PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
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Deafness due to Impulse Noise [and Discussion]

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Deafness due to impulse noise

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Introduction

The evaluation of the hazards to hearing experienced by exposure of the ear to noise has resulted in the specification of the physical characteristics of the noise in terms of damage risk criteria. In the case of steady state and relatively long on-period intermittent noises the researches carried out have resulted in the formulation of many such criteria (Glorig, Ward & Nixon 1962; Burns 1965; C.H.A.B.A. 1965; Kryter, Ward, Miller & Eldredge 1966), the interpretation of which in terms of an internationally agreed standard is at present being undertaken by the International Organization for Standardization (I.S.O.).

For exposure to very short duration steady-state noise, for noise superimposed with impulsive components, and for high-intensity impulsive noise, there is little information regarding damage risk. What does exist and the problems associated with the assessment of deafness due to impulse noise will be discussed in this paper. It must be borne in mind, however, that no criterion will clearly demark safety from danger and, being based on the light of the best available knowledge, may be subject to change as new evidence becomes available.

1. Exposures to steady state and intermittent noise

(a) *Existing specifications*

If a sound level-meter measurement is taken, then depending upon the duration of the exposure, levels in excess of 85 to 90 dB (A) are likely to constitute an auditory hazard. For example, a slight modification and extrapolation of an existing specification (Burns 1965) is shown in table 1 and in figure 3 which closely summarizes current opinion.

The need often arises, however, for closer spectral evaluation of the noise for the purposes of noise control or detailed hearing conservation programmes. Recourse can then be made to spectral analysis and the family of contours discussed in a specification of exposure to intermittent wide-band and narrow-band noises and to pure tones (Kryter *et al.* 1966). These additionally make provision for varying exposure durations down to less than 2 min, providing the level does not exceed 130 to 135 dB. It is in the specifications of the shorter duration exposures that more research is needed in order that the use of extrapolated material can be avoided.

(b) *Damage risk criterion*

The criterion to be applied to such specifications is not easy to define although such a form is shown in table 2, which was prepared by the U.S. National Academy of Sciences, C.H.A.B.A. Working Group 46 (1965). This states that the noise exposure will be acceptable if it produces a noise induced permanent threshold shift (n.i.p.t.s.) after 10 years of near daily exposure, of values not exceeding those indicated (Kryter *et al.* 1966; Ward 1966).

The work on which these evaluations has been made is mainly based on retrospective surveys or temporary threshold shift measurements. The difficulties of interpretation of the former, together with the moral obligations to protect ears at risk and the time span needed for the more desirable prospective survey, has led to the use of experiments involving the measurement of temporary threshold shifts (t.t.s.) of subjects exposured to carefully controlled noise situations.

TABLE 1. RELATIONSHIP BETWEEN EXPOSURE LEVEL AND DURATION FOR EQUAL AUDITORY HAZARD

sound pressure level (dB(A))		
based on Burns (1965)	extra-polation	duration (min)
80	—	up to 480
—	90	300
91	—	240
94	—	120
—	95	100
97	—	60
—	100	35
101	—	30
—	105	18
107	—	15
—	110	10
113	—	7
—	115	6
—	120	3·5
—	125	2

TABLE 2. DAMAGE RISK CRITERION FOR ACCEPTABLE EXPOSURE TO A NOISE SPECIFICATION (C.H.A.B.A. 1965; Kryter *et al.* 1966)

frequency (Hz)	proportion of people showing loss of		
	50 %	20 %	10 %
1000	10 dB	20 dB	30 dB
2000	15	30	45
3000	20	40	60

2. IMPLICATIONS OF T.T.S. MEASUREMENTS

(*a*) *Interpretation of measurements*

The specification of a criterion in terms of t.t.s. studies requires careful interpretation with respect to n.i.p.t.s. Three postulates have been suggested (Kryter *et al.* 1966) which form the basis of this type of work, and these are:

(i) Average t.t.s. (2 min) (t.t.s. measured 2 min after exposure) is the most consistent measure of the effects of a day's noise exposure (conversion to t.t.s. (2 min) from other exposure-retest intervals (Kryter 1963) is possible.

(ii) All exposures that produce a given t.t.s. (2 min) will be equally hazardous.

(iii) In principle average t.t.s. (2 min) = n.i.p.t.s. (10 years), although variations with frequency are thought to occur up to ±5 dB.

