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ACOUSTIC LOCATION OF INFILTRATION OPENINGS IN BUILDINGS

D. N. KEAST

BOLT BERANEK AND NEWMAN, INCORPORATED
CAMBRIDGE, MASSACHUSETTS

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FINAL REPORT

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Prepared by
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CAMBRIDGE, MASSACHUSETTS 02138

for
BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
UPTON, NEW YORK 11973

UNDER CONTRACT NO. EY-76-C-02-0016 WITH THE

U. S. DEPARTMENT OF ENERGY

Division of Buildings and Community Systems

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The work described in this report was conducted by Bolt Beranek and Newman Inc. for Brookhaven National Laboratory (BNL) under BNL Contract No. 427075-S. It is part of a program of RD&D in Buildings Conservation managed by BNL for the U. S. Department of Energy

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ABSTRACT

Unnecessary air infiltration ("draftiness") in buildings can be a major cause for excessive energy consumption. A method for using sound to locate, for subsequent sealing, the openings of air infiltration leakage paths in buildings has been investigated. The results of pertinent analytical studies, laboratory experiments, and field applications of this acoustic-location method are reported; and a plan is provided to encourage national implementation of the method.

Low-cost, readily available equipment and procedures are described whereby the average building contractor or homeowner can use acoustic leak location to pinpoint many of the air infiltration openings in a building.

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1. SUMMARY

A major enemy of efficient heating and cooling of buildings is air infiltration — cold air invading heated buildings, hot air seeping into air-conditioned buildings. Some of this unwanted air moves through obvious openings, such as kitchen and bathroom ventilators or open windows and doors. But there are other, less obvious openings through which air may be flowing freely even when occupants consider the building completely closed up. While these leaks remain unplugged, heating or cooling systems work overtime, and energy is wasted.

This report describes a simple, inexpensive, and speedy way to locate openings of many hidden air leaks in buildings. The method uses sound, because sound passes readily through many openings in building structures, just as air does. The method is called "acoustic leak location," and it can be used by the average homeowner with equipment as basic as a vacuum cleaner and a mechanic's stethoscope.

Other methods exist for finding air leaks in buildings, and they are summarized in Sec. 3 of this report: thermography, smoke testing, and pressurization. All present some problems. Equipment needed for thermography is very expensive, far beyond the wallet of the average homeowner or contractor. Smoke testing, though inexpensive, requires evacuation of the building being tested. Pressurization, although the best alternative to the acoustic leak-location method, also requires special equipment and demands a pressure differential across the entire envelope of the building that can be difficult to obtain.

The acoustic location method described in Sec. 4 overcomes some of these drawbacks. Basically, the method is this: A sound source is placed on one side of a building envelope; a system to listen to that sound is used on the other. The user moves a listening device, such as a microphone or a stethoscope, back and forth between places that are obviously sealed (such as the center of a window pane) and places where leaks might occur. An increase in sound level indicates a leak. The operator marks the spot with chalk or tape so that it can subsequently be sealed, and moves on. Once leaks are sealed, the method can be used again to ensure that they are adequately caulked or weatherstripped.

Equipment for the acoustic leak-location method is both portable and inexpensive. Almost any sound source can be used, though preferably it should be steady and broadband. As described in Sec. 5 of the report, sounds from a home vacuum cleaner, a dishwasher, a washing machine, and an organ music recording have been used. However, most testing performed for the work described in this report used a prerecorded tape that provided a "warble" tone – a siren-like sound. The listening system is equally basic. A mechanic's stethoscope, a plastic headset such as those handed out to airline passengers, small rubber hoses from an auto parts store, and Type I or II Sound Level Meters have been used. However, most of the field testing was done with a listening system that included a battery-powered microphone and battery-powered headphones, all available at modest cost from hi-fi stores.

In the course of this project, 8 buildings were tested by Bolt Beranek and Newman Inc. (BBN) using both the acoustic leak-location and pressurization methods: 5 single-family houses, 2 commercial buildings, and 1 school. Most of these buildings were found to be surprisingly leaky, through such openings as floor penetrations for heating and water pipes, the jambs of interior doors to unheated attics and basements, electrical outlets, sash-weight boxes, and where the structure rested on the foundation.

In addition to tests by BBN staff members, three home-repair organizations experimented with the method. One contractor reported that he found the results of the acoustic leak-location method "very impressive," and added that homeowners who witnessed the testing were "impressed by the simplicity and accuracy of the device." Another reported the method "extremely effective in testing for infiltration."

The acoustic leak-location method has three limitations:

- The inability of the method to identify the openings of air-leakage paths that follow long, complex routes through buildings, particularly if they are filled with fibrous insulation;
- The unavailability of a low-cost sound level meter;
- The need for further data on the acoustic and air flow properties of weatherstripping.

The first limitation means that the method is most useful in drafty, rather than in tightly sealed buildings. But draftier buildings are those most in need of energy conservation treatment. In the case of the second limitation, the technology exists to produce a low-cost sound level meter; only the market is lacking. DoE is in a position to initiate such a market. The third limitation can be resolved by additional experimentation.

Section 6 of this report is an implementation plan to bring the acoustic leak-location method to the public's attention. It is recommended that the method be offered as an adjunct to one or more existing programs directed toward energy conservation. The Department of Energy's Energy Extension Service could implement the necessary educational and public outreach programs for promoting the method. A detailed time schedule is included for introducing the acoustic leak-location method to the public.

2. CONCLUSIONS AND RECOMMENDATIONS

- Acoustic leak location is a simple, low-cost method for identifying many air-leakage openings in buildings. Leaks are detectable because they transmit sound levels that are about twice as loud as those through adjacent, sealed locations. When compared with local air-flow rates in depressurized buildings, the transmitted sound level correlates roughly with a measure of the air-flow rate, and is thus an indication of leak size.
- Acoustic leak location will not identify the openings of most air-leakage paths that follow long, complex routes through building structures, particularly if cavities in the structure are filled with fibrous insulation. As a result, limited tests show the method is most useful in draftier buildings and least useful in tight buildings.
- A majority of the building-trade organizations that have tried the acoustic leak-location method have responded favorably to it. They have found it particularly useful as a sales demonstration and as an inspection tool.
- An implementation plan is recommended to bring the acoustic leak-location method to the attention of the building industry and the public. This plan recommends that the major outreach effort be borne by DoE's Energy Extension Service (EES). The benefit-cost ratio of the plan is estimated to be 90 to 1.

- To enhance the utility of the acoustic leak-location method, two recommendations are made:
  - That DoE encourage the marketing of a low-cost ($50 to $100) sound meter of suitable configuration for acoustic leak location. This could be aided by purchases to equip the EES — one step in the plan mentioned above.
  - That data be gathered and published on the acoustic and air-flow properties of weatherstripping for operable doors and windows as a function of type of weatherstripping, quality of installation, and exposure to use.

3. BACKGROUND

3.1 Need and Purpose

The infiltration of air through building envelopes typically accounts for 30 to 50% of the building heating load and, in air-conditioned buildings, for 5 to 20% of the cooling load [*1*]. When a building is retrofitted for reduced thermal conductivity of the envelope, infiltration becomes an even greater percentage of the building energy load. If air infiltration in buildings can be reduced to the minimum necessary for the health and comfort of the occupants, considerable savings can be achieved in operating cost and energy consumption.

Some of the infiltration of air through buildings occurs via pathways that are generally obvious: openings of doors, kitchen and bathroom ventilators, furnace and fireplace flues, window and door cracks, etc. However, about two-thirds of the total flows through paths that are less apparent: electrical wall outlets, air-duct penetrations, structural joints, etc. [*2*]. Reduction of infiltration through such openings means they must first be located, then sealed with a suitable caulking, gasketing, or weatherstripping. There is a need, therefore, for leak-location methods — building inspection techniques that will locate infiltration openings for subsequent treatment.

During the contract effort reported herein, an acoustic-location method for pinpointing infiltration openings in buildings has been refined and evaluated. This method, described in detail in Sec. 4, takes advantage of the tendency of sound to pass readily through openings in building structures in the same way that air does. It is important to recognize that this is not an infiltration-*measurement* method. (There are other methods for quantifying infiltration rates through building envelopes [3,4].) Rather, it is a means for locating openings in need of treatment. The emphasis has been on developing a simple, low-cost method that could be widely used in the immediate future — perhaps by the average homeowner himself — for the location of infiltration openings. We have purposely avoided the development of an improved measurement tool or of a research instrument that might be beyond the means of the average building owner.

Other methods, listed below, are presently available for locating infiltration openings in building envelopes. These other methods have advantages and disadvantages that should be borne in mind as the reader studies this report on the acoustic-location method.

Thermography [5,6]

Thermography is a technique for visualizing small temperature differences on heat-radiating surfaces. Its greatest utility is that it can locate flaws in the thermal insulation of a building envelope. Under some circumstances, air leaks can also be located. With skill, the method is semiquantitative.

The use of thermography requires a temperature and pressure difference across the building envelope. Its greatest limitation, however, is that the necessary equipment is very costly — so costly, in fact, the widespread commercial use of this technique is unlikely in the foreseeable future.

Smoke Testing [7]

It is possible to fill a building with smoke and, perhaps with the aid of a small applied pressure, examine where the smoke comes out. The method is very inexpensive; obviously, however, it renders the building uninhabitable during testing and for some time thereafter. In addition, the procedure is unattractive, and subject to the implication, at least, of lingering toxic after-effects.

Pressurization [8]

Pressurization testing (including depressurization) is a widely used method for observing the air-flow rate through building envelopes. It is pseudoquantitative in that it allows structures to be rank-ordered in about the way that they would be if infiltration caused by natural forces were observed. The equipment has been refined by the Center for Environmental Studies at Princeton University so that it can be rapidly installed and operated in a building door [9].

During pressurization testing, it is possible to go around the building and feel air flow coming through leakage openings. In this way, the openings can be located in about the same length of time that would be required by the acoustic method. Quantitative information can be obtained by selectively sealing and opening individual leaks. However, this time-consuming process is generally of value only for research purposes.

The location of leaks during building pressurization is enhanced somewhat by a temperature difference across the wall and disturbed by windy conditions out-of-doors. Of all the location methods, however, it is the least disruptive of the ongoing activities of building occupants.

One limitation of the pressurization method of locating leaks is the cost of the equipment, which can be 3 to 5 times that required for acoustic testing (although it is still much less expensive than that required for thermography). Furthermore, the equipment is relatively heavy and bulky. An even more serious limitation is the problem of developing an adequate pressure differential across the building envelope (0.1 in. H_2O or more is desirable) with a fan system that can be operated from an ordinary 120-V power receptacle. (In older, poorly wired buildings, such as many low-income homes, fuse blowing can be a problem.) In very leaky buildings, or in buildings much larger than a single-family residence, achieving an adequate pressure differential is often not possible. The problem is that the more the building is in need of sealing, the less effective the pressurization method may be for locating the leaks.

Of course, if special provisions must be made to power the pressurization system or if buildings must be sealed off in sections for testing, one section at a time, the pressurization method becomes less practical, when the objective is simply to locate leaks. Nevertheless, the pressurization method is clearly the most viable alternative to the acoustic method for the location of air leaks in buildings. Furthermore, it has the distinct advantage of allowing the location of *all* the building leaks, rather than just some of them.

3.2 General Description and Prior Applications of the Acoustic-Location Method

It has long been known that small openings through building structures serve as paths for both air infiltration and sound. Cracks around an unweatherstripped exterior door can, for example, admit cold drafts in the wintertime, hot air in the summer, and traffic noise all year around. Sealing such cracks can result in improved interior thermal conditioning, lower heating/cooling costs, and a quieter interior acoustical environment.

Studies of building infiltration have generally concentrated on measuring the gross flow rates of air through buildings and building elements and on observing how these flow rates vary with temperature and pressure differences. In general, these studies have not been concerned with locating particular leakage openings, although the openings are often visually obvious.

Studies of sound transmission through building walls and wall elements have indicated that very small openings in walls can significantly increase the acoustic transmission through a wall relative to that of the same wall when sealed [10]. Data are usually reported showing, in effect, the acoustic energy transmitted through a penetrated wall relative to that transmitted through the sealed wall. Again, such data give no information as to the location of the penetrations — just their contribution to the total acoustic energy radiated into the listening room.

At this point, it is useful to introduce some of the terminology applied to the acoustic properties of spaces ("rooms") and of barriers. Consider two rooms separated by an intervening barrier wall that is uniform in structure. Sound is produced in one room with a sound pressure level, P_S. The resulting (lower) level observed in the receiving room is P_R. The difference $P_S - P_R$ (in decibels as a function of frequency) is related not only to the acoustical properties of the intervening barrier, but also to the size of the barrier, to the volumes of the two rooms, to the amount of acoustical absorption in the two rooms, to the angle of incidence of the sound at the barrier, and to some less important parameters like humidity. The difference $P_S - P_R$ is called *acoustic isolation* if the sound pressure levels are A-weighted.* Obviously, this difference is site specific and not very useful for predictive purposes.

To overcome this limitation, it is common to report the *transmission loss* (TL; also called *acoustic insulation*) of barriers, measured under standardized and very carefully controlled laboratory conditions and corrected for site-specific factors. Transmission loss, or insulation, is defined as:

$$TL = 10 \log_{10} \frac{W_S}{W_R} \quad ,$$

where W_S is the acoustic power in watts incident upon the wall on the source side in a diffuse (random-incidence) sound field, per unit wall area. W_R is the acoustic power in watts radiated from the receiving side of the wall into a perfectly absorbing space, per unit wall area.

Transmission loss is a function of sound frequency. A single-number rating of TL, called *Sound Transmission Class* (STC), can be determined by comparing the TL spectrum of a wall to a set of standarized spectra in accordance with ASTM #413-73.

When sound propagation is measured through a building envelope in the field, only acoustic *isolation* can be observed, for the controlled conditions necessary to observe TL or acoustic insulation do not generally exist. In the particular situation of this study — locating potential air-leakage openings — we probe with a listening device very close to the sound-output side of the wall, seeking local, anomalous increases in sound

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*For an explanation of A-weighting, see footnote pp 66 and ref. 18.

level. Thus, the requirements for observing TL on the basis of an average of the sound energy radiated from the whole wall are further violated.

In actual practice, when an acoustician attempts to locate faults in a wall installation that does not perform acoustically as predicted, he often probes with a listening device, trying to locate where wall penetrations (sound-leakage paths) might be. He is trying to solve the problem, and he has to know where there are leakage openings in need of sealing. This field practice is described in Appendix Section A4.5.2, "Checks for Flanking Transmission," of ASTM E336-71 [11]. Furthermore, many of the methods for eliminating sound-leakage paths in buildings are identical to those necessary for reducing air infiltration [12].

What has been demonstrated in this program is that this acoustic noise-control method can be "turned around" and readily applied to the location of air infiltration openings in buildings without particularly demanding constraints. It is necessary only to create a sound on one side of the building envelope and to listen in a prescribed way on the other side. Almost any sound source can be used: There is no need to generate highly controlled acoustic signals or to have special equipment for sensing otherwise inaudible sounds, such as ultrasound. As described in Sec. 4.2, much of what is needed for acoustic leak location is already available in the average house.

3.3 Analysis

For the purposes of this study, it is convenient to divide infiltration paths in building structures into two general classes: "simple", or approximately straight-through paths, and "complex" paths involving intricate flow patterns through wall structures. Although the static infiltration flow rates through a simple and a complex path might be the same, their acoustic transmission properties could be quite different. Typical simple and complex paths are illustrated in Figs. 1 and 2, respectively.

3.3.1 "Simple" paths

The sound transmission properties of simple paths through a barrier have been studied analytically by numerous investigators. For example, Lord Rayleigh, often considered the father of modern acoustics, analyzed the transmission of normal-incidence plane sound waves through slit-like apertures for barriers having negligible thickness [*13*]. For barriers of finite thickness (compared to the sound wavelength), the problem has been treated by Gomperts [*14,15*], and by Ingerslev and Nielsen [*16*]. The latter used an electrical equivalent-circuit approach. Most of this analysis has concentrated on cylindrical holes ("bullet-holes") through walls, although some work has been done on slits. Gomperts's work, the most comprehensive, will be summarized here.

Gomperts's Analysis of Slit-Shaped Openings

Consider the geometry of Fig. 3, where

r = the distance from the slit to the receiving microphone,

P_w = the original sound pressure on the source side at the slit (when closed) in the party wall,

P_r = the sound pressure on the receiving side at distance r from the slit in the wall,

ℓ = the thickness of the wall = the depth of the slit,

β = the breadth of the slit,

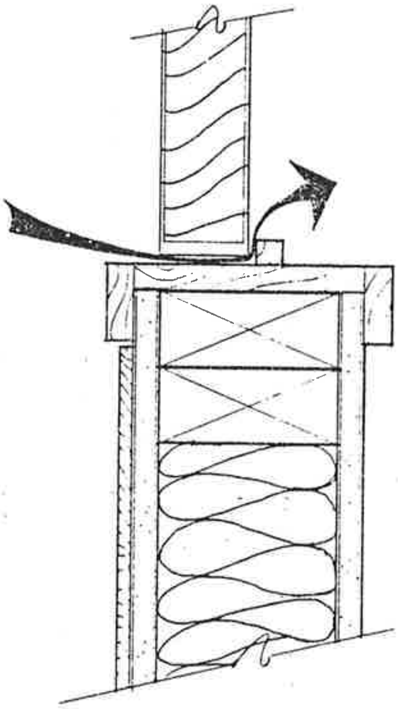

Figure 1. A "simple" path.

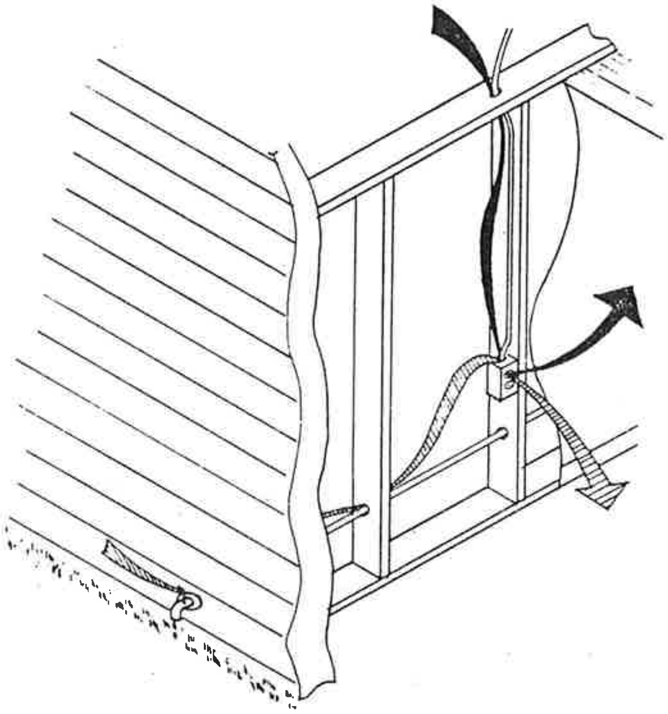

Figure 2. "Complex" paths.

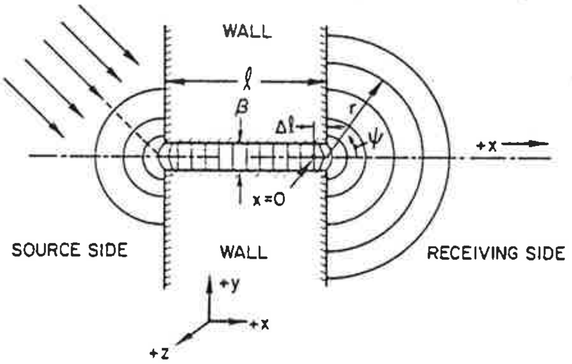

Figure 3. Schematic representation of the wave fronts of sound passing through a slit-shaped aperture in a wall. (From Ref. 14, Fig. 6.)

$k = \frac{2\pi}{\lambda}$; λ is the wavelength of the sound waves generated,

α = the end correction of the slit,

n = 1 if the slit is in the middle of the wall, and 1/2 if the slit is in the corner, or edge of the wall, and

$e = \alpha/\beta$,

$K = k/\beta$,

$L = \ell/\beta$.

Then, for the case of a diffuse sound field on the sound-source side, the square of the ratio of output to input sound pressures is determined by Gomperts to be (neglecting viscous losses):

$$\left(\frac{P_r}{P_w}\right)^2 = \frac{\beta \ K \ \cos^2 Ke}{2\pi r n^2 \left\{\frac{\sin^2 K(L+2e)}{\cos^2 Ke} + \frac{K^2}{2n^2}\left[1 \mp \cos K(L+2e) \cos KL\right]\right\}} ,$$

where

$$e = \frac{\alpha}{\beta} = \left[\frac{\left(\ln \frac{K}{8} + \gamma'\right)^2 + \left(\frac{\pi}{2}\right)^2}{\pi^2}\right]^{\frac{1}{2}}$$

and γ' is Euler's constant = 0.57722.

This is a sequence of resonances and antiresonances along the frequency (k) scale, such as illustrated by the Gomperts's calculation in Fig. 4. For example, at the resonant wavelengths λ_r such that:

$$\ell + 2\alpha = s \ \frac{\lambda_r}{2} \quad ,$$

where s is a positive integer (i.e., where the effective length of the slit through the wall is an integral number of half wavelengths), then:

$$\left(\frac{P_r}{P_w}\right)^2 = \frac{\lambda_r}{(4\pi)^2 r} \quad .$$

Obviously, this can be much greater than the sound transmission through a solid wall (which is typically 10^{-2} to 10^{-5}). Indeed, close to the opening of the slit, the ratio can be greater than unity [$\lambda_r > (4\pi)^2 r$], indicating an increase in pressure at the output of the slit relative to that at the input. One of the objectives of the experimental program reported herein was to search for these resonant peaks in the sound transmission through infiltration leaks in real building configurations. We never detected any, presumably because the cracks in buildings are usually much narrower than those studied by Gomperts and the National Bureau of Standards.

Gomperts supports his analysis with experimental data like that illustrated in Fig. 4. Here, the calculated sound insulation (i.e., transmission loss) of a brick wall penetrated by an 11-mm-wide slit is compared with the corresponding measured values for 8-mm and 16-mm-wide slits. (Measured data were not available for an 11-mm-wide slit.) A simple calculation is also shown that is based upon area ratios assuming the slit to be acoustically transparent.

In a later paper, Gomperts investigated the effects of viscous losses on sound transmission through cylindrical holes [*15*]. This research led to the kind of results illustrated in Fig. 5. As expected, viscosity limits the pressure "gain" through such apertures at resonance, but does not affect the resonant frequencies.

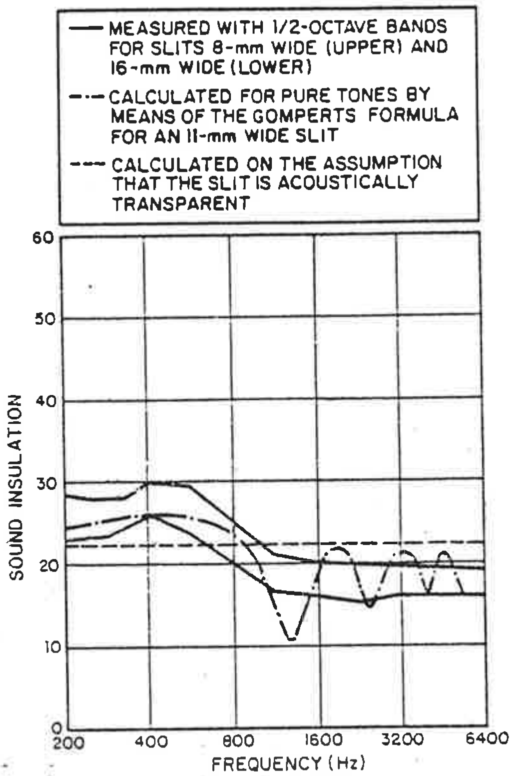

Figure 4. Sound insulation of a 1/2-brick lime-sand wall-11 cm thick (1.9 m x 1.9 m) with a slit in the middle over the entire height (1.9 m). (From Ref. 14.)

