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INSULATING BUILDINGS FROM AIRCRAFT NOISE

by J.D. Quirt

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SOMMAIRE

Des calculs sur place ont été effectués dans le cas de divers composants de bâtiments pour déterminer la quantité d'isolant pour la protection contre les bruits causés par les aéronefs. À partir de ces calculs, on a mis au point des indices mesurant l'isolation sonore, et on a présenté une méthode pour l'utilisation de ces indices. L'article examine la relation entre l'isolation sonore réelle et la balance spectrale du bruit causé par les aéronefs.

Insulating buildings from aircraft noise

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Field measurements of insulation against aircraft noise were made for a wide range of building components. Single-figure ratings of noise insulation were derived, and a design procedure for use of these ratings is presented. The dependence of the effective sound insulation on the spectral balance of aircraft noise is examined.

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INTRODUCTION

Despite the high noise levels inevitable in the regions surrounding major airports, the economic pressure of urban expansion has resulted in extensive residential development in these areas. Except for a reduction in the noise at source, little can be done about the outdoor noise climate, but the penetration of aircraft noise into the interiors of buildings can be controlled by suitable design of the exterior envelope.

For a typical North American house, designed with minimal attention to acoustics, the difference between the exterior and interior noise levels seldom exceeds 25 dB. Doors and windows are usually dominant transmission paths, with the obvious extreme case of windows left open to provide ventilation. Any attempt to substantially reduce the indoor noise levels generated by exterior sources must clearly begin with a ventilation system other than open windows. Given such a system, other elements of the external envelope—such as roofs, walls, and windows—should be selected on the basis of their acoustical performance.

In 1972 the Division of Building Research of the National Research Council of Canada was consulted in the preparation of a design guideline for residential construction near airports. A guideline[1] was produced based on available test information, but several problems were recognized. No quantitative information was available for some important parts of the building, such as typical roof–attic–ceiling systems. Even for those elements for which full laboratory test data were available, there remained the fundamental problem of trying to relate a single figure for measuring outdoor noise, for example the Noise Exposure Forecast (NEF), to an appropriate single figure for indoor noise by way of a single-figure index of sound insulation, such as the ASTM Sound Transmission Class (STC).[2] Since assumptions about spectral balance enter into all three measures, one must be cautious about combining them.

To obtain the necessary information, an extensive series of field measurements was made at a test building constructed by the Central Mortgage and Housing Corporation, a Canadian government agency. This special composite structure is described in Sec. II. Measurement procedure and a summary of the experimental results are presented in the following sections.

I. DESIGN GUIDELINE PROCEDURE

Although the basic principles of the design guideline have been discussed in a previous publication,[3] the main features are reviewed because of their relevance to this paper. Perhaps the most important feature is that several major simplifications were adopted to facilitate the use of the guideline by designers lacking expertise in acoustics. A guideline of this nature must be based on an assessment of the noise climate at the site, criteria for acceptable indoor noise levels, and a procedure for achieving acceptable levels in the presence of the noise climate. For land use purposes the predicted noise from aircraft operations near major Canadian airports is described in terms of a Noise Exposure Forecast (NEF). This index[4] is based on the Effective Perceived Noise Level (EPNL) for each flypast and the number of events in the daytime and nighttime periods.

On the basis of social survey data and studies of noise reduction by "typical" homes, the design criteria for acceptable *indoor* noise exposure forecast were set at NEF = +2 dB for living rooms and NEF = −3 dB for bedrooms where the more restrictive criteria for sleep arousal pertain. Estimates of attainable noise reduction suggest that these criteria can be met, using fairly standard constructions, for an outdoor noise exposure forecast up to NEF = 35 dB. For outdoor noise exceeding this limit, residential development is not recommended, primarily because the inhabitants may be expected to venture outdoors occasionally. The lower limit for application of the guideline is set by the practical consideration that NEF contours cannot be calculated with adequate precision below NEF = 27 dB. The problem remaining is to specify a procedure for designing a building's exterior envelope to achieve the required reduction in NEF, which is essentially equivalent to achieving the same reduction in EPNL for each flypast.

If only one component were transmitting sound, the noise reduction obtained would depend both on the construction used and on the ratio of component area to the room's acoustic absorption. For well-furnished bedrooms and living rooms, field studies typically show a room absorption in sabins (or metric sabins) equal to 80% of the floor area. [Because the absorption is provided primarily by the furnishings, it generally increases in proportion to the floor area, especially if

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FIG. 1. Building constructed for experimental measurements, as viewed from the south.

the floor is carpeted. This absorption corresponds to a reverberation time of approximately 0.5 s for a room height of 2.4 m (8 ft).] To minimize the acoustical concepts required for use of the guideline, absorption and component area were allowed for by assigning to each construction a series of values for various ratios of component area/floor area (as in Tables I–III) rather than a single noise insulation rating. This form of presentation is readily accepted by architects because requirements for light and ventilation are commonly expressed in terms of the ratio of window area to room floor area. This rating, which is a measure of reduction in the EPNL normalized for component area and typical room absorption, has been named the "Acoustic Insulation Factor" (AIF).[5]

The exterior envelope of a room may include up to four possible components: doors, roof-ceiling system, exterior walls, and windows. In this study, for example one window or several similar windows would be considered as "one component," and the total window area used would be the component area for the AIF. The difference between indoor and outdoor NEF depends on the combined sound energy transmitted by all the components. In the case of a room with N components, the guideline requires that no component should transmit more than $1/N$ of the sound energy that would give the desired indoor NEF. Although in principle one can compensate for the low AIF of one component by a superior value for another, the lowest one always dominates. Therefore, the equal-power concept applied here may be conservative by one or two decibels, at most.

