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Risk to Hearing from Overflight Noise of Military Aircraft

B.W. Lawton and D.W. Robinson

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INSTITUTE OF SOUND AND VIBRATION RESEARCH

Audiology and Human Effects Group

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Authors:

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CONTENTS

SUMMARY

The question to be considered was what maximum level of aircraft noise the ear could be exposed to without significant potential for causing permanent noise-induced hearing loss. In the absence of a quantitative statement of what would be considered significant in this context, no definite limit value for noise can be asserted. However, it is possible by several avenues to estimate the risk of hearing loss for particular values of noise exposure. As a peg on which to hang such estimates, this report employs a datum value of 125 dB(A). The reason for selecting this particular value is a practical one: it is the authors' understanding that military aircraft operations in the UK do not normally expose members of the public to noise levels higher than this. A review is first made of the probable origin and technical interpretation of this benchmark figure.

A systematic database search is then described; this search failed to reveal any published reports of permanent hearing threshold shift due to aircraft noise. However, some evidence exists that a small amount of temporary threshold shift may be induced by noise at levels in the region of 125 dB(A), which would nevertheless be without permanent effect.

By characterizing overflight noise by its total exposure value (taking into account overflight duration), comparisons are made with existing damage-risk criteria. Predictions of permanent threshold shift, using established relationships, suggest that there is no credible risk to hearing even for long-term repeated exposures on the basis of several events per day at 125 dB(A).

The nature of the relationship between noise exposure and permanent threshold shift, as it relates to the most susceptible fraction of an exposed population, inhibits the specification of a unique level which would guarantee total freedom from noise-induced hearing loss in every individual. However, there appears to be a practical margin of safety in the case of aircraft noise producing a maximum level of 125 dB(A) during the overflight. This conclusion rests upon experimental evidence of the course of noise level versus time, typical of military aircraft overflights. Taking the margin of safety into account, recommendations are made which, while suggesting that the existing criterion value be maintained, offer guidance on its interpretation and practical implementation.

ACKNOWLEDGEMENT

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1. INTRODUCTION

1.1 Terms of reference

The Ministry of Defence operates a policy of purchasing property where dwellings are exposed to a maximum sound level in excess of 125 dB(A); it is also the policy to review noise levels around military airfields every five years. As part of this on-going process, a meeting was convened by D Med Org(RAF) on 12 February 1990. At this meeting it was decided to initiate further study into the potential for permanent noise-induced hearing loss to result from exposure to such a noise level, and in particular to a single event at that level. The study task was specified in the following terms of reference:

> "i. To consider the single exposure level of noise, (from aircraft), to which the human ear can be exposed without the significant potential for permanent noise-induced hearing loss. The statistical implications should form part of the report.
>
> Particular consideration is to be given to the circumstances that apply in both the vicinity of airfields and under military aircraft during low level flying training. Thus, peak levels, time histories and exposure duration should be taken into consideration.
>
> This study should be conducted by means of an extensive literature search. The findings should be summarised, conclusions drawn and formal recommendations made.
>
> ii. To submit reports in accordance with the requirements of Clause 8 [of the Agreement]."

The ISVR was commissioned to undertake the task under Agreement reference D/ERI/9/4/2040/490/Med(F&S).

1.2 Plan of report

The first paragraph of the Terms of Reference above invites an abstract, or generalized, approach to the relationship between noise and permanent hearing threshold shift, but it leaves undefined the question of what might be considered significant. This is an open-ended question requiring a value judgement which we did not feel competent to address. We have therefore approached the task in a more concrete way, starting from two premises. Firstly, any limit that might be set must bear some relation to the context of the study, that is, military aircraft operations as they actually occur. Secondly, the level of risk for hearing is discussed in relation to the existing administrative noise limit of 125 dB(A). A judgement may then be made as to the maintenance or possible revision of that limit insofar as it concerns risk of permanent hearing loss.

We have been struck, not only by the want of specific reference to the origins of the apparently inflexible noise limit mentioned above, but also by a certain technical imprecision in the meaning to be attached to it (a maximum sound level has to be qualified by the manner or instrumentation by which it is measured). Accordingly, we first investigate the likely source of the figure 125 dB(A) and its audiological significance (Sub-Chapter 1.3); we then review in Chapter 2 a number of purely technical questions related to the measurement of aircraft overflight noise.

With regard to hearing damage, we approach the problem in two ways. Firstly, in Chapter 3 we give the results of an extensive database search for reports of hearing damage directly related to aircraft overflight noise, both in the context of operations in the vicinity of airfields and in the more general area of occasional noise elsewhere. Secondly, in Chapter 4, we draw upon existing knowledge of hearing loss due to noise (not specifically aircraft noise) to determine approximate equivalences, both in respect of permanent threshold shift (PTS) and of temporary threshold shift (TTS). Using these sources, we examine the question of individual susceptibility to noise-induced hearing loss and the associated questions of statistical risk.

Our conclusions and recommendations are given in Chapter 5.

1.3 Historical background

Concern over noise from military aircraft appears to have arisen initially in relation to the environs of airfields. The primary consideration was to establish an environmental noise exposure criterion akin to those used in the neighbourhood of UK civil airports, where the exposure measure *noise and number index* (NNI) determines eligibility for sound insulation grants. The formula for NNI is:

$$NNI = (L_{PNmax})_{av} + 15 \log N - 80$$

where the first term is the logarithmic average of the maximum values of perceived noise level of all in-flight aircraft noises in the accounting period (usually 12 h) which exceed 80 PNdB, and N is the number of such noise events.

When this matter was discussed in the 1970's within the then Flying Personnel Research Committee (FPRC) and its Otological Sub-Committee, it was appreciated that the pattern of aircraft movements differed so greatly between the civil and military cases that the NNI would be inappropriate, and recommendations were made to characterize the military noise by means of the more general quantity L_{Aeq} (equivalent continuous A-weighted sound pressure level) taken over a representative time interval.

Equivalence of the two measures is necessarily imperfect because of their essentially different formulations, although they are correlated. In particular, overflight durations and time histories are not used explicitly in calculating NNI, but are implicit in the uniformity of typical civil aircraft operations around airports (takeoffs and landings). They are, in effect, taken into account through the coefficient 15 of the term log N. This coefficient would have been 10 if the effective duration had been included within the noise measure of each event (as is the case with the aircraft noise certification measure EPNL). The same coefficient, 10, underlies the measure L_{Aeq}, and the time history of each event is automatically allowed for by what amounts to a total acoustic energy measure.

Practical estimates of the L_{Aeq} values equivalent to certain NNI values were later determined by HIGGINSON (1983)*, and established that 50 NNI (the qualifying level for grants) equates roughly to 70 dB(A) on the $L_{Aeq,12h}$ basis.

The Ministry of Defence adopted the measure $L_{Aeq,12h}$, initially at the level 75 dB(A), as the qualifying level for sound insulation, but simultaneously specified an overriding maximum level for individual events of 125 dB(A), above which there was considered to be a possible hearing risk. During the review of these provisions carried out by the Ministry around 1984, the qualifying level for sound insulation grants was lowered to 70 dB(A), to be more in line with the civil airport provisions of that epoch. An additional band of noise exposure was defined (for dwellings within the footprint of 83 dB(A) on the $L_{Aeq,12h}$ basis, or which were exposed regularly to maximum sound pressure levels between 117 and 125 dB(A)), qualifying for purchase of properties at the owners' discretion. The overriding limit of 125 dB(A) was not amended, but rather ratified in the following words (quoted from a report by the RAF Environmental Noise Advisory Committee (ENAC)† in 1984):

> "At the upper limits of the ENAC recommendations, it is considered that even a single exposure to noise levels of 125 dB(A) or greater has the potential to damage hearing and that compulsory purchase remains the only option."

Essentially the same words have been repeated as Ministry policy in the ensuing years. For example, BOARDMAN (1986) writes, on behalf of the review body referred to above:

> "We accepted the view [expressed in an unreferenced MOD Internal Policy Document] that even a brief exposure to noise levels of 125 dB(A) or higher had such potential [i.e. to damage hearing]".

More recently, Ministry policy has been publicly stated on various occasions in these words:

> "The Ministry would seek to purchase, by compulsory means if necessary, any dwelling near to a military airfield which is exposed to a maximum

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* The relation given by Higginson is: $L_{Aeq,12h} = 0.748\ \text{NNI} + 32.5$.

† This body was later disbanded but revived from 1987 to 1990 as a Tri-Service committee. The problem of military flying noise was not reopened.

noise level for military aircraft of 125 dB(A) or more. This policy has been endorsed by the RAF Environmental Noise Advisory Committee who consider that a single exposure to such high noise levels has the potential to damage hearing."

It will be observed that the figure of 125 dB(A) is traced back to the same source in each case. Inasmuch as there is no single level of noise, applicable to everyone, below which zero effects are observed and above which effects can be positively asserted, it is evident that some judgement, other than purely scientific, was exercised in postulating the value 125 dB(A) and its potential consequences. It is of considerable interest, therefore, to trace the origin of this criterion level, and its audiological 'pedigree'. Pointers to the probable course of events leading to this criterion are as follows:

(i) It is clearly recalled by various individuals (including one of the present authors who was a member of the FPRC Otological Sub-Committee at the time) that the number 125 was derived from 138 PNdB by subtraction of the quasi-constant 13 dB which approximates the difference between L_{PNmax} and L_{Amax} for a wide range of aircraft noises (principally civil jet aircraft).

(ii) Why would a hearing risk figure have been expressed in PNdB, a most unnatural scale for an audiological criterion? Although recollections have faded on this point, we believe that the figure 138 must, itself, have been derived from a simpler acoustical quantity, by correction. At the time (early 1970's) aeronautical circles were firmly wedded to the use of PNdB and, because the problem in hand was being studied in an aeronautical context, it was natural that minds would turn to using that unit.

