Reducing Aircraft Noise Impact by Sound Insulation of Houses

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ABSTRACT: Aircraft noise is a major environmental issue of concern to people living close to airports. Several thousand houses are situated on land near Sydney Kingsford Smith airport which is not considered suitable for new residential development due to high aircraft noise exposure. Aircraft noise reduction provided by existing houses near the Sydney airport has been measured and typical data is presented. Acoustic upgrading measures that can be undertaken to improve the aircraft noise insulation of houses are described. Information on typical costs of acoustic upgrading measures is also given.

1. INTRODUCTION

Environmental issues, of which noise is a major one, are likely to place significant constraints to the future development and expansion of airports around the world as well as in Australia. On the other hand, the need to increase the capacity of existing airports is becoming acute as air travel by jet aircraft for both business and leisure activities has become a routine part of modern societies. The factors that will contribute to increase in air travel in Australia include: growth in tourism, increasing integration of the Australian economy with emerging global markets and reductions in real airfares due to competition and market deregulation. Figure 1 shows forecasts of total passenger movements and total aircraft movements made by the Federal Airports Corporation in 1993 for Sydney's Kingsford Smith airport up to the year 2011–2012.

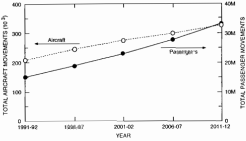


Figure 1. Forecast of total passenger movements and total aircraft movements for Sydney's Kingsford Smith airport.

While the general economy benefits from growth in the number of air passengers, for people living near the airport it can mean a greater degree of aircraft noise annoyance. Georgiou [1] has estimated that, in 1990, approximately 0.2% of the Australian population were exposed to ANEF greater than 30 and 0.7% were exposed to ANEF greater than 25.

The jet age commenced in 1958 when Boeing 707 and Douglas DC8 aircraft started commercial flights. Their maximum A-weighted sound levels were typically about 20 dB(A) higher than the propeller-type aircraft that they replaced. In early jet engines, the noise was controlled by multiple, corrugated nozzle-based devices which shifted much of the sound energy to higher frequencies, but for each dB of noise reduction with such devices about 1% thrust loss occurred, which is a significant performance penalty. Further research led to the so-called low-bypass jet engines which improved the thrust performance and lowered the full-power jet noise during take-offs, but at the expense of increase in noise during landings. In the 1970s, a move to high-bypass ratio and advances in materials and engine cooling technologies led to significantly quieter aircraft. This led the Federal Aviation Administration in the United States to introduce new lower noise limits, called Stage 3 limits, for type certification of new aircraft. The earlier noisier limits were called Stage 2 limits, and limits for older unregulated aircraft were designated Stage 1 limits. Similar limits were developed by International Civil Aviation Organization and are published in its Annex 16 of November 1985.

Kingsford Smith airport in Sydney began operations in 1919 and over the past 30 years questions about its capacity to meet the needs of the Sydney region have been raised from time to time. The idea to construct a third runway at the Sydney airport was first proposed in the 1960s but was rejected in favour of a second airport in the 1970s. The delays for aircraft landings and take-offs became much worse in the 1980s and eventually in 1989 it was decided that a third runway, parallel to the existing N-S runway, be built. This third runway is now operational at the Sydney airport. The use of the E-W runway was restricted under the previous Government, but this policy was overturned by the present Government and a new policy that utilises all three available runways with an aim to spread and share the aircraft noise burden was adopted.

2. AIRCRAFT NOISE

Aircraft noise can vary depending on the aircraft type, engine type, aircraft weight, loading factor, landing or take-off mode and engine speed, and can exhibit directional patterns. Even a particular type of aircraft can be equipped with different engines or different models of the same engine. The aircraft pilot may have to choose different engine thrust to achieve critical airspeed in the runway length available and because not all aircraft take-off precisely from the same point on the ground, the height attained by an individual aircraft (and thus noise level) at a given location can vary. The propagation of sound waves from the aircraft to an observer on the ground can be affected by meteorological factors such as temperature, humidity, wind velocity and turbulence. Atmospheric turbulence should not affect the long-term average aircraft noise levels received at a given site but will cause fluctuations at shorter time scales due to scattering of sound waves especially at low frequencies.