In many types of noise exposure t.t.s. occurs maximally in the 4000 to 6000 Hz region and changes into n.i.p.t.s. more rapidly in the first 10 years, diminishing in rate and spreading in frequency involvement thereafter. A t.t.s. which approaches and exceeds

40 dB is considered to be on the borderline of a serious exposure, recovery from which occurs at a much slower rate and may not be complete. It is usually considered that for t.t.s. < 40 dB recovery occurs quickly, often within minutes, but up to a maximum of about 16 h.

(*b*) *Reliability of individual and group exposure*

The use of t.t.s. measurements involves the assessment of both group and individual susceptibility to t.t.s. Evidence quoted (C.H.A.B.A. 1965; Kryter *et al.* 1966; Ward 1966) suggests that a group average t.t.s. (2 min) of about 20 dB resulting from exposure to steady-state types of noise would have a standard deviation (S.D.) of about 6 to 7 dB, and a given ear to similar exposures on different occasions a S.D. of about 4 dB. For impulse noise it is thought (Hodge & McCommons 1966) that the scatter due to individual t.t.s. on different occasions is so large as to be unable to permit generalizations, but group mean t.t.s. varies only slightly and therefore provides a reliable measure although with a wider scatter about the mean than is the case with steady-state noise. It has also been suggested (Kryter 1966) that it is not unreasonable to suggest that t.t.s. to both steady state and impulse noise is caused by the same fundamental process. However, this is a matter of some controversy and in fact the nature of t.t.s. would seem to be too complicated for a simple explanation (Ward, Glorig & Selters 1960) and may be a function of the relatively slow mechanical bending of the tectorial membrane to conform to the deflexion envelope of the basilar membrane, and is therefore a mixture of mechanical as well as the more usually accepted neural processes (Crane 1966). In spite of the limitations indicated above it is still likely that the best indicator of hazard would be the t.t.s. (2 min) end-of-exposure measure.

(*c*) *Group susceptibility grading*

The concept of the average response does not seem to be totally acceptable in view of the wide variety of parameters affecting t.t.s. It would seem more appropriate to split people into three groups (Rice & Coles 1965) depending upon their noise sensitivity (e.g. tough, average, tender ears) and treat each group separately including the derivation of separate t.t.s. (2 min) corrections appropriate to each group.

(*d*) *Acoustic reflex*

Another factor complicating t.t.s. is the part played by the reflex contractions of the middle ear muscles in affording a limited degree of protection in the presence of certain types of noise. While the evidence (U.S. Army 1963; Ward 1962) suggests that protection can be provided for certain pulse repetition rates, taking into account the latency of the contractions (20 to 150 ms), recent work has shown that the reflexes appear to be of little practical importance in defining individual susceptibility to t.t.s. (Brasher, Coles, Elwood & Ferres 1966) from constant level or intermittent widely separated impulses. This result is based on an experiment designed to see if reflex threshold and strength of supra-threshold muscle contraction in response to impulse and steady-state sounds, coupled with t.t.s. measurements allows separation of the tough and tender eared person. Whilst correlations between various acoustic reflex measurements were high, correlation between t.t.s. from different types of noise was low, and no relation appeared to exist between the acoustic reflex measurements and t.t.s.

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3. Exposure to short duration and impulse noise

(*a*) *Existing criteria*

From consideration of the specifications for noise exposure it appears that as the duration becomes shorter the ear becomes more tolerant to an increasing level. However, a 135 to 140 dB limit has generally been accepted (Burns 1965; C.H.A.B.A. 1965; Kryter *et al.* 1966) as the maximum permissible exposure level, until recently when the relevance of whole body and ear exposure to explosions and small-arms types of noise was discussed (Rice & Coles 1965; Coles *et al.* 1968). It is now thought that levels well in excess of the 140 dB ceiling can be tolerated depending upon the pulse durational characteristics and

