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Review of International Research on Community Reaction to Aircraft Noise: Report 1: Overview of Aircraft Noise Metrics

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This research report was commissioned by Sydney Airport Community Forum *(SACF).* Hence, the views expressed in the report are those of the author and may not represent the opinions of SACF. This is Report 1 of an anticipated five reports in a comprehensive International Review of Aircraft Noise. The full list of proposed reports is:

- **Report No.1: Aircraft Noise Metrics (i.e., current report);**
- Report No.2: Socio-Acoustic Research in the U.K. (c.f., report completed);
- Report No.3: Socio-Acoustic Research in the EU and Canada (report to be commissioned);
- Report No 4: Socio-Acoustic Research in the U.S. (addressing U.S. report on new study due in 2018; report to be commissioned);
- Report No.5: Implications for Australia of Recent International Research (report to be commissioned).

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Sydney Airport Community Forum

Dr Andrew Hede
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Dear Dr Hede

The Sydney Airport Community Forum (SACF) met on 1 September 2017 and discussed your letter of 18 August 2017 regarding recent research on aircraft noise.

You indicated in your letter you would be willing to undertake a review of international noise studies. SACF seeks your advice on the scope and cost of the services in your letter. Whilst we are seeking this information from you, it should be noted there is currently no Government funding available for noise studies at this time, however SACF may be willing to lobby the Minister for Infrastructure and Transport about this work.

Should you be in a position to assist SACF by providing this information, I would be grateful for your reply by 15 November 2017. This would allow sufficient time for SACF members to review your advice prior to the next meeting which is scheduled for 24 November 2017.

Yours sincerely

John Alexander OAM MP
Chair
3 November 2017

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Review of International Research on Community Reaction to Aircraft Noise: Report 1: Overview of Aircraft Noise Metrics

Andrew J Hede

Executive Summary

The Australian Noise Exposure Forecast (ANEF) is one of only six metrics used internationally to assess aircraft noise including Australia's four 'comparator' countries, U.K., U.S., Canada and the EU. These metrics all share the key characteristic of being based on the *'equal energy'* principle in that they all calculate aircraft noise exposure around airports by summating the total noise energy from all overflights during a specified period. The current report presents the first full comparative analysis of the world's primary aircraft noise metrics. If Australia were to adopt an alternative to ANEF as its primary aircraft noise metric then it would have to choose from the five other metrics available internationally, all of which share its essential features.

Contrary to common belief, Australia's ANEF metric is fully comparable with the world's other primary metrics differing only in the specific weightings used to take account of varying community response at different times of day. Over the past 40 years, socio-acoustic studies worldwide have consistently shown that 'equal energy' metrics such as ANEF, are more accurate at predicting community reaction to aircraft noise than all other metrics including so-called 'supplemental' metrics based on factors such as the number of noisy overflights.

Although the primary aircraft noise metrics (such as Australia's ANEF, America's *DNL* and the EU's *Lden*) are as accurate as the world has got, they are all very complex measures for reasons of both noise physics and human psychology. This combination gives rise to a paradox in human noise reaction which is not fully understood by researchers anywhere. Many members of the community find these primary metrics more confusing than supplemental indices such as N70 (viz., the number of overflights exceeding 70dBA) which relate more directly to their own subjective experience (i.e., *'how many noisy ones today?'*). An obvious solution that is being increasingly adopted in leading countries relevant to Australia is to package aircraft noise impact statements and related documents with exposure information based on both a primary metric (such as ANEF, DNL, LAeq, etc.) together with one or more supplemental metrics (such as N70).

It is not clear how best to design aircraft noise information which is both engaging and explanatory for residents. For example, consider the case of Australia's standard on aircraft noise which states that a 20 ANEF exposure level is 'acceptable' for siting residential buildings thereby implying that residents should not be *'annoyed/affected'* by noise below that level. Both the community and public officials in Australia seem to be unaware that at the supposedly 'acceptable' exposure level of 20 ANEF, the only authoritative and internationally accepted national survey of aircraft noise in Australia (Hede & Bullen, 1982) indicates that a large proportion of the population find such exposure 'unacceptable', specifically, that 11% are 'seriously affected' by the noise and 22% are 'moderately affected'.

It is important to note that, from recent international research, the indications are that community response levels have most likely increased over the almost four decades since the previous national survey of aircraft noise in Australia. The question of whether it is time for an update of that study will be addressed in the proposed fifth and final report in this international review.

1. International Overview of Aircraft Noise Metrics

1.1 Background

The Chair of Sydney Airport Community Forum (SACF), John Alexander OAM MP, invited the researcher to provide advice:

> ***"on the status of any international studies recently completed or currently underway which may provide new evidence on the continued effectiveness of the 1982 National Acoustic Laboratories (NAL) study and the Australian Noise Exposure Forecast (ANEF) system."*** (c.f., SACF Letter dated 2nd August, 2017).

In response, the researcher recommended focusing on studies published since 2000 from four countries, namely, U.K., U.S., Canada and the EU. These countries can be considered appropriate *'comparators'* for Australia as they share many of our cultural and socio-political characteristics. In particular, Australia has long looked to the U.S. and the U.K. for guidance on a range of constitutional and public policy matters (hence the 'cheeky' term *'Washminster'*). Further, it was decided to divide the current review into separate reports starting with the present overview of aircraft noise metrics (see Report No.1, Hede, 2018a) together with a report on socio-acoustic research in the U.K. (see Report No.2, Hede, 2018b) followed by reports on the other comparator countries as appropriate.

1.2 Primary Aircraft Noise Metrics

An aircraft noise metric can be defined as: ***an overall computation of all the physical noise characteristics of all the aircraft overflights and ground operations around an airport, designed to provide an accurate total noise measure which can be used to predict its impact on residential communities.*** It is notable that Airports Council International (ACI) which represents the operators of 1800 major airports in 170 countries lists only five metrics as the primary measures of aircraft noise exposure for land-use purposes worldwide, namely: LAeq, DNL*[Ldn]*, Lden, NEF and ANEF (see ACI, 2015). Significantly, these are the five metrics used in Australia plus the four comparator countries under consideration in the present review. These five primary metrics are:

1. **ANEF (Australian Noise Exposure Forecast) – Australia**
2. **NEF (Noise Exposure Forecast) – Canada**
3. **DNL *[Ldn]* (Day-Night Average Sound Level) – U.S.**
4. **Lden (Day-Evening-Night Sound Level) – EU**
5. **LAeq (Equivalent Continuous Sound Level) – U.K.**

In terms of the provenance of the various aircraft noise metrics, it is relevant that the world's five leading measures were acknowledged by the International Civil Aviation Organization 30 years ago in a published table headed *"Noise indices in use in ICAO contracting states"* (see ICAO, 1988, p20). The ICAO list contained the present five metrics including Australia's ANEF, the latter having been first developed only six years previously (see Bullen & Hede, 1983).