(iii) The likely explanation is that the figure 138 PNdB derived indirectly from a statement in the Wilson Report (COMMITTEE on the PROBLEM of NOISE, 1963) at paragraph 522, that "no unprotected ear should be exposed, however short the period of exposure, to a sound pressure level [unweighted] exceeding 135 dB" (our parenthesis). This dictum is attributed to the British Medical Association, based on the proposition that "since pain is considered a sign of physiological damage, the noise level in the ear canal should never exceed [the threshold of pain] no matter how short the exposure period" (Wilson Committee's parenthesis). It is interesting to note that the same overriding limit came to be included in the UK Code of Practice (HEALTH and SAFETY EXECUTIVE [formerly Department of Employment], 1972).

(iv) How precisely did the figure of 135 dB get transformed to 138 PNdB? This, we suspect, was the result of examining reports of aircraft noise in which both overall (or C-weighted) sound pressure levels and perceived noise levels were tabulated (no doubt along with other measures). The particular source of the conversion factor of 3 units is obscure, but we have found three relevant references suggesting that a difference of 3 units was not wide of the mark. HECKER and KRYTER (1968) list, among other test noises, a case of pure-jet overflight noise at take-off (case 11, Table I of the reference). This was a C135-A aircraft at 2000 ft altitude, for which the following differences are reported:

$$L_{PNmax} - L_{Cmax} = 4.4 \text{ dB}$$
$$L_{PNmax} - L_{Amax} = 11.3 \text{ dB}$$
$$L_{Cmax} - L_{Amax} = 6.9 \text{ dB.}$$

For fan jets, jets with suppressors and propeller aircraft the values are rather different and need not concern us. KRYTER, JOHNSON and YOUNG (1970), in the course of further tests, included the noise of a F-106 aircraft at take-off with afterburner, at altitudes from 850 to 4000 ft. In Table VII of the reference, various measures of this noise for 1700 ft altitude are listed, from which the following differences are abstracted:

$$L_{PNmax} - L_{Cmax} = 4.2 \text{ dB}$$
$$L_{PNmax} - L_{Amax} = 11.7 \text{ dB}$$
$$L_{Cmax} - L_{Amax} = 7.5 \text{ dB.}$$

As in the previous reference, somewhat different relations held for other types of aircraft. Both references agree quite closely on a value of 4 dB for the relation between perceived noise level in PNdB and C-weighted sound pressure level. Overall sound pressure level would not differ appreciably from the C-weighted value for these noises, to judge from the spectrum displayed in Figure 6 of KRYTER, JOHNSON and YOUNG. In a similar series of trials, OLLERHEAD (1971) gave numerous noise measures for a wide range of different aircraft, but only two out of 200 or more were pure turbojets. These two were civil aircraft (Learjet 23 and HS-125). These cases yielded the following differences:

$$L_{PNmax} - L_{max} = 6, \; 6 \text{ dB respectively}$$
$$L_{PNmax} - L_{Amax} = 11, \; 9 \quad \text{"}$$
$$L_{max} - L_{Amax} = 5, \; 3 \quad \text{"}$$

These values are of the same order as in the previous references, and support an average of some 5 dB for the unweighted/PN-weighted difference.

(v) If our surmise is correct, the 135 dB SPL was first transformed (conservatively) to 138 PNdB and later, by another empirical conversion, to 125 dB(A). The latter conversion followed the introduction of the equivalent continuous level (L_{Aeq}) concept, for which one of us was directly responsible as official adviser to the FPRC Otological Sub-Committee. The reason for this advice was, as already mentioned, that NNI (which utilizes the PNdB unit) and which the Otological Sub-Committee probably had originally in mind to follow, was shown to be inapplicable to the relatively irregular movements at military airfields, whereas L_{Aeq} was a universal measure, independent of the temporal pattern of events.

Be this reconstruction of events as it may, the criterion level of 125 dB(A) seems sure to have had its origin in a concept no more definite than the one suggested here (i.e. the Wilson Committee's identification of the pain threshold). We therefore feel that this particular value has no very substantial audiological foundation. However, it has acquired an aura of authenticity from repetition (e.g. by BAXTER *et al*, 1989) and its embodiment in Ministry policy. It is worth noting, irrespective of our interpretation of the intermediate history, that the A-weighted equivalent of the 135 dB overall sound pressure level might have been arrived at more directly from the two respective physical measures, both easily calculated from one-third octave band spectra, without involving the perceived noise level at all. The references above would have suggested a difference of between 3 and 7 dB for the pure-jet military take-off noises illustrated here, yielding a corresponding criterion level between 128 and 132 dB(A). An extensive series of later field tests (FETHNEY and HAZELL, 1983) suggests different values but these were, of course, not available at the time of the FPRC discussions. For up-to-date data, see Sub-Chapter 2.2.

2. CHARACTERIZATION OF AIRCRAFT OVERFLIGHT NOISE

2.1 General remarks

The terms of reference of this study require that a noise exposure level be arrived at "without the significant potential" for causing PTS. Further, this level, if such can be postulated, has to be related to the measures used to characterize aircraft overflight noise. It may be remarked, in passing, that the word "significant" has undertones of a statistical meaning, and this aspect is developed in Chapter 4. Here we are concerned purely with the relevant objective characteristics of aircraft noise, which in turn brings into the question both definitions of quantities and the properties of measuring instruments.

As previously stated, the *de facto* noise limit of 125 dB(A) appears to have been derived from a value measured in the scale of perceived noise level (PNdB). The factors governing the relation between these measures therefore comes into consideration, and in particular the 'translation constant' of 13 units which appears to have been used. The value of this 'constant' depends, however, on the shape of the noise spectrum; values ranging from 9 to 17 have been reported for different types of aircraft noise. Secondly, the unqualified unit "dB(A)" leaves open the question of time weighting: different choices affect the maximum value given by the measuring apparatus. Finally, in order to relate a maximum permissible noise *exposure* to the corresponding maximum *sound pressure* or *sound pressure level*, it is indispensable to take into account the time history of the level during the overflight. The three above aspects are considered in the following Sub-Chapters.

2.2 Aircraft overflight noise spectrum

The sound of interest is confined to that occurring around the time of maximum level, for events of the kind producing levels in the region of the critical value, 125 dB(A). In practice, this means the sound of Tornado at some 250 ft altitude with reheat (although we understand that this is not a normal operation); other types (Phantom, Jaguar, Lightning) produce similar levels under the same operating conditions. Relevant extracts from FETHNEY and HAZELL (1983) are given in Table I. Fourteen examples for the slant distance 250 ft at the moment of maximum L_{PN}, in the climb (with reheat) and in cruise conditions, are listed with the measures L_{max}, L_{Amax}, L_{PNmax} and L_{AX}. The four cases starred have L_{Amax} values above 125 dB(A). Perceived noise levels in PNdB were calculated according to ISO 3891 (BS 5727). Average 'translation constants' for the 14 examples are as follows, with average values for the four starred cases in brackets:

$$L_{PNmax} - L_{max} = 10.7 \ (9.8) \text{ dB}$$
$$L_{PNmax} - L_{Amax} = 12.6 \ (13.0) \text{ dB}$$
$$L_{max} - L_{Amax} = 1.9 \ (3.2) \text{ dB.}$$

If the starting point were, as is surmised, 135 dB SPL, the above data would have led to a limit for Tornado of 132 rather than 125 dB(A). This equivalence assumes that the time weighting associated with the determination of both measures is the same.

2.3 Time weighting

This term refers to the integration time of the measuring instrument. For the calculation of perceived noise level, the time weighting to be used for the measurement of the one-third octave band sound pressure levels is specified in IEC 561 (BS 5647), and it corresponds closely to the S time weighting of sound level meters specified in IEC 651 (BS 5969). The time constant of the S-weighted smoothing circuit operating on the square-law rectified signal is 1 s, corresponding to a rectangular-window integration time of 2 s. The PNdB-to-dB(A) relation discussed in 2.2 thus strictly applies to S time weighted measurements.

The weighting employed by the Ministry and its technical contractors for the direct measurement of maximum A-weighted sound pressure levels is not always explicit in the documentation, but it appears that the F time weighting is implied; this is the setting most commonly applied to fairly rapidly time-varying events, e.g. in the motor vehicle acceleration test standards. The F time weighting has an equivalent rectangular-window integration time of 0.25 s, only one-eighth that of S weighting. The effect of changing from S to F weighting is to 'roughen' the overflight time history and at the same time to advance in time and somewhat increase the highest value attained. Data requisite to estimate this difference for Tornado overflights are not available to us, but they might fairly readily be obtainable from tape recordings of flight trials. The difference may well exceed 1 or 2 dB, particularly for very rapid overflights.

The above applies to direct readings on a sound level meter or from the trace of a level recorder coupled to the sound level meter output. Different considerations enter when the results are obtained from digital or hybrid digital/analogic frequency analysis equipment. In the study by FETHNEY and HAZELL, the integration times are clearly stated (see Table I, Note 1, below), and lie between those of the conventional F and S time weightings. We have also become aware of the use of very much shorter integration times (10 ms), e.g. in measurements on Tornado carried out by the National Physical Laboratory in 1989. The use of such a short integration time increases the amount of fine structure seen on a time history, and appears to add some 1 to 2 dB to the maximum level; the mechanical characteristics of the pen recorder also come into question at these speeds of response.

The above remarks and comparisons, although far from rigorous, are sufficient to illustrate that an unqualified statement of maximum A-weighted sound pressure level is inadequate when drastic action may flow from exceedence of a limit value. The indications are that the F-weighted limit might well have been set appreciably above 125 dB(A) if it had been based upon Tornado characteristics and upon an equivalence with a particular value in PNdB as the point of departure.

2.4 Time history

This term refers to the variation with time, during an overflight, of the sound pressure level with specified time and frequency weightings. Although the choice of weighting will affect the detailed appearance of the graphical display, and in particular the absolute maximum attained, it does not in any way alter the area* under the curve. It is this area, corresponding to the total acoustic energy received at the measuring point, that can be related to hearing damage. Use of an integrating sound level meter (IEC 804 or BS 6698) renders unnecessary the detailed depiction of

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* Strictly, the area after antilogarithmic transformation of the ordinate scale.

the time history; this instrument automatically delivers the sound exposure in the measure known as L_{AX}. The value of L_{AX} is equal to the level of a steady signal which, if persisting for 1 s, would represent the same total sound energy as the actual event. Calculations have been made for the case of Tornado overflights at the Bedford trials of 1989, for which the overflight time histories were available to us in graphical form. For Events Nos 1 and 7 the relations found were as follows:

Evt 1: alt. 250 ft, airspeed 425 knots, 91.2% rpm: $L_{AX} - L_{Amax} = -0.9$ dB
Evt 7: alt. 250 ft, airspeed 500 knots, reheat: $L_{AX} - L_{Amax} = -4.2$ dB.