Thus one obtains the design criterion in terms of the AIF:

$$\text{Required AIF} = \text{NEF (outside)} - \text{NEF (inside)} + 10\log_{10}(N)\,, \qquad (1)$$

where N is the number of components in the room envelope.

A designer using the guideline simply determines the required AIF from a table based on Eq. (1), and selects the appropriate components from tables similar to Tables I–III.

II. DESIGN OF THE TEST BUILDING

The test structure, shown in Fig. 1, not only incorporated many of the features of single-family residential units, but also included a segment with construction similar to that in apartment buildings.

The "apartment" area (which formed approximately half of the ground floor) had concrete block walls 200 mm (8 in.) thick, parged on the outside and finished inside with gypsum board 13 mm ($\frac{1}{2}$ in.) thick, mounted on 38 by 38 mm ($1\frac{1}{2}$ by $1\frac{1}{2}$ in.) furring strips. Approximately two-thirds of the area of the third external wall consisted of two sliding-door units, each 3 m (9 ft) wide, with factory-sealed double glazing (two 4-mm-thick panes spaced 10 mm apart). Stub walls extended beyond this facade (the right-hand end of the building in Fig. 1) to provide an enclosure similar to the balconies on many high-rise apartment blocks.

The segment above the "apartment" and the two-story segment forming the other end of the building were of wood-frame construction. The basic wall structure had 38×89 mm ($1\frac{1}{2}\times 3\frac{1}{2}$ in.) studs spaced 0.4 m (16 in.) on center (o.c.), with R8 low-density fiber-glass batts in the cavity spaces between studs. A plastic vapor barrier and gypsum board 13 mm thick were fastened directly to the inner face of the studs; 13-mm-thick sheathing covered with building paper was fastened to the outer side. The exterior finish of the segment above the "apartment" was clay brick veneer 100 mm (4 in.) thick. Half of the two-story segment had an exterior finish of stucco applied on an expanded metal lath; the other half had 13-mm ($\frac{1}{2}$-in.) thick wood shiplap siding. For the first part of the test series, a simulated mansard construction (asphalt shingles applied over 13-mm-thick plywood sheathing supported on wood framing) was attached to the upper story of this segment (top left in Fig. 1). The mansards were later removed and replaced with an exterior finish matching that on the lower story.

The peaked roof above the brick veneer segment consisted of asphalt shingles (10 kg/m^2) fastened to 13-mm-thick plywood sheathing supported by wood trusses spaced 0.6 m (24 in.) o.c. The attic space was ventilated by openings under the eaves. Low-density fiberglass batts (R8) were placed between the joists, to the underside of which was fastened the 13-mm-thick gypsum board forming the ceiling of the rooms below.

The roof on the two-story segment of the building was changed part way through the test series. The initial roof was flat and had a basic structure of 38 by 184 mm ($1\frac{1}{2}$ by $7\frac{1}{4}$ in.) joists spaced 0.3 m (12 in.) o.c. A built-up roof of tar and stones, asphalt roofing felt, and 50-mm (2-in.) thick rigid insulation was applied over 13-mm-thick plywood sheathing that was fastened to furring strips over the joists. The 13-mm-thick gypsum board forming the ceiling of the rooms below was fastened directly to the joists. This structure was later replaced with a peaked roof similar to that on the other half of the building.

The window sashes were removable; 11 sashes were provided for each window to permit studies of five different thicknesses of glass. Both single and double glazing (two sashes per window with interpane separations of 63 or 100 mm) were tested. A set of factory-sealed windows with double 4-mm glazing at 10-mm spacing was also tested. All windows fitted snugly and had spring-metal weather stripping.

A combination of movable interior partitions and heavy panels that could be used to block window openings permitted large variations in both the window area and floor area of any room.

III. MEASUREMENT OF SOUND INSULATION FOR A ROOM ENVELOPE

A. Experimental details

One or more 1-in. condenser microphones (B & K) Type 4145 with Type 2619 preamps and 2801 power supplies) were placed in each room of the building and connected to the inputs of two seven-channel FM instrumentation tape recorders (Philips Analog-7). When necessary, a Honeywell Accudata 112A multichannel amplifier system increased signal levels at the recorder inputs. A multiplexer system permitted essentially simultaneous monitoring of eight of the data channels on a Tektronix 502 oscilloscope. An additional B & K 4145 microphone mounted on a mast at the end of the brick veneer segment of the building, 2 m above the peak of the roof, measured outdoor noise. A B & K 4220 pistonphone was used to calibrate all channels for each recording session.

A 1-kHz toneburst recorded on the voice track of both tape recorders at the beginning of each flypast permitted accurate synchronization of the data records when they were played back for analysis. Data analysis was performed using a General Radio 1921 real-time analyzer coupled to the recorder outputs through a General Radio 1566 amplifier-multiplexer and interfaced to a Xerox CF16 minicomputer. For each $\frac{1}{2}$-s interval of a flypast, the computer stored the *A*-weighted sound level and the $\frac{1}{3}$-octave band levels from 50 Hz to 10 kHz for the outside microphone and for each inside microphone. For each channel, the computer then calculated the Perceived Noise Level (PNL) and the Tone-Corrected Perceived Noise Level (PNLT), and the differences between outside and inside values of the PNL, PNLT, and *A*-weighted sound level. The calculations were made for each $\frac{1}{2}$-s interval. In addition, the standard STC rating curve[2] was fitted to the $\frac{1}{3}$-octave band differences between the outside and inside levels. These results were printed out for the intervals for which the outdoor PNLT was within 20 dB of its maximum value. One-third-octave band spectra and level differences were also printed out in selected cases.