Aircraft noise differs from road traffic noise in that the difference in noise levels between the frontyard and backyard can be as much as 20 dB(A) for traffic noise but for aircraft noise, little difference exists [2]. In jet engines the turbulent jets act as aerodynamic quadrupoles with radiated sound power that varies as the 8th power of the jet velocity. In propeller-type aircraft the propeller itself is the most important source of noise and, for a given thrust, the noise is a function of blade tip speed and consists of peaks at the fundamental blade pass frequency and its harmonics. These days propeller aircraft form a small proportion of the commercial fleet and generally aircraft with a capacity of more than 100 passengers have jet engines.

Many single number noise descriptors have emerged over the years for describing aircraft noise, usually they are related to the maximum A-weighted sound pressure level, L_{Amax}. The advantage of using L_{Amax} is that it is easily measured and understood, but it does not take into account the duration of the noise event or the rate of occurrence of noise intrusions. Time-integrated descriptors such as sound exposure level, L_{AX}, which integrates the sound energy present during the entire noise event can be used to include the duration factor. To ensure that integration time is sufficiently long for achieving a measurement accuracy of 0.1 dB, one has to integrate down to 20 dB below the maximum value during which signal-to-noise ratio problems might be encountered. To estimate L_{AX} from L_{Amax} for aircraft noise, the following approximate relation [3] that incorporates a duration correction can be used:

$$L_{\mathrm{AX}} = L_{\mathrm{Amax}} + 10 \log_{10} (t/2)$$

where t is the time in seconds between the 10 dB downpoints from the peak level.

The day-night sound level, L_{dn}, is used in the United States and is basically L_{Aeq} but includes a 10 dB penalty for noise levels that occur at night between 10.00 p.m. and 7.00 a.m. If no noisy operations occur during the night penalty hours, the L_{dn} becomes $L_{\mathrm{Aeq,24h.}}$. For commercial aircraft, the L_{dn} and L_{Amax} are approximately related by:

$$L_{\mathrm{Amax}} = L_{\mathrm{dn}} + 20$$

For aircraft noise certification, a complexly derived number called effective perceived noise level, L_{EPN}, is used that expresses the noise annoyance caused by a single aircraft flyover at a given location. The L_{EPN} is determined by weighting the 24 one-third octave band levels between 50 Hz and 10,000 Hz in accordance with equal noisiness contours and then summing their values using a prescribed procedure which has allowance for tones as well as duration. The L_{Amax} values are lower than L_{EPN} values but the precise difference between the two will depend on the spectrum involved. Although L_{EPN} is a good measure of aircraft noisiness and is used for the certification of new aircraft, it is seldom used for setting noise level limits or noise level restrictions because of its complexity.

The loudness, described by the A-weighted sound pressure level, is not an adequate or sufficient attribute for subjective annoyance. The loudness does not include the duration, and the longer the duration, the more unacceptable and annoying the noise is likely to be. Furthermore, noise-induced annoyance includes both acoustic and non-acoustic factors. Loudness increases monotonically with levels but annoyance is not directly proportional to the absolute level of the noise, as can be gauged by the annoyance from a dripping tap. Non-acoustic factors include: adaptation, personality characteristics, predicability of noise, involvement with or economic dependence on the operation of noise source, apparent necessity of noise intrusions and socio-economic levels of individuals. Presence at home during the day and/or during the weekend also affects annoyance and persons always at home are likely to be more annoyed by noise intrusion into the house. If non-acoustic factors control the annoyance response, the degree of annoyance may not change in direct proportion to the reduction in noise exposure. As the noise is reduced to sufficiently low value, the annoyance curve becomes asymptotic, suggesting that a small percentage of people are very sensitive to noises and find them annoying even at low levels. Annoyance can, therefore, be only described in a statistical sense and a number of indices for predicting noise annoyance have been proposed, these are often based on regression analysis of data sets generated from community surveys. The correlation between noise exposure and annoyance in individuals is, however, generally low and correlation coefficients of about 0.4–0.5 are common.