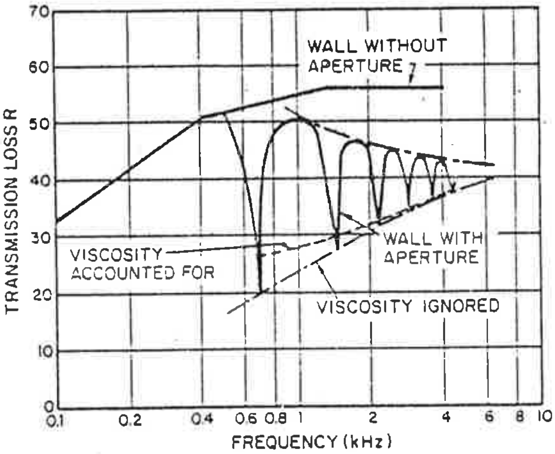

Figure 5. The transmission loss "R" of a wall, 22 cm thick and 11 m^2 in area, with and without a cylindrical aperture 2.2 cm in diameter. (From Ref. 15.)

Experimental Results of the National Bureau of Standards

As part of an extensive experimental program to determine the acoustic and thermal properties of typical building elements, the National Bureau of Standards has measured the acoustic transmission properties of simple cracks in walls [*10*]. For this purpose, NBS built specially controlled cracks, illustrated in Fig. 6.

Typical results from the NBS experiments, compared to calculations according to Gomperts (without the effects of viscosity), are shown in Figs. 7a and 7b. Note that for wide (1/4-in.) cracks, there is much better agreement between theory and data than for narrow (1/32-in.) cracks. Although there is experimental evidence of the resonant maxima in sound transmission in both cases, the actual transmission tends to be less than predicted, more so for the narrower crack.

In this experimental program, NBS also measured the air-leakage rate through a number of closed but unsealed windows and correlated this rate with the transmission loss (STC) of the windows. In general, they found that the greater the leakage rate, the more the STC of the "leaky" window fell below that of a corresponding "sealed" window. NBS reports the empirical relationship:

$$STC_1 - STC = 10 \log \left[1 + \frac{0.00229\ \dot{V}/S}{10^{-STC_1/10}} \right] ,$$

where STC_1 is a measure of the acoustic transmission loss of a sealed window in dB, STC is a corresponding measure of the acoustic transmission loss of the window in a "leaky" configuration, S is the area of the window in sq ft, and $\dot{V}$ is the air leakage in cfm at a pressure of 0.3 in H_2O, determined in a manner similar to that prescribed in ASTM E283-73 [*8*].

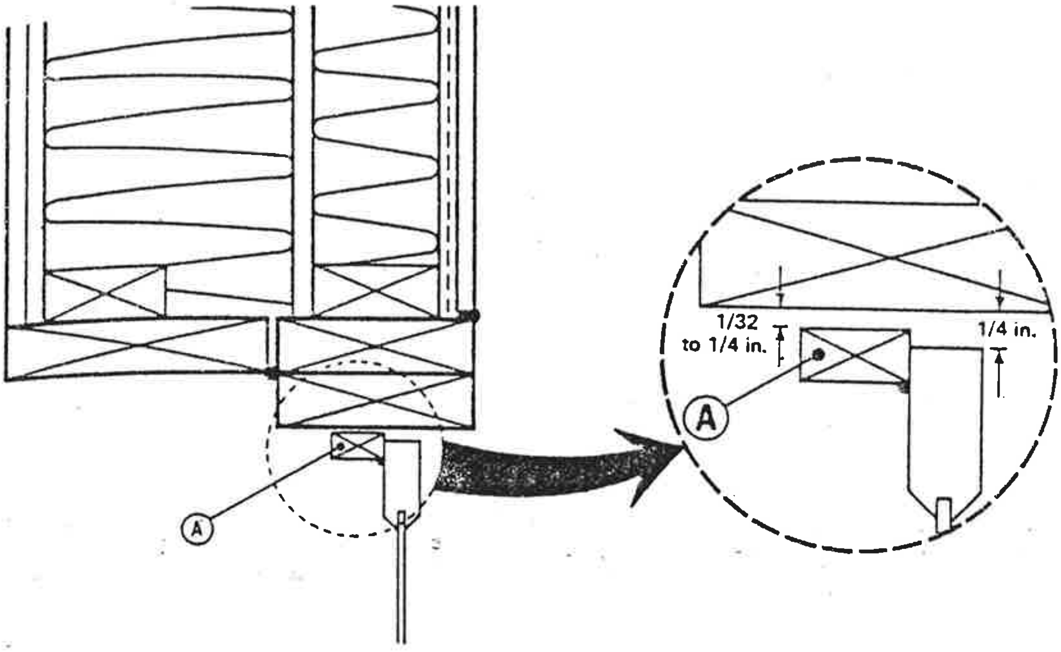

Figure 6. Detail of framing in filler wall to receive picture window sashes. Strip A was shimmed out to provide perimeter cracks ranging from 1/32 to 1/4 in. (Illustration from Ref. 10.)

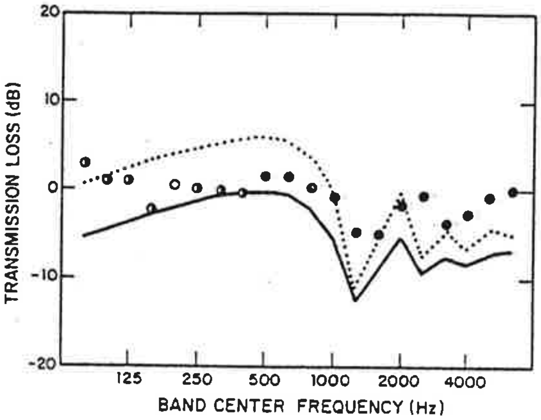

Figure 7a. Comparison of experimental results and theoretical predictions for the sound transmission loss of 1/4-in. cracks around picture windows. Solid symbols indicate that the transmission loss of the sealed window was at least 9 dB greater than that of the leaky window, while half-filled symbols 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 Gomperts [14] 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. (From Ref. 10.)

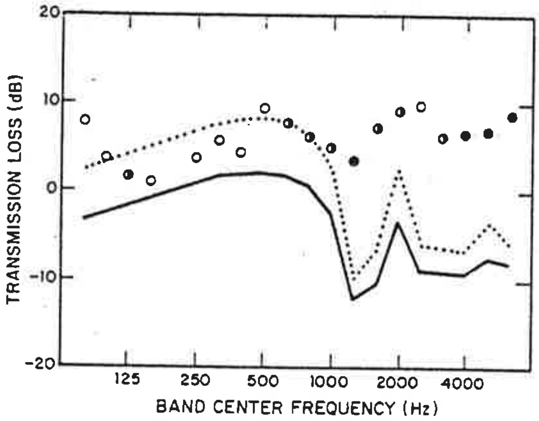

Figure 7b. Comparison of experimental results and theoretical predictions for the sound transmission loss of 1/32-in. cracks around picture windows. The effective width of the slit was taken as the uniform width which would contain the same volume of air as the actual slits, for the latter consisted of two segments of different widths. (From Ref. 10.)

A measure of the data scatter about this empirical relationship is illustrated in Fig. 8. In this figure, the actual measured decrement in STC caused by the window leaks is compared to the value computed from the above equation and based upon the measured air flow rates. Although the data fit is not particularly exciting, it suggests the possibility of a *quantitative* relationship between STC decrement and air-leakage rates. This indication has not been pursued during this project, however, because of the difficulty of measuring TL or STC under field conditions.

Summary of Expected Performance

An idealized illustration of the acoustical performance of a typical wall with a simple crack is given in Fig. 9. Assume that a steady, broadband sound of 80-dB sound pressure level (SPL) re 20 μPa at all frequencies is produced inside a room of a building. (See the straight line at 80 near the top of Fig. 9.) The resulting SPL spectrum outside the sealed wall would be that illustrated by the lowest curve in Fig. 9, assuming it is otherwise quiet outside. There is a peak at low frequency caused by the first resonance of the wall on its supporting structure (125 Hz in the idealized illustration). Another peak occurs at a high frequency (3500 Hz) because of wave coincidence.* At frequencies above the first wave coincidence, the sound level is steady or may increase with frequency.

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*Coincidence occurs when the trace velocity of an acoustic wave, impinging on the wall at some oblique angle, matches the flexural wave velocity in the wall. The frequency at which this occurs is a function of the thickness and material of the wall.

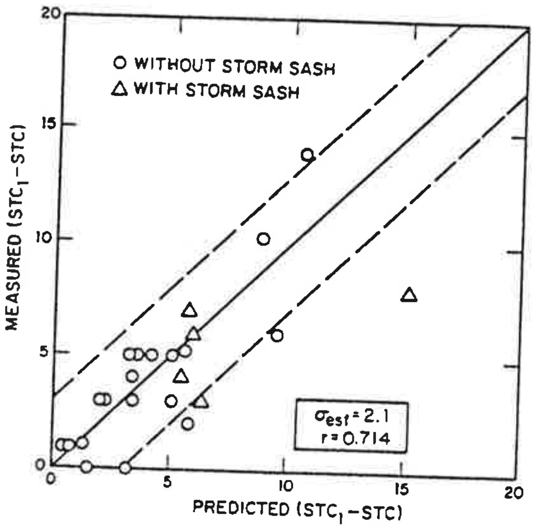

Figure 8. Measured values of the decrease in sound transmission class due to leaks around windows or doors vs values predicted using empirical equation in text. (From Ref. 10.)

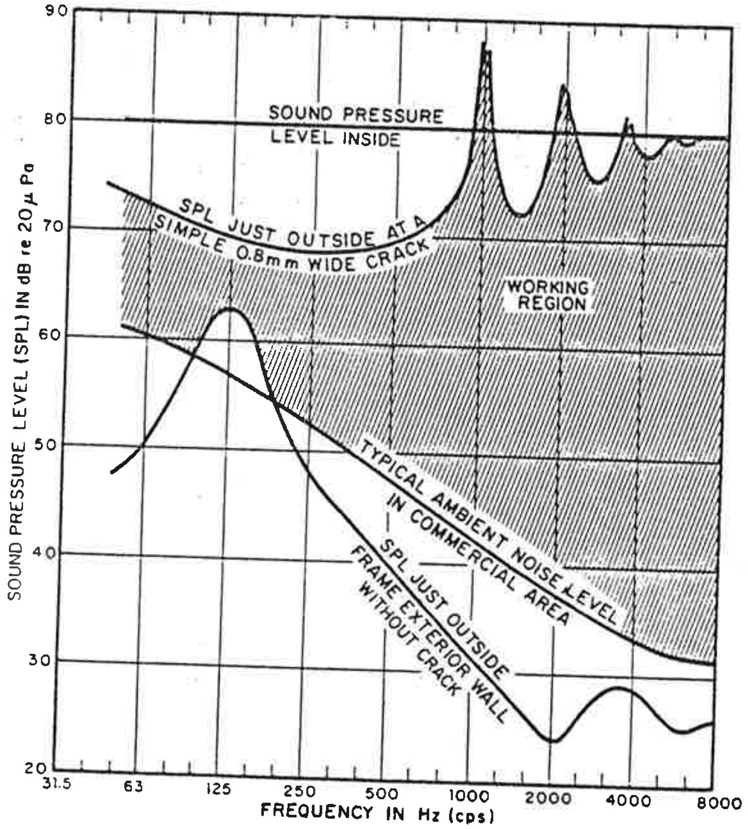

Figure 9. Idealized sound spectra inside and outside a frame-construction wall with a simple 0.8-mm-wide crack.

If there is a simple 0.8-mm crack in the wall, the SPL spectrum just outside this crack would ideally be as illustrated by the second curve from the top. From Gomperts's analysis, this spectrum exhibits resonant peaks at frequencies where the thickness of the wall (crack depth) is roughly equal to an integral number of half-wavelengths. These resonances become less pronounced for deep, thin cracks because of viscous losses.

Also shown in Fig. 9 is a typical outdoor noise spectrum in a business or commercial district. Clearly, sounds coming through the wall or the crack from inside could not readily be observed if they are less than this "background" noise level.* Thus, the cross-hatched portion of the illustration is the "working region" within which acoustic location of the crack would be feasible.

The working region is bounded on the bottom by the acoustic transmission properties of the sealed wall or by the background noise. It is bounded on the top by the acoustic transmission properties of the crack. Clearly, there is more chance of success of crack location at high frequencies (500 Hz and above) and at the frequencies where crack resonances occur.

To illustrate how "idealized" the curves in Fig. 9 actually are, some measured data from the NBS study are shown in Fig. 10 [*10*]. The upper curve showing the sound level just outside a 3-mm (1/8-in.) crack is calculated from their data sample W-14-71.

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*The background-noise limitation can be eliminated by increasing the sound level inside the room. However, this sound level in turn is limited by equipment capabilities and human tolerance of the sound.

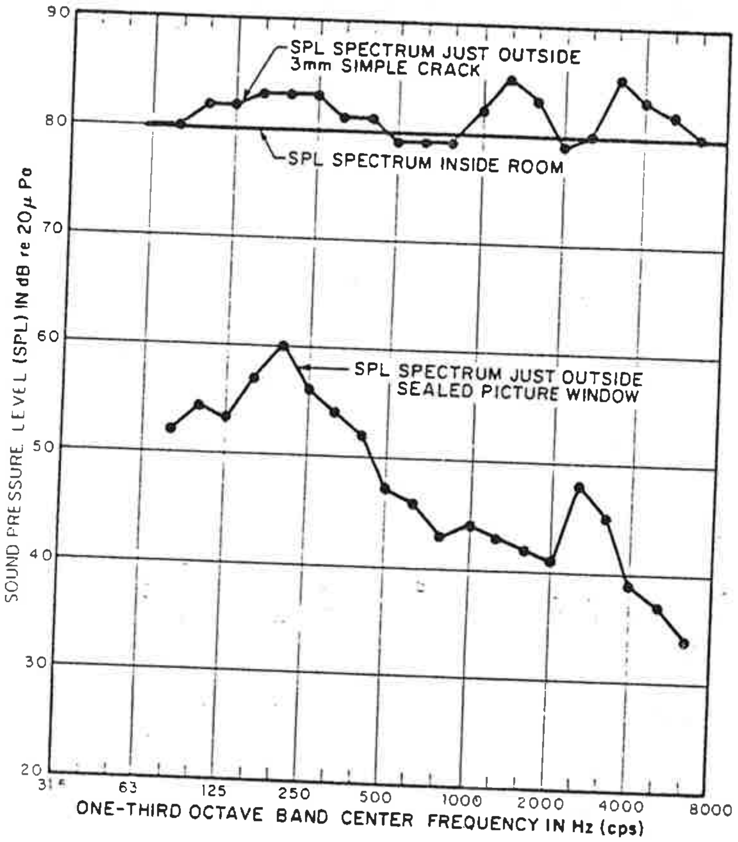


Figure 10. Sound spectra inside and outside a picture window with a simple, 3-mm-wide perimeter crack. (Calculated from measured data reported in Ref. 10.)

The crack is around the parameter of a 1.8 m × 1.5 m (6 ft × 5 ft) double-glazed picture window. The SPL just outside the sealed window is calculated from data sample W-10-71 in the reference. Note that the panel resonance and coincidence frequency of the glass are evident, as are two resonances of the crack.

3.3.2 "Complex" paths

The literature reveals no analytical work similar to that of Gomperts on the sound transmission properties of "complex" leakage paths. Of course, a wide variety of such leakage paths is possible, and it is unlikely that any single analysis could handle all of them. Nevertheless, some qualitative generalizations can be made.

Complex leakage paths would consist of small openings to interior cavities of walls, followed by other small openings to the outside of the building (or *vice versa*). In some cases, additional small openings, such as through studs between separate wall cavities, would come into play. To a first approximation, the small openings involved are like simple paths, and could be analyzed as such. Resonance could occur at fairly low frequencies between the air mass in the wall openings and the compliance of the cavities. For balloon construction with typical-sized stud interstices, these resonances would be below a few hundred Hertz and would be highly damped by any fibrous insulation within the wall cavity.

In the important special case of leakage through electrical conduit, acoustic propagation could be very good, if there is adequate clearance between the wiring and the inner wall of the conduit (reminiscent of "speaking tubes" in older ships).

If one considers the case where the wall cavities are filled with fibrous material (thermal insulation), it is likely that acoustic propagation losses through this material will be the primary determinant of how much sound can propagate through the cavity. Fibrous materials are very effective in absorbing sound; the attenuation of sound in coarse fibrous materials typical of building insulation is illustrated in Fig. 11. These data, taken from Beranek [*17*], are for Johns-Manville No. 302 Rockwool and Owen Corning Type TWF 4 lb/ft^3 Fiberglas. Note that the attenuation can be very large, particularly at the higher frequencies. Through a single thickness of R-11 insulation, it would be about 9 dB at 1 kHz. For a more typical leakage distance of, say, 5 ft, it would be 152 dB! Clearly, the openings of complex leakage paths through fibrous insulating material cannot be located acoustically if the paths are very long. The chances of locating them improve if the acoustic excitation frequency is low — just the opposite of the frequency requirement for locating simple leakage openings.

For further comparison, the sealed picture window of Fig. 10 is equivalent in sound transmission characteristics to leakage paths of the following lengths, through fibrous materials.

Frequency, Hz	Path Length Equivalent to Sound Transmission of Picture Window
125	77 cm (30 in.)
250	45 cm (18 in.)
500	44 cm (17 in.)
1000	37 cm (15 in.)
2000	31 cm (12 in.)
4000	25 cm (10 in.)

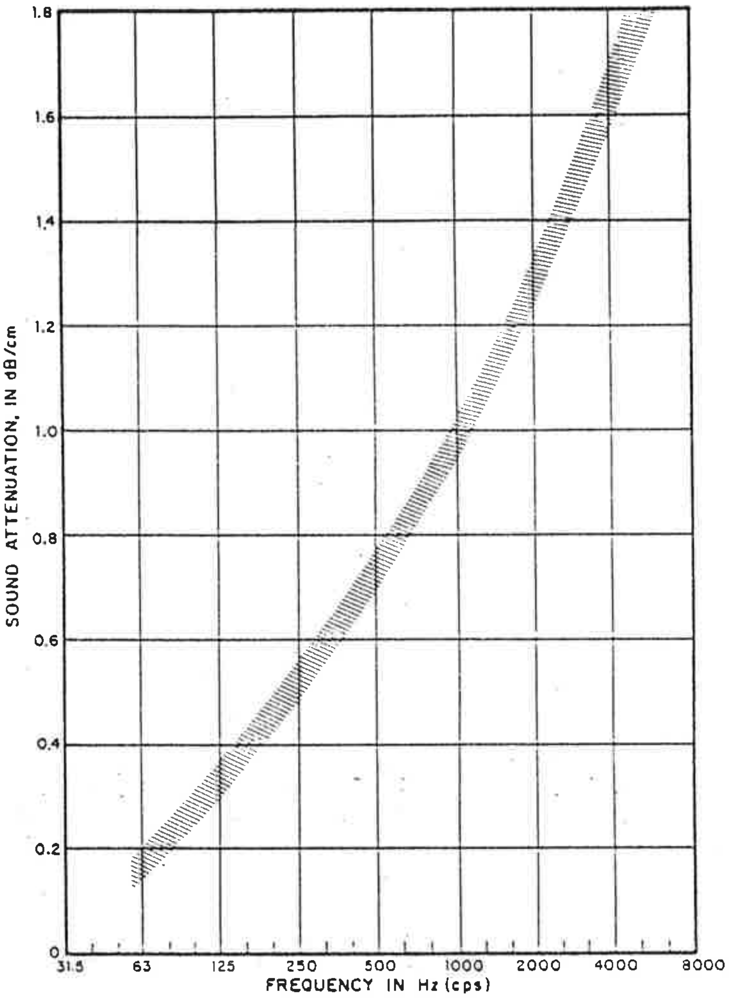


Figure 11. Attenuation of sound propagated in fibrous materials (after Beranek [17]).

Path lengths equal to or greater than these would be acoustically undetectable in the vicinity of the picture window.

This is a major limitation to the acoustic location of the openings of complex infiltration paths. However, the amount of infiltration through such paths is not generally as large as that through simple paths. The fibrous insulation will restrict the infiltrating air flow as well as the passage of sound.

4. THE METHOD

4.1 Applications

Acoustic leak location can be used to:

- Locate air-infiltration openings in building envelopes
- Inspect caulking/weatherstripping installations for adequacy to prevent air infiltration
- Demonstrate to building owners the need for caulking/ weatherstripping.

4.2 Equipment Required

Acoustic leak location requires a source of sound on one side of a building envelope and a means for observing sound at discrete locations on the other side.

4.2.1 Sound sources

Almost any sound source of sufficient loudness can be used, although it is preferable that the sound produced be steady and broadband (i.e., containing many frequencies). Low-pitched sounds (i.e., with frequencies below 500 Hz) are less likely to be satisfactory for the reason illustrated in Fig. 9. Very high-pitched sounds (with frequencies above 5000 Hz) will also be less satisfactory because such sounds are less audible and are more readily attenuated in the atmosphere and absorbed by building furnishings. Typical sound sources that have been used successfully in this program are:

Indoors

- a home vacuum cleaner
- a kitchen dishwasher
- recorded organ music (Bach's "Toccata and Fugue")
- a washing machine
- a television set
- a particularly noisy hair dryer
- a special test tape cassette (see below) reproduced through a home "hi-fi" set.

Outdoors

- traffic noise in a commercial district
- an idling power lawnmower.

For the majority of our field testing, however, the system illustrated in Fig. 12 was used. This is a portable, lightweight system available at low cost from most local "hi-fi" shops. Two nationwide retail sources for such equipment are listed in Table 1. Comparable, acceptable equipment is also available from other vendors.

The sound signal was obtained from a prerecorded 1-hr-per-side magnetic tape cassette prepared at BBN's laboratory. Recorded on one side of this cassette is a saw-tooth warble tone that sweeps in frequency from about 500 Hz to 8000 Hz about three times per second. The spectrum of this recording is illustrated in Fig. 13. This test signal works best in the field because it is so readily discernible. However, some people find the sound

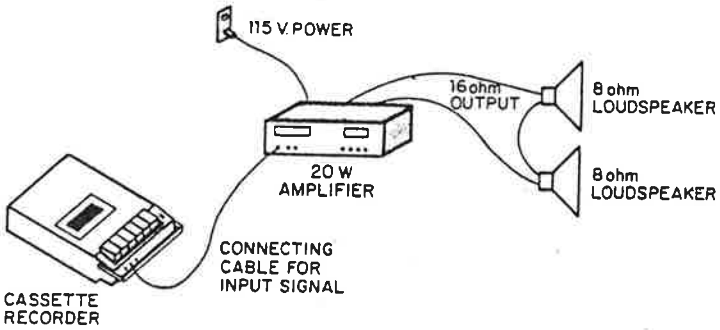


Figure 12. The sound source used for most field testing.

Table 1

Sound Source Equipment Available at Retail Outlets Nationwide (Comparable, Acceptable Equipment is also Available from Other Vendors)

		Radio Shack ("Realistic") Brand*				Lafayette Brand†			
Item	Quantity Required	Model No.	Catalog No.	Power Required	Unit Price	Model No.	Catalog No.	Power Required	Unit Price
Cassette Recorder	1	CTR-43	14-870	4 ea. 1.5 V C battery	$29.95	"Criterion 121"	99A16560	4 ea. 1.5 V C battery	$29.95
Amplifier 20 Watts	1	MPA-20	32-2020	120 V, 60 Hz 40 W	$79.95	"PASO 20-watt"	44A66009	120 V, 60 Hz	$89.99
Loudspeaker 8 ohms	2	-	40-1244	-	$10.95 ea.	-	99A46435	-	$ 9.99 ea.
Connecting Cable	1	-	42-2433	-	$ 2.49	-	99A10407	-	$ 2.49
Prerecorded Magnetic Tape Cassette	1		Recorded by Bolt Beranek and Newman Inc. (See text.)						

*Radio Shack 1978 Catalog No. 289.

†Lafayette 1979 Catalog.