The test building was located directly under the flight path 1.6 miles from the end of Runway 32 of Ottawa International Airport. Preliminary measurements were made for approaching commercial flights. They provided direct information on the range of noise levels and spectra associated with such operations, but the performance of the various components of the building could not be evaluated in detail. For this purpose test flights were arranged.

The majority of the data reported here were obtained in 20 recording sessions, each consisting of 20–25 low-altitude flypasts by a Lockheed Jetstar aircraft operated by the Canadian Ministry of Transport. Consistency of the aircraft's power settings and foreknowledge of its distance of nearest approach minimized the problems of obtaining satisfactory tape recordings. Large brightly colored markers on the ground permitted the pilots to line up on several specific flight paths parallel to each facade of the building, such as that indicated in Fig. 2. It was possible, therefore, to analyze the data for effects associated with variations in aircraft position.

B. Possible accuracy limitations

Normally only one microphone was used in each room because of practical limitations on the number of microphones and tape recorder channels. The microphone was placed near the center of the room. To assess variation of noise levels within the room, a series of measurements was made with several positionings of a three-microphone array. To avoid pressure buildup effects, all measuring positions were at least 1 m from the nearest room boundary. It was found that the central position provided a reasonable average although slightly higher values were measured in the immediate vicinity of the windows. However, the difference between noise levels at any two microphones was also observed to fluctuate from one $\frac{1}{2}$-s measurement interval to the next during the course of a flypast.

The rms magnitude of the intermicrophone differences was less than 1 dB for the $\frac{1}{3}$-octave bands above 160 Hz, increasing to about 2 dB for the 50-Hz band. For the $\frac{1}{3}$-octave bands centered at 125 Hz or lower, the smaller rooms of the test building would not satisfy the standard diffuse field requirement of ten normal modes per bandwidth. Intermicrophone variations in the observed noise levels could have resulted from changes in the relative excitation of the room modes as the noise source moved past the building. It should also be noted that the short measurement interval and the filter band-

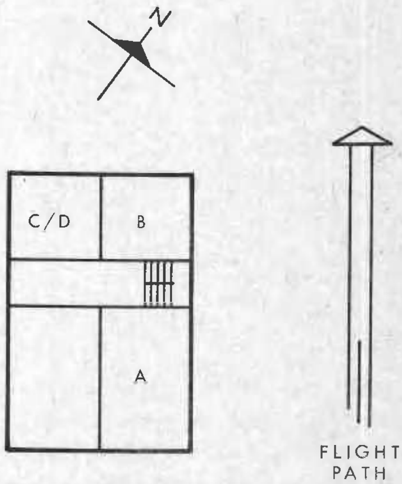

FIG. 2. Sketch of building layout indicating aircraft flight path for data in Figs. 3–5.

widths give rise to an inherent uncertainty in measurements of the same magnitude as the observed fluctuations.

In any case, the resulting intermicrophone differences in the A-weighted sound level, or the PNL, were 1 dB or less for any given $\frac{1}{2}$-s interval and less than $\frac{1}{4}$ dB when averaged over a flypast.

A potentially more serious problem affecting the measurement accuracy was the limited dynamic range of the recording system (approximately 50 dB from maximum signal level to the noise threshold in the worst $\frac{1}{3}$-octave band). The comparatively weak high-frequency content in the indoor noise resulted in signal/noise ratios near unity for the $\frac{1}{3}$-octave bands at 4 kHz or higher, when the signal level fell to 20 dB below the flypast maximum. However, careful analysis of the data showed that this limitation seldom affected the calculated PNL for any interval by as much as 1.5 dB and that the resulting average error in the AIF for a typical flypast was less than $\frac{1}{4}$ dB.

C. Calculation of AIF for a room envelope

Inherent in the design guideline, and thus in the application of the measurements reported here, is the assumption that the acoustic absorption in a "typical" furnished room is 80% of the floor area, for all frequencies. Because the actual measurement conditions differed from this, experimental determination of the room absorption and normalization of the experimental results to the guideline criterion were required.

Because of the limitations of the minicomputer memory, applying absorption corrections to each $\frac{1}{3}$-octave band level for each room was not feasible, and a simplified procedure was adopted. Noise with spectral balance similar to that observed during a flypast was generated using a noise source and loudspeakers, and the decay rate of the A-weighted level was measured. The resulting reverberation time (T_{60}) was used to determine the room absorption (A) in sabins calculated using the Sabine formula

$$A=(0.049\,V)/T_{60}\ , \qquad (2)$$

where V is the room volume in cubic feet. The measured AIF for a room envelope was then determined from

$$(\mathrm{AIF})_{\mathrm{room}}=\mathrm{PNL\,(outside)}-\mathrm{PNL\,(inside)}+10\log(A_r/A)\ , \qquad (3)$$

where A_r corresponds to 80% of the floor area.