These same five metrics were included in a U.K. university thesis by Burton (2004) which analysed the main aircraft noise metrics in use worldwide and also covered those then used by the various European countries (Burton, 2004, pp35-45; note that all EU countries have now adopted the Lden metric – see *EP, 2002*). Burton's comprehensive study gave specific attention to the ANEF metric with an important conclusion expressed as follows:

> *"…the Australian ANEF system, coupled with the corresponding criteria in that country, appears to be the **most stringent**, with the systems and criteria in the USA being the least strict".* (Burton, 2004, p76, *emphasis added*).

The key feature of the above five primary metrics is that they are all *'equal-energy'* measures of the amount of aircraft noise affecting communities, a fact apparently misunderstood by many of the critics of ANEF in Australia (e.g., Cooper, 2010; Senate Select Committee, 1995). To elaborate, these metrics which are based on extensive research over many years in the various leading countries, all calculate aircraft noise exposure by summating the total noise energy from all aircraft operations during a specified period (typically a day or part thereof).

However, these 'equal-energy' metrics differ from each other in the specific penalty-weightings which are applied to evening and night-time overflights in order to take account of the heightened effect on residents of noise during these sensitive hours (covering, specifically, domestic activities in the evening and sleeping at night).

A summary of these five primary aircraft noise metrics including their descriptions, defining formulae, time-of-day penalty weightings and countries of application, is provided in the following tables (see Tables 1a – 1d).

Table 1a: Summary of Primary Aircraft Noise Metrics – NEF and ANEF

Metric Name	Description & Formula	Time-of-Day Penalties	Countries
NEF Noise Exposure Forecast	Long-term average of the total sound energy from all aircraft overflights with a penalty-weighting for those at night. ***NEF = EPNL + 10log*** $_{10}$ ***(*** N_D ***+ 16.7*** N_N ***) - 88 (dB)*** *(Ref: ICAO, 1988, Appendix A)* NB. Each overflight is measured in terms of EPNL which takes account of negative human reaction to audible tones and noise duration.	12.2dB Night *(* N_{Night} *)* (2200-0700 hours); (i.e., all overflights during night-time hours are assigned a penalty-weighting of 12.2dB). NB. NEF metric was initially developed and adopted by the US before the advent of DNL – see Table 1b below.	• Canada • Hong Kong (NEF = Lden - 23.3; *Ref: Mikroudis & Vogiatzis, 2016);* NEF = DNL - 35 (*Ref: Cointin, FAA, 2015).*
ANEF Australian Noise Exposure Forecast	Equivalent to NEF but with Australian research-based weighting penalties for both evening and night-time overflights. ***ANEF = EPNL + 10log*** $_{10}$ ***(*** N_D ***+ 4*** N_E ***+ 4*** N_N ***) - 88 (dB)*** *(Ref: Bullen & Hede, 1983)* NB. Legislative basis for ANEF in Australia: *Airports Act 1996* (Cth)	*See formula in previous column:* 6dB Evening *(* $N_{Evening}$ *)* (1900-2200 hours); 6dB Night *(* N_{Night} *)* (2200-0700 hours); 0dB Day *(* N_{Day} *)* (0700-1900 hours); (i.e., a penalty-weighting of 6dB is applied to all overflights between 1900 and 0700).	• Australia NB. The ANEF metric was introduced in 1982 on the basis of the Australian 'five-airport' survey by NAL in 1980.

Table 1b: Summary of Primary Aircraft Noise Metrics – DNL *(Ldn)*

Metric Name	Description & Formula	Time-of-Day Penalties	Countries
DNL *(Ldn)* Day-Night Average Sound Level ▪ **DNL** is the official name of the metric; ▪ **Ldn** is the equivalent mathematical term	Energy-averaged sound level over a 24-hour period (with a penalty-weighting for night-time overflights). $DNL = 10\log \frac{1}{24}\ \{15\,(10^{\frac{Ld}{10}}) + 9\,(10^{\frac{Ln+10}{10}})\}$ *(Ref: EPA [U.S.], 1974)* NB. Each overflight is measured in terms of SEL which is the sound level over 1sec equivalent in energy to the whole noise event.	*See formula in previous column:* 10dB Night *(Ln)* (2200-0700 hours); (i.e., a penalty-weighting of 10dB is applied to overflights in night-time hours). (For comparison of DNL and Lden, see Miedema & Oudshoorn, 2001).	• United States • Brazil

Table 1c: Summary of Primary Aircraft Noise Metrics – CNEL and Lden

Metric Name	Description & Formula	Time-of-Day Penalties	Countries
CNEL Community Noise Equivalent Level	Metric identical to DNL (see previous) but with the addition of an evening penalty-weighting.	5dB Evening *($L_{evening}$)* (1900-2200); 10dB Night *(L_{night})* (2200-0700 hours).	• California (USA)
Lden Day-Evening-Night Sound Level	Energy average sound level for a 24-hour period with both a night and an evening weighting. ***Lden = 10log 1/24 {12**** $10^{\frac{Lday}{10}}$ **+ 4*** $10^{\frac{Levening+5}{10}}$ **+ 8*** $10^{\frac{Lnight+10}{10}}$ **}** *(Ref: EP, 2002)* NB. Metric identical to CNEL except for variation in defined hours (viz., 2300 vs 2200 for evening-to-night).	*See formula in previous column:* 5dB Evening *($L_{evening}$)* (1900-2300); 10dB Night *(L_{night})* (2300-0700 hours); 0dB Day *(L_{day})* (0700-2300 hours).	• European Union • Japan • Vietnam

Table 1d: Summary of Primary Aircraft Noise Metrics – LAeq

Metric Name	Description & Formula	Time-of-Day Penalties	Country
LAeq,16hr Equivalent Continuous Sound Level	Energy-average sound level equivalent to a continuous noise emission (SEL over 1 sec) during a specified time period (viz., Day = 16hrs). Level is A-weighted to match human hearing across sound frequency range. ***LAeq,16hr = (SEL)avg + 10 x log10*** ***N_{16hr} – 47.604*** *(Ref: Critchley & Ollerhead, 1990)*	No time penalties but separate levels are calculated for day- and night-hours: N_{Day} 0700-2300; N_{Night} 2300-0700 hours. NB. Metric is based on measurements over 16 hours (0700-2300) during summer months (viz., mid-June – mid-Sept).	• United Kingdom NB. The U.K. replaced NNI (Noise and Number Index) with LAeq,16hr in 1985.

