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An Exploratory Study of the Biological Effects of Noise

CONTRACT N6 ori-020 TASK ORDER 44
ONR PROJECT NR 144079

THE UNIVERSITY OF CHICAGO

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An Exploratory Study of the Biological Effects of Noise

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The University of Chicago

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ABSTRACT

With the development of more and more powerful jet engines for aircraft, the noise produced by such engines is becoming an increasingly serious hazard to the personnel on the flight line and on the flight decks of aircraft carriers.

The BENOX group of scientists was organized to make a survey of existing information, to conduct preliminary experiments, and to make recommendations as to the course of action to be followed in order that men can continue to perform effectively in situations where intensity levels of noise are very high.

Noise levels to which men are now routinely exposed are great enough to produce temporary hearing losses and, if exposures are repeated frequently over a period of weeks or months, to produce permanent damage to the inner ear. Insert type ear defenders such as the V-51-R which has been adopted by the Navy, Air Force, and Army provide reasonable protection from noise levels now encountered. The ear defenders are not, however, being distributed and used as widely as they should be. A program to educate personnel as to the importance of ear protection and the proper use of ear defenders is recommended.

Evidence of physiological effects other than loss of auditory acuity has not been clearly demonstrated although excessive fatigue, occasional nausea, and loss of libido are common complaints of men working in noise. The use of ear defenders to prevent excessive stimulation of the central nervous system by way of the auditory and, perhaps, vestibular end-organs should provide partial protection, at least, from these more general stress reactions which appear to be taking place.

In many situations voice communication is now impossible. The development of better visual communication systems and of a training program to teach visual communication in noise is an urgent need.

Our knowledge of the effects of very intense noise on man must be extended by research in the field and in the laboratory. There is no existing laboratory which is equipped to conduct the kind of research that must be done. Such a laboratory should be established without delay.

By drawing upon the results of past research, equipment and methods can be devised to enable men to carry out their required duties in the noise fields to which they are currently exposed. As the power of jet and rocket engines is increased, we shall soon encounter noise levels with which we shall be unable to cope unless our knowledge acquired through research has advanced at a comparable rate.

A more extensive and detailed list of recommendations for immediate action and for research is given in Chapter I.

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I

RECOMMENDATIONS

For immediate action

1. For intensities of noise to which men are now routinely exposed (140 db overall and below) the ear is the channel through which detrimental biological effects are mediated.

Therefore, it is recommended that without waiting for results from further research studies, an educational and advertising campaign be started on a broad scale at once to sell the idea of using insert type ear defenders to personnel exposed to intense noise. The V-51-R ear defender which has already been adopted by the Air Force, Navy and Army is as good as any ear defender which has been tested and is better than most. Some steps which may be taken in a campaign to promote the use of ear defenders are these:

a. Expedite the production and distribution of films describing ear defenders and the importance of using them.

b. In addition to the educational films on ear defenders now being planned, direct instruction should be given to all personnel exposed to noise. For example, during the early part of their training, maintenance men who are to work around jet engines should be given ear defenders by a medical officer or other appropriate person and should be instructed as to the importance of using these ear defenders to protect themselves from suffering hearing loss. If they wear ear defenders during early training, they will become accustomed to listening for the sounds which have significance for engine function. They should also be taught how to insert the defenders and how to keep them clean.

The crews who handle the planes on a flight deck may be given similar instructions before they start to work with jet planes. The instruction might well include demonstrations in noise to show that the use of ear defenders does not interfere with voice communication in high level noise environments.

c. Other media, e.g. different Air Force and Navy bulletins, should be used to publicize the importance of using ear defenders when exposed to high intensity noise. Publicity should emphasize the danger of permanent deafness which will result if ears are not protected. Other advantages of ear defenders can also be pointed out: (1) they make noise less irritating; (2) they enable a man to stay in the noise field and accomplish his job without hurrying; (3) they prevent ringing in the ears after exposure; (4) they improve communication under certain conditions.

d. A special directive should be sent to all flight surgeons and other officers (e.g. the Air Officers on carriers) who deal directly with men exposed to noise. This directive should call attention to the importance of educating men now in the use of ear defenders. It should point out that in the near future, as more powerful engines are produced, it will be imperative that all men exposed to the noise of jet engines wear ear defenders. It should also be noted that there is no easy solution to the problem of providing ear protection that can be worn comfortably and put on and taken off with with ease. Any device that gives protection will be slightly disagreeable to wear, but so are oxygen masks and other kinds of equipment which are essential under certain extreme environmental conditions.

2. Improve the distribution of ear defenders. Be sure that they are readily available to all personnel.

3. It seems likely that the sound levels produced by new and more powerful power plants will soon exceed the limits for which reasonable protection to hearing can be provided by ear defenders or by any other personal protective device which may be invented. Immediate consideration should be given, therefore, to changes in operating procedures so that plane handlers, maintenance men, and others who ordinarily work around operating planes will be able to carry out their duties from a distance or will be protected by a shelter at the times when the plane is running a full power.

The present operating procedures which have been developed without any special planning for protection should be examined to see if men are being exposed to high noise levels unnecessarily.

Although jet planes with afterburners can undoubtedly be handled in such a confined area as the deck of a carrier, it is obvious that some changes in procedures for handling afterburner planes will be necessary.

4. Training courses on communicating in noise should be established for both officer and enlisted personnel. In basic courses, standard phraseology and standard procedures would be taught. In intermediate and advanced courses, emphasis would be placed on teamwork under simulated and actual operating conditions. Ear protection should be used during training.

In these courses on communicating in noise, both voice and visual communication should be taught; for both, it is essential that men learn standard signals or phraseology and appropriate procedures. Because little emphasis has been placed on visual communication systems of this sort in the past, a research program to develop new procedures and methods is necessary. (See p. 8, below.) As part of the communication training indoctrination in the desirability of wearing ear defenders should be included.

5. Besides instruction on protection of their ears when exposed to noise and on methods of communicating, men who are to work around jet planes

should be given careful instruction as to how to deal with all hazards peculiar to their job.

6. Because men (e.g. men on the flight deck of a carrier) working in intense noise environments are dependent upon vision for most of the information they are to receive from men and objects around them, special attention should be given to the vision of such men and to the protection of their vision.

7. Special attention should be given to screening out individuals who have any past medical history suggesting epilepsy; intense noise may be an effective releaser of epileptic seizures.

8. In any situation where it is possible to do so, routine audiometric checks should be made for all men who are exposed to the noise of jet engines. Such examinations will not only be of value in protecting men from suffering unnecessary damage to hearing but also in adding to present knowledge of the effects of repeated exposures.

9. There is an urgent need for a laboratory especially designated to conduct research on the biological effects of high intensity noise. Essential features of such a laboratory would be:

a. Sound sources capable of generating tones or noise at extremely high levels.
b. Adequate space for research with both animal and human subjects.
c. Equipment and instruments for physiological, psychological, and medical studies.

The laboratory should be designed to accommodate both in-service and contract research. Because of the scarcity of scientific talent, it would appear impractical if not impossible to provide a permanent staff competent to deal with all aspects of the biological effects of noise. Therefore, a most important aspect of a laboratory for research on effects of high intensity noise is that it be able to provide convenient working arrangements for visiting researchers. The BENOX group feel very strongly that this feature of the laboratory is of top importance. The facilities of the laboratory must be planned with flexibility of use in mind and the permanent staff must, from the start, accept willingly the responsibility of assisting and cooperating with visiting investigators.

<u>For research</u>

1. The direct effects of airborne sound on the body tissues, i.e. transmission by routes other than special receptors, needs to be studied carefully. At the present time some information is available for intensities of sound below 150 db but almost nothing is known about the effects of intensities above 150 db. The factor of exposure time should be considered.

2. To extend the research that has already been done on temporary deaf-

ness, particular attention should be given to the effects of frequencies below 500 cps.

3. Determine to what extent there is a cumulative effect of repeated exposure to noise which produces only a temporary hearing loss after a single exposure. Factors such as length of exposure time and degree of recovery between exposures should be examined. In order that this study may be carried to the desired end, i.e. the production of a permanent hearing loss, it will have to be done, in part at least, with animal subjects. Research conducted under carefully controlled laboratory conditions should be supplemented by audiometric studies of military personnel who are repeatedly exposed to noise.

4. Using high speed photography or stroboscopic illumination, photograph the motion of the ossicles and ear drum of an animal or fresh cadaver during stimulation by sound at pressure levels up to the point at which rupture of the eardrum occurs.

5. The Committee on Hearing and Bio-Acoustics should take the responsibility for initiating research to explore further the possibilities of different kinds of voice-communications systems for use in noise.

6. A program of research should be undertaken to develop better methods and procedures for visual communication. Many factors need to be considered, for example:

   a. For many purposes it is necessary that the visual communication system retain as much as possible the flexibility of ordinary voice communication.
   b. To improve the effectiveness of hand and arm gestures such as are now in use, a careful analysis should be made of the intelligibility and confusability of such gestures so as to eliminate some gestures which are readily confused with others and to attach meaning to the signals such that those which are most alike have meanings which, if confused, will not lead to serious mishap. The use of gestures having natural meaning, such as beckoning with the hands to signal come forward, should be retained insofar as possible.
   c. The development of more effective use of signal lights in simple sequences and in patterns appears to have promise.

In general the whole program on visual communication could be patterned quite closely after the researches which have been done on voice communications by the Bell Telephone Laboratories, Harvard Psycho-Acoustic Laboratory, and other groups.

7. As part of No. 6 above, or as a closely related project, studies should be made to improve training methods used to teach communication (both voice and visual) in noise.

8. Forms of person-to-person communication with other than auditory or visual signals should be explored. The senses other than vision and hear-

ing are not readily stimulated from a distance. Nevertheless, as a long term project, it would appear desirable to examine the possibility of using these other senses, in particular the tactual sense, for person-to-person communication.

9. Conduct studies to determine for man the threshold characteristics of vestibular stimulation by airborne sound. Threshold curves in terms of frequency and intensity should be found for both the protected and unprotected ear and with unilateral and bilateral exposure. As measures of response both reports of sensory experience and objective signs of vestibular disturbance should be included. Sounds of high enough intensity for this work can be produced by a siren such as the one in use at the Bio-Acoustics Laboratory, WADC. Tests with wide-band noise might also be made as part of this research project.

10. Observe and measure postural adjustments, eye movements, and coordination of animals subjected to unilateral and bilateral auditory exposure to very intense sounds (140 db and above). Because sound of intensities in this range will often produce permanent hearing losses, research must be done with animals. Preliminary experiments might be done with lower mammals but it would seem most profitable to work as much as possible with monkeys because of their upright posture and their ability to manipulate objects.

11. Electrophysiological studies should be conducted to find out where the spill over into the vestibular system occurs when the ear is stimulated by intense sound.

   a. At the end-organ level, the electrical activity of different parts of the labyrinth sould be measured.
   b. In the central nervous system, the electrical activity of the vestibular and auditory centers needs to be carefully examined. As yet, the possibility remains that the stimulation of the vestibular system by airborne sound may occur through spilling over in the central nervous system rather than at the end-organ. Tracing of activity aroused by intense sound through the central nervous system centers and pathways is a difficult and complex problem; the aspects mentioned here must be considered in relation to those discussed under Nos. 12 and 13 below.

12. As part of No. 11 above, or as a separate project, the muscular consequences of overstimulation by intense sound might be better understood through the use of electromyographic recording from appropriate muscle groups to determine pathways by which disorienting effects of intense sound gain expression in muscular movements.

13. Examine the role of the reticular activating system in the overall neural effects produced by intense noise. This is closely related to 11 (b) above, but emphasis of the research would be in a somewhat different direction.

14. Thorough study should be made of the changes in the EEG produced by exposure to intense sounds. It should be confirmed that the ear and the auditory nervous system are the channel through which EEG changes are mediated. The thresholds for EEG change in terms of frequency and intensity of the stimulus should be more adequately measured.

Special attention should be given to the possibility of acoustic driving analogous to photic driving. Observations should include exploration of interaction of the two modalities.

15. Careful neurological examination should be made of human subjects exposed to intensities above 140 db. Common clinical tests such as those for tendon reflexes, past-pointing, heel-knee tibia, rebound, dysmetria, rapidly alternating movements and the like should be used.

15. Because the potential danger of exposing epileptic individuals to high intensity noise fields is great in terms of hazard to others as well as to themselves, it would seem to be justified to determine whether seizures can be precipitated in some or all epileptics by exposure to sounds of very high intensity. The recording of EEG during exposure would be an essential part of such experiments.

17. From the preliminary experiments which have been done it appears a likely possibility that intense sounds produce discharge of the anterior reticular formation and this may activate the pituitary to release ACTH. If this is true, a refractory state of the adrenal may develop resulting in chronic fatigue. This problem should be investigated in the following circumstances: (a) men long exposed under working conditions to intense sound, and (b) young men exposed on an experimental basis. Urine samples should be collected for both groups and analyzed for urinary steroids indicative of adrenal precursors.

The value of the above investigation would be enhanced if it were combined with a study of the psychological characteristics of the experimental subjects. A battery of standardized psychological tests such as those used in the preliminary experiments described by Halstead in Chapter XII might make it possible to relate performance on psychological tests to stress resistance as indicated by adrenal measures.

18. Further study should be made of psychomotor performance in noise at sound pressure levels above 140 db. Tests should be constructed which measure not only complex performance, but more important, the ability of the subject to follow instructions carefully for a period of time and do exact work despite pressure to get the job done. As part of this or as related experiments, time perception and incidental learning during intense noise stimulation might be examined.

19. The critical incident technique should be used to get further and more accurate data from the field as to the effects of jet noise on personnel exposed. This technique has been used to good advantage in studies of pilot errors in plane accidents or near accidents and it may have application at the present stage of investigation of biological effects of noise.

II

INTRODUCTION

Hallowell Davis
Central Institute for the Deaf
St. Louis, Missouri

Biological Effects of Noise

Noise is an unavoidable by-product of the power of modern machinery. Some small fraction of the power is lost as sound, just as some must always be lost as friction. Military aviation places a great premium on speed, which implies great power, and one result of the development of high-performance aircraft is the incidental generation of noise at absolutely unprecedented levels. This noise may affect man in four general ways. It may disturb and annoy him and suggest unpleasant thoughts by its associations. It interferes with his communication by voice. It may injure his hearing. It may interfere with other mental and bodily functions so seriously as to reduce his military efficiency and thereby cause delays and accidents.

All of these effects are serious. The first has created a major and urgent problem for the Air Force in the form of unfavorable community reactions. The Air Force also shares with the Navy the problems of communication, of injury to personnel and of direct interference with military efficiency. These three latter problems are combined in dramatic form on the deck of a carrier when jet planes are being launched, but the Air Force shares them in only slightly less urgent form on the maintenance line of airports and in contemplated unconventional operations.

The present study and report is directed specifically to the twin problems of interference by intense noise with functions other than hearing and the possibility of the direct injuries, including injury to the ears, that noise may produce. It assesses the known limits of human tolerance and the possibilities of personal protection. It discusses the biological effects of noise as medical and as operational problems and it suggests many lines of research that should be undertaken to supplement our present knowledge.

Historical

Early in 1952, in anticipation of the use of more powerful jet engines and jet engines with afterburners, the Navy sponsored some shipboard studies of the sound fields to which flight deck personnel were exposed. This survey (Project NM 004 005.03.06) was conducted by Lt. Cdr. D. E. Goldman and Mr. E. S. Mendelson and resulted in a report entitled "Preliminary Report on a Noise-Level Survey of Flight Operations Aboard the

U.S.S. Coral Sea (CVB-43)." The results of the survey indicated that the Navy soon would be faced with an acute noise problem on carriers. For this reason the Navy consulted the NRC Committee on Hearing. In May 1952 the NRC Committee on Hearing recommended a survey to asses available research facilities and personnel active in this area or who might turn their attention to the noise problem. This survey was conducted in the summer of 1952 by Drs. W. A. Rosenblith, D. E. Wheeler and Cdr. H. Smedal. One of the recommendations made in their report ("Problems of High-Intensity Noise: A Survey and Recommendations," PNR-133) was for a "quickie" summer study by men of various scientific backgrounds to evaluate possible extra-auditory effects of noise. The NRC Committee on Hearing approved this recommendation and the Navy then took the problem to the Research and Development Board Committee on Medical Sciences. Colonel Gagge (Air Force) at that time pointed out that there was a need for an organization of consultants on hearing and bioacoustics similar to the Armed Forces-National Research Council Committee on Vision. The request for the formation of such a committee was made, and representatives of the three services met in December 1952 with representatives of the National Research Council and organized the Armed Forces-National Research Council Committee on Hearing and Bio-Acoustics (CHABA).

The interests of CHABA include the effects and control of noise, auditory discrimination, speech communication, the fundamental mechanism of hearing, and auditory standards.

At the first meeting of the CHABA Council a working group was appointed to evaluate the recommendation contained in the Psycho-Acoustic Report "that a short-term 'quickie program' be set up, composed of perhaps a dozen scientists, at a location at which high noise levels can be produced by synthetic means and by actual jets with afterburners, and that this group be charged with the responsibility of making detailed recommendations for future research." The working group, as organized by the Executive Secretary, consisted of Dr. H. Davis (Chairman), Major H. O. Parrack, Prof. W. A. Rosenblith and Prof. W. D. Neff. This working group recommended the formation of a short-term study project based on a contract between the University of Chicago and the Office of Naval Research, with Prof. Neff as chief investigator, and it outlined a program and the tentative composition of an appropriate team of scientists. This contract was executed, with the Air Force providing half of the necessary funds. The project became known as BENOX (Biological Effects of Noise, Exploratory). The Working Group was instructed by CHABA to continue to "review and guide the progress of Prof. Neff's project" and Cdr. C. P. Phoebus was invited to join this advisory working group.

The program as laid out for BENOX consisted of 1) a three-day indoctrination session at Wright Air Development Center; 2) an experimental session at WADC lasting approximately a week; 3) a cruise aboard a carrier to witness carrier operation with jet-propelled aircraft; 4) a writing session held at the Psycho-Acoustic Laboratory, Cambridge; and 5) presentation of the report for criticism to the full meeting of CHABA, 9 October 1953. This program has been carried out as planned.

The primary personnel of the BENOX Project was as follows:

Name	Field	Academic Position
W. D. Neff	Psychology: Audition	Assoc. Prof. of Psychology University of Chicago
H. W. Ades	Neurophysiology: Equilibrium	Prof. of Anatomy Emory Univ. Med. School
H. Davis	Physiology: Audition, Bioacoustics	Director of Research Central Inst. for the Deaf
W. C. Halstead	Medical Psychology	Prof. of Experimental Psychology Dept. of Medicine and Psychology Univ. of Chicago
J. D. Hardy	Physiology: Pain	Professor of Physiology Univ. of Pennsylvania
W. R. Miles	Psychology: Vision, Psychomotor functions	Professor of Psychology Yale Univ. Med. School
I. Rudnick	Physics and Engineering: Acoustics	Assoc. Prof. of Physics Univ. of California, L.A.
A.A. Ward, Jr.	Surgery: Neurophysiology	Asst. Prof. Surgery, Head, Div. of Neurosurgery Univ. of Washington Med. School

In addition, Lt. Cdr. David E. Goldman (biophysics) and Dr. Donald H. Eldredge (otology and bioacoustics), Technical Aide to CHABA, attended the indoctrination session and participated in the writing session. Dr. H. von Gierke (physics) of the Bio-Acoustics Unit of the Aero Medical Laboratory participated actively in the experimental session and contributed important results of his recent work on ear protection. Dr. H. Hoagland (biology, endocrinology), Director of the Worcester Foundation of Experimental Biology, served as a consultant to the group during the final writing phase. Dr. Garth J. Thomas, Department of Psychology, University of Chicago assisted in the editing of the final report.

The indoctrination session was attended by the primary BENOX members listed above and also by many Naval and Air Force officers and technical personnel and by three invited civilian consultants, Drs. Henry Beecher(pharmacology), K. N. Stevens (acoustics), and W. A. Rosenblith (communications and psychoacoustics). The entire roster of the indoctrination session was as follows:

Clifford P. Phoebus, Capt., USN	Office of Naval Research
Dr. Henry A. Imus	Office of Naval Research

Merrill H. Goodwin, Capt., USN	Office of Chief, Naval Operations
T. J. Sullivan, LCDR, USN	Bureau of Ships, USN
Dr. Wilbert Annis	Office of Naval Research
Samuel I. Brody, Cdr., USN	Bureau of Aeronautics
T. Ferwerda, Capt., USN	Bureau of Medicine
R. T. Morgan, Cdr., USN	Com Air Lant
John T. Smith, Capt.	Com Air Lant
Thornton F. Spindler, Lt., USN	Naval School of Aviation Medicine
Vernon C. Bragg, Lt., USN	Naval School of Aviation Medicine
David E. Goldman, LCDR, USN	Naval Medical Research Institute
Emanuel S. Mendelson	Naval Air Material Center
Charles E. White	Naval Medical Research Laboratory
Robert S. Gales	Naval Electronics Laboratory
Jack Carmichael, Lt.Col., USAF	Office of Surgeon General, USAF
Lewis E. Jones, Major, USAF (MC)	Office of Surgeon General, USAF
P. J. Maher, Major, USAF	Headquarters, USAF
Robert H. Blount, Col., USAF	Aero Medical Laboratory, WADC
Horace O. Parrack, Major, USAF	Aero Medical Laboratory, WADC
Elizabeth Guild, Major, USAF	Aero Medical Laboratory, WADC
Dr. Henning E. von Gierke	Aero Medical Laboratory, WADC
Dr. W. W. von Wittern	Aero Medical Laboratory, WADC
Jack E. Steele, Capt., USAF	Aero Medical Laboratory, WADC
Max H. O'Connell, 1/Cdr, RAF	Aero Medical Laboratory, WADC
Harry Jerison	Aero Medical Laboratory, WADC
D. A. Dickey	Propeller Laboratory, WADC
O. R. Rogers	Aircraft Laboratory, WADC
Dr. W. J. Brown	Power Plant Laboratory, WADC
J. R. R. Jenkins, Wing/Cdr, RAF	RAF Liaison Officer
Dr. Harlow W. Ades	Emory Univ. Medical School
Dr. Henry R. Beecher	Harvard Univ. Medical School
Dr. Hallowell Davis	Central Institute for the Deaf
Dr. Donald H. Eldredge	Central Institute for the Deaf
Dr. Ward C. Halstead	University of Chicago
Dr. James D. Hardy	University of Pennsylvania
Dr. Walter R. Miles	Yale University Medical School
Dr. William D. Neff	University of Chicago
Dr. W. A. Rosenblith	Massachusetts Institute of Technology
Dr. Isadore Rudnick	University of California, L. A.
Dr. K. N. Stevens	Bolt, Beranek and Newman (MIT)
Dr. Arthur A. Ward, Jr.	Univ. of Washington Medical School

A digest of a large part of the indoctrination session is given in the next section of this report.

The experimental session followed immediately the indoctrination session. The BENOX scientists made use of the facilities of WADC and enjoyed the cooperative assistance of members of the staff of the Aero Medical Laboratory. Some of the visitors had also brought special equipment of their own. The studies were exploratory, to determine whether certain lines of study seemed important and practical and to enable the BENOX group to base recommendations for future research on first-hand observation and experience. The effort was also made to determine approximate thresholds at which various undesired effects appear in order to provide temporary guides to thinking about operational problems. In several cases such critical sound levels were identified.

The reports of the results of the experimental session and the recommendations for future research based on them constitute the main body of the present document. These and the discussions during the indoctrination sessions also form the basis for another series of recommendations for implementation of future research and some recommendations concerning immediate medical and operational problems. It was the consensus of the primary BENOX members, however, that recommendations of the operational type should be formulated and submitted by a group that is better acquainted with operational problems and the military point of view. This responsibility therefore fell automatically on the CHABA working group that had been directed to "review the work of the BENOX project." The commentary and report of the working group is to be prepared following the discussion of the BENOX report by the full CHABA meeting on 9 October 1953.

III

SURVEY OF THE PROBLEM

Hallowell Davis
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The military problem of the biological effects of noise on man is not new. It has simply become more acute and urgent because of recent increases in power and the consequent increases in noise produced by the powerplants of modern high-performance aircraft. Therefore the first step taken by the BENOX group when it convened at the Wright Air Development Center was to hear reports from engineers, from aviators, from medical officers, from scientists, from line officers and others as to the present state of knowledge and the exact nature of the practical problems involved. (The names of these individuals are given in Chapter II, and to them BENOX is greatly indebted.) The entire group also inspected the types of aircraft involved and listened at short range to the sounds of jet engines.

The work done subsequently by the BENOX project can best be appreciated by starting with a review based on these preliminary discussions which served as a background for the later experimental work.

Effects of Sound on Man

The following paragraphs summarize the discussion by several speakers of a variety of effects produced by noise. They are arranged roughly in order of the intensity of the noise as it reaches the man. Some of the problems lie within the competence of the BENOX group, while others represent related problems.

"Fear reaction"

Faint sounds affect man only through his ears, and only by conveying information about events at a distance. The information may be very important. The amount of information conveyed depends greatly on the listener's previous experience: for example, on whether he understands the meaning of certain words or whether he has learned to recognize a distant airplane amid sounds of automobiles and electric fans. The effect of such a faint noise on a man will then depend on his associations with the noise that he recognizes. Basically, does it mean friend or foe? A very important effect of a very moderate noise may thus be the so-called "fear reaction." Biologically this is the reaction to a specific warning of real or imaginary danger.

Disturbance and annoyance

At a higher level noise may disturb sleep or rest. Biologically this is a general non-specific arousal or warning. The amount of noise needed to "disturb" varies greatly with different circumstances but loud, unusual and changing sounds are always more or less disturbing.

Interference with communication by speech

The next effect is interference with communication by speech. This is annoying, frustrating or an actual handicap, depending on how effectively the noise masks out the sounds we wish to hear and how much more effort we must make to listen more carefully, to speak louder, or to seek assistance in communication from mechanical or electrical devices. The interference with or "masking" of desired communication is a very important undesired effect of noise. The communication that is masked may be from man to man, but it may also be from machine (or animal) to man, as when a look-out or sonarman listens for an enemy vehicle, aircraft or ship, or when a mechanic or pilot listens for faulty performance of his own machine.

Avoidance

As noise becomes still louder it causes a new kind of discomfort that is more than mere annoyance. It is simply "too loud" and we have a strong instinctive desire to get away from it. This "avoidance reaction" can be overcome by will power, but some effort and self control is needed. The reaction is probably linked closely with a primitive function of hearing as a warning of danger. A very loud sound implies great power of some sort at close range. In the simple code of the instincts this is not good; it means danger, and it must be avoided actively. There is another strong impulse, namely, to cover and protect the ears if we must remain in the noise.