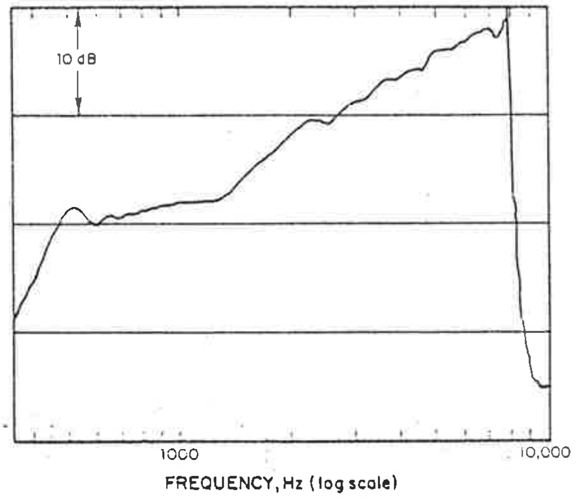


Figure 13. Spectrum of tone sweep recorded on tape cassette.

irritating. The other side of the cassette contains 1 hour of broadband Gaussian noise with a similar spectrum (Fig. 14). This test signal is less irritating to listen to, but more difficult to distinguish from normal background noises.

The pronounced high-frequency preemphasis that is evident in the recorded spectra in both Figs. 13 and 14 is an attempt to compensate for the high-frequency losses caused by the acoustical absorption usually encountered in typical rooms. Thus, when the tape is reproduced indoors in a typical living room, the spectrum of the reverberant sound pressure level is like that of Fig. 15.

4.2.2 Sound-detecting equipment

On the listening side of the envelope, it is necessary to have a means for observing the sound right against the barrier and over a very small spot — preferably less than 1-cm diameter. For this purpose, the following equipment has been used:

- A mechanic's stethoscope
- A plastic headset of the kind handed out to airline passengers
- Small rubber hoses, available at auto-parts stores, sized to fit comfortably into the end of the ear canal
- Type I and Type II Sound Level Meters per ANSI S1.4-1971 *[18]*
- Low-cost sound meters (see below).

For the majority of our field testing, however, the equipment illustrated in Fig. 16 and listed in Table 2 was used. This is a simple, battery-operated listening system, available at low cost. It is comfortable to use and works quite well.

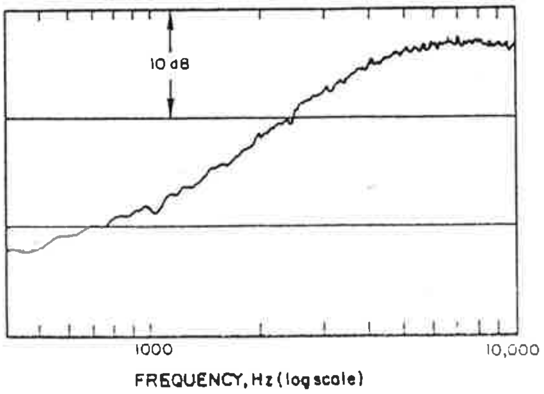


Figure 14. Spectrum of random noise recorded on tape cassette.

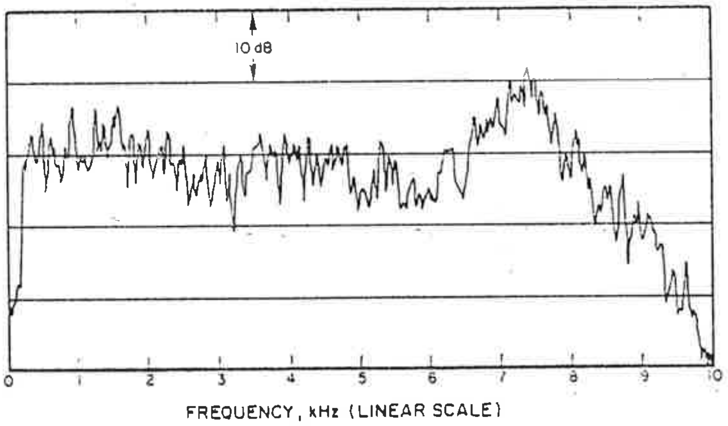


Figure 15. Spectrum of SPL produced in the reverberant field of a typical living room when cassette recording of Gaussian noise is reproduced through the system of Fig. 12.

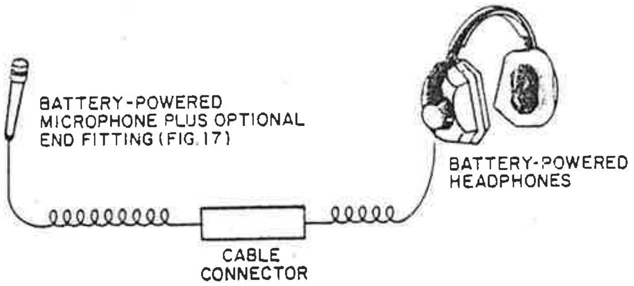


Figure 16. Listening system used for most field investigations.

Table 2

Sound Listening Equipment Used in Most Field Tests (Comparable, Acceptable Equipment may be Available from Other Vendors.)

		Brand Used					Alternate Source				
Item	Quantity Required	Brand	Model No.	Catalog No.	Power Required	Price	Brand	Model No.	Catalog No.	Power Required	Price
Microphone (electret condenser)	1	"Realistic" (Radio Shack)	-	33-1050	1-1.5 V battery N-size	$17.95*	Lafayette	-	99A46898	1-1.3 V battery (Mallory PX-400 or equal)	$16.99**
Headphone (built-in battery-powered amplifier)	1	Univox†	UPH-2	-	1 ea. 9 V "Transistor" (Mallory MN 1604 or equal)	$32.00	Lafayette (Univox)	-	25A05527	1 ea. 9 V "Transistor" (Mallory NM 1604 or equal)	$44.99**
Adaptor: F. phone to F. phone	1	Switchcraft	361A	-	-	$ 3.70	Lafayette	-	32A52012	-	$ 0.99**
Microphone end fitting (optional)	1	Machined by Bolt Beranek and Newman Inc. (See Fig. 17 and text.)									

*Radio Shack 1978 Catalog No. 289.

†Manufactured by Unicord Inc., 75 Frost Street, Westbury, NY 11590

** Lafayette 1979 Catalog.

For probing small cracks located close together, such as joints in the casing around door and window frames, the microphone end fitting illustrated in Fig. 17 enhances the performance of the listening system. It restricts the listening area to a 1/8-in. (3-mm) circle and reduces interference from background noise.

With the listening system illustrated in Fig. 16, the user simply compares the loudness of the sound at a suspected leak opening to that at a nearby and obviously sealed point on the wall. A marked increase in loudness at the opening indicates a leak and is quite noticeable to the human ear. This technique does have drawbacks, however. A quantitative indication of the increase in loudness is sometimes useful, particularly for inexperienced users. Furthermore, only one observer at a time (the one wearing the headset) can detect an opening. It is often helpful, particularly when an inspector is demonstrating the technique to other observers, to have a method where several observers can see the results at the same time.

To overcome these limitations, considerable work was done with meters replacing the equipment in Fig. 16 to indicate the magnitude ("level") of sound at the microphone. For example, a wide variety of commercially available standardized sound level meters was used [*18*]. However, since these instruments generally cost $500 or more, they do not satisfy one of the major objectives of this program: very low-cost equipment. Unfortunately, all of the low-cost ($50 to $100) sound meters presently on the market have limitations that restrict their utility for our present purpose. These are described below.

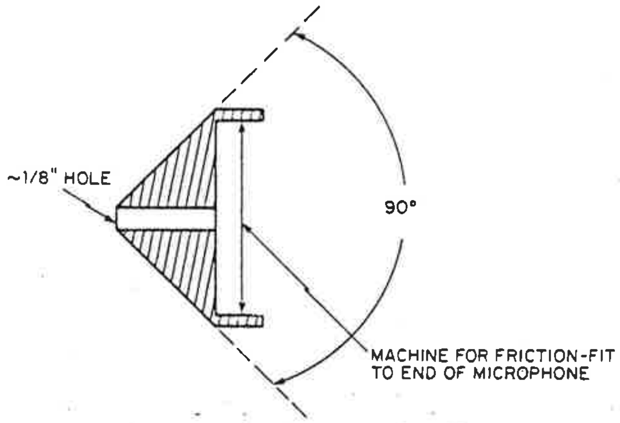


Figure 17. Microphone cap for probing narrow cracks and crevices (material: nylon or other hard plastic).

"Realistic" (Radio Shack) Sound Meter Cat. No. 42-3019: $39.95

This is an excellent sound meter for the price. It is widely available and very simple to use. Its major limitation is that it lacks sensitivity, and readings below 60 dB are not possible. Furthermore, the microphone is fixed to the meter case, so that in many locations the meter cannot be easily read when the microphone is placed on a crack. (The ideal meter for this application should have a microphone connected through a short cable to the indicating instrument. This arrangement allows the user to move the microphone around with one hand while holding the indicating instrument at a convenient viewing location in the other hand.)

Onsoku Sound Meter Model SM-6: $46.50 (1977) Plus Duty

This meter is available by import from Star Bridge International, Inc., No. 3-15 Hiratsuka 1-Chrome, Shinagawa-ku, Tokyo, Japan. Minimum order is 20 units. The current price is probably higher than indicated above. The most serious limitation of this meter is that it is difficult to procure. However, it is also cumbersome to use, with very poorly configured user controls. As with all these low-cost meters, the microphone is fixed to the meter case. (BBN modified one of these instruments by adding a cable to make the microphone remote, and the instrument still worked adequately for leak location. However, the modification must be done by someone who is skillful with a soldering iron.)

Castle Associates Sound Meter Model No. CS-15C: $95.00

This meter is available from Castle Associates, P.O. Box 59, Woodside, California 94603. It is almost twice as expensive as the other products, and the microphone is fixed to the case.

Intrigued by the leak-location application, Castle offered some months ago to custom-build a meter for BBN's evaluation. Although there has been correspondence about this offer, we have not yet seen the instrument.

Clearly, there are no significant technical problems associated with producing a $50-to-$100 sound meter for acoustic leak location. In some cases (as we have demonstrated), it would require no more than the addition of a cable between the microphone and the indicating instrument. At present, there is nothing suitable on the market because the potential manufacturers do not yet see a market need for such a product. One of the recommendations of this study is that DoE attempt to create this market need.

When a sound meter is used in place of the system illustrated in Fig. 16, it eliminates the need for the microphone shown in the figure. However, it is best to continue to use headphones (or a single earphone) connected to the meter output so that the operator can aurally verify that the meter is indicating the test sound and not some extraneous noise interference. Furthermore, the meter should be operated on the "A-weighting" scale, if available, to help discriminate against interfering noise.

4.3 Test Procedures

The acoustic leak-location method requires that one side of the envelope be "noisy" and the other side quieter. Obvious openings through the envelope (an open window, for example) must be closed. Once a suitable sound is available on one side of the wall, the user has only to listen on the other ("quiet") side with equipment such as described in Sec. 4.2.2. By moving the microphone back and forth between places that are obviously sealed (the center of a window pane, for example) and potential leaky locations, the operator looks for a noticeable increase in the sound level coming through the barrier. The process is very fast, because the closer the microphone is to a leak opening, the louder is the sound. Typically, the operator marks the leaks with chalk or masking tape so that they can be sealed later.

The same technique can later be used as an inspection aid to verify that leaks have been properly sealed.

Acoustic leak location can be used in either direction through a building envelope. If the building is on a busy street, outside traffic noise can be used as the sound source, and the operator can listen inside. Alternatively, sound can be produced inside the building and detection done outside. Because the leak outlets will be located on the side of the wall where detection is done, it is best to listen on the side that is to be caulked — usually the outside of the building. However, in cold climates it may be desirable to seal the heated side of the wall in order to minimize condensation problems.

Testing a typical two-story house with an attic and basement requires 1/2 to 1 hr when the following procedure is used:

1. Place the sound source in the basement, close basement doors and windows, operate source as loudly as possible without distortion, and test *outside* the basement at:

- window sashes and frames
- door jambs and frames
- sill plate, where house attaches to foundation
- foundation cracks and mortar joints

- wall penetrations for utility pipes, water faucets, etc.

Then, if it is desired to seal the basement from the first floor, listen *inside* the first floor:

- around the baseboard of each room
- around heating duct/pipe and water pipe penetrations of the first floor
- around fireplace hearths
- around duplex outlets and wall switches
- around the door to the basement.

2. Place the sound source on the first floor, and operate it as loudly as possible without distortion. Open all interior doors. In large houses, it may be necessary to move the sound source from room to room inside as the operator listens outside the first floor:

- at door and window frames and sashes
- alongside exterior chimneys
- at corners of the structure
- around other envelope penetrations.

3. Place the sound source on the second floor, and listen outside the second floor at the same kinds of places observed outside the first floor. The microphone can be placed on the ends of a lightweight pole to facilitate working from the ground.

4. Place the sound source in the attic, if unheated, and measure *inside* the second floor:

- around the attic door
- at ceiling light fixtures
- at wall switches and duplex outlets.

When testing storm windows, open the main window sash inside and test around the storm. Then open the storm, and close and test the main sash. Do the same where storm doors are installed.

4.4 Limitations of the Method

Certain limitations to the use of the acoustic leak-location method have been identified and are discussed below.

Lightweight Barriers

Sound comes through openings in walls, and also directly through the sealed portion of the wall. Though the sound through the sealed wall is generally much less than that which comes through the leaks, it is always there (see Sec. 3.2).

The amount of sound that comes directly through a wall is (approximately) inversely proportional to the mass-per-unit area of the wall. Heavy walls transmit little sound, whereas light walls transmit more. A pane of glass transmits more than a heavier frame structure. This is why, when listening for leaks, the user must always compare the sound level at the possible leak location with that at a nearby location of similar structure that is obviously sealed, to see if the level at the leak is greater. As a result, the method will not locate leaks in very lightweight structures (such as storm windows made of plastic sheeting). For most practical applications, this is no problem; but it is an inherent physical limitation of the method of which the user should be aware.

Insulation

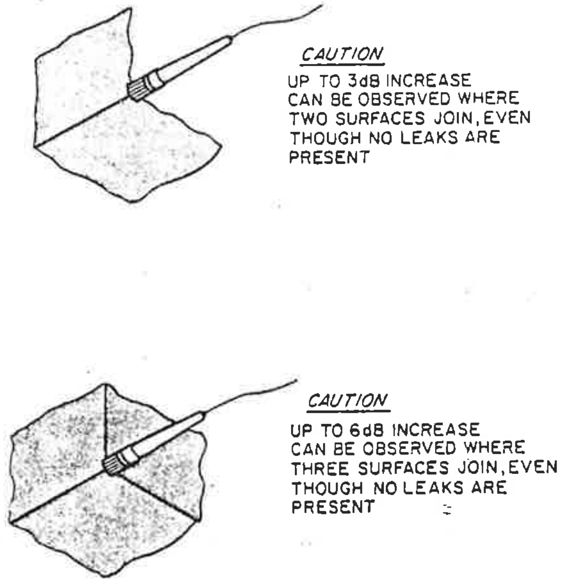
As indicated in Sec. 3.2.2, fibrous thermal insulation in a wall will greatly reduce the sound passing through long (i.e., a foot or more) and complicated air passages in the wall. It will have less effect on the air flow through such passages. Thus, acoustic testing will usually not locate the openings of complicated air passages through insulated walls, although it will locate straight-through passages in insulated walls, such as around a chimney or door frame.

This limitation will be noticeable when the user looks for leaks through duplex outlets and light switches that are wired with "Romex" rather than metal conduit. Such leaks can be found in uninsulated interior walls, though usually not in insulated exterior walls.

Of course, thermal insulation will reduce air flow as well as sound propagation through leakage passages. Thus, leakage through insulation-filled passages is not often a major contributor to the total building infiltration. Nevertheless, sound is attenuated by insulation much more than air leakage is reduced, and this is another physical limitation of the method.

Reflections at Corners

When a sound wave is reflected from a wall, the sound pressure right at the wall will be double that observed at some distance away from the wall. Because of this fact, there is usually an increase of as much as 3 dB observed where two walls meet, and as much as 6 dB where three walls meet, relative to the level some distance away from such joints. See Fig. 18. These increases can be detected, but do not signify the presence of an



CAUTION

UP TO 3dB INCREASE CAN BE OBSERVED WHERE TWO SURFACES JOIN, EVEN THOUGH NO LEAKS ARE PRESENT

CAUTION

UP TO 6dB INCREASE CAN BE OBSERVED WHERE THREE SURFACES JOIN, EVEN THOUGH NO LEAKS ARE PRESENT

Figure 18. Conditions where anomalous indications are possible.

air leak. If there is a leak, the increase will be much greater — 10 dB or more.

The user can avoid this characteristic of the method by always comparing the sound level in corners suspected of having leakage openings with the level in sealed corners that have the same configuration.

Improvements

The acoustic-location method needs improvement in two areas:

- A commercially available low-cost meter is needed to read the level of the sound issuing from leakage openings. (Suitable laboratory instruments costing $500 or more are readily available.) Producing a meter in the $50-to-$100 price range presents no technical problems, but there is just nothing suitable on the market at present. (See Sec. 4.2).
- More data should be acquired on the acoustic vs air-flow properties of weatherstripping — particularly after periods of use. Theory and available data suggest a correlation between the two, but differences over the wide range of types and styles of weatherstripping, before and after extensive use, have never been studied.

Education

Potential users of the method need some education about its purpose and its principles of operation. Some users may not realize that infiltration represents a significant energy loss in buildings, because they have been conditioned to think that thermal insulation will solve all heat-loss problems. Some need repeated reminders that acoustic location will not generally indicate the presence or absence of thermal insulation in walls (and that thermal insulation in walls will not "soundproof" a building!) Some will attempt to locate the leaks around the frames of open windows, failing to realize that the sound passing through the open windows will nullify the chance of detecting other leakage openings. Some feel that the method is a means for measuring infiltration rate, rather than simply a method for locating leakage openings.

4.5 Benefits of the Method

The benefits of the acoustic leak-location method include:

- *Wide availability of the necessary equipment*

Equipment for acoustic leak location can be obtained at almost any "hi-fi" shop. Many people already own much or all of the equipment necessary to apply the method.

- *Low equipment cost*

The necessary equipment can be purchased for about $200 at retail stores.

- *Easy to learn and to use*

The method, once a person has been instructed and has tried it, is easy to use. Building tradesmen and homeowners can easily do it.

- *Independence from weather conditions*

Acoustic leak location requires no pressure difference or temperature difference across the building envelope.

- *Safety; minimal occupant interference*

  The method is completely safe, and it creates only a minimal interference with activities of building occupants during its use.

5. EXPERIMENTAL WORK AND FIELD APPLICATIONS OF THE METHOD

Experimental work with the acoustic-location method was divided into three phases:

- Laboratory measurements, where both acoustic and air leakage were measured through known paths under controlled conditions
- Local field studies of buildings in the Boston area by BBN personnel
- Field applications of the method at several different locations in the United States, performed by building retrofit organizations.

Each of the phases is described below.

5.1 Laboratory Measurements

The objectives of the laboratory measurement program were:

- To determine the possibility of locating air-leakage paths acoustically
- To determine the simplest methods for acoustic location of air-leakage openings
- To determine the simplest and least expensive equipment for acoustic location
- To determine the correlation of acoustic leakage with the air-flow leakage through various leakage paths.

The laboratory measurements were conducted in BBN's reverberation-chamber test facility, illustrated in Fig. 19. One room, the "indoor" room, was sealed airtight, and a typical

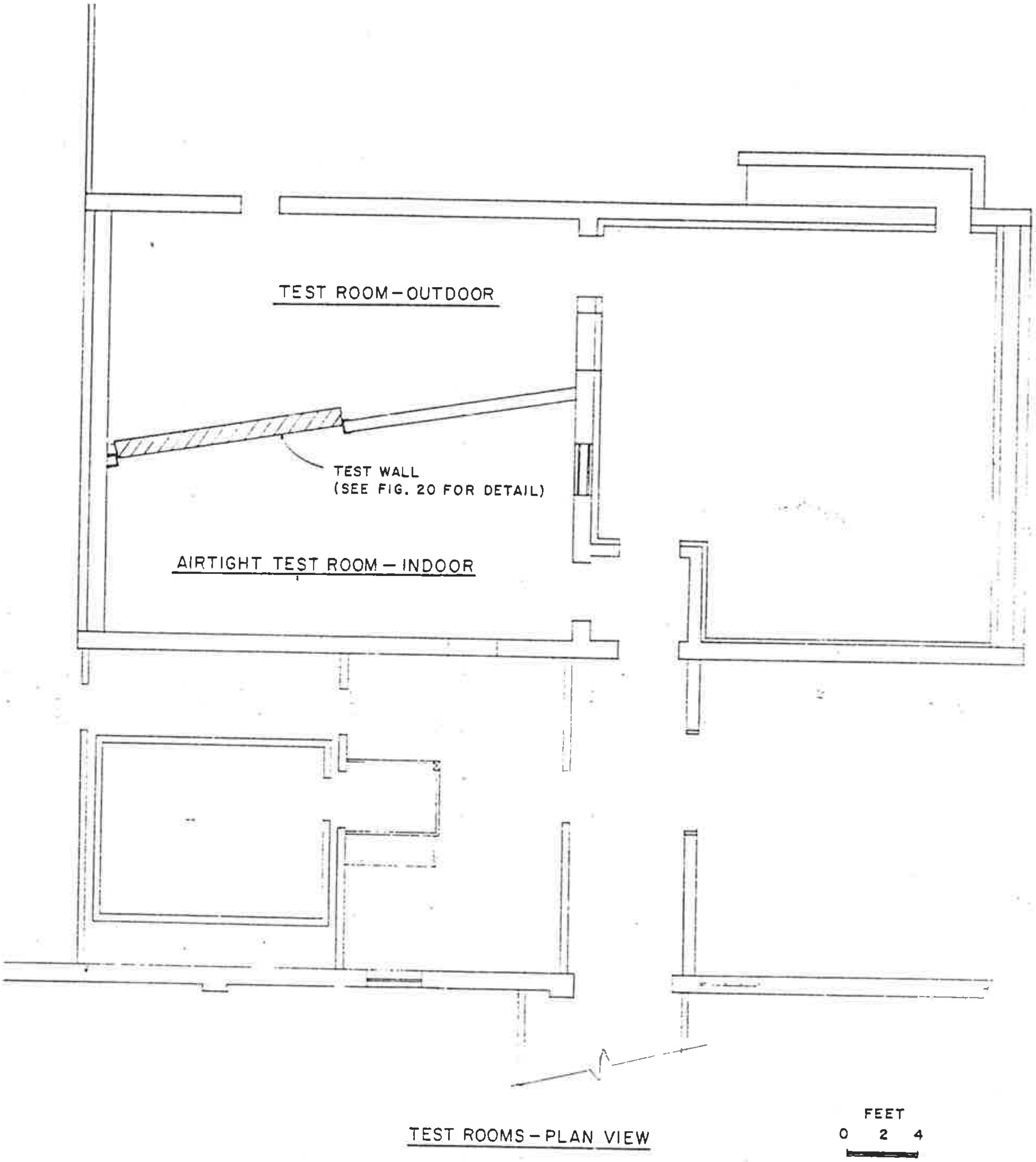


Figure 19. BBN test facility in which laboratory measurements were conducted.

residential exterior wall panel was built between this room and the "outdoor" room. Acoustic and air-leakage tests were conducted across the test wall.

The test wall built between the two rooms is illustrated in Fig. 20. This wall was of typical residential frame construction, and had the following controllable leakage paths:

- Through a metal-flap mail slot in the door
- Between the door and the door jamb
- Between the structural framing and the prehung door
- From a duplex outlet through an uninsulated inter-study cavity to a wiring hole drilled in the top plate
- From a duplex outlet through an insulated (R-11) inter-stud cavity to a wiring hole drilled in the top plate and to an exterior water faucet
- Between the sill plate and a solid concrete-block foundation
- Around the double-hung window sash, and through the meeting rail of the window
- Between the prehung window frame and the structural framing.

Photographs of the wall during construction are shown in Fig. 21.

