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THE PROTECTION OF HEARING

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NUMEROUS appliances for the protection of hearing are being manufactured and in some areas a free distribution of ear defenders has been made to the general public. The recent progress of scientific experiment and the needs of certain branches of the fighting services make it advisable to survey existing knowledge about wartime dangers to hearing and the best methods of preventing traumatic and occupational deafness.

It is possible to differentiate between two principal types of war injury to the organs of hearing. There is the risk of excessive atmospheric pressure which may be of exceedingly brief duration, due to impulsive and transient sound in the neighbourhood of an explosion. It is clear from the survey of the literature published by Bunch in 1937 that chronic deafness can be caused by the explosion of a single shell or mine.

The phenomena of non-auditory sensation arising from aural stimulation by very loud sound have been investigated by Wegel and by Bekesy. The former discovered that there is a maximum loudness level, approximately 120 to 130 phons, which the normal ear can endure without discomfort or pain. The existence of a mechanism appears to be indicated which warns the listener of the onset of acute danger to hearing from excessive sound. Pain is the danger signal and is most likely

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to be caused by sound which ranges in frequency from 1,000~ to 3,000~. Unfortunately this protective mechanism does not indicate the presence of danger to hearing from sound which is less intense, and therefore not painful, but which may, if experienced over a sufficiently long period, cause auditory fatigue leading to chronic deafness. The best indication of the risk of injury arising in this manner is probably a regular experience of tinnitus after each spell of work. Thus some observers have reported a " singing in the ears " on going to bed, which has been prevented by the adoption of suitable methods of ear protection. Laboratory experiments have proved that occasional and brief exposure to sound loud enough to cause tinnitus does not produce chronic deafness. It must be emphasized that only when tinnitus is of daily or nightly occurrence and when its association with exposure to noise can be clearly proved, does it constitute a warning sign.

The investigation by exact methods of the danger to hearing from this second source, i.e. noise of a continuous and prolonged nature, has become possible only since the introduction of audiometry. This modern technique is well adapted to the investigation of occupational and traumatic deafness, because it is possible to compare the exact extent of hearing loss at different points in the frequency range with similar physical measurements of the noise to which the deafness is attributed.

The present writers, with T. S. Littler, have described in a previous communication how flying and ground personnel of the Royal Air Force were found prone to high tone deafness after as little as a hundred hours exposure to aeroplane noise. It was shown, however, that the risk of injury to hearing was greatly diminished by suitable methods of protection whose operation had been investigated experimentally.

To insulate the ears from sound of low pitch proved to be remarkably difficult. Measurements were made of the noise experienced in or close to various types of service aircraft. Its chief components are due to the engine (mechanical exhaust) and the propeller. The frequencies giving the highest relative intensity were found to be those below middle C, viz. between 30~ and 200~. It seemed difficult to avoid the conclusion that very intense sound of low pitch might be responsible for high tone deafness. Previous workers on auditory fatigue had observed maximum deafness over a range of pitch approximating to that of the fatiguing tone.

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A problem of immediate significance was therefore involved, whether insulation against low-pitched noise is essential if ear protection is to be fully effective. Improvement in the design of ear defenders would be greatly facilitated if this problem could be solved. Much of the present paper describes recent experiments made by the writers to this end.

Available Methods

Two principles have been followed by designers of ear defenders. The first is the traditional conception of occluding or plugging the external canal. The second is to cover the external ear or even the whole head. Sometimes both methods have been tried in combination.

The difficulties of blocking the meatus can be stated shortly. It is a curving passage and variable in size and shape among individual subjects. Sometimes there is a difference in these respects between the two ears of the same subject. Ideally the whole passage should be plugged but as the tympanum is approached the pressure of a foreign body causes acute discomfort and then pain. There are, therefore, subjective as well as anatomical obstacles to the most effective use of ear plugs. Confidence and thoroughness can only be developed by instruction, as in the case of gas masks. It will be shown later that well-fitting ear plugs inevitably diminish capacity to hear speech just as the gas mask affects vision. Effective occlusion of the meatus causes the subject's own voice to seem abnormally loud to him, all the more since the accustomed background of external sound is partially eliminated. A minimum of training is needed to habituate the mind to these unfamiliar conditions of hearing.