Fidell et al. [4] carried out a review of a larger number of social surveys on noise annoyance and updated the earlier work of Schultz [5] on community annoyance from transportation noise. Their data and the least-square quadratic fit is shown in Figure 2 to illustrate the large scatter that is observed in such surveys. The best-fit equation expressing the percentage highly annoyed (% HA) as a function of L_{dn} is given by:

$$\% \text{ HA} = 0.0360\, L_{dn} - 3.2645\, L_{dn} + 78.9181$$

It should be mentioned that the equation is for general transportation noise and not for aircraft noise only. It is possible that by excluding data from other transportation noise sources, a different best-fit curve could result.

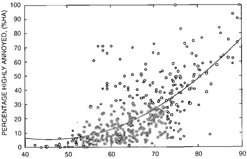
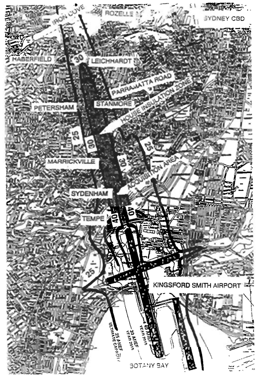


Figure 2. Relationship between percentage highly annoyed and L_{dn} based on community surveys on transportation noise (after [4]).

3. AIRCRAFT NOISE AND BUILDINGS

Aircraft noise as heard on the ground is transient and intermittent, with levels that first rise, reach a maximum and then fall. Field measurements near the Sydney airport indicate that typical aircraft noise reduction (ANR) for the bedrooms of houses with open windows is about 10–15 dB(A). For intermittent noise, interference with low-level conversation is not likely to become noticeable if the noise level at the listener's ear is less than 50 dB(A) [6]. The guidelines in the Australian Standard 2021–1994 [7] for the construction of houses exposed to aircraft noise suggest that design indoor sound levels for sleeping and relaxing areas be taken as 50 dB(A) for the purpose of determining the level of ANR required. Thus, internal sound levels for houses with open windows are likely to exceed recommended values if they are exposed to aircraft noise levels in excess of 65 dB(A). Because aircraft noise levels in excess of 65 dB(A) are common, it follows that lifestyle or building designs that call for open-window living cannot offer a satisfactory acoustic environment for locations near the airport.



For land use planning purposes and to define noise impact zone boundaries, it is convenient to draw contours using the ANEF concept described in AS 2021–1994. The ANEF contours around the Sydney airport adopted by the Federal Government for the aircraft noise insulation project are plotted in Figure 3. A number of assumptions on the future mix (number and type) of aircraft, flight paths, number of night-time operations and sound propagation conditions have to be made to arrive at the ANEF contours, and their accuracy will obviously depend on the accuracy of the underlying assumptions. According to AS 2021–1994 recommendations, land situated in the zone greater than ANEF 25 is not considered suitable for new residential development, but in the case of Sydney airport, it is estimated that approximately 4200 dwellings are situated in the ANEF 30–40 zone and about 16,000 are situated in the ANEF 25–40 zone. There were approximately 150 houses in the ANEF 40+ zone, but the government has offered to purchase these houses from the owners.

To determine the aircraft noise exposure of a given site, AS 2021–1994 states that one must use the long-term arithmetically averaged maximum aircraft noise levels provided in tabular form in the Standard. The use of field measurements, unless carried out over sufficiently long time to obtain an accurate long-term average, risks the possibility that short-term measurements may not be indicative of the long-term average, as noise levels from individual aircraft can vary due to several factors as discussed earlier in Section 2.