The effective durations were thus 0.8 and 0.4 s respectively. The FETHNEY and HAZELL report yields differences ($L_{AX} - L_{Amax}$) of −4.1 dB for Tornado and −4.2, −6.8, −3.1 dB for the other three starred cases in Table I, in each case for a slant distance of 250 ft and speeds around 500 knots; the average of these four cases is −4.55 dB, corresponding to an effective duration of 0.35 s. The authors note, though, that this may be somewhat of an underestimate due to the higher than normal airspeeds in the particular operating conditions of their trials. Use is made of these data in Chapter 4.

NOTE:

The measures L_{Amax} and L_{AX} are not uniquely related. L_{Amax} does not involve the motion of the source, whereas L_{AX} (for the same value of L_{Amax}) falls by 3 dB for each doubling of the speed of the source (the scale of time is effectively halved). Moreover, the value of L_{Amax} declines at an approximate rate of 7 dB per doubling of distance, whereas L_{AX} declines at the slower rate of about 4 dB per doubling of distance (the theoretical difference between these two rates is exactly 3 dB).

Table I: Aircraft noise data (1) for a slant distance (2) of 250 ft
(Extracted from FETHNEY and HAZELL, 1983)

Case #	Aircraft	Configuration (3)	Airspeed (knots)	L_{max} (4)	L_{Amax}	L_{PNmax}	L_{AX}
1	Tornado	Climb, reheat	433	130.7	126.5*	139.4	122.4
2		Cruise, 96%	417	117.3	116.8	129.7	115.8
3		Cruise, 89%	419	107.3	105.4	117.9	102.4
4	Phantom	Climb, reheat	587	132.2	128.7*	141.9	124.5
5		Cruise, 98%	368	120.0	119.2	131.7	121.6
6		Cruise, 85%	303	104.3	101.0	113.9	100.1
7	Jaguar	Climb, reheat	461	127.6	125.6*	138.6	118.8
8		Cruise, 100%	400	116.7	116.1	128.7	114.1
9		Cruise, 95%	345	109.2	108.0	119.9	104.0
10	Lightning	Climb, reheat	494	129.2	126.1*	139.0	123.0
11		Cruise, 100%	457	116.4	115.3	127.5	119.0
12		Cruise, 90%	331	101.1	98.9	110.3	98.3
13	Buccaneer	Climb, 95%	494	119.1	118.8	130.8	119.6
14		Cruise, 88%	407	101.6	100.2	113.2	101.1

NOTES:

(1) Results are based on average spectra in one-third octave bands from $3n$ measurements, where n is the number of nominally identical aircraft runs; there were 3 independent microphones on the ground track:
$n = 1$ #12; $n = 2$ ##1,2,4,5,7,8,11,14; $n = 3$ ##3,6,9,10,13
The effective integration time is $3n \times 125$ ms, due to the way that the results were averaged from individual samples at 125 ms intervals. These times fall between those of the F and S time weightings (see Sub-Chapter 2.3).

(2) The overhead altitude is not known exactly, but will be less than the slant distance of 250 ft.

(3) The 'climb' tests were actually made in level flight, with speed and power setting simulating normal climb conditions.

(4) Overall sound pressure level *re* 20 μPa, in dB.

* Cases with L_{Amax} exceeding 125 dB(A).

3. REVIEW OF RESEARCH REPORTS ON HEARING LOSS DUE TO AIRCRAFT NOISE

3.1 Database survey

To cover the literature quickly, a computerized database was searched. The Medline database contains over six million citations from world-wide medical and medical-related literature from 1966 onwards. Searching is done by the use of a dictionary of keywords (or phrases); these keywords are provided by the authors of items cited in the database, and also by the reviewers who make entries into the database.

The topic of interest here is: hearing loss produced by aircraft overflight noise. This phrase contains the the seeds of a number of keywords from the database dictionary. The search proceeded along the lines shown in the listing below, with the results indicated.

Keyword (or phrase)	Number of citations: Single keyword	Number of citations: Intersection of keywords
Sensorineural hearing loss (SNHL)	5298	
Noise aetiology	1745	
SNHL + noise		6579
Aircraft	2009	
SNHL + noise + aircraft		114
SNHL + noise + aircraft + English language		76

The resulting 76 entries were listed by author, title and source; only 6 appeared to be directly relevant to the present study. The remainder dealt with:

hearing loss in ground crew;
" " " aircrew;
" " " passengers;
sonic boom;
annoyance;
mental health; and
animal studies.

After the listing of these 76 citations, resulting from the directly relevant keywords, several less direct approaches were made to the database. Different keywords were tried, singly and in appropriate combinations:

auditory threshold;
auditory fatigue;
sudden deafness;
temporary / permanent;
military personnel;
sonic boom (not);
occupational diseases (not);
firearms (not); and
English language.

These secondary searches did produce database entries, but nothing relevant to the present study.

3.2 Summaries of research reports

In the following two sections, brief reviews will be offered of research reports dealing with hearing loss (either temporary or permanent) resulting from the noise of aircraft overflights. It is worth noting that not all of the reports included here were uncovered by the database search; approximately half were found independently. We also consulted the Fifth Report of the HOUSE OF COMMONS DEFENCE COMMITTEE (1990) but could find no reference to hearing loss due to low flying, or to any research data on this subject, other than hearsay evidence of a single case involving a hearing aid user.

3.2.1 *Loss due to occasional overflight noise*

ISING, REBENTISCH and POUSTKA (1989)

This manuscript for publication describes an investigation contrasting areas in the Federal Republic of Germany subject to different noise exposures from low-level overflights by military aircraft. For this study, the quantities measured were subjective annoyance, blood pressure and ear symptoms; only hearing thresholds, from the ear symptoms, need concern us here.

At the time of this investigation, there was a nation-wide lower altitude limit for military flying: 150 m. However, in certain ares this minimum altitude was relaxed to 75 m. The investigation centred on two regions, Münsterland and Franconia, with zones subject to both altitude limits. Noise levels from low-level flying were surveyed in the four zones over a period of several months. In the Münsterland 75 m zone, the authors recorded a maximum overflight noise level of 116 dB(A); this maximum level occurred approximately once a day (12 times over a period of 10 days). In the comparable area of Franconia, a maximum level of 125 dB(A) was observed, again about once a day. Lower level occurrences were more common; levels in the range 100-104.5 dB(A) were observed approximately 19 and 21 times per day (average over 10 days) in the 75 m zones of Münsterland and Franconia, respectively.

In each of the four survey areas, the investigators enquired whether children, aged 9-13 yr, had ever experienced tinnitus lasting more than one hour, after exposure to loud noise (no particular reference was made to the noise of low-level military flying). Of more interest here is the authors' study of hearing threshold levels; it was asserted that hearing damage had occurred as a result of military flying. Reliance was put upon the results of screening audiometry for "school beginners", performed by the local health authorities. In Franconia, but not Münsterland, the incidence of hearing impairment among young children was found to be significantly different between the 75 and 150 m flying zones. Hearing impairment was defined (by the health authorities) as a hearing threshold level greater than 30 dB HL, for any of the frequencies 0.5, 1, 2, 4 and 6 kHz. The incidence of such hearing impairment, in the Franconia 150 m zone, ranged from 3.5% (for the frequencies up to 4 kHz) to 4.5% (6 kHz). For the more highly exposed 75 m zone, the comparable incidences of impairment were 4.5% and 6%. The authors found these differences to highly significant. No comment was offered on what part aircraft noise might play in low-frequency hearing loss, or why the difference appears to be constant across the frequency range. These incidence figures may well show statistically significant differences, but the authors have not satisfactorily established a cause-and-effect relationship between aircraft noise and the incidence of what, in young children, must be considered a pronounced hearing deficit.

These considerations notwithstanding, the authors offer their own hearing threshold measurements from children, aged 9-13 yr, resident in the two zones of Franconia. The numbers tested were 320 and 490 in the 150 and 75 m zones, respectively. Absolute hearing threshold levels were not reported; instead, a mean difference was given for the frequency range 2-8 kHz. The mean difference of 2.0 dB, suggesting better hearing amongst the children of the 150 m zone, was found to be highly significant. This finding was not developed or discussed.

As an overall result of their investigation, the authors conclude that both subjective annoyance and health risk could be substantially reduced if a maximum noise limit of 115 dB(A) were imposed upon low-level flying. This limit may well be valid for annoyance and hypertension in the noise-exposed populace. In the opinion of the reviewers, however, no convincing evidence or argument has been offered that this limit is necessary to protect hearing.

BAXTER, WEST and MILLER (1989)

The Government of Canada directed its Department of National Defence to encourage the NATO allies to increase their use of the military flying facilities at Goose Bay, Labrador. This has resulted in a substantial increase in military flying in Labrador, with the Royal Air Force and the German Air Force making a total of approximately 5 300 aircraft operations during 1986. The authors refer to plans to make Goose Bay a NATO training centre, in which case there might be as many as 40 000 operations per year.

Both the present and planned levels of military flying operations have produced protest from the inhabitants of the area, mainly aboriginals. It is reported that the Indians of the region feel that noise from low-flying aircraft can cause hearing loss. In response to these expressed concerns, the Government of Newfoundland and Labrador initiated an independent health study to explore the potential and actual effects of low-level military flying. The authors of the paper under review were appointed to undertake the independent study.

To examine the problem of hearing loss from low-flying activity, two approaches were adopted. First, the authors visited areas of low-flying operations, but "... did not see any person who claimed to have suffered hearing loss or ear disease due to the overflights. Otolaryngological examinations and hearing tests were made available to the population, ...but they did not take advantage of the offer." If we assume that the authors made an honest and widespread effort to advertise their presence and purpose, then their negative report really does not help us to understand what actually happened. From their brief mention, it is unclear whether no-one presented because there was no hearing loss, or because the investigators' offer was the subject of a boycott.