To cover the external ear involves less potential discomfort but once more the chief physical difficulty is to obtain a perfect seal. It must be emphasized that no device is effective unless it is completely tight-fitting. Sound penetrates through minute apertures, hence the very small amount of protection given by plugs of dry cotton wool, which is somewhat harsh as well as porous and therefore for both reasons leaky.

Pure-tone measurements

An experiment was made at Manchester to determine the average amount of protection obtained by a group of eight untrained subjects. Preliminary tests of ten appliances had

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indicated four kinds of defenders as being the most effective which could be made available for public use.

The average results obtained by two trained workers in a series of tests provide control figures for two of these types.

Type A was a plug with metal core inserted in a soft rubber casing, the latter attached to the metal in such a way as to enclose an air space between the two materials.

Type B was a wax plug covered by soft fabric, softened by contact with body temperature and therefore capable of being moulded to the shape of the individual ear.

Type C was a tapering rubber tube closed at the outer end. The material was somewhat harder and less flexible than that of type A.

Type D consisted of two specially designed soft leather pads, one for each ear, to be strapped on the head and fastened under the chin.

The method of test was to measure the minimum increase in intensity above the subject's normal threshold of audibility which was needed to make the sound heard when he or she was wearing each of the protective devices. The subject listened binaurally and the source of sound was a loud-speaker placed three metres from his head in prepared acoustic conditions.

It has not proved satisfactory to test the sound insulating properties of ear-plugs or caps by holding the telephone over them. This method, when attempted, gave variable and, as regards low frequencies, exaggerated results, which seemed to depend upon the extent to which the air space within the ear cavity was filled up by an ear-plug as well as on the amount of protection afforded.

Littler has described elsewhere an investigation indicating that the external auditory meatus must be regarded as a resonator, having in its normal condition a characteristic natural period which may be altered by being partially filled with solid material.

It was an essential part of our experiment that the protective devices should be supplied to the untrained subjects in the same conditions as those in which they are at present sold to the general public. No preliminary instruction was therefore provided by us. The printed directions which are

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regularly enclosed in packages of plugs of types A and B were undoubtedly helpful to the untrained subjects.

The trained workers probably scored an advantage through having had experience in earlier work aimed at achieving the maximum elimination of speech and other sound. They also endeavoured to straighten each auditory canal when inserting any of the plugs. Neither set of printed directions provided by the makers included advice to that effect and this precaution was not taken by any of the untrained subjects.

The following table A shows the average amount of protection at three levels of frequency obtained by each set of subjects.

TABLE A.

Amount of protection (dbs) obtained by lay subjects and by trained workers.

Form of protection.	Subjects.	Level of frequency.		
		250	1000	3000
Type A.	untrained	4·4	0·6	19·4
	trained	20·3	18·5	26·8
Type B.	untrained ..	5·0	5·6	20·6
	trained	11·3	17·5	34·5
Type C.	untrained ..	3·8	0·6	15·6
Type D.	untrained ..	3·8	1·3	16·3

A number of observations may be made on the results.

(1) Like all other means of protection tried by the writers these four devices were more effective in excluding sound of high than of low frequency. This conclusion holds good in general for materials applied to the elimination of noise, when tested as sound partitions. In daily life voices can often be heard through room walls and closed doors, but the sound is distorted by transmission through the intervening solid materials. The high-frequency components of speech, on which its intelligibility mainly depends, are largely suppressed, so that the resulting sound is blurred and muffled.

(2) The ear-plugs of the two more solid types were superior to the plugs of lighter material and to the leather pad. This again is consistent with results usually obtained in tests of the transmission of sound through solid partitions. In the construction of sound-proof rooms brick or concrete walls play the chief part.

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(3) The trained workers secured much more protection than the untrained at all frequencies. This appears attributable to the greater success of the former in achieving a tight seal. The precaution was taken of examining critically the results of all the subjects in the threshold tests made without protection. The average thresholds of audibility of the untrained subjects were found to approximate closely to those of the trained. There was therefore no underestimation of the amount of protection secured by the untrained through lack of skill on their part in hearing sound at very weak intensities.

(4) All four types of protection were definitely effective, although in varying degrees.