When using AS 2021–1994, one finds instances where improvements to the standard could be made and these include:

- The standard does not provide any information on the typical accuracy that could be expected from the tabulated noise levels for different aircraft types. Aircraft noise prediction models typically yield values that can vary by about 3 dB(A) from the measured values.
- The indoor design sound levels in Table 3.3 for houses and flats are divided into two categories only and there has been confusion/conflict in the interpretation or intentions of the standard as far as various internal spaces of a house are concerned.
- The method in the standard is based on calculations that have to be carried out on a room-by-room basis. During the aircraft noise insulation project, it was found that many householders prefer a perimeter insulation approach, and alternative guidelines for achieving recommended internal levels by building an effective acoustically shielded perimeter would be useful.
- For the Boeing 747 aircraft type, which is the noisiest aircraft type (excluding aircraft that are to be phased out), the tabulated data is for series 200 only. It would be desirable if the standard mentioned whether these levels also apply to other commonly used series such as series 300 and series 400, otherwise separate tables for these series are needed. Furthermore, as the noise levels received at a point on the ground, especially during take-off, can be affected by the loading factor, it would be useful if the standard stated whether the levels are based on light, moderate or fully loading condition or are the long-term average over all loading conditions.
- The standard provides numbers for the mean value only and does not provide any indications of the shape of the distribution curve around the mean. By evaluating a large number of measured data at distances up to 12 km, Meyer [8] of Germany was able to determine a statistical distribution function that yielded the rate of occurrence of certain maximum levels expected from a large number of aircraft passing over a given point. The distribution function was calculated by Meyer around the logarithmically averaged values, which can be slightly different from the arithmatically averaged values recommended and tabulated for use in AS 2021–1994. The distribution function is as follows:

If x is the difference between the individual value L_{Amax} and the logarithmically averaged value $\overline{L}_{\mathrm{Amax}}$, then the number n of aircraft exceeding a maximum noise level $L_{\mathrm{Amax}} = \overline{L}_{\mathrm{Amax}} + x$ out of N aircraft of the same type, assuming that the maximum levels that are 10 dB(A) above and are more than 6 dB(A) below that mean value $\overline{L}_{\mathrm{Amax}}$ do not occur, is given by:

for $-6 \leq x \leq -0.5$

$$\frac{n}{N} = 0.404408 - 0.28747x - 0.21019x^2 - 0.083947x^3 - 0.015333x^4 - 0.0010509x^5$$

and for $-0.5 \leq x \leq 10$

$$\frac{n}{N} = 1.005 - \frac{1}{\sqrt{2p}} \int_{-\infty}^{x} e^{-u^2/2} \, du$$

where $u = (x + 0.5)/3$.

It can be shown from the integral that the exceedance percentage for +3 dB(A) is 12.6%, for +4 dB(A) is 7.2% and for +5 dB(A) is 3.9%.

Caution is needed when using this distribution function as a universal function because the exact nature of the distribution around a specific airport may be dependent on the flight path patterns and other site-specific factors, but it does indicate that about 4% of the flyovers can generate levels that are 5 dB(A) above the logarithmically averaged value.

4. EXISTING AIRCRAFT NOISE REDUCTION (ANR) OF HOUSES

The results of the measurements of ANR provided by 20 houses situated in Sydenham near the Sydney airport are shown in Table 1. A typical house in Sydenham is of single-storey brick construction of about 100 m² floor area with a pitched tile roof in the front and a skillion metal-clad roof at the rear. The houses were occupied and furnished with normal furnishings at the time of measurements, and measurements were made with windows and doors closed. The external aircraft noise levels were measured by a Bruel and Kjaer outdoor microphone unit type 4184 connected to a Bruel and Kjaer real-time frequency analyser type 2143. The internal noise levels were measured at three locations (main bedroom, living room and kitchen) using Bruel and Kjaer's sound level analysers type 2260 and a precision integrating sound level meter type 2230 connected to Bruel and Kjaer sound level recorders type 2317. A-weighted sound pressure levels using 'S' time-weighting characteristic were measured at a microphone height of 1.2 m. The difference between the external and internal maximum A-weighted sound pressure levels during an aircraft flyover, averaged for typically about ten aircraft flyovers, was taken as the ANR of the area monitored.