Flow Tests

In order to measure air-leakage rates, a differential pressure was established between the two test rooms in accordance with the procedures of ASTM E283-73 [*8*]. The "inside" of the

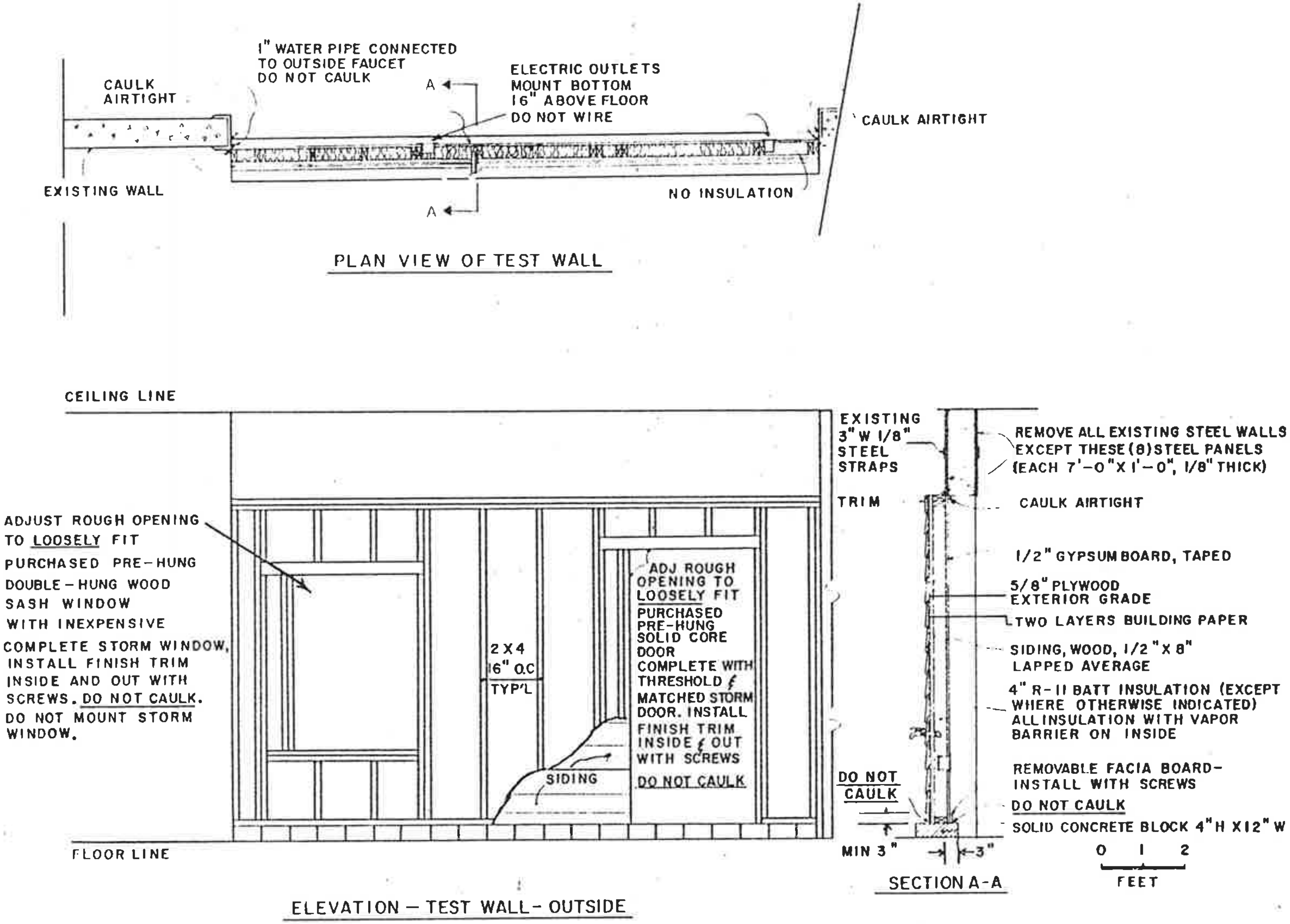
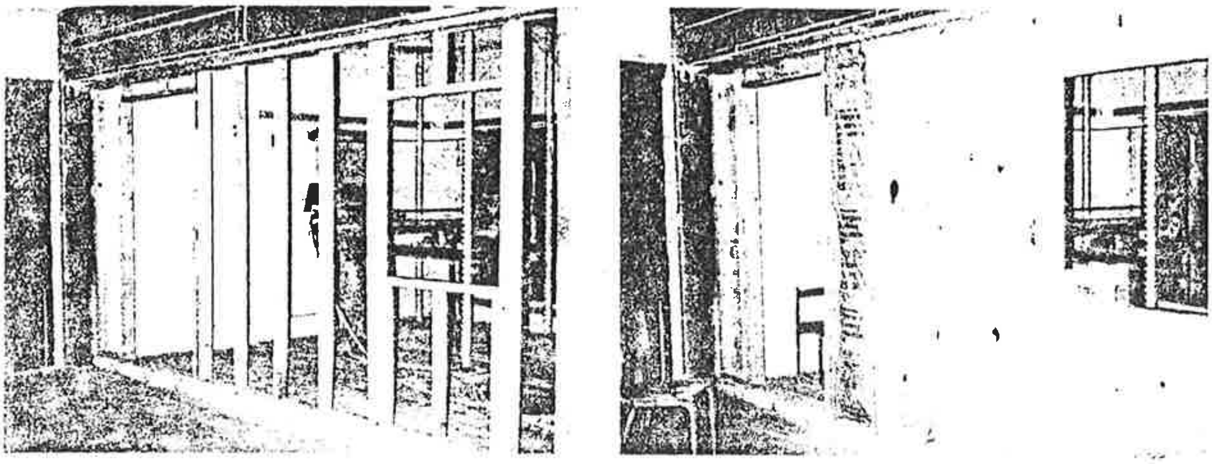
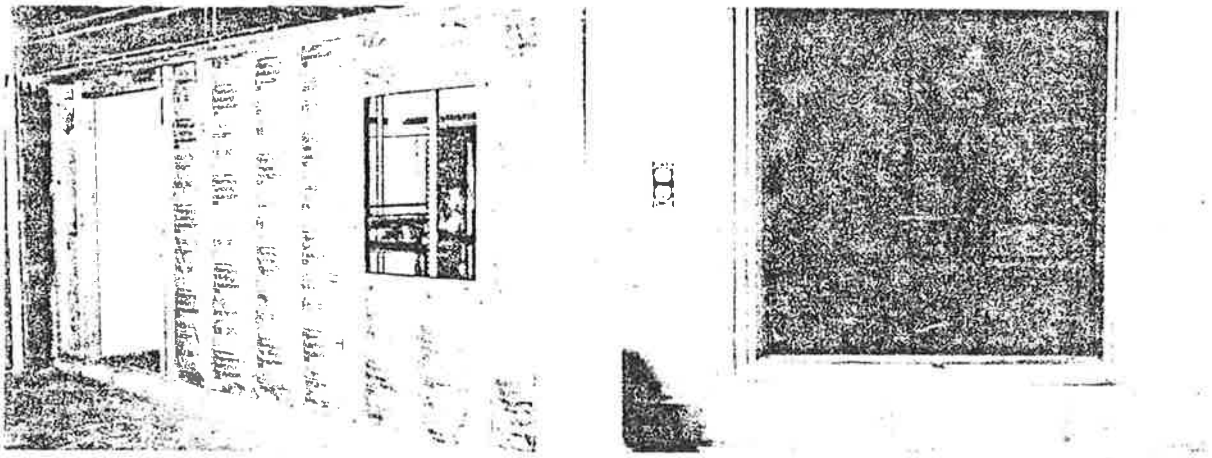


Figure 20. Test wall built for laboratory measurements.



FRAMING

SHEATHING



INSULATION

DRY WALL AND DOOR FRAME DETAIL

Figure 21. Photographs of test wall during construction.

wall was established at a negative pressure with respect to the "outside." Measurements were made of the flow rate vs differential pressure at several pressures for each of the various leakage paths. The results were extrapolated or interpolated to the flow rate at a differential pressure of 0.3 in. H_2O, corresponding to the stagnation pressure of a 25-mph wind. All flow data tabulated herein are at this 0.3 in. H_2O pressure.

Prior to the construction of the test wall in Fig. 20, the tare leakage of the room (with a sealed, steel wall in place of the test wall) was measured as follows (see Appendix A, Fig. A.1):

Tare leakage of "sealed" room	8.9 cfm .

Following construction of the test wall, all known leaks in the test wall were sealed, and the tare leakage was again measured:

Tare leakage of room with all known leaks in test wall sealed	23.5 cfm .

All data reported herein have been corrected by subtracting the latter tare leakage.

The results of the flow-measurement tests are listed in Table 3. It is noted that both the door jamb and window sash (especially the meeting rail) were quite leaky — a problem obvious by visual inspection. Some of the other leaks, such as those under the sill plate and around the window and door frames, were not visually obvious.

Table 3

Summary of Results of Air-Flow Tests at 0.3 in. H_2O Differential Pressure (for Raw Data, See Appendix A)

Leakage Paths	Flow, cfm	Crack Length, ft	cfm per ft of Crack
Wall Leaks (Fig. A.2)			
Duplex outlet in insulated wall	11.2	--	--
Duplex outlet in uninsulated wall	13.0	--	--
Sill plate-top of trim	5.3	11.0	0.48
Sill plate-bottom of trim	10.5	11.0	0.95
Window Leaks (Fig. A.3)			
Sash only (without meeting rail)	12.3	10.5	1.2
Sash and meeting rail	38.0	12.8	3.0
Entire window, including frame	83.0	24.8	3.4
Door Leaks (Fig. A.4)			
Mail slot	3.6	2.3	1.6
Frame trim, outer, 3 sides	17.0	16.75	1.0
Frame trim, outer and inner, 3 sides	37.5	33.25	1.1
Under threshold	21.5	--	--
Jamb (except threshold)	118.0	16.0	7.5

Subsequent testing (see below) indicated a wide variation in local leakage rates along a single defined crack. Often, most of the leakage was found to be flowing from only limited regions of a crack. As a result, metrics such as the average leakage rate per linear foot of crack were not particularly meaningful for this test configuration.

Acoustic Location Studies

Acoustic studies were made by producing sound on one side of the wall and probing the other side with a small microphone. The sound level at potential air-flow locations (cracks) was observed relative to that at obviously sealed "reference" locations in the same structure. Where a significant difference was noted, a sound-leakage (and thus an air-leakage) path was deemed to exist.

A large quantity of data was acquired by using a variety of acoustic test signals and propagating sound in both directions through the wall. A typical example is shown in Fig. 22, where sound was propagated from the "outside" of the wall to the "inside." Measurements were made at various locations on and around the inside of the door, as indicated in the figure. The noise source was broadband random noise, which accounts for the "jagged" nature of the curves. The jaggedness is not otherwise of any significance.

The acoustic pressure observed with the microphone was analyzed with a narrowband spectrum analyzer to produce the curves of sound pressure level vs frequency shown in the figure. This analysis was an attempt to identify resonances as predicted by Gomperts (Sec. 3.3). The signal obtained with the microphone

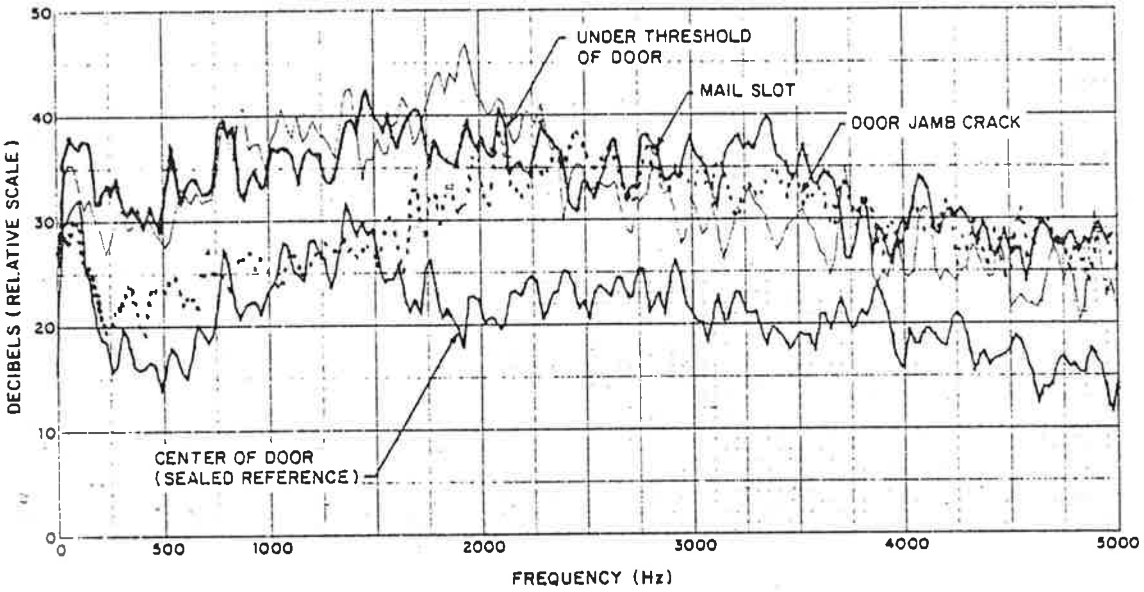


Figure 22. Sound spectra observed on and around inside of door with random-noise source outside.

held against the center of the door was selected as a reference signal, because there was obviously no air leakage possible through this solid-core wooden door. The significant results, shown in Fig. 22, are:

- The sound pressure level under the threshold of the door is 10 to 15 dB (3 to 5 times) greater than the reference, as is the sound pressure level in the mail slot.
- The sound pressure level with the microphone held against the door jamb is about 10 dB (a factor of 3 times) greater than the reference above 2 kHz, but essentially the same as the reference below 1.5 kHz.

A number of tests like those in Fig. 22 showed that sound propagation through cracks is relatively insensitive to acoustic frequency, at least at the higher frequencies. The resonant propagation predicted by Gomperts was not detected, presumably because of losses introduced by the complex geometry of the cracks. Thus, the narrowband spectrum analyzer was not dispensed with. Additional measurements were made in 1/3-octave bands per ANSI S1.11 [*19*], and with a sound level meter set to the "A-weighting" scale* [*18*], simplifying the measurement procedure and bringing us closer to a practical field technique.

Typical 1/3-octave spectrum differences are shown in Figs. A.5 through A.7 in Appendix A. These indicate that maximum sound transmission through leaks, relative to that at suitable sealed locations nearby, is generally observed above 500 to

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*The A-weighting scale of a sound level meter adjusts the frequency response of the meter to approximate that of the human ear, so we measured what an observer could hear if he listened to the sound coming through the crack.

1000 Hz, but not at resonant peaks. Maxima of 5 to 15 dB in some 1/3-octave bands are observed. The spectra differ depending upon the direction of propagation through the crack (Figs. A.6a and A.6b), but have the same general characteristics.

Subsequent to the measurements that provided results such as those illustrated in Figs. 22 and A.5 through A.7, all of the leakage openings were sealed and retested. The significant differences were then no longer observed.

In the final phase of the laboratory experiments, a suitable sound source was located on one side of the wall, and A-weighted sound-levels were observed at a number of locations on the other side, both where cracks were known to exist and where cracks were known not to exist. The differences between these observations were then tabulated. In general, the level at the window pane was used as a reference for measurements around the window; the level at the door was used as reference for measurements around the door; and the level at the wall (gypsum board) was used as reference for measurements along the sill plate.

The differences in A-weighted levels determined in this way do not correlate well with the gross flow-rate data in Table 3, because the size of each crack varies along its length. The gross flow-rates of Table 3 are presumably related to the average crack dimensions, whereas the sound level observed at a point on the crack is a function only of the crack dimensions within a few inches of the measurement location. (This is one of the fundamental reasons why acoustic leak location cannot readily be used as an inflation-rate measurement technique.)

A small hot-wire anemometer was used to obtain a measure of air-flow rate that could be compared with acoustic measurements at discrete locations along cracks. A differential pressure of 0.3 in. H_2O was established across the test wall. Local flow-velocity measurements were made at several locations along known cracks. Acoustic level differences were observed at the same locations. These results are plotted as open circles in Fig. 23.

Each of the cracks studied in this way was then caulked and the measurements repeated. The air flow was, of course, eliminated by the caulking, and the sound level differences were found to have decreased correspondingly. These data are plotted as the solid circles in Fig. 23. (The solid circles are plotted on the abscissa at the flow rate that existed before caulking, for comparison with the corresponding open circles.)

The important conclusion from Fig. 23 is that, if the sound level at a point on a crack is 5 dB(A) or more above that at a nearby, sealed location, the flow at that point will be 100 ft/min or more with a differential pressure of 0.3 in. H_2O across the wall. Sound level increases of less than 5 dB at a crack are not indicative of an air-flow path (see Fig. 18).

Acoustic location failed to detect the presence or absence of thermal insulation in wall cavities, except in one special case. In this case, sound was radiated into the duplex electrical outlets, one mounted into an uninsulated interstud cavity and the other mounted into an insulated cavity. See Fig. 20. A sound-level increase could then be detected at the wiring-clearance hole on the top plate above the uninsulated cavity, whereas none could be detected about the insulated cavity.

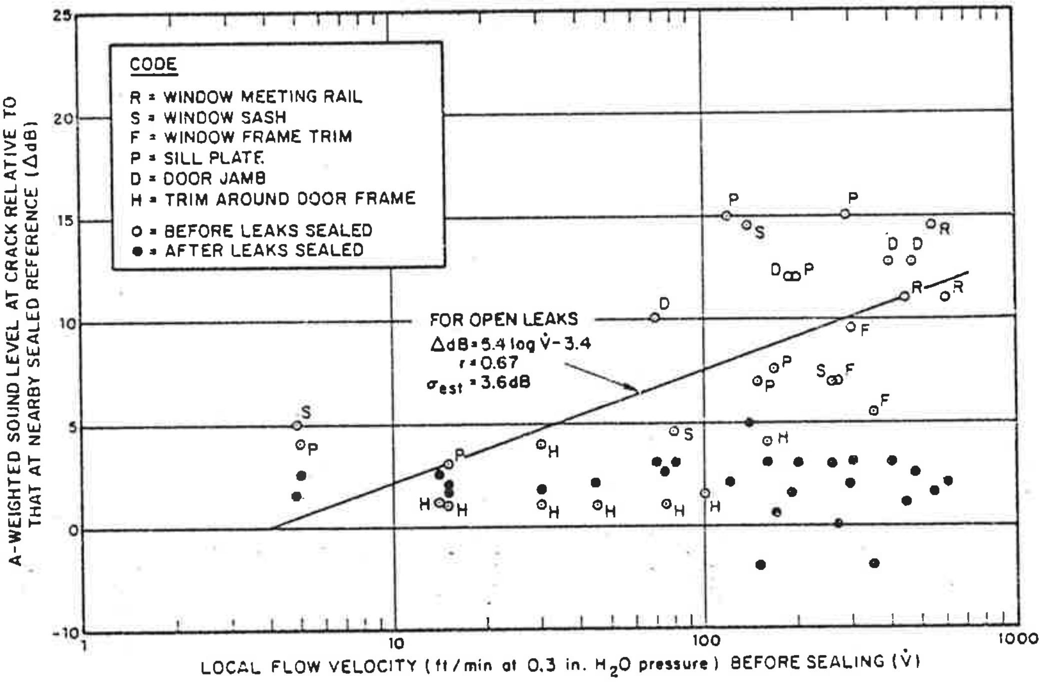

Figure 23. Increase in sound level near crack vs local air flow from crack at 0.3 in. pressure differential.

In general, leakage paths through insulated wall cavities could not be located acoustically.

The balance of the laboratory program was devoted to the selection and evaluation of low-cost equipment for performing acoustic leak location in the field; it resulted in selection of the equipment listed in Tables 1 and 2.

Conclusions

Conclusions, based upon the results of the laboratory tests described above, are:

A. Simple leakage paths are readily detectable acoustically. These include both the visually obvious ones (door jamb, window sash, window meeting rail) and the hidden ones (door and window frames, sill plate).

B. Complex leakage paths through insulated walls are not generally detectable by acoustic tests (i.e., duplex outlets).

C. Under some conditions, acoustic tests can be used to determine the presence or absence of fibrous insulation in a wall cavity (such as between a duplex outlet and a remote wire-passage hole).

D. Acoustic testing can be done either from outside-to-inside or from inside-to-outside.

E. The form of the acoustic test signal is not critical to the test results. It is only important that it have adequate high-frequency content (above 1 kHz) and sufficient level to be readily detectable above the background noise.

F. A small increase in acoustic level [5 dB(A) or less] can occur at joints where orthogonal surfaces meet, even though no air-leakage path exists at such locations.

G. A sound level increase of more than 5 dB(A) at a crack is a strong indication that the crack will have a local flow of 100 ft/min or more at 0.3 in. H_2O pressure difference.

5.2 Field Studies by BBN Personnel

BBN personnel conducted acoustic-location studies and related measurements in 8 buildings, as follows:

Single-family residences:

- "W" Home
- "H" Home
- "A" Home
- "P" Home
- "K" Home

Commercial buildings:

- Meat Market
- Supermarket

School Building:

- Carlisle Elementary School.

These field studies were performed to obtain comparisons between air flow and acoustic location of leakage openings and to perfect field-testing methods.

Information on the buildings studied and associated measurements are included as Appendix B. In this section, we discuss the principal results and conclusions of these field studies.

5.2.1 Flow testing

All of the five residences studied were suprisingly leaky, when tested in accordance with ASTM 283-73. They showed a range from about 5 to about 17 air changes per hour at 0.1 in. H_2O differential pressure.* In the draftier houses, the major leaks were "simple" leaks as defined in Sec. 3.3.1, and were readily located by the acoustic method. These include:

- the sill plate where the building was attached to its foundation
- joints in mortared store foundations
- floor penetrations for heating and water pipes
- unweatherstripped jambs of interior access doors to unheated attics and basements
- the usual door-jamb and window-sash leaks.

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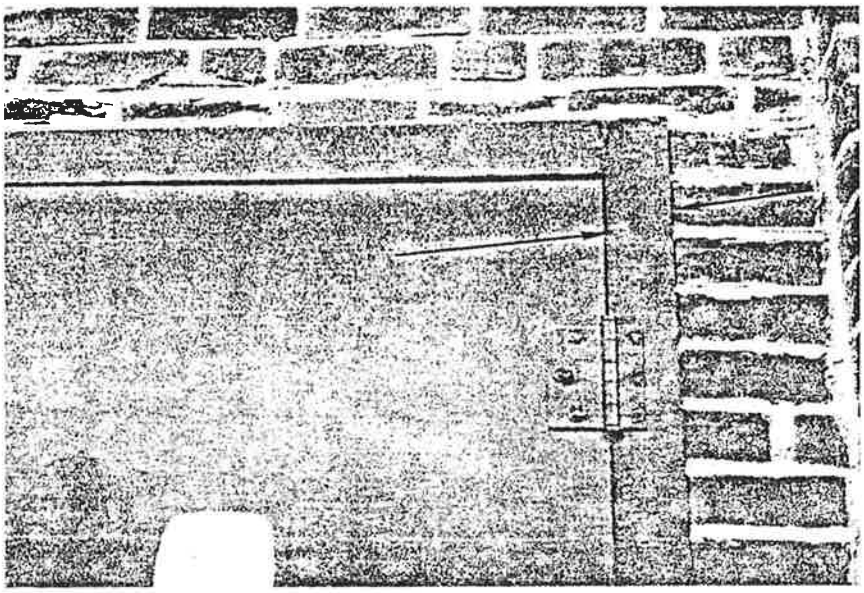
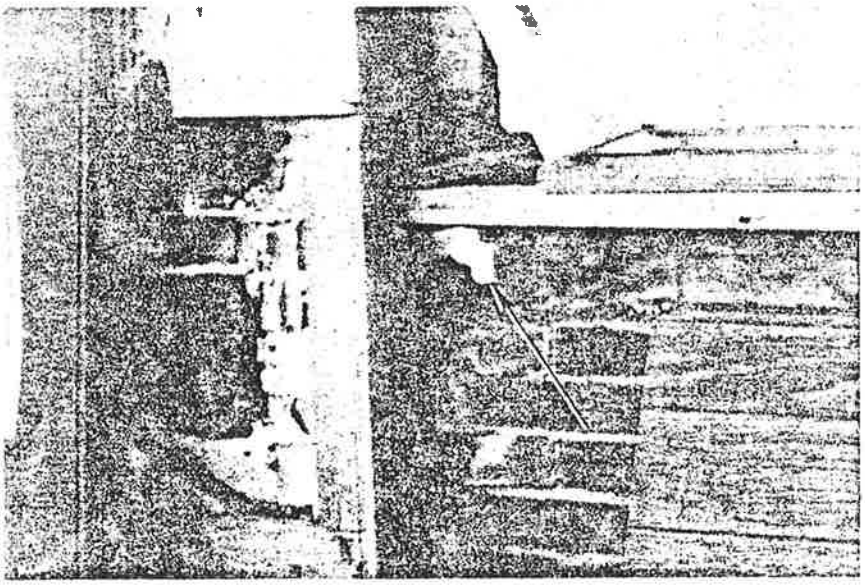
*Air-change rate is the total volume of air per hour drawn through the building with a fan applying 0.1 in. H_2O differential pressure across the envelope, divided by the volume of the heated living area of the building. The air-change rates reported here are high compared to what would be observed without an artificially induced differential pressure. Some investigators divide such rates by 2, under the assumption that air would be entering through half the leaks and exiting through the other half under natural conditions. Other investigators divide by 4, under the assumption that a natural, wind-induced differential pressure could occur on only one side of the building at a time. No such correction factors have been used in this report.