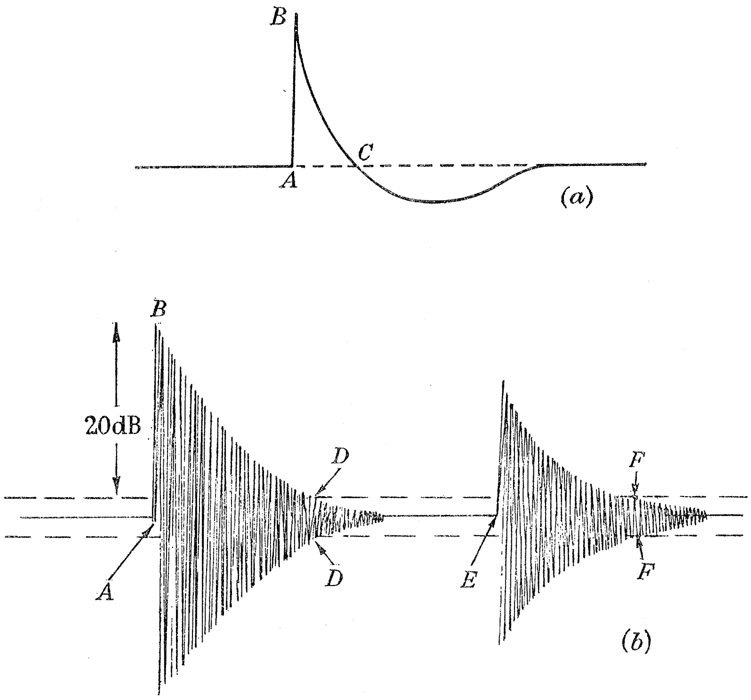

Figure 1. Idealized evaluations of oscillographic waveforms of impulsive noises. Peak level = pressure difference AB, rise time = time difference AB. (*a*) *A* duration = time difference *AC*. (*b*) *B* duration = time difference *AD* (+*EF* for example in the case of a relatively long time reflexion).

the number of pulses, and that ear-drum rupture is most likely to occur at about 185 dB (von Gierke 1966; Rice & Coles 1968). Other published work (von Pfander 1965) also states that levels of up to 165 dB are safe provided the duration does not exceed 3 ms. This relates to steady-state noise bursts or to exponentially decaying pulses when the duration is defined as the product of the time the level is within 10 dB of the peak value times the number of impulses, with an equal energy correction for varying levels.

(*b*) *Hazardous exposure to impulse noise*

A contemporary review and evaluation of the hazards of high intensity impulse noise, together with new evidence obtained by t.t.s. and loudness studies, has enabled the formulation of a specification and damage-risk criterion (Coles *et al.* 1968). The noise is defined in terms of peak level and duration as shown in figure 1. The specification is shown in figure 2 and the criterion values are not to exceed t.t.s. (2 min) of 10 dB at or below 1000 Hz, 15 dB at 2000 Hz and 20 dB at or above 3000 Hz for the 75 percentile of the population exposured to the noise. Reference to the 50 percentile is achieved by raising the contours by 5 dB and to the 90 percentile by a lowering of 5 dB.

The following allowances must also be taken into account, departures from which would require special consideration:

(i) Repetition rates are in order of 6 to 30 impulses per minute, 50 to 200 impulses per occasion up to 10 occasions per year.

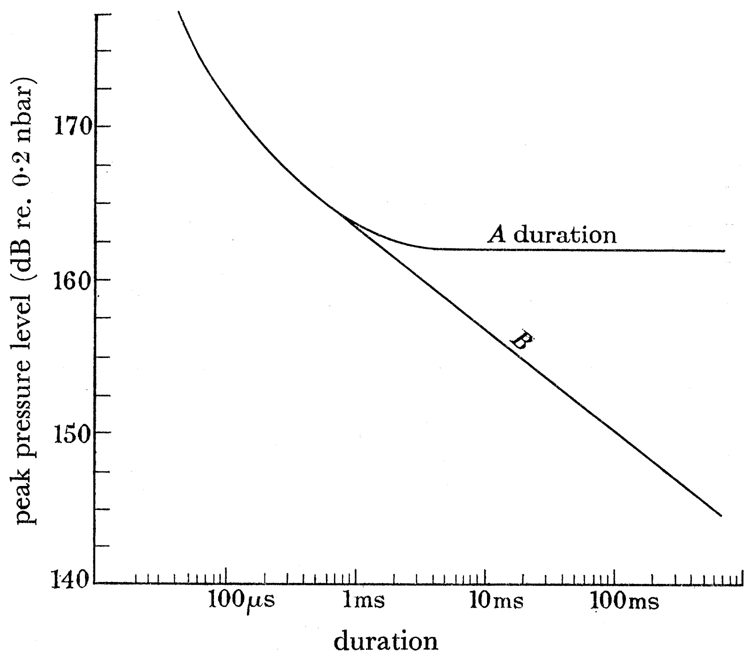

FIGURE 2. Specification of impulse noise.