(5) As regards the two most effective devices—the untrained subjects were more successful, at all three frequencies tested, with type B than with type A. The figures suggest that plugs of type A require more skilful manipulation. The evidence of these two series of tests thus emphasizes the importance of care in adjustment and of the minimum time required for fitting. The experiments were not timed but it is probable that type D (leather pad) could be more quickly fixed in place than any of the three kinds of ear-plugs.

The choice of the most suitable method of ear protection for a particular noise background must depend partly on whether the device has usually to be fitted in a hurry and for a sudden emergency or whether, as in the case of the aeroplane mechanic or the riveter, the danger to hearing is of a routine nature synchronizing fairly constantly with regular hours of work.

Noise Tests

The effects of very intense complex sound on the ear cannot be understood without reference to factors additional to those already mentioned. They are not to be elucidated solely on the basis of pure tone tests, although those provide the most exact known method of measuring hearing.

Since our last publication on ear protection, we have been able to investigate further the efficiency of certain methods of ear protection in actual working conditions of very intense noise. Tests have been made in the air and in a workshop where aeroplane engines are run at considerable speeds on the bench.

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Plugs of type A were tried by a number of expert subjects with a 480 h.p. engine running at 2,300 r.p.m. on the test bench. The noise level was very high—130 phons. It was found that wearing the plugs made the noise tolerable, but that partial deafness began after an exposure to it of about 15 minutes. Complete recovery did not take place until approximately 15-30 minutes after it had ceased. Attempts to shut out the noise by inserting the plugs more deeply were unsuccessful and caused marked discomfort.

Ear defenders designed to occlude both the auditory canal and the auricle were tested during flight in a twin-engined bomber. Again it was found that if the sealing of the ear was made effective by careful fitting, " the sting was taken out of the noise " but deafness was not prevented. This experiment was made by one of us as subject.

Thirdly, the type A plugs were worn during a flight of about one hour in a twin-engined bomber at an altitude of 2,000 to 3,000 ft. and at 2,200 r.p.m., also in another twin-engined bomber during a flight of $1\frac{1}{2}$ hours at 2,000 ft. and at 2,300 r.p.m. There was in both cases some diminution of auditory acuity as measured with a 4096~ tuning fork on landing. As we have reported elsewhere, it is at this frequency that the onset of temporary and of chronic deafness due to aeroplane noise is first apparent. Deafness was more marked in the ear which was nearer to the engine. A sensation of woolliness in the ears was experienced after these flights.

Finally, several engineers undertook to wear flying helmets of the high altitude type during test bench work. Their observations may be summarized as follows :

(1) The helmets increase comfort but give insufficient protection in extreme cases. When they are used in conjunction with ear plugs of plasticine and even of cotton wool the result is improved.

(2) Use of the helmets alone prevents the singing in the ears which is ordinarily experienced at night after their kind of work.

(3) The head becomes uncomfortably hot after about two hours use of the helmet. (A lighter helmet, which nevertheless affords protection from noise, has been made to meet this difficulty, which is also experienced by personnel flying in enclosed cockpits.)

These practical tests of ear protection have been made in

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noise conditions which are never equalled in civil life. The noise level of 130 phons measured in the experiments with aircraft engines on the test bench was considerably greater than that which was met in the earlier part of our investigation. It exceeds that found in the cockpit of twin-engined bombers, and this, no doubt, accounts for the incompleteness of the protection given by the well-adjusted flying helmet.

Measurements which we have been able to make in the laboratory indicate approximately the extent to which methods of ear protection diminish the intensity of a complex sound as a whole. The method of test was as follows:

Sound was reproduced from selected H.M.V. gramophone noise effect records. The apparatus consisted of a piezo-electric pick-up connected through a calibrated attenuator system to a four-stage amplifier in which a high-tension battery supply of about 400 volts was used for excitation of the last valves. The output from this amplifier was taken to a Western Electric 555 moving coil loud-speaker fitted to an 11 ft. exponential horn. The maximum intensity level of sound available by these means when measured with a Western Electric noise meter, model 30505-A was found to fluctuate between 96 ± 4 phons, using the circuit weighted to give an ear-like response.

The loudness of sounds may also, in certain circumstances, be estimated from measurements of the extent to which they mask other sounds of known frequency and intensity. A well-known method is to switch on a given pure tone and to increase its intensity until its presence is just detectable in presence of the noise. Owing to the large intensities at which we were reproducing our masking noises and to avoid fatiguing the ears of the subjects, we found it advisable to reverse this procedure.