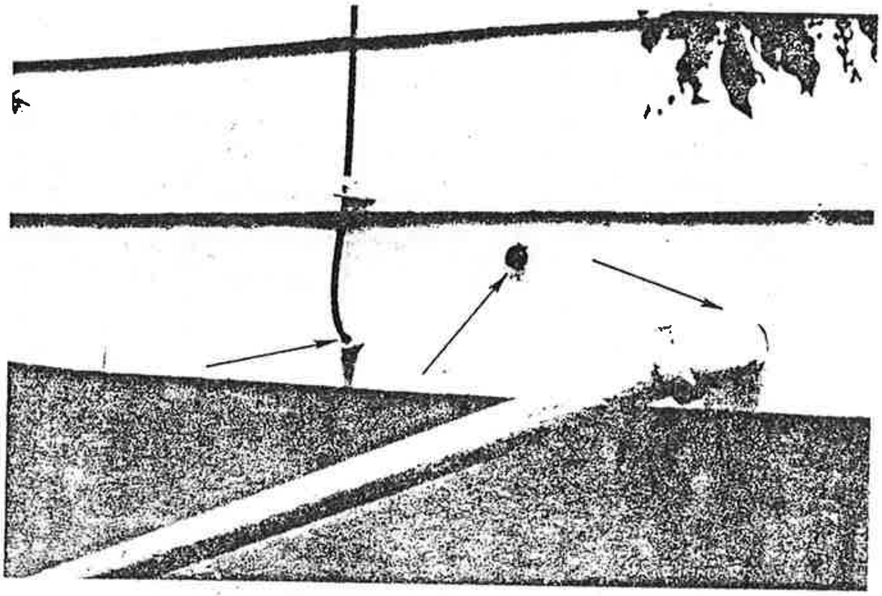


DOOR JAMB & FRAME AT MEAT MARKET

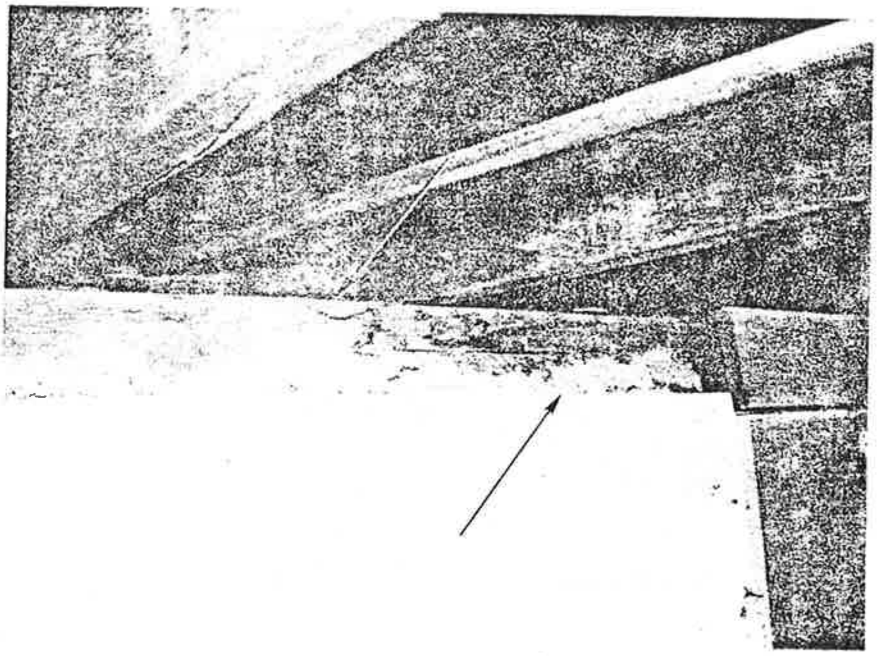


HOLE IN WALL AT SUPERMARKET

Figure 24. Typical openings of "simple" leaks.



EXTERIOR WALL PENETRATIONS, "A" HOUSE



SILL PLATE, "A" HOUSE

Figure 24. (Continued)

As noted in the laboratory studies, there was marked variation in both air flow and acoustic transmission along the lengths of most simple cracks. Typical leakage locations are illustrated in Fig. 24.

In the tighter structures, "complex" leakage paths were more evident. These included paths:

- through subflooring and out from built-in kitchen and bathroom cabinets
- through interior plaster walls where baseboard heating pipes enter rooms
- from remote points through walls and thence out around door and window frames; and interior openings in sash-weight boxes.

In many such cases, the "ends" of a given leak are not at all obvious, and the leak could involve air flow for many feet through wall and floor/ceiling cavities. Such leaks were generally, but not always, undetected by acoustic means.

Data from those structures where local air flow and acoustic leakage were both measured at the same location are plotted in Fig. 25. When the data from acoustically undetectable "complex" leakage paths are deleted, the results show a correlation of +0.74, with a standard error of estimate of ±3 dB. Note that the air-flow measurements were not all made at the same differential pressure.

Front-door weatherstripping at one building, the "W" house, appeared to produce an adequate seal against air flow, but was a significant acoustic leak (see Fig. 26). The reason for this anomaly is unknown, but it may be related to the small motion of the door due to the imposed static pressure.

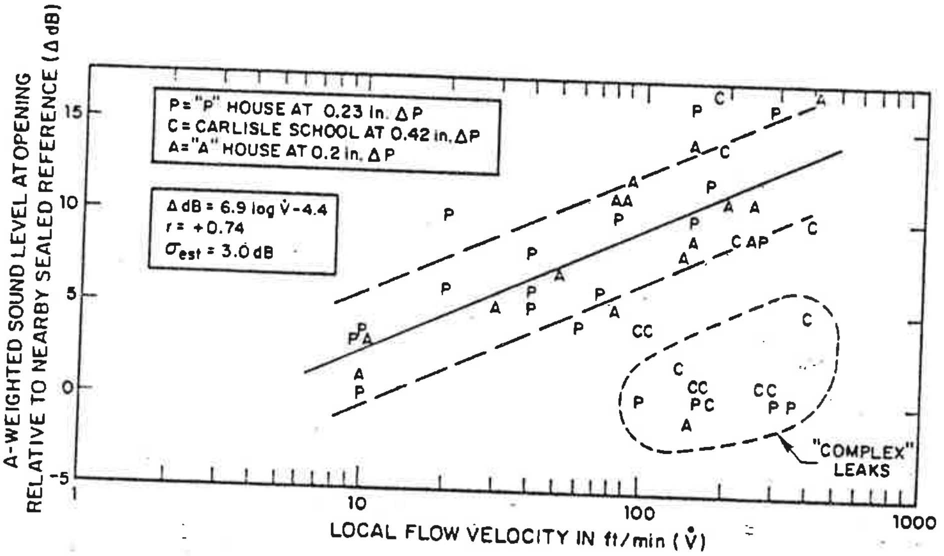


Figure 25. Increase in sound level near cracks vs local air flow from same crack.

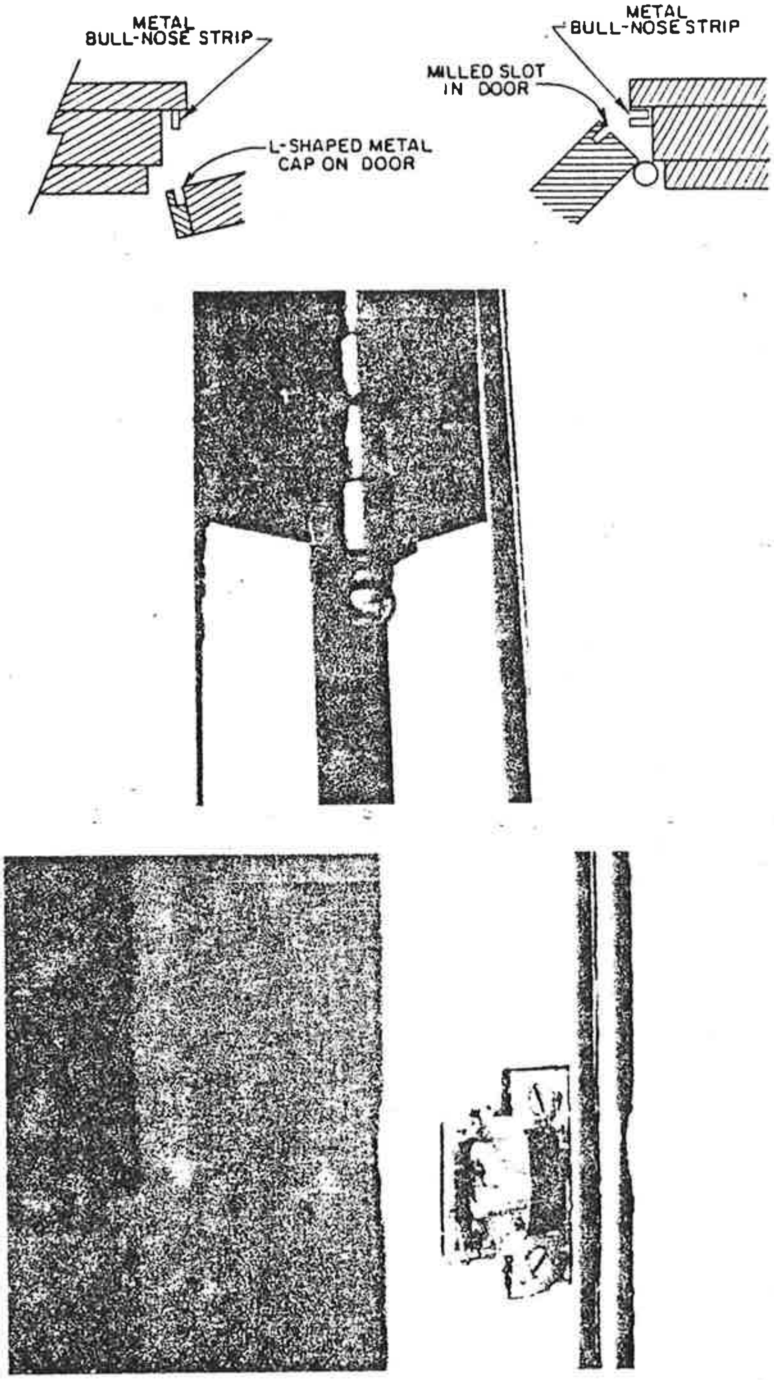


Figure 26. Front door weather-stripping of W-house, which provided an adequate air-flow seal but leaked acoustically.

5.2.2 Other results of acoustic studies

Although most of the buildings were tested acoustically by producing sound indoors and listening out-of-doors, the reverse was done successfully at the "K" house, the meat market, and the supermarket.

In the case of the two markets, external traffic noise was used as the sound source, so that no artifically produced sound was necessary. Because traffic noise is inherently fluctuating, it was found most convenient to make observations at the times of maximum noise level, such as when a vehicle was passing adjacent to the building. Nevertheless, this method was judged somewhat more difficult and less accurate than the use of a controlled sound source.

Certain complex leaks were located at the "K" house by acoustic means. These included:

- Paths from the attic through wiring access holes to switchplates and duplex outlets in uninsulated interior walls. Leakage through ceiling light fixtures was also detected in this way.
- Some heating-pipe penetrations of interior plaster walls, with the sound source outside. It is important to note that these same leakage openings could not be located in the reverse direction, with the sound source inside and detection equipment outside.

In general, as indicated in Appendix B, simple leaks produced local sound-level increases of 4 to 31 dB(A) [mean 10.5 dB(A), std. dev. 5 dB(A)]. Such increases were eliminated when the leakage openings were caulked [mean 1.2 dB(A), std. dev. 5 dB(A)].

The results of this admittedly limited set of field studies suggest that acoustic leak location can identify many leakage openings in buildings having leakage rates of 10 or more air changes/hr (at 0.1 in. pressure). The method is less useful in buildings having leakage rates of 5 changes/hr or less, because most of the leakage paths in such buildings are complex.

5.3 Field Studies by Others

An important part of this program has been to introduce the acoustic-location method to various individuals and groups concerned with building retrofit for energy conservation, and to solicit their comments and criticisms of the method. Toward this end, 11 different organizations were contacted with regard to the method. Of these, six have so far either tried the method or indicated their intention to do so. The organizations contacted and the status of each contact are listed in Table 4.

5.3.1 Brockton Self Help

Brockton Self Help (BSH) is a local community action agency involved with retrofitting the homes of low-income families for energy conservation. Work is done by generally inexperienced CETA employees, under the direction of experienced supervisors. Turnover of the CETA staff requires constant training by the supervisors, which, in turn, provides a stringent proving ground for new diagnostic methods.

The acoustic-location method was demonstrated to members of the Brockton staff, and suitable equipment for acoustic testing was provided to them by BBN. It was originally intended that the method would be applied by BSH in five residences to be extensively

Table 4

Other Organizations Contacted With Regard to the Acoustic Location of Infiltration Openings in Buildings

Organization	Sent Preliminary Instructions for Method	Demonstrated Method	Provided Test Tape	Plan to Apply Method	Have Applied Method
Brockton Self Help	x	x	x	x	x
National Home Improvement Council (NHIC) Members					
• Alumbabilt, Boston, MA	x	x	x	x	x
• Schonemann, Washington, DC	x	x	x	x	x
• Houston	x				
• Los Angeles	x				
Building Energy Research Organizations					
• LBL	x	x		x	
• Center for Environmental Studies, Princeton	x	x	x		
• ORNL	x			x	
• Naval Civil Engineering Laboratories	x	x	x	x	
Boston Gas	x				
Southern California Gas Company	x				

retrofitted by them. BBN was to perform corresponding "before-and-after" pressurization tests on these buildings in accordance with ASTM E283-73. However, because of difficulties encountered by BSH in obtaining an adequate number of CETA workers, only two of these buildings were completed in time for this report. The results for these two are shown in Figs. 27 and 28.

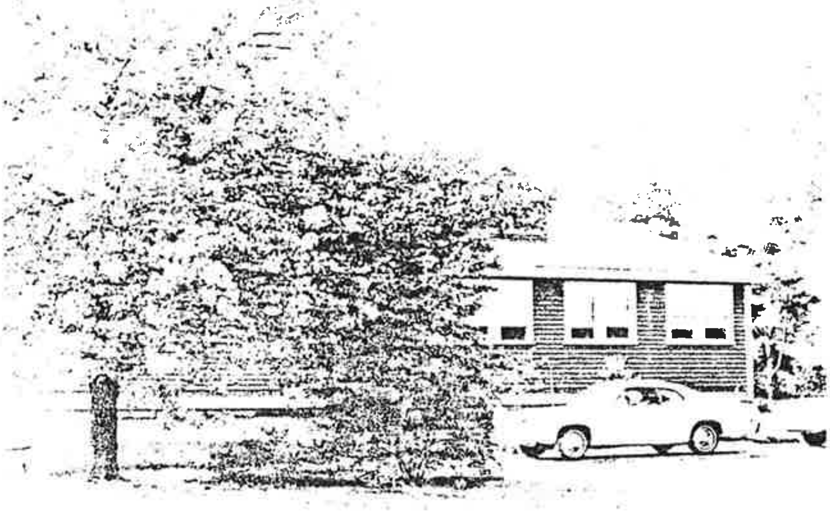
It is seen that the retrofit actions resulted in some reduction of infiltration rates: from 24.5 to 21 air changes/hr in one house and from 17.6 to 12.2 air changes/hr in the other. However, subsequent visual and acoustic inspection revealed a number of leakage openings still in need of attention. These included:

- unweatherstripped doors to an unheated attic and to an unheated basement
- improperly installed or improperly adjusted weatherstripping
- numerous utility penetrations from unheated basements into the living areas of the houses
- leakage at the horizontal joint of a Dutch door.

BSH's comments on the acoustic-location method are included in Appendix C.

5.3.2 Members of the National Home Improvement Council

Through its association headquarters, members of the National Home Improvement Council (NHIC) were asked to try the acoustic-location method. Many members of this association are in the business of installing weatherization treatments in residences.



Front

Rear

Description:

- 1-story frame construction with unheated attic and basement
- 1800 sq ft living area and unheated front porch
- retrofitted with storm windows; attic and wall insulation; some weatherstripping.

Air Flow Tests	ΔP, in. H_2O	$\dot{V}$, cfm	Changes/hr*
Before Retrofit	0.025	2113	17.6
After Retrofit[†]	0.06	2272	12.2

*At 0.1 in. H_2O ΔP; scaled from $\dot{V} = A(\Delta P)^{\frac{1}{2}}$.

[†] Before inspection and acoustic testing.

Figure 27. "R" house retrofitted by Brockton self help.

Front

Description:

- 1-story frame construction with unheated attic crawl space and unheated basement
- Approximately 850 sq ft living area
- Retrofitted with new roof; attic and wall insulation; storm windows, storm doors, and weatherstripping.

Air Flow Tests	ΔP, in. H_2O	$\dot{V}$, cfm	Changes/hr*
Before Retrofit	0.07	2182	24.5
After Retrofit[†]	0.08	1992	21.0

*At 0.1 in. H_2O ΔP; scaled from $\dot{V} = A(\Delta P)^{1/2}$.

[†] Before inspection and acoustic testing.

Figure 28. "S" house retrofitted by Brockton self help.

BBN initially sought to work with NHIC members in the Boston, Washington, D.C., Houston, and Los Angeles areas. However, we were unable to locate interested members in the latter two cities. An NHIC affiliate in Houston pointed out why this was so: There was at the time no significant commercial market for building-energy conservation products and services in those warmer cities. Heating requirements are small, and electric rates for air conditioning are one-half to one-third of those in the northeastern part of the country. Contractors in the Houston area who invested in equipment to install insulation at the time the National Energy Plan (with its homeowner tax credits) was announced were finding that equipment painfully idle. Homebuilders in Los Angeles were steaming about the recently imposed California State Building Code requirements for increased building insulation.

As a result, our activities were restricted to two NHIC members, Alumabilt of Newton, MA (a Boston suburb) and Schonemann of Germantown, MD, outside Washington, D.C. For both these organizations, BBN demonstrated the acoustic-location method and supplied equipment for applying the method. Their comments are included in Appendix C.

In general, skilled contractors like NHIC members believe that they can visually identify most major air-leakage openings and are concerned about the cost (time) required to run diagnostic tests. Upon using the acoustic method, however, they were sometimes surprised to located unexpected leaks, and they found that the method was useful in convincing building owners of the need for repair work for infiltration control.

5.3.3 Building-energy research organizations

The acoustic location method has been demonstrated to the DoE's building-energy research group at the Lawrence Berkeley Laboratories (LBL) and to the United States Navy's Civil Engineering Laboratories at Port Hueneume, CA.* Both groups said they planned to try the method themselves, but to our knowledge have not yet done so. The method has been demonstrated to members of the staff of Princeton University's Center for Environmental Studies, and information has been mailed to DoE's Oak Ridge National Laboratories (ORNL). The people at ORNL "plan to try it on their own homes."

In general, these building-energy research activities have far more powerful tools at their disposal for the location of air leaks and the measurement of infiltration rates.

5.3.4 Utilities

Building-energy conservation groups at the Boston Gas Company and the Southern California Gas Company have been mailed a written description of the acoustic leak-location method. Both report that they have "turned it over to their engineers for consideration." Further actions on their part, if any, are unknown.

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*See Appendix C.

6. IMPLEMENTATION PLAN

6.1 Introduction

Broad national availability of the acoustic leak-location method would be useful only to the extent that the method made some contribution to energy conservation in buildings. Toward this end, what really is to be "implemented" is a program to reduce unnecessary air infiltration in buildings. The acoustic method — and other diagnostic methods — would simply support and facilitate that infiltration control effort. In themselves, diagnostics save no energy. They simply show people how they can save energy if they take some further action after using the diagnostics.

The implementation plan proposed here assumes that acoustic leak location would become an adjunct to one or more existing programs directed towards building-energy conservation. Integration into such existing programs is the only cost-effective way to bring to the public whatever benefits might be derived from the method. In particular, it is proposed that the major outreach effort in implementing acoustic leak location be provided by DoE's Energy Extension Service (EES). Other suggested actions, such as the preparation and distribution of press releases and the conduct of technical conferences, can also be done by DoE in conjunction with ongoing energy-conservation promotion programs.

6.1.1 Purpose and approach

From the work that has been done to date, it is clear that the method of acoustic location of air infiltration openings in buildings is both practical and useful. It is practical to the extent that it is simple and inexpensive to apply, and it is useful in that it can locate many of the air-leakage openings in buildings that lead to unnecessary energy consumption for heating and cooling. The question addressed here is: How can the method be brought into widespread use, so that the nation as a whole can begin to realize any energy-saving benefit that it offers? The purpose of this plan is to outline a course of action for "commercializing" the acoustic-location method.

In the absence of regulatory mandates, implementation is really a marketing problem. A market need must exist; a target audience ("customers") with this need must be identified; and that audience must be convincingly informed that the "product" will fill their need. Finally, the product must indeed do what the customer wants it to do. All of these steps are intended to enhance the natural process whereby people tend to act in what they believe to be their own best interest.

This is a very simplified description of what is really a complicated sociological process. It does, however, provide a structure for planning, and it emphasizes that we are dealing with a sociological rather than a technical task.

6.1.2 The audience groups: their needs and objectives

DoE's purpose, should the agency choose to commercialize the acoustic-location method, would be to help bring about a significant reduction in the energy required to heat and cool buildings in the United States. Several different audience groups would have to be addressed to achieve DoE's purpose. The needs of these groups differ, and might be quite different from DoE's purpose in addressing them. Each group must be approached in the framework of its own perceived needs. Consider the various audience groups listed in Table 5.

Table 5

Audience Groups: Their Needs and the Objective of Addressing Them

Group	Objective of DoE/BNL's Approach	Needs of Group
Technical Professionals	Gain credibility	Must be shown validity and utility of method
Builders, Retrofit Contractors, and Suppliers	Gain secondary promotion to building owners	Increase sales and/or reduce costs
Building Owners	Reduce energy consumption	Reduce utility costs
Government Agencies	Gain secondary promotion, and reduce energy consumption	Various, including public service, consumer protection, energy saving, and cost reduction

Technical professionals in the building area, such as architects, HVAC engineers,and their trade associations, must be informed of the acoustic-location method and must endorse the method if it is ever to come into widespread use. The objective of approaching these groups is to increase understanding of, and gain credibility for, the method.

These groups will need to be shown that the method is technically valid and that it is of practical use. Many professionals will want to withhold judgment until they try the method themselves. Many will offer constructive criticism and suggestions for improvement. This process will undoubtedly lead to improvement in the method and to an enhanced public receptivity for the method.