TABLE 1

Typical ANR for houses near Sydney airport

S.N.	Main bedroom	Living room	Kitchen/dining
1	32	25	25
2	35	24	21
3	28	31	27
4	25	28	28
5	30	30	24
6	27	28	23
7	27	25	20
8	31	25	21
9	34	24	16
10	28	29	23
11	31	28	20
12	29	27	18
13	26	29	29
14	35	31	28
15	36	28	22
16	23	31	29
17	24	22	14
18	32	32	32
19	33	23	23
20	30	30	36

It can be seen from Table 1 that the ANR for bedrooms with windows closed is substantially higher than typical ANR with windows open, suggesting that one thing the occupants can do themselves to reduce the aircraft noise impact is to close the windows and doors, if practicable and convenient.

The individual ANR values for the main bedroom of the 20 houses range from 23 dB(A) to 36 dB(A); for unfurnished rooms the expected ANR would be somewhat lower than these values because of the absence of sound absorption. Kitchen/dining areas tend to have acoustically hard surfaces and generally also have openings for the removal of odours and fumes, and thus their ANR is frequently lower than the bedrooms.

5. ACOUSTIC INSULATION TREATMENTS

When a new house is to be built in an area affected by aircraft noise, usually there is a greater degree of flexibility in the choice of materials and design, but for existing dwellings the choice may be limited because of the construction materials and design features that already exist. There are four competing issues that require consideration when acoustic upgrading measures for existing houses to improve their sound insulation characteristics are being planned. These are:

- Acoustic issues – from an acoustic viewpoint, the upgrading work should start at the acoustically weakest component or element and then progress towards the next weakest link and so on. The relative areas of the building elements and the balanced construction concept (i.e. elements transmit equal amount of sound energy) should be kept in mind at all times.
- Cost issues – not only the cost in absolute terms but also the additional cost versus incremental benefit can be an important issue, especially if a large-scale sound insulation project is being considered.
- Practicability issues – this covers issues such as the need to minimise any impact on the functional use of the internal space and requirements for major structural alterations.
- Acceptability to occupants and local councils – proposed acoustic upgrading measures that are not aesthetically pleasing or are cumbersome to use are likely to be unacceptable to the occupants. Local Councils may not approve of changes that affect the heritage value, streetscape, or general appearance of a house, and will certainly not approve alterations that do not comply with relevant building codes and regulations.

The weakest links in a house are the gaps, openings and vents exposed to outside. These have to be identified and appropriately closed. The external doors (both front and back) should at least be upgraded to solid-core with perimeter seals and, in high noise exposure situations, one may have to use sound-rated doors. Existing fireplaces can be made airtight and, if not used, can be sealed. The need for timber floors to breathe means that in such houses the subfloor area cannot be sealed, however, adequate amounts of subfloor ventilation can be provided with noise-attenuated vents built using the lined-duct principles.