This procedure permitted the treatment of absorption normalization as a final correction, rather than a detailed calculation for each $\frac{1}{2}$-s interval, and stressed the frequency range most significant to subjective evaluation of the noise level. Because of the considerable variation in absorption expected in actual homes, the simplified procedure seems adequate for this application

IV. DETERMINING THE ACOUSTIC INSULATION FACTOR (AIF) OF INDIVIDUAL COMPONENTS

A. General considerations

Ideally every design problem should be evaluated using detailed information on the outdoor noise levels and the building sound insulation at each frequency. This would require extensive calculations, especially when the building envelope is composed of several dissimilar elements. To simplify this process the AIF was devised to provide the designer with a single-figure rating of the noise insulation provided by each element of the building. The AIF, like other single-figure ratings, has inherent limitations resulting from the simplifying assumptions on which it is based.

The subjective impression of noise insulation provided by a structure depends on an interplay between the frequency dependence of the noise reduction and the spectral content of the noise source. The widely used Sound Transmission Class (STC) rating for interior partitions[2,6] is based only on the sound transmission losses in 16 $\frac{1}{3}$-octave bands, although the method of evaluation is appropriate for typical indoor sounds such as speech. Its correlation with subjective impression of the noise reduction may be lost when the source spectrum differs appreciably from that of speech. In contrast, the AIF is derived from outside and inside noise spectra and is therefore dependent on spectrum shape as well as on the building properties.

B. Variation of AIF with source spectrum

Isolation of the effect of changes in source spectrum on the AIF required a second index of noise insulation that would provide similar sensitivity to the angle of incidence and acoustic shadowing effects, but would be independent of the source spectrum. This need was met by an index calculated by fitting the standard STC contour to the $\frac{1}{3}$-octave-band sound-pressure-level differences and adding the same absorption normalization correction $[10\log(A_r/A)]$ as was used for the AIF. This rating, which is labelled STC′ because of its superficial resemblance to the STC rating,[6] was introduced only to meet a specific need of this analysis. Its relationship to the STC is discussed further in Sec. VI. The consistency of the value (AIF-STC′) for all rooms of the building (and hence various angles of incidence) for any $\frac{1}{2}$-s interval of a flypast suggests that this difference correlates primarily with the spectral balance of the outdoor noise rather than other parameters.

Curve A of Fig. 3 presents the (AIF-STC′) data of room B for a Jetstar flypast on the path indicated in Fig. 2. The zero of the time axis in Fig. 3 is the midpoint of the interval for which the outdoor PNL is maximum. The trend of the (AIF-STC′) values is in general very similar for all the rooms, although the values depend on both the type of aircraft and the components of the room envelope. Curve B of Fig. 3 shows the corresponding data for that room with the same windows during the flypast of a DC-9-30 on a landing approach. Figure 4 presents the $\frac{1}{3}$-octave band spectral for two

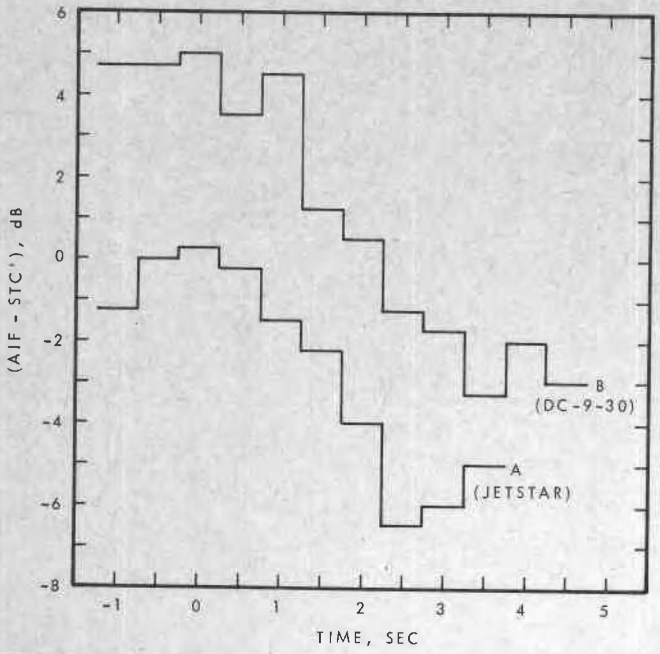

FIG. 3. Difference between AIF and STC′ measured in room B during flypasts on the path shown in Fig. 2. This difference is indicative of the effect on the AIF of changes in spectral balance of the outdoor noise. The upper curve shows the result for a flypast by a DC-9-30 and the lower curve the result for a Jetstar.

specific $\frac{1}{2}$-s intervals of each flypast. These spectra have been normalized relative to their levels in the 1-kHz band in order to stress the differences in spectral balance.

The change in the values of (AIF-STC′) during a flypast and the difference between the (AIF-STC′) curves for the two aircrafts are primarily caused by differences in source spectrum. When the Jetstar is nearly overhead (time = 0 in Fig. 3), the outdoor PNL is dominated by the frequencies above 1 kHz. As the aircraft moves away, the sound changes in character to a low-frequency rumble, and the difference between the indoor and outdoor PNL values (and hence the (AIF) becomes smaller because sound insulation tends to be less at lower frequencies. The same general trend is observed in the data for the DC-9, although the high-frequency content is relatively stronger than in the Jetstar noise (and the AIF correspondingly higher).

Because of this strong dependence on the source spectrum, self-consistency of the measured AIF values required that they all be obtained for similar source spectra. The experimental results presented in the following sections (unless otherwise specified) were obtained by averaging over the data from Jetstar flypasts as discussed further in Sec. IV D. Thus the measured AIF values presented in the tables correspond to source spectra intermediate to the two spectra shown for the Jetstar in the upper half of Fig. 4.