Fatigue

The evidence that loud noise may produce fatigue is fragmentary and contradictory. Fatigue is a common word but actually has many meanings and it is difficult to define precisely. In the BENOX discussion it was agreed that, quite apart from any disturbance of sleep or rest, very loud noise probably does add significantly to the subjective sense of fatigue at the end of a day's work. Some reports from the field strongly suggest that this effect is important among maintenance men on the flight lines and for the deck crews on carriers. Here we have referred to the way a man feels and performs after a hard day's work. He can still do well on brief specific tasks, particularly if his motivation is high, but he must try harder in order to maintain his normal performance and he is likely to be less vigilant, less alert, to react more slowly, less vigorously and less accurately. He wants to rest, and he does so if the opportunity offers.

Stress and chronic fatigue

In the military situation the very loud noise, which not only stimulates the ear very powerfully but also calls other sense organs such as touch into action, certainly adds to the total stress of what is already a difficult and perhaps dangerous overall situation. The very massiveness of the total sensory stimulation is tremendous. This is something that must be heard and felt personally to be appreciated. Under condition of stress, such as heat, cold, partial starvation or physical injury, the body reacts in a special way through the nervous system and ultimately through certain hormones to mobilize its defenses and meet the stress. It is proper to think of sound at very high levels as a true "stress" in the physiological sense and not only as a subjective or "psychological" phenomenon. The effects of continued or repeated exposure to such stress are not apparent immediately and can be measured only with difficulty, but it is generally agreed that the body pays a price ultimately for the repeated mobilizations of its biological defenses. Such cumulative effects of repeated stress are included in our concept of "chronic fatigue." Special attention should be given to the possibility that the contribution to a state of "chronic fatigue" may be an important undesired biological effect of noise on man.

Temporary hearing loss

It is well known that loud noise can cause temporary hearing losses. The effect is something like temporary blinding by a very bright light, but the ears may require 24 hours or more to regain full sensitivity. The frequencies for which there is loss of sensitivity depend on the frequency spectrum of the noise. The amount of loss depends on both the intensity and the duration of the noise, and some ears are more resistant to noise than others. There is much more to be learned about the production of and recovery from these temporary hearing losses, but it was agreed that no special attention would be given to this problem by BENOX because the direction for future research in this area seems clear and other problems, notably the problem of permanent injury to hearing, are more important.

Permanent hearing loss

Permanent injury may occur after a single very severe exposure to noise, such as an explosion, or it may appear very gradually as a cumulative effect if a temporary hearing loss is produced over and over again day after day over months or years. In civil life this effect is known as "industrial hearing loss." It is quite different from the annoyances, discomforts, fatigues, and temporary adaptations produced by weaker sounds. This is injury, permanent injury. Injury from acoustic stimuli occurs to the ear before any other organ of the body, because the ear is designed to be specially sensitive to sound.

Aural pain

Pain in the ears due to changes of barometric pressure ("barotrauma") is familiar and is undoubtedly due to stretching of the drum membrane and perhaps other structures of the middle ear. Aural pain can also be produced by very intense sound, either explosions or intense steady noise. The anatomic origin of this pain is not entirely clear. Pain in general seems to be a warning signal of injury to tissue, but the sound level at which sound produces aural pain seems to be considerably higher than the level that can cause permanent hearing losses if repeated often enough. A dangerous sound in this sense, although usually "uncomfortably loud," is not necessarily painful.

Dizziness and nausea

Reports from the field suggest that intense sound may cause nausea, dizziness and even vomiting in some individuals. These symptoms are rather sporadic but some cases are well authenticated. They somewhat resemble seasickness, and probably depend on stimulation by sound of the sense of spatial orientation which is served particularly by the nonauditory part of the inner ear, the "labyrinth." Stimulation of abdominal sense organs may also contribute, but the symptoms are usually prevented by plugging the ears. The threshold for such acoustic stimulation of the non-auditory labyrinth has not been determined. The effects can evidently be very incapacitating in susceptible individuals.

Interference with touch and muscle sense

All of the effects described so far are produced in or through the organ of hearing. Below the level of pain in the ear, however, other sense organs, notably those for touch, are stimulated. Loud sound may be felt in the ear and also in other parts of the head, the abdomen, the hands and elsewhere. In general these effects are simply distracting and annoying. They may, however, interfere with the normal use of these sense organs for tasks that require delicate touch or muscle sense. The interference is analogous to the masking of sounds that we wish to hear by a louder noise. It is an interference with biological communication within the body, but it has never been studied systematically.

Interference versus injury

In the above list of possible effects of noise on man there are two general groups that differ greatly in their promptness of onset. The effects also differ according to their duration. In general the effects that depend on interference with voice communication, interference with sense of touch and so on, begin when the sound begins and cease promptly when it ceases. Interference with the sense of orientation is prompt. The development of nausea and of temporary hearing loss may require some minutes, but they are still relatively prompt. But those effects that depend on long-term fatigue or cumulative injury may require hours, days or months to develop. Of course, the stronger the sound the more rapidly the latter effects develop, but there is nevertheless a fundamental difference between immediate interference with some normal function and the slow development of fatigue and injury.

In general, when it is a question of injury, the limit of tolerance depends not only on how severe is the strain but also on how long it lasts. The ear, for example, can withstand for many seconds, with only a temporary hearing loss, sounds that would undoubtedly cause permanent injury if continued for minutes or hours. The immediate effects that depend only on interference do not depend on the duration of exposure or on repeated exposures. The importance of these distinctions between temporary interference at one extreme and permanent injury at the other will appear in the analysis of interference by intense sound with the performance of military duties as opposed to the production of injury to personnel.

Accommodation

One more effect of time is important. Repeated exposure to intense sound usually leads to some "accommodation" that makes the reactions to it less severe. This is particularly true of the original psychological "avoidance reaction." Men soon become accustomed to working in very intense sounds and tend to become careless or indifferent about the use of ear protectors. Even the threshold of pain is reported to rise 3 or 4 db if tests are made repeatedly on successive days. There is no evidence, however, that the ear becomes any more resistant to injury. The "accommodation" to intense sound must therefore be regarded as a weakening of one of nature's protections against injurious effects.

Operational Problems of Noise

The above effects of noise on man can be grouped broadly into three major operational problems. One of these is the effects of noise on civilians and military personnel living in the neighborhood of airbases; another is interference with communications as encountered in aircraft, on carriers and in control towers; the third is the limits of human tolerance for intense sound. All three of these were reviewed and the relation of the BENOX project to each was considered.

The community noise problem

Members of the Air Force discussed the very important problem of the unfavorable reaction of the residents of communities near airports and aircraft test installations to noise produced by aircraft or powerplants. This "neighborhood reaction" is closely linked to operational problems. The effect of the noise on man is partly the "fear reaction," partly annoyance and partly the interruption of communication. The problem originates in the same intense noises that create the problems for which BENOX was primarily organized, namely the direct biological effects on men who are actually in very intense sound fields. The community noise problem is important because of the large area over which neighbors and personnel are exposed to moderate intensities of noise while the BENOX problem exists because of the very high intensities that are encountered in certain small but important areas. The members of BENOX appreciated the importance of the community noise problem but soon concluded that its scientific problems of sound generation and sound transmission were not within their special competences and that they were not at all qualified to deal with the psychological, sociological, political and economic questions that are equally a part of the overall problem.

Interference with communication

The practical problems arising from interference by the noise of jet engines with voice communication was discussed at some length, particularly the problems of the flight deck and the island of a carrier. Dr. K. N. Stevens outlined a recent survey of acoustic problems of aircraft carriers made from the point of view of acoustic engineering and sound control. Among the recommendations mentioned by Dr. Stevens were (1) develop mechanized operations where possible; (2) take account of the directionality pattern of the aircraft noise; (3) improve the island structure acoustically; (4) design communication devices for use on the deck, such as portable FM sets. The BENOX project strongly endorses these recommendations. Any additional study of the acoustic and engineering aspects of the problem of communication was considered to lie outside the special competence of the BENOX members. Further study of these aspects would therefore have been inappropriate, and they would have been an unnecessary duplication of the very competent study reported by Dr. Stevens. However, in the body of this report will be found some further discussion of certain psychological aspects of communication, both auditory and visual, that relate directly to the carrier problems.

Limits of human tolerance

The organization of the BENOX project was stimulated directly by increasing evidence that very intense sound, such as is encountered near the exhausts of jet engines on the flight deck of carriers and only to a slightly less degree on the maintenance line of an airbase, is beginning to cause injury to military personnel and to interfere with the proper performance of their duties. The BENOX objectives were primarily to explore and assess these dangers and limitations and to suggest remedial measures and further research. Its members were chosen because of special competence in fields that were believed to be relevant to this type of biological effect of noise.

Bioacoustics of Tissue, Vibration and Ultrasonics

Because of the special interest of several of the BENOX team with the possibility of direct physical injury to tissues by very intense sound the following statement of certain relevant principles of bioacoustics, prepared by Lt. Commander D. R. Goldman, is included here in some detail:

> "Sound may be considered as an alternating mechanical force which, in impinging on the body, not only excites the auditory system, but affects other parts as well. When airborne sound strikes the surface of a liquid or solid body whose dimensions are large compared with the wavelength of the sound, nearly all the incident energy is reflected and very little enters, less than 0.1% for water or material with a high water content. When the dimensions of the body are less than or comparable with the wavelength of the sound the body is enveloped by the waves. The motion may be complicated and larger tissue elements tend to respond as units according to their own resonance and damping characteristics.
>
> "There is thus translation, distortion and compression of the tissue material and if this is large enough, sensory stimulation and eventually tissue damage may occur. Very little is known of the detailed mechanical characteristics of the body elements and considerable research will have to be done before predictions of specific tissue responses can be made.

"In addition to mechanical damage, thermal injury can also occur when the sound energy is converted into heat faster than the body can dissipate it. Such conversion occurs increasingly at higher frequencies but is also dependent on internal damping characteristics of tissue and is increased by the geometrical complexity which can multiply the path lengths of the waves and increase opportunity for absorption. Also the presence of surface absorbers (fur on animals or certain types of clothing) may produce generation of heat rapidly enough for surface burns to occur.

"The ear is exceptional in that it is adapted for efficient transfer of sound energy within a definite frequency range and is therefore more sensitive to injury.

"From the point of view of risk, a sound pressure level of 155 db (single frequency or critical band) seems to be, roughly, a sort of threshold for direct injury to tissues other than the ear especially at frequencies below about 200 cps. Probably even higher levels are required to produce significant effects, but the factor of exposure time also enters. Some research on the mechanical characteristics of the body and its parts is now being carried out but a great deal more is needed to clarify the mechanism of such injuries and the frequencies, durations and intensities needed to produce them. It is possible, however, that details of anatomy or the special sensitivity of an important organ like the brain may cause special difficulties that cannot be predicted accurately. It will always be necessary to keep a lookout for unexpected points of weakness as men are exposed to stronger and stronger sound fields.

Low frequency mechanical vibration (below 200 cps)

"When sound or vibratory energy is transmitted to the body through a liquid or solid medium by direct contact, the energy transfer to the body is relatively great. Such sound as is of low enough frequency to excite mechanical systems as wholes rather than to produce wave motion is usually referred to as 'mechanical vibration.' The vibration can be felt if surface of the skin is excited by motion with an acceleration as low as a thousandth of a gravity unit ('g') at frequencies up to a few hundred cycles. When the body is exposed to accelerations of a few tenths of a g below about 100 cycles the vibration is usually considered highly objectionable although there is no evidence that it is injurious. Of course, such accelerations interfere with fine muscular activity.

"Among the few things known about the mechanical characteristics of the human body are that the various organs and tissues have considerable damping. The mammalian body is of course well adapted to resist mechanical forces. The abdominal viscera appear to have a maximum response at a few cycles per second. The head suspended on the neck seems to resonate at 12 to 15 cps. A resonance of the eyeball has been found at 40 to 80 cps. Alternating forces great enough to produce injury are, however, difficult to produce since physical material and metal failures occur as easily as tissue damage except where particular care has been exercised in design and construction. Long exposure (weeks or more) to vibration levels of the order of 10 g or more does produce injury. Particularly well known are the chronic injuries of the hand resulting from continued use of pneumatic and high speed rotary hand tools. These injuries are localized in those parts of the body directly in contact with the applied forces.

"In short, mechanical vibration as ordinarily encountered may produce mechanical interference with performance and may contribute seriously to the production of fatigue but except in special cases is unlikely to be a cause of direct injury.

Ultrasound: above 15,000 cps

"With the advent of jet propulsion machinery there arose a fear that the noise generated might contain enough ultrasonic energy to be dangerous to man. However, the same principles which apply to audible sound also apply to ultrasound. Evidently only extremely high intensities of ultrasound in air are potentially dangerous. Not only is the amount of ultrasonic energy generated by current and foreseeable power plants considerably less than the audible energy, but high frequencies are much more rapidly absorbed by the transmission media than low frequencies. Hence, the hazards of airborne ultrasound may be considered negligible."

Engineering Aspects of Aircraft Noise

An obvious solution to the operational and medical problems of intense noise would be to reduce the noise at the source. The chief source of intense noise of military importance is aircraft and particularly the power plants of high performance aircraft. There has been a steady increase in the power of and the sound levels produced by aircraft. In order that the BENOX group might be aware of the engineering point of view and know what to expect in the way of noise levels in the future, the physical and engineering aspects of the generation of noise by aircraft were presented by several members of the staff at Wright Air Development Center and by Dr. K. N. Stevens.

They made clear why noise is unavoidable in the operation of aircraft. The primary mission of aircraft in the military context is to carry payload and to carry it fast. Anything which increases the weight, or reduces the speed of the plane is not acceptable if there is any possible alternative. In regard to propellers the present trend is in the wrong direction from the point of view of noise because it is toward small propellers with tips that move at supersonic velocities. Aerodynamic noise is important when the plane is in flight at high speed. The noise increases as the three and three-quarter power of the indicated air speed. On the other hand, supersonic speeds of flight do not create new and special noise problems for the occupants of the aircraft. In regard to the noise of a jet engine exhaust, there is a linear relation between the watts of acoustic energy produced and the total horsepower of the jet stream. The mechanism of the production of the noise by the jet stream is not clearly understood. The fraction of energy that is lost as acoustic power is small, being less than one per cent, but it seems to be quite constant and the present trend is toward more and more powerful power plants.

Clearly the greatest help for the greatest number of noise problems would come from a reduction of noise at the source. One of the most troublesome sources is, and is likely to remain, the jet engine. A significant reduction in the percentage of the power that is lost as sound may or may not be possible. The first step is to learn the mechanism of this sound production. Research to learn this mechanism and to reduce the sound at the source should therefore be given high priority. The BENOX group emphatically endorses this recommendation. It is also clear that assistance from this source will come, if at all, only through modifications of engine design and is at best several years in the future. For the present we must prepare for more and more noisy powerplants according to the present well-established trend.

IV

ACOUSTIC PROPERTIES OF PRESENT DAY MILITARY AIRCRAFT

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Comparison of Various Propulsive Units

A comparison of the maximum overall intensity levels generated at a distance of 300 feet by various propulsive units is presented in Fig. 1; the data used for this figure were normalized to correspond to a thrust of 5000 lbs. (1). In Fig. 2, a comparison is made of the acoustic directional properties of several propulsive units; the data for these figures were normalized to give equal maximum values (2). Since the directivity patterns for overall sound pressure levels are symmetrical about the thrust axis, only half of each pattern is shown.

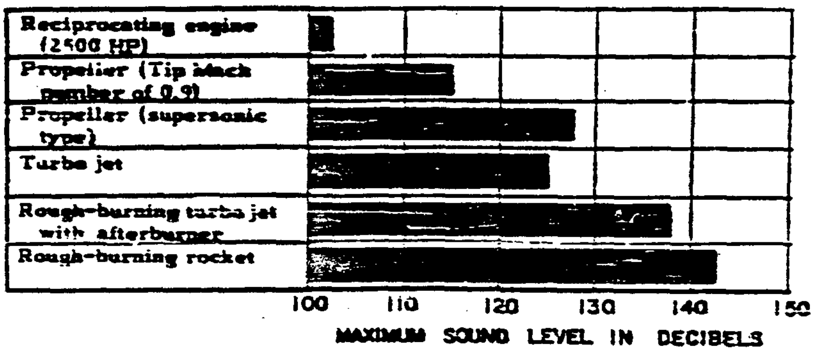

Fig. 1. Comparison of the maximum overall sound intensity levels generated at a distance of 300 feet. (Data normalized to correspond to a thrust of 5000 lbs.)

In Fig. 3 the spectra of various jets and of a rocket are compared (2). Data for rotating airscrew planes are not given in the figure and a few words about them are appropriate. In propeller driven aircraft the noise generated is principally due to the propeller rather than the engine, as can be seen by comparing the top three entries in Fig. 1. The sound produced by a propeller is principally made up of a fundamental whose frequency is equal to the blade passage frequency, plus the harmonics of this fundamental at tip Mach number 0.9. The fundamental and these harmonics are equal in amplitude. For supersonic tip speeds the spectrum of these harmonically related frequencies may have a broad maximum near one of the higher harmonics. Superposed on the line spectra will be a continuous band of frequencies which will be due to the vortices shed by the propeller blade plus a turbulent component. At supersonic velocities there will also

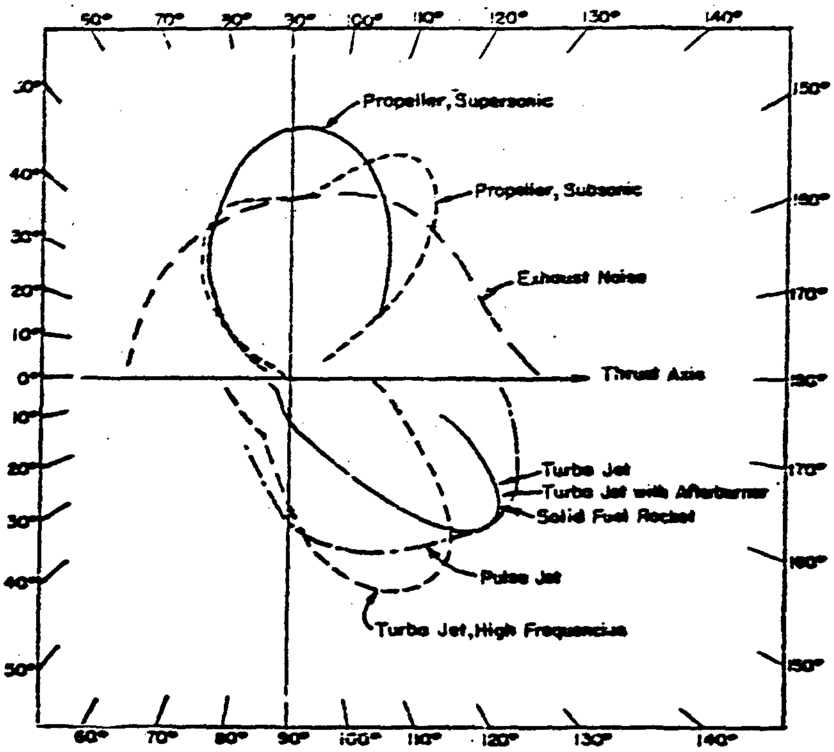

Fig. 2. Directivity patterns of the overall sound pressure amplitude around various aircraft noise sources. The patterns are adjusted to show equal maximum value. Only one half of the rotationally symmetrical patterns are shown. 0° is in front of the engines.

be sound associated with the shock wave generated at the blade tip. In view of the above it is clear that the spectrum of an airscrew will be determined by its rotational blade frequency which in turn will be determined by its diameter, and the multiplicity of blades.

A study of Figs. 1 and 2 verifies the fact that conventional jet engines without afterburner are perhaps 6-10 decibels noisier than conventional propeller driven aircraft. Since, as between the two, they represent the greatest noise problem they will be discussed in some detail at this point. Two aircraft, the F2H-2 and F94-B with afterburner will be considered. The noise levels and spectra are representative and other existing jet aircraft of the same power will not greatly differ from these in their acoustic properties. Following this discussion brief comments will be made about more powerful engines.

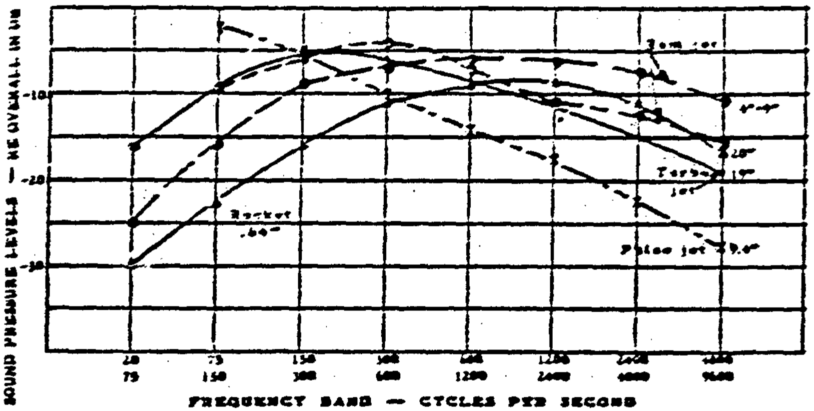

Fig. 3. Sound pressure level in octave bands relative to the overall noise level of turbojet, ramjet, pulsejet, and rocket. The figures on the lines indicate the nozzle diameters in inches.

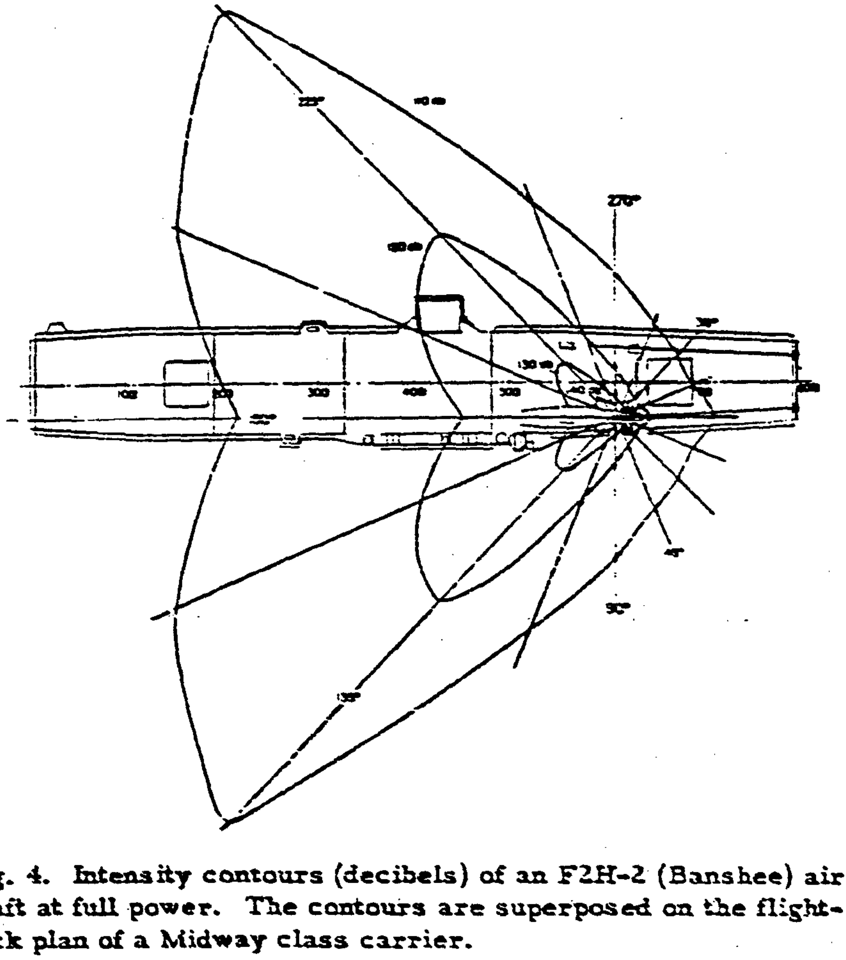

Fig. 4. Intensity contours (decibels) of an F2H-2 (Banshee) aircraft at full power. The contours are superposed on the flight-deck plan of a Midway class carrier.

Sound Field of the F2H-2 (Banshee)

Fig. 4 is based on a study made aboard the Coral Sea (3). Sound levels at various points about the aircraft at full power were measured. Based on these, lines of equal intensity are plotted. It is probable that the field is very complex in the immediate neighborhood of the aircraft and it is not pretended that the lines drawn represent accurately the conditions in this neighborhood, but they do represent approximate conditions and it can be seen that there are large regions about the craft where overall levels between 130 and 140 db prevail, especially near the aft part of the airplane. Furthermore, in a restricted cone aft of the exhaust, levels of slightly above 140 db can be encountered. The background plot is that of a Midway class carrier. Operationally the situation so far as sound levels are concerned can be summed up by saying that the launching crew is routinely subjected to levels between 130 db and 140 db. Moreover, since the aircraft will essentially carry the indicated sound levels along with it as it is launched, all personnel forward of the position of the plane at rest on the catapult will be swept by fields from 130 db to 140 db as the plane is launched.

Another point of great interest is the levels encountered in the cockpit. Table I (3) verifies the commonly observed fact that the levels are considerably below those observed on the flight deck.

Table I

Noise Levels in Aircraft Cockpit of F2H-2 under Various Conditions

Engine (RPM)	Altitude (Thousand feet)	Indicated Air Speed (Knots)	Cockpit Sound Level (db)
91.5 both engines	22 climb	230	101
84 " "	23	240	100
85 " "	23-15 dive	240-400	100-104
97 " "	21	345	109
80 " "	20	230	93
92 single engine	20	220	94
35 both engines idling	On deck canopy open		114

Sound Field of F94-B

Fig. 5 shows an analysis by octave bands of the J-33-33 turbo jet at 50 feet with and without afterburner (4). The principle acoustic effects of adding an afterburner are 1) the overall noise level is increased by approximately 8 db and 2) the low frequency component of the acoustic radiation is comparatively accentuated. The latter is not clearly evident from Fig. 5. Fig. 6 shows equal intensity contours of an F94-B aircraft with engine (J-33-33) at full power and with afterburner operating. For purpose of pointing out the noise problem in operating aircraft equipped with after-

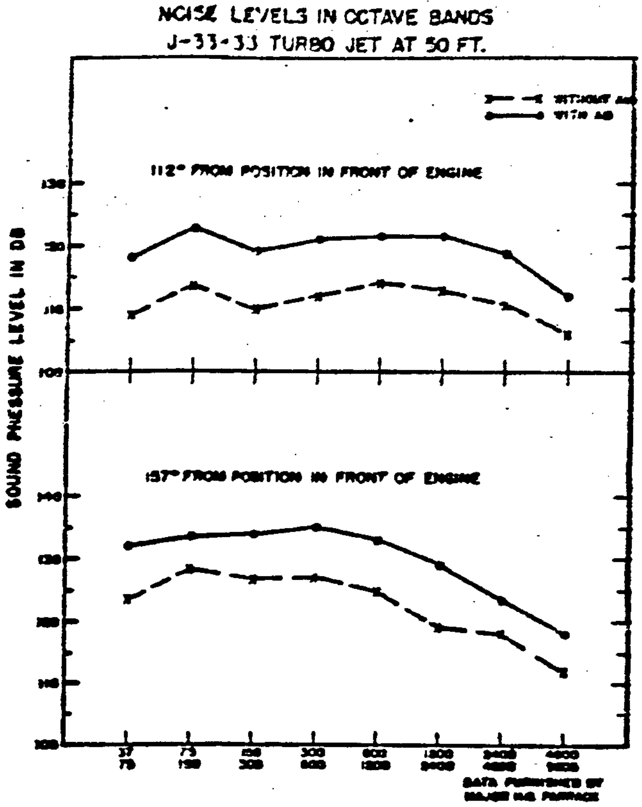

Fig. 5. Sound pressure level by octave bands measured 50 feet from a J-33-33 turbojet with and without afterburner.