Second, the authors allude to a literature review of permanent hearing loss due to aircraft noise. No indication was given of the extent of this effort, which necessarily centred on civil aviation and the noise around airports. In addition to conclusions on the effects of aircraft noise on aircrew and passengers, the authors concluded that "... the people in a community surrounding an airport are in no danger of hearing damage due to aircraft under normal circumstances." It was admitted, however, that low-level, very loud overflights are not normal circumstances. The review did not uncover a single reference to hearing loss resulting from overflight noise.

In addition, noise measurements were made of subsonic overflights by military jet aircraft stationed at Goose Bay. No information was given of aircraft type, altitude, speed or indeed any operating or test condition. The authors state only that the jets were engaged in "low-level practice maneuvers". The highest sound level recorded during the survey was reported to be 128 dB(A), with an average level of 109 dB(A). Flyover durations were stated to be 5 seconds. From these noise survey results, it was concluded "... that neither the intensity nor the duration is sufficient to cause noise-induced hearing loss".

To supplement their own noise survey data, the authors were provided with additional data from the USAF and RAF. Examples are given in the Table below. On the basis of this information, the authors further concluded "... that occasionally low-level subsonic overflights produce noise levels that could be potentially damaging to hearing. Susceptible people exposed to such noise could be affected". The reasoning behind this conclusion is not given.

The further information provided to the authors, and presented in the Table below, has only clouded the issue. No relation is given between L_{PN} and L_A. These reviewers are left wondering if the authors have accepted L_{PN} data without considering the unit. It would appear that they decided to equivocate.

Aircraft	Airspeed (knots)	Power	Altitude (ft above ground)	Perceived noise level (PNdB)
USAF F-4	300	92% cruise	200	120 - 125
"	300	100% afterburner	200	140 - 148
RAF Tornado	420	89% cruise	200	120
"	433	full afterburner	200	142

In summary, this paper promised much, but delivered nothing of use. Measurements were made of the noise from unspecified military jets, but no operating conditions were stated, only that a maximum level of 128 dB(A) was observed. The authors state that no-one presented with hearing loss due to overflight noise (presumably of the type surveyed); their method or diligence in seeking such hearing loss was not described. The authors performed a literature survey, but were unable to find a single reference to hearing loss resulting from low-level overflights. However, the extent of their search was not stated. On the basis of what the authors have actually stated, the reviewers are left with a sense of disappointment, for an opportunity apparently wasted.

3.2.2 *Loss due to flight operations around airfields*

PARNELL, NAGEL and COHEN (1972)

Determinations were made of hearing threshold levels for residents of two neighbourhoods in Los Angeles, one severely affected by the noise of commercial jet takeoffs, the other quiet. Although not directly overflown, the affected residential area lay between the extended centrelines of two runway complexes of Los Angeles International Airport, less than a mile from the end of each of four runways. In the year of the study, this neighbourhood was subject to the noise of over 500 jet takeoffs daily, at a rate of one every 150 s. Maximum noise levels in the area were as high as 101 dB(A); 50% of the aircraft operations had levels greater than 86 dB(A).

Also in the year of this study, the noise-affected residential area was condemned and compulsorily purchased, due to the "intolerable aircraft noise conditions"; the buildings were later demolished.

In contrast to the area adjoining the airport boundary, a quiet neighbourhood was selected as a control. In this quiet residential area, noise levels rarely exceeded 60 dB(A). In the two neighbourhoods, the dwellings were of similar construction, and of similar value as assessed for tax purposes; socio-economic status of the residents was similar between the two areas.

Participants in the hearing measurement programme ranged in age from 10 yr to over 70 yr; all had been resident in their respective neighbourhoods for at least 9 yr. A number of exclusions were applied to the participants: occupational noise exposure; certain types of military service; noise exposure from certain leisure pursuits; unfavourable medical history; otological irregularities; and unilateral hearing loss. In all, 269 and 310 subjects were selected from the noisy and quiet areas, respectively; approximately 50% of households were represented in the experimental and control samples.

Each participant gave hearing threshold levels at 0.5, 1, 2, 3, 4 and 6 kHz, for each ear. These data were used to compare the two areas, by age group, sex, ear and frequency. For the higher audiometric frequencies 3, 4 and 6 kHz, the airport neighbours had slightly, but insignificantly, higher (less acute) thresholds levels. This finding was attributed to a slight age mismatch between the two samples. In the noise-exposed sample, no significant correlation was found between hearing threshold levels and length of residence near the airport boundary. The authors were unable to offer any substantial conclusion to establish jet aircraft noise as the cause of the small difference of hearing threshold levels between subjects living just off the takeoff groundtrack and those living further afield.

ANDRUS, KERRIGAN and BIRD (1975)

Audiometric tests were performed on over 3 000 primary and secondary schoolchildren living in the vicinity of Logan International Airport in Boston; the aim was to determine if noise from aircraft operations had any significant effect on hearing. Noise exposure was not measured directly; instead, each subject was put into one of four exposure classes by residence address. Those children with the highest exposure lived directly underneath flight paths, or immediately adjacent to runways. At the other end of the noise exposure classification scale were those children with exposures characteristic of urban living only. All the subjects, aged 6-17 yr, attended schools within 2 miles of the airport.

Hearing tests were performed to identify those children with bilateral, sensorineural hearing losses. The difference of hearing threshold levels determined at 0.5 and 6 kHz was employed as an index of hearing loss which might be attributed to noise exposure. For the subjects tested, this index had a mean value of approximately 5 dB; there was no apparent relation between the index and noise exposure classification. The authors concluded that the noise of aircraft operations had no measurable effect upon the hearing thresholds of children living very near the airport.

WARD, CUSHING and BURNS (1976)

This paper reports an investigation of the amount of Temporary Threshold Shift (TTS) which might occur amongst persons residing at the end of, or adjacent to, the end of the runway of a large metropolitan airport. Tape recordings of airliner takeoff and landing operations were played repeatedly to young, normally-hearing listeners, whose hearing threshold levels were determined before, during and after the test period.

Two tape-recorded aircraft operations were used as noise stimuli for this study: a takeoff by a DC-8; and a landing by a 720-B. Both of these aircraft are (were) civil airliners, with four jet engines. When presented by loudspeakers to the subjects seated in a reverberant chamber, both aircraft stimuli reached a maximum level of 111 dB(A). The takeoff duration ('20 dB down' points) was approximately 11 s, the landing, 5 s. Four experimental conditions were tested: takeoffs or landings, presented at intervals of 3 min or 1.5 min. Each of the four exposures lasted 6 h.

One group of five listeners heard the recorded noises at 3 min intervals; another group of five heard the noises at the shorter interval. Using pre-test hearing threshold levels as a baseline, TTS was determined at several frequencies, and at times of 1, 2 and 4 h into the exposure, and also at 6 h, the end of the exposure period. More determinations were made at 0.25, 0.5, 1, 1.5 and 2 h post-exposure.

Listed below are the mean TTS values determined at the end of the 6 h exposure. The results listed are for 4 kHz, the audiometric frequency at which noise-induced hearing loss is usually first manifested. From these mean results, the authors concluded: "It is clear that little average auditory hazard is involved." These averages are, of course, composed of

	Mean TTS (dB)	
	1.5 min interval	3 min interval
Takeoff	1.9	2.2
Landing	4.3	1.6

TTS values from individual subjects. Maximum individual threshold shifts never exceeded 14 dB at 4 kHz, for single ears at any listening condition. The investigators offer the comment that a TTS value greater than 10 dB "... although not really alarming, underscores the fact that when dealing with short noise bursts at high intensities of high-frequency sound, one must take individual differences into account". A further comment is offered: that higher maximum noise levels, greater than 111 dB(A) spread over 6 h, would be expected to produce TTS values approaching 20 dB in the more susceptible individuals. This 20 dB value "... marks the beginning of hazard in the sense that full recovery might not occur before the next day's exposure." It should be restated that the experimental subjects were exposed to a maximum of 240 recorded aircraft noises reaching a maximum level of 111 dB(A).

On the basis of their experimental findings of minimal TTS, the authors offer an overall conclusion concerning *permanent* threshold shift. "The possibility of suffering a measurable permanent loss of hearing as a result of aircraft flybys in a residential neighbourhood is remote, even for persons who live immediately adjacent to a busy airport."

KABUTO and SUZUKI (1979)

This paper describes a Japanese study intended to determine the TTS produced by realistic exposures to transportation noise. The investigators used tape recordings of the noise inside a railway carriage, road-side traffic noise and a jet aircraft landing. Only that portion of the study employing the jet noise need be reviewed here.

The jet noise was that of a 747 landing, recorded at the end of a runway at Tokyo International Airport. On playback by loudspeakers, the noise had a maximum level of 97 dB(A) with a '20 dB down' duration of approximately 13.5 s. This stimulus was presented to the listeners once every 2 min for 6 h on each of three successive days.

The subjects for the aircraft noise portion of the study were 19 normally-hearing males, aged 19-27 yr. Before the first noise exposure, each subject gave five hearing threshold levels by self-recording audiometry at 4 kHz, for the better ear. The first measurement was discarded; the remaining four determinations were averaged to give a pre-test threshold level. During the jet landing exposures on each test day, each subject gave 4 kHz hearing threshold levels at intervals throughout the session, and at the end of the exposure.

The authors report the statistics below for TTS at 4 kHz, after each 6 h test session. The mean values were found to be not significantly

Day	TTS (dB) at 4 kHz Mean	Standard deviation
1	1.8	3.3
2	−0.5	2.0
3	1.5	2.2
All 3 days	1.0	2.7

different from zero. This finding indicated to the authors that exposure to aircraft noise, which in the vicinity of a major airport would be considered severe, should have little effect upon hearing.

FISCH (1981)

This investigation was conducted to determine if there was a greater-than-normal incidence of hearing impairment amongst children living in areas exposed to high levels of aircraft noise. The experimental sample comprised 100 children, aged 3-16 yr, resident within a one-mile radius of London-Heathrow airport and subject to high noise levels and numbers of overflights by commercial aircraft. No data were given on noise levels and numbers of aircraft operations for the experimental sample. A control sample was formed of 100 children in two schools, in areas not exposed to significant aircraft noise. The members of the control sample were age-matched to those of the experimental sample.