Builders and building-retrofit contractors and suppliers — all those who sell to building owners — must be addressed because they will actually use the method, and because they could help convince building owners that application of the method will reduce building-operating costs. Before they will do this, however, these groups must be shown that the method will increase their sales and/or reduce their costs.

Building owners (those who pay the utility bills) are the ones who will pay for the testing and for the resulting energy-saving treatments. They need to be shown that that will be money well spent and that it will reduce their costs for heating/cooling energy.

Finally, many government agencies are active in the building-energy conservation field. Some are concerned with reducing operating costs of government buildings (DoD, GSA), some with public service (CSA, DoE), and some with consumer protection (HUD).

Each of these agencies should be approached from the point of view of their own mission — the objective being either to facilitate direct energy savings in government buildings or to encourage secondary promotion of the method.

6.2 Suggested Implementation Steps

Separate implementation procedures for technical improvements and for approaching each of the four audience groups listed in Table 5 are given below. A summary of all of the steps suggested is given in Table 6.

6.2.1 Technical building professionals

Comprehensive oral and written papers should be prepared and presented to ASHRAE and to at least one other suitable association on the acoustic leak-location method. Formal technical criticism of the method should be sought, and assistance to others wishing to try the method should be offered. The preparation of an industry Recommended Practice based upon the method should be encouraged.

The technical papers can be based upon the final report of this contract. A Recommended Practice, however, will have to await the time when several members of an interested technical society have tried the method, and the society believes that such a Practice is desirable.

6.2.2 Builders and retrofit contractors and suppliers

Builders and building-retrofit contractors may begin to use the acoustic leak-location method simply because their customers ask for it. It is more likely, however, that they would adopt the method if they could be shown that it will increase their

Table 6

Implementation Steps

1. Technical Building Professionals
    - 1.1 ASHRAE paper
        - 1.1.1 Oral
        - 1.1.2 Written
    - 1.2 Other paper(s)
        - 1.2.1 Oral
        - 1.2.2 Written
    - 1.3 Assistance on trial usage
    - 1.4 Recommended Practice
2. Builders, Retrofit Contractors, and Suppliers
    - 2.1 Press release to trade associations and trade journals
    - 2.2 Instructional pamphlets (cassettes)
        - 2.2.1 Ready source of prerecorded cassettes
    - 2.3 Trade-journal articles
    - 2.4 Trade-show/convention demonstrations
        - 2.4.1 Film (videotape)
        - 2.4.2 Booth demonstration kit
    - 2.5 Personal contact with key individuals
    - 2.6 Local demonstration/promotion
        - 2.6.1 EES
        - 2.6.2 Building-materials distributors
        - 2.6.3 Countertop display kits: rental/loan

Table 6 (Continued)

3. Building Owners
    - 3.1 Press release to professional building owners' and managers' associations, and to related trade journals
    - 3.2 Instructional pamphlets for "Do-It-Yourselfers"
    - 3.3 Popular articles
    - 3.4 Local demonstration/promotion
        - 3.4.1 EES
        - 3.4.2 Materials suppliers and distributors
4. Government Agencies
    - 4.1 Conference(s)
        - 4.1.1 EES
        - 4.1.2 Other federal agencies
        - 4.1.3 State energy offices
    - 4.2 Training and equipping of the EES
    - 4.3 Personal contact and technical assistance
5. Technical Improvements
    - 5.1 Suitable low-cost sound level meter
    - 5.2 Investigation of weatherstripping

sales and/or reduce their costs of operation. From the builders' point of view, the acoustic (and other) methods of leak location can

- demonstrate to prospective customers the need for caulking/weatherstripping services
- rapidly locate leaks for sealing
- inspect caulking/weatherstripping work after completion for conformance with specifications and standards.

The approach to this diverse audience should emphasize these applications of the method.

Of course, there have been and continue to be numerous government and commercially sponsored promotional efforts directed towards building-energy conservation. We do not recommend another such campaign. Rather, it is suggested that the dissemination of information on the acoustic leak-location method be integrated, where appropriate, as one element in existing, ongoing government promotional efforts directed at the building industry.

The steps to be followed are listed in Table 6, and are described below. A press release from DoE/BNL should be sent to all trade associations and trade journals potentially concerned with infiltration control in buildings. (Directories listing candidate associations and journals are readily available.) The release should indicate the availability of the method, its applicability to the builder's needs, and sources of additional information.

Instructional material, in the form of a pamphlet directed specifically at this audience, should be prepared and made available. The pamphlet should contain sufficient "How To" information so that the method can be successfully applied by the reader. DoE/BNL should establish a ready source of prerecorded test-signal tape cassettes which can be sold at modest cost. (Some thought should be given to recording an instructional script on the cassette, along with the test signal.)

Articles should be written and submitted to trade journals for publication. In addition, material should be prepared for demonstrations at trade shows and conventions of the building industry, perhaps in the form of films or videotapes. A doll-house-size model of a building with which the technique could be tried by trade-show attendees might be useful. This could be presented as one part of a display booth operated by DoE to demonstrate a variety of building energy-conservation techniques.

The method should be demonstrated by direct personal contact with key individuals in pertinent industries. For example, the major manufacturers of caulking and weatherstripping materials will be interested in techniques to increase their sales. They might establish a secondary promotional program incorporating the acoustic-location method. This program could include countertop displays for building materials supply stores. It is possible that kits of equipment for acoustic leak location could be made available for rental or loan to customers buying caulking and weatherstripping materials.

In some parts of the country, energy utilities have become a major local force in encouraging building-energy conservation. They would perhaps apply the method and/or encourage its use by others through bill stuffers, etc.

Although it is to be hoped that demonstration and promotion of the method will be encouraged at the local level through building-materials suppliers and distributors, DoE's own Energy Extension Services (EES), trained and equipped to apply the method, should carry the major burden of promoting its wider use. (See Sec. 6.2.4.)

6.2.3 Building owners

Building owners — those who pay to heat and cool buildings — can be approached through many of the mechanisms described in Sec. 6.2.2. For this audience, the theme should be how to reduce building operating costs, and the presentation should be more general. It should be directed at reducing infiltration to save money and simply indicate what diagnostic tools are available to facilitate infiltration control. Finally, it should be at a lower level of technical sophistication to accommodate that portion of the audience unfamiliar with building technology.

The objective of the approach should be to encourage actions that will minimize unnecessary infiltration and, thus, bring pressure on building contractors to use appropriate tools for such actions.

As with the building industry, there are already numerous programs promoting energy conservation to building owners. Infiltration control is a feature of many of these programs. To the maximum possible extent, the efforts described below should be incorporated within these existing programs.

The suggested steps (Table 6) include a press release to trade associations and to trade publications serving professional building owners and managers. This release should be different from the one mentioned in Sec. 6.2.2, and should be directed at operating cost reduction. The release should indicate the availability of the diagnostic method, its applicability, and sources of additional information.

For the homeowner and "Do-It-Yourselfer," a simple instructional pamphlet should be prepared, describing how the acoustic-location method can be applied with equipment normally found around the house. A vacuum cleaner or "hi-fi" set could be used as an indoor sound source. (Street traffic or a power lawnmower could be used as an outdoor source.) A listening system could be made with a few pieces of hose. Similarly oriented articles should be prepared and submitted for publication to magazines like *Popular Science*.

Local demonstration and promotion of the method should be encouraged by the EES and possibly by appropriate building-materials suppliers and distributors.

6.2.4 Government agencies

Almost every agency of the federal government has some interest in building-energy conservation, if only for reducing the operating cost of the agency's own buildings. The same can be said of state and local governments. The major government agencies that should be approached include:

- The General Services Administration (GSA), because this agency operates many federal buildings
- The Department of Defense (DoD), which also operates many buildings

- The Federal Housing Administration of the Department of Housing and Urban Development (HUD/FHA), because of its interest in performance standards for residential buildings
- The Community Services Administration (CSA), which has a program to retrofit low-income homes for energy conservation
- The Building Sciences activity of the National Bureau of Standards, Department of Commerce (NBS), that serves in a technical advisory capacity to many government and private activities concerned with building-energy conservation
- The Energy Extension Service of the DoE (EES), which is a major public outreach activity of the DoE
- The State Energy Offices, because they serve as outreach agencies on building-energy conservation for the various states and can be expected to have good communication both with DoE and with local agencies within their states.

We assume that numerous intergovernmental organizations already exist through which these various agencies share information on energy conservation. It would be most logical to introduce the acoustic-location method to other governmental agencies through this existing communication network. The following steps assume that the network would be used to the maximum extent possible.

One or more conferences should be held, preferably in Washington, at which the acoustic-location method is described and demonstrated. This final report and other available materials could be distributed. As many as three such conferences can be anticipated: one for the EES, one for other federal agencies, and one for the State Energy Offices.

The material presented to certain of the governmental agencies should cover a subject that has not been treated elsewhere: the regulatory applicability of the acoustic-location method. To the extent that building codes and standards may contain caulking and sealing requirements similar to those of ASHRAE Standard 90-75 ("Energy Conservation in New-Building Design") or DoE Document SAN/1230-1 ("Model Code for Energy Conservation in New Building Construction"), the acoustic method could prove useful in establishing compliance with such requirements.

In addition to any general conference presentations, a detailed effort should be made to train and equip the field teams of the EES to (1) apply the acoustic location method and (2) demonstrate its use at the local level.

Finally, it is likely that some personal contact and technical assistance will be requested by various governmental agencies as they proceed to apply the acoustic-location method to their needs. DoE should be prepared to respond to such requests.

6.2.5 Technical improvements

As indicated previously, there are two areas where technical improvements in the acoustic method for locating leaks are possible and desirable. Both should be resolved by DoE early in any effort to commercialize the method.

Low-Cost Meter

A suitable, low-cost sound level meter would greatly facilitate the adoption of the acoustic location method. Supplying such a meter is not a technical problem, for one could be made with simple modifications to products now available in the $50-to-$100 price range. That no such product exists reflects the fact that there is presently no market need evident to potential vendors. It is possible that by meeting with potential suppliers, DoE can induce them to offer meters suitable for this application. Such an inducement would be enhanced if DoE were to purchase a quantity of meters for its own use — presumably by the EES.

Performance of Weatherstripping for Operable Doors and Windows

It is apparent, from the work done under this contract, that there is wide variability in the air-leakage properties of weatherstripping for operable doors and windows. This is due not only to differences in types of weatherstripping, but also to differences in installation practices and to deterioration with use. We can find no comprehensive body of data on the air-leakage properties of weatherstripping, nor do there appear to be any industry standards on the air-leakage performance of these materials.

There is corresponding lack of information on the sound-transmission properties of weatherstripping. Although available data and physical reasoning suggest that there should be a correlation between sound transmission and air-leakage properties of weatherstrpping, there are not enough data to support such a conclusion.

Therefore, we suggest a measurement program on the leakage and sound-transmission properties of weatherstripping. The program should have two phases. The first — a laboratory study — should establish these properties for a wide selection of weatherstripping materials and techniques, when new, over a range of installation conditions. The second phase should be a field program to quantify the same properties of the materials/techniques after they have been in use for various periods of time.

The experimental program would have two objectives:

1. To make available to the building industry and to the public at large a body of data on the air-leakage performance of various types and styles of weatherstripping, on optimum installation techniques, and on deterioration of performance with use.

2. To develop correlations between sound-transmission and air-leakage properties of various types of weatherstripping so that the acoustic leak-location method can be applied with confidence to the inspection of weatherstripping in buildings.

6.3 Estimated Costs and Timing of Implementation: Anticipated Benefits

A possible time schedule for implementation is indicated in Fig. 29. This schedule assumes that the major burden of the outreach effort is borne by the EES, which would be suitably trained and equipped to demonstrate and perform acoustic location studies in each of the 50 states. It is also assumed that the purchase of low-cost meters by the EES would provide the initial market incentive necessary to make such devices available to the country at large.

The estimated effort in person-months and out-of-pocket costs for the implementation plan are shown in the last column of Fig. 29. The total estimated effort is 208 person-months, of which 150 would be expended by the EES (50 states x 1 p.mo./yr x 3 yr). The major out-of-pocket expense would be the purchase of 50 acoustic-location test kits for the EES.

The benefit of implementing an infiltration-reduction program supported by techniques like the acoustic-location method is estimated as follows: Total U.S. Energy Consumption (72×10^{15} Btu)

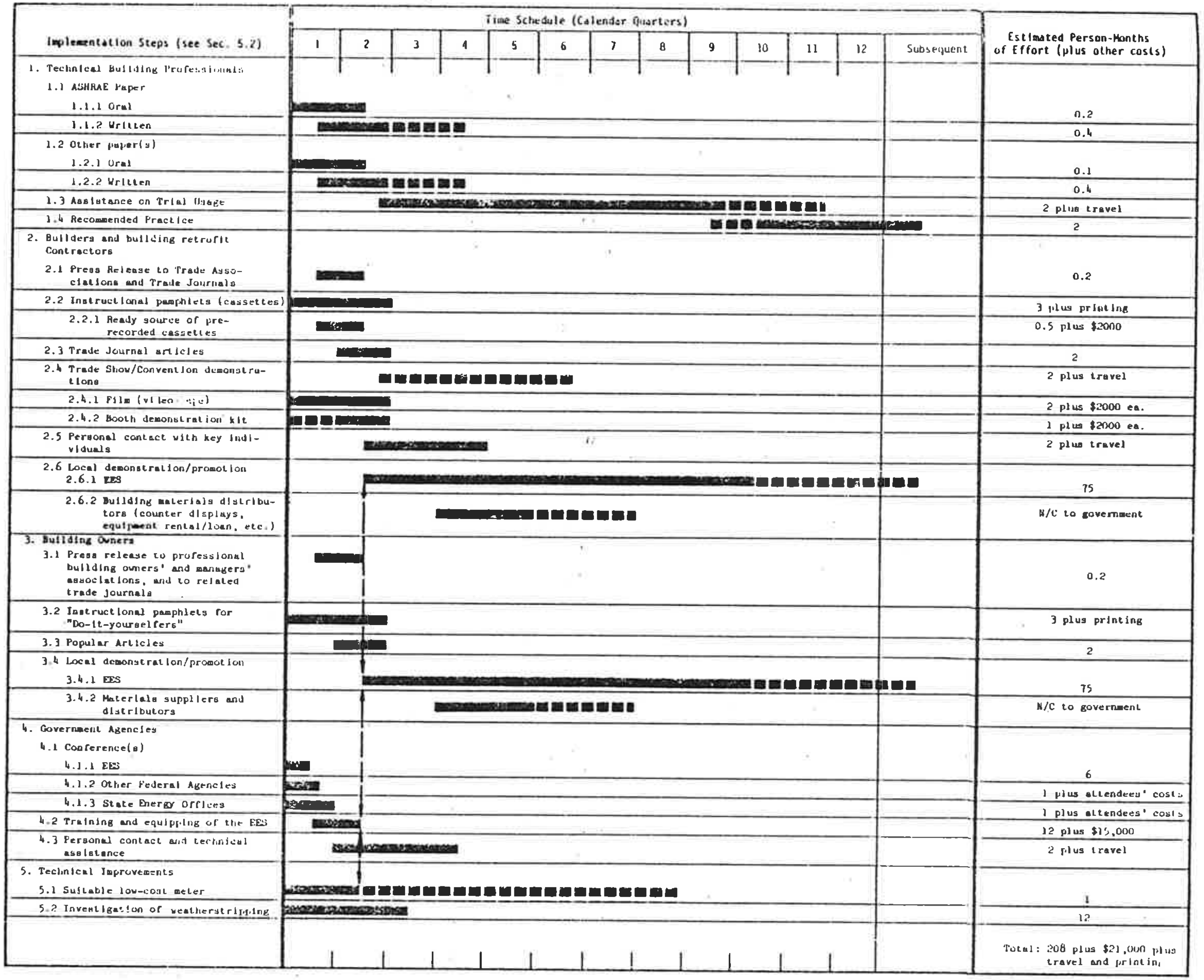

Figure 29. Time schedule and labor estimate for implementation.

times Portion of Residential-Commercial Use (33%) times Space Heating and Cooling Consumption (70%) times Portion of energy consumption in these buildings due to unnecessary infiltration (20%) times Portion of infiltration losses corrected by this method, over and above those corrected by present methods (10%) times national response to promotion of infiltration reduction (25%) = 3×10^{13} Btu.

This is assumed to be distributed as 60% gas, 35% oil, and 5% electricity.

Fuel	Energy Savings (Btu/Year)
- Gas	1.8×10^{13}
- Oil	1×10^{13}
- Electricity (@ 10,500 Btu/kWh)	1.5×10^{12}

Total building operating-cost savings are estimated as follows:

Gas:	$1.36/mmBtu × 1.8×10^7 mmBtu	= $24 × 10^6
Oil:	$2.60/mmBtu × 10^7	= $26 × 10^6
Electricity:	$\dfrac{\$0.035/\text{kWh} \times 1.5 \times 10^{12}\text{Btu}}{3413\ \text{Btu/kWh}}$	= $15 × 10^6
	Total	$65 × 10^6

Assuming the total cost for the program in Fig. 29 is $7 × 10^5, the return on investment to the public would be about 90 to 1.

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APPENDIX A

DATA FROM LABORATORY MEASUREMENT PROGRAM

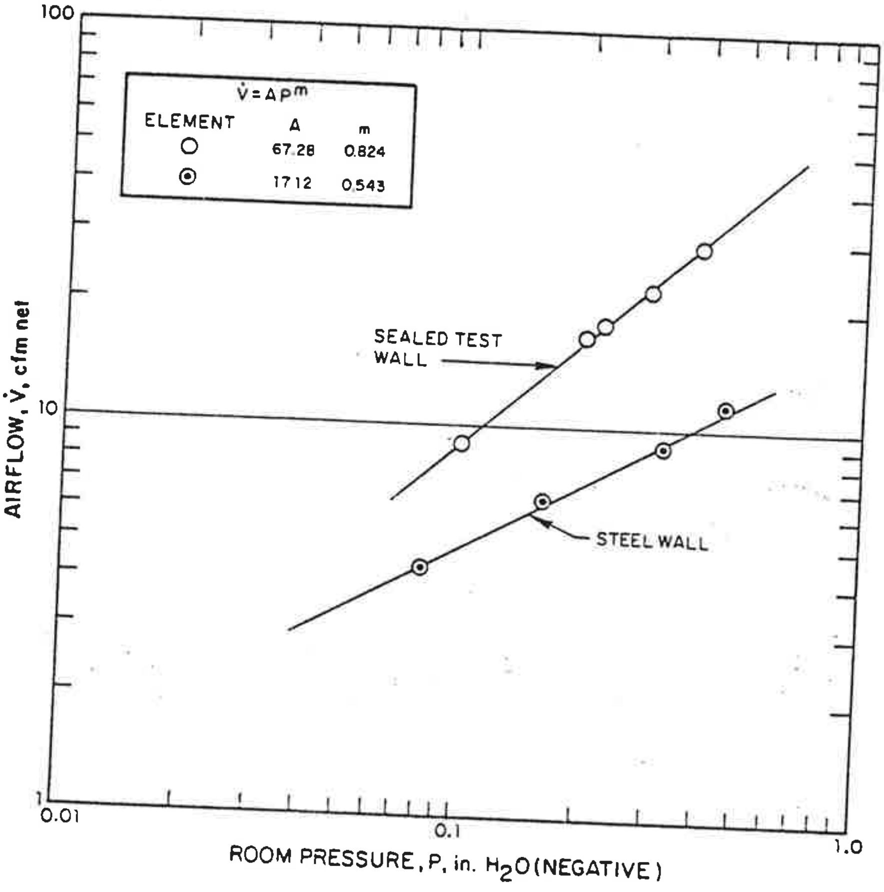


Figure A.1. Tare leakage measurements of laboratory test facility.

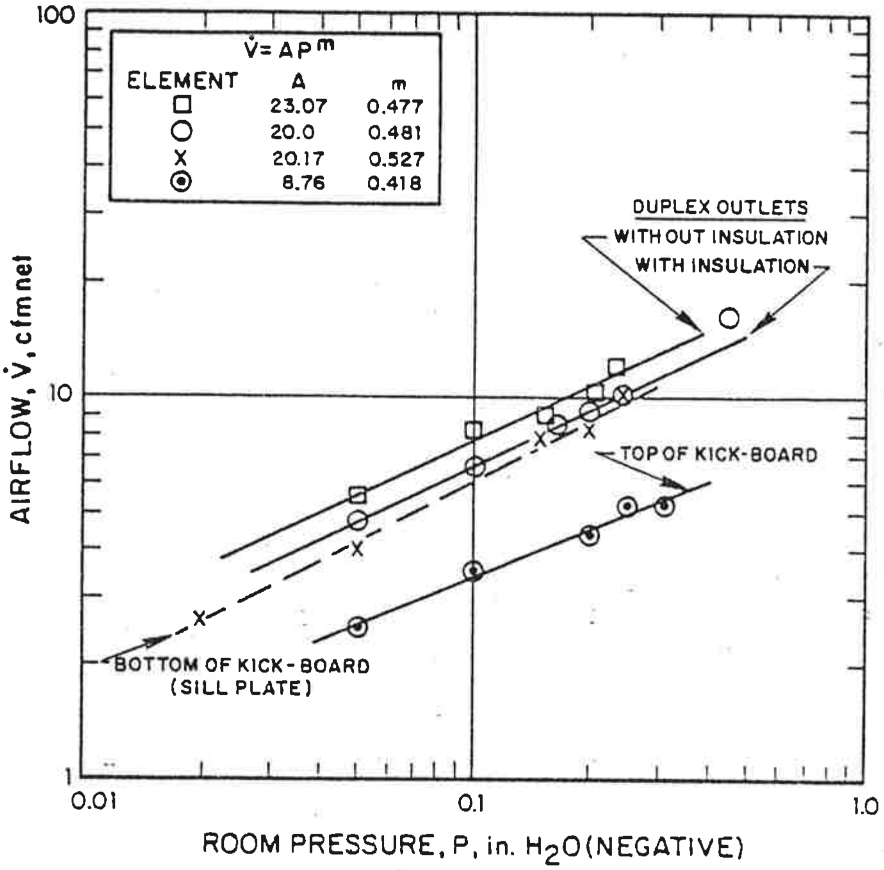


Figure A.2. Measured air leakage through wall elements (net).

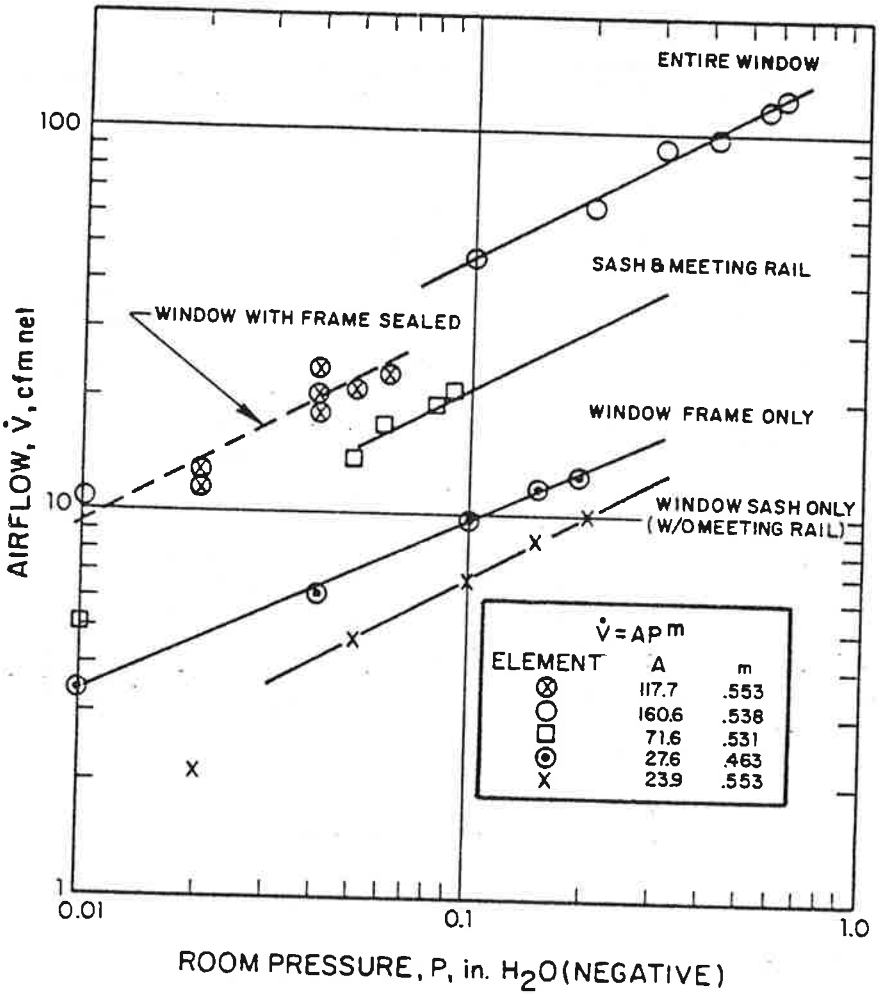


Figure A.3. Measured air leakage through window elements (net).

