	Same as TT-020-71 but with window unlocked.	0	--	28.6	71.1	-13.8	78.0	-23.0
TT-025-71	Same as TT-024-71	0.25	30.2	29.3	69.0	-10.3	75.8	-16.1
TT-026-72	Same as TT-020-71 plus single glazed wood storm window.	0	--	27.6	71.7	-16.4	78.3	-23.1
TT-027-72	Same as TT-026-72	0.25	32.6	27.6	69.1	-13.9	75.3	-19.8
TT-028-72	Same as TT-026-72 but with window unlocked.	0	--	28.7	71.8	-14.3	77.3	-20.8
TT-029-72	Same as TT-028-72	0.25	39.7	28.2	68.7	-12.3	73.3	-18.0
TT-032-72	Same as TT-020-71 except double glazed sashes.	0	--	26.0	68.1	-16.0	74.5	-22.4
TT-033-72	Same as TT-032-72	0.25	39.7	28.4	68.2	-11.3	74.2	-17.2
TT-034-72	Same as TT-032-72 but with window unlocked.	0	--	27.2	70.3	-15.9	76.8	-22.8
TT-035-72	Same as TT-034-72	0.25	50.1	32.4	69.7	-4.9	74.4	-10.1
TT-040-72	Same construction as above but with wood picture window, 6 x 5 ft., single glazed, divided light.	0	--	24.5	57.1	-8.1	72.1	-20.4
TT-046-72	Same as TT-040-72	0.25	3.2	26.2	58.1	-5.6	73.1	-17.3
TT-044-72	Same construction as above but with wood picture window, 6 x 5 ft., double glazed, single light.	0	--	24.8	61.2	-11.6	72.0	-21.4
TT-045-72	Same as TT-044-72	0.25	4.9	24.7	61.5	-12.0	72.8	-21.6
TT-049-72	Same construction as above but with pre-hung, 1-3/4 in. thick solid wood flush door, 3 ft. x 6 ft.-8 in. Spring brass weatherstrip on top and sides, half-round plastic closure strip at bottom. Fiberglas 3-1/2 in. Friction Fit Building Insulation in cavities.	0	--	26.0	66.6	-14.4	72.7	-20.6

Table D-1 (continued)

Test No.	Net Heat Flow	Apparent Amount of Net Heat Flow due to Air Leakage	Effective* Thermal Conductance (surface-to-surface)	Effective* Thermal Transmittance (air-to-air)	Effective* Hot Air Film Conductance	Effective* Cold Air Film Conductance	Effective* Thermal Resistance (surface-to-surface)
	Btu hr^{-1}	Btu hr^{-1}	Btu hr^{-1} ft^{-2} $°F^{-1}$	Btu hr^{-1} ft^{-2} $°F^{-1}$	Btu hr^{-1} ft^{-2} $°F^{-1}$	Btu hr^{-1} ft^{-2} $°F^{-1}$	Btu^{-1} hr ft^2 °F
TT-020-71	1670	--	0.156	0.133	1.7	2.0	6.41
TT-021-71	3560	2345	0.340	0.293	3.9	4.6	2.94
TT-024-71	1730	--	0.162	0.136	2.0	1.5	6.17
TT-025-71	3935	2995	0.394	0.340	4.6	5.4	2.54
TT-026-72	1410	--	0.127	0.110	1.7	1.7	7.87
TT-027-72	4110	3350	0.393	0.343	5.3	5.5	2.54
TT-028-72	1410	--	0.130	0.114	2.0	1.7	7.69
TT-029-72	4610	3915	0.452	0.401	8.0	6.4	2.21
TT-032-72	1420	--	0.134	0.116	1.8	1.8	7.46
TT-033-72	4665	3920	0.466	0.405	6.2	6.3	2.15
TT-034-72	1465	--	0.135	0.117	1.8	1.8	7.41
TT-035-72	5335	4570	0.568	0.501	9.1	8.1	1.76
TT-040-72	2135	--	0.260	0.183	1.1	1.4	3.85
TT-046-72	2260	310	0.282	0.198	1.2	1.5	3.55
TT-044-72	1585	--	0.173	0.135	1.2	1.3	5.78
TT-045-72	1960	500	0.212	0.165	1.4	1.6	4.72
TT-049-72	1380	--	0.135	0.117	1.8	1.8	7.41

*Effective refers to the value calculated from measured heat flow. In tests with an imposed pressure difference, this value includes energy consumed in heating the leakage air from cold side to warm side temperature.