The resulting audiograms indicated that the gramophone records of aeroplane noise and of thunder, which were most used, produced complex sounds with components of more uniform intensity over the frequency range 250 to 3000 than characterizes the results of noise frequency in service aircraft shown in Fig. 1 below. Nevertheless the sound at $250\sim$ was found to have a loudness level of about 75 phons and the results of the experiments are helpful in indicating the relative efficiency of the different methods of protection when measured in this way by trained workers.

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TABLE B.

Noise tests of ear protection.

Method.	Type.	Protection (in decibels).
Plugs	A	25
,, ...	B	25
,, ...	C	15
Leather pad	D	10
High altitude flying helmet fitted with telephones as during use in Service conditions		20
Helmet and plugs	A	35
,, ,, ...	B	35
,, ,, ...	C	30

The maximum protection by helmet and plugs combined was thus considerable but less than the sum of the protection obtainable from either plugs or helmet worn separately. The subjects were invited to make qualitative observations on the effects of each form of protection. They agreed in concluding that while type A plugs seemed to reduce the loudness of the noise components in a relatively uniform manner throughout the frequency range involved, the helmet, when worn without plugs, appeared to eliminate much of the high-pitched sound while leaving the bass components prominent.

Causation of deafness by noise

Comparing the observations made in the aircraft workshop with the laboratory measurements it may be concluded tentatively that a reduction of the loudness level of aeroplane noise from 130 to 105 phons, by means of ear protection, made the noise tolerable but not innocuous. A further reduction in noise intensity to 95 phons, by increasing the amount of protection, seems to have eliminated the risk of deafness.

It is evident that effective protection for workers in boiler factories and weaving sheds, where the maximum noise level is about 100 phons, is much easier to obtain than for flying personnel and aircraft engineers and mechanics.

With constant increases in engine power the noise level within military aeroplanes or in close proximity to them has come not infrequently to exceed 125 phons. More detailed study of the problem necessitates reference to the results of noise frequency analysis. The four diagrams below, show measurements made in types of military aircraft.

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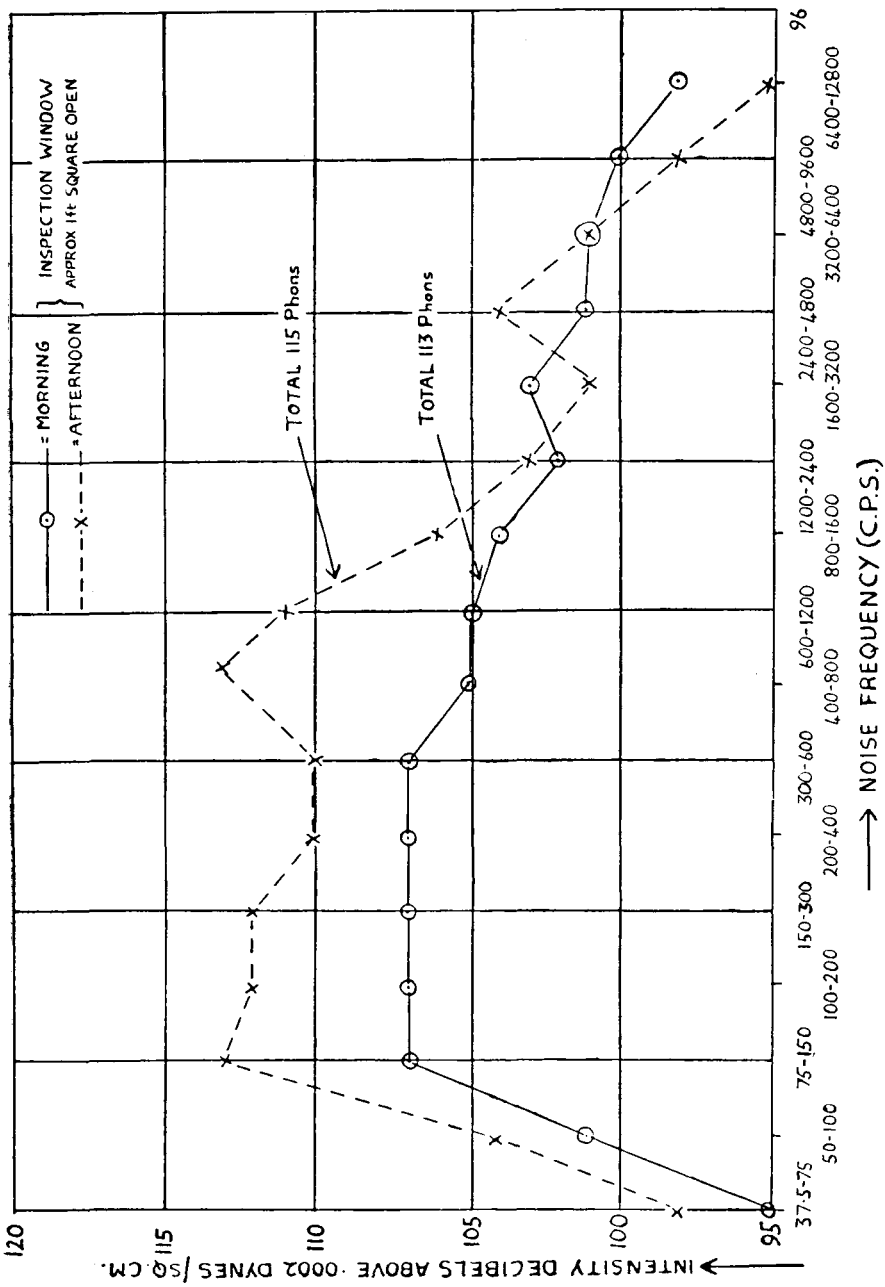