(ii) The contours should be lowered by 5 dB where the impulses reach the ear at normal incidence, except under reverberant conditions.

(iii) For exposure to occasional single impulses the contours may be raised by up to 10 dB.

(iv) The attenuation provided by good quality ear defenders varies between 20 and 35 dB depending upon whether plugs or muffs are used and upon type and fit (Rice & Coles 1966).

A recent extension of this work (Forrest 1967) has defined more clearly the problems associated with the measurement of the noise sources, and resulted in the formulation of a modified damage risk criterion. This takes into account the number of exposures, extrapolates to longer durations and discusses the limitations in data interpretation.

(c) *Discussion*

Thus the specifications which exist for a single exposure to noises of known duration and to which an equivalent criterion can be applied are shown in figure 3. The curves shown in this figure are thought to be valid for a first order of approximation and are based on table 1 and figure 2. Allowance has been made in the contours to account for a single exposure, conversion from the 75 to 50 percentile, peak to r.m.s. allowance, and conversion from exponentially decaying to continuous noise burst.

From this it can be seen that a distinct gap appears in the region of exposure durations of 1 to 100 s, and for exposure to steady-state noises which have impulsive components superimposed upon them. This is a problem which needs attention, preferably by controlled t.t.s. investigations and by long-term prospective surveys in such noise environments as present this type of noise problem.

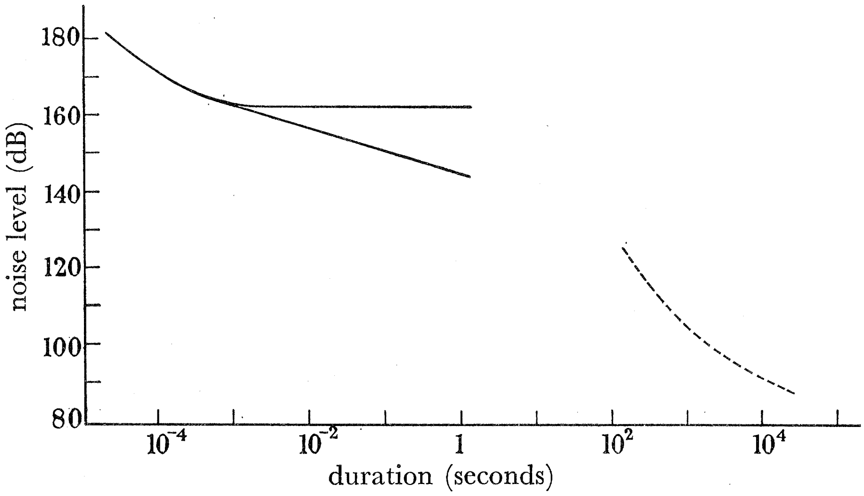

FIGURE 3. Specification for damage risk (levels not to be exceeded according to criterion). ——, after Coles, Garinther, Hodge, Rice 1968; ----, after Burns 1965.

4. EVALUATION OF IMPULSE NOISE SOURCES

(a) *Typical industrial noises and existing methods of assessment*

Of the varied industrial types of impulse noise which commonly occur most can be assessed to some extent by the existing criteria. Take for example a strip metal blanking process which is subjectively most unpleasant, has a background level of 109 dB (A), a repetition frequency of 5 pulses per second and a true peak level taken from oscillographic recordings of 126 dB. The steady-state criterion allows a daily exposure of about 10 min to a noise of 109 dB (A) so that further evaluation is irrelevant for the full-time worker, as this level already constitutes a hazard, and hearing conservation measures should be instituted. However, additional corrections could be made for peak/r.m.s. ratio as the impulse noise criterion (Coles *et al.* 1968) is not applicable in this case. For repetition rates above about 1 or 2 per second therefore a single meter reading correcting for peak/r.m.s. ratio by using a fast time constant might give an intermediate level which is a somewhat more realistic appraisal of the time hazard. Such a meter should also give normal sound level meter readings once the impulses become fused together.