C. Variation of the AIF during a flypast

As noted previously, changes in source spectrum introduce a systematic trend towards lower AIF values in the later part of a flypast record. However, this is not the only source of variation in the AIF of a room envelope during a flypast.

Because noise reduction of a facade varies with the angle of incidence and because some facades are directly exposed to the source for only part of the time, the room AIF depends strongly on aircraft position. Figure 5 presents typical AIF data for four rooms for the same Jetstar flypast depicted in curve A of Fig. 3. As indicated in Fig. 2, rooms A, B, and C are on the building's upper floor and room D is directly under room C. The time axis in Fig. 5 is the same as that of Fig. 3; the zero on the axis is the midpoint of the interval during which the aircraft is directly opposite the northeast facade.

The AIF for room A is dominated by noise transmission through the windows of the northeast facade, which is exposed throughout the flypast. The AIF exhibits a maximum when the angle of incidence is nearest normal (as might be expected), and a minimum when the angle is in the range of 70°–80° from the normal to the facade. The rise in the AIF values at extreme

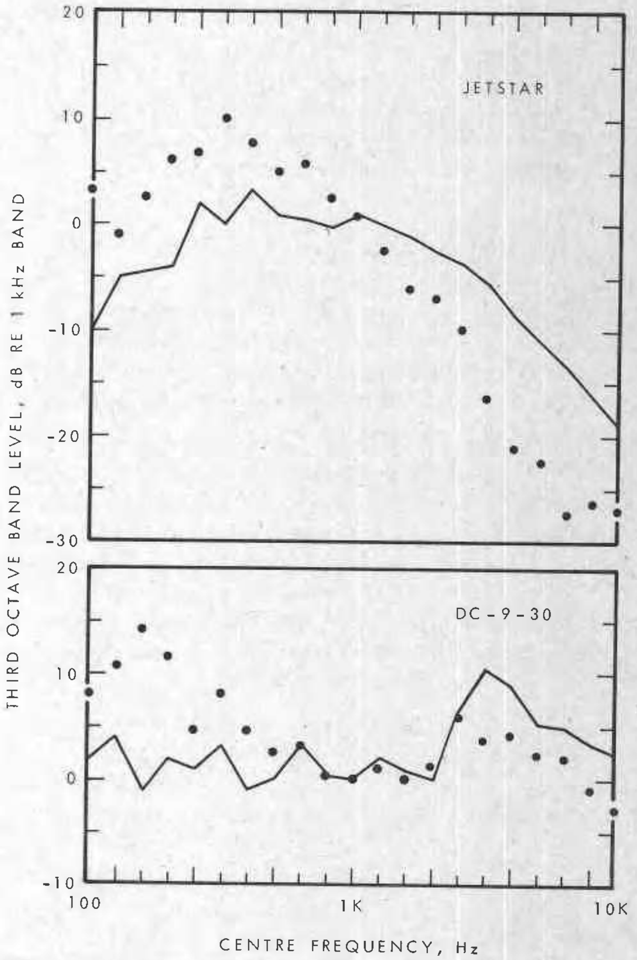

FIG. 4. Outdoor spectra for specific time intervals of the flypasts for which (AIF-STC′) data were presented in Fig. 3. The solid curves correspond to the spectra for the interval at time = 0, and the dotted curves are for the final interval of each record. These curves were normalized to 0 dB for the 1-kHz band to emphasize the differences in spectral balance.