Table 1e: Summary of Primary Aircraft Noise Metrics – WECPNL

Metric Name	Description & Formula	Time-of-Day Penalties	Countries
WECPNL Weighted Equivalent Continuous Perceived Noise Level	Energy average of the maximum A-weighted levels from overflights at different times of day and night. ***WECPNL = L_A + $10log_{10}$ {N_2 + $3N_3$ + $10(N_1 + N_4)$}*** *(Ref: ICAO, 1971)*	*See formula in previous column:* 0dB Day (N_2) 0700-1900; 3dB Evening (N_3) 1900-2200; 10dB Late night (N_4) 2200-2400; 10dB Night (N_1) 0000-0700. NB. WECPNL ≈ Ldn + 13dB (Guoqing *et al.,* 2012).	• Korea • China • Nigeria

In addition, details are also provided of a sixth aircraft noise metric, namely, WECPNL (Weighted Equivalent Continuous Perceived Noise Level – see Table 1e above), which is the only other primary aircraft noise metric used in any major country besides the five already presented. Note that the WECPNL metric which is currently used in several major countries (viz., Korea, China and Nigeria; see Table 1e) can be converted directly from the U.S. metric DNL (i.e., WECPNL ≈ DNL + 13dB; Guoqing *et al.,* 2012) or from the EU Lden metric (i.e., Lden = 0.7683 WECPNL + 2.2993; Kim *et al.,* 2010). Note that WECPNL is also an *'equal-energy'* metric fully comparable to the five primary metrics used in other leading countries as reviewed above (see Tables 1a – 1d).

In all of the above primary aircraft noise metrics, the formulae were derived from socio-acoustic studies involving social surveys of community reaction around one or more airports plus either direct field measurements and/or statistically modelled estimates of aircraft noise exposure at each residence surveyed (e.g., AEDT – see FAA, 2015; INM – FAA, 2007). In the numerous socio-acoustic studies conducted worldwide over several decades since the 1980 NAL study in Australia (Hede & Bullen, 1982), 'equal-energy' metrics have been found to provide the best statistical predictor of community reaction to aircraft noise in the relevant country. The main socio-acoustic studies reported recently are reviewed in the country-specific sections of this report series commencing with the U.K. (see *Hede, 2018b – Report No.2: Socio-Acoustic Research in the U.K.).*

In considering the application of the world's six primary metrics (see Tables 1a – 1e), we need to appreciate that aircraft noise ***exposure*** correctly refers to the *amount* and *extent* of physical noise energy from aircraft operations around an airport (see Burn, Stusnick & Ehrlich, 1995; Fidell *et al.,* 2011). Aircraft noise exposure can be appropriately measured by means of various types of index such as the 'equal-energy' index ANEF and the 'number above' index N70. Aircraft noise ***impact***, on the other hand, refers to the *effects* of noise exposure on people (or animals) (Borst & Miedema, 2005; Brink *et al.,* 2010; Kroesen & Schreckenberg, 2011). It is generally agreed that the most critical and widespread impact of aircraft noise is that on residential communities (Fidell *et al.,* 2014). Such impact can be best described in terms of the percentages and numbers of residents annoyed or affected to various degrees by aircraft noise around an airport as determined by dose-response functions (Schomer, 2005).

This report has shown that there are only six primary aircraft noise metrics adopted throughout the developed world, all of which are similarly based on the 'equal-energy' principle but which vary in terms of time-of-day weightings and/or acoustic index (viz., *LAeq,16hr*, DNL*[Ldn]*, Lden, NEF, ANEF & WECPNL – see Tables 1a – 1e above). The various leading countries have conducted their own socio-acoustic studies from which they have developed their own primary metric with its own exposure cut-off for land-use purposes (e.g., 25 ANEF equivalent to 65 DNL) or else they have borrowed from another leading country with or without their own confirmatory research. An exception is the EU which directed all of its member countries to adopt the Lden metric based on international research (European Parliament, 2002). Overall, there appears to be a tendency for countries to adopt their own primary aircraft noise metric and to find empirical justification for continuing to stick with it.

As reviewed in the second report in the present series (see Report No.2, Hede, 2018b), the U.K. originally adopted the NNI metric following research in 1961 but replaced it 20 years later with *LAeq,16hr* which survey research showed to be superior (Brooker *et al.,* 1985). Recent socio-acoustic research has confirmed that this metric (*LAeq,16hr*) is the best predictor of community reaction (Devine-Wright & Turner, 2017). Note that the findings of the FAA's major survey around 20 U.S. airports is expected in late 2018.

1.2.1 'Equal-Energy' Paradox

As we have considered above, the primary aircraft noise metrics that are adopted in leading countries (see Tables 1a – 1e) are all based on the 'equal-energy' principle which gives rise to a paradox about community reaction (see Hede, 2015).

1) Essentially, the ***'equal-energy' paradox*** means that although repeated social surveys around the world over the past five decades have found that residents respond to aircraft and other transportation noise sources mainly on an 'equal-energy' basis (Fidell, 2003; Fidell *et al.,* 2014), anecdotal evidence suggests that they react more directly to the number of noisy overflights (see Senate Select Committee, 1995).

2) Compare, for example, two residential situations around a major airport:
   a) Suburb X is exposed to 100 overflights per day averaging a peak level of 75 dBA per overflight;
   b) Suburb Y has an exposure of 50 overflights with an average maximum of 78 dBA.

   NB. Assume for this example that overflight duration and other relevant factors are equal in the two situations. Therefore, because a doubling in number equals a 3 dBA increase in sound intensity, the aircraft noise energy impacting on the two suburbs is equal (i.e., *'equal-energy').*
3) From well-established research knowledge about psychoacoustics, we can also confidently assert that for residents in both suburbs, the overflights are experienced as 'noisy' but that Suburb Y's 78 dBA events are each perceived as *'just noticeably'* (= 3 dBA) louder than the 75 dBA events in Suburb X.
4) If we asked the average informed resident which aircraft noise exposure pattern they would prefer, the vast majority would opt for the Suburb Y situation (i.e., half as many overflights each *'just noticeably'* louder) (see Senate Select Committee, 1995, pp183,200). However, if you conducted a best-practice scientific social survey, the results would almost certainly confirm the findings of the hundreds of social surveys now on record worldwide that indicate that the two situations would be reported by residents as equivalent (see Fidell *et al.,* 2014; Fidell *et al.,* 2011).
5) The original 1980 NAL study (Hede & Bullen, 1982) specifically addressed this issue of energy versus number in aircraft noise exposure and found that while an 'equal-energy' index (such as ANEF) is the best predictor of resident reaction, it can be improved by incorporating the number of noisy overflights (Bullen & Hede, 1986).
6) Nevertheless, the 'equal-energy' paradox still remains unresolved. It would appear that despite much research over many years, we still need innovative research focussed specifically on: *what is the relative contribution of average noise energy versus number of noisy events in determining how residents in Australia react to aircraft noise?* Unless the Australian Government initiates such research, this paradox will continue to impose a burden on communities exposed to aircraft noise.