Hearing threshold levels were obtained by manual, pure-tone audiometry for both groups of children. A measured threshold greater than 20 dB HL at one or more audiometric frequencies, in either ear, placed a child in the "hearing impaired" group. Among those living in the noisy area, ten were found to have a high-frequency sensorineural hearing loss, the type of loss which might be attributed to noise exposure. Among the controls at the quiet schools, eight were found to have similar losses.

On the basis of these approximately equal numbers of hearing impairments in the quiet and noisy areas, the author concluded: "This investigation provided no convincing evidence to show that aircraft noise in a residential area close to Heathrow Airport caused any hearing impairment in children". The cause of the observed losses, in both the exposed and non-exposed samples, was considered to be genetic in the majority of cases.

In the opinion of the reviewers, this investigation has not properly addressed the problem. If the hypothesis of hearing loss due to aircraft noise were indeed true, and if each of the experimental children had received a lifetime exposure to the noise of aircraft overflights, the resultant hearing losses might be expected to cover a considerable range, due to variability in individual susceptibility and exposure. However, this study sought only high-frequency sensorineural losses greater than 20 dB HL, a 'fence' which would have excluded a large proportion of the noise-induced hearing losses waiting to be discovered. The impairment criterion employed here must surely be too coarse for the aim of the study.

GREEN, PASTERNACK and SHORE (1982)

The authors undertook a study with the expressed aim of establishing an association between aircraft noise and hearing loss in New York City schoolchildren. Neither of these variables was measured directly by the investigators. Aircraft noise data were obtained in the form of *Noise Exposure Forecast* (NEF) contours for areas of New York. Audiometric data were provided by a hearing clinic dealing with children referred after failing school screening audiometry tests.

The experimental sample comprised 201 children with verified high-frequency hearing loss. In the sample, low-frequency (0.25, 0.5 and 1 kHz) hearing threshold levels were less than or equal to 30 dB HL; for the high frequencies (3, 4 and 6 kHz), the maximum hearing threshold level was at least 25 dB worse than that for the low frequencies, in each ear. This 25 dB difference ensured that each child had an audiologically significant high-frequency loss. A control sample of 208 children was formed, using the clinic records of referred children found not to have a significant loss.

For each child, an aircraft noise exposure value was determined by locating the child's residence within an NEF contour band. The two samples were distributed as below. The investigators applied a number of statistical procedures to the samples, seeking a regression between noise exposure and the incidence of significant hearing loss. No significant association was found.

The authors' negative finding is hardly surprising. The hearing impairment criterion was chosen to be extreme, perhaps in hopes of making a stark contrast between children with and without an impairment, in relation to aircraft noise exposure. Instead, the data show the impaired children to be largely male, and thus subject to sex-linked genetic hearing

NEF at place of residence	Numbers in sample Hearing impaired	Control
<30	156	177
30–33	20	17
33–36	10	8
>36	15	6
Total	201	208

disorders; this was confirmed by high incidences of parents and siblings with hearing deficits. Additional comparisons with the controls showed that the impaired children were more likely to have been born prematurely, with breathing difficulties at birth. With these influences at work in the hearing-impaired sample, it is little wonder that aircraft noise exposure at home was found to be not significantly linked with hearing loss. The authors seemed to be unaware of the serious shortcomings of their subject selection procedures, which tainted their investigation from the start.

3.3 Conclusions from the research summaries

Having reviewed the available literature on the relation between hearing loss and aircraft overflight noise, the reviewers have found two distinct approaches to the question. Laboratory investigations have sought to induce TTS by controlled noise exposure, and field surveys have attempted to document differences in hearing threshold levels between population groups exposed and not exposed to aircraft overflight noise. Neither research method has demonstrated a significant effect.

In the opinion of the reviewers, the laboratory studies should be given more weight. This opinion derives from the experimental method employed; close control of the experimental conditions allowed determination of small changes in hearing threshold levels. The studies by WARD *et al.* and KABUTO and SUZUKI employed tape-recorded aircraft noises, presented repeatedly at realistic levels over several hours. Thresholds were determined at the end of the exposures, to be compared with the pre-test thresholds; no statistically significant TTS was found in either case. It is a truth universally acknowledged that if a daily occupational noise exposure produces no TTS, neither will it produce PTS over a period of years. This truth must surely apply equally to the noise of aircraft.

A logical extension to the TTS studies mentioned above is found in the population survey reported by PARNELL *et al.* Hearing threshold levels were determined in a population living at the ends of two runways at a major international airport, and subjected to "intolerable aircraft noise conditions". These airport neighbours were compared to a population living remote from the airport; no significant difference in hearing threshold levels was found.

A surprising number of studies were found to address the hypothesis that aircraft noise, both of occasional overflights and regular airport operations, produces hearing pathology in children. This hypothesis would seem to be based upon the notion that young ears are more susceptible to noise damage than are the ears of adults. See, for example, MILLS (1975) and PRICE (1976). LANE and MEECHAM (1974) give full expression to the fear of hearing damage in children attending school underneath the flight path of a major airport; however, these authors provided no direct evidence in support of their assertion. Four studies have been reviewed here, each dealing with the relation between aircraft noise and (considerable) hearing loss in schoolchildren. None of the studies found sufficiently strong evidence to reject the null hypothesis: the noise of aircraft overflights has no effect upon the hearing threshold levels of children.

On the basis of the literature reviewed here, an overall trend is obvious. Whether in the case of TTS or PTS, laboratory or field studies, adults or children, there appear to be no reports of significant hearing damage attributable to the noise of aircraft overflights. Although the noise level of individual civil operations is considerably below that of the military overflights of primary interest for the present report, this factor is more than outweighed in equal-energy terms by the much larger numbers of operations.

4. ASSESSMENT OF HEARING DAMAGE RISK

4.1 Nature of loss

For the assessment of hearing damage which might be attributable to the noise of aircraft overflights, one basic assumption is made: any hearing deficit will be the result of damage to the cochlea. It is known that the conductive mechanism of the ear may suffer damage as the result of very high sound pressures, as might be typical of blast or explosion. However, such conductive pathology (*e.g.* rupture of the eardrum or disruption of the ossicular chain) is inherently random and unpredictable. The discussion to follow will deal solely with sensorineural hearing loss.

4.2 Published information

4.2.1 *Documents which relate hearing loss to noise exposure*

4.2.1.1 CHABA damage-risk criteria

CHABA, the Committee on Hearing, Bioacoustics and Biomechanics (a joint committee of the US National Academy of Science and the National Research Council) was asked to specify damage-risk criteria for exposure to noise. The recommendations of CHABA, published in the report of its Working Group 46 attributed to KRYTER (1965), were more publicly presented by KRYTER, WARD, MILLER and ELDREDGE (1966). The basic criterion adopted by the Working Group was that a noise exposure would be "deemed acceptable" if, after 10 years of near-daily exposure, the resulting median hearing loss did not exceed 10 dB at 1 kHz, 15 dB at 2 kHz and/or 20 dB at frequencies 3 kHz or greater. Hearing losses due to age or pathological influences were not considered.

The CHABA criteria are described as being based partly on experimental studies of noise-induced PTS from the then-available open literature, and partly on studies of TTS. In reality, the latter was the determining factor. The relation of TTS to PTS was encapsulated in the rule that TTS measured 2 min post-exposure ("TTS_2") after a single day's noise will correlate with the PTS after a period of repeated similar exposures; the quantitative relation was taken to be equal effects at 1 kHz, 5 dB less PTS than TTS at 2 kHz, and 3 dB less PTS than TTS at 4 kHz, after 10 years. The authors further asserted that:

> "TTS_2 that approaches or exceeds 40 dB can be taken as a signal that danger to hearing is imminent", and that "fewer than 1% of young, normal ears exposed on one occasion to a noise exposure on the contours [of the CHABA report] would sustain TTS's that exceed 40 dB. .... Thus, it is certain that only a very small proportion of the population would exhibit clear signs of possible danger to hearing if the exposures on the contours were widely spaced in time and limited to young, normal ears."

The recommended damage-risk criteria were presented in the form of contours (referred to above) of maximum permitted levels for noise bands of different centre frequencies; these band level contours were "deemed acceptable" for one exposure per day of variable duration. Given in the Table below are the maximum specified band levels for a duration of 2 minutes, the shortest time specified in the Standard. If any single band level exceeds the damage-risk values given for this shortest specified duration, then the noise should be considered as "potentially unsafe".

One-third octave band centre freq. (kHz)	Maximum permitted level (dB *re* 20 μPa)
0.25	130
0.5	130
1	128
2	116
4	111
8	120

The CHABA authors warn that it is not safe to extrapolate from the contours. On the other hand, there is some comfort to be gained from their assertion (regarding very short exposures) that the contours based on TTS allow somewhat more intense exposures than would be indicated by extrapolating to shorter durations on an equal-energy basis. It does not seem unreasonable, therefore, to apply the CHABA criteria to the noise of low-altitude overflights by military aircraft. The reader of the present report is directed back to Table 1 of Chapter 2, which reproduces overflight noise data from a survey reported by FETHNEY and HAZELL (1983). Of particular interest here are the four overflights at full reheat (cases 1, 4, 7 and 10), with recorded noise levels greater than 125 dB(A) for altitudes less than 250 ft. Reference to the spectra given by FETHNEY and HAZELL indicate that the reheat condition gave levels in the 4 kHz one-third octave band exceeding the damage-risk criterion listed above, in one case by 3 dB. By a strict interpretation of the CHABA criteria, the noise of low-level overflight by Tornado, Phantom, Jaguar and Lightning aircraft in reheat might be considered hazardous to the hearing under certain conditions, namely that:

a) reheat is used at altitudes less than 250 ft. (We understand that this flight condition is forbidden to pilots, except in cases of emergency.)
b) the duration of the noise exposure is as long as 2 min. (It is difficult to imagine any flight operation which could have such a long duration.)
c) a person on the ground is so exposed once a day for 10 yr.