FIG. 1.

Noise Frequency Analysis in a Twin-engined Aircraft.

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In the first case there was a slight reduction in the noise level when the window was closed as compared with when it was open. The components with greatest intensity are of low pitch but sound up to 4800~ was recorded with an intensity of 100 decibels above the threshold of audibility.

Reference to Table A above indicates that by wearing plugs of type A a trained observer could enjoy protection which would reduce the noise to a level of about 95 decibels above the audible threshold.

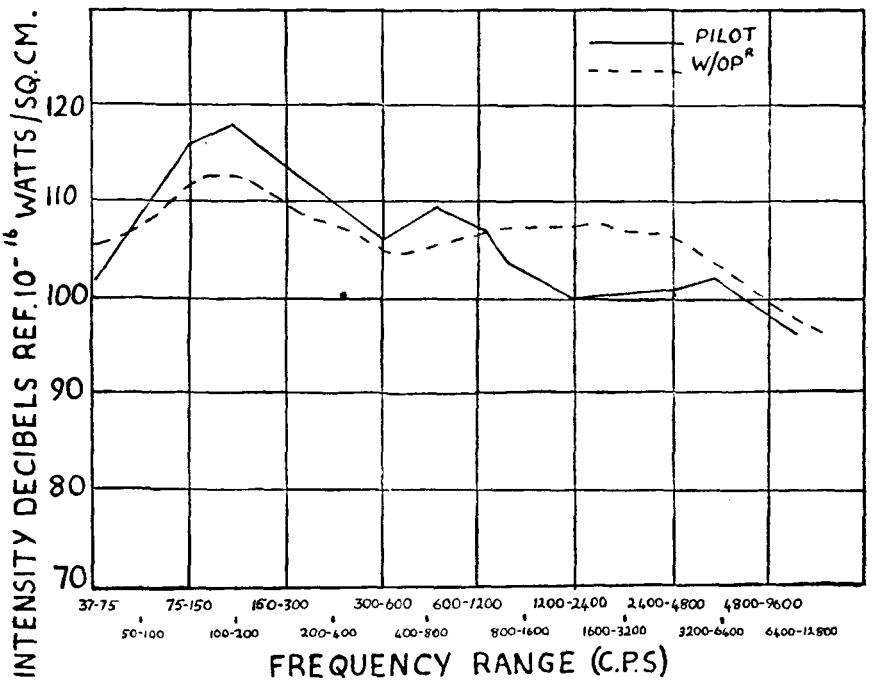


FIG. 2.