Table D-1. (continued)

Test No.	Wall Description	Pressure Differential	Air Leakage	Mean Wall Temp.	Hot Surface Temp.	Cold Surface Temp.	Mean Hot Air Temp.	Mean Cold Air Temp.
		in. water	$ft^3 min^{-1}$	°F	°F	°F	°F	°F
TT-050-72	Same as TT-049-72	0.25	21.7	25.1	64.6	-14.2	70.8	-20.2
TT-055-72	Same as TT-049-72 but with aluminum storm door.	0	--	27.2	67.7	-13.1	74.8	-20.0
TT-056-72	Same as TT-055-72	0.25	19.9	25.5	65.3	-14.2	73.3	-19.7
TT-059-72	Same as TT-049-72 but with prehung, 1-3/4 in. thick steel flush door with urethane foam core, 3 ft. x 6 ft.-8 in. Magnetic weatherstrip on top and sides, plastic flaps on bottom.	0	--	26.0	67.7	-15.6	74.6	-20.8
TT-060-72	Same as TT-059-72	0.25	14.9	25.2	66.3	-15.8	73.4	-20.7
TT-063-72	Same as TT-049-72 but with 1-3/4 in. thick, foam filled Fiberglas reinforced plastic panel door, 3 ft. x 6 ft.-8 in. Extruded plastic weatherstrip on top and sides, half-round rubber closure strip at bottom.	0	--	25.8	67.3	-15.5	74.2	-20.9
TT-064-72	Same as TT-063-72	0.25	7.1	25.1	66.2	-15.8	73.9	-20.9
TT-065-72	2 x 4 in. studs on 16 in. centers, 1/2 in. gypsum board interior surface, 1/2 in. wood fiber sheathing plus 4 in. brick veneer exterior surface. No insulation.	0	--	26.2	62.7	-10.1	73.5	-19.7
TT-066-72	Same as TT-065-72	0.25	1.8	25.9	62.4	-10.5	73.4	-19.9
TT-069-72	Same construction as TT-065-72 but with Fiberglas 3-1/2 in. building insulation in cavities, polyethylene vapor barrier.	0	--	26.6	70.5	-17.1	76.1	-21.5
TT-070-72	Same as TT-069-72	0.25	1.9	26.3	69.9	-17.2	75.6	-21.6
TT-036-72	2 x 4 in. studs on 16 in. centers, 1/2 in. gypsum board interior surface, 3/4 in. styrofoam TG sheathing and 10 in. wide redwood lap siding exterior surface.	0	--	27.8	67.1	-11.5	75.9	-20.1
TT-037-72	Same as TT-036-72	0.25	1.7	27.2	66.4	-12.0	75.4	-20.5

Table D-1 (continued)

Test No.	Net Heat Flow	Apparent Amount of Net Heat Flow due to Air Leakage	Effective* Thermal Conductance (surface-to-surface)	Effective* Thermal Transmittance (air-to-air)	Effective* Hot Air Film Conductance	Effective* Cold Air Film Conductance	Effective* Thermal Resistance (surface-to-surface)
	$Btu\ hr^{-1}$	$Btu\ hr^{-1}$	$Btu\ hr^{-1}\ ft^{-2}\ °F^{-1}$	$Btu\ hr^{-1}\ ft^{-2}\ °F^{-1}$	$Btu\ hr^{-1}\ ft^{-2}\ °F^{-1}$	$Btu\ hr^{-1}\ ft^{-2}\ °F^{-1}$	$Btu^{-1}\ hr\ ft^{2}\ °F$
TT-050-72	3200	2135	0.314	0.279	4.1	4.3	3.18
TT-055-72	1200	--	0.118	0.100	1.3	1.4	8.47
TT-056-72	2770	2000	0.277	0.237	2.7	3.9	3.61
TT-059-72	1110	--	0.106	0.092	1.3	1.7	9.43
TT-060-72	2390	1515	0.231	0.202	2.7	3.8	4.33
TT-063-72	1115	--	0.107	0.093	1.3	1.7	9.35
TT-064-72	1645	725	0.159	0.138	1.7	2.6	6.29
TT-065-72	1795	--	0.196	0.153	1.3	1.5	5.10
TT-066-72	1885	180	0.205	0.160	1.4	1.6	4.88
TT-069-72	925	--	0.084	0.075	1.3	1.7	11.90
TT-070-72	1045	200	0.095	0.085	1.5	1.9	10.53
TT-036-72	1495	--	0.151	0.124	1.3	1.4	6.62
TT-037-72	1580	175	0.160	0.131	1.4	1.5	6.25