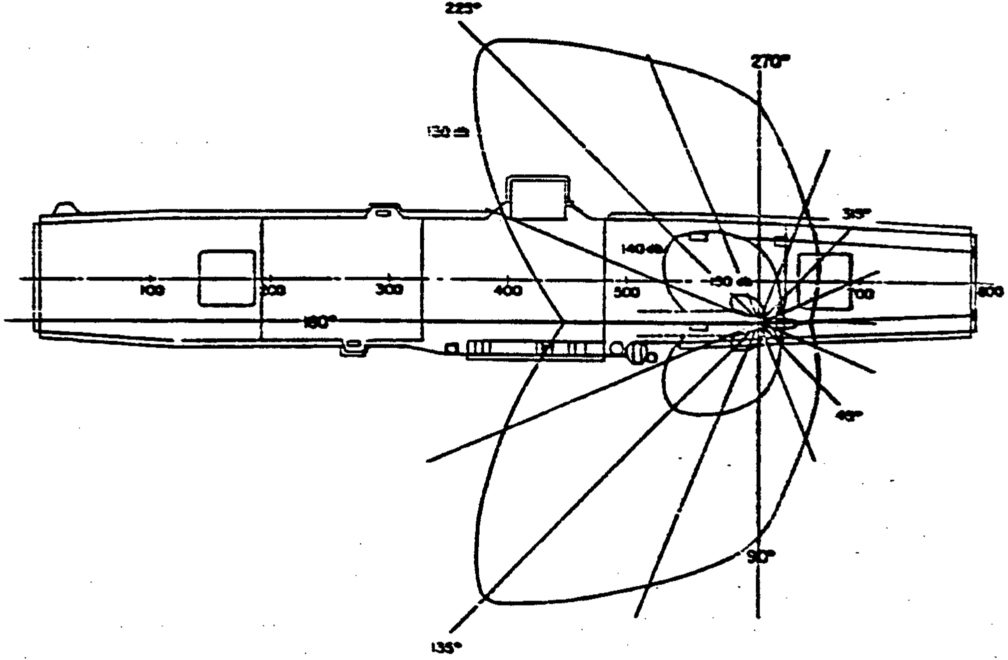

Fig. 6. Intensity contours (decibels) of an F94-B aircraft at full power. The contours are superposed on the flight-deck plan of a Midway class carrier.

burner on carriers, the plot is superposed on the flight deck plan of a Midway class carrier. It is seen that maintenance and checkout procedures when the afterburner is operating are made in noise fields whose overall levels in the after region about the airplane are between 140 and 150 decibels. Moreover in the hypothetical case of carrier operation the 140 db level will be reached over large areas of the flight deck.

Fig. 7 is a plot of the far field of this airplane at full power with afterburner operating. It is based on an extrapolation of the data of Fig. 6 with the added assumption that a slight wind exists which introduces an attenuation of db per 1000 feet in the overall level (5). Under calm night-time conditions when a temperature inversion occurs the attenuation will be negligible and the levels indicated in Fig. 7 should be increased by 5 db for each 1000 feet. Under conditions in which a high gusty wind occurs or in the presence of a steep negative temperature gradient such as might occur on a clear calm hot day, the contours will be crowded very much closer to the source.

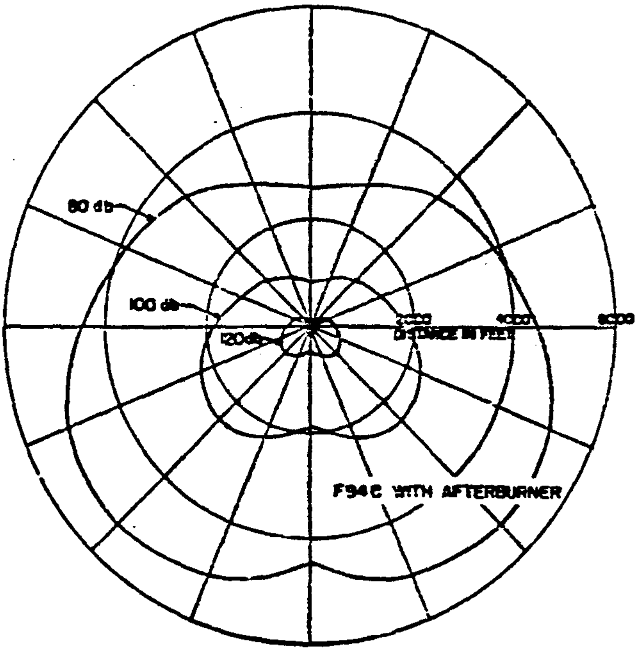

Fig. 7. Intensity contours (decibels) of an F94-B aircraft. An attenuation of 5 db per 1000 feet has been assumed. For calm night-time conditions there is no attenuation and 5 db must be added to the above figures for every 1000 feet from the source.

Noise Fields of Aircraft in Flight

At low speeds, the acoustic radiation pattern of the aircraft in flight is the same as that of the same plane at rest (see Figs. 6 and 7). From the community standpoint the most troublesome noise situation is likely to occur in those residences which are directly in line with the takeoff direction since at takeoff the plane will be at full power and will be a minimum distance from the residences. As an example, an F84 at takeoff under full power with afterburner operating, which passes 500 feet above residences at a speed of 200 m.p.h., will subject the houses in its path to a level in excess of 100 db for a time of about ten seconds.

At high altitudes and high speeds the data which are available indicate that the total noise emanating from the aircraft is reduced by virtue of 1) the decrease in velocity of the exhaust relative to the ambient air and 2) the decreased density of the air. At high altitudes noise is not a problem for either the occupant or observers on the ground.

Sound Levels To Be Expected of Future Engines

The trend toward more and more powerful military aircraft engines will undoubtedly continue. It is clear from Fig. 1 that present models of powerful engines are all fairly efficient noise producers, and that aside from the propeller engine with many-bladed propellers operating at low tip speed, no other conventional propulsive unit produces any less noise than does a turbojet. No published data are available on a smooth burning rocket and it is assumed that rough burning does not increase the level more than 17 db.

What then may we expect as the thrust of turbojets is increased? Enough is known about conventional turbojets so that it is possible to make rough predictions about their noise output. Measurements made on six different types of turbojet engines, all of approximately the same size (19 inch jet nozzle) and in the same power class, indicate that for a given Mach number of the jet stream the acoustic output is the same for the group (6). Fig. 8, which is based on the data reported by Mawardi and Dyer (6), presents a plot of acoustic power as a function of jet stream power. The cross hatched area is the area in which practically all observed points fall. The break in the slope occurs at a Mach number of 1 and it is seen that beyond this point the acoustic power increases with the sixth power of the exhaust velocity. The horizontal line is drawn at an

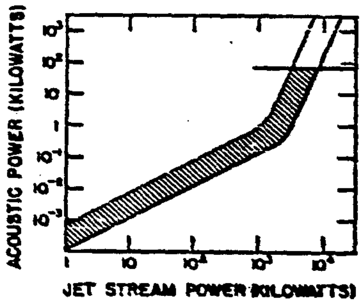

Fig. 8. Acoustic power output as a function of exhaust jet stream power for 19 inch turbojets.

acoustic power of 75 kw., the measured output of a 19" jet engine at full power without afterburner (2). If one were to attempt to increase the thrust of such an engine by increasing the flow through it, a strict application of the sixth power law would indicate that an increase of exhaust velocity by a factor of 1.46 would be attended by a 10 db increase in acoustic power output. It is likely that if there is any error it is on the conservative side--namely, there would be a greater increase in acoustic power.

If on the other hand an increase in thrust is sought by scaling the size of the engine up so that the exhaust area is increased, present knowledge would indicate that at comparable exhaust velocities and temperatures the acoustic power output will increase approximately as the thrust, i.e. as the exhaust area.

It would appear then that any increase in thrust produced by increasing exhaust velocity or by scaling up the engine in size while maintaining the exhaust velocity will result in an increase in acoustic power which will at least be proportional to the thrust increase. If any gain is made on the noise problem it can be done only by paying special attention to the noise producing properties of the engines. Present estimates indicate that the prospects for a large decrease in acoustic output are not bright but even small improvements are desirable. There are reports from England of reduction in noise by adding elements so as to affect the mixing region of the jet. There are qualitative observations which indicate that coupling jet engines affects their noise output. Also there is evidence that the shrouds around the engines alter the sound energy. These and other effects should be investigated.

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V

AURAL PAIN PRODUCED BY SOUND

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The presence of pain is commonly associated with injury and malfunction. Indeed, the pain evoked by heating the skin is known to signal some degree of tissue damage. However, as severe wounds are sometimes not painful it is clear that pain does not indicate the seriousness or degree of injury. The relation of pain to injury has been clarified for thermal pain by the demonstration that pain is more closely related to the production of the injury than to the amount of damage caused. In this sense, pain serves as a danger signal but does not indicate how far the damage has progressed. On the other hand, it is well known that serious injury from radioactivity is painless at the time the original injury is sustained. It is important to know if aural pain (pain referred to the ear) serves as a satisfactory danger signal for the integrity of the hearing function. That is, does aural pain signify damage to the ear and if so, to what part of the ear?

A "just noticeable pain" can easily be recognized after a few trials and can be consistently reported when subjects are exposed to strong chemical, electrical, thermal, or mechanical stimuli. This makes it possible to measure a "threshold" for pain, i.e., the amount of heat, sound, electricity or other agent required to cause the just noticeable pain. Stimuli weaker than the threshold will in general not cause pain, and stimuli stronger than threshold will usually evoke a more intense pain than just noticeable. Techniques for measuring the pain threshold and a subjective scale for estimating pain intensity are described elsewhere (1).

Pain in the ear produced by intense sounds has long been recognized and its threshold has been measured. The most recent and extensive study reported by Silverman, (2) located the pain threshold at about 140 db for both normal and for hard-of-hearing ears. The same sound intensity in the form of either speech or pure tones (250-4000 cps) caused a just noticeable or threshold pain. The measurements were made by sound exposure through an earphone and not in a free-sound field. The sensation of pain ("it hurts") was distinguished clearly from the sensations of auditory discomfort ("it is too loud") and of touch ("it tickles," or "I feel something in the ear").

The BENOX experiments were done:

a. To compare the threshold of pain measured in an acoustic field produced by a loudspeaker, siren, or jet engine with measurements using an earphone. (This was desirable to determine to what extent field and laboratory measurements can be expected to agree.)

b. To extend the frequency range for the pain threshold down to "static" pressures.

c. To compare the pain threshold with the threshold for disturbances of the sense of equilibrium and for the production of temporary hearing loss.

d. To identify the anatomical source of the pain.

e. To evaluate the effect of loud sound upon the threshold for cutaneous (thermal) pain.

Subjects, Methods and Calibration

Five volunteer male subjects, including three of the authors, were used. Three subjects (D., P., G.) had had considerable previous experience with high intensity sound exposures while two subjects had not. None of the group had worked routinely in high intensity noise fields. All were indoctrinated in reporting the threshold of cutaneous (thermal) pain as measured by the thermal radiation method. This thermal pain served as a subjective standard for pain produced by sound. The thermal pain threshold for all subjects was in the normal range and no difficulty was experienced in the identification of the "just noticeable pain."

The sound sources used to produce aural pain in these experiments included:

a. A mercury manometer connected with the external ear canal by a plastic tube passing through a perforated earplug. Pressure in the ear canal, above and below atmospheric, was produced by raising or lowering a large weighing bottle.

b. A pistonphone, for measurements up to 50 cps, delivering alternating pressures through the same plastic tube and perforated earplug.

c. A 300-watt loudspeaker for the frequencies of 50, 100 and 2000 cps. For the latter frequency, the ear was in the plane of the mouth of a large open horn and for the two lower frequencies, a large pipe with padded aperture to admit the ear was substituted for the horn and formed a closed system.

d. A powerful siren (in the anechoic chamber of the Bio-Acoustics Section of the Aero Medical Laboratory) for the frequencies of 350 and 880 cps.

e. A jet engine (J-48), with afterburner, located at an outdoor test stand (free sound field).

The sound pressure produced by the pistonphone was measured by a condenser microphone operated in a high frequency carrier circuit. This system had a flat frequency response from 0 to 2000 cps. In the loudspeaker sound field, the siren sound field, and in the jet noise the subject was wearing a headband with a small condenser microphone attached. This microphone measured the sound pressure near the entrance of the external auditory meatus without disturbing the sound wave significantly or obstructing the ear canal. When the closed pipe was used instead of the loudspeaker horn the microphone was mounted inside the pipe in the same position relative to the ear canal.

The method of measuring the aural pain threshold was varied so as to adapt to the particular method of applying the acoustic stimulus. All pain thresholds were taken for only one ear of each subject. For each individual the same ear was used on all tests. For the mercury manometer, the pressure was raised or lowered slowly (within 10-15 secs.) until the report of pain was made. With the pistonphone, the subject himself altered the frequency or the pressure until pain was evoked. The subject also altered the sound output of the loudspeaker so as to produced threshhold pain. For the siren and the jet engine, the subject, wearing a calibrated microphone over one ear, walked slowly toward the sound source with ears plugged with his fingers. As he advanced in the sound field, he unplugged one ear for a second or so and evaluated his sensations. When pain was felt, he stopped and the sound pressure level registered from the microphone at his ear was measured as the pain threshold.

The jet engine was approached at an angle of 90° to the jet axis. The approximate sound pressure levels of this noise in the different octave bands were the following (in db relative to the overall sound pressure):

Octave bands in cps	db re overall SPL	Octave bands in cps	db re overall SPL
2.3 - 4.6	-30	150 - 300	-10
4.6 - 9.2	-21	300 - 600	- 6
9.2 - 18.5	-21	6000 - 1200	- 6
18.5 - 37.5	-20	1200 - 2400	- 8
37.5 - 75.0	-15	2400 - 4800	-10
75.0 -150.0	-12	4800 - 9600	-14

For measurement of the thermal pain threshold, the radiant heat method was used and the forehead was taken for the test surface. Tests were made in the quiet laboratory and in the intense sound field (140 db, 1000 cps) of the loudspeaker to determine the effect of the loud sound upon the ability of the subjects to perceive thermal pain.

Results

All observers identified the acoustic pain as of aching quality and located "deep in the ear." The pain could be eliminated by plugging the ears with the fingers or with well-fitted earplugs.

The average thresholds of aural pain for the various subjects are plotted in Fig. 1. Each point represents the mean of two to four trials for a particular subject. For the variety of conditions involved in making the tests, the consistency is considered surprisingly good. Within the accuracy of our measurements, the threshold of aural pain is very close to 140 db from 15 to 2000 cps, in good agreement with measurements previously reported by Silverman (2) and by von Békésy (3). Below 15 cps, there is a rapid rise in the pain threshold to 175-180 db for very low frequencies (0.05-0.1 cps), i.e., "static" pressure.

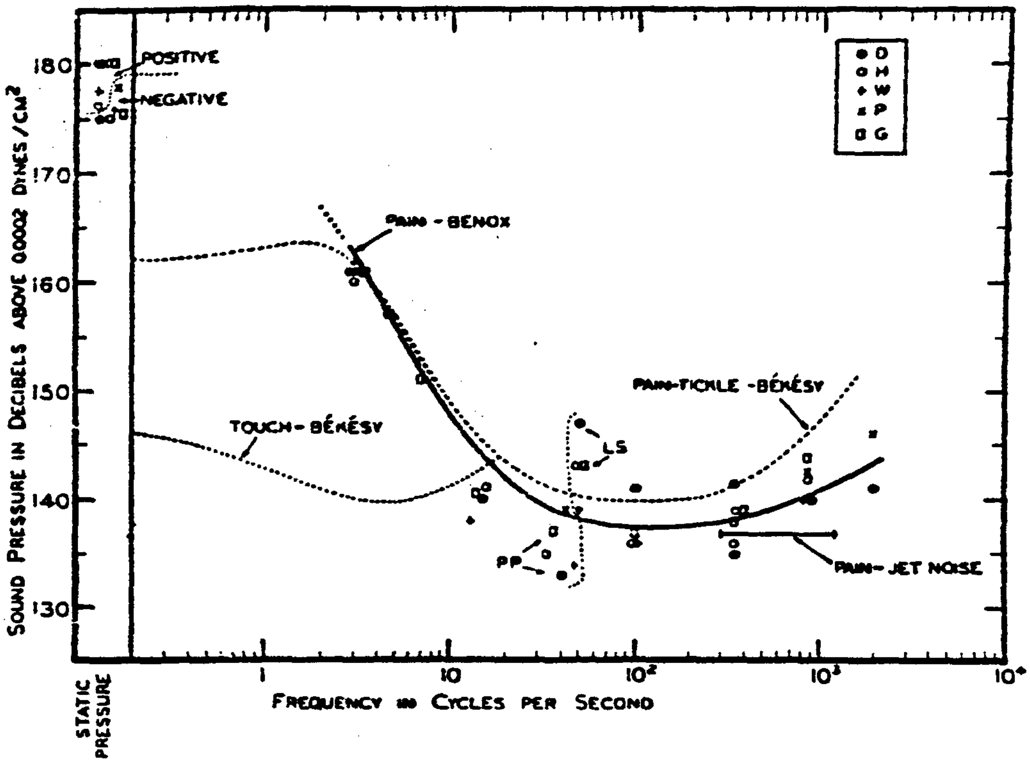

Fig. 1. Thresholds for aural pain produced by pure tones and jet noise. Points represent means of 3-4 determinations. Duplicate points represent means taken on different days. Positive and negative static pressures in the external ear canal are referred to atmospheric pressure. Line representing jet noise threshold is placed at overall sound pressure level and extends to the frequencies of the octave bands (300-600 and 600-1200) carrying most of the sound energy. (Touch and Pain-Tickle thresholds after Békésy (3).)

For positive static pressure (inward motion of the tympanic membrane) the pain threshold was found at a pressure level 2-5 db higher than for negative static pressure (outward motion of the tympanic membrane). This difference in the pain threshold agrees with the differences found by Kobrak (4) and others in the deflection of the tympanic membrane for positive and negative static pressure of this magnitude. Therefore, at least for these low frequencies, the pain threshold seems to be definitely connected with the deflection amplitude of the middle ear.

At frequencies higher than 2000 cps, the pain threshold may rise again although the present measurements did not cover this range.

The pain threshold for the jet engine noise was also found at 134-140 db (overall). The sound levels in the most intense octave bands (150-300, 300-600, and 600-1200 cps) are comparable to the pain thresholds for the corresponding pure tones.

We made no systematic observations that would show any upward drift of pain threshold as the subject becomes accustomed to listening to the very intense sounds. However, our casual observations confirmed the previously reported fact that by repeated exposure the pain threshold is raised 3 to 4 db. Also, since the experiments were all done within about two weeks, the observation of von Békésy that the character of the pain changes when experiments are repeated for several months could not be confirmed.

It should be noted that there is some difference, possibly only semantic, between the thresholds measured here and those reported by von Békésy. Von Békésy was exploring the limits of the auditory area and all the sensations to be found therein. He described the threshold given in Fig. 1 as "pricking," "tickle" or "pain-tickle." In the present study the subjects concentrated their attention as much as possible only on the sensation of pain. Here the sensation of just noticeable thermal pain served as a common standard of reference. We did not attempt to measure the threshold of "discomfort," to study the loudness of tones near the pain threshold, or to evaluate other sensations such as touch, tickle, itching, etc. which occur with different character, usually close to the pain threshold. It was clear, however, that below about 50 cps, aural pain was felt while there was little or no "loudness." In fact, below 20 cps, the subjects did not identify any true "tone" corresponding to the fundamental frequency but merely a rhythm in the overtones and in the incidental noises of the pistonphone. For "static" pressure, the first sensation was tactile, a sense of fullness in the ear; as the pressure was further increased the pain began. In the frequency range 800-2000 cps, the sound became "uncomfortably loud" at sound levels well below the pain threshold.

In several of these experiments, the subjects were careful to observe any sensations of disturbed equilibrium, position or posture. The details are given in another section, but in general, no such sensations were noted at frequencies below 30 cps up to the threshold of pain. Our observations do not justify any statement concerning the range from 30 to 800 cps, except to note that the jet engine noise (with maximum of its spectrum near 600 cps) at or near pain threshold did not evoke any such effects. Between 800 and 2000 cps, all subjects experienced sensations of movement of the visual field, of forced movements ("being pushed"), or unsteadiness of some kind. These sensations appeared at or slightly below the threshold of pain (800-2000 cps) and were clearest when one ear was suddenly opened and then closed again, or when the subject turned his head.

In all subjects, the thermal pain threshold was elevated by the presence of the loud sound (140 db, 1000 cps, no earplugs). This elevation varied from 10 per cent to 30 per cent and, as has been previously reported, is apparently due to distraction (1).

Discussion

From these observations, at least partial answers can be given to the questions originally posed. It may first be noted that the threshold for pain-tickle obtained by Békésy (3) (for an unknown but small number of subjects), by Silverman, (2) (for 92 subjects), and by this group, all agree well in spite of the variety of techniques used. It should be noted that the sound pressures given for the new data are largely derived from calibrated microphones at the external auditory meatus. These measurements do not necessarily reflect the sound pressure at the tympanic membrane. However, in the frequency range up to 1000 cps, only differences of the order of ±1 db will exist.

Secondly, it should be noted that the onset of pain in the ear has no relation to the levels that are dangerous for the organ of Corti of the inner ear. For the usual audio-frequencies and for exposures lasting longer than a few minutes, dangerous levels are reached at levels much lower than those which produce pain. Both temporary and ultimately permanent hearing losses can be produced by levels of 120 db. On the other hand, for very low frequencies such as 15 cps, the pain threshold is reached at levels that probably do not involve any hearing risk. Therefore pain is not a reliable indicator for danger to the most sensitive part of the auditory apparatus.

It was hoped that the present study might help to localize the anatomic source of aural pain produced by sound. It is certainly conceivable that the pain threshold might be reached at a given degree of loudness of the sound. In the usual audio-frequency range, the relationships of the family of equal loudness contours to the successive thresholds for discomfort, tickle, and pain show a plausible continuity. The new data, however, show that the threshold for pain actually crosses the threshold for "uncomfortably loud" in the region of 50-200 cps. Similarly, Békésy (3) described the threshold for auditory sensation as crossing the threshold for "touch" at a frequency of 1.5 cps. For this reason, and because the pain produced by static pressure is subjectively the same as that produced by acoustic pressure, we are quite certain that pain is not directly related to the loudness of the sound but is produced in the middle ear.

Using a Y-shaped link which connected both his own ear and the ear of a fresh cadaver in parallel with a sound source, Békésy (5) observed a sensation of touch in his own ear for positive static pressures and for frequencies up to at least 20 cps when the displacement of the stapes in the ear of the cadaver was sufficient to bring it in contact with the mucosa of the promontory. At this point the stapes had changed its axis of rotation and rocked around the long axis of the footplate rather than on the end of the footplate. A decrease in the sensation of loudness accompanied the change in motion.

Békésy (6) has also noted that the joint between the malleus and the incus is subject to considerable stress and with high static pressures may actually be dislocated. Normally, little or no relative motion occurs at this point. Instead the malleus and incus move together as a unit. It is conceivable that the frictional and elastic components of the restraint in this joint, provided either by its own fibrous capsule or by other attached fibrous bands and the ossicular muscles, govern the motion in this joint so that the critical or painful displacement as a function of frequency corresponds to the pain threshold function. This source of pain would of course be unrelated to the loudness function, and a moderate amount of stretching of these ligaments could account for the slight elevation of the pain threshold with succeeding trials.

Summary

1. Threshold: The threshold for aural pain produced by sound was measured in the frequency range from 0-2000 cps. In the auditory range the pain threshold was roughly 140 db. Below 15 cps it increased to 179 db for "static" pressure.
2. Anatomic location: Aural pain most probably arises from a region of the middle ear which includes the drum membrane and the ossicles and not from the organ of Corti. The threshold of aural pain does not serve as a danger signal for injury to the organ of Corti or for hearing loss.
3. Laboratory and field measurements compared: Measurements of aural pain threshold in the laboratory are entirely comparable to those made in the field. There was no significant difference in the measurements of pain threshold made around the jet engine and those made in the anechoic chamber. These thresholds are also almost identical with earlier measurements for speech and for tones heard through earphones.
4. Thermal pain thresholds as affected by loud sounds: The thermal pain threshold is raised by the presence of intense noise. The production of tissue damage by heat is not so readily detected. Therefore when pain is perceived from any source in an intense sound field, the limit of physiological safety has presumably already been surpassed and continued exposure to such a stimulus is dangerous.

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VI

HEARING LOSSES AND PROTECTIVE MEASURES

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Personnel whose duties require that they work in the close vicinity of jet engines are being subjected to intensity levels of noise which are known to produce irreparable hearing losses if exposure of the ears is repeated at frequent intervals for a period of several months.

Noise Levels of Jet Planes and Damage-Risk Criteria

Many factors, such as frequency range of the sound, its durations, suddenness of onset, frequency of repetition, and the susceptibility of persons exposed have to be considered in establishing safety standards for sound exposure. A number of different individuals (otologists, audiologists, acoustical engineers, etc.) and committees representing professional groups have suggested damage-risk criteria--i.e. the noise levels and conditions of exposure which should be considered as maximal for the ear to withstand without permanent damage.

For the purposes of the present discussion, the damage-risk criterion suggested by Rosenblith*, Stevens, et al. (1) will be accepted as representative. The upper curve (A) of Fig. 1 shows the sound pressure levels for octave bands for the frequency range 20 to 10,000 cps; this curve is used in setting damage-risk limits for wide-band noise such as that from jet engines. It should be noted that the sound pressure levels of noise must be measured in octave bands in order to make use of curve (A) of Fig. 1. The lower curve (B) of Fig. 1 is used for pure tones or for bands of noise in which the major portion of the energy is concentrated in a band narrower than the critical band.§

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* This criterion is a modification of that suggested by Kryter (2) and agrees closely with that proposed by Parrack (3).