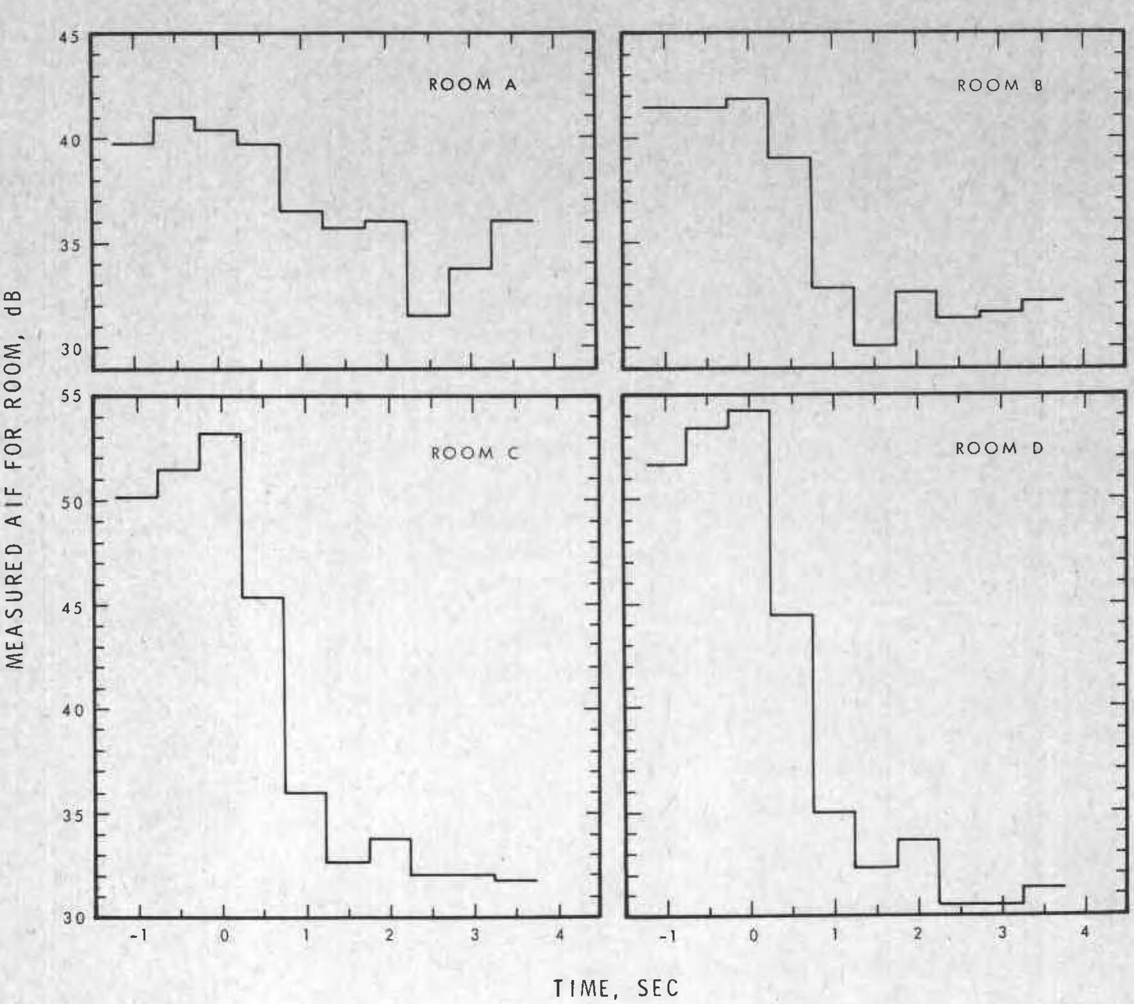

FIG. 5. Variation of the AIF measured for rooms A–D during a Jetstar flypast on the path indicated in Fig. 2.

angles of incidence may be explained by partial shielding of the windows, which are inset approximately 13 cm (5 in.) relative to the outer face of the brick veneer wall.

The data for the other three rooms show the effect of the onset of line-of-sight exposure of the northwest facade slightly after time interval zero. The differences between the AIF for rooms C and D in the final intervals of the flypast record are consistent with their differences in window glazing and window/floor area ratios. The similarity of the values of the AIF for rooms C and D for times less than zero suggests that the roof is not limiting the AIF for room C during this period.

The basic features exhibited by the data in Fig. 5 are typical, although the extent of the maxima and minima depend on the specific components; the trends are sometimes partially masked because of fluctuations in the source spectrum.

D. Calculation of AIF for specific components

As indicated in the preceding discussion, the measured AIF varies considerably during a flypast. For purposes of the design guideline, a single rating for each construction was extracted from these data.

One may not simply use the AIF for the interval when the outdoor PNL is maximum because the EPNL (and hence the NEF) depends not only on maximum noise level but also on flypast duration. The indoor PNL remains within 10 dB of its maximum much longer than does the outdoor PNL, because, for the reasons discussed earlier, the AIF is largest when the aircraft is nearby. Therefore, using the value for time interval zero gives an unrealistically high AIF. Simply calculating the indoor EPNL and subtracting this from the outdoor EPNL is also unsatisfactory, because of the strong acoustic shadowing effects observed in the test situation. In a normal residential area, reflections from other buildings would significantly reduce shadowing effects such as those observed for rooms C and D in Fig. 5 when their facades were not in line of sight from the aircraft.

With this in mind, the final values were obtained by averaging the AIF data for those portions of the flypasts when the facade of interest was directly exposed. It was desirable to average over as broad a range of angles of incidence as possible, to properly assess data such as that for room A in Fig. 5. On the other hand, in some cases it was necessary to sort out contributions that arrived via two exposed facades, on the basis of aircraft position relative to the respective facades.

TABLE I. Acoustic Insulation Factor (AIF) for some double-glazed windows. Values marked by asterisks are measured results.

	Window area as percentage of total floor area								
Window type	12.5	16	20	25	32	40	50	63	80
3 mm (10-mm space) 3 mm	33*	32*	31*	30*	29	28	27	26	25
3 mm (63-mm space) 3 mm	39*	38*	37	36	35	34	33	32	31
3 mm (100-mm space) 3 mm	41	40*	39	38	37	36	35	34	33
4 mm (63-mm space) 4 mm	43	42*	41	40	39	38	37	36	35
4 mm (100-mm space) 4 mm	47	46*	45	44	43	42	41	40	39
6 mm (63-mm space) 6 mm	43	42*	41	40	39	38	37	36	35
6 mm (100-mm space) 6 mm	47	46*	45	44	43	42	41	40	39

For window evaluations, the data averaging was restricted to flypast geometry like that for the northeast facade of room A in Fig. 2 after time interval zero (i.e., for the portion of the flypast when only the northeast facade was directly exposed). Most of the data for the windows were obtained for room A (brick veneer walls, peaked roof) because the good sound reduction of this wall–roof combination ensured that the windows gave the most important contribution to the AIF for the room envelope. Their contribution was determined by comparison of the AIF with each type of window versus that obtained when the windows were blocked with heavy panels. The calculation here was similar to the procedure for "energy addition" of sound pressure levels. For example, combining a wall that by itself would have an AIF of 40 dB, with windows that would give an AIF of 40 dB in a perfectly insulating wall, yields a system with AIF = 37 dB. This follows directly from adding the sound energy transmitted by the various components (keeping in mind that the AIF has taken account of area and absorption effects).

Applying this procedure and assuming that the AIF obtained with the windows blocked is the combined value for all other room components, the window AIF for the applicable window to floor area ratio was calculated. The assumed decrease of 3 dB of the AIF per doubling of the component area was experimentally verified for window areas ranging from approximately 5%–25% of floor area.