*Effective refers to the value calculated from measured heat flow. In tests with an imposed pressure difference, this value includes energy consumed in heating the leakage air from cold side to warm side temperature.

Appendix E. Detailed Air Infiltration Test Results

Table E-1

Air Infiltration of 3 x 7 ft Exterior Doors

Doors normally closed and latched

Door	Weather Strip	Air Flow $ft^3\ min^{-1}$ 0.1 in. water	0.3 in. water	0.7 in. water
Wood, flush solid core	Brass	4.6	10.2	18.2
	Plastic	9.4	19.8	35.0
Same, plus aluminum storm door	Plastic	7.5	17.2	31.0
Wood, flush hollow core	Brass	5.3	8.9	13.0
Wood, french	Brass	5.6	11.4	19.9
FRP panel	Plastic	---	4.0	8.5
Steel, flush	Magnetic	6.6	15.4	28*

*extrapolation

Notes:

1. All doors were tested in the same frame except the steel door, which was prehung in a different frame.

2. The flush solid core wood door was prehung in frame with brass spring weather stripping supplied. Other wood doors were trimmed as needed to fit this frame.

3. Plastic weather stripping was substituted for the brass in the same frame.

4. FRP panel door was slightly oversize and made very tight fit against plastic weather stripping.

Table E-2

Air Infiltration of Windows

Material	Type	Size	Glazing	Storm Sash	Air Flow (ft^3 min^{-1}) Locked 0.1 in. water	Locked 0.3 in. water	Locked 0.7 in. water	Unlocked 0.1 in. water	Unlocked 0.3 in. water	Unlocked 0.7 in. water
Wood	Double hung	3 x 5 ft	in-7/16 in.		11.0	24.6	47.0*	31.5	70.3	----
Wood-plastic	Double hung	3 x 5 ft	ss		2.6	5.0	8.8	2.0	4.7	8.8
			in-3/8 in.		3.6	6.0	9.7	2.3	5.1	9.3
			ss	ss	1.1	3.9	7.7	1.3	4.4	8.5
			in-3/8 in.	ss	2.1	4.9	9.0	1.9	5.0	9.3
	Awning	3 x 4 ft	ds		5.2	10.4	17.3			
			in-3/8 in.		4.9	9.4	15.8			
	Fixed casement	3 x 5 ft	ds		----	2.2	4.3			
	Operable casement†	4 x 5 ft	ds		5.2	9.3	14.0	7.0	14.9	17.0
								16.0	27.4	35.5
	Sliding glass door	6 x 7 ft	lam-3/16 in.		6.4	15.6	28.5	6.9	17.3	31.5
Aluminum	Sliding	3 x 4 ft	ss		8.4	16.3	27.0			
			ss	ss	9.1	18.6	34.0*			
	Operable casement	3 x 4 ft	ds		11.0	26.0	50.0	23.0	44.6	71.0*
	Single hung	3 x 4 ft	in-7/16 in.		1.3	5.6	11.8	2.9	10.0	20.0
	Jalousie	3 x 4	1/4 in.		40.0	82.6	----			

†unlocked with locking lever partially and fully open, respectively

*extrapolation

Table E-3

Air Infiltration of Windows with Cracks and Openings

A. 6 x 5 ft Picture Window

Gauged crack around partial or full perimeter

Crack width	Air Flow (ft^3 min^{-1} per foot crack length) 0.1 in. water	0.3 in. water	0.7 in. water
1/32 in.	1.7	3.65	6.8*
1/16 in.	4.7 4.8	9.0 9.3	14.4*
1/8 in.	10.8 11.0 11.4	19.0 20.4	31.2
1/4 in.	18.8	33.0 35.2 35.7	52.0*