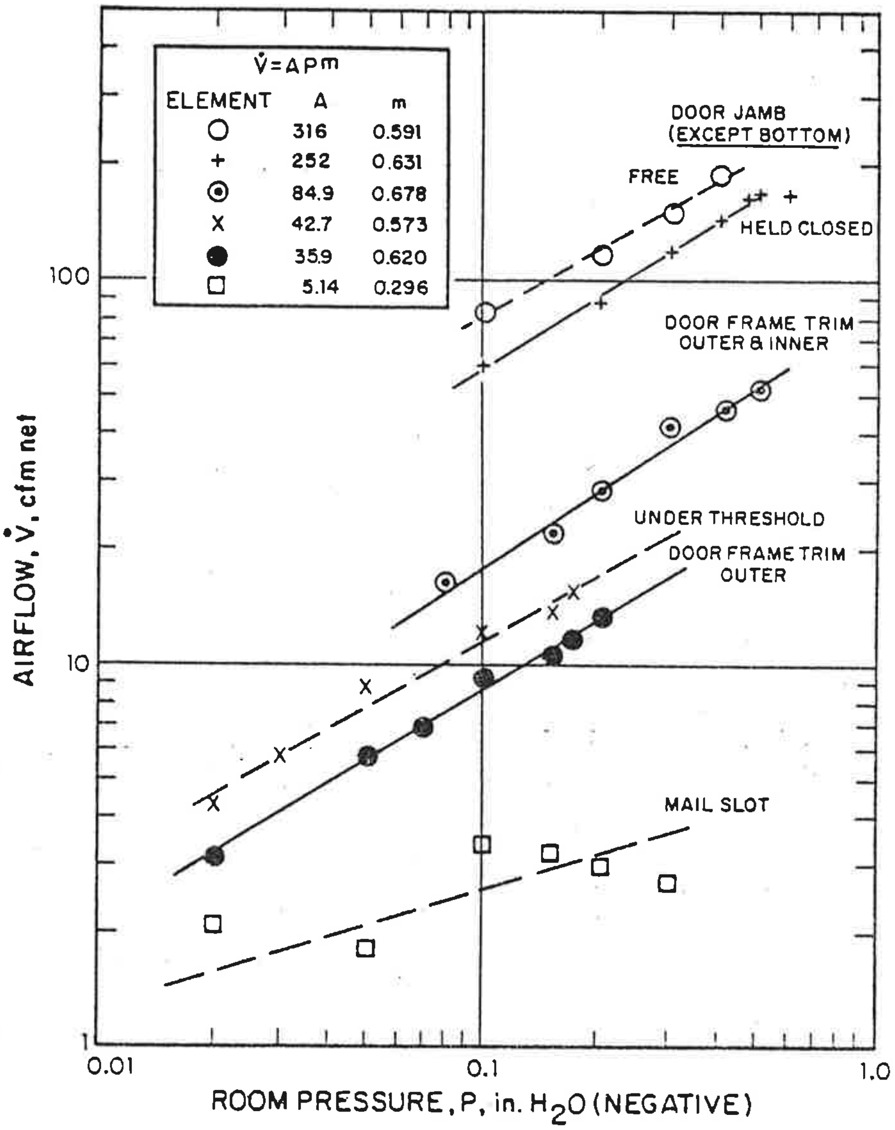


Figure A.4. Measured air leakage through door elements (net).

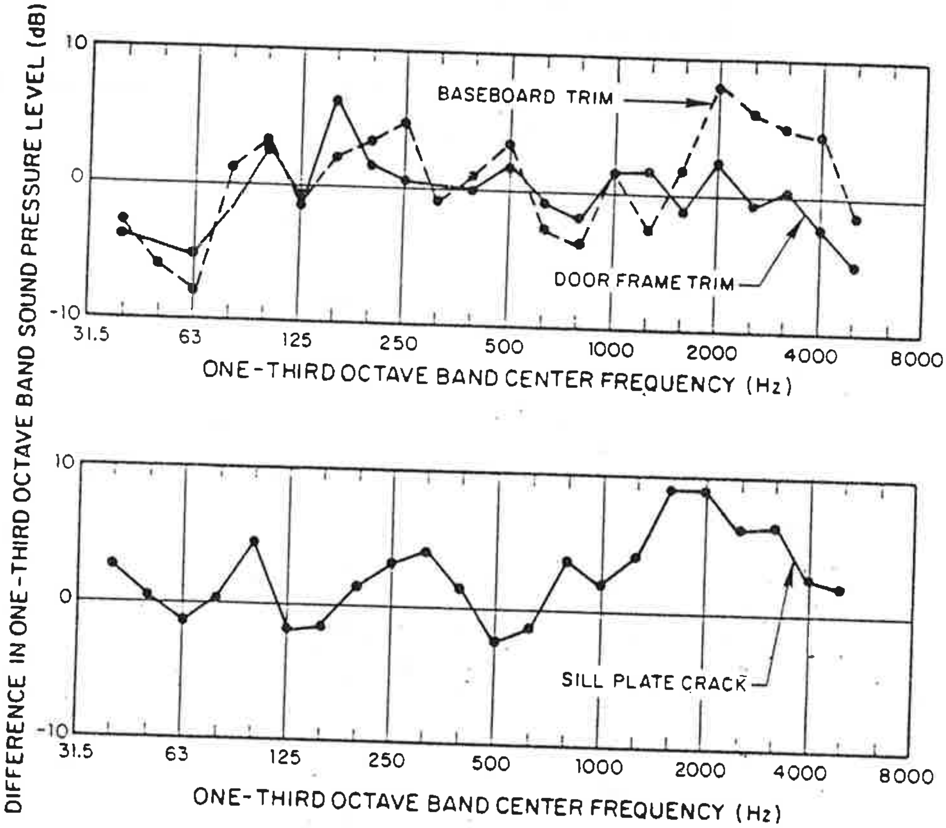


Figure A.5. SPL spectrum of sound propagated through wall leakage elements relative to that propagated through sealed location on wall. Source outside, measurements inside. (Sound not detected through duplex outlets.)

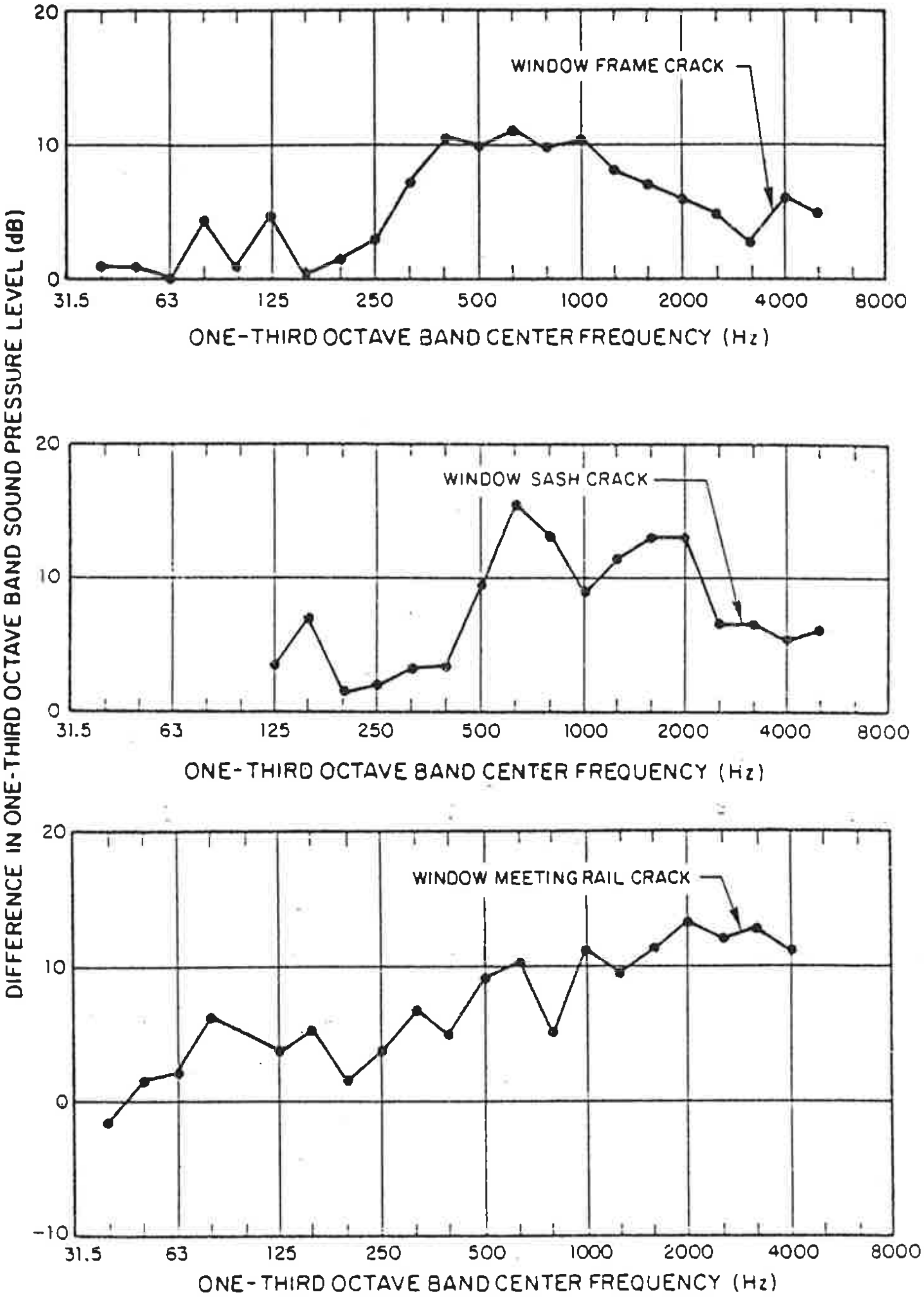


Figure A.6a. SPL spectrum of sound propagated through window leakage elements relative to that propagated through window pane. Source inside, measurements outside.

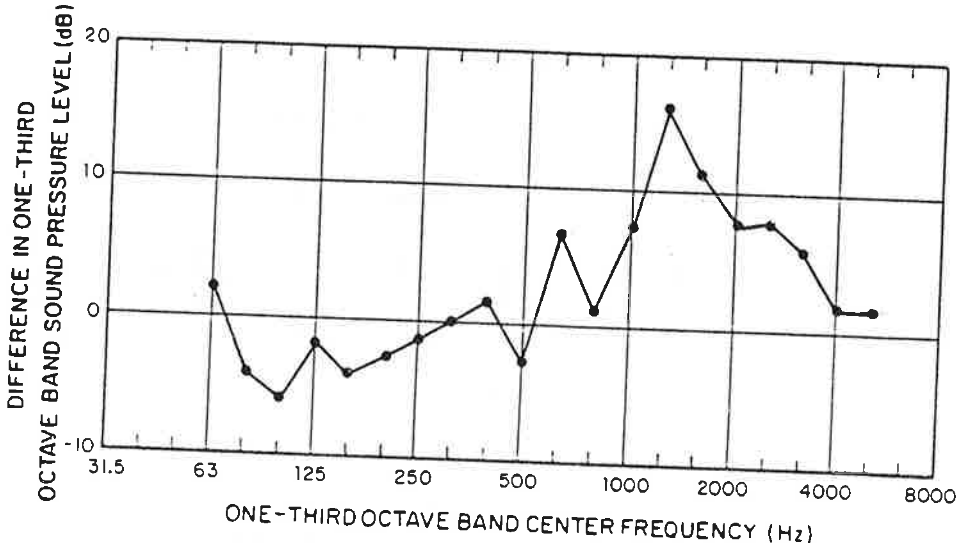


Figure A.6b. SPL spectrum of sound propagated through window sash crack. Source, outside, measurements inside.

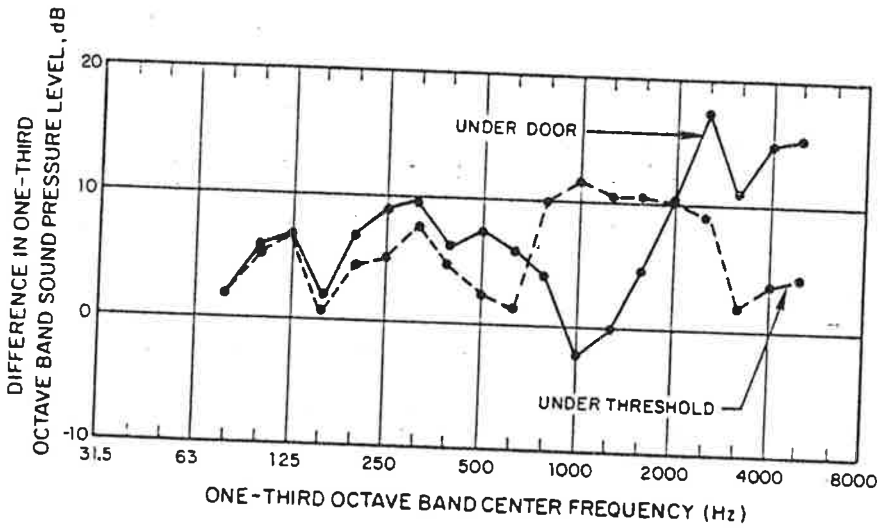


Figure A.7. SPL spectrum of sound propagated through door leakage elements relative to that through center of door. Source inside, measurements outside.

APPENDIX B

BUILDINGS STUDIED BY BBN PERSONNEL

W-HOUSE

Description:

- Frame two-story with unheated attic and basement
- Exterior walls uninsulated
- Mortared stone foundation
- Age: approximately 75 years
- Storm windows (closed for air-leakage tests)
- Living area: 600 sq ft/floor = 1200 sq ft.

AIR-LEAKAGE DATA (EVACUATED)

Condition	ΔP, in. H_2O	$\dot{V}$, cfm	Changes/hr*
As is (storm windows on)	0.05	1890	16.7
Attic door and bath vents sealed	0.07	1890	14.0
Attic door, both vents, and basement door sealed	0.08	1890	13.0

*At 0.1 in. H_2O ΔP; scaled from $\dot{V} = H\,(\Delta P)^{\frac{1}{2}}$. See footnote on p. 68.

W-HOUSE *(Cont.)*

General Observations:

Numerous leaks at foundation sill and through cracks in stone foundation. Hot-air heating system leaks in basement.

Acoustic Location Observations:

[Sound source with warble tone inside, sound detection outside, in dB(A).]

SOUND SOURCE IN BASEMENT

Leak Location	ΔdB Before Sealing	ΔdB After Sealing
Sill under porch	6	0
Gas pipe penetration	8	0
Electrical service penetration	13	0
Window frame (L)	18	-1
Window frame (R)	27	-12
Sill	13	-1
Mortar crack	11	-1
Mortar crack	6	--
Mortar crack	11	4
Mortar crack	31	-6
Mortar crack	14	NA
Exterior basement door	13	NA
Mortar crack	4	NA
Sill crack	11	NA
Sill crack	10	NA
Sill crack	15	NA
Sill crack	11	NA
Sill crack	20	NA
Window frame	19	NA

SOUND SOURCE INSIDE FIRST FLOOR

Leak Location	ΔdB Before Sealing	ΔdB After Sealing
Front porch window *frame*		
Bottom L	20	NA
Bottom R	8	NA
Bottom	9	NA
Front porch window *sash*, without storm windows		
Top	16	NA
Bottom	9	NA
Side	6	NA
Front door		
Storm door jamb	4	NA
Main door threshold	13	NA
Main door jamb	9	NA

H-HOUSE

Description:

- Frame two-story with unheated attic and basement. Some portions of second floor unfinished. Some portions over crawl space.
- Exterior walls uninsulated
- Mortar and stone foundation
- Age: 150 years (post-and-beam construction)
- Storm windows (closed for air-leakage tests)
- Living Area: 1185 sq ft first floor
  550 sq ft second floor
  1735 sq ft total

H-HOUSE *(Cont)*

AIR-LEAKAGE DATA (EVACUATED)

Conditions	ΔP, in. H_2O	$\dot{V}$, cfm	Changes/hr*
As is, storm windows closed	0.08	2041	10
Kitchen & pantry only†	0.18	1990	12
Kitchen only†	0.31	1782	13

*At 0.1 in H_2O ΔP; scaled from $\dot{V} = A\ (\Delta P)^{\frac{1}{2}}$.

†(Doors to balance of house closed but not sealed).

General Observations:

Storm windows and doors tight, except front door. Numerous leaks through stone foundation, at sills, and through window sash-weight boxes; six poorly sealed fireplace flues; numerous penetrations between basement and first floor.

With kitchen only, evacuated @ 0.31 in. H_2O pressure, local flow velocities observed at leaks:

1¼-in. hole in floor	2200 ft/min
range vent	200 ft/min

Acoustic Location Observations:

[Sound source with warble tone inside, in dB(A).]

H-HOUSE *(Cont)*

SOUND SOURCE IN BASEMENT; MEASUREMENTS INSIDE FIRST FLOOR

Location	ΔdB	
Dining Room, base of wall (1)	4	(no leak)
Dining Room, base of wall (2)	4	(no leak)
Dining Room, base of wall (3)	3	(no leak)
Radiator pipe, penetration	6	(no leak)
Planking seam	0	(no leak)
Planking seam	6	(no leak)
Planking seam	3	(no leak)
Planking seam	4	(no leak)
Planking seam	8	
Fireplace hearth	11	
Fireplace hearth	12	
Duplex outlet	-2	(no leak)

MEASUREMENTS OUTSIDE

Location	ΔdB	
Sill	9	
Sill	16	
Sill	11	
Window frame	10	
Oil-filter pipe opening	15	
Sill	6	
Gas pipe penetration (caulked)	2	(no leak)
Window sash	2	(no leak)
Mortar crack	20	
Mortar crack	9	

H-HOUSE *(Cont)*

SOURCE INSIDE FIRST FLOOR, MEASUREMENTS OUTSIDE

Location	ΔdB
Crack in front door	16
Crack in front door	11
Crack in window sash	16
Corner of siding above sill	12
Corner of siding above sill	10
Window frame	8
Window frame	10
Door jamb	11
Siding seam	5
Siding seam	9

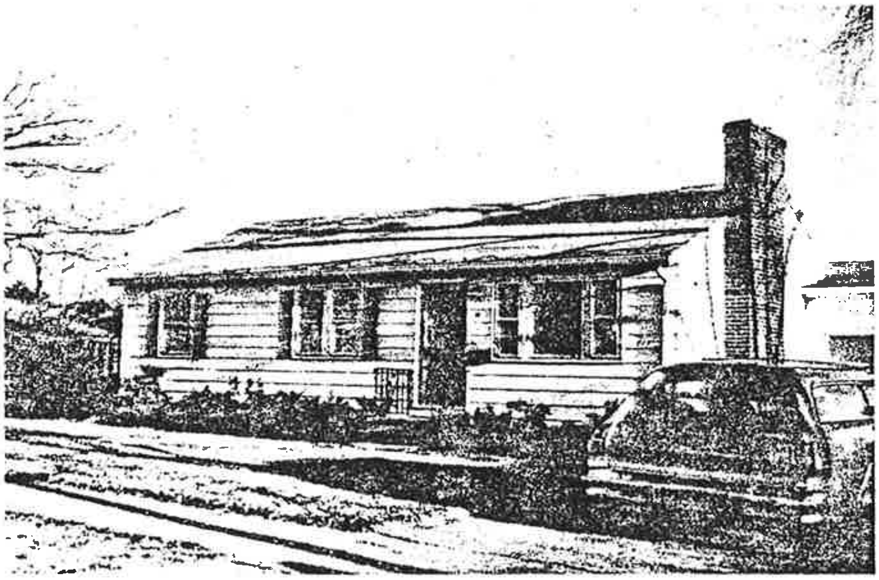
A-HOUSE

Description:

- Single-story frame ranch with attic crawl space and full basement, partially finished
- Exterior walls insulated
- Poured concrete foundation
- Age: 22 years
- Storm windows (closed for air-leakage tests)
- Living space: 1000 sq ft main floor

  300 sq ft finished basement

  1300 sq ft total.



A-HOUSE *(Cont.)*

AIR-LEAKAGE DATA (EVACUATED)

Condition	ΔP, in. H_2O	$\dot{V}$, cfm	Changes/hr*
As is	0.21	1992	10.3 (7.9)†
Basement door sealed	0.23	1942	9.6
Attic access and basement door sealed	0.24	1890	9.2
Fireplace, attic access, and basement door sealed	0.24	1942	9.4
Fireplace, attic access, basement and exterior doors sealed	0.26	1890	8.8
Kitchen vent, fireplace, attic access, basement and exterior doors sealed	0.27	1890	8.6

*At 0.1 in. H_2O ΔP; scaled from $\dot{V} = A(\Delta P)^{\frac{1}{2}}$.

†7.9 changes/hr for 1300 sq ft (i.e., including finished basement); 10.3 changes/hr for 1000 sq ft. All other rates assume 1000 sq ft.

General Observations:

Reasonably "tight" house, except for leaky sill plate, leaks in hot-air heating ducts in basement, and door seals.

LOCAL LEAKAGE-RATE MEASUREMENTS (WITH HOT-WIRE ANOMEMETER) AT ΔP = 0.26 in. H_2O

Location	Leakage Rate; ft/min (fpm)
Kitchen hood	300
Electrical outlets	
External wall (with insulation in wall)	100
Interior wall (without insulation)	350
Floor penetration	150

A-HOUSE *(Cont.)*

Location	Leakage Rate; ft/min (fpm)
Supply air grille (kitchen)	40
Supply air grille (dining)	80 ~ 100
Return air grille	100
Around furnace frame	100 ~ 150
Door top (front door with storm door gasketed)	150 ~ 200
Door side (front door with storm door gasketed)	10
Door side (front door with storm door ungasketed)	170 ~ 250
Door bottom (front door with storm door ungasketed)	10
Storm door:	
Corner and bottom	350 ~ 540
Side	80
Back door	200 ~ 500

ACOUSTIC AND LOCAL AIR-FLOW OBSERVATIONS (SOUND SOURCE INSIDE FIRST FLOOR)

Location	Flow, ft/min at 0.2 in. H_2O (positive)	ΔdB(A)
Jamb of rear door	50	7
Jamb of rear door	250	11
Jamb of rear door	420	17
Jamb of rear door	250	9
Jamb of rear door	30	5
Jamb of rear door	200	11
Wall penetration	150	-1
Jamb of storm door, front	80	11

A-HOUSE *(Cont.)*

Location	Flow, ft/min at 0.2 in. H_2O (positive)	ΔdB(A)
Jamb of storm door, front	90	12
Main front door (storm door open)	150	14
Main front door (storm door open)	80	11
Main front door (storm door open)	150	9
Storm window sash	10	1
Storm window sash	80	5
Main window sash (storm window open)	140	8

ACOUSTIC LOCATION OBSERVATIONS BEFORE AND AFTER CAULKING (SOUND SOURCE INSIDE BASEMENT)

Location	Before Caulking, ΔdB(A)	After Caulking, ΔdB(A)
Hose faucet	5	2
Sill plate	18	NA
Sill plate	22	NA
Sill plate	8	NA
Sill plate	8	NA
Window frame	2	4
Window frame	14	10
Electrical service entry	0	--
Electrical service entry	5	1
Window frame	5	NA
Sill plate	13	8
Exterior door to basement	20	11
Exterior door to basement	6	0
Exterior door to basement	16	NA

P-HOUSE

Description:

- Dormered Cape of frame construction. Unheated attic, unheated basement
- Exterior walls insulated
- Concrete foundation
- Age: Approximately 20 years
- Storm windows (closed for leakage tests)
- Living area: 533 sq ft first floor
  585 sq ft second floor
  1118 sq ft total

P-HOUSE *(Cont)*

AIR-LEAKAGE DATA (EVACUATED)

Conditions	ΔP, in. H_2O	$\dot{V}$, cfm	Changes/hr*
As is, but fireplace flue sealed	0.11	2400	15
Fireplace and basement door sealed	0.13	2400	14
Fireplace; basement, upstairs bedroom and attic doors sealed	0.22	2136	9.7(20)†

*At 0.1 in. H_2O ΔP; scaled from $\dot{V} = A\ (\Delta P)^{\frac{1}{2}}$.
†20 based upon first floor area only.