Measurement of the AIF for walls or roof–ceiling components was complicated by flanking paths with comparable or greater noise transmission. However, for the peaked roof–attic–ceiling combination this problem was bypassed by the use of a two-stage measurement process. Microphones were placed in the attic space and the difference between outdoor and attic space PNL was measured; then using loudspeakers in the attic as a noise source, the additional noise reduction provided by the ceiling structure in each $\frac{1}{3}$-octave band was measured. These results (which agreed reasonably well with laboratory measurements on the same construction) were combined with spectra measured in the attic space during a flypast, to determine the PNL that would be observed in the room if this were the only transmission path. The difference between the outdoor PNL and the calculated PNL in the room gave the component AIF after a suitable room absorption correction was applied. Once the AIF for the peaked roof–ceiling system was established, it was possible to extract values for the exterior walls from the AIF data for the room envelope, obtained with the windows blocked.

In these comparisons, careful attention to aircraft position was required for reasonable certainty concerning which facades were contributing predominantly to the noise transmission. This restriction of the averaging to specific portions of a flypast record introduced a biasing effect, which was corrected for by comparison with more complete flypast data.

The AIF for the flat roof-ceiling system was derived in two ways: from changes in the AIF of rooms B and C when the flat roof system was replaced with a peaked roof, and from differences between the data for rooms B and C with the flat roof and the data for the downstairs rooms below.

V. APPLICATION OF RESULTS TO THE BUILDING DESIGN GUIDELINE

Tables I–III present the major experimental results of the study and extrapolation to component/floor area ratios other than those actually studied. This is the presentation used in the guideline. Values obtained directly from the experiments are indicated by asterisks.

Because the sound insulation performance of any given construction depends on the spectral balance of the outdoor noise, an appropriate "typical" spectrum for the AIF must be selected. The values in the tables were obtained by averaging over data from Jetstar flypasts, and are therefore valid for outdoor noise spectra intermediate to those shown in the upper half of Fig. 4. These results are very similar to experimental results

TABLE II. Acoustic Insulation Factor (AIF) for exterior walls. Values marked by asterisks are measured results.

	Exterior wall area as a percentage of floor area								
Exterior wall type	25	31	40	50	63	80	100	125	160
Wood siding	42	41	40	39	38*	37	36	35*	34
Simulated mansard	44	43	42	41	40*	39	38	37	36
Stucco	45	44	43	42	41*	40	39	38*	37
Brick veneer	53	52	51	50	49*	48	47	46	45

TABLE III. Acoustic Insulation Factor (AIF) for roof–ceiling systems.

Type of roof	Roof–ceiling area = floor area
Flat built-up roof	44
Peaked, ventilated attic	51
Peaked, no ventilation	54

for commercial flights (DC-8's, DC-9's, and Boeing 707's) taking off over the test building.

Because the noise emitted by aircraft on takeoff considerably exceeds the noise during a landing approach, this is presumably the dominant noise at a majority of the sites near any airport, and the AIF values in the tables should provide a reasonably accurate measure of the sound insulation.

It should be recognized, however, that the typical outdoor spectrum (and hence the actual reduction in PNL) may vary considerably from site to site, even along a given NEF contour, depending on the proximity of flight paths and whether they are used predominantly for landings or takeoffs. For example, near flight paths used mainly for landing approaches, the typical outdoor spectra would resemble those in the lower part of Fig. 4, and the effective sound insulation would be greater (by up to 4 dB) than the ratings in the tables. These effects cannot be taken into account in a building design guideline whose sole descriptor of the noise climate at a site is the NEF (or a noise index based on A-weighted sound levels).

VI. COMPARISON OF THE ACOUSTIC INSULATION FACTOR (AIF) WITH OTHER INDICES

A. Relation to *A*-weighted sound levels

Although the AIF is superior to the STC as a rating of insulation against aircraft noise, it suffers from two obvious defects. The PNL, on which the AIF is based, is not a widely accepted quantity, largely because quite sophisticated instrumentation and calculations are required for its determination. Secondly, manufacturers of building components such as windows or doors have no obvious means of determining the rating for their products.

The A-weighted sound level is by far the most commonly used measure of noise and also correlates well with subjective impressions of loudness or noisiness. For these reasons the difference between outdoor and indoor A-weighted sound levels (Δ_A) was measured in addition to the corresponding difference in PNL (Δ_{PNL}). In general, Δ_A exhibited trends very similar to those of Δ_{PNL}, except that Δ_A was slightly less sensitive to changes in the source spectrum. Noise insulation ratings similar to the AIF, but based on Δ_A, are given in Table IV for several types of double glazing. The values in the table are appropriate for sites where the spectral balance of the outdoor noise is comparable to that shown in the upper half of Fig. 4, as discussed in Sec. V. When the outdoor noise has more high-frequency content, the effective noise insulation could be greater by several decibels. Tables comparable to Table IV may be obtained for walls and for roof–ceiling systems by adding 1 dB to the values in Tables II and III, respectively.

B. Comparison with laboratory measurements of sound transmission loss

It is not feasible to include tests of the type described here on all possible variants of exterior walls, windows, roofs, and doors. To some extent it is possible to interpolate or extrapolate to obtain the performance of other constructions by a synthesis of the field test results with laboratory measurements. However, it is apparent that some rule is needed for assigning ratings to the slightly different products of each manufacturer. In North America the most common rating of the sound insulation properties of building components is the STC. The standard[2] (ASTM E413-70T) has specifically recommended against the use of the STC rating for protection against outdoor noise sources such as aircraft, but this is nonetheless the measurement that most manufacturers obtain and advertise.