In experiments previously reported by Ewing and Littler it was found that at 2048~ the minimum intensity which would cause aural fatigue in the average normal listener was 85 decibels above the threshold of audibility although it was indicated that there is greater susceptibility in some individuals. Severe auditory fatigue was caused only by sound of considerably greater intensity.

Interest attached to the pitch at which the components of aeroplane noise are loudest—namely at low levels of frequency.

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It will be remembered that it is here that it is most difficult to provide protection. Yet the evidence, in these and in our earlier tests, has been that the onset of occupational deafness may first be detected through measurements of the subject's acuity round about the frequency of 4096~. This is apparently true both of the temporary deafness which can be described as aural fatigue and also of the chronic deafness

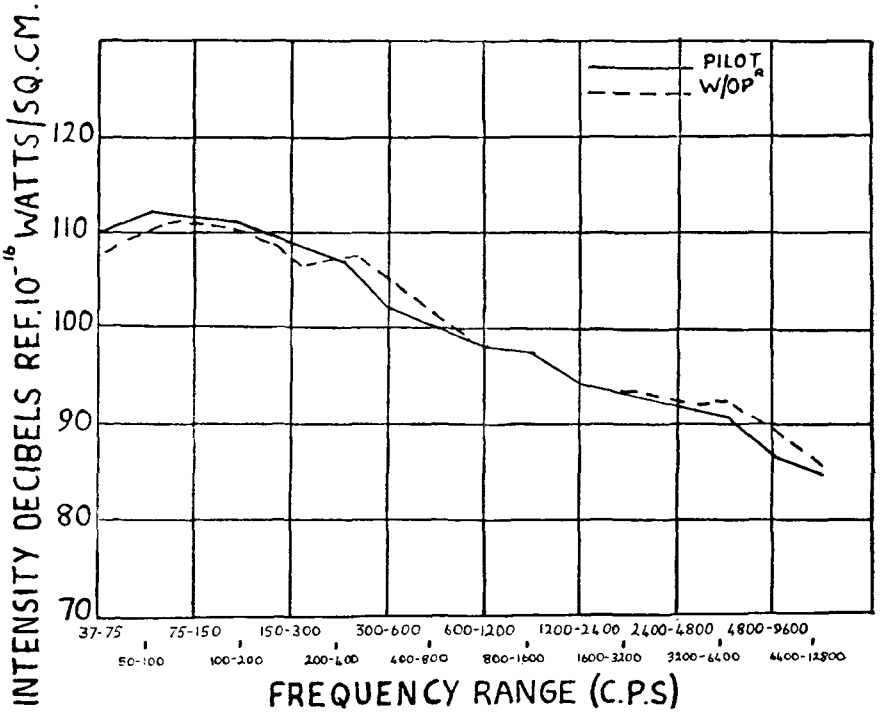


FIG. 3.

which eventually supervenes as the result of regular and continued exposure to noise.

There was a possibility that noise frequency analyses of aircraft noise, such as that shown in Fig. 1, might be misleading through inability of the instrument used to respond to noise components of exceedingly brief duration but of larger intensity than those measured. Such transients might conceivably occur about the level of 4096~ and might therefore account for the observed aural fatigue.

An experiment during flight in a service aeroplane was

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therefore made by one of us to compare the noise level recorded by two types of noise meter, one of which measured the effective (R.M.S.) noise intensity and the other the peak intensity. The two meters used for this purpose were as follows :

(*a*) C.R.Co. sound level meter type 759. This meter gives the effective (R.M.S.) sound intensity in decibel references to a zero level of 10^{-16} watts sq. cm. sound energy transfer. No weighting network to simulate ear response was used on this occasion, but a correction is applied to the results to afford