The next weakest links in a house are likely to be windows. In many houses near the Sydney airport, the existing windows are double-hung with no seals and generally cannot be replaced because of issues mentioned earlier. One can improve their acoustic performance slightly by adding seals. For extra cost, one can increase existing glass thickness from 3 mm to 5 mm (existing frames usually can't take higher thickness). New secondary windows are still necessary and can be installed behind existing windows without affecting street appearance. For domestic-type windows, the practical limits for glass thickness are 6–10 mm for float glass or approximate equivalent if laminated glass is used. The acoustic benefit of secondary glazing will depend not only on the glass thickness but also on the airspace between the panes. The minimum airspace recommended for acoustic applications is generally 100 mm and often the minimum airspace has to be adopted during sound insulation upgrading work because of small room size of houses near the Sydney airport and the need to minimise intrusion into the room as well as for aesthetic reasons. Doubling the airspace typically increases the STC by 3 and it can also improve the low frequency performance, as can be seen from laboratory STL measurements carried out at the CSIRO-DBCE North Ryde laboratory on 7 mm laminated glazing (3/1/3 mm) and 5 mm glazing at different airspaces (Figure 4). Further small increases in sound insulation can be achieved by adding sound-absorption in the window reveals. It should be mentioned that the overall noise reduction provided by a window system is governed by the window type and size, window seals, window frame, method used for glass mounting and of course installation details.

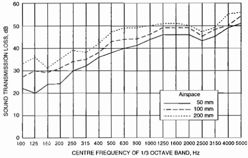


Figure 4. Sound transmission loss of 7 mm (laminated) and 5 mm double-glazing.

The typical STC range for a pitched roof/ceiling construction or metal-based roof/ceiling system is 33–35. By adding fibrous thermal insulation material such as batts or blanket, the sound insulation of the roof/ceiling construction can be improved, but further increases are necessary to reduce aircraft noise impact. One upgrading method is to add an additional layer or layers of plasterboard or rigid timber board on top of the ceiling joists after installing sound-absorptive material in the cavity between the joists. This method imposes significant practical difficulties and cost penalty and can involve structural upgrading. An alternative method in which one or two layers of loaded vinyl material (such as Wavebar or Acoustiflex) of mass/area in the range 4–8 kg/m^2 are installed on top of the ceiling joists by overlapping sheets and taping, has been used for houses near the Sydney airport. Additional mass/area of about 12 kg/m^2 can be easily added to the existing roof/ceiling of houses, but some structural strengthening may be necessary if higher values are used.

Ideally one would like to compare the STL versus frequency curve for complete roof/ceiling systems as modified by additional plasterboard and as modified by additional loaded vinyl, but in the absence of such data, one may make an approximate comparison by examining the STC for a layer of 10 mm plasterboard and a layer of 4 kg/m^2 loaded vinyl, keeping in mind the limitations of single-number STC ratings. Typically a layer of 10 mm plasterboard yields an STC of about 26–27 and, according to manufacturers' data sheets, the STCs of 4 kg/m^2 Wavebar and Acoustiflex are 26 and 25 respectively. Measurements made at the RMIT laboratory in Melbourne on 4 kg/m^2 Wavebar by installing the material in a steel frame comprising 64 mm steel studs at 600 mm centres, however, yielded an STC rating of 23. Changing the plasterboard thickness to 13 mm or changing the mass/area of loaded vinyl to 6 kg/m^2 is likely to add about 2 or 3 to the STC ratings.

For brick houses, considering the level of sound insulation of windows and roof/ceilings, after the upgrading treatment described above, the walls can be left untreated. On the other hand, walls of lightweight construction will require upgrading if they are not to become the weak link. Measures that can be undertaken for upgrading such walls include conversion to brick-veneer or improvements made by adding cavity absorption and additional mass in the form of layers of plasterboard or loaded vinyl. If sufficient internal space is available, the layers can be added internally by fixing timber battens to existing lining. Exposed timber floors can be upgraded by constructing a brick perimeter enclosure with sufficient vents (noise attenuated, if necessary) to allow the floor to breathe.

For the aircraft noise insulation project, the owners have been given some flexibility and choice in deciding on the acoustic treatments adopted for their houses. For example, an owner may prefer sliding windows instead of casement windows or may choose to leave a particular area untreated. As a result, the actual ANR achieved may be slightly less than the optimum possible value.