The pile drive operator is another person at risk but in this case the impulse is less regular and the time spacing between impulses may be several seconds or even minutes. The actual impact noise of the pile being driven does not always appear to constitute an acute hazard to the operator if interpreted by the impulse noise criterion (Coles *et al.* 1968). The main hazard comes from the generating plant on the operators platform which in the case studied had a background noise level of 98 dB (A). The true peak level being about 132 dB depending on the pile and the depth already sunk. Again it is obvious that an additional correction ought to be made and in view of the rather long interpulse interval, perhaps the dB(A) reading (in one case 109 dB(A)) taken with the sound level meter would be suitable, bearing in mind that subjectively the impulse noise was not particularly unpleasant.

Another commonly occurring impulse noise is that due to a craftsman beating metal, which is not too hard to assess in terms of the number of impulses and the physical characteristics of the noise. If the impulse damage risk criterion (Coles *et al.* 1968) is used, then a fairly close evaluation can be made as is evidenced by the marine coppersmith striking a metal hemispherical shell with a hammer. The typical true peak level recorded was 147 dB with a 'B' duration of 150 ms, which together with a 5 dB allowance for the characteristic pure tone ring of the shell which was distinctly unpleasant, enables evaluation in terms of the existing impulse noise criterion without undue recourse to extrapolation.

It is evident therefore that many industrial impulse noises are accompanied by background noises which are hazards in their own right, and the need for sophisticated interpretation may be unnecessary.

(*b*) *Problems in impulse noise measurement*

The most convenient means of measuring steady-state noise is with the sound level meter. For very short duration and for certain noises which contain impulsive components, limitations occur due to the ballistic characteristics of the meter being unable to represent the increasing peak/r.m.s. ratio, and the lack of information afforded regarding the durational characteristics of these components in the noise.

For impulsive noise the ear seems to be affected by the instantaneous rather than the average power, which means that alternative forms of measurement must be found. Such a device might be the impact sound level meter, although this has not proved particularly useful for the measurement of the high-intensity short-duration single impulses discussed earlier (Rice & Coles 1965; Coles *et al.* 1968). The main use of such a device would appear to be rather in the noise control of impulse sounds, in which case if either or both the peak value and time average readings are reduced, then the subjective and hazardous nature of the noise might also be presumed to be reduced (A. Peterson 1967, personal communication).

The use of oscillographic recording techniques, although cumbersome, enable amplitude-time histories of the noise to be made, and this method seems most applicable in the present state of knowledge of data interpretation (Coles *et al.* 1968). The use of tape recordings and filtering enables the spectral distribution to be analysed, although impulse noises of high intensity generally have a broad-band spectral distribution and such detailed analyses may not always be so necessary. The hazards due to the impulsive components would seem to depend upon many additional characteristics including pulse shape, pulse repetition frequency, and burst-background noise ratio and even if evaluation of the noise in terms of all these additional parameters could be achieved, their incorporation into a commercial instrument might be difficult.

It is possible that a relatively simple meter, having fast-time constant facilities and enabling the instantaneous weighted over-all and the maximum narrow-band pressure level readings to be corrected for peak r.m.s. ratio and pulse repetition frequency, might suffice provided suitable correlation with t.t.s. measurements could be achieved. In any case it appears that a time integrated reading somewhat closer to the true peak level than the r.m.s. value provided by existing sound level meters is required, but even this might not account completely for the durational characteristics of the impulse noise.

(*c*) *Loudness of impulse noise*

Several methods (Pollack 1958; Garrett 1965; Zwicker 1960, 1961; Port 1963; Pfeiffer 1964; Niese 1965; Reichardt & Niese 1965–66; Zepler & Harel 1965; Rice & Zepler 1967) have been suggested for the measurement and evaluation of the loudness of varying types of impulse noise, but few have been applied to those types of noise likely to cause a hazard to hearing. Due to the controversy which exist between the relative merits of these methods and the unproven hypothesis that loudness is related to damage, it is probably unwise to read too much into the value of loudness studies in the assessment of impulse noise hazards. However, the use of loudness meters as they become commercially available should not be overlooked, particularly if they incorporate the faster time constants discussed in the preceding section.

Conclusions

The prediction of deafness due to impulse noise has reached a stage where very careful planning of future research is needed. If not, then the uncertainties and extrapolations used for the establishment of steady-state noise criteria will persist. In particular the over-sophistications which could arise in the measurement and interpretation associated with impulse noise are likely to become the paramount problems compared with the real object which is the assessment of the auditory hazard.