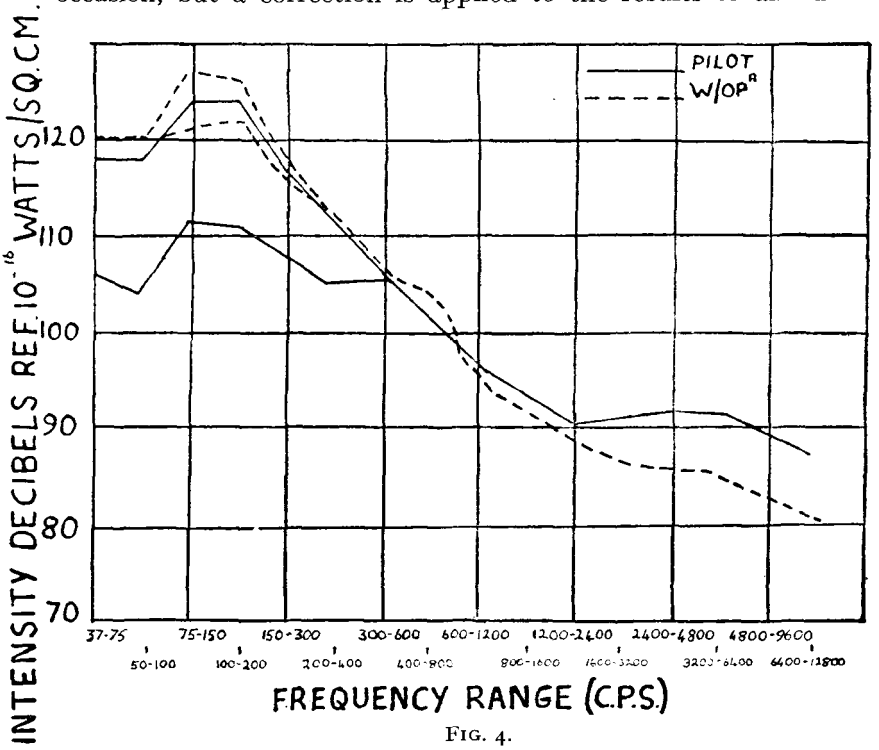


FIG. 4.

direct comparison with those obtained on the second noise meter, namely,

(*b*) S.T. & C.Co. noise meter type 74101-A. This meter works on the " Leaky peak " principle to allow for the response to noises of an impulsive character. A weighting network to simulate ear response at a level of 90 phons is incorporated.

Before flight the meters were compared and with pure tones from a loud speaker source at 1000 were found to yield readings which were in agreement to within 1 decibel.

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The following results were obtained in cruising flight at 180 m.p.h. at an altitude of 2,000 feet, with engine r.p.m. 1950. By means of a noise frequency analysis previously obtained in the same aircraft it was possible to ear weight the readings obtained with the C.R.Co.'s meter at 90 phons to afford direct comparison with measurements made with the second instrument.

TABLE C.

Measurements of peak intensities of aeroplane noise

Position of microphone.	Sound level (decibels above reference point).		
	C.R. Meter.		S.T. and C. Meter.
	Unweighted.	Weighted.	Weighted.
In cabin	112	108	110
By pilot's head ..	116	112	118

It will be noted that the difference in intensity level between the sound measured at the two positions is considerably more marked on the peak type of meter. Also discrepancies between the level recorded on the two meters appear to be 2 decibels in the cabin (which is partially sound-protected) and 6 decibels by the pilot's head, where the impulsive characteristics of the noise are accentuated by proximity to the air-screw tips.

It would appear that the characteristics of aircraft noise are such that the noise measurements conducted with a peak type of meter are more in accordance with aural impressions than effective (R.M.S.) measurements. These results therefore tend to emphasize the impulsive nature of aircraft noise, of which, as has been said already, the engine explosions are an important constituent.

Speech Tests

It has sometimes been stated that effective protection can be given to the sense of hearing without thereby reducing the intelligibility with which speech is heard.

To investigate this statement tests were made in the following conditions. Lists of monosyllables, prepared and standardized by Collard, were called to an observer two metres away at a loudness level approximating to 68 phons. The caller was helped to speak at a uniform level of intensity by watching the

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deflection of an output meter as he uttered each word. The meter was connected to a high quality microphone and amplifier system. Caller and observer were highly experienced in this form of experiment.

TABLE D.

Effects of ear protection on capacity to hear speech.

Method of protection.	Percentage of sounds heard correctly.	
	Vowels.	Consonants.
None	100	97
Plugs, Type A	98	60
,, ,, B	91	50
,, ,, C	98	83
,, ,, B (with flying helmet)	93	15

These results show an agreement with those of the pure tone and noise tests of protection given in tables A and B respectively. The more effective the protection the greater is the extent to which it interferes with the distinctness with which speech is heard. This is emphasized by applying the formula used by telephone engineers in arriving at a figure of merit for telephone systems, i.e. $I=VC^2$, where I is the percentage ratio of accuracy with which syllables are heard, and V and C the respective percentage ratios for vowels and consonants. This formula has proved necessary because it was found that consonants contribute considerably more to the intelligibility of speech than vowels.