§ The critical band is defined as "the width of a band of noise (of the continuous type of spectrum) whose energy is equal to that of a given pure tone at its masked threshold. The frequency of the pure tone is equal to the center frequency of the band of noise" (1), p. 3.

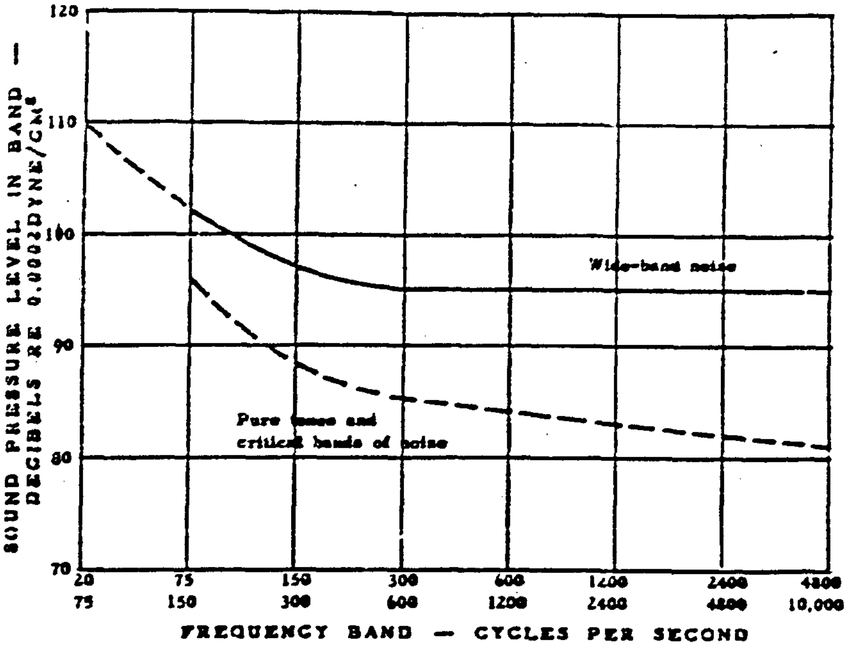


Fig. 1. Damage-risk levels for wide-band noise (upper curve) and for pure tones and critical bands of noise (lower curve).

Rosenblith, et al. (1) suggest that the following qualifications should be applied when the DR criterion represented by the curves of Fig. 1 is utilized:

"1. These contours are not to be taken too literally since deviations of the order of 1 or 2 db in either direction could probably be disregarded. Contours such as these should be interpreted as zones with some uncertainty attending the measurement of the exposure stimulus, and biological variability modifying the probability of damage. We feel, however, that contours 10 db lower would involve negligible risks indeed, while contours 10 db higher would result in significant increases in hearing loss.

"2. The levels are considered to be safe in terms of exposures during working days for durations up to a lifetime.

"3. The criterion levels apply to exposure noise that has a reasonably continuous time character with no substantial sharp energy peaks.

"4. For wide-band noise, the curve designated 'wide-bands' should be used. For pure tones or for noise in which the major portion of the energy is concentrated in a band narrower than the critical band, the curve designated 'critical bands' should be used. In the latter case, the abscissa should be interpreted as a logarithmic frequency scale rather than a scale of octave bands of frequency.

"5. The criterion should be considered as tentative only, and is subject to further revision as new laboratory and field data are reported," p. 218.

For exposures which are brief (one minute approximately) and do not occur too frequently, Rosenblith recommends that the maximal overall sound pressure level which can be considered safe is of the order of 145 to 150 db. If exposure is repeated often or if the duration is more than a minute or so, levels above 140 db are not safe. Although sufficient evidence for man is not available, it appears likely that single exposures for even very brief durations may cause permanent damage to the ear at an overall sound pressure level somewhere in the range 150 to 160 db. It is known that brief exposures to tonal stimuli at sound pressure levels as low as 130 db will produce permanent damage to inner ear structures in the anesthetized cat (4) or guinea pig (5).

In Fig. 2, sound pressure levels measured for a turbojet engine operating at full power with and without afterburner are known on the same plot with the curve describing the damage-risk criterion for wide-band noise. The measurements of sound pressure levels for the jet engine were

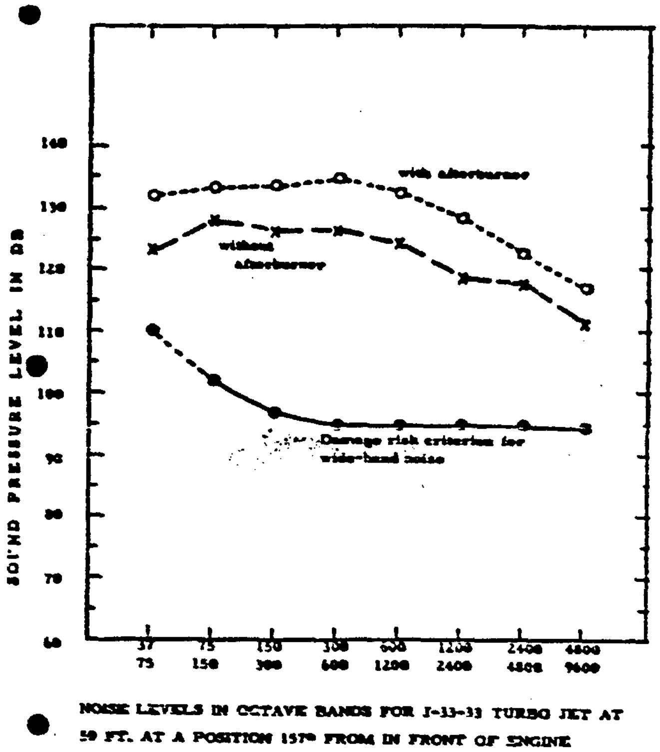


Fig. 2. Sound pressure levels measured in octave bands for a turbojet engine at full power with and without afterburner compared with the damage-risk criterion for wide-band noise.

made in a position 50 feet from the rear of the plane and at an angle of 23° from the axis of the plane. It is apparent at a glance that the sound pressure levels produced by the jet engine far exceed the levels considered safe for the unprotected ear. The sound pressure levels for the jet engine noise given in Fig. 2 are not unusually high. Many men in the flight line, and particularly on the flight decks of a carrier during launching operations, are exposed to sound pressure levels as high as those shown for the jet without afterburner. Measurements made by Goldman (6) would indicate that nearly all of the men on the flight deck, in the catwalks and on the island structure are intermittently exposed to sound pressure levels which exceed the criterion which has been set as safe for frequent exposure over a long period of time.

Direct Evidence of Hearing Losses after Exposure to Jet Noise

Conclusive evidence that personnel exposed to jet noise have suffered permanent hearing losses has not yet been obtained. To get such evidence, careful examination of the hearing of exposed personnel must be made before any exposure and at regular intervals over a period of months or years. Medical records which would take into account diseases and infections which might affect hearing would also be necessary.

Surveys which have been made indicate, however, that the average hearing loss for men who have been regularly exposed to jet noise is greater than that for men of comparable age in the normal population (6, 7, 8). Mendelson has commented as follows on the audiometric measurements made during the survey on the U.S.S. Coral Sea (9):

> "Audiometric observations as well as physical measurements were undertaken aboard the aircraft carrier. The audiograms have been studied and restudied without leading to any convincing conclusions. However, three things appear worthy of mention: (1) the few individuals who protected their ears on the noisiest occasions appear to retain their auditory acuity, while some who did not or could not utilize ear protection showed auditory depression. (2) Of 100 individuals between the ages of 17 and 45 years (average [illegible]) the vast majority showed evidence of decidedly depressed thresholds, whether acute or chronic could not be determined. (3) Great willingness to try ear plugs was expressed by most of the subjects, but very few continued to wear them; the reasons given were vague but suggested that the men lost their usual auditory cues when they used the plugs in noise situations to which they were accustomed and adapted without ear protection. Earlier training might have helped."

Temporary Hearing Loss

Temporary hearing losses after exposure to white noise or to the noise of propeller planes have been described by a number of investigators (10, 11, 12). Fig. 3 taken from the Summary Technical Report of the Harvard Psycho-Acoustic Laboratory (11) shows the typical hearing losses produced by exposure to white noise and to noise simulating that inside a bomber. Time for recovery from such hearing losses varies to some extent with the degree of initial loss. It may take place after a few hours but often requires days or even weeks (11, 12).

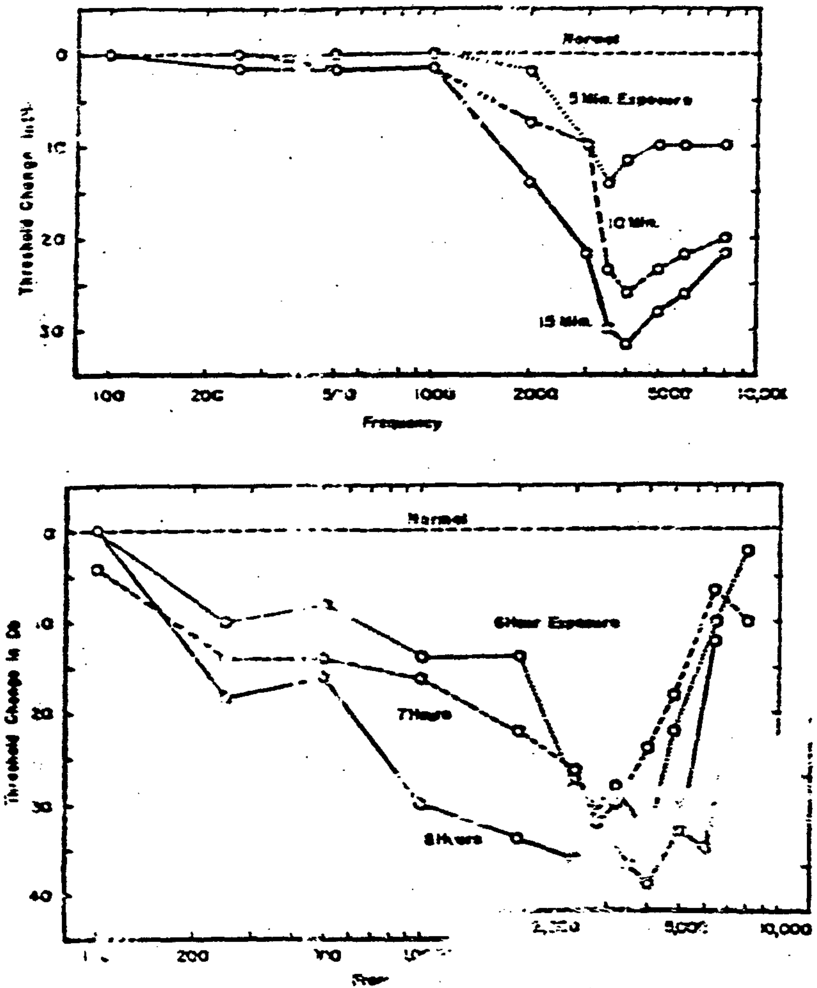
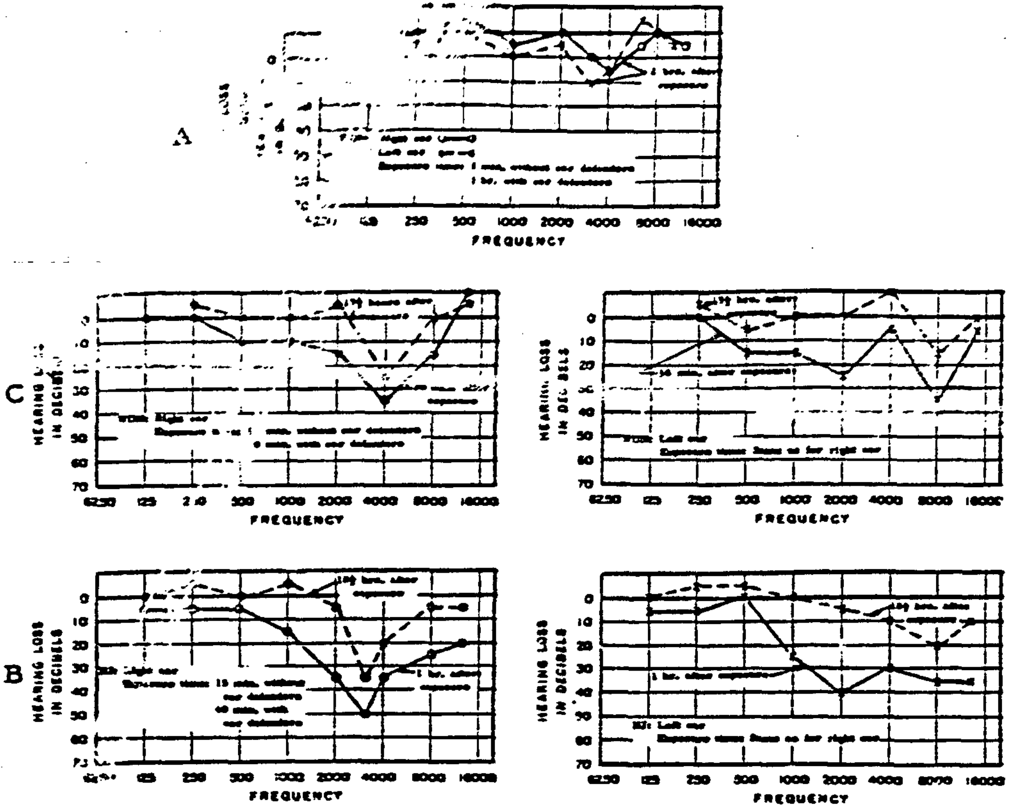


Fig. 3. Hearing losses after exposures of various durations to white noise (upper graph) and to simulated bomber noise (lower graph). (From PAL 3 [illegible]

During the course of exploratory experiments by the BENOX group at Wright Field, audiograms were obtained for a number of subjects before and after exposure to the noise of a J-48 engine mounted in an outdoor test [illegible]

The typical hearing losses which occur after brief exposure to the noise of a jet engine are shown in Fig. 4, A, B, and C. The curves of Fig. 4A show the very slight loss which was present approximately two hours [illegible] subject had a bri exposure ([illegible] without ear plugs plus approximately one hour wit he V-51R [illegible] ters being worn. In B and C of Fig. 4 the more se re losses [illegible] sult from exposure of 15 minutes without ear defende are [illegible] subjects whose audiograms are shown in Fig. 4 were mo ng [illegible] the jet engine during the exposure periods. The sound press [illegible] levels in the area varied from 125 to 140 db overall.

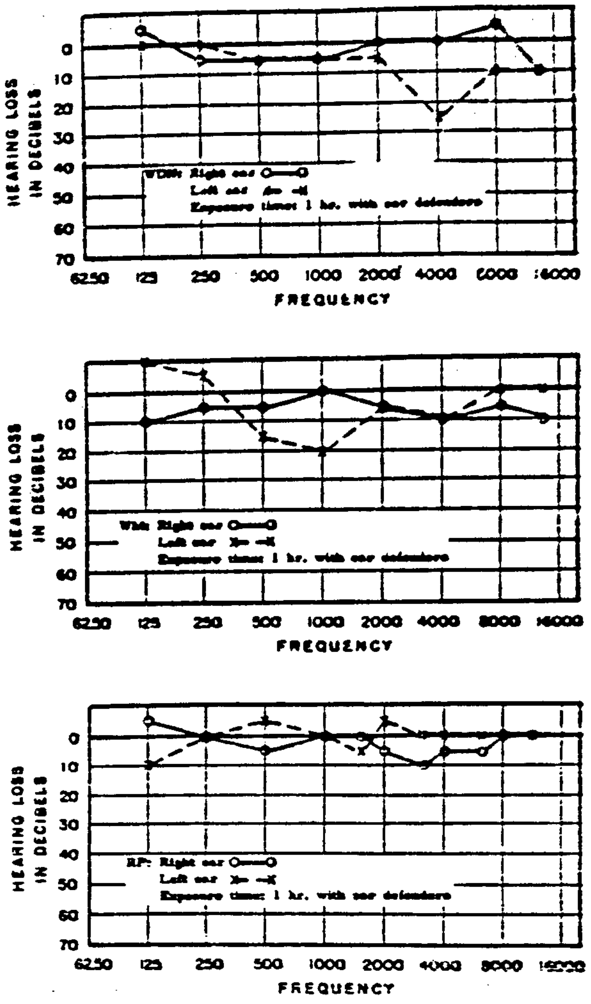


HEARING LOSSES AFTER EXPOSURE TO JET NOISE

Fig. 4. Typical hearing losses resulting from brief exposures to jet engine noise. For A (top graph) thresholds were taken two hours after exposure for two minutes without ear defenders plus one hour with ear defenders. The two middle graphs (B) show thresholds taken 30 minutes and 19.5 hours after exposure of 15 minutes without plus 40 minutes with ear defenders. The two bottom graphs (C) show hearing losses determined one hour and 18.5 hours after exposure of 15 minutes without plus 40 minutes with ear defenders.

It should be noted from Fig. 4, B and C that even 18 to 20 hours after exposure hearing had not yet completely recovered to the normal pre-exposure level.

When ear defenders were worn during exposure to the noise of the J-48 engine, very small hearing losses were found for some subjects and no change in threshold of hearing for others (see Fig. 5A, B and C). The subjects whose hearing loss curves are shown in Fig. 5 were exposed to the J-48 noise for a period of approximately one hour; during less than ten minutes of this time the afterburner was cut in. Accurate sound pressure levels could not be obtained when the afterburner was operating. At all times the sound pressure level to which the subjects were exposed was at least 125 db (overall) and probably exceeded 140 db at maximum.



HEARING LOSSES AFTER EXPOSURE TO JET NOISE

Fig. 5. Hearing losses of three subjects resulting from exposure of one hour to jet engine noise while wearing ear defenders.

The curves of Fig. 5 suggest that long exposure to jet noise may often result in slight hearing losses even when ear defenders are worn. The ear defender may not make a good seal in the ear canal at all times or even with a good seal it may not provide sufficient protection for noise levels as high as those produced by a jet engine with afterburner.

A rather severe tinnitus which lasted for many hours was reported by the subjects who exposed their ears unprotected to the jet noise. They also reported that sounds around them appeared changed: the hum of a car motor was quieter and speech of others during a conversation sounded like it was coming through a loud speaker of low fidelity. Many of the subjects who wore ear defenders while they were in the jet noise also reported some tinnitus at the time their post-exposure audiograms were taken.

Although it has not been shown experimentally that there is a cumulative effect of repeated temporary hearing losses such that permanent hearing loss eventually occurs, it seems a reasonable prediction to make, particularly if the temporary loss is severe and re-exposure occurs before complete recovery.

Protection

The question, "how can the ear best be protected from damage by intense noise?" keeps reappearing and often leads to long and vigorous arguments despite the fact that the results of thorough, careful research studies have furnished a clear and unequivocal answer (11, 13, 14).

Several kinds of insert ear defenders (ear plugs) have been developed which provide about the maximum amount of protection that can be expected (see Chapter VII for a discussion of the limits of ear protection). Among the best of the insert type ear defenders is the V-51R which was adopted for use by the Armed Services in World War II. It is reasonably cheap to manufacture, easy to keep clean, as comfortable to most persons as any kind of good insert defender can be, and, in its different sizes, provides a good fit for the large majority of individuals. The acoustic insulation provided by the V-51R ear defender is shown by the curve of Fig. 6. There is no evidence that any other kind of ear defender offers better protection from noise than the V-51R; many kinds are definitely inferior.

Designers of over-the-ear protectors have been persistent in their efforts and inventive in their designs. Unfortunately they have been unsuccessful in developing a device that provides protection equal to that furnished by the insert-type defender. Over-the-ear protectors give less protection than the insert type; they are particularly poor for frequencies below 1000 cps.

It is possible that an over-the-ear protector might be devloped which would more nearly approach the level of protection provided by the insert defender. However, to accomplish this end, the over-the-ear protector would have to fit very tightly against the ear or against the head surrounding the ear. (The typical ear-cup in a helmet or on a headband does not furnish an adequate acoustic seal.) If the protector exerts much pressure

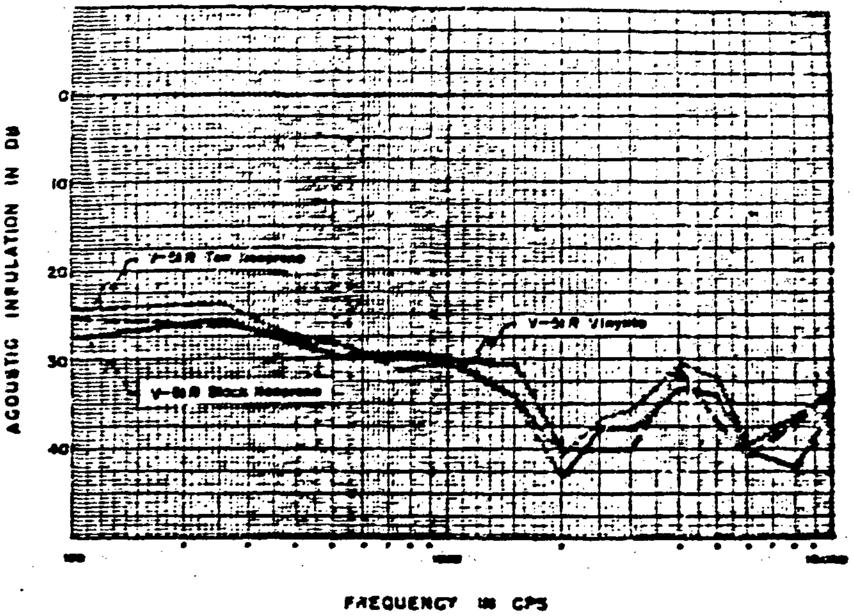


Fig. 6. Acoustic insulation provided by the V-51R ear defender.

on the pinna of the ear, the discomfort soon becomes unbearable; if it exerts pressure only on the skin surrounding the pinna, it may be endurable but uncomfortable. Therefore the development of an adequate over-the-ear protector would in all likelihood not eliminate the complaints of discomfort which are sometimes made by those who are asked to wear insert ear defenders. Particularly in warm climates, a tight-fitting cover over the ear or over part of the head would not be tolerated.

If the cost of manufacture and distribution is considered, it is difficult to imagine any kind of over-the-ear protector which would not be many times more expensive than the insert defenders.

In answer to those who argue that any protection is better than none and that comfortable over-the-ear protectors which men exposed to noise will wear are to be preferred to insert defenders which they will not wear, a word of caution and a prediction as to the future should be made. The wearer of a protective device which eliminates some of the high frequency noise generated by jet planes may feel that he is being adequately protected from the noise, because the majority of people find the high frequencies most annoying. Reducing the annoyance of noise does not necessarily reduce its damaging effects. The low frequencies which are not attenuated by the ear protector can produce temporary, and over a long period, permanent injury to the inner ear.

If the experiences of the BENOX group during its conduct of experiments at WADC can be taken as representative, it seems safe to predict that in the near future men exposed to jet engine noise will use insert ear defenders without complaint. All of the personnel (both military and civilian) working in the near vicinity of the J-48 engine running a full military power with or without afterburner utilized the ear defenders provided; no special urging was needed. An attempt to get some of the experimental subjects to expose their ears unprotected or to wear only helmets with over-the-ear covers met with little success.

The problem in the future will be to provide an adequate supply of ear defenders and to instruct personnel exposed to noise so that they learn to utilize the defenders to full advantage. As noted in Chapter VIII on Communication, particular attention needs to be given to demonstration of the fact that wearing ear defenders will, under certain noisy conditions, improve voice communication rather than interfere with it.

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VII

PROTECTION OF THE EAR FROM NOISE: LIMITING FACTORS

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Introduction

The high noise levels associated with today's aircraft operation make it necessary to provide for the human ear the best possible protection. Under most circumstances insert type earplugs provide enough protection to avoid permanent damage to hearing but occasions requiring more protection become increasingly more frequent. It can be predicted that this demand will become more urgent in the near future as more powerful propulsive units are developed. It is therefore timely to ask whether present day ear protectors can be improved, and if so, what are the limits for these improved designs.

Tests of insert type plugs by the threshold shift method indicate that there is a limit to the amount of attenuation that can be achieved. This limit seems to lie between 25 and 30 db for frequencies below 500 cps; above 500 cps the attenuation may reach values between 35 and 40 db. These limiting values apply up to 8000 cps, the highest frequency used in these tests (1, 2, 3). Once this limit is reached, further changes in the design of the earplug yield no improvement in performance. The following discussion examines quantitatively the reasons for these limits in order to permit us to maximize the protection afforded by the plugs. The protection obtained by using ear muffs, alone or in combination with earplugs, is also discussed as is the protection to be expected from a sound excluding helmet. Some of the conclusions arrived at need to be checked. However, today's best quantitative estimates should assist in the further development of protective devices.

The Transmission of Sound to the Inner Ear

When the unprotected human body is exposed to a random, free sound field, all body surfaces absorb vibratory energy. The highest energy per unit area is absorbed by the eardrum. The fraction that is transmitted to the inner ear gives rise to the responses associated with hearing of air-conducted sound. Given the mismatch in impedance between the air and the body surface, the acoustic energy absorbed by the skull, chest abdominal wall, and other parts of the body is relatively small. Under normal conditions this energy absorbed by the body has only a negligible effect on the inner ear. But if we assume the auditory canal to be completely occluded by an ideal earplug so that no sound is admitted and so that no motion of the drum results from an ambient sound field, this bone- and tissue-conducted sound becomes important and imposes the theoretical limit for all types of ear protectors. The question is, how far does the threshold for bone- and tissue-conducted sound lie above the threshold for air-conducted sound.

An approximate answer is given by experiments in which small, specific areas of the body were exposed to sound waves confined within a metal tube. The tube, closed at the one end by a loudspeaker (300 watt source), had a rubber pad around the rim of the open end. This end was placed over the unoccluded ear to measure the threshold for air-conducted sound. Then the open end was pressed against the forehead and the threshold of hearing for bone-conducted sound was determined. For the bone-conduction test and those following, the ear was occluded by V-51R earplugs and ear muffs. Great care was taken to assure that the sound to which the observer responded entered by way of the forehead and not through the auditory canal in spite of the earplug. The signal heard by the subject at threshold was considered to be truly bone-conducted only when the experimenter, who had acute hearing, could not hear the signal when his unoccluded ear was placed beside the point of contact between the subject and the tube, i.e. at the seal between the sound source and the listener's head. The same tests were repeated by placing the tube on the sternum and on the abdominal wall.