Of particular relevance in this context are the comments by one of the experts on the latest U.K. socio-acoustic study conducted in 2014 (called SoNA; see Devine & Turner, 2017). In a recent email to the current researcher, this U.K. expert states as follows:

> *"A specific aim of SoNA was to compare equal energy metrics (LAeq16hr, Lden) against linear ones (e.g. N70). What we discovered, see Appendix B Figure 11, is that N70 tends to zero for LAeq16hr levels of 52-54dB, pretty much our current most contentious communities who felt our 1982 ANIS study 'threshold of significant annoyance' of 57dB ignored them. N70 can be zero for quite moderate LAeq levels, because Lmax levels in the high 60s and high numbers of events will easily give LAeq values of 54"* (Rhodes, 2017) [see further discussion in Report No.2, Hede, 2018b].

1.3 Supplemental Aircraft Noise Metrics

In addition to the above primary metrics, there are a range of aircraft noise metrics commonly described as 'supplemental' or 'supplementary' (including: *'Number Above'* such as N70; *'Time Above'* such as TA65; *'Persons Events Index',* PEI; '*Percentile Level'* such as L50 [Eagan, 2007; Gasco *et al.,* 2017; NoiseQuest, 2018, 2006; Porter *et al.,* 2014; Southgate, 2000]). While international socio-acoustic research, including the original 1980 NAL study in Australia, consistently indicates that such metrics are not as accurate at predicting community reaction as 'equal-energy' metrics, these supplemental metrics have proven consistently effective in communicating to residents their aircraft noise exposure using concepts and terms they can relate to (Eagan, 2007; Southgate, 2011).

As stated in the influential paper by Eagan (2007, p175): *"In recent years, there has been increasing use of supplemental or other non-traditional metrics to describe the impact of aviation noise on people.* ***Implicit in this usage has been an assumption that supplemental metrics are better understood by the community*** (*emphasis added*)*".*
Eagan concludes her analysis of supplemental metrics as follows:

> *"Depiction of supplemental noise metrics using the noise effects of most interest to airport neighbors can provide an opportunity to engage in more informed policy making. Use of intuitively understandable metrics also can enable informed discussions that ultimately could lead to better outcomes for airports, communities, and the air transport system in general."* (Eagan, 2007, p182).

The main supplemental metrics currently used in various countries are as follows:

Number Above - NA. This metric refers to the number of aircraft noise events over a neighbourhood which exceed a specified level (e.g., 70 dBA = N70; 60 dBA = N60) during a specified period (Gasco *et al.,* 2017). According to one expert commentator, *"The N70 level is suggested not as a planning tool but as a guide to indicate the degree of disturbance that may occur as a result of aircraft overflights"* (Cooper, 2010, p4). Most international observers would agree that NA (Number Above) has become the most widely known and adopted supplemental metric worldwide largely due to the promotion of N70 by Southgate (2011, 2007, 2000).

Time Above - TA. This metric refers to the length of time (alternatively, the percentage of time) during which aircraft over a neighbourhood exceed a specified level during a specified period. An example provided by NoiseQuest (2018) is this: *"a TA65(60) calculated over a 24-hour day [which] describes an area within which the noise level exceeds 65 dB for 60 minutes or more in a 24-hour day."* (see also Gasco *et al.,* 2017).

Persons Events Index - PEI. This measures the number of occasions when a person is exposed to an aircraft noise event which exceeds a specified level during a specified time period. According to one published source, *"The PEI is summed over the range between N min (a defined cut-off level) and N max (the highest number of noise events louder than x dB(A) persons are exposed to during the period of interest). It is effectively calculated by summing at each cell, the number of events above Lmax of say 65 dB multiplied by the population within the cell. The minimum cut off value is say 50 events. The PEI is therefore expressed as PEI (65,50).*" (Porter *et al.,* 2014, p5; see also: Southgate, 2000).

Percentile Levels - L90, L50. This less-adopted metric refers to the aircraft noise level which is exceeded for N% of a specified time period (viz., 90%, 50%) (Gasco *et al.,* 2017).

The U.S. university research centre, NoiseQuest, observed some years ago that supplemental metrics are being used *"to look inside DNL by calculating the number of minutes the maximum sound level exceeds specified thresholds in the average annual day Above, or TA) and the number of times within the selected time period that noise levels exceed a specific threshold (Number of events Above, or NA."* (NoiseQuest, 2006, p1).

On this view, primary aircraft noise metrics such as DNL (and others based on equal-energy – see Tables 1a – 1e above) can be enhanced as means of communicating with residents, by supplemental metrics such as NA and TA (defined above). Further, these university-based researchers reported that *"Several airports have now included some level of NA and TA analysis in their recent noise studies, and in each instance, the public response has been very positive"* (NoiseQuest, 2006, p1).

1.4 Discussion

We see then, that there is increasing acceptance internationally that residents living around airports are entitled to be fully informed about the noise exposure they experience from aircraft movements particularly any changes in airport operations that impact on them (Gasco *et al.,* 2017). While the primary ('equal-energy') metrics used in leading countries (see Tables 1a – 1e above), have been found to be more accurately predictive of community reaction and thus to provide the most solid basis for land-use planning around airports, these metrics are generally accepted as being commonly misunderstood by many if not most residents (Southgate, 2000).

Supplemental metrics, on the other hand, have been shown to contribute towards a more complete assessment of aircraft noise exposure by informing residents about their actual in-home experience, for example, how many 'noisy' aircraft overflights (i.e., above 70 dB) their house will receive on an average day (viz., N70) (Southgate, 2011, 2000). The obvious solution as adopted by an increasing number of countries, is to provide residents with aircraft noise exposure information (e.g., contour photo-maps plus dose-response tables) that is expressed in terms of both primary and supplemental metrics.