The following recommendations are suggested:

(1) Monitoring audiometry should be initiated on all people at the commencement of their employment in noise environments, and the results made available for assessment.

(2) Carefully controlled t.t.s. experimental and prospective surveys must be carried out in order to assess correctly the additional hazards due to impulse noise exposure.

(3) The evaluation of the noise in terms of its physical characteristics and the incorporation of the means for measurement of the information is required in a relatively simple meter.

(4) If a sound-level meter reading gives a value that is close to or exceeds the steady-state criteria, and impulsive components are present, then it may be presumed that an additional hazard exists and this should be allowed for in the assessment of the hazard using existing criteria.

The author wishes to thank the Royal Naval Medical School, Alverstoke, and the Medical Research Council for their support of the work leading to the establishment of the impulse noise damage risk criterion to which frequent reference has been made (Coles *et al.* 1968).

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Discussion

Comments on the papers by Rice, and Passchier-Vermeer, and van Leeuwen

By R. R. A. Coles, *R.N. Medical School, Alverstoke*

Noise-induced hearing loss is not restricted to the high frequencies. With Knight (Knight 1962; Coles & Knight 1965) I have shown that intense low-frequency non-impulsive noise has caused handicapping hearing losses in the 500 to 2000 Hz region when measured about 6 weeks after last noise exposure. Low-frequency noise as a possible cause of mid-frequency hearing loss should not be overlooked in consideration of hearing conservation criteria. As a matter of further interest these men recovered their hearing, in most cases completely and in the remainder almost completely, during a 2-year period of relative freedom from noise (Knight & Coles 1965). This finding makes it very difficult in any form of audiometric survey or in a case for compensation to be sure how much hearing loss is permanent, and any conclusions in terms of likely permanence drawn from examinations performed within, say, 6 months of noise exposure should be very guarded.

Another difficulty in conducting either audiometric surveys or t.t.s. experiments is the fact that the amount of t.t.s. at the end of a day's exposure bears an inverse relation to the hearing level at the start of the day. The data of Ward (1966*a*) showed such a relation, but whereas the persons with normal hearing only got an average of 30 dB t.t.s. at 4000 Hz, those with 40 dB initial hearing level still got some t.t.s. (about 10 dB); that is, for every decibel increase of initial hearing level the amount of t.t.s. to be expected from a day's exposure to the same occupational noise decreases by considerably less than 1 dB. If t.t.s. at the end of the day does indicate eventual likelihood of permanent loss (Glorig, Ward & Nixon 1961), then it is difficult to explain the data commented upon other than by assuming those with normal hearing to start with had less *average* noise sensitivity, and those with markedly elevated hearing levels to start with had acquired their hearing loss because they were *on average* more sensitive to noise. In assessing individual cases the speaker agrees with Ward (1966*a*, *b*) that finding greater than average hearing loss does not necessarily mean a greater than average noise sensitivity, but maintains his premise (Coles & Knight 1966) that, in groups of similar general environmental background, dividing into subgroups by initial hearing level is an index of average noise susceptibility within each subgroup. Irrespective of these arguments though, the suggestion made by Dr van Leeuwen of measuring the total hearing loss (p.t.s. + t.t.s.) at the end of a working day seems a most reasonable way of assessing the ultimate p.t.s. likely to develop from regular unprotected exposure to the noise concerned.

In considering Mr Rice's paper on the auditory effects of impulses superimposed on a high background noise level, it may be relevant to consider the experiment by Ward, Glorig & Sklar (1958) in which he showed that the t.t.s. arising from 101 dB noise was the same as that caused by a noise alternating between 106 and 96 dB: on the basis of this, they state that the average sound pressure rather than average energy is the rule for assessing the effects of fluctuating noise levels. However, the amount of high-frequency t.t.s. (Kylin 1960), or of permanent hearing loss as shown in the paper by Mrs W. Passchier-Vermeer caused by a given duration of exposure does not increase linearly with the sound-pressure level of the noise, i.e. auditory effects tends to grow by increasingly greater amounts as sound-pressure level rises. It may, therefore, be that a considerable loading should be given to the higher intensities in a fluctuating or semi-impulsive noise when assessing its auditory hazard potential.

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