Such a combination of circumstances must be considered unlikely in the extreme. It must therefore be considered equally unlikely that there would be any person exposed to such a degree as to exhibit a noise-induced hearing loss as great as 10, 15 and 20 dB at 1, 2 and 3 kHz, respectively.

4.2.1.2 British Standard 5330

In common with the CHABA damage-risk criteria, British Standard 5330:1976 is based upon the concept of a hearing loss fence, specifying a relationship between occupational noise exposure and the expected incidence of "hearing handicap". For the purpose of the Standard, a handicap is deemed to exist if the average hearing threshold level at 1, 2 and 3 kHz is equal to or greater than 30 dB HL in relation to audiometric zero. The measure of noise exposure is derived from the equivalent continuous A-weighted sound level over one working day (assumed to be of 8 h duration), and is expressed as a *noise immission level* for a given number of years of daily noise exposure.

Although exposure to the noise of low-flying military aircraft would not normally be considered occupational noise exposure, the Standard may be applied to predict the expected incidence of hearing handicap. For the quantification of noise exposure, the reader should refer back to Sub-chapter 2.4 of the present report. Reference is made to the difference quantity ($L_{AX} - L_{Amax}$) for aircraft overflights measured by FETHNEY and HAZELL. For the four loudest overflights of Table 1, indicated by asterisks, the average difference was found to be −4.55 dB, corresponding to an effective duration of 0.35 s. For application of the British

Standard, let us characterize an aircraft overflight with L_{Amax} equal to 125 dB(A) as having all of its acoustic energy compressed into a duration of 0.5 s, slightly longer than the calculated value for the reason set out at the end of Sub-chapter 2.4. This exposure of 125 dB(A) for 0.5 s is found, by mathematical extension of the tables of the Standard, to be equivalent to 77.4 dB(A) for 8 h. However, for any noise of duration less than 2 min, the Standard imposes what amounts to a penalty: any noise of duration shorter than 2 min is arbitrarily assigned this minimum value. For aircraft overflight noise of the type under consideration here, this restriction in the application of the Standard imposes a short-duration penalty of 23.8 dB(A): an actual level of 125 dB(A) assigned a notional duration of 2 min is equivalent to 101.2 dB(A) for 8 h.

The Table below shows how the Standard might be applied to the noise of low-flying military aircraft. The first column gives the actual and penalized values of equivalent continuous sound level for one overflight per day. If such equivalent levels were to occur each day for the hypothetical durations of the second column, then the noise immission levels of column three would result. The hypothetical durations listed in the Table need not really occur; the same noise exposure could result from one year at the higher noise immission levels listed. By the use of this simple expedient, compressing 40 yr of noise exposure into 1 yr at a much higher level, it is possible to estimate the percentage of the population suffering "hearing handicap" as a result of the noise exposure alone; age-related hearing loss is eliminated from consideration. Column four lists the percentage of 20 yr old persons "handicapped", having received an exposure equivalent to one overflight per day for 1, 10, 20 and 40 yr.

Equiv. contin. level (dB(A))	Hypoth. duration (yr)	Noise immission level (dB(A))	Percent handicapped
77.4	1	77.4	0
	10	87.4	0
	20	90.4	0
	40	93.4	0
101.2	1	101.2	1.5
	10	111.2	13
	20	114.2	21.5
	40	117.2	32

The values in the Table, which are free of any age effect, indicate that no noise-induced hearing handicap should result from 40 yr of one overflight per day at the assumed level of 125 dB(A) lasting 0.5 s. However, strict application of the Standard, with its implied short-duration penalty, gives handicap percentages considerably inflated from the true values. In our opinion, the short-duration penalty is unjustified in the case under consideration here. There should be no expectation of hearing threshold level greater than 30 dB HL averaged over 1, 2 and 3 kHz.

4.2.1.3 HSE tables

In a research report published by the Health and Safety Executive, see ROBINSON (1988), tables were given for the estimation of hearing loss due to the combined effects of noise exposure and ageing. Two types of populations were considered, both comprising equal proportions of males and females: in one population, individuals were screened for otological normality; the other was an unscreened, typical population. Both populations were considered to start their noise exposure at age 20 yr, and to continue in the same noise level for periods up to 40 yr, on a regular basis of 8 h per day over a working week of 5 days. For the purpose of the HSE document, hearing loss was defined in terms of hearing threshold levels averaged over the frequencies 1, 2 and 3 kHz for both ears.

For both populations, tables of average hearing threshold level against age (and years of noise exposure) are given for values of L_{Aeq} ranging from 83 dB(A) to 102 dB(A); tables are also given for no noise exposure, showing only the ageing effect for both normal and typical populations. As far as the present discussion is concerned, a single aircraft overflight per day, having an equivalent continuous level of 77.4 dB(A), is below the range of the tables. By implication, a single overflight per day would produce negligible PTS in either the normal or typical population, for any number of years of exposure.

Such an outright dismissal of the noise of a single overflight per day, although justified, is not particularly helpful. The present discussion would be better served by an illustration; let us consider the hearing loss which might be expected from six overflights per day, each with a maximum level of 125 dB(A) and notional duration of 0.5 s. This overflight noise exposure has an equivalent level of 85 dB(A), permitting use of the HSE tables. Given below are values of expected hearing loss due to age and noise (six overflights per day) for the normal and typical populations; values are given for the median (50%) and the 5% worst-hearing fractiles of both populations. Comparable values are also listed for populations having no noise exposure.

Population	Duration (yr)	Average hearing threshold level (dB HL)			
		Exposed		Not exposed	
		5%	50%	5%	50%
Normal	1	10.8	0.4	10.4	0.1
	10	14.4	3.3	11.9	1.0
	20	18.8	6.8	15.7	3.2
	40	32.5	16.0	30.0	11.8
Typical	1	11.7	2.9	11.4	2.6
	10	18.1	6.4	15.9	4.1
	20	25.8	10.0	23.3	6.5
	40	46.2	20.9	44.9	17.0

The effect of six overflights per day may be seen in the difference between the average hearing threshold levels for the exposed and non-exposed groups. In no case does this exposure produce more than about 4 dB of noise-induced hearing loss, and then only if repeated 5 days per week for 40 yr. Correspondingly, a single overflight per day may be expected to result in less hearing loss.

4.2.1.4 International Standard ISO 1999

This International Standard specifies a method of calculating the expected noise-induced PTS occurring in adult populations subject to various levels and durations of noise exposure. The measure of such exposure for a population at risk is the A-weighted sound exposure expressed as equivalent continuous sound pressure level, L_{Aeq}, over an 8 h working day, for any given number of working years. The calculation method specified is directly applicable to noise exposures ranging from 75 dB(A) to 100 dB(A) for an 8 h day; the period of daily exposure may last up to 40 yr.

For the estimation of cochlear hearing impairment due to noise exposure, formulae are given for the calculation of PTS for the audiometric frequencies 0.5 to 6 kHz. These mathematical formulations are a compromise between those of ROBINSON and SHIPTON (1977) and PASSCHIER-VERMEER (1968). As well as median values of threshold shift, the statistical distribution above and below the median may be calculated for percentiles from the 5th to the 95th. For any given noise exposure, the median and distribution of noise-induced threshold shift are assumed to be the same for males and females.

As discussed previously, we shall characterize an overflight by a military aircraft as having a value of L_{Amax} of 125 dB(A) and a duration of 0.5 s. This very brief exposure may be equated to one of 77.4 dB(A) lasting 8 h, the assumed working day, which has the same value of L_{Aeq}. For the purpose of illustration here, we shall postulate that this single overflight is repeated five days out of seven, for 40 yr to make an exposure lifetime. For this exposure, the median noise-induced PTS values were calculated for all frequencies, 0.5 to 6 kHz. As might be expected, that for 4 kHz was the greatest. Given below are values representing the worse-hearing half of the lifetime-exposed population.

Percentile of population	Noise-induced PTS (dB)
50	0.38
10	0.52
5	0.56
1*	0.67
0.1*	0.72

* extrapolated

It is usually at this frequency, 4 kHz, that noise-induced permanent threshold shift is first manifested; it is also this frequency which shows the greatest loss after a period of hazardous exposure. For the exposure hypothesized here, one overflight per day for 40 yr, the expected PTS is not as much as 1 dB for even one in every thousand of the exposed population. For less severe exposures, perhaps by overflights less frequent than one per day, the expected PTS should be smaller. For occasional overflights, the proportion of the exposed population expected to suffer any measurable threshold shift, even at the frequency most vulnerable to noise damage, must be vanishingly small.

4.2.2 *Regulatory documents*

4.2.2.1 Defence Standard 00-27

Aircraft overflight noise is not impulsive in the usual sense of the word. Nevertheless it is of short duration, and for very rapid overflights there is a convergence with the upper limit of the so-called "B-duration" of the oscillatory-type impulse noises discussed in the literature (COLES *et al*, 1968). Such impulses are characterized by a high initial sound pressure peak (attained in a time of the order of a millisecond or less), followed by an exponential decay of the envelope of the ensuing oscillatory sound pressure fluctuations.

Damage risk criteria have been specified for exposure to such impulses, in a Ministry of Defence document referred to below as DEF STAN 00-27; see ANON. (1985). Duration for these impulses is defined as the time for which the envelope of the sound pressure waveform exceeds one tenth of the peak sound pressure, provided it is in the range up to 1 s. This duration may be approximately equated to the time interval between the '20 dB down' points of an aircraft overflight time history. For the Tornado at 500 kt and altitude 250 ft the '20 dB down' duration appears to be in the region of 2 s, and thus nearly comparable with the B-durations specified for impulses. DEF STAN 00-27 offers both a "maximum" and a "preferred" limit of exposure, the more rigorous "preferred" limit for a B-duration of 1 s being given as 130 dB peak sound pressure *re* 20 μPa, but this is where the assumed exposure is 100 impulses per 24-h period. An allowance of 5 dB per 10-fold reduction in numbers, down to 1 event per day, is permitted. This would equate to 140 dB peak sound pressure once per day. Adequate data are not to hand for the peak sound pressure in an overflight with a maximum F time-weighted, A frequency-weighted, sound pressure level of 125 dB(A), but a value can be inferred indirectly. For the four asterisked cases in Table I of this report, the difference ($L_{max} - L_{Amax}$) averages 3.2 dB; hence 125 dB(A) is equivalent to about 128 dB SPL for aircraft noise of the crucial type in question. The peak sound pressure defining this maximum level would be higher according to the crest factor of the noise waveform. Even making a generous estimate of crest factor, the peak value could hardly reach 140 dB. This is directly comparable to the "preferred" DEF STAN 00-27 criterion, which is stated as "admitting a very low risk of hearing loss". The "maximum" limit, "not to be exceeded under any peacetime circumstances", is placed 10 dB higher than the "preferred" limit, and by inference would imply a definite, though unquantified, risk to hearing. There are a number of intangibles in the above comparisons and it would probably be unfruitful to pursue them further; a rough equivalence does, however, seem to exist between the DEF STAN and current MOD military aircraft noise limits.