A caution needs to be raised about the use of the supplemental metric N70 to improve residents' understanding about their aircraft noise exposure especially when they already feel confused by the primary metric they have encountered (be it ANEF, DNL, or Lden). It is known that all 'number above' indices are unable to account for the amount by which aircraft overflights exceed the defined benchmark (viz., 60 dBA or 70 dBA). To cite one typical example with N70, this metric assumes that 10 overflights with noise levels peaking at 70 dBA are equal in aircraft noise exposure to 10 identical overflights peaking at 80 dBA despite the fact that the latter overflights would each be perceived by residents as being *twice as loud* and thus would have a higher negative impact on the community.

In Australia, there has been a trend in the past two decades towards adopting a binary approach incorporating both equal-energy (viz., ANEF) and supplemental (e.g., N70) metrics. The *'Falling on Deaf Ears'* report showed that despite its rigorous research credentials, ANEF has serious limitations as a public information source because it is poorly understood by the community (Senate Select Committee, 1995). This is particularly so when environmental impact statements typically present aircraft noise exposure in the form of noise contours which cover only part of the area significantly impacted by aircraft noise. That is, covering only areas above 20 ANEF when authoritative research clearly shows exposures of 10-15 ANEF cause more than a quarter of residents to be at least 'moderately affected' by aircraft noise) (see Table 3 below; Hede & Bullen, 1982).

In the Government report *'Expanding Ways',* the supplemental metric N70 was advocated as ideal for informing residents about their aircraft noise exposure (Southgate, 2000). In that report ANEF was proposed as ideally confined to land-use planning where it *"continues to be the most technically complete means of portraying aircraft noise exposure"* (Southgate, 2000, page *v)*. This view was elaborated by Southgate in another report 10 years later as follows: *"The Australian Noise Exposure Forecast (ANEF) system remains the fundamental tool for achieving land use compatibility around airports in Australia."* (Southgate, 2011, p2, *emphasis added*).

The land-use planning application of the ANEF metric relates mainly to the Australian Standard on aircraft noise (ref., Standards Australia, AS2021, 2015). This standard lists the ANEF cut-offs approved for building siting. Specifically, the Standard provides a table prescribing that areas exposed to less than 20 ANEF are considered 'acceptable' for such listed building types as 'house', 'school', and 'hospital' (see Standards Australia, 2015, Table 2.1, p12). This standard uses the term *'acceptable'* only to mean acceptable for specified land uses (e.g., 'less than 20 ANEF' is rated as 'acceptable' for new residential development). However, public officials and community members often misinterpret this to mean that 'less than 20 ANEF' is an 'acceptable' amount of aircraft noise and by implication, that this amount of noise is 'insignificant' or 'negligible' not only for residential land use but also for 'permissible' human reaction.

By misapplying land-use planning information and restricting aircraft noise exposure contours and population data only to areas above 20 ANEF (which the Australian Standard classifies as 'acceptable' for residential land use), there is evidence of instances of misinformation over the past several decades that have confused the Australian community (see Senate Select Committee, 1995). For example, the '*Falling on Deaf Ears'* report cites an official Department of Transport and Communications pamphlet from 1989 asserting that *"Noise exposure less than 20 ANEF is* ***not a problem*** *for most people"* (Senate Select Committee, 1995, p205; emphasis added). While statistically accurate, such a statement distorts the nature of community reaction.

Unfortunately, the community's confusion re the ANEF metric was not addressed in the latest revision of the aircraft noise Australian Standard which was released recently (Standards Australia, AS2021, 2015). For example, the revised standard repeats the following misleading statement from the previous version dated 2000: *"However, it should not be inferred that aircraft noise will be* ***unnoticeable*** *in areas outside the ANEF 20 contour"* (Standards Australia, 2015, p11; emphasis added; see Table 3 in present report). Again, while not strictly inaccurate this is misleading – more precise dose-response information is available that would give residents a better understanding of their aircraft noise exposure and likely reaction. Another example is the Draft Environmental Impact Statement for the Western Sydney Airport released in 2015. Although the Draft EIS does well to display contours for the supplemental metrics N70 and N60 down to 5 overflights, it displays primary metric (ANEF) contours only down to the 20 level, thereby confusing the community about what constitutes ***significant*** exposure. It also perpetuates the distortion that any aircraft noise below the 20 ANEF level is 'acceptable' and therefore, 'negligible' while not 'unnoticeable' for residents.

The key problem with the claim that ANEF is ideal for land-use applications is the worldwide use of aircraft noise metrics for estimating community impact. This is done by consulting the dose-response function for a particular country and summating the percentage of residents who are 'highly annoyed' (≡ 'seriously affected' in NAL 1982). The most widely adopted dose-response function is the curve initially synthesised by Schultz in 1978. This dose-response function and its revisions which are known collectively as the 'Schultz curve', have become accepted as providing the defining relationship between residential community response and noise exposure (typically expressed in terms of the U.S. metric DNL). Importantly, the Schultz curve was updated with additional studies up to the early 1990s (including the Australian data from the NAL five-airport study) (see Fidell *et al.,* 1991) and subsequently with a further review of studies into the early 2000s (Fidell, 2003).

Some Australian critics including several who should be better informed on such matters, have portrayed the ANEF dose-response curve as atypical of the international aircraft noise research scene. However, Figure 1 below illustrates that far from being idiosyncratic, Australia's dose-response data using ANEF falls right on line with other leading countries using different primary aircraft noise metrics (e.g., DNL, Lden). Indeed, the various major compilations of dose-response data by top researchers published the past few decades (e.g., Janssen & Vos, 2011; Janssen *et al.,* 2011; Miedema & Oudshoorn, 2001; Miedema & Vos, 1999; Miedema & Vos, 1998; Fidell *et al.,* 1991) all confirm that Australia's aircraft noise metric, ANEF, is consistent with the dose-response curves based on other 'equal-energy' metrics (see Figure 1).