The results are shown in Fig. 1. The ordinate represents the difference between the auditory threshold for sound absorbed through the

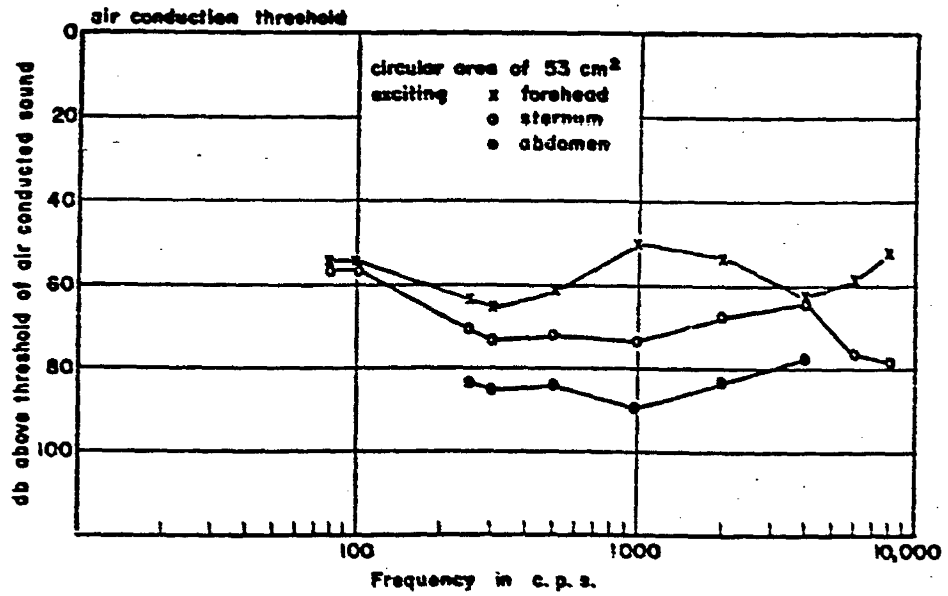

Fig. 1. Threshold of hearing for sound absorbed by different body areas relative to the threshold for air-conducted sound.

several tissue pathways and the threshold for air-conducted sound presented to the ear through the tube. Each curve represents the mean values of three subjects. The thresholds for excitation of the forehead lie roughly 60 db above the air-conduction threshold; the thresholds for the sternum are about 70 db above, and the thresholds for the abdomen are between 80 and 90 db above the air-conduction threshold.

Unfortunately the excitation of a small circular area on the head or body does not set up the same vibrations of the skull or in the body as when the whole body is surrounded by a free sound field. Nevertheless, it is felt that the data provide some approximate, realistic figures for the differences in these thresholds. For high frequencies, where the body dimensions become greater and greater compared with the wave length, the data should become more and more similar to the ones in the free sound field, which unfortunately are not easily measured directly.

The threshold for bone- or body-conducted sound must be assumed to change with the degree of occlusion of the auditory canal, the quality of the earplug, the depth of its insertion, etc. Such a shift is neither the consequence of a remaining leakage path for air-conducted sound nor the result of variable masking by ambient noise but is primarily attributable to a change in the effectiveness of the so-called osseo-tympanic pathway. Bone-conducted sound sets up vibrations in the air of the occluded part of the auditory canal and the eardrum. This fact, though often contradicted, seems to be quite well established (4, 5, 6, 7). Fig. 2 shows this lowering

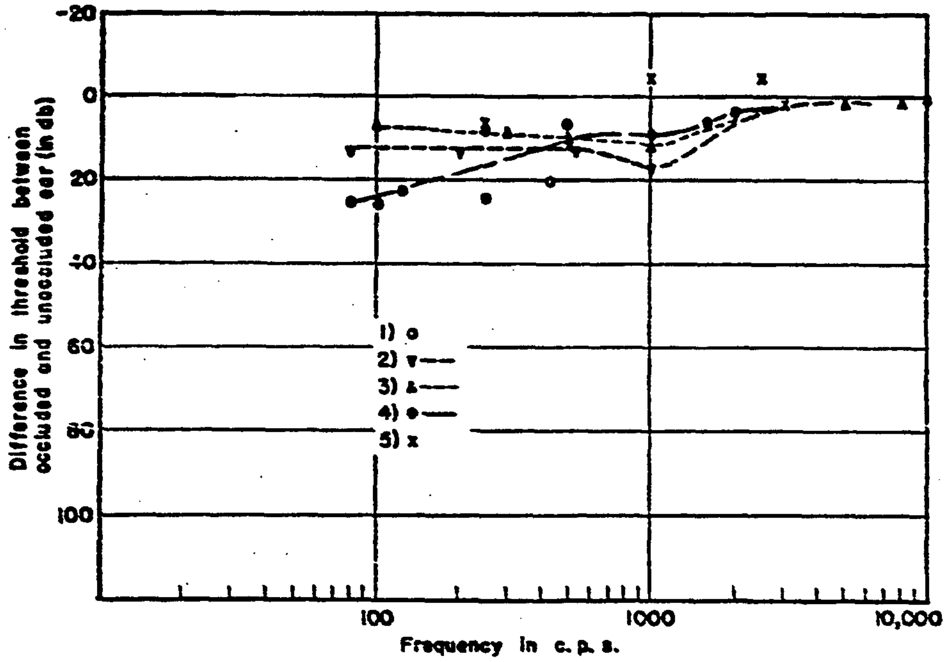

Fig. 2. Difference in bone conduction threshold with and without the ear occluded (threshold is lower with ear occluded): 1) from reference (4); 2) from reference (5), Fig. 12; 3) from reference (5), Fig. 13; 4) from reference (6); 5) from reference (7).

of the threshold for bone-conducted sound when the auditory canal is closed. For frequencies below 2000 cps it amounts to 12 db on the average. In the tests previously described, if the ears had not been occluded and covered, the thresholds shown in Fig. 1 would have been about 12 db higher for low frequencies.

The data for the threshold of bone-conducted sound received by the forehead can be compared with the data given by von Békésy for the thresholds of bone-conducted sound received by the entire skull in a free sound field. The calculated and measured values obtained by von Békésy are given in Fig. 3. They were obtained by rather different methods (1) and are valid for unoccluded ears. In order to obtain the threshold curve for bone-conducted sound received by the entire skull in a free sound field while the ears are occluded, the correction of Fig. 2 was applied to the measured curve of Fig. 3. The result is the solid curve labeled "1" on Fig. 4.

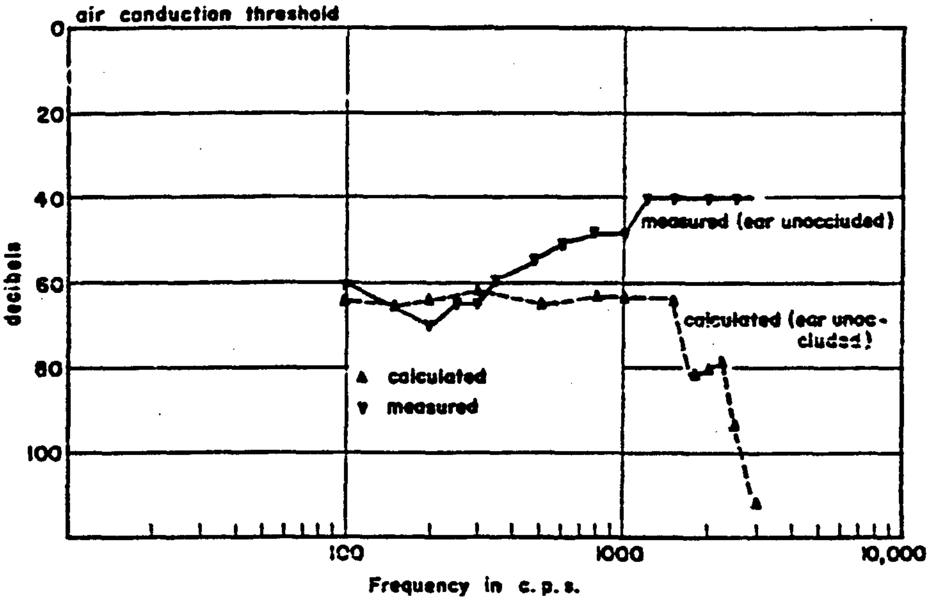

Fig. 3. Difference in db between sound level required to produce equal loudness of tones heard by air and bone conduction in a free sound field. (Values from reference (1).)

To compare this curve with our measurements it is assumed that reception by bone conduction is the result of vibrations of the skull as a rigid body; this assumption has been shown to be valid for low frequencies (1). Then we can calculate the free sound field that would be required to produce the same effective force acting on the head as the force that is acting on the circular area of the forehead. The equations are given by von Békésy (1). In this way we can get from the threshold curve for bone-conducted sound received by the forehead (Fig. 1) to a calculated threshold curve for bone-conducted sound received by the entire head in a free sound field with the ears occluded. This calculated threshold curve is the dashed curve (number 2) in Fig. 4. It compares quite favorably with the solid curve (number 1) in the same figure which was obtained by applying the occlusion correction to von Békésy's data.

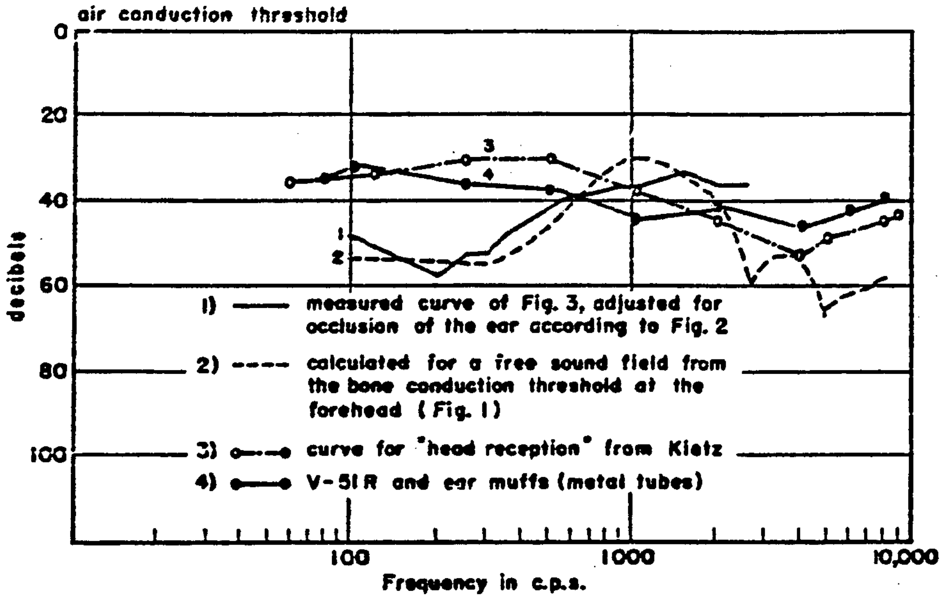

Fig. 4. Difference in threshold between air- and bone- conducted sound in a free sound field. (With earplug.)

All experiments designed to measure directly bone-conduction thresholds for the entire skull in a free sound field by occluding the auditory canal as completely as possible by means of earplugs or even earplugs combined with ear muffs have resulted so far in threshold curves that lie closer to the air-conduction threshold curve than curves numbered 1 and 2 in Fig. 4. One such curve labeled in the literature (8) as threshold for bone-conducted sound (head reception) is given by curve number 3 in Fig. 4. Our own efforts to measure the threshold curve for bone conduction in this way yielded the rather similar curve number 4. This curve represents the average values measured on six subjects wearing earplugs (V-51R) and ear muffs made of large metal tubes and with sponge rubber doughnuts for the seal. Great care was taken to obtain the best possible seal which resulted in considerable discomfort. Since in all the experiments that led to curves exemplified by numbers 3 and 4 we cannot be sure that air conduction or ear muff vibration (see below) were completely excluded, the higher values for the bone-conduction threshold given by curves numbered 1 and 2 are by no means invalidated and are probably more realistic.

Thus if one could design and wear ideal earplugs, curves numbered 1 and 2 in Fig. 4 probably indicate best the maximal protection they would afford the ear against outside noise in a free sound field. More attenuation by the earplug would not decrease the sound stimulating the inner ear because the air-conduction path through the earplug and auditory canal would be "shorted out" by the bone-conduction path. If one could shield the whole head completely against sound waves, for instance by an ideal helmet, we would still produce only about 10 db more protection (and at low frequencies, not even that much) as Fig. 1 indicates.

The schematic diagram of Fig. 5 shows how the different branches of the complex system conduct sound energy to the inner ear. An electrical circuit analagous to the mechanical system has been chosen. Each non-ideal protective devise transmits the sounds three ways: 1) sound transmission through the material of the earplug (or muff or helmet) itself; 2) sound conduction through an inadvertent or designed air leak; 3) movements of the earplug, muff or helmet, vibrating as a rigid body because of the elasticity of the supporting seal or the elasticity of the supporting tissue.

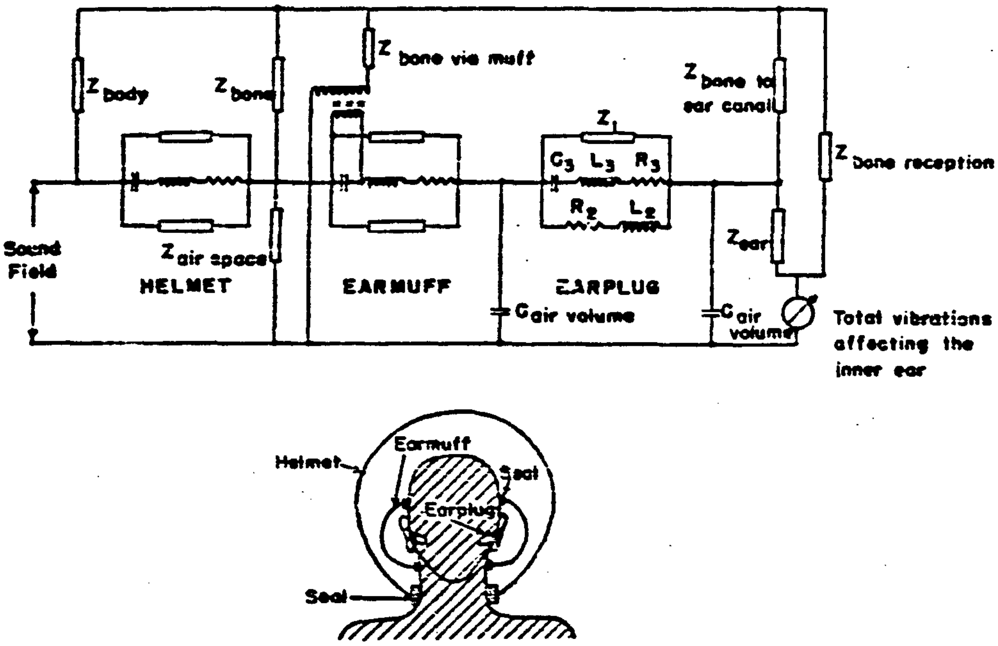

Fig. 5. Sound protection devices on the human head (equivalent circuit).

These three possibilities are represented in Fig. 5 by the three branches for the earplug, the helmet and the ear muff. When the helmet is ideal all three branches have infinite impedance and energy from the sound field can reach the inner ear only by going through the body (Z_{body}). If the helmet is not ideal, vibratory energy is conducted to the air space ($Z_{air\ space}$) inside the helmet. Part of this energy might enter the bone directly (Z_{bone}) and go to the inner ear and part of it could be transmitted by the ear muff to the air volume inclosed under it ($C_{air\ volume}$). Vibrations of the whole ear muff might result in an additional bone-conduction component exciting the area where the muff touches the skull ($Z_{bone\ via\ muff}$). The air volume under the muff transmits the sound to the earplug, which, depending on its quality, conducts some of the energy to the air volume ($C_{air\ volume}$) enclosed in front of the eardrum. This sound together with the bone-conducted sound add up in the inner ear and together represent the acoustic stimulus that would give rise to a response. Part of the sound originally entering the head via bone might at some frequencies be transmitted to the middle ear through vibrations of the auditory canal, the ossicles or the tympanic cavity ($Z_{bone\ to\ ear\ canal}$) and finally enter the inner ear through the same route as the air-conducted sound.

The Earplug System

Physical constants of the earplug system

An investigation of the constants of the three branches of the earplug system will show how the overall frequency response of the earplug (pressure on the eardrum/pressure outside the earplug) results from the conduction through the three branches, and it will reveal which branch conducts most of the sound and is thus responsible for the earplug not being ideal.

When the impedances of the circuit are known, the frequency response of the earplug can be calculated. The impedance Z_1 of the material itself is always very high so that the sound leakage through the material can be neglected for most types of ear defenders. Our own measurements showed this assumption to be correct for rubber, plastic, and impregnated cotton earplugs. The same is reported by Watson and Knudsen (2). The complex impedance Z_1 is therefore not of great interest because the limits of attenuation are given by branches 2 and 3.

In branch 2 we have the mass of the air (L_2) in the air channel through which the sound leaks, and the friction (R_2). These two parameters, which are both frequency dependent for such narrow ducts, can be calculated by assuming a certain width of the duct. They form together with $C_{air\ volume}$ and Z_{ear} a resonant circuit (Helmholtz resonator). If we assume the duct to be about 2 cm long and an inclosed air volume in front of the eardrum of 0.5 cc, then for certain diameters of the leak branch 2 alone would give us the attenuation curves numbered 2 and 3 in Fig. 6. The attenuation of this duct is always zero when we approach zero frequency.

The constants of branch 3 were measured for a certain earplug (V-51R) by vibrating the inserted earplug with an impedance measuring device. The experimental arrangement was the same as the one used by Franke (9). With this method the shear compliance of the skin lining of the external ear canal (C_3) and the friction in this skin lining (R_3) were measured. They were found to be constant up to the highest frequencies measured (c.a. 600 cps.). The compliance (C_3) was 4.8×10^6 dynes/cm^2 and the friction (R_3) was 4.4×10^3 dynes/ cm^2. These figures are the mean values determined from several insertions of the earplug in the auditory canal of one subject. In these measurements, the earplug was filled with a solid piece of plastic so that the elasticity and friction of the skin alone were measured. These constants should therefore be about the same for all types of earplugs independent of shape and material. Only the length over which the earplug touches the skin lining, and the pressure with which the plug is inserted, should modify these constants. For most earplugs commonly used today these parameters do not change much and we can assume in the following calculations that the constants measured with the V-51R earplug represent approximate values for most types of earplugs. An individually molded earplug might increase the elasticity up to about three times the given values. It would probably represent the the maximum value of the elasticity.

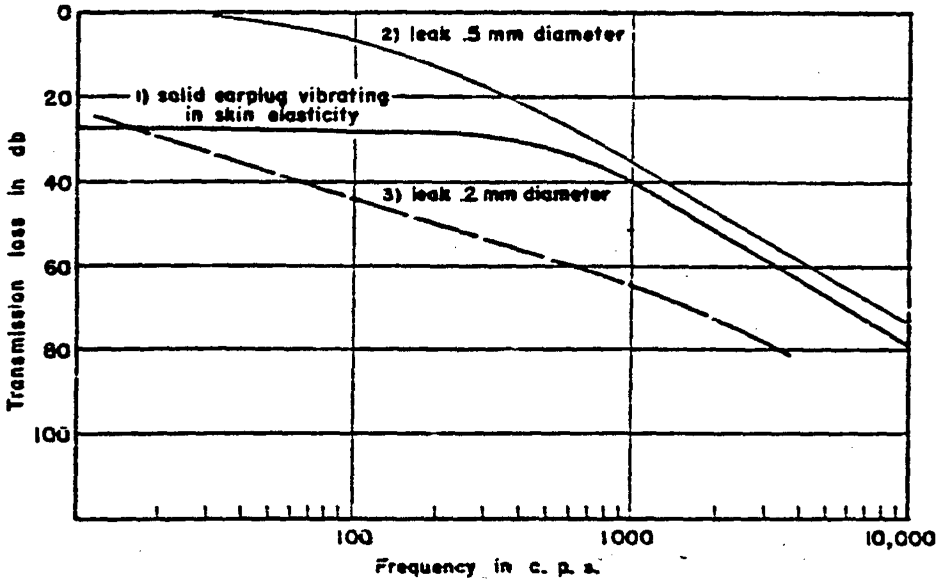

Fig. 6. Calculated curves for sound transmission through earplugs and leaks (curve 1 for V-51R plugs).

Since the mass of the earplug (L_3) can be found by weighing, all constants of branch 3 are known. In the case of the V-51R earplug the mass is 0.5 gr. The air volume inclosed in front of the tympanic membrane (C) was measured as about 0.5-0.8 cm^3. Its impedance is, at the lower frequencies (at least below 2000 cps), large compared to the impedance of the eardrum ($Z_{eardrum}$) and can therefore be neglected. The impedance of the eardrum below 500 cps is equivalent to the impedance of an air volume of 1.5-2.0 cm^3. For the calculation of the attenuation of an earplug, $C_{air\ volume}$ and $Z_{ear\ drum}$ were therefore combined into one impedance. This impedance was assumed for the entire frequency range to be equivalent to the elastance of an air volume of 2 cm^3 upon which the earplug acts over an area of about 0.6 cm^2. Above approximately 500 cps this assumption is not justified any more; $Z_{ear\ drum}$

remains larger than the air volume elastance and changes its phase. However, the measurements of $Z_{eardrum}$ are not extremely accurate as considerable individual variability is exhibited. Also the area of the ear canal and $C_{air\ volume}$ will vary from individual to individual. Hence the elastance for an air volume of 2 cm^3 was assumed as the combined impedance for the entire frequency range. (In the worst instance in which $Z_{eardrum}$ is large compared to the impedance of an air volume of 2 cm^3, the error would amount to 12 db at the highest frequencies, since under these circumstances, $C_{air\ volume}$ equal to 0.5 cm^3 would represent a better approximation to the impedance on which the earplug acts than the combined impedance value of 2 cm^3.)

The attenuation of an ideal V-51R earplug without any leakage and sound transmission through the material (impedances of branches 1 and 2 infinite) was calculated using the discussed constants and is shown in curve number 1 of Fig. 6.

The maximum attenuation that is practically obtainable with earplugs

The attenuation provided by the best possible earplug (no leakage, no sound transmission through the earplug) is limited at low frequencies by the compliance of the skin in the ear canal (curve 1, Fig. 6). Therefore at these low frequencies (below 500 cps) we can never hope to occlude the auditory canal sufficiently to reach the upper limit for protection set by bone-conduction (Fig. 4). At 100 cps the V-51R plug provides (under favorable conditions) only about 28 db instead of 50 db attenuation, where bone-conduction would start to make further attenuation worthless. At higher frequencies (above 1000 cps for the V-51R) the attenuation provided by the earplug would increase with the square of the frequency. However, this increasing attenuation of the earplug is of no use in view of the behavior of the bone-conduction threshold curve in this frequency region. As the attenuation provided by the plug increases to between 40 and 50 db, bone-conducted sound stimulates the inner ear, thus bypassing the pathway through the earplug. With the best earplug we would design, we can not expect, therefore, to measure a higher attenuation than the dashed curve in Fig. 7. Naturally, as pointed out before, this curve (combined from curve 1 in Fig. 6 and Fig. 4) has been only roughly determined so far and is tentatively presented here. At high frequencies bone-conduction is certainly not transmitted by vibrations of the skull as a rigid body, and we have no direct measurements in free sound fields on which to base the threshold of bone-conduction. But the curve has to stay above curve number 2 of Fig. 4 and at the highest frequencies, certainly above the curve given for the forehead in Fig. 1. That means the bone-conduction threshold and therefore the limit for protection by earplugs should lie from 40 to 50 db above the threshold for air-conduction.

Fig. 7 shows both calculated and measured values for the attenuation provided by earplugs. The data from other authors (2, 3, 10) as well as our own were determined by the threshold shift method. The data are quite close to an optimal attenuation curve that has been suggested by the dashed curve in Fig. 7. At low frequencies all measured values are particularly close to the 26 db value we theoretcially calculated taking account of the measured shear compliance of the skin. This agreement shows that all tested earplugs, even at the lowest test frequency (100 cps), give practically an ideal seal, i.e. the leak is smaller than the one given by curve number 3, Fig. 6.

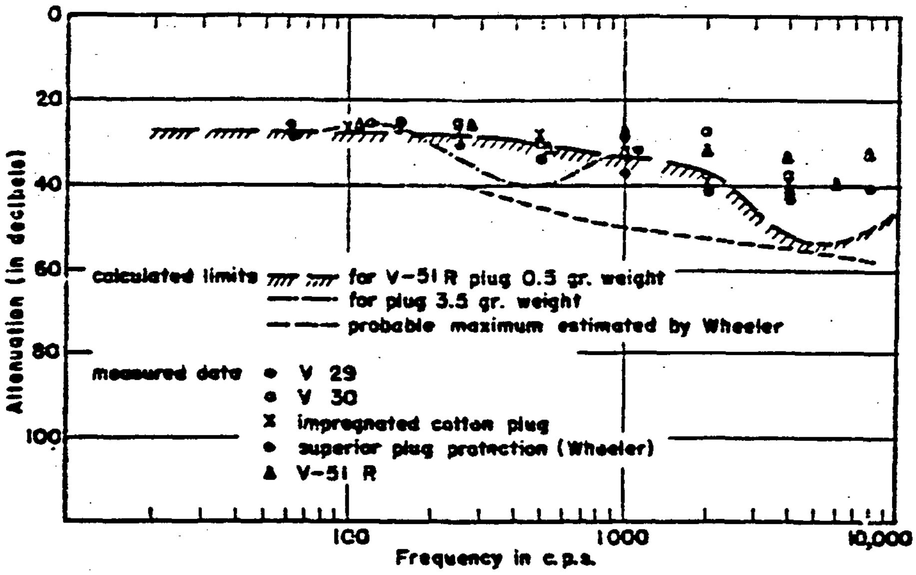

Fig. 7. Practical and theoretical limits for protection by earplugs.

The shear compliance of the skin determines the low frequency end of the curve in Fig. 7; the bone-conducted sound determines the high frequency region of the curve. The intermediate range depends on the mass of the earplug. We cannot hope to achieve a big improvement by designing a much heavier earplug. For example we might assume, instead of the 0.5 gr. mass of the V-51R earplug, a heavy earplug weighing 3.5 gr. For this earplug we obtain the second curve in Fig. 7. The small improvement probably does not justify the difficulties and the discomfort such a heavy plug would entail.

Thus it seems we are able to calculate quite accurately the possible attenuation of earplugs. With the data available the upper limit of protection does not appear to be quite as high as the curve suggested by Wheeler (3). The results of our own measurements on impregnated cotton plugs, shown in Fig. 7, demonstrate once more that the mass of the plug and its material do not change its attenuation very much. The attenuation provided by these plugs is close to the one of the V-51R. At 100 cps we obtain even for this plug an attenuation of 26 db, a value that results from the measured skin elasticity.