General Observations:

Numerous leaks at foundation sill, doors, windows, around chimney.

Acoustic and Local Air-Flow Observations:

[Sound source inside first floor, flow measured inside with hot-wire anemometer, acoustic measurements outside.]

Location	Flow, ft/min @ 0.23 in. H_2O (negative)	ΔdB(A)
Around chimney trim	300	-
Around chimney trim	350	-
Around front entrance door (w. storm)	10	3
Around front entrance door (w. storm)	10	3
Around front entrance door (w. storm)	60	4
Around front entrance door (w. storm)	40	5
Around front entrance door (w. storm)	80	10
Around front entrance door (w. storm)	70	6
Around front entrance door (w. storm)	150	16
Around front entrance door (w. storm)	170	11
Around front entrance door (w. storm)	290	16

P-HOUSE *(Cont)*

Location	Flow, ft/min @ 0.23 in. H_2O (negative)	ΔdB(A)
Around rear entrance door	20	6
Around rear entrance door	40	8
Around rear entrance door	20	10
Around rear entrance door	260	9
Around rear entrance door	10	3
Around rear entrance door	150	10
Around rear entrance door	40	6
Electrical switch	160	-
Duplex outlet	100	-
Kitchen vent (closed)	10	-

Acoustic Observations Before and After Caulking

[Sound source in basement]

Location	Before Caulking, ΔdB(A)	After Caulking, ΔdB(A)
Electric service entrance	9	0
Window sash	5	
Window sash	10	
Window sash	9	
Window sash	2	
Sill plate	8	1
Sill plate	3	
Window sash	7	
Window sash	7	
Window sash	7	
Window sash	5	
Sill plate	4	2

P-HOUSE *(Cont)*

[Sound source in first floor]

Location	Before Caulking, ΔdB(A)	After Caulking, ΔdB(A)
Storm window sash	7	
Storm window sash	2	
Main window sash (storm open)	6	
Main window sash (storm open)	10	
Main window sash (storm open)	2	
Meeting rail	4	

K-HOUSE

Description:

- Raised ranch, unheated attic, finished and heated basement
- Exterior walls insulated
- Poured concrete foundation
- Age: 10 years
- Storm windows (closed for leakage tests)
- Living area: basement 676 sq ft
  main floor 1800 sq ft
  2476 sq ft total

AIR-LEAKAGE DATA (EVACUATED)

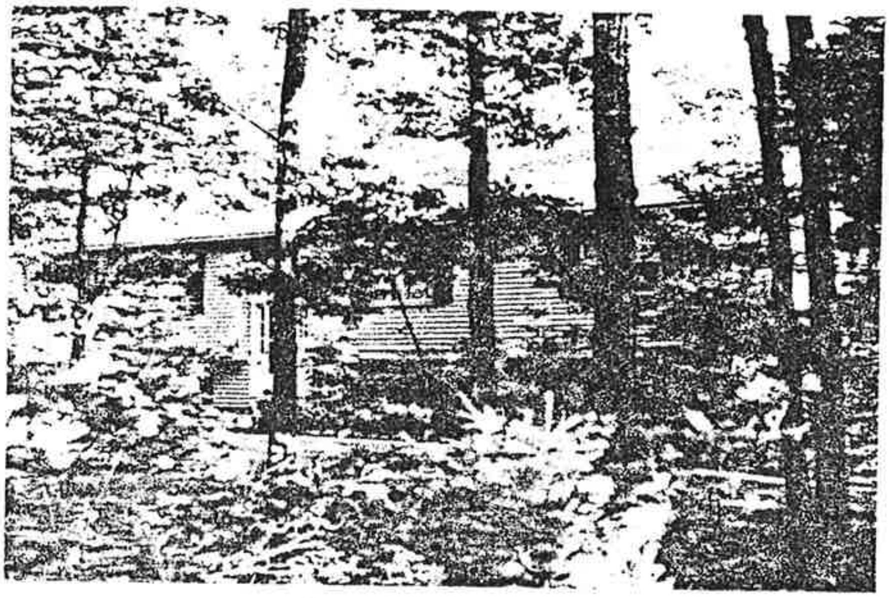
Condition	ΔP, in. H_2O	$\dot{V}$, cfm	Changes/hr.
As is, except kitchen vent and utility room door sealed	0.14	2090	5.3*
Kitchen vent, utility room door, attic access, and fireplace sealed	0.16	2090	4.5†
	0.14	2041	
	0.08	1260	
	0.08	1667	
	0.03	630	

*@ 0.1 in. H_2O ΔP, scaled from $\dot{V} = A (\Delta P)^{1/2}$
†Interpolated

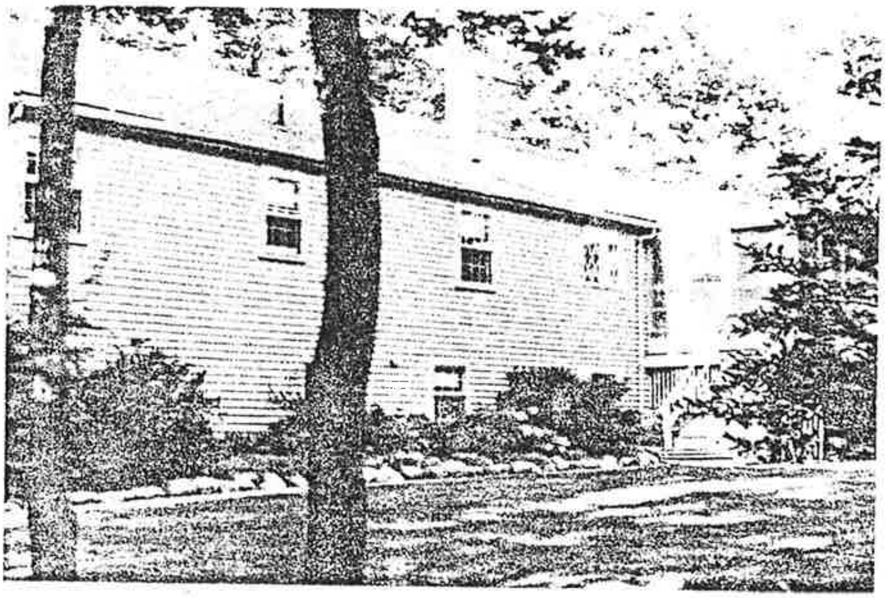
General Observations

Tightest house studied. Most leaks follow complex paths through wall structure.

K-HOUSE (*Cont*)



Front



Rear

K-HOUSE (*Cont*)

Acoustic Location Observations

Location	ΔdB(A)
[Sound source outside]	
Corner of bedroom at entrance of hot water heating pipe	8
Corner of bedroom at entrance of hot water heating pipe	7
Under radiator	0
Under radiator	0
[Sound source inside above bedroom, outside opposite above leaks]	0
[Sound source in attic]	
Electrical switch (interior partition)	7
Duplex outlet (interior partition)	5
Ceiling light fixture	15
[Sound source inside finished basement]	
Around sash/jamb of sliding glass door	6
Around sash/jamb of sliding glass door	8
Around sash/jamb of sliding glass door	7
Around sash/jamb of sliding glass door	4
Around sash/jamb of sliding glass door	10
Around sash/jamb of sliding glass door	6

K-HOUSE (*Cont*)

Location	ΔdB(A)
Around front of sliding glass door	4
Around front of sliding glass door	7
Around front of sliding glass door	10
Around front of sliding glass door	6

MEAT MARKET (*Vacant*)

Description

- One story concrete block structure with brick veneer; furred drywall interior
- Slab floors
- Exterior walls uninsulated
- Age: approximately 20 years
- No storm windows, storm doors, or vestibules
- Area approximately 10,000 sq ft.

Air-Leakage Data

None (too large to evacuate).

General Observations

Structure appears tight, except for leaks around rear receiving doors.

Acoustic Location Observations

[Sound source was traffic noise on street outside.]

Location	ΔdB(A)
Delivery door, frame	7
Delivery door, jamb	5
Delivery door, jamb	4
Plate glass window (gasketed and inoperable)	6
Plate glass window (gasketed and inoperable)	2

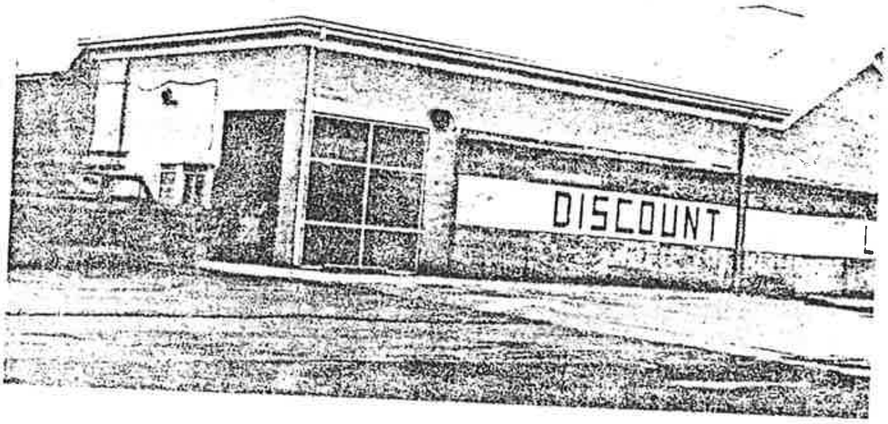
SUPERMARKET (*Vacant*)

Description

- One-story concrete block structure with brick veneer; furred dry wall interior, partial unheated attic, windows boarded up.
- Slab floor
- Exterior walls uninsulated
- Age: approximately 20 years
- No storm windows, storm doors, or vestibules
- Area approximately 20,000 sq ft.

Air Leakage Data

None (too large to evaluate).



SUPERMARKET (*Cont*)

General Description

Building generally tight, except frames of windows and doors.

Acoustic Location Observations

[Sound source was traffic noise on street outside.]

Location	ΔdB(A)
Corner of gasketed inoperable plate glass window	12
Corner of gasketed inoperable plate glass window	6
Frame of above	4
~5 sq.in. hole in wall	18
Door frame	10
Door frame	6
Door frame	7
Door frame	11

CARLISLE ELEMENTARY SCHOOL

Description

- One-story frame construction with brick veneer, extensive glass. Unheated attic, 10 ft ceilings
- Exterior walls insulated
- Slab foundation
- Age: 12 years
- Area: Classroom studied: 915 sq ft.

CARLISLE ELEMENTARY SCHOOL (*Cont*)

AIR-LEAKAGE DATA (EVACUATED)

Condition	ΔP, in. H_2O	$\dot{V}$, cfm	Changes/hr.*
As is	0.135	996	5.5
	0.16	1091	
	0.235	1443	
	0.35	1782	
	0.41	1941	
Ventilation grills and interior partitions sealed	0.115	740	4.8
	0.18	1220	
	0.29	1477	
	0.35	1606	
	0.42	1863	
As above, but with window sashes and door jambs sealed	0.16	891	4.3
	0.185	996	
	0.23	1178	
	0.34	1477	
	0.43	1782	

*At 0.1 in. H_2O ΔP

General Description

Building appears reasonably tight, except for firedoors to exterior, and awning-type steel frame casement windows.

Acoustic and Local Air-Flow Observations

[Sound source inside.]

Location	Flow, ft/min @ 0.42 in. H_2O	ΔdB(A)
Fire door jamb	400	10
Fire door jamb	100	4
Fire door frame	240	6
Fire door frame	190	

CARLISLE ELEMENTARY SCHOOL (*Cont*)

Location	Flow, ft/min, @ 0.42 in H_2O	ΔdB(A)
Fire door frame	220	
Fire door frame	150	
Fire door frame	140	
Fire door frame	220	9
Fire door frame	160	1
Window sill and framing	100	4
Window sill and framing		2
Window sill and framing	270	1
Window sill and framing	180	0
Window sill and framing	300	1
Window sill and framing	400	5
Window sill and framing	140	2
Window sill and framing	160	1
Window sash	180	17
Window sash		2
Window sash	190	14

Acoustic Observations

[Sound source outdoors]

Location	ΔdB(A)
Fire door frame	6
Fire door frame	5
Crack in fire door	6
Fire door jamb	12
Fire door jamb	8
Fire door jamb	11
Fire door jamb	4

CARLISLE ELEMENTARY SCHOOL (*Cont*)

[Sound source indoors]

Location	ΔdB(A)
Fire door frame	6
Crack in fire door	3
Fire door jamb	8
Fire door jamb	8
Fire door jamb	11
Fire door jamb	9

APPENDIX C

COMMENTS BY OTHER USERS OF THE ACOUSTIC-LOCATION METHOD

1. Brockton Self-Help
2. Naval Civil Engineering Laboratory
3. Schonemann Home Insulating Co.
4. Alumabilt Inc.

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CAA

SELF HELP INCORPORATED

THE COMMUNITY ACTION AGENCY OF GREATER BROCKTON
232 MAIN STREET, BROCKTON, MASS. 02401 TEL. (617) 588-5440
"AN EQUAL OPPORTUNITY EMPLOYER"

October 6, 1978

RECEIVED
OCT 10 1978

AVON
ABINGTON
BRIDGEWATER
BROCKTON
CANTON
E. BRIDGEWATER
EASTON
HANSON
HOLBROOK
MANSFIELD
RANDOLPH
ROCKLAND
SHARON
STOUGHTON
W. BRIDGEWATER
WHITMAN

Mr. David N. Keast
Bolt Beranek and Newman Inc.
50 Moulton Street
Cambridge, Ma. 02138

Dear Dave:

The acoustic-test equipment developed by BBN has proven to be extremely effective in testing for infiltration.

It was of particular interest to my staff that the acoustic-test located air leaks not usually considered or accounted for in the visual inspection.

The majority of energy audits being performed today are completed either by visual means or by the use of an infrared heat machine.

In contrast to the heat machine, the low cost of the acoustic-test equipment would make it readily available to Community Action Programs or small businesses new in the energy conservation field.

I believe the acoustic-test will be a very useful tool in conducting an efficient energy audit and again in monitoring the weatherization work after completion.

We have enjoyed working with you and appreciate your patience with our staffing problems.

As always, I remain

Very truly yours,

Ruth

Ruth O'Neill
Energy Director

RON:jb

CHILD DEVELOPMENT CENTER • COMMUNITY GARDENS • COMMUNITY ORGANIZATION • ENERGY • FOOD ADVOCACY
FOOD SERVICES • HEAD START • HOUSING LEGAL SERVICE • INFORMATION AND REFERRAL • SUMMER LUNCH
SERVICIOS HISPANOS • TRANSPORTATION • WELFARE ADVOCACY • WINTERIZATION

CIVIL ENGINEERING LABORATORY
NAVAL CONSTRUCTION BATTALION CENTER
PORT HUENEME, CA 93043

IN REPLY REFER TO:
L64/JCK/lc
3924/1
Z0829-01-006

RECEIVED
JUN 16 1978

13 JUN 1978

Mr. David Keast
Bolt Beranek and Newman Inc.
50 Moulton Street
Cambridge, Mass. 02138

Dear Mr. Keast:

We appreciated your visit here on 11 May to demonstrate equipment for acoustic location of air infiltration paths in existing buildings.

We were impressed with the equipment and believe it can be a useful tool in our air infiltration test program involving SF_6 and pressurization measurement techniques. We would appreciate receiving a copy of the plans and parts list so that a unit can be assembled here. Also, we would like information on how to acquire copies of the noise-generating cassette tapes.

Yours truly,

John C. King
John C. King
Mechanical Engineer
Military Projects Division

Copy to:
DOE Sponsor:
Mr. L.M. Woodworth
Dept of Applied Sciences
Bldg. 120
Brookhaven Nat. Lab
Upton, Long Island, N.Y. 11973

SCC

SCHONEMANN HOME INSULATING CO.

Division of

SCHONEMANN CONSTRUCTION COMPANY

17620 ROGER DR. GERMANTOWN, MARYLAND 20767 (301) 428-0344

RECEIVED

OCT 2 1978

September 29, 1978

David Keast
Bolt Beranek and Newman Inc.
50 Moulton Street
Cambridge, Mass. 02138

Dear Mr. Keast:

As requested by your organization, I have used your sound test method to test for air leaks in existing houses, around windows, doors, weatherstripping, etc.

Upon testing four different types of homes in various locations in the Washington, D.C. area, I have found the results to be very impressive.

The sound waves definitely follow a distinct route with the air current leaking around old caulking, faulty or no weatherstripping, and even old cracking putty in multipane window and door sashes.

The homeowners themselves are impressed the the simplicity and accuracy of the device.

As for checking leaks around walls, I think that I was thrown off by the sound reverberating around the wall by natural deflection and could not be sure how air tight the walls were.

As for weatherstripping, caulking, puttying, etc., I don't think that a finer or less expensive test method could be devised. I certainly prefer it to the infra-red camera idea.

Keep up the good work and I hope that this report has been of some help to you.

Specialists in Blown Insulation
Storm Doors and Windows
Weather Stripping

SCC

SCHONEMANN HOME INSULATING CO.

Division of

SCHONEMANN CONSTRUCTION COMPANY

17620 ROGER DR. GERMANTOWN, MARYLAND 20767 (301) 428-0344

(cont'd)

I do think that the idea will need some strong marketing to prove it worthwhile for the homeowner to spend $50 to $100 or more for a survey. Because of the time involved for an accurate survey, a contractor cannot afford to make it for free.

Thank you for the opportunity to serve you and your company, and I hope to hear from you in the future.

Sincerely,

Gerald K. Schonemann

Gerald K. Schonemann

Specialists in Blown Insulation
Storm Doors and Windows
Weather Stripping

ALUMABILT INC.
1387 Washington St., West Newton, Mass. 02165
(617) 969-0500

NATIONAL CONTRACTOR OF THE YEAR AWARD
BIRD "BEST DRESSED HOMES" AWARD
ALSCO-ANACONDA "SUPERIOR CRAFTSMANSHIP" AWARD

RECEIVED
OCT 26 1978

October 24, 1978

Mr. David Keist
Bolt, Beranek and Newman
50 Moulton Street
Cambridge, Massachusetts 02138

Dear Mr. Keist:

We utilized your sounding system in our evaluating fuel loss in several homes and my findings are pretty much consistent with your original explanation as to how this equipment could best be used.

Obviously, in areas where there was space or gaps, the sounding was more pronounced. This sounding system was consistent in areas around windows and doors. We found, however, it was not effective when tested on a flat wall that had no openings. I am not sure that the application of this system as it now exists is helpful beyond determining the changes in sound before and after an opening is sealed.

Sincerely,

John M. Marshall

JMM: smk

ALUMABILT IS ONE OF THE OLDEST AND LARGEST ESTABLISHED HOME IMPROVEMENT FIRMS IN THE BOSTON AREA.

APPENDIX D

STATEMENT OF WORK

STATEMENT OF WORK

The statement of work included in the contract covering work described in this report is reproduced below.

TASK 1: Literature Search and Design of a Measurement Program

Bolt Beranek and Newman Inc. (BBN) will survey the available technical literature on acoustic measurements, and on infiltration measurements in existing structures. Emphasis will be placed on low-rise-residential and commercial units most amenable to the acoustic leak detection method. On the basis of this literature survey, a field measurement program will be designed to:

a) Evaluate various commercially-available, off-the-shelf, low-cost sound production and listening systems suitable for use by building retrofit contractors as acoustic leak-detection aids.

b) Perform simultaneous acoustic leak-detection tests and infiltration measurements on about 10 existing structures of various types in order to evaluate the correlation between the two methods. Some laboratory testing may also be performed to refine techniques prior to initiating field measurements.

Infiltration testing in existing structures will be done by the pressurization method, similar to that outlined in ASTM E 283-73. Following the closure of obvious openings in each test structure, a large fan attached to a door or window will be used to pressurize the structure to a few tenths of an inch of H_2O. The resulting air flow at the fan will be measured.

The final output of Task 1 will be a memo report and measurement plan that will be submitted to ERDA for review and approval prior to BBN's proceeding with Task 2.

TASK 2: Perform Field Measurements

Following ERDA's approval of the measurement plan, BBN will conduct laboratory and field measurements on existing buildings in accordance with the plan.

It is expected that the experimental program will be done in three phases, as follows:

1. Laboratory tests of representative building elements, (such as doors and windows), in BBN's dual reverberation chamber facilities.

   The purpose of these tests will be to measure the acoustic and infiltration leakage of various common types of building elements to develop simplified procedures, and to accumulate a list of inexpensive, off-the-shelf instrumentation.

2. Field tests by BBN personnel in BBN's own industrial and commercial buildings in Cambridge*, and in the

---

*Typical office buildings of various ages and structural types, and a "Butler-type" industrial building will be made available by BBN at no direct cost to this contract.

homes of BBN-Boston area employees. The residential units will be selected to cover a range of ages and structural types, and will be volunteered at no cost to this contract.

3. Field tests by building-insulation-retrofit contractors in Boston, the Washington, D.C. area, Houston and Los Angeles. These tests would be monitored by BBN technical staff in the BBN offices in these cities, and would be performed in a variety of buildings volunteered for the purpose at no rental cost to this contract.

In each case, infiltration leaks located by acoustic testing would be caulked/weatherstripped and retesting performed to demonstrate the change in results. "Before and after" data would be correlated to aid in the evaluation of the acoustic test method.

The final result of this measurement task will be:

a) Specifications for suitable off-the-shelf, low-cost acoustic leak detection equipment

b) Simplified "How-to: instructions for building retrofit contractors on how to perform acoustic leak detection on existing buildings

c) Measured data illustrating the correlation of acoustic-leak detection results with actual infiltration in existing buildings.

TASK 3: Implementation Plan

Effective promotion of the acoustic-leak detection methodology and of the results of the validation experiment performed under Task 2 could in itself lead to general, voluntary acceptance of the method by the building-retrofit trade. Alternately, the technique could be adopted by the Federal government as an energy-audit tool in the implementation of the widespread energy audits that may be required under Federal Law. In addition, building-code-compliance inspections could be performed with this method. These and other options will be examined and, when promising, described in detail under this task. Costs, benefits, implementation rates, and levels of market adoption of the technique will be estimated. This analysis will take into consideration the then-current Federal posture and programs directed towards building energy conservation.

The end result of this task will be a detailed implementation (or "commercialization") procedure for promoting acoustic-leak-detection methodology.

The procedure will be submitted in memo form to ERDA for review. Following ERDA's review and the incorporation of their comments, the plan, as amended, will be included as a section of the final report (Task 4).

TASK 4: Final Report (Meetings and Progress Reports)

BBN will prepare and submit a final report covering a history of the contract effort, and:

a) A synopsis of past work and an analytical description of the acoustic leak detection method (Task 1)

b) Specifications for suitable, off-the-shelf, low-cost acoustic-leak-detection equipment

c) User-oriented instructions for the method

d) Analyzed data obtained during the measurement program (Task 2)

e) The finalized implementation plan developed under Task 3

f) Conclusions and recommendations

Furthermore, BBN will prepare and submit periodic cost and technical reports in accordance with a schedule established by ERDA, and will attend planning and review meetings when requested by ERDA.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1979—614-036/18