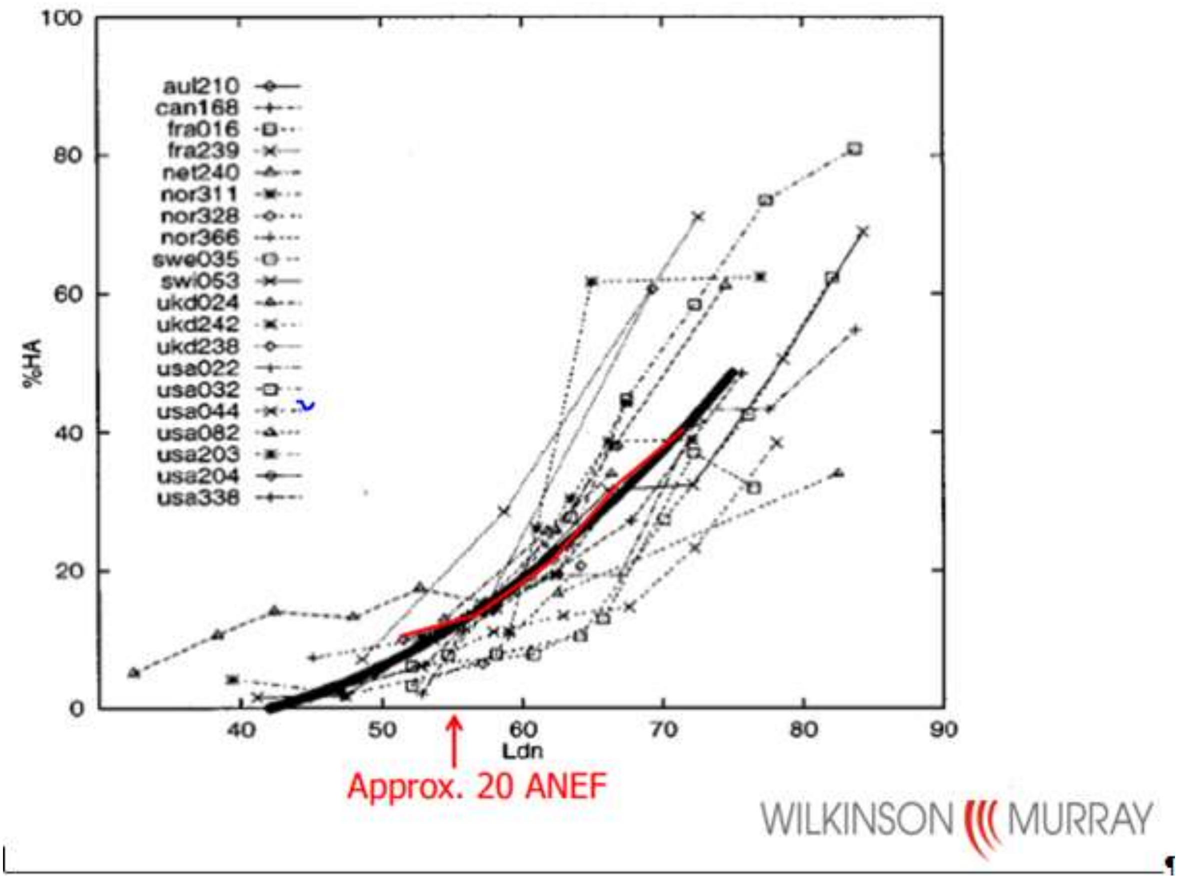


Figure 1: The above data is for combined aircraft noise surveys including Schultz (1978) as collated by Miedema & Vos (1998). Note that the first-listed data-set in the graph *(viz., 'aul210')* displays that from the Australian survey by NAL in 1980. Further, the value for 20 ANEF has been marked in red by Australian consultants, Wilkinson Murray.

As cited above, there are a number of important studies which collate combined data-sets from various researchers which illustrate dose-response curves from across the world (– see Table 2a below from the compilation by Janssen *et al.,* 2011, and Table 2b as compiled by Miedema & Oudshoorn, 2001). Note that both tables include the NAL survey data from 1980 (identified as 'AUL-210') thus indicating the continued international relevance of the Australian five-airport survey (Bullen & Hede, 1986).

Study ID	Name of the survey	Reference	Airports	N	*Year*	*Contact*	*% Resp*	*Scale*
USA-022	U.S.A. Four-Airport Survey (phase I of Tracor Survey)	Hazard (1971)	4	3499	1967	3	79	5
UKD-024	Heathrow Aircraft Noise Survey	Knowler (1971)	1	4515	1967	3	—	4
USA-032	U.S.A. Three-Airport Survey (phase II of Tracor Survey)	Hazard (1971)	3	2883	1969	3	—	5
USA-044	U.S.A. Small City Airports (Small City Tracor Survey)	Pattersen and Connor (1973)	2	1954	1971	3	—	5
USA-082	LAX Airport Noise Study	Fidell and Jones (1975)	1	702	1973	2	—	5
CAN-168	Canadian National Community Noise Survey	Hall *et al.* (1981)	1	631	1978	3	75	11(5)
USA-203	Burbank Aircraft Noise Change Study	Raw and Griffiths (1985)	1	924	1979	3	80	5
AUL-210	Australian Five Airport Survey	Bullen *et al.* (1986)	4	3007	1980	3	82	5
UKD-242	Heathrow Combined Aircraft/Road Traffic Survey	Brooker and Richmond (1985)	4	1993	1981	3	—	4
UKD-238	Glasgow Combined Aircraft/Road Traffic Survey	Diamond and Walker (1986)	1	598	1984	3	—	10(4)
FRA-239	French Combined Aircraft/Road Traffic Survey	Vallet *et al.* (1986)	1	565	1984	3	—	10(4)
NET-240	Schiphol Combined Aircraft/Road Traffic Survey	Diamond *et al.* (1986)	1	573	1984	3	46	10(4)
NOR-311	Oslo Airport Survey	Gjestland *et al.* (1990)	1	1548	1989	2	52	4
NOR-366	Vaernes Military Aircraft Exercise Study	Gjestland *et al.* (1993a)	1	391	1990	2	—	4
NOR-328	Bodo Military Aircraft Exercise Study	Gjestland *et al.* (1993b)	1	702	1992	2	51	4
NET-371	Amsterdam Schiphol Airport Survey (GES 1)	TNO/RIVM (1998)	1	11 150	1996	1	39	11
NET-379	Groningen Airport Eelde Survey	van Dongen *et al.* (1999)	1	407	1998	3	58	11
NET-522	Amsterdam Schiphol Airport Sleep Disturbance Study	Passchier-Vermeer *et al.* (2002)	1	804	2000	1	—	11
SWI-525	Zurich Airport Survey	Brink *et al.* (2008)	1	1787	2001	1	52	11(7)
NET-533	Amsterdam Schiphol Airport Survey (GES 2)	Breugelmans *et al.* (2004)	1	5753	2002	1	46	11
SWI-534	Zurich Airport Survey (Follow-up)	Brink *et al.* (2008)	1	1710	2003	1	52	11(7)
GER-531	Frankfurt Airport Survey	Schreckenberg *et al.* (2010)	1	2273	2005	3	61	11(5)

Table 2a: Compilations by Janssen *et al.,* (2011) of aircraft noise data from leading international studies (including Australia's five-airport NAL study 1980; Bullen & Hede, 1986; See ref. in table: 'AUL-210').