*extrapolation

B. 3 x 4 ft Wood-Plastic Awning Window, glazed double strength

Upper and lower sashes opened by gauged amounts at bottom

Opening	Air Flow (ft^3 min^{-1}) 0.1 in. water	0.3 in. water	0.7 in. water
Cranked tight shut	5.2	10.4	17.3
1/32 in.	10.3	19.9	29.0
1/16 in.	17.3	32.4	46.5
1/8 in.	50.9	94.9	----

NBS-114A (REV. 7-73)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBS BSS 77	2. Gov't Accession No.	3. Recipient's Accession No.
4. TITLE AND SUBTITLE Acoustical and Thermal Performance of Exterior Residential Walls, Doors and Windows			5. Publication Date November 1975 6. Performing Organization Code
7. AUTHOR(S) H.J. Sabine, M.B. Lacher, D.R. Flynn, and T.L. Quindry			8. Performing Organ. Report No.
9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, D.C. 20234			10. Project/Task/Work Unit No. 11. Contract/Grant No.
12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)*			13. Type of Report & Period Covered Final 14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

Library of Congress Catalog Number: 75-600084

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Laboratory tests of sound transmission loss, thermal transmittance, and rate of air leakage were conducted on full scale (9 feet high x 14 feet wide; 2.7 x 4.3 meters) specimens of typical residential exterior wall constructions, either unbroken or penetrated by a door or window. The walls were of wood frame construction with gypsum board drywall interior finish and exterior finishes of wood siding, stucco, or brick veneer. Additional acoustical tests were run on a number of individual doors and windows. A total of 109 acoustical tests and 48 thermal tests are reported. The resultant data are compared with literature data on similar constructions. Correlations developed among the several quantities measured will assist more rational design where both energy conservation and noise isolation must be considered.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Acoustics, air infiltration, air leakage, architectural acoustics, building acoustics, doors, energy conservation, heat loss from buildings, heat transfer, sound transmission loss, thermal resistance, thermal transmittance, windows.

18. AVAILABILITY ☐ Unlimited	19. SECURITY CLASS (THIS REPORT) UNCLASSIFIED	21. NO. OF PAGES 170
☐ For Official Distribution. Do Not Release to NTIS ☒ Order From Sup. of Doc., U.S. Government Printing Office Washington, D.C. 20402, SD Cat. No. C13.29/2:77 ☐ Order From National Technical Information Service (NTIS) Springfield, Virginia 22151	20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	22. Price $2.35

USCOMM-DC 29042-P74

(cut here)

Announcement of New Publications in Building Science Series

Superintendent of Documents,
U.S. Government Printing Office,
Washington, D.C. 20402

Dear Sir:

Please add my name to the announcement list of new publications to be issued in the series: National Bureau of Standards Building Science Series.

Name ____________________

Company ____________________

Address ____________________

City ____________ State ____________ Zip Code ____________

(Notification key N-339)

NBS TECHNICAL PUBLICATIONS

PERIODICALS

JOURNAL OF RESEARCH reports National Bureau of Standards research and development in physics, mathematics, and chemistry. It is published in two sections, available separately:

• Physics and Chemistry (Section A)

Papers of interest primarily to scientists working in these fields. This section covers a broad range of physical and chemical research, with major emphasis on standards of physical measurement, fundamental constants, and properties of matter. Issued six times a year. Annual subscription: Domestic, $17.00; Foreign, $21.25.

• Mathematical Sciences (Section B)

Studies and compilations designed mainly for the mathematician and theoretical physicist. Topics in mathematical statistics, theory of experiment design, numerical analysis, theoretical physics and chemistry, logical design and programming of computers and computer systems. Short numerical tables. Issued quarterly. Annual subscription: Domestic, $9.00; Foreign, $11.25.

DIMENSIONS/NBS (formerly Technical News Bulletin)—This monthly magazine is published to inform scientists, engineers, businessmen, industry, teachers, students, and consumers of the latest advances in science and technology, with primary emphasis on the work at NBS. The magazine highlights and reviews such issues as energy research, fire protection, building technology, metric conversion, pollution abatement, health and safety, and consumer product performance. In addition, it reports the results of Bureau programs in measurement standards and techniques, properties of matter and materials, engineering standards and services, instrumentation, and automatic data processing.