4.2.2.2 HSE Code of Practice

The 1972 **Code of Practice for reducing the exposure of employed persons to Noise** contains an advisory limit for continuous noise, in effect giving helpful advice to the "reasonable and prudent employer" on protecting his noise-exposed workforce against noise-induced hearing loss. A hazard to hearing was deemed to exist if the value of $L_{Aeq,8h}$ equalled or exceeded 90 dB(A). Lower exposures were considered acceptable. As noted above, a single aircraft overflight noise has been characterized as having an 8 h equivalent level of 77.4 dB(A). Such an exposure would therefore have been considered acceptable under the Code of Practice; indeed, there would have been a margin of some 12 dB(A) permitting multiple overflights.

The 1972 Code contains, in addition to an advisory limit for continuous noise, an overriding limit (also advisory) that the unprotected ear should not be exposed to an F time-weighted SPL exceeding 135 dB. Drawing on the discussion of the previous section, an overflight with an F time-weighted SPL of 125 dB(A) would have a corresponding unweighted maximum SPL of 128 dB, within the limit set out in the HSE Code of Practice. A second overriding limit is also set out in the 1972 Code: in the case of impulse noise, the unprotected ear should not be exposed to an instantaneous SPL exceeding 150 dB. In Sub-chapter 4.2.2.1, it was suggested that the peak level could scarcely reach 140 dB, and thus well below the overriding peak limit of the Code.

4.2.2.3 Noise at Work Regulations 1989

The **Noise at Work Regulations 1989**, which superseded the advisory 1972 Code described above, are mandatory. Legally binding limits are specified in terms of $L_{Aeq,8h}$. The lowest of the limits, or "Action Levels", is set at 85 dB(A); at this level, exposed workers are entitled to demand suitable and efficient hearing protectors, which the employer is required to supply. A single overflight, with $L_{Aeq,8h}$ equal to 77.4 dB(A), does not breach this "First Action Level", again allowing a margin for multiple overflights.

In addition to limits for exposure to noises which are essentially continuous, the 1989 Regulations also contain a limit for impulse noise. Employers are required to reduce the noise exposure of any employee likely to suffer a peak sound pressure of 200 Pa or more. This "Peak Action Level" corresponds to an instantaneous unweighted SPL of 140 dB *re* 20 μPa. From the argument above, it appears that an aircraft overflight noise of 125 dB(A) might approach the "Peak Action Level", with a slight possibility of breaching the more conservative 1989 Regulations. It is implicit in these Regulations that noise exposures exceeding any of the Action Levels constitute a hazard to hearing if such exposures were to be repeated on a regular basis; for occasional instances, such as aircraft overflight noise, the hazard to hearing must be correspondingly remote.

4.2.3 *Other documents*

In addition to the documents already discussed in relation to aircraft noise or damage-risk criteria, there exist a number of other relevant research reports which bear upon the effect of high-level noises upon human hearing and provide useful comparisons.

BROWNSEY and EDMONDSON (1968)

At the time of this paper, virtually all TTS studies had focused on impulse noise, with duration less than 10 ms, or continuous noise lasting 10 min or longer. The investigators undertook a study, applicable to the electricity supply industry, to determine the TTS resulting from noise exposures lasting from approximately 0.5 s to 10 min. Because the durations were short, very high sound pressure levels were employed to produce measurable TTS values in the experimental subjects; the highest A-weighted SPL used was 129 dB(A). Two broad-band noise stimuli were presented by loudspeaker: (a) bursts of 'pink' noise, with controlled duration; and (b) a tape-recorded air-blast circuit-breaker noise. Noise (b) would be more generally called a long-duration impulse, the duration of which was estimated, by the reviewers, to be 0.5 s between the '20 dB down' points. Given below are the test conditions most appropriate to the present question: threshold shift resulting from high-level, short-duration noises.

Twenty subjects participated in the study; all were in the age range 20–40 yr, with hearing threshold levels not greater than 15 dB HL for the audiometric frequencies 0.5, 1, 2, 3, 4 and 6 kHz. Before each noise exposure, hearing threshold levels were determined for both right and left ears of each subject. Each test ear was exposed individually, in turn, with the non-test ear protected. Following each exposure, a post-test audiogram was obtained. The 2 kHz post-exposure threshold was directly measured as TTS_2; post-test thresholds for other frequencies were corrected to estimate values of TTS_2. Also listed below are the median values of temporary threshold shift for each audiometric frequency, and for each relevant experimental condition; values of standard deviation are given in parentheses.

Condition number*	Stimulus level (dB(A))	Stimulus duration (s)	Number of ears tested
22	109	12	40
23	114	12	40
24	119	12	40
25	124	12	38
26	119	1	38
27	124	1	34
28	129	1	34
29	117	0.5*	28
30	122	0.5*	28
31	127	0.5*	28

* Estimated from an oscillogram by approximating the envelope shape by an exponential function of time.

Condition number†	Median and (standard deviation) of TTS_2 (dB) 0.5 kHz	1 kHz	2 kHz	3 kHz	4 kHz	6 kHz
22	0.5(2.7)	0.5(2.1)	0.5(2.7)	1.3(2.7)	2.5(4.5)	7.9(4.8)
23	0.6(2.5)	0.8(2.2)	1.2(2.9)	2.6(3.3)	4.2(3.5)	8.3(7.8)
24	0.5(3.0)	0.5(2.5)	1.8(3.8)	3.9(3.7)	5.9(5.1)	11.7(8.4)
25	1.3(3.7)	1.2(2.8)	2.9(4.0)	6.6(3.3)	7.5(3.8)	12.7(7.9)
26	0.5(2.4)	0.9(2.6)	0.9(2.4)	1.5(3.0)	1.9(3.6)	5.3(4.3)
27	0.0(2.4)	1.0(2.0)	1.3(2.8)	2.4(2.8)	2.9(3.5)	5.5(4.6)
28	1.0(2.6)	1.3(2.3)	1.4(2.9)	3.0(3.3)	3.6(4.2)	7.0(6.6)
29	1.0(2.4)	1.1(1.9)	1.0(3.0)	1.3(3.1)	2.9(3.7)	5.0(6.0)
30	0.9(3.0)	1.2(3.4)	0.3(2.3)	1.0(3.0)	2.5(3.9)	5.3(7.3)
31	0.6(3.0)	1.2(1.3)	1.9(2.4)	2.8(2.3)	3.4(3.6)	7.5(7.0)

† Conditions 22-28 - 'pink' noise; conditions 29-31 - circuit-breaker

The investigators did not attempt statistical analysis to show the significance of any of the median values of TTS_2; considering the reported values of standard deviation, no median value would be found to be significantly different from zero. However, consideration must be given to the fact that all the reported medians are positive; this must surely indicate that some TTS resulted from the high-level exposures.

For the question of hearing loss attributable to the noise of aircraft overflights, several of the experimental exposures are particularly applicable. Conditions 26 and 27 have equivalent levels which bracket the notional overflight noise used here, namely 125 dB(A) for 0.5 s; the same applies to conditions 30 and 31 although in these two cases the durations listed above are only estimates. Considering the values of median TTS_2 and standard deviation listed for these experimental conditions, and the investigators' report that the TTS values closely followed the Gaussian distribution, the estimated range of TTS_2 has been calculated for presentation here; see the Table below. In the discussion of the CHABA report above, a TTS_2 of 40 dB was identified as the hazard criterion for a noise exposure. From the data in BROWNSEY and EDMONDSON, our estimates of the maximum values of TTS_2, resulting from one experimental exposure, are very small in relation to this 40 dB criterion, with possible exception of 6 kHz. In the case of conditions 30 and 31, the somewhat larger TTS values might be attributed to the impulsive character of the air-blast circuit-breaker noise.

Condition number	Estimated range of TTS_2 (dB) 0.5 kHz	1 kHz	2 kHz	3 kHz	4 kHz	6 kHz
26	−4 +5	−4 +6	−4 +6	−4 +7	−5 +9	−3 +14
27	−5 +5	−3 +5	−4 +7	−3 +8	−4 +10	−3 +14
30	−5 +7	−6 +8	−4 +5	−5 +7	−5 +10	−9 +20
31	−5 +7	−1 +4	−3 +7	−2 +7	−4 +11	−7 +21

According to the authors, the observed values of TTS in all cases recovered in a matter of minutes. Also worth noting here is the authors' observation that no subject showed any permanent shift of hearing threshold level over the course of their tests.

PARNELL, NAGEL and COHEN (1972)

This report has been summarized in Chapter 3, but deserves further attention here. The investigators surveyed the noise environment in a neighbourhood severely exposed to the noise of airport operations; hearing threshold levels were also sampled amongst the residents. No statistically significant hearing loss was observed in these people.

The investigators reported an outline distribution of the values of L_{Amax} recorded in various locations in the exposed neighbourhood; the distribution for the most severely exposed area is reproduced below. On the basis of 531 jet take-off operations per day, this distribution of

Percentile	L_{Amax} (dB(A))
95	101
75	95
50	92
25	86
5	80

noise levels was analysed, for presentation here, to yield a total noise level (as if for a single operation) ranging from a lower bound of 120.6 to an upper bound of at least 122.4 dB(A), depending on the distribution of individual events within decile bands derived graphically from the values in the Table above.