Earplugs with static pressure on the tympanic membrane

Positive or negative static pressure in front of the tympanic membrane decreases the effectiveness of sound stimulation on the ear, especially for frequencies below 1000 cps. Such pressure can be obtained accidentally or purposely with tightly fitting plugs. This pressure, for instance, is the reason why an attenuation 10 db or more greater than the calculated 26 db can occasionally be achieved at low frequencies with a V-51R earplug. This pressure is also the reason why the results of earplug tests often vary considerably from one test to the next. A normal insertion of a V-51R earplug sometimes gives rise to positive and sometimes to negative pressures. Pressures up to 15 cm H_2O have been observed in front of the eardrum and such pressures result in threshold shifts of about 10 db. Such static pressures may constitute the only way of increasing to any significant degree the protection provided by insert type earplugs at low frequencies. This added protection does not result from a high attenuation provided by the plug but from less efficient transmission in the middle ear. Tests with earplugs specially designed (patent applied for) to permit the building up of static pressures have given promising results. At low frequencies, up to 20 db additional protection has been measured. Just how desirable such a procedure is from a medical point of view remains to be determined. Even if the technique should find medical approval, the problem of comfort will still have to be dealt with.

Protection by Ear Muffs

The theoretical limit for sound protection by ear muffs is likewise determined by the threshold curve of bone-conduction in a free sound field (Fig. 4). As a practical matter this limit is approached most closely if one presses one's thumbs against the tragus, thus occluding the auditory canal. At 100 cps this method sometimes yields from 40 to 50 db attenuation, i.e. values that are probably close to the bone-conduction threshold. Earcups usually provide much less attenuation. Physical tests prove that the elastic material (sponge rubber cushion) used to seal the hard cup to the head does provide attenuation approaching the theoretical limit for the muff, at low frequencies. Usually an air leak reduces the protection afforded by the muff as can be seen in Fig. 8. The curves were determined for one subject by the threshold shift method. The same muff was measured once with an ordinary seal and then measured with the best seal which could be obtained (strong, uncomfortable pressure). Increasing of the effectiveness of ear muffs is therefore almost exclusively a question of improving the seal without sacrificing comfort.

Some experiments indicate that even with a nearly perfect seal the attenuation at low frequencies is still far from the theoretical limit set by bone-conduction. It may be that the whole muff vibrates relative to the skull. The fact that the total attenuation provided by earplugs and ear muffs used in combination is not as large as the sum of the attenuations that each device gives individually, suggests that muff vibrations are transmitted to the skull directly, thus stimulating bone reception at levels below the threshold for normal bone-conduction ("bone via muff" in Fig. 5). We are not yet able to supply exact data or a totally satisfactory theoretical account of this problem.

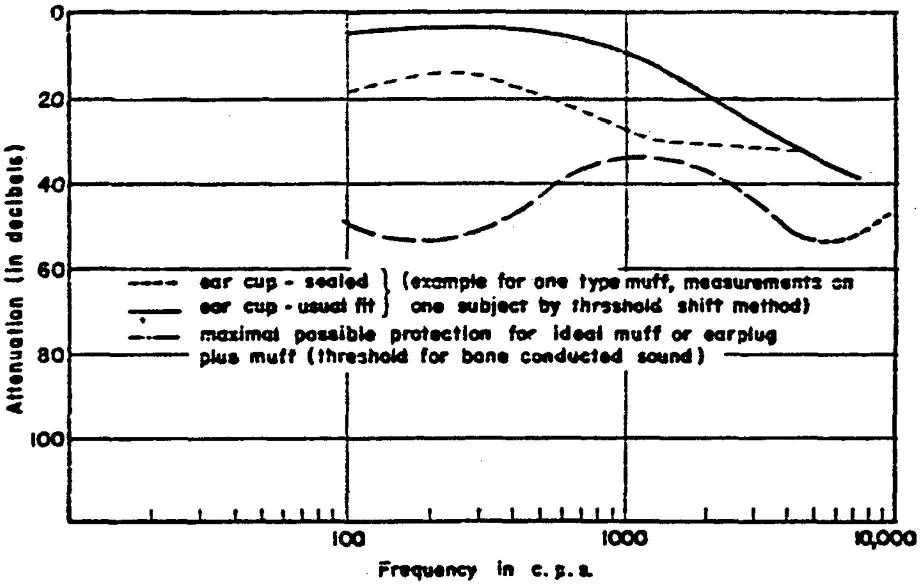

Fig. 8. Practical and theoretical limits for protection by ear muffs.

At frequencies above 1500 cps the theoretical limits set by the bone-conduction threshold can be reached, if care is taken and uncomfortable pressure is applied to the muff. Combination of earplugs and muffs brings almost no additional attenuation in this frequency range if each, individually, is perfect. However, if one of them has leaks at certain frequencies, only the combination can provide the maximum possible attenuation of 40 to 50 db.

To demonstrate the findings just discussed, the attenuation characteristics measured by the threshold shift method are given in Fig. 9 for the following three conditions: 1) subjects wearing earplugs (V-51R, carefully inserted and sealed); 2) subjects wearing ear muffs pressed hard against the head (metal tubes, 25 cm long, 7.5 cm wide, filled with cotton and with doughnut cushions for sealing made of sponge rubber 3 cm thick and covered by solid rubber); 3) subjects wearing earplugs and muffs combined. The curves represent the averages of measurements made in a free sound field on six subjects. The sum of the attenuations obtained for earplugs and muffs worn separately (curve number 4 of Fig. 3) is clearly greater than the attenuation obtained when both devices are worn together. Curve number 3 of Fig. 9 has already been given and discussed as curve number 4 in Fig. 4. It was at that time compared with data obtained with carefully fitted muffs and plugs (curve number 3 in Fig. 4).

In the low frequency range both curves show about 15 db less attenuation than one might expect on the basis of the assumed bone-conduction threshold (Fig. 4). The following question needs further investigation. Is it theoretically possible to obtain more attenuation or are some of the assumptions and experiments that entered into our reasoning not directly applicable? In particular there is the possibility that the threshold values for bone-conduction are somewhat too high in the critical low frequency range.

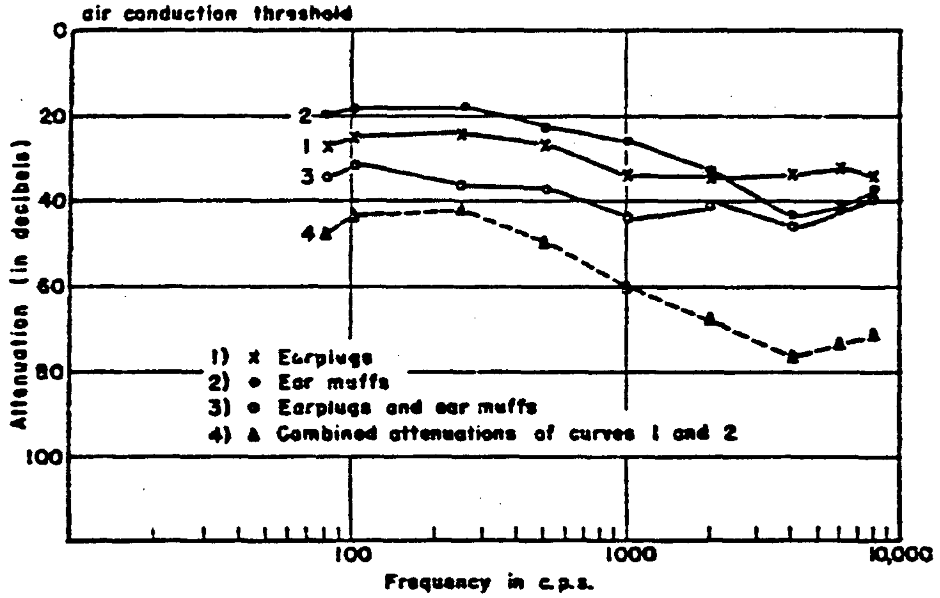

Fig. 9. Attenuation measured by the threshold shift method for 1) earplugs (V-51R), 2) ear muffs (metal tubes), 3) combination of plugs and muffs. 1) to 3) represent the averages for six subjects. Curve 4) is the calculated, combined attenuation from curves 1) and 2). Compare curve 4) with curve 3).

Protection by Helmets

No data on the sound protection by helmets designed to reduce bone-conducted sound received by the whole head or major areas of it are available at this time. Projects to explore this possibility are under way. In view of the technical difficulties that one has to overcome in the design of sound protective helmets covering the whole head (e.g. seal, breathing, ventilation, weight) it is doubtful if such a solution will prove feasible. This reservation is especially appropriate when one considers Fig. 1, which shows that general body reception does not require much higher levels than those that give rise to bone reception by the head. It might actually prove more practical for some applications to check into the possibility of covering the whole man by a sound protecting shell. However, such a device would have to be moved by power equipment.

Summary

Measured attenuation provided by earplugs agrees satisfactorily with values predicted from theoretical considerations. At frequencies below 1000 cps the elasticity of the skin lining the ear canal determines the practical limit for the attenuation to be obtained with insert type earplugs. Above 1000 cps the attenuation actually provided by earplugs reaches the limit set by the fact that sound reaches the inner ear not only by air-conduction but also by bone-conduction. These considerations show that little improvement can be expected from changes of the material, the shape, or the fit of insert type earplugs. A complete analysis of this problem requires a more thorough investigation of the bone-conduction threshold in a free, random sound field, especially for frequencies above 1000 cps.

It was also shown that the limits for the protection by ideal ear muffs are likewise set by the bone-conduction threshold. Usually less protection is obtained with ear muffs since practicable seals are imperfect. Approximate values are also given for differences in threshold when the acoustic stimulus is to the head or to other areas of the body.

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VIII

COMMUNICATION

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In order that any kind of voice communication, either direct or by phone system can be continued in the vicinity of operating jet planes, personnel must be given every possible protection from the noise. It is not the purpose of this report to suggest engineering changes which might improve communications in noise, but it does seem advisable to consider how communications might be improved through 1) the training of personnel and 2) through the use of non-auditory signals.

Training

During World War II a number of research projects were established to study the problem of selection and training of persons using voice communication equipment. (For reports of major projects, see Summary Technical Report of NDRC, Division 17, Volume 3, Combat Instrumentation and Summary Technical Report of NDRC, Applied Psychol. Panel, Volume 2, Training and Equipment and OSRD Report No. 4795.) One outcome of these projects was the establishment of training programs for voice communication in nearly all branches of the armed services; another was the development of standard procedures for use of telephone circuits and standard phraseology for messages to be communicated.

The introduction of high noise levels increases the difficulty of voice communication but, insofar as this form of communication remains a possibility, the methods and procedures developed during World War II are directly applicable.

It has been a common misconception that wearing ear defenders as protection from ambient noise will interfere with ability to understand speech. A careful study done by Kryter (1) has shown that for high voice levels the wearing of the V-51R ear defender does not lower intelligibility of speech. Instead, it slightly improves it. As may be seen from Fig. 1, for the noise (simulated propeller plane) used in the Kryter experiment articulation scores were better with earplugs for noise levels of 85 db (overall) and above.

As Kryter (1) has pointed out, however, it is not the overall noise level that is important in determining whether or not wearing of ear defenders will interfere with the perception of speech; it is the effective masking of the ambient noise that is the critical factor. If the spectrum

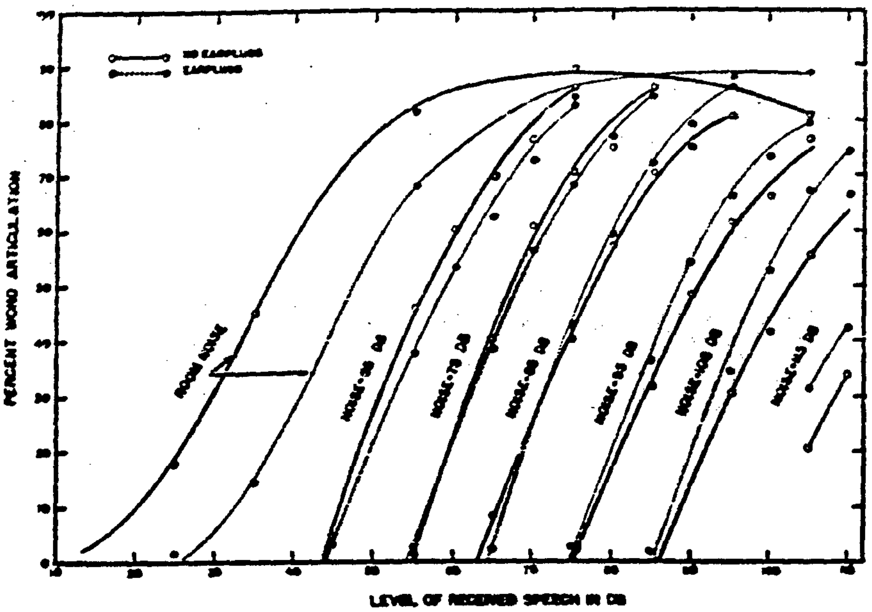

Fig. 1. Curves showing the relation between percent articulation and speech level with ambient noise level as the parameter under two conditions of listening (with and without earplugs). The ambient noise, electronically produced, simulated that of a propeller-driven bomber. At noise levels 85 db (overall) and above, ear defenders do not interfere with speech reception. Instead, speech reception as measured by articulation scores is improved and the amount of improvement increases as intensity of ambient noise increases. (From PAL, STR. See Ref. (1) or (2).)

of the noise produces an effective masking of 60 db or more, wearing ear defenders will improve the hearing of speech.

The typical noise spectrum from a jet plane is such as to produce very effective masking. Therefore, men working in the vicinity of jet planes, where noise levels are 85 db or more overall, will be able to communicate by voice as well or better when wearing ear defenders as when not. Furthermore, they will be less likely to suffer temporary deafness which can interfere with voice communication even during periods of relative quiet which may come between exposures to very high levels of noise.

Non-Auditory Communication

When one or more jet planes are running above minimum power, communication among men working on the planes or nearby is conducted primarily by visual signals. This is particularly true on the flight decks of a carrier during launching operations; the guiding of pilots by the plane directors and the reports of catapult crews to the launching officer are examples of critical communication links which are maintained during certain operations entirely through the use of visual signals. During day operations these visual signals consist primarily of hand and arm gestures; at night, signal lights held in the hands are used and similar gestures are made.

The problem of visual communication was discussed by members of the BENOX group with some of the officers and men of the U.S.S. Wasp. From these discussions it appears that a somewhat standardized system of visual signals has been developed. To a large extent all use the same signals to mean the same thing. Many of the signals have obvious meaning, e.g. the plane director instructs the pilot to move his plane forward by beckoning with both hands and he instructs him to stop by holding his hands out palms toward the pilot. Other signals are less readily interpreted by the uninstructed observer.

Officers and men apparently learn the visual signal system by watching others and by being told by their co-workers. The situation is exactly what we might expect. All of us in our everyday activities use words and respond to words whose meaning we do not completely understand. Likewise, some pilots and flight deck personnel are not sure of the exact meaning of the visual signals which they are using.

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IX

ORIENTATION IN SPACE

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The problem of equilibrium is probably never synonymous with that of vestibular function, although vestibular function is nearly always a part of the total problem of equilibrium. Our problem is the broader one of orientation in space. This includes, then, vestibular, as well as other sensory systems (possibly all others) and the integrative and motor centers and pathways through which sensory experience finds expression in terms of adjustments which are necessary to maintain true orientation, both subjective and physical. We should, therefore, include in this discussion all of the reports and experimental data suggestive of motor incoordination as well as that suggesting vestibular disfunction as such. These observations should, in turn, interdigitate with those having to do with central nervous system function in general, and, more specifically, those which indicate a clear effect of intense noise on the reticular activating system with its consequent effects on cortical discharge and the implied effect on such factors as alertness and attention.

There are several scattered reports, narrative accounts and a little experimental data that indicate, as noise levels increase beyond 140 db (overall), there will probably be a sharp increase in the equilibratory manifestations which at levels below 140 db appear to be still slight (1,2). It is not possible, at this time, to indicate more exactly the nature and probable severity of the dysfunctions to be expected. It is a good guess that they may well become disabling at levels above 140 db. It is, however, possible to outline experimental studies which should make possible a more practical and significant anticipation of the nature of future problems Such suggestions will be the subject of some of the later paragraphs of this section.

Assuming that there are sufficient indications of potential or actual non-acoustic effects of high-intensity noise, it may be assumed that these will affect the sense organs and the central nervous system primarily or secondarily. Such effects will (a) distort the input by overstimulation, or (b) by destruction of tissue, or, successively, in both ways. Several questions immediately present themselves.

(1) What sensory systems are so affected?
(2) What central mechanisms are so affected?
(3) By what routes are these effects introduced?
(4) How do the effects express themselves in subjective experience and/or behavior?

(5) What means of protection of sense organs and CNS may be adequate?

The operational, clinical and experimental observations bearing on the foregoing questions will be taken up in that order.

Reports of Operational Complaints

Included in reports of jet-aircraft and test-cell operations from U.S.A.F. and U.S.N. are the following:

Complaints of operating personnel at Muroc AFB jet-engine test cells led to a noise survey by the Aero Medical Laboratory. The operating personnel described several reactions to intense sound fields, including (a) temporary deafness, (b) nausea and vomiting, (c) excessive irritability, (d) lethargy, (e) excessive fatigue and (f) strong psychological reactions adversely affecting work performance. Of particular interest to this discussion are the reports of nausea, dizziness, and related phenomena. In one case, the individual, at the engine controls of a J-47 (TG-190) engine at RPM 6500, experienced dizziness and "quivered inside." When the RPM was increased to 7500 the dizziness increased and a sensation of faintness developed. Upon leaving the controls, he became nauseated and vomited, thereby gaining some relief, although the "shaky" feeling persisted for some hours.

A second individual, at the controls of a J-35 (TG-180) engine operating at 6500 RPM, deliberately walked away from the instruments, leaving them running, and stating he "could not stay (in the noise field) any longer." His story of the situation did not emphasize any particular reaction, but indicated, rather, that the general psychological reaction dominated the situation. It may be supposed that this psychological state was the result of the additive effects of stimulation of several sensory pathways, no one of which was demonstrably predominant, whereas, in the first case, vestibular overstimulation would seem to have been dominant.

These two and similar cases fail to support the statement frequently made that the initial reactions to intense noise are most marked and that further experience leads to adaptation. All of the individuals whose reactions were cited in the Muroc report had been engaged in jet test cell operations for one to three years. The author of the report expressed the opinion that the sound fields exceeded the capacity of the human body to adapt to them.

The Muroc Report further mentions certain difficulties in locomotion experienced by personnel working close to the tailpipe of an engine under test (i.e. in sound levels of approximately 140 db overall). No elaboration of this observation is included in the report.

Both nausea and vertigo are included in the effects of intense noise as reported from aircraft-carriers. There is no information as to how often these have been observed nor of the exact location and activity of the personnel involved.

Word of mouth reports from personnel on the maintenance line at Wright-Patterson AFB indicate that some individuals experience difficulty in motor coordination exemplified by such things as a tendency to stagger and the inability to rise from squatting or kneeling position in the high noise field of a jet plane operating at 100% power.

Clinical Observation and Human Experiments

Among the most reliable subjective observations of the effects of intense noise which are available to us are those made by Davis, Hardy, Eldredge and others (cf. this report, Chapter V, Aural Pain Produced by Sound) from experiments in the siren room and the outdoor jet-engine test stand at Wright-Patterson AFB. These are worth recounting in some detail both for their intrinsic informational value and their significance in pointing toward further research. The experimental methods are detailed elsewhere in this report, and it is sufficient to indicate here that the basic method consisted in approaching the siren by a series of three fixed stages, the subject being equipped with ear defenders except for brief periods when he would remove one or both for unprotected exposure to the noise-field. These stages for our present purpose are best described in terms of measured overall sound levels at each. We can speak, then, of 132 db, 135 db, and 140 db stages.

Various disturbances, apparently related to vestibular function, were reported by the several individuals at different sound levels. In general, the effects were most consistent and marked when one ear was unplugged at a time. The most delicate, hardly more than premonitory, sign of labyrinthine stimulation was a relatively slight, apparent shift of the visual field toward the exposed ear, although in one instance the shift was away

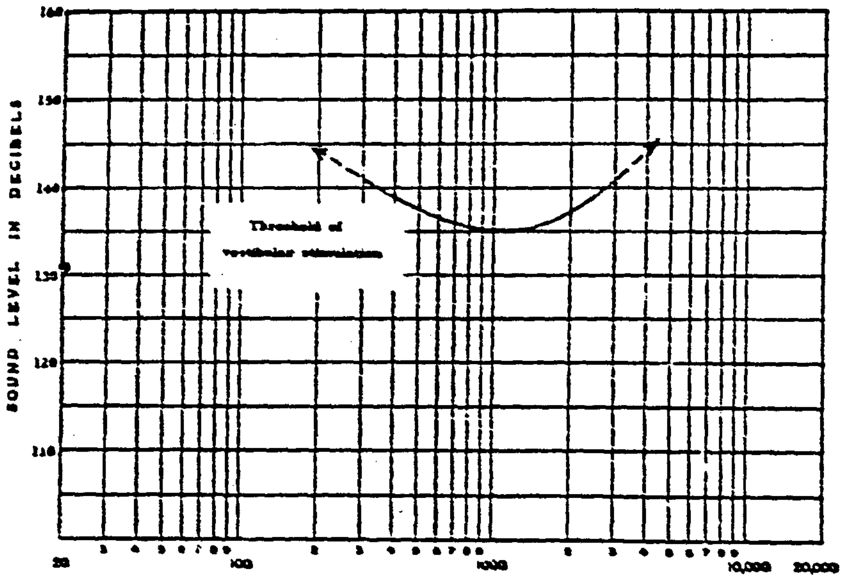

Fig. 1. Threshold for vestibular stimulation from noise as indicated by a slight apparent shift in the visual field when one earplug was removed briefly.

from the exposed side. This effect usually occurred at approximately the 135 db level in the most sensitive frequency range, which lay between 1000 and 1500 cps (see Fig. 1.).

At the 140 db level the degree and variety of labyrinthine disturbance due to exposure of one ear increased. The subjects consistently reported a sensation of being pushed sideways, away from the exposed side but without any sense of turning. One subject, facing away from the siren, noticed a displacement of the visual field toward the exposed side, estimated at 8 inches at a distance of 8 feet, combined with a feeling of unsteadiness. If the exposed ear were turned toward the siren, there was a feeling of falling away from the siren.

The foregoing effects of exposure of one ear at the 140 db stage might be described as static. More variety of response is introduced if the subject is in motion during exposure. The subjects uniformly reported that, if they turned the head suddenly to one side, there was a distinct sense of exaggeration of the turning movement. This phenomenon seemed to be greatest in the frequency range of 800-1000 cps. (No effects were reported below 300 or above 3000 cps, Fig. 1.) From a stationary position, no such rotational effect occurred.

The experience of one subject (Eldredge, personal narrative) in a sound field of 155 db deserves special attention. At this level, *even with earplugs,* sensations similar to those related above occurred. *If he turned suddenly,* he felt as though he was forced to continue the turn beyond the intended point, even to the extent of involuntarily putting out a hand to catch himself from a seemingly imminent fall. Besides this clearly labyrinthine effect, he had a distinct feeling of oppression and experienced difficulty in performing simple motor acts, though not approaching incapacitation. He did not expose his ears. These effects were probably maximal in the 1000-1500 cps range, and cut off at 3000 cps.

One subject (siren at 140 db) made the interesting observation that certain of the labyrinthine effects were clearest when, with one ear exposed, the noise was abruptly cut off. This apparently indicates that during the exposure period a rather strenuous effort had to be made to compensate for the tendency to fall away from the sound, and, that when the sound was cut off, the resulting response was a sensation of being pushed *toward* the siren.

One subject reported inability to stand on one foot at the 140 db stage, (siren) but thought this might have been due to the shaking of his knee.

Only one subject reported even the slightest labyrinthine effect at 140 db in the jet-engine noise field. It consisted of a questionable visual field shift toward the unplugged ear if the unplugging were done suddenly.

To summarize, briefly, the following points seem to emerge from this series of observations:

(1) The threshold for labyrinthine disturbance in the unprotected ear exposed to siren noise is roughly 135 db in the 1000-1500 cps range, rising to 140 db at 300 and at 3000 cps, beyond which extremes no vestibular disturbance was noted at any level.

(2) The threshold of labyrinthine disturbance for the protected ear is about 155 db with the greatest effect again occuring in the fre-

quency range 1000-1500 cps.

(3) There are hints that from 140 db up, some postural difficulties begin to express themselves which are not demonstrably and directly of labyrinthine origin. These may be premonitory of more general proprioceptive effects. They are not prevented by the use of ear plugs.

(4) Up to 155 db, the use of ear defenders is apparently effective in preventing vestibular disturbance. This is in accord with the observation (cf. this report, section on CNS) that the desynchronizing effect of 140 db noise on the electroencephalogram of one subject was noted only during the brief periods when the ear defender was removed from one ear.

Acoustical stimulation of the vestibular apparatus was reported by v. Békésy in 1935 (3). He registered graphically the head movements of subjects who listened, with earphones, to interrupted tones and he also noted a constant deviation of the head in response to a steady tone. The deviations were small, of the order of a millimeter, but they were produced by sound pressures as low as 100 db. His effects showed no clear relation to frequency. He mentions eye movements, sensations of forced movement, and apparent motion of the visual field. He also states that vertigo is produced by a two-minute exposure to a tone of 100 cps at 120 db interrupted three times a second. The chief difference between v. Békésy's observations and our own seems to be that he used a more delicate method and endpoint and selected a form of interrupted sound that is particularly effective, and he therefore obtained considerably lower thresholds. Our own endpoints were relatively crude, but our threshold values are probably closer to the sound levels at which acoustic stimulation of the vestibular apparatus may become practically significant.

Observations on human subjects in the noise field of the jet engine with and without afterburner show in some cases changes in tendon reflexes which reflect the heightened discharge of the reticular activating system as noted below. These are described in detail in the CNS section of this report (Chapter X).

Experiments on Cats

Several rather crude exploratory experiments were done in the siren room at the Aero Medical Lab. An effort was made to examine the effects of exposure to noise on postural reflexes of cats. Both continuous and fluctuating noise was used. In one animal an exposure to continuous sound of a siren at 960 cps, 140 db re .0002 dynes/cm^2 produced profound deficiencies in placing and hopping reflexes and in the righting reflexes. These proved to be transient, the reflexes being quite normal by the following day. At that time, exposure was repeated, this time with noticeable, but much less effect than after the initial exposure. A third exposrue period, less than an hour after the second, produced no appreciable effect on postural reflexes.

A second animal, treated in essentially the same fashion as the first, except that the sound was rapidly but irregularly altered over the range

200-2000 cps, failed to show any post-exposure deficiencies of postural reflexes.