Although the STC′ index used in this study resembles the standard STC rating, it differs in two important respects. First, the absorption correction for the STC is normalized to the sample area, whereas that for the STC′ is normalized to an assumed room absorption. These corrections coincide when the sample area equals 80% of the room's floor area. Second, the nature of the source field is quite different. The STC′, like the AIF, is measured relative to the incident (free

TABLE IV. Noise insulation rating comparable to AIF, but based on differences in A-weighted sound levels (Δ_A). Values marked by asterisks are measured results.

	Window area as percentage of total floor area								
Window type	12.5	16	20	25	32	40	50	63	80
3 mm (10-mm space) 3 mm	32	31*	30	29*	28	27	26	25	24
3 mm (63-mm space) 3 mm	39*	38*	37	36	35	34	33	32	31
3 mm (100-mm space) 3 mm	42	41*	40	39	38	37	36	35	34
4 mm (63-mm space) 4 mm	44	43*	42	41	40	39	38	37	36
4 mm (100-mm space) 4 mm	48	47*	46	45	44	43	42	41	40
6 mm (63-mm space) 6 mm	45	44*	43	42	41	40	39	38	37
6 mm (100-mm space) 6 mm	48	47*	46	45	44	43	42	41	40

TABLE V. Comparison of AIF, STC′, and STC results for several varieties of double glazing. Values for AIF and STC′ are presented for window area = 80% of floor area to give absorption normalization comparable to that for the laboratory STC data.

Window type	AIF (Window area = 80% of floor area)	AIF-STC′	STC′ (Window area = 80% of floor area)	Nominal laboratory STC
3 mm (10-mm space) 3 mm	25	0.0	25	27
3 mm (63-mm space) 3 mm	31	−1.5	32	35
3 mm (100-mm space) 3 mm	33	−2.5	36	37
4 mm (63-mm space) 4 mm	35	−2.4	37	37
4 mm (100-mm space) 4 mm	39	−1.7	41	38
6 mm (63-mm space) 6 mm	35	−2.5	38	38
6 mm (100-mm space) 6 mm	39	−2.3	41	39

field) outdoor sound level because that is the quantity predicted in calculations of the NEF. By contrast, the laboratory measurement of Sound Transmission Loss (and hence the STC, which will ultimately be related to the AIF) is taken relative to a reverberant field in a source room. In addition to the obvious effect of reflection from the facade, there is also a different distribution of contributions from various angles of incidence.

To study the relation between the STC and STC′ rating a series of laboratory measurements were made with the same windows that had been used at the test building. The results of these tests are presented in Table V together with the corresponding values of AIF and STC′. To avoid the scatter associated with variation in the seals around the sashes, the STC was measured with the windows sealed to the frames, and "typical" corrections for leakage were subtracted from these results. These corrections were 3 dB if the STC was less than 30, and 5 dB if it was greater than 30. The considerable scatter evident in the differences between the STC and STC′ results has prompted a supplementary study, now in progress at the test building, using carefully sealed windows and a loudspeaker system as the noise source.

In the interim, an average of the results in Table V suggests that, for double-glazed windows, the AIF (for component area = 80% of floor area) is 2 dB less than the STC; this correction is essentially the same as the value of (AIF-STC′). A sharp dip in the transmission loss (at ~400 Hz in our test specimens), which affects the STC more than the AIF, makes 0 dB the appropriate correction for factory-sealed double glazing with small interpane separation. For components such as walls, the AIF was found to be 3–4 dB lower than the STC.

VII. SUMMARY

The results reported here do not include all relevant window and wall constructions, and barely examine the possible variants of roof structures. However, they cover a sufficient range to permit reasonable estimates of the performance of most constructions of interest in typical residential buildings.

The sound insulation data exhibit a significant dependence on the spectral balance of outdoor noise. This dependence, while not unexpected, does interfere with developing a single-figure rating of noise insulation. Although the NEF contours provide a reasonable indication of the outdoor noise near an airport, an additional index with different emphasis on spectral balance is needed if the indoor levels are to be predicted with good accuracy at all sites. In the absence of such an index the ratings presented here were determined for a range of source spectra that should provide a representative value for sound insulation at most sites.

One area requiring further study is the comparison of field measurements reported here with laboratory results for the same constructions. An additional series of field measurements using a loudspeaker system as the noise source is under way.

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[1]"New Housing and Airport Noise," supplement to the *Site Planning Handbook*, Central Mortgage and Housing Corporation, Ottawa, K1A OP7, Canada.

[2]"Determination of Sound Transmission Class, Tentative Classification for," ASTM E 413-7OT (Am. Soc. Test. Mater., Philadelphia, PA).

[3]R. J. Donato, "Insulating houses against aircraft noise," J. Acoust. Soc. Am. **53**, 1025–1027 (1973).

[4]W. J. Galloway and D. E. Bishop, "Noise Exposure Forecasts: Evolution, Evaluation, Extensions, and Land Use Interpretations," Federal Aviation Administration Document FAA-NO-70-9 (1970).

[5]The "Acoustic Insulation Factor" introduced here is essentially equivalent to the Acoustic Insulation Factor introduced by R. J. Donato in Ref. 3.

[6]"Measurement of Airborne Sound Insulation in Buildings, Standard Recommended Practice for," ASTM E 336-71 (Am. Soc. Test. Mater., Philadelphia, PA).