Annual subscription: Domestic, $9.45; Foreign, $11.85.

NONPERIODICALS

Monographs—Major contributions to the technical literature on various subjects related to the Bureau's scientific and technical activities.

Handbooks—Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications—Include proceedings of conferences sponsored by NBS, NBS annual reports, and other special publications appropriate to this grouping such as wall charts, pocket cards, and bibliographies.

Applied Mathematics Series—Mathematical tables, manuals, and studies of special interest to physicists, engineers, chemists, biologists, mathematicians, computer programmers, and others engaged in scientific and technical work.

National Standard Reference Data Series—Provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated. Developed under a world-wide program coordinated by NBS. Program under authority of National Standard Data Act (Public Law 90-396).

NOTE: At present the principal publication outlet for these data is the Journal of Physical and Chemical Reference Data (JPCRD) published quarterly for NBS by the American Chemical Society (ACS) and the American Institute of Physics (AIP). Subscriptions, reprints, and supplements available from ACS, 1155 Sixteenth St. N. W., Wash. D. C. 20056.

Building Science Series—Disseminates technical information developed at the Bureau on building materials, components, systems, and whole structures. The series presents research results, test methods, and performance criteria related to the structural and environmental functions and the durability and safety characteristics of building elements and systems.

Technical Notes—Studies or reports which are complete in themselves but restrictive in their treatment of a subject. Analogous to monographs but not so comprehensive in scope or definitive in treatment of the subject area. Often serve as a vehicle for final reports of work performed at NBS under the sponsorship of other government agencies.

Voluntary Product Standards—Developed under procedures published by the Department of Commerce in Part 10, Title 15, of the Code of Federal Regulations. The purpose of the standards is to establish nationally recognized requirements for products, and to provide all concerned interests with a basis for common understanding of the characteristics of the products. NBS administers this program as a supplement to the activities of the private sector standardizing organizations.

Federal Information Processing Standards Publications (FIPS PUBS)—Publications in this series collectively constitute the Federal Information Processing Standards Register. Register serves as the official source of information in the Federal Government regarding standards issued by NBS pursuant to the Federal Property and Administrative Services Act of 1949 as amended, Public Law 89-306 (79 Stat. 1127), and as implemented by Executive Order 11717 (38 FR 12315, dated May 11, 1973) and Part 6 of Title 15 CFR (Code of Federal Regulations).

Consumer Information Series—Practical information, based on NBS research and experience, covering areas of interest to the consumer. Easily understandable language and illustrations provide useful background knowledge for shopping in today's technological marketplace.

NBS Interagency Reports (NBSIR)—A special series of interim or final reports on work performed by NBS for outside sponsors (both government and non-government). In general, initial distribution is handled by the sponsor; public distribution is by the National Technical Information Service (Springfield, Va. 22161) in paper copy or microfiche form.

Order NBS publications (except NBSIR's and Bibliographic Subscription Services) from: Superintendent of Documents, Government Printing Office, Washington, D.C. 20402.

BIBLIOGRAPHIC SUBSCRIPTION SERVICES

The following current-awareness and literature-survey bibliographies are issued periodically by the Bureau:

Cryogenic Data Center Current Awareness Service

A literature survey issued biweekly. Annual subscription: Domestic, $20.00; foreign, $25.00.

Liquefied Natural Gas. A literature survey issued quarterly. Annual subscription: $20.00.

Superconducting Devices and Materials. A literature survey issued quarterly. Annual subscription: $20.00. Send subscription orders and remittances for the preceding bibliographic services to National Technical Information Service, Springfield, Va. 22161.

Electromagnetic Metrology Current Awareness Service Issued monthly. Annual subscription: $100.00 (Special rates for multi-subscriptions). Send subscription order and remittance to Electromagnetics Division, National Bureau of Standards, Boulder, Colo. 80302.

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

OFFICIAL BUSINESS

Penalty for Private Use, $300

POSTAGE AND FEES PAID
U.S. DEPARTMENT OF COMMERCE
COM-215

SPECIAL FOURTH-CLASS RATE
BOOK

U.S.MAIL

AMERICAN REVOLUTION BICENTENNIAL
1776-1976