Finally, it should be mentioned that after the acoustic insulation work has been carried out on a house, some form of mechanical ventilation will become necessary for the well-being of occupants. Such systems have been installed in all houses that have been sound insulated near the Sydney airport. When offered a choice between reverse-cycle air-conditioning and other forms of mechanical ventilation system, the owners showed a clear preference for air-conditioning. Proper design and careful installation of such systems is necessary to prevent them becoming a source of unnecessary noise nuisance.

6. COST OF INSULATION TREATMENT

For an initial group of about 200 houses acoustically insulated in the Sydenham area, the typical acoustic upgrade costs have averaged almost $37,000 per house. Of this amount, provision of reverse-cycle air-conditioning averages about $9000–10,000. These relatively high air-conditioning costs reflect standards above those common in domestic installations. In particular, the units have been customised for the project to be concealed in the roof space wherever possible and to shut down in the event of smoke detection; they are designed to deliver adequate fresh air necessary due to the sealed nature of an acoustically insulated house; they are built to be highly economical in operation; and they comply with property boundary noise constraints. Typical costs for the treatment of building elements are about $3000–4000 for closing gaps, vents and installing or replacing doors/door seals, about $1300 per window for the sealing of existing window and the installation of secondary window, and about $90–105 per m^2 for installing a layer of sound absorptive material plus two layers of 6 kg/m^2 loaded vinyl in the roof/ceiling space.

7. IMPROVEMENT AFTER TREATMENT

Measurements made on brick houses after the acoustic upgrading treatment work described above, suggest that typically it is possible to achieve an ANR of about 40 dB(A) in the bedrooms. The actual ANR achieved will vary from house to house depending on several factors, including the amount of absorption present in the room concerned. The improvement in ANR for a particular house will depend on the initial ANR before acoustic treatment and for houses with relatively high initial ANR, the additional improvement expected should be smaller. The before and after ANR measurement results for the main bedroom of ten occupied houses which were monitored after acoustic treatment by commercial builders without specialist knowledge of acoustics are shown in Table 2. For house S.N. 10 in Tables 1 and 2, the main bedroom before treatment refers to bedroom 2, as the front main bedroom (bedroom 1) was being used as a home office, but the after-treatment ANR was measured in bedroom 1.

TABLE 2
The ANR of main bedrooms of houses before and after acoustic treatment

S.N.	ANR of main bedroom, dB(A)	
	Before treatment	After treatment
1	32	41
2	35	39
3	28	36
4	30	42
5	33	40
6	32	46
7	35	39
8	36	44
9	27	43
10	28	40

The final ANR of areas other than bedrooms will depend on the extent of the acoustic upgrading work undertaken for these rooms or spaces. If some areas are not treated, the possibility of sound entry via these areas to the treated areas should not be overlooked and should be prevented as much as practicable.

In timber houses, unless the external walls are upgraded to a masonry-type construction, such as by conversion to brick-veneer, an ANR as high as 40 should not be expected. However, the ANR of timber houses before acoustic upgrading treatment can be about the same as for brick houses because the overall sound insulation is generally controlled by the gaps, openings, windows and doors rather than the walls of the house.

8. CONCLUSION

There are several thousand houses near Sydney's Kingsford Smith airport that are located in ANEF zones not considered suitable for new residential construction if the criterion of the Australian Standard 2021–1994 is used. The majority of residents of these houses are likely to be highly annoyed by noise because of the exposure to high levels of aircraft noise. The aircraft noise reduction (ANR) provided for occupied houses near Sydney airport has been measured both before and after undertaking acoustic upgrading measures and the results indicate that, for brick houses, typically an ANR of about 40 can be achieved for bedrooms by carrying out the measures described in this paper. Some form of mechanical ventilation system is necessary after the acoustic upgrading work has been done, and the house owners have clearly preferred air-conditioning systems rather than other types of mechanical ventilation. Typical costs in 1996 dollars for carrying out the acoustic insulation work for the houses by licensed commercial builders are given in Section 6.

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