The greater extent to which all the available methods of protection interfered with hearing for consonants as compared with hearing for vowels is attributable to the established fact that consonants tend to be both higher in frequency and weaker in intensity than vowels. These results emphasize once more the greater success which is possible in insulating the ear from sound of high than of low pitch.

Loss of speech intelligibility through effective occlusion of the meatus renders it impracticable to wear ear-plugs in combination with the high altitude flying helmet. The resulting difficulty in hearing speech signals through the headphones would be too serious.

General Conclusions

(1) Pure tone and noise tests showed a considerable variation in the amount of protection provided by the best methods at present generally available. The most effective

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devices tested were ear-plugs of a solid but very pliable character, capable of immediate adaptation to the size and shape of the individual meatus.

(2) Trained workers obtained considerably more protection than a group of untrained observers.

(3) Combination of effective ear-plugs with the high altitude flying helmet prevented the development of aural fatigue and tinnitus. Such a combination is practicable for ground but not for flying personnel on account of the resulting interference with the intelligibility of speech signals. Each of these two methods, used singly, "took the sting out of" the noise caused by aircraft engines in close proximity to the listener, but neither when used alone was completely successful in preventing aural fatigue.

(4) All the methods of ear protection which were tested diminished the intelligibility with which speech could be heard. The extent of this interference with capacity to hear speech approximated closely in degree to the efficiency of the protection, as measured by pure tone and noise tests.

(5) Measurements of aeroplane noise with a peak type of meter emphasized its impulsive character, especially when they were made beside the pilot's head, near their source.

(6) The phenomenon of a high tone deafness caused by a predominantly low-pitched noise may be explicable, in the circumstances under review, on the grounds that the chief components of aircraft noise are essentially impulsive and explosive in character. Stevens and Davies, in their summary of physiological experiments on the response of the ear to clicks and to on-and-off effects, say "When we analyse a brief auditory stimulus, we find that the sudden beginning and the sudden termination of a tone are equivalent to the appearance of acoustic energy over a wide range of the spectrum." The basal turn of the cochlea, whose function it is to respond to high-pitched sound, is known to be highly susceptible to lesions, possibly because of its proximity to the oval window, which may expose it to the initial violence of thrusts of the stapes in response to impulsive sound.

(7) Should this interpretation of the effects of aeroplane noise on the auditory acuity of flying and ground personnel be correct, there is hope that they may be effectively protected from the danger of deafness by the skilled application of methods which exclude a great part of the noise, even although

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its low-pitched components cannot be wholly prevented from reaching the ear.

SUMMARY

An account is given of recent experiments, made by the writers, to ascertain how far devices, at present available to the fighting services and to the general public, afford protection to the sense of hearing. The tests have been made in aeroplanes during flight, in the laboratory, and by engineers testing aircraft engines on the bench. Data are given to show the variations in the amount of protection provided and the need of training personnel in the use of ear defenders. Complete elimination of the risk of deafness can be assured only through occlusion of the meatus combined with efficient covering of the ears. Either of these methods if applied singly makes the noise much less dangerous to hearing and more tolerable. The investigation included fresh analyses of aeroplane noise which indicate that noise components of middle or low frequencies may be responsible for numerous cases of occupational deafness observed among flying and ground personnel. The new measurements emphasize the transient and explosive character of aeroplane noise. Stevens and Davies are quoted for the view that clicks and on-and-off effects stimulate the cochlea throughout its entire length.

The first symptom of occupational or traumatic deafness is usually a loss of acuity to sound of frequency about 4096~. This may be because response to such sound is greatest in the basal turn of the cochlea which is adjacent to the middle ear and which has therefore to bear the brunt of stimulation by noise due to explosions.

Effective protection against noise diminishes the intelligibility with which speech is heard, unless, as in the high altitude flying helmet, telephones form part of the protection.

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Mr. D. Mackensen, of the Royal Aircraft Establishment, has been responsible for the analysis of aeroplane noise during flight.

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