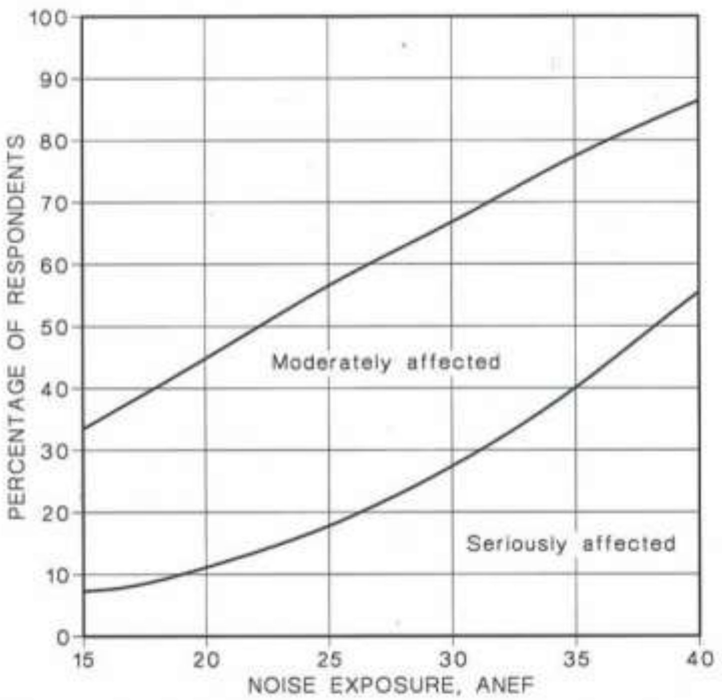
Fields' code (6)	Name of survey (year)	Determination of DENL
Aircraft		
AUL-210	Australian Five Airport Survey (1980)	
	Richmond & Perth	*
	Sydney & Adelaide	DNL + 1.2
	Melbourne	DNL + 0.3
CAN-168	Canadian National Community Noise Survey (1979)	*
FRA-016	French Four-Airport Noise Study (1965)	*
FRA-239	French Combined Aircraft/Road Traffic Survey (1984)	
NET-240	Schiphol Combined Aircraft/Road Traffic Survey (1984)	
NOR-311	Oslo Airport Survey (1989)	*
NOR-328	Bodo Military Aircraft Exercise Study (1991–1992)	*
NOR-366	Vaernes Military Aircraft Exercise Study (1990–1991)	*
SWE-036	Scandinavian Nine-Airport Noise Study (1969, 1970,1971, 1972,1974, 1976)	*
SWI-053	Swiss Three-City Noise Survey (1971)	*
UKD-024	Heathrow Aircraft Noise Survey (1967)	
UKD-242	Heathrow Combined Aircraft/Road Traffic Survey (1982)	
UKD-238	Glasgow Combined Aircraft/Road Traffic Survey (1984)	
USA-022	U.S. Four-Airport Survey (phase I of Tracor Survey) (1967)	
USA-032	U.S. Three-Airport Survey (phase II of Tracor Survey) (1969)	
USA-044	U.S. Small City Airports (Small City Tracor Survey) (1970)	
USA-082	LAX Airport Noise Study (1973)	*
USA-203	Burbank Aircraft Noise Change Study (1979)	*
USA-204	John Wayne Airport Operation Study (1981)	*
USA-338	U.S.A. 7-Air Force Base Study (1981)	*

Table 2b: Compilations by Miedema & Oudshoorn (2001) of aircraft noise data from leading international studies (including Australia NAL 1980; See ref. in table: 'AUL-210').

The definitive dose-response relationship for aircraft noise in Australia was issued by NAL following release of the main research report (Hede & Bullen, 1982) and depicts the percentages of residents 'moderately affected' and 'seriously affected' at different exposure levels expressed in ANEF (see Figure 2 below). This figure is also reproduced in the Australian standard on aircraft noise for land-use planning purposes. An issue that arises from the use of the present Figure 2 in the Australian Standard is that the guidance offered for land-use purposes is commonly misinterpreted when applied out of the context of residential and similar building siting. The advice in the Australian Standard is as follows (see AS2021, 2015, Figure A1, p140):

- Less than 20 ANEF = *"Acceptable"* (for residential building-siting);
- 20-25 ANEF = *"Conditionally Acceptable"* (for residential building-siting);
- Greater than 25 ANEF = *"Unacceptable"* (for residential building-siting).

While the above categories make sense for residential planning purposes, when residents are told by planners that housing areas exposed to less than 20 ANEF have an *'acceptable'* amount of aircraft noise (AS2021), residents have to grapple with the implication that their personal experience of noise disruption is effectively invalidated by official exposure estimates if they don't find the exposure 'acceptable'. In a poignant variant on *'shoot the messenger'* it is understandable that residents tend to *'blame the Government and/or the ANEF metric rather than the aircraft noise'* as the cause of their daily noise burden and noise disrupted life. Effectively, residents' lives are continually disrupted by 'acceptable' levels of aircraft noise and they are consequently convinced someone's to blame.



NOTE: This graph was derived from the National Acoustic Laboratories Report No. 88.

Figure 2: Australian dose-response function from NAL 1980 data Hede& Bullen, 1982) as used in Standards Australia AS2021 for estimating community impact from aircraft noise metric (ANEF) for residential areas around airports.

ANEF ZONE	10-15	15-20	20-25	25-30	30-35	35-40
% Seriously Affected	7	9	15	23	34	48
% Moderately Affected	28	40	51	62	72	82

Table 3: Estimates of percentages *'seriously affected'* and *'moderately affected'* across ANEF zones (as derived from Figure 2 above, using researcher averages of dose-response values for the endpoints of each ANEF zone).

For example, the NAL dose-response function shows that well over a third of residents (40%) will be 'moderately affected' by aircraft noise exposure of 15-20 ANEF and further that more than a quarter of residents (28%) will be 'moderately affected' by exposures of 10-15 ANEF (see Figure 2 & Table 3 above). And yet the Australian Standard persists in describing all exposure below 20 ANEF as being 'acceptable' not just for residential land-use but by implication, for community reaction itself on the dubious grounds that it's not reasonable for residents to be negatively affected by 'acceptable' noise levels. Similarly, those preparing environmental impact statements in Australia repeatedly ignore the aircraft noise impact on residents who are exposed to less than 20 ANEF. There is an urgent need to provide residents with accurate information about their aircraft noise exposure by using both primary metrics and supplemental metrics.