Bearing in mind that the typical duration of take-off noise around airports, between '20 dB down' points, is of the order 15 s, or an 'equivalent rectangular' time of 10 s, the above limits for L_{Amax} translate to L_{AX} values between about 130 and 132 dB(A). This may be contrasted with the estimated 122 dB(A) for our notional military overflight at a maximum level of 125 dB(A) and equivalent duration 0.5 s. The residents suffering a daily exposure level some 10 dB(A) above this showed no PTS.

US Environmental Protection Agency (ANON., 1974)

This agency of the US Goverment has specified environmental noise levels requisite to protect the hearing of the general population. Several considerations were basic to this endeavour, among which were:

i) the human ear, when damaged by noise, is typically first affected at the audiometric frequency 4 kHz;

ii) changes of hearing threshold level less than 5 dB are generally not considered noticeable or significant; and

iii) individuals at the high end of the hearing level distribution are less affected by noise exposure, that is, individuals with elevated thresholds cannot be damaged by sounds which are inaudible to them.

An equivalent level of 73 dB(A), determined over an 8 h day for each working year, was stated to protect virtually the whole population against noise-induced PTS. In order to apply this limit to aircraft overflight noise, a number of corrections are required. If any environmental noise is intermittent, the level may be 5 dB(A) greater with no increase in PTS. In addition to this correction generally applicable to environmental noise, it may be supposed that persons on the ground would be exposed to overflights by military aircraft during daylight hours only. Lengthening the duration of potential exposure from 8 h to 12 h per day would require that the criterion level be reduced by a further 1.8 dB. For our purposes, the final criterion level is 76.2 dB(A). Exposure to this level for an indefinite period would not be expected to produce a noise-induced PTS of 5 dB or more at 4 kHz, in virtually any member of the population.

Our notional single exposure to military overflight noise has been quantified as 77.4 dB(A) over one day; this exceeds the criterion value by a small amount, 1.2 dB. The EPA was notoriously conservative in its approach but, if the criterion value is to be trusted, the implication is that some very small proportion of the population would sustain a lifetime noise-induced PTS greater than 5 dB. Neither the actual proportion, nor the amount of hearing deficit, may be quantified from the information available in this document.

4.3 Individual susceptibility, statistical aspects and percentage at risk

Individual variations of susceptibility to noise-induced PTS are manifested as a wide dispersion of hearing threshold levels in groups of people exposed for comparable times to the same or equivalent noise environments. At the present state of knowledge, noise-susceptible persons cannot be individually identified before exposure, but it is possible to predict that a proportion of an exposed population will suffer a specified degree of hearing damage from their collective noise exposure. Such calculations may be attempted with the aid of published data, and for illustration the International Standard 1999 will be used. As seen in the discussion above, our notional overflight noise with an 8 h equivalent level of 77.4 dB(A) would be expected to produce a noise-induced PTS of less than 1 dB at 4 kHz in 999 out of every 1 000 persons exposed on a daily basis for 40 yr. It must be recognized that this estimate is a two-fold linear extrapolation, and thus of dubious validity. Firstly, the equivalent level is at the low extreme of the range of the Standard; the expected hearing damage effects are an extension of the underlying data used to produce the mathematical formulations of the Standard. Secondly, the proportion affected, 1 of every 1 000, is itself a linear extrapolation beyond the given range of the Standard, namely 5 of every 100; given that the hearing threshold level distribution according to the Standard is Gaussian, this extrapolation appears not unreasonable.

With these *caveats* in mind, larger hearing losses would be expected in correspondingly smaller fractions of the exposed population. Let us consider a noise-induced PTS of 5 dB: this degree of hearing damage, the minimum suggested to to be noticeable or measurably significant, is more than 40 standard deviations removed from the expected median hearing loss. Such an extreme extrapolation is clearly untrustworthy; common sense suggests that the distribution of aircraft noise-induced PTS values cannot be Gaussian at either extreme. In the final reckoning, we can only offer an unsupported (but conservative) guess: overflights by military aircraft, with a noise level of 125 dB(A) and notional duration of 0.5 s, repeated once per day over a number of years, will probably not produce significant shifts of hearing threshold. Bearing in mind also that the above analysis assumes that the population remain outdoors for the full exposure time, *viz.* 12 h per day, 5 days per week, the risk will be even smaller in practice. For an event occurring once, or a few times only, the risk may surely be described as infinitesimal.

As a final point, it must be made plain that there cannot be a stated overflight noise limit which will protect every single individual from hearing damage. At very high noise levels, above those of interest here, it is certain that some individuals would suffer sudden sensorinueral hearing loss as a result of a single 'acoustic accident'. However, at realistic noise levels for overflight noise, the risk of such instant and catastrophic damage recedes to insignificance.

5. CONCLUSIONS AND RECOMMENDATIONS

(a) This report addresses the question of possible hearing loss due to aircraft overflight noise. The question is approached by focusing on a notional overflight, based on experimental data for existing military aircraft, and evaluating the risk from such an event, or series of events. For this evaluation, the current MOD maximum noise limit of 125 dB(A) is taken as the model.

(b) It was noted that the specification of a maximum sound pressure level, as presently stated in Ministry of Defence policy documents, is technically incomplete and capable of differing interpretations. Possible uncertainties due to this cause are examined, the most significant point being the time weighting (or averaging time) of the instrumentation used to monitor or verify observance of the limit.

(c) We recommend that the specified limit be explicitly qualified to mean the value obtained when the measurement is made with a calibrated sound level meter complying with Type 1 or better of BS 5969:1981, as amended by AMD 4413:1983, with the controls set to A frequency weighting and F time weighting. If other equipment (e.g. spectrum analyser) is used, the sampling and integration time should be chosen to be equivalent to the F time weighting, and the equipment should conform in other respects to the above specification. Standard practice should be followed with respect to microphone height above ground, and to calibration of the equipment for sound incident on the microphone in the same direction as that of the overflight noise being measured.

(d) The audiological foundation of the stated value, 125 dB(A), is obscure. The history of limits for high-level noise and the probable origin of the Ministry of Defence criterion are discussed; it seems likely that the level was set conservatively.

(e) Hearing loss due to noise may be of two distinct kinds:

(i) in the nature of an acoustic accident, the loss (which may either be conductive or sensorineural in nature, or a combination of both) being sudden and traumatic; such acoustic trauma is usually associated with explosion or blast at peak sound pressures higher than those in question; or

(ii) sensorineural and cumulative in nature, characterized by its relation to the total noise exposure over a period of time rather than by the magnitude of the noise level alone.

(f) One approach to the hearing loss question was to ascertain whether reliable evidence of actual loss (of either kind), clearly attributable to high noise-level aircraft overflight noise, already exists. In common with other investigators, we have found no such reports published, at least in the English language.

(g) In the absence of such evidence, two conclusions were drawn:

(i) no definitive statement can be made about the possibility of traumatic hearing damage at levels of the order 125 dB(A), beyond the observation that it is either non-existent, or so rare as not to have featured in the medical literature; and

(ii) the most profitable line of enquiry was the question of possible sensorineural hearing loss due to a single event, or a succession of events, representing noise exposure comparable to that stated in (a); conductive hearing loss was not considered a predictable result of noise exposure.

(h) On the basis that sensorineural noise-induced hearing loss is determined by a measure of total noise exposure, the limit value in (a) was interpreted in these terms, in order to facilitate comparisons with existing knowledge of the relationship between noise exposure and hearing threshold shift. To this end, data on the overflight noise levels of military aircraft in operational configurations which produce maximum levels in the order of 120 dB(A) or more were examined. These data were used to establish the typical shape of the noise spectrum, and hence the relationships between the overall sound pressure level, L, the A-weighted sound pressure level, L_A, and the A-weighted sound exposure level, L_{AX}, these being the measures which permit comparison with existing experimental data and published criteria. The data also yielded a typical value of about 0.5 seconds for the 'equivalent rectangular time window' of military overflights at the maximum level in question, that is 125 dB(A).

(i) The literature search did uncover a small number of population surveys of hearing loss related to aircraft noise. Quantitative results are scanty, and only one investigation produced audiometric results linked to noise measurements; even then threshold shifts as such were not determined. This study related to civil aircraft noise affecting residential areas, in which the cumulative noise 'dose' in a day's operations corresponded to about 10 times that of a single overflight producing a maximum noise level of 125 dB(A). No hearing loss was found in the affected population.

(j) The main body of information with which comparisons can be made of the hearing damage risk from military overflight noise is to be found in standards and regulatory documents published by various organizations. Comparisons are made with recommendations of ISO, BSI, US EPA, and HSE, and with regulatory documents (Noise at Work Regulations, Defence Standard 00-27). It is concluded, on the basis of these comparisons, that the risk of hearing loss due to a single event of 125 dB(A) maximum level and equivalent duration of the order 0.5 seconds is small, even after repeated daily occurrences over several years. The risk from a single exposure may be regarded as infinitesimal, based on extrapolation from population statistics of the variable incidence of threshold shift between individuals under the same conditions.

(k) Supplementary experimental evidence, involving temporary threshold shift (TTS), showed that a small amount of TTS might be engendered by military overflight noise at the levels in question, but that this would have no significant long-term effect even on the more susceptible ears.

(l) We consider that it is unrealistic to specify a limiting criterion level without explicit reference to the means used to implement it in practice. We do not believe that observance of a limit can, or should, rely on direct measurement at potentially affected sites, since there are circumstances (e.g. instrumentation error or emergency) which may cause the indicated sound level to deviate unavoidably from the norm or true value. We therefore recommend that the criterion value should be interpreted as the value held on file (from controlled flight trials) for the aircraft type in question operating in specified nominal conditions corresponding to those at the potentially affected sites where the aircraft is permitted to fly in those conditions.

(m) Our review and analysis indicate that occasional brief exposure to levels as high as 125 dB(A) should produce no lasting shift of hearing threshold. We believe that there remains a small margin of safety at this level. If, therefore, the criterion level is interpreted as in (c) and (l) above, we see no reason to vary the existing limit on grounds of potential hearing damage from military overflying.

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