In a second type of experiment, the electrical activity of the vestibular and lateral reticular nuclei of a cat were recorded during exposure to the continuous, steady noise of the siren with characteristics of 960 cps at 135-140 db re .0002 dyne/cm^2. These experiments are described in detail elsewhere in this report (see Chapter X).

However, it should be noted in the context of this section that, coincident with a marked activation of the reticular system, there occurred a distinct but less profound activation of the vestibular nucleus. The vestibular system is known to have strong connections to the reticular system as is true also of other sensory pathways, perhaps to lesser degree than the vestibular. Even from this crude experiment, it seems probable that the activation of the vestibular nuclei is related to that of the reticular, and provides one avenue of input into the latter, as well as into other neural systems. If one may put this evidence together with that of the apparent vestibular effects on the human subject with unprotected ears, it seems reasonable to assume that at these overall noise levels (135-140 db), the principle pathway to the vestibular nuclei and thence to reticular nuclei is by way of the ear, and the deleterious equilibratory effects can be be effectively blocked by use of ear defenders. It is further indicated that the effects of still higher sound levels on these neural mechanisms should be investigated. Similar techniques should be used to explore other potential avenues of input to the reticular formation.

Most of the experiments and clinical observations noted above were conducted in the relatively pure-tone sound field of the siren at the Aero Medical Laboratory, Wright-Patterson AFB. A few were made in the jet-engine noise field. In several instances where more or less direct comparison is possible, there are indications that the noise of the jet engine may be less effective in producing non-auditory effects than the more nearly pure tone of the siren, the sound pressures being roughly equivalent. In future experiments every effort should be made to explore the effects of both kinds of noise. Animal experiments involving the use of electrical recording equipment (i.e. amplifiers, oscilloscopes and the like) are scarcely feasible at outdoor jet-engine test stands. Consequently, the possible feasibility and accessibility of indoor test-cell facilities must be explored. With certain refinements of the facilities at the Aero Medical Laboratory siren, it would be possible to pursue further this type of experimentation with some profit.

Discussion and Summary

The deleterious effects of noise with respect to equilibratory and other postural functions, so far as we now know them, fall entirely into the acute category (i.e. those which are observed, only during exposure). We have not the faintest hint of any which could be classed as chronic. It is all the more rational to concentrate on acute manifestations when we reflect that permanent deficits of function of the vestibular and postural mechanisms are among the neurological dysfunctions most easily compensated for by remaining intact neural tissue.

For the subject with unprotected ears, the evidence gives us reasonable assurance that the threshold of labyrinthine dysfunction is in the vicinity of 135-140 db in the 300-3000 cps range.

The relative ineffectuality of jet engine noise of comparable intensity levels in producing labyrinthine dysfunction is probably to be explained by the fact that the highest energy components of the jet noise lie in the frequency range 300-400 cps. This is barely within the effective pure tone range at 140 db. It is to be expected that still greater sound pressures of 300 cps and lower would effect tactle and proprioceptive-end organs almost as soon as the vestibular.

In the 300-3000 cps range, the deleterious effects of sound levels of 135-155 db can be effectively blocked by use of good ear protection. At 155 db, however, less extensive but still rather convincing evidence is at hand to indicate that the threshold of equilibratory disturbance for the protected ear has been reached. This is supported by an increasing body of anecdotal material characterized by experience of severe postural weakness and both subjective and physical disorientation. Observation of effects of still higher sound levels is virtually nonexistent.

In the light of the foregoing paragraphs, it seems a very good guess that up to 155 db, the route of input resulting in postural disorders is the ear. At 155 db and higher, the meagre evidence available makes reasonable a further guess that involvement of more general proprioceptive end organs (i.e. muscle, tendon and joint endings) as well as tactile, becomes significant. This results in further distortion of the sensory input which is translated into equally distorted postural adjustment.

All of these findings require corroboration and amplification by more systematic and comprehensive experimentation. Much of the experimentation should be done with human subjects, but there are some aspects which will doubtless lend themselves to animal experimentation.

Assuming general confirmation of the tentative results reported above, it becomes desirable to know more about the mechanisms of stimulation of the labyrinthine sense organs by sound, a type of stimulus which is inadequate for the labyrinth at ordinary intensities. It is even more of a conjecture as to what the mechanism may be for stimulation of general proprioceptive end organs by intense sound pressures. Several avenues of approach to these problems suggest themselves. They call for expert attention from someone intimately familiar with the finer structure and function of the inner ear. These problems may not yield entirely to the most careful study of the end organs alone, but may require concomitant investigation of central mechanisms having to do with thresholds and the like, of sensory pathways, which may, in turn, be influenced by the reticular activity, known (from the cat experiments) to be induced by high intensity sound.

We have sufficient indications from the limited animal experiments we were able to do that much more elaborate neurophysiological experimentation should be undertaken. These should be directed toward exploration of the routes of input and the consequent activation of central mechanisms, the degree and kind of distortion of normal electrical activity, and the probable consequences of these in terms of experience and behavior. Such studies should take cognizance of the apparent fact that neural systems not ordinarily activated by sound become so activated if the sound intensities become great enough. They should be carried out at sound intensity levels, at least as high as those we have set as representing thresholds of non-auditory sensory systems.

It should be emphasized that the most systematic evidence presented here comes from observations of effects of exposure to the relatively pure tone of siren or horn. In the further investigations, both human and animal, more attention must be given to the effects of noise, simulating that of the jet engine since 1) this is the crucial operational problem, and 2) there is reason to believe that effects of the two kinds of noise source are not always physiologically equivalent.

Finally, it seems probable that, in view of the increasing volume of spontaneous complaint from individuals working in high intensity noise fields, there may be much more potential narrative evidence available than has yet come to light. This could be more systematically exploited to good advantage than has yet been done, and might be expected to yield further suggestions as to direction of continuing research along several lines.

Conclusions

(1) The first sensory system after the auditory to be assaulted by intense noise is the vestibular.

(2) In the frequency range 300-3000 cps, thresholds for vestibular stimulation are approximately 135-140 db for the unprotected ear, and 155 db for the protected ear. The most sensitive part of the range is 1000-1500 cps.

(3) At 155-160 db, it is probable, though good evidence is lacking, that a threshold for general proprioceptive stimulation is approached.

(4) Manifestations of equilibratory and postural disturbance include vertigo, nausea, nystagmus and visual field shifting, feelings of forced movement, staggering and falling.

(5) At intensity levels below 155 db, in the effective frequency range, the ear defender provides adequate protection from such manifestations, from which it follows that the route of entry at these levels is the ear.

(6) It is probable, though there is only meagre suggestive evidence, that as intensity of frequencies below 300 cps increases above the 140 - 150 db level, general proprioceptive and tactile stimulation will become more and more severe with consequent distortion of activity of postural mechanisms. These, combined with vestibular distortion, will lead to incapacitation which will probably be temporary, during the time of actual exposure.

(7) No chronic dysfunction due to vestibular and general proprioceptive stimulation by intense sound is known or necessarily to be expected.

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X

CENTRAL NERVOUS SYSTEM EFFECTS

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Narrative accounts of possible deleterious effects of high intensity noise fields on the human organism include such symptoms as fatigue and irritability, dizziness, postural instability, nausea and vomiting, muscular weakness and blurred vision. These are all symptoms of nervous system dysfunction at some level. It appears, therefore, that if intense noise produces effects on the human body, these effects are most likely mediated through the sense organs and the nervous system. In discrete terms, we must look for possible alterations at all levels of nervous system activity from the sense organs, simple cord-reflex activity through changes in integrative activity of the brain of known physiological types to behavioral changes which, in turn, must be based on these activities. Certain of these topics are covered in detail elsewhere and the present discussion will be confined to alterations in function of the central nervous system once the impulses resulting from high intensity noise stimulation of the end organ have reached the central integrative circuits.

The human being, when placed in a high intensity noise field such as that produced by a jet engine, is obviously subjecting his nervous system to a high energy sensory input. At overall noise levels below 145 db, the major portion of this sensory input is entering the nervous system over the eighth nerve. There are, in general, two major systems by which such sensory volleys coming in over the eighth nerve may participate in the total function of the brain. The classical primary sensory pathways to colliculi and auditory and vestibular cortex have been extensively studied, particularly with regard to the cochlear component. However, it seems unlikely that even saturated activation of the cochlear pathways would produce the symptoms which have been experienced in noise fields of high intensity. Thus we must look to the second major system to which the eighth nerve projects--the reticular activating system.

The reticular activating system has only recently come into prominence and neither the anatomical and physiological limits of this system nor the terminology for its description are clearly established. In general, the reticular activating system represents the central core of the brain, starting at the medulla and running up the center of the brain stem tegmentum as the histologically nondescript reticular formation and merging with the midline thalamic and intralaminar nuclei of the diencephalon. Direct stimulation of this cephalically directed system reproduces the electrical pattern of wakefulness in the cerebral cortex while at the same time it facilitates lower motor activity and thus arouses the nervous system generally. The cephalically directed portion of this system is distinct from the afferent sensory pathways. Selective destruction of this portion is followed by clinical somnolence and EEG synchrony. These changes do not follow selective interruption of the ascending somatic and auditory pathways in the midbrain and after this latter injury, both somatic and auditory stimuli are still capable of awakening the sleeping animal and activating its EEG (1). This system thus plays a major role in control of rather generalized activities of central integration which include such factors as sleep, arousal and attention. it should also be noted that minute lesions in the rostral mesencephalon result in profound changes in behavior of experimental animals and man. It is known that there are rich collaterals to this region from the acoustic pathways (2,3), and there is presumptive evidence (4) that the labyrinthine component of the eighth nerve plays an even greater role in maintaining the normal activity of this region. Further careful experiments are needed, however, to define more clearly the relationships of these afferent systems to the reticular system.

Experimental Data

Reticular activation

The obvious experimental application of these concepts is to determine whether or not high intensity noise will produce changes in the spontaneous electrical activity of the brain stem reticular formation. One crude experiment was carried out on the cat during our work at WADC. The animal was anesthetized with nembutal, and using fine needle electrodes, electrical activity was recorded 1) from the bulbar reticular formation at mesencephalic and pontine levels and 2) from acoustic pathways in the brain stem. During exposure to a siren tone of 880 cps at an overall sound level of 137 db as measured at the animal's ear, definite changes were noted in the response of these structures. There was an increase in frequency of the electrical activity of the reticular formation as recorded by the unipolar technique, with only minimal increase in amplitude. A bipolar recording from a rather wide area of the brain stem in which the electrical field of recording presumably included the primary auditory pathways as well as other structures revealed a generalized activation of electrical discharge with a superimposed modulated response at 10-12/sec. There was minimal if any change in the spontaneous activity of the cerebral cortex. Areas explored included the auditory and vestibular projection areas. Since it has been demonstrated that barbiturate anesthesia effectively blocks the multisynaptic pathways involved in activation of the cortical EEG, this lack of cortical response would be predicted. Continuous recording of the electrocardiogram likewise revealed no changes in wave-form or rate.

This high intensity noise not only produces rather intense activation of auditory and vestibular nuclei but increases the background electrical activity of the reticular activating system. This was found to occur in the cat in the presence of anesthesia although it is known that barbiturates tend to block this type of activity rather selectively. Obviously, the more suitable experimental conditions would include the use of stereotaxically placed recording electrodes in an encephale isole preparation. In addition to the increase of activity recorded locally in the medial and lateral reticular formation, a rather bizarre modulated response was observed in records obtained from bipolar electrodes widely spaced in the brain stem. It has been shown (5) that the recruiting thalamic nuclei have a high degree of inherent rhythmicity and that the single discrete impulse of a cortical strychnine spike may cause in these diffuse nuclei a 6/sec. bursting discharge which is somewhat reminiscent of the modulated response seen in this one experiment.

EEG Changes

Since it is well known that stimulation of the brain stem reticular formation will cause activation of the cortical EEG (6), one would anticipate, on the basis of the animal experimental data reported above, that the human EEG would show significant changes when the subject is introduced into high energy sound fields. This matter was investigated in the siren room at the Aero Medical Lab, WPAFB, using conventional EEG recording. Exposures were carried out at frequencies varying between 245-700 cps and at overall levels between 120-137 db. There was no detectable change in the scale EEG when the subject was exposed (with ear defenders) to these sound fields. Striking and exceedingly prompt abolition or desynchronization of the parieto-occipital alpha rhythms occurred when one ear was unplugged and exposed to the siren at 137 db. At the same time, good activation of the EEG in the fronto-temporal region bilaterally was present, consisting of desynchronization with an increase in the low potential fast activity. When the eyes were open, the addition of siren noise to one ear added nothing to the alpha blockade already present. Activation in the fronto-temporal regions may have occurred; the results obtained were not conclusive. Insufficient data are available to indicate whether or not these CNS responses are critical with regard to sound frequency and no definite threshold with regard to intensity was established. Good EEG alterations were obtained at the 137 db level and rather minimal alpha blockade at 133 db. These EEG effects appeared to become less marked with repeated opening of the ear during any given run, suggesting the possibility that adaptation of central neural circuits can occur under these circumstances.

It has been known for some time (7) that tonal stimuli will block the alpha rhythm and that acoustic stimuli at frequencies between 250 - 2000 cps will not only check the alpha but will also yield on- and off-effects (8). Under suitable conditions "anticipatory" on-effects or off-effects can occur depending on the psychological set at the time; these have led investigators in the past to consider such EEG effects of acoustic stimuli as alerting phenomena. However, effects produced by acoustic stimuli at low intensity levels may not have any relation to effects noted in the present experiment where presumably both the acoustic and vestibular portions of the eighth nerve were activated by the intense noise.

Reflex changes

It has already been mentioned that activation of the bulbar reticular formation yields caudally directed effects in the motor sphere consisting of alterations in the deep tendon reflexes, changes in tone, and alterations in motor response. Certain of these effects are mediated directly by action on the internuncial pool around the anterior horn cell. It has also been shown recently (9) that bulbar reticular stimulation may selectively accelerate or inhibit the activity of small gamma efferent fibers of the ventral root innervating the muscle spindles, thus regulating the rate of discharge in the spindle afferents. This modulation of the end-organ alters the feedback properties of the system and thus may have profound effects on local, segmental cord activity. Since it has been demonstrated experimentally that high intensity noise above 135 db will cause activation of the reticular system, one might anticipate that reflex changes would occur in persons exposed to intense noise.

This matter was tested in five subjects during exposure to jet engine noise at overall levels of 134 - 136 db. In three of the subjects no ear plugs were worn during the period of observation and in two of these an increase in the deep tendon reflexes could be demonstrated which was so marked in one that clonus was almost elicited. There was no ataxia, incoordination, dysmetria, past-pointing, or change in the ability to carry out rapidly alternating movements. The Romberg was negative in the entire group during the period of exposure to noise at these levels. The observed alterations in the deep tendon reflexes were present only when the CNS was subjected to the afferent auditory and vestibular volleys and ceased when the noise stopped.

Discussion

Clinical symptoms

The initial crude experimental data would thus indicate that high intensity noise can stimulate the reticular activating system. Our results also tentatively suggest that activation of this reticular system by high intensity noise stimulation produces cephalically directed effects on central integration and diffuse activity of the cerebral cortex. The changes that were observed in deep tendon reflexes in some individuals while being subjected to jet engine noise is in agreement with the suggested caudally directed influence of the reticular formation occurring over reticulo-spinal pathways that have been indicated by previous studies. The data obtained thus yield a possible basis for some of the narrative reports which have slowly accumulated from operational activities in the field. The reported muscular weakness could well result from the reflexes and changes in muscular tone which might follow reticular activation. One need not necessarily postulate interference with normal proprioception. The reported blurred vision may be secondary to the vestibular inflow and may not be based on peripheral mechanical vibration of the eyeballs. Incidental observations suggest that the apparent shift in the visual field does not occur in sound fields of 137 db until one ear plug is removed thus increasing the likelihood of direct stimulation of the vestibular apparatus. The relationship of these mechanisms to possible incoordination, nausea and vomiting etc. are covered elsewhere in this report.

Stress

Introspection by trained observers in high intensity noise associated with after burner operation clearly indicates that stress mechanisms would seem to be activated. The present experimental observations seem to give some neurophysiological clue as to the basis for a possible activation of the adrenal stress mechanism. It has been shown (8) in cats and monkeys that a marked increase in electrical activity occurs in and only in the posterior hypothalamus in the presence of stress stimuli (hypoxia, insulin, epinephrine, etc.). The adrenal response to such stressful stimuli, e. g. drop in eosinophile count, increase in excretion of 17-ketosteroids, is said to be blocked by minute, discrete lesions in this region. It would seem probable that these nuclei, which constitute the final common path within the CNS for stress reactions, are activated by the reticular activating system. Since intense noise has been shown to increase the activity in this reticular system, it would be possible that, given sufficient stimulation by noise, the endocrine stress mechanisms would be mobilized.

Epilepsy

Stimulation of the reticular activating system such as has been shown to occur can be anticipated to act as a strong precipitating mechanism in individuals who are subject to chronic recurrent seizures. Although the details of mechanism are unknown, it is well documented that acutely stressful situations often precipitate seizures in epileptic patients. At the experimental level, monkeys with epileptogenic cortical scars can easily be precipitated into a generalized seizure by the use of loud yelling accompanied by threatening activities. In fact the laboratory technician catching such a monkey comes up to the cage yelling and banging on the cage until the monkey goes into a seizure and, during the post-ictal coma, simply reaches in and picks up the prostrate and comatose animal. For that reason the epileptic individual would be in an extremely hazardous location in the noise field surrounding a jet engine.

Since the incidence of head injury might be relatively high in the history of individuals of this type, particularly among personnel on board a carrier, it must be remembered that somewhere between one and 15% of individuals sustaining closed head injuries of sufficient degree to be comatose will subsequently develop epilepsy.

Noise threshold

Although initial estimations of threshold for appreciable influence on the reticular activating system have not been determined in terms of sound pressure level, it would seem that the observations reported here were obtained just as threshold for physiological effects. The noise fields used ranged between 135-140 db. It is difficult to predict the neurophysiological effect of noise above 140 db. The acute animal experiment reported was carried out under general anesthesia at overall noise levels of 137 db. In unanesthetized animals neurophysiological effects might be expected to be more marked. Presumably even higher levels of stimulation would yield appreciably more than the relatively mild activation recorded.

Possible effects above 140 db

The effect of overall noise levels above 140 db would depend first on the end organ. It would seem that current noise levels are approaching saturation for the cochlea so that future increases would not appreciably increase the amount of central activation from this source. However, subjective data would indicate that the threshold for labyrinthine stimulation has just been reached and that higher noise levels would very appreciably increase the amount of central stimulation.

As the amount of central stimulation coming in over the eighth nerve increases, one might anticipate an accentuation of the physiological changes already described which might include more definite and marked changes in peripheral muscle tone, reflex changes, alterations of the postural reflex mediated by the brain stem, additional activation of the central pathways mediating the stress response as well as possible alteration of more general properties of central integration. In spite of the large safety factor built into cortical circuits, these can always be over loaded with occasional dramatic and sudden alterations of function. In more specific terms, it has been shown (2) that the preponderant cortical effects of reticular-diffuse thalamic activation lies in the frontal association cortex. If, as has been suggested (2), this system carries subcortically synthesized impressions of an affective nature, it is feasible that, through its projections, changes can be caused in cortical interpretation and type of response to environmental stimuli. This might have grave significance for an individual such as a jet engine mechanic who is required to carry out rather precise operations involving quick and accurate judgments.

As higher levels of noise are achieved, one must consider the possibility of CNS activation by other sensory channels. It has been experimentally demonstrated (3) that generalized activation of cortical activity by means of reticular mechanisms is best achieved with pain stimuli and with proprioceptive, auditory and optic stimuli being effective in that decreasing order. No observations have been made on the role of the labyrinthine input in this regard. In any case, it would seem that purely auditory input is not of primary importance for these phenomena and that with increasing intensity of the polysensory input, other sense modalities may have to be considered. All of the CNS effects thus far described seem to be quite effectively prevented by reducing the input over the eighth nerve by the use of ear defenders. If the polysensory input over other channels reaches a sufficient level, the same effects may be seen in the absence of labyrinthine and acoustic input although this would intuitively seem to be unlikely with foreseeable levels of noise.

With rising noise levels, a point will obviously be reached where the attenuating effect of ear defenders will still not reduce the sensory input below threshold for central effects. This will be particularly true for low frequencies where the after burner operation poses a major problem. The possibility may also be considered that labyrinthine stimulation by bone conduction quite possibly occurs at overall noise levels around 155 db. The relationship between this effect and skull resonance remains to be determined.

Possible Methods of Protection

Mechanical

The experimental data gained with human subjects indicates that the CNS effects of noise levels in the 135-145 db range can probably be effectively blocked by the use of adequate ear protectors. The attenuation required to reduce the end-organ stimulation below CNS thresholds is of course dependent on the overall noise levels and since the labyrinth presumably responds most effectively to the lower end of the spectrum, this attenuation problem becomes more critical. As sound levels rise to the 150 db level and higher, the attenuation by ear protectors becomes insufficient and the possibility of bone-conducted activation of the labyrinth must be considered. If sound levels are reached where polysensory stimulation becomes the dominant factor, one must consider the possibility of sound-attenuation suits in which certain body areas, where the cutaneous or other sensory input is maximal, are adequately protected.

Pharmacological

In addition to mechanical devices which attenuate the noise before it reaches the end-organs, possible methods exist which may protect the central nervous system itself against the described effects. These methods are pharmacological.

In both the experimental animal and man, evidence is available that the circuits of the brain stem reticular formation are peculiarly susceptible to the action of anti-cholinergic drugs. It would seem that this is why such anti-cholinergic drugs are effective in the treatment of Parkinson's disease (11). Although no data are available regarding the action of such drugs on the alterations of central activity induced by noise, it might be anticipated that scopolamine, Pagitane (Lilly 08958) and Diparcol would be effective in that order. Dramamine, which is also an anti-cholinergic compound, might also be of benefit. It has also been shown that barbiturates are effective in reducing the spontaneous activity of the reticular system. but the current evidence would indicate that the drug levels would have to be such that the operational use of this method in the field would not be feasible.

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XI

IMMEDIATE PSYCHOLOGICAL EFFECTS

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Introduction

The old tongue twister "A noisy noise annoys an oyster" applies also to man, who has no convenient shell to close out the intense higher frequencies. His hands, which can serve this need, must often be otherwise employed. The sense of hearing is our ever-ready wide-open channel for information from the environment. When hearing is over-loaded from intense noise energy its aid to behavior as a psychological resource is practically lost to us. This loss becomes a double burden. Intense noise, brief or prolonged, claims attention and distracts from the job. If the energy received produces pain there is a physiological demand on attention.

When auditory cues are blanked out, an increased vigilance load is required from the sense of sight. Vision is highly directional, and in order to secure from the noisy environment the information sequels needed for both work and safety, the eye movements and head movements must be multiplied. Vision, and also the tactual-muscular senses, are further burdened by the vibration of material which must be manipulated and adjusted while in the intense noise field.

Psychomotor efficiency and intense noise

This problem is not new . Man had to learn to labor while the elements were in a state of storm. It isn't easy to shave or to get a meal in the presence of a lustily crying baby. Factories are often of necessity too hard on the ears for working comfort. The problem has a very long past, but a brief scientific history which for the purposes of this survey dates from about 1940. It was then that the effects of noise and vibration on the performance of pilots in military planes became a problem of acute concern. To guard or guarantee working efficiency of personnel, is it necessary to devise methods of reducing acoustic stress ? A large intensive research program was undertaken at the Psycho-Acoustic Laboratories, Harvard University, in an attempt to answer this practical question (1).

The Harvard studies were conducted in a large basement room of a brick building which stood well apart from other buildings. The laboratory was equipped especially for this program of research. A voltage of uniform spectrum and one of low frequency rich in harmonics were properly mixed, amplified, filtered, and equalized, and led to a battery of loudspeakers. The result was a near match to the noise found in a typical bomber plane of that time. In preliminary studies, subjects were exposed to about 115 db for 3-hour periods. A wide variety of 1) psychological, 2) psychomotor, and 3) physiological tests were tried. Group 1) included coding, card sorting, span of apprehension, and judgments of distance; group 2)--serial reaction time, tapping, marksmanship, and two or more types of pursuit meter tests; group 3)--muscular tension, tremor, standing steadiness, blood pressure, visual and auditory acuities.

Results from the 3-hour exposures to 115 db (overall) showed no change, or in some instances slight facilitation, in psychomotor functions. Subjective reports, however, were unanimous that the men felt more tired and "washed out" than when the same tests were run in quiet. Certain visual tests gave a positive decrement from the intense noise. Speed of accommodation (changing the point of fixation from near to far and from far to near) required an increased time, and there was some evidence that lateral shifts of eye fixation were accomplished more slowly in the noise. When subjects were in a chair with vibration amplitude of .001 inch (1 mil), visual acuity was reduced 25 per cent on the average. The conclusion drawn was that tests of longer duration than three hours should be made to determine if the effects thereby became more evident.

A second set of Harvard studies was conducted which emphasized tests of psychomotor efficiency in seven-hour runs with 115 db contrasted with similar periods of 90 db intensity. Five good subjects were used for two months in these tests. At first the men learned their performance tasks well, and then a counterbalanced order of testing in 90 and 115 db fields was started and continued for four consecutive days in each of four consecutive weeks. All five men completed these tests.

One of the tests--Coordinated Serial Reaction-Time--in which the subjects, by means of airplane controls, directed a beam of light at a series of targets--showed 5.4 per cent slower average response time and also an increase of 5.4 per cent in errors for 115 db as compared with 90 db. This was the most effective of all the tests for showing an effect of the noise. Uniformly there were hearing losses after these prolonged exposures, greatest for 3000-5000 cps, and sometimes amounting to 30 db at frequencies as low as 250 cps. After all tests with 115 db all subjects reported tinnitus. Only one subject on one 90 db day reported ringing in his ears. The general outcome of these Harvard studies of working efficiency in intense noise (115 db without ear defenders) points to what seems a reasonable conclusion. Although subjectively quite uncomfortable and tiring as a working environment, noise of itself appears to influence work output but little, especially when motivation and health are normal and the work consists of well-practiced routines.

Noteworthy studies were also made on the effects of noise and vibration on psychomotor efficiency at the State University of Iowa (2). In a small stone building, well isolated, provision was made for a 24- by 30-foot testing room and two smaller rooms for housing the control and recording equipment. The spectrum of noise was made to conform in a general way to the frequency characteristics of airplane noise (3). A special chair was built to provide various vibration amplitudes, 4 to 6 mils. The chief psychomotor testing apparatus was a modified Mashburn unit (4). The modifications were: the mounting of the platform on springs so it could be vibrated without also vibrating the banks of lights; using 39 light-matching responses per test run in place of the regular 40; and employing stepping relays to bring up new combinations of stimulus lights in succeeding tests.

In the first series of tests randomly selected groups from a total of 30 male college student subjects were studied under six conditions: 1) silence; 2) noise--85 db; 3) noise--110 db; 4) vibration--4 to 6 mils; 5) noise--85 db and vibration--4 to 6 mils; 6) noise--110 db and vibration--4 to 6 mils. In addition to performance on the Mashburn apparatus (main test) some observations were made on heart rate, breathing, tilt perception, brain waves and hearing acuity. The results showed no consistent significant differences between the groups tested under the six conditions in these one-hour sessions.

At Iowa, as also at Harvard, it appeared to the investigator that the lack of positive results might be due to the relative shortness of exposure to stress. A second series was undertaken in which 36 civilian pilot training primary course applicants spent four and one-half hours each in the testing situation. This time, four testing conditions were compared: 1) silence; 2) noise--110 db; 3) vibration--4 to 6 mils; 4) noise--110 db and vibration--4 to 6 mils. Again, the results proved negative for the noise level and duration used, as also for noise and vibration combined, 110 db and 4 to 6 mils vibration.

Noise and performance efficiency 1953 status of the problem

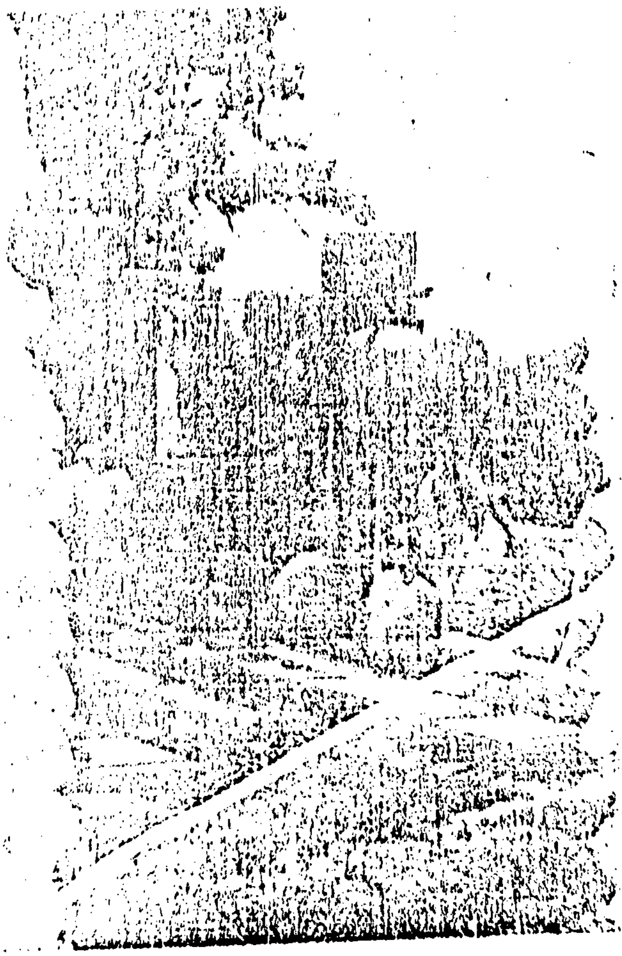
The Harvard and Iowa investigations outlined above were conducted in the early 40's. Two reviews of the effects of prolonged high intensity noise on human behavior have appeared rather recently (5,6). Each of these contains many references and enumerates in outline various studies conducted in industry and in psychological and other laboratories. Always, the same preliminary illusion or hunch beckons the would-be "scientific discoverer" -- "the effect of noise must be measurable on a human performance scale." But in general, significant verifiable decrements in performance have not been found to result from noise (80-115 db with ears open). Especially is this true if the industrial and some other experiments are viewed critically from the standpoint of design and adequacy of controls.

It seems probable that specific visual-motor spot tests can be so chosen and complicated as to suffer some interference from vibration and noise. These are extreme instances and not representative of duty-tasks around well-designed airplanes; nevertheless they are worthy of study. A recent report (7) describes a test employing twenty steam-pressure gauges disposed about a hollow square. The subject stands in the middle of the open side a few feet away, instructed to note any pointers reading more than a danger mark. When such a pointer is found, he is to step up and turn it down with the knob below that particular dial. Random pointer signals, five per half-hour, were used in runs one and one-half hours long. Ten subjects each served for five days with the environmental sequence: quiet, quiet, noise, noise, quiet. (Quiet = 70 db, and noise = 100 db re .0002 dynes/sq. cm.) Efficiency on noise days was poorer than on the quiet ones preceding and following by about 1/3 the score level found for quiet. When the dials were replaced by dim lamps that lighted on signal and had to be turned out, the task seemed easier and with a group of ten subjects showed no overall effect of noise.

The 1953 version of the problem of noise and its effects has developed around the fact that present jet planes produce noise fields 10 or 20 decibels higher than the U.S. military planes in use during World War II. And it seems reasonable to assume that still larger and more noisy planes will be produced in the future. Data previously collected on performance efficiency in sound fields with intensity ratings of 100 to 120 db are of minor value when attempting to appraise the noise stress hazards now present on U. S. Navy carriers and Air Force operational flying fields. The most significant general fact applicable to the present is that maintenance and other personnel now engaged in servicing and operating our jet planes appear to be efficient in their work and willing to continue in their jobs, and that the great majority of these men use no ear protection.

Psychomotor tests made at Wright Field

Some members of BENOX, while surveying the noise problem at Wright-Patterson Field, July 6 to 17, 1953, spent some time conducting performance studies on volunteer subjects near an out-of-door testing block on which a J48P5 jet engine with afterburner was operated. The general conditions for these tests may be readily understood from Fig. 1. Groups of 4 to 6 young adults from the Aero-Medical Laboratory and the Bio-Physics Laboratory were recruited from day to day, to serve as subjects. Most had never before served in an experiment under intense noise. New subjects were used on each day. This was not by design, but because they could not be spared from duties or did not wish to absent themselves from other activities. The ambient noise in the area where the subjects performed their test tasks was usually 128 to 135 db (overall). When the afterburner was running, the level was close to 140 and continued only a few minutes. All subjects and others engaged in these tests wore ear defenders, most of which were of the type V-51R (8). The acoustic insulation provided by these ear wardens was determined at the Psycho-Acoustic Laboratory and found to range from about 26 db at the low frequencies to 40 db at the higher frequencies. The noise levels in the ears of subjects studied by the testing block were therefore not as high as in the Harvard study. But the experimental conditions were more complex and distracting.



[illegible] Jet engine testing block area where psychological studies were made July 19[illegible] by BENOX members. The engine used was a J-48 P5, pictured second from the right hand side.

Table 1

ltaneous Right- and Left-Hand Grip Test. Results on four young
[illegible] subjects examined at Wright Field jet-engine testing block area
[illegible] 10, 1953, Scales given in kilograms.

Testing Periods

Subject	I Quiet		II Quiet		III Noise*		IV Quiet	
	R.	L.	R.	L.	R.	L.	R.	L.
	48.0	32.0	45.0	35.5	49.0	31.0	44.5	32.5
	[illegible]	39.0	49.0	29.5	48.0	32.0	48.0	32.0
	[illegible]	[illegible]	39.0	41.5	31.5	35.0	46.0	35.0
	[illegible]	37.0	38.0	42.0	43.0	37.0	43.5	37.0
3	49.5	30.5	49.0	30.0	46.5	34.0	50.0	34.0
	47.0	32.5	42.0	38.0	46.0	34.0	47.0	33.0
4	37.5	42.5	36.0	42.0	45.0	33.5	40.5	38.0
	40.0	38.5	42.0	35.5	44.0	35.0	37.0	40.5
Ave.	42.3	37.4	42.5	36.8	44.1.	33.9	44.6	35.4
Ratio $\frac{\text{Left}}{\text{Right}}$	88%		87%		77%		79%	

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*Jet engine J48P5 with afterburner going.

Simultaneous right- and left-hand grip test

Two regular Smedley hand dynamometers* fastened back-to-back as a single unit were used to test both hands at once. The instructions were: "Don't push or pull; just squeeze as hard as you can with both hands at once, then pass the instrument back to me." The task is symmetrical for both sides of the body. The position of the hands is made uniform from subject to subject. The separate scores for the two hands are logically comparable in that the subject's efforts tend to be less prolonged and he indulges in fewer bodily contortions than when tested one hand at a time. The four subjects were each given two tests before lunch and two after lunch in relative quiet. They were given two trials when the jet engine was running with afterburner and, finally, two more shortly after the engine was turned off. Each man's score with each hand was recorded to the nearest 0.5 kilogram. These admittedly fragmentary data are presented

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*Available from C. H. Stoelting Co., 424 Homan Ave., Chicago.

in Table 1. Individual scores are given for the right and left hands separately, and for both trials made in each period. Periods I and II represent relative quiet conditions, Period III was in jet with afterburner noise, and Period IV followed shortly after the intense noise had stopped and when the men were in a mood to leave promptly. Inspection of the averages at the bottom of Table 1 indicates that Periods I and II were close checks on each other and that the ratio of left-hand squeeze to the right was 88 per cent and 87 per cent respectively. In Period III the right hand appears to show an increase of 1.7 kg and the left a decrease of 3.2 kg with a ratio of 77 per cent compared to the mean of Periods I and II. Period IV results differ from those of I and II and resemble those for III in showing a left to right ratio of 79 per cent. However, if we count I, II and IV as quiet-condition periods to be averaged for comparison with III, the following deduction may be made for the effect of intense noise: (a) The right-hand performance was increased 2 per cent. (b) The simultaneous left-hand performance was decreased 10 per cent. (c) The total output for right and left hand was decreased 2 per cent. (d) These men as a group did not or could not conform to instructions--squeeze both hands at once as hard as you can--under the noise condition as well as in quiet.

Block assembly test

If the reader will imagine a wooden cube 3 inches on each edge, painted red on all six sides, and then cut up into 1 inch cubes, he will understand the materials used in this test. Obviously there will be 27 one-inch cubes: 8 with red paint on three sides, 12 with paint on two sides, 6 with only one side painted and one completely unpainted. The subject's task is to assemble the 27 one-inch cubes into a built-up 3-inch cube on which all the red paint shows. If he covers up any paint inside his structure he must find it and place it properly before the task may be considered finished. The score is total time.

The subject sits at [illegible]ble with a shallow box on it. In the bottom of the box is a mirror and on top a piece of heavy plate glass. The 27 blocks lie on the glass at one side one layer deep and arranged in chance order and position as dice might have been dropped. The examiner points out that the mirror may be useful for seeing if the bottom of a cube has red color on it. In this test the subject is forced to make use of immediate memory since he can't see all six sides of a solid cube at once. But any cube the subject may pick up, except the unpainted one, will serve as a start for the assembly; the cubes do not have to be sorted first. With repeated trials this test ordinarily shows a considerable amount of learning. The learning may also include developing good technique for searching out a 1-inch square of color that has been inadvertently hidden.

The same four subjects who served in the hand grip tests were used on that occasion for the cube test. One trial on each subject came before lunch and one after. These were both administered in quiet in the testing-block area. Trial III was under conditions of the jet engine running 100 per cent without the afterburner, noise 130-135 db but with ear defenders in use.

The score results in seconds as recorded by stop watch are [illegible] ed in Table 2. The subjects did not stay for a final test in quiet. This [illegible] unfortunate. They expressed willingness to come again but [illegible] were human. In Trial I, Subject 1 spent about 3 minutes at the last [illegible]ing for hidden pains. S2 also faced this difficulty but explored planfully [illegible] rapidly. S3 did his hunting less well, but S4, although he had no pains, [illegible]ed all the blocks before starting to build. The average time score was [illegible]2 sec. (6 min. and 12 sec.). In Trial II all but S2 made large gains [illegible] he lost only 13 sec. The average time score for the group was 224 sec. ([illegible] min. and 44 sec.). In Trial III with the regular [illegible] noise condition the average score of 236 sec. represents a loss over II of 12 sec. or about 5 percent increase

Table 2. Results for Block Assembly Test

(Scores given in seconds)

Subjects	Testing Periods		
	I Q	II Q	III N
1	427	185	180
2	188	201	260
3	345	190	314
4	[illegible]29	32[illegible]	191
Average	272	224	236

Table 3. Results for Visual Reaction Time

Scores given in msec [200 msec = 1/5 second]

Subjects	Testing Periods					
	I Q	II Q	III N	IV N	V Q	VI Q
1	232	259	335	258	258	260
2	347	254	212	245	2[illegible]3	319
3	300	135	360	353	[illegible]65	346
4	236	250	239	229	246	265
5	230	304	271	321	[illegible]	[illegible]
Average	321	302	237	234	2[illegible]	299

in time required. S2 and S3 were considerably slowed up in III compared with II [illegible] very slightly better, and S4, the methodical slow learner, made a considerable gain in III over II. Ordinarily the time scores in the first few trials for such a group of subjects become progressively shorter. Since it was not possible to do a fourth trial in quiet for comparison, we note only that the third trial, performed during noise and bothersome vibration of the table and wooden blocks, required about 5 per cent longer time than did Trial II instead of the usual improvement due to additional practice.

Visual reaction time to an indistinct signal

If the reader will imagine looking at an ordinary stop watch at a distance of [illegible] feet from his eyes and releasing a telegraph key when he notes that the sweep hand has started to move, he will know the setup for this [illegible] subject sat at a table with his finger resting on a key that closed his end of an electric circuit. An electric clock with a dial 1-1/2 inches in diameter and a thin sweep hand was mounted on a panel facing him, and had no apparent vibration. The experimenter stood near the clock watching it also and had a push button in one hand out of the subject's view. With the other hand he gave a ready signal and then one or more seconds later pushed the button which closed the clock circuit. A loud electric buzzer was running constantly to mask the clock noise during quiet runs. The clock hand was not set to zero between reactions; hence the visual signal started from different positions. The subject responded by releasing his key, thus stopping the clock. The total time for 20 reactions by each subject was accumulated before reading the clock. The sound field for the subject when the jet engine was running measured 130-134 db (overall) and all subjects wore ear defenders.

This reaction test required about one minute after the subject had been seated and instructed. Data for five subjects, all new to this particular test, are presented in Table 3. Periods I and II were in quiet except for the masking buzzer, Tests III and IV were made during noise when the jet engine was running 100 per cent without afterburner, and V and VI were in buzzer-quiet after the engine was turned off. Inspection of the group averages shows Periods I and II as close checks and while III and IV were both in noise and agree closely, they represent a 5 per cent speedup in performance when compared to I and II. In Period V similar behavior to that shown in the noise appears to continue while in VI there is a regression to the slower tempo present in I and II. This analysis is oversimplified and must be examined in reference to individual differences between subjects.

A clearer and at the same time more detailed view of our reaction time results may be had from Table 4. Here I and II are combined (averaged for each subject) to represent quiet before noise, and V and VI are averaged for quiet results after the jet engine was stopped. From the left-hand side of the table S1 shows himself slowed up in the noise: 326 msec. compared with 270 before noise and 259 msec. after. Subjects 3 and 5 demonstrated no obvious change in reaction speed while Nos. 2 and

Table 4. Consolidated Results for Visual Reaction Time
Scores given in msec [200 msec = 1/5 second]

Subjects	Testing Periods			Individual Differences		
	I + II Q	III + IV N	V + VI Q	Ratio	$\frac{\text{Behavior in Noise}}{\text{Behavior in Quiet}}$	Change
1	270	326	259	$\frac{326}{265}$	Speed rank 1	+21%
2	300	227	286	$\frac{227}{293}$	Speed rank 3	-23%
3	367	359	350	$\frac{359}{359}$	Speed rank 5	0%
4	278	219	255	$\frac{219}{267}$	Speed rank 2	-18%
5	292	296	305	$\frac{296}{298}$	Speed rank 4	0%
Average	301	285	291		$\frac{285}{296}$	-4%

4 were accelerated when working in the noise field. The right-hand side of Table 4 shows these results given as ratios, average score during noise over the average scores during quiet including before and after noise. Subject 1 was slowed down 21 per cent, Nos. 3 and 5 show zero change and Nos. 2 and 4 were speeded up 23 per cent and 18 per cent respectively. The subjects ranked in terms of overall speed during quiet runs show interesting differences in noise effect on behavior. The two slowest men, ranks 4 and 5, showed zero change. The fastest man was slowed down while ranks 2 and 3 were speeded up by the noise environment. We may conclude that although all subjects dislike the noise as a condition in which to work, the results for the effect of intense noise on such simple behavior as reaction time will vary widely according to individual differences.

Two-hand coordination test

The equipment for this test exercise is simple (9). It consists of an impulse counter responding to 60 cycles 110 volts, stepped down by a transformer and mounted in the center of a board 20 x 18 inches. Directly below the counter is a button which, if pressed, stops it. Mounted on the board, one to the right and one to the left of this button, are two hardwood blocks each of which contains two 3/8-inch holes, 1-1/2 inches deep. A 3-inch length of standard lead pencil 5/16 inches in diameter stands in one of the holes in each block. The subject presses his right index finger on the clock button and when ready lets go, and reaching over shifts the right-hand pencil from one hole to the other (in the same block), returning to the button as soon as he can to stop the clock. He then takes over the button pressure with his left index finger and executes a similar coordination with his left hand on the other pencil. The use of each hand is alternated with the other, and the objective is to accumulate the least possible amount of time on the clock in a trial of five pencil shifts with each hand alternately. In these tests made near the jet engine the subjects turned on the electric switch at the start and were carefully instructed to turn it off when they had completed five trials with each hand. Total time was taken from "on" to "off" with a stop watch by the experimenter who stood nearby.

This two-hand coordination test was used at Wright Field on two days, July 14 and 15, 1953, on two completely different groups of subjects who were not accustomed to working on or near jet engines. The first was a group of four subjects. These results are exhibited in Table 5. The upper portion of the table shows the time accumulated on the clock for each man in each test period. The range was from 10.8 to 15.3 sec. The average for the four men indicate but little learning. In Periods I and II before lunch the mean of the averages was 12.69 sec.; for III and IV after lunch it was 12.98 sec. A similar mean for V and VI in noise (128-130 db with ear plugs) gave 13.41 sec., or 4.4 per cent slower performance. Subject 3 was not available for the final test in quiet, VII, therefore a set of averages is given for the group reduced to three. Comparison of the results for the two tests in noise, V and VI, with IV and VII for quiet shows slower performance by 8.5 per cent. If all the scores in quiet periods for the three subjects are compared with the two in noise, the effect shows up as a 7.7 per cent retardation. So far as these data may be taken to indicate a trend it seems clear that the coordinated acts attempted were slower and/or more clumsy during noise.

The lower portion of Table 5 shows the total time used by each subject for the test, i.e., action time away from the button plus resting time on the button. The time on the button is ordinarily used to take a psychological breath between attempts at quick accurate coordination. The bottom line in Table 5 records the proportion of the total time spent on the button (clock stopped). In quiet tests I, II and III this proportion was in excess of 50 per cent. In Period IV subjects realized that tests under jet noise were to come next and in V and VI with the noise the time on the button falls below a 50 per cent level.

The second set of results on the two-hand coordination test represents a group of five other subjects examined in the engine testing-block area. What appears to have been an important deviation from our usual conditions must be mentioned. The early morning plan was to take the subjects to the area for two tests in quiet before lunch. Before the subjects could be recruited it was learned that the crew on "our engine" had some engine tests which they wished to make and that our turn would come about 2:00 p.m. Following lunch the subjects arrived at 1:15 p.m. before the engine tests were completed. All five subjects were equipped with ear defenders during the half-hour or more while the engine was run part of the time with afterburner. The subjects kept out of the way and out of the more intense noise fields. When the engine was turned off the experimenter began instructing the subjects, one at a time, on how to perform the coordination test. All five proved difficult to instruct, their receiving capacity for ir-

Table 5. Results for Two-Hand Coordination Test

(Scores in seconds and decimals)

Subjects	Testing Periods						
	I Q	II Q	III Q	IV Q	V N	VI N*	VII Q
1	12.18	12.08	13.80	13.82	13.32	15.09	11.42
2	11.61	12.37	12.95	12.08	13.54	11.73	10.82
3	15.30	13.25	12.41	13.23	14.14	12.61	---
4	13.65	11.09	12.97	12.62	13.89	13.00	13.50
4-Ave.	13.18	12.20	13.03	12.94	13.72	13.11	---
3-Ave.	12.48	11.85	13.24	12.84	13.58	13.27	11.91
1	26.4	25.8	28.6	22.2	23.2	26.0	21.8
2	35.0	24.8	29.0	29.2	25.0	19.8	26.0
3	39.0	31.4	27.6	24.0	32.0	25.0	---
4	25.2	19.2	25.0	26.0	24.0	20.2	21.8
Ave.	31.4	25.3	27.9	24.7	26.0	22.7	---
Ratio	58%	52%	53%	47%	47%	42%	---

formation seemed poor, all made one or more false starts before a Period I score in quiet could be secured from them.

The results for this second set of tests are given in Table 6. They need not be discussed at length. The score range for accumulated time, 11.2 to 17.9 sec., proved wider than for the previous group. The effect of the noise (no afterburner) again appears as a slowing down of performance amounting here to 6 per cent. The lower part of this table again suggests a tendency to make haste under the psychological stimulus of intense noise, both present and prospective.

The foregoing account of preliminary studies done at Wright Field in July, 1953, includes only those conducted by the writer of this section of the BENOX report. Other studies by personnel of the Aero-Medical

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* In Period VI N all four subjects lost mental count in this test and had to be told when to stop.

Laboratory H. J. Jerison and W. J. White and others, were made at this area on the same dates, and will doubtless be reported elsewhere.

Table 6. Results for Two-Hand Coordination Test

(Scores in seconds and decimals)

Subjects	Testing Periods			
	I Q	II N	III Q	IV Q
1	12.83	11.42	11.17	11.87
2	13.35	15.38	14.42	12.66
3	13.50	12.94	11.58	11.97
4	14.22	15.15	12.64	13.25
5	17.87	16.14	15.50	14.91
Ave.	14.35	14.21	13.06	12.93
1	34.0	25.0	23.2	22.4
2	20.6	20.2	20.6	18.4
3	23.2	17.4	16.8	17.0
4	15.4	19.6	16.2	16.4
5	26.0	23.6	23.2	21.6
Ave.	23.8	21.2	20.0	19.2
Ratio	40%	33%	35%	32%

Observations aboard U. S. S. Wasp during training operations

The experience of living on board a carrier for three days, while it was engaged in training operations with jet planes, greatly expanded our understanding of many aspects of the intense noise problem as it relates to human performance and efficiency. The officers of this ship were highly cooperative and every opportunity for observing operations was afforded. No experimental tests on personnel were attempted, but members of the BENOX group interviewed systematically a number of enlisted men and officers engaged in flight operations.

Impressions gained from observing personnel and interviewing a few men on the U. S. S. Wasp now operating jet planes not equipped with afterburners include the following:

1. A condition of very high morale exists favorable to efficient teamwork in many if not all phases of jet-engine operations.
2. The majority of young men become acclimated to intense noise when it seems a necessary evil.
3. The majority of personnel working with jets do not wear ear defenders. This is a fact which may be interpreted in various ways which need not be detailed here.
4. The teamwork seen for the launching and recovery of jet planes appeared well organized and efficient. No obvious slowness or clumsy movements were noted.
5. Personnel appeared to be well relaxed and emotionally flexible between stints of intense work. The sociability index seemed high.
6. The nature of work on the flight deck places an extra burden of reliance on prompt seeing, therefore special attention to the vision, condition and protection of the eyes of crewmen should be provided by ships' officers.
7. The hand signals might well be made more prominent and less brief.
8. The flag signals, white and red, from the view of the plane starter are deflected by wind and poorly visible. These signals might be made stiff semaphore type or changed to lights for both day and night use.
9. Instruction, demonstration and training in reference to jet noise hazards and ear protection would appear desirable from several points of view. The impression was received that the check-out of new crewmen in reference to their jobs is inadequate. More care should be taken to acquaint the men in advance with all aspects of the job they are to undertake and, particularly, to emphasize the special difficulties which result from the high noise environment. Special instruction should be given as to the best method of dealing with these difficulties.

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XII

NEUROPSYCHOLOGICAL EFFECTS OF CHRONIC INTERMITTENT EXPOSURE TO NOISE

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Human operators differ greatly in wants and aversions. With the possible exception of sexual stimulation, where adequate data are lacking, man appears to find comfort, security, and optimal social expression in environments which provide moderate levels of stimulus intensity. When moderate levels of intensity are exceeded, either downward or upward, wants change to aversions. The "silence" of the range or of the sea will sooner or later help the cowboy and the fisherman seek the bright lights and bright sounds of the city.

Noise has been defined as unwanted sound. At the lower intensities, noise is chiefly of importance to the engineer in his attempts to maximize signal-to-noise ratios. At higher intensities, noise induces an aversion in the normal individual. This is ordinarily reacted to by avoidance. Yet individual differences manifest themselves here. Psychiatry well recognizes that many individuals are abnormal in their responses to aversive stimuli and <u>seek</u> rather than avoid them. Such individuals may in other respects appear normal. They are not readily detected by screening and personnel selection techniques. Where essentially "closed" environments exist, as in many industrial and military situations, these individuals may feed their neurotic needs behind a facade of elaborate defenses. Such individuals may deny biological maladaptive influences of the environment even though they are undergoing gradual disruption or disorganization.

The neurotic individual is significant in the context of the present discussion not only because he is difficult to detect in working groups of men, but because he may mask or distort the normal reactions, both mental and physical, to the extremes of environmental stress. As Dr. Ross McFarland has pointed out, a high correlation was noted between neurotic symptom formation, including physical collapse, and low levels of anoxia induced by simulated altitude where the normal individual was unaffected (1). This is the reverse side of the coin. It is well known that the outcome in brain injuries may be markedly influenced by the pre-morbid personality structure (2). The neurotic may overreact or he may underreact. Failure to take into account the presence of the cryptic neurotic personality in specified populations has led numerous otherwise well-designed investigations to culminate in the rediscovery of neurosis. A survey team such as BENOX is extremely vulnerable to the Lorelei of hidden neurosis. The apparent presence or the apparent absence of biological effects of environmental stress such as high levels of noise cannot be evaluated at more than a superficial level without painstaking investigation. Ideally, such investigations result in specification of three major sources of variance in the individual. These are the assessment of neural forms of regulation, of extraneural forms of regulation, and of "personality" structure. Seldom are these goals achieved in other than long-range studies. To achieve them requires the cooperation of widely diversified research personnel. The problem is greatly complicated by the fact that equivalent behavioral disturbances may arise from all of the above sources. It is only recently, for example, that medicine has been able to trace certain forms of brain disease to tumors arising in association with the endocrine glands (3).

Preliminary Testing of Civilian Maintenance Personnel at Wright Field

In surveying the possible chronic effects of repeated exposures to high level noise it seemed desirable to combine both interviewing and testing techniques. Arrangements were made by the