The original commission from SACF (Sydney Airport Community Forum) requested advice:

> *"on the status of any international studies recently completed or currently underway which may provide new evidence on the continued effectiveness of the 1982 National Acoustic Laboratories (NAL) study and the Australian Noise Exposure Forecast (ANEF) system."* (Letter dated 2nd August 2017, from SACF Chair, John Alexander OAM MP).

In order to properly assess Australia's aircraft noise metric (ANEF) in an international context, this report has provided a comprehensive review of all the primary aircraft noise metrics currently in use worldwide. We have seen that there are only five primary metrics used in Australia (ANEF) and its 'comparator' countries, namely: U.S. (DNL/Ldn), U.K. (*LAeq,16hr*) Canada (NEF), and EU (Lden). It is notable that these five measures of aircraft noise exposure (plus China and Korea's 'non-comparator' metric WECPNL) are all 'equal-energy' metrics and are virtually identical in their composition with the exception of variations in the weightings used to take account of residents' sensitivity to aircraft at different times of day, evening and night (see Tables 1a – 1e). Incidentally, ANEF was the first metric to include both evening and night weightings (because the NAL 1980 survey indicated that evening hours in addition to night-time hours already covered in NEF, were particularly sensitive for Australian residents (Bullen & Hede, 1983). It is also noteworthy that the European Union adopted a common aircraft noise metric in 2002 such that the Lden metric applies to all of its 28 current members comparable to the U.S. metric (DNL) but incorporating both evening and night-time weightings (EP, 2002).

1.5 Conclusion

In the past twenty years, the ANEF metric has received considerable 'bad press' in Australia largely because of its misapplication as an information tool which causes confusion among the residential community (see '*Falling on Deaf Ears',* Senate Select Committee, 1995) and the perpetuation by Standards Australia (AS2021) that aircraft noise exposure below 20 ANEF is 'acceptable' (≡ 'negligible') despite clear research evidence and extensive residential experience that such exposure can be quite disturbing for a large proportion of the community (see Table 3 above). Note that no other developed country uses a metric that is any better at informing the community regarding aircraft noise exposure than Australia's ANEF (see Tables 1a – 1e above).

There does not seem to be any international discussion about the possible standardisation of aircraft noise metrics across countries. This is surprising given that there has been agreement for some years re an international standard on social survey questionnaires re aircraft noise (Fields *et al.,* 2001; ISO, 2003). But regarding exposure metrics, each leading country appears content to conduct their own socio-acoustic studies from which they develop their own exposure metric and their own exposure cut-off for land use purposes (see Tables 1a – 1e). This inter-country variation could well be due to human individual differences or perhaps to subtle socio-political factors. Again, specific research is needed to address this issue.

For example, the recently published national socio-acoustic study in the U.K. (SoNA) has reported that the existing U.K. metric has the highest correlation with community reaction (viz., $r^2=0.87$), thereby justifying their metric (viz., $L_{Aeq,16hr}$; see CAA, 2017). Notably, this major U.K. study evaluated only one other primary metric (viz., L_{den}) plus two supplemental metrics (N70, N65). This contrasts with the more than 50 different primary and supplemental metrics evaluated in the original NAL study which found that ANEF is the best available predictor of community reaction in Australia (Bullen & Hede, 1986).

The main implication of recent research regarding aircraft noise metrics is that while there is no international consensus about a single standard, all of the primary indices used around the world share the key feature of being 'equal energy' indices differing only in how they address time-of-day variability in community reaction. Australia's metric, ANEF, suffers considerable local opposition because it does not communicate aircraft noise exposure to residents in a simple and unambiguous manner (Senate Select Committee, 1995). But, if Australia were to replace its primary metric, ANEF, then its only alternatives available worldwide would be the 'equal energy' variants of its own metric as adopted by leading countries and reviewed in this report (see Tables 1a – 1e).

In conclusion, we have seen that the primary aircraft noise metrics used by the world's leading countries (all of which are 'equal-energy' metrics) are commonly regarded as less than satisfactory for providing clearly understandable exposure information to residents. The strong international trend is to use in addition to primary metrics, 'supplemental' metrics which residents seem able to directly relate to their own experience (e.g., 'Number Above' such as N70; 'Time Above' such as TA65; 'Persons Events Index', PEI; and 'Percentile Level' such as L50; see Section 1.3 above).

We have also seen that Australia's recent experience with aircraft noise metrics has indicated that ANEF is inadequate in informing residents about their exposure and that supplemental metrics such as N70 are needed to provide satisfactory information. The best solution based on the current international review appears to be to offer residents (particularly in environmental impact statements and similar documents) a range of information to meet their differing needs including that listed below.

1.5.1 Key Components of Ideal Information Package for Residents Around Airports

1) Informative and engaging descriptions of the primary aircraft noise metric in Australia (viz., ANEF) noting its basis in research and its comparability with metrics used in comparator countries (see Tables 1a – 1d);
2) Informative and engaging descriptions of the main supplemental metrics acceptable in Australia (such as N70 and N60) noting that they are intended to supplement the exposure information provided by ANEF;
3) Tables of land-use information with clear explanations for areas below 20 ANEF (described inaccurately as *'acceptable'* and *'not unnoticeable'* in the influential document *'Standards Australia, 2015; AS2021')*. It is here recommended that if such information is to be accurate, then environmental impact statements should provide exposure contours in 5-ANEF steps down to at least the range 10-15 ANEF (equivalent to a community reaction of 28% 'moderately affected');

Key Components of Ideal Information Package for Residents Around Airports (Cont'd)

4) Tables of community exposure in terms of supplemental metrics (viz., N70 and N60);
5) Engaging information in the form of (ANEF and N70) contours superimposed on orthophoto maps depicting community impact from aircraft noise around the airport.
6) A 'text box' printed near the edge of all contour maps depicting a table of the dose-response relationship between aircraft noise exposure and community reaction (for both 'seriously affected' and 'moderately affected'). This should be accompanied by an explanatory note by which the resident can readily apply dose-response information to their own situation.

Note that the information packages provided to the community re their in-home aircraft noise exposure (in terms of both ANEF and N70 as outlined above) need to be quite innovative so that they are fully explanatory at both the intellectual and emotional levels (supported by appropriate graphics and illustrations).

Finally, the concluding question we need to ask in this report concerns what current international research indicates regarding Australia's ANEF metric. The answer is that none of the five primary metrics in use by other leading countries is superior to ANEF in terms of either predicting community reaction or communicating aircraft noise exposure to residents. Clarifying this issue would require a full socio-acoustic study comparable to that originally conducted by NAL in 1980. This issue can be explored more fully in the final report this series (see *'Report No.5: Implications for Australia of Recent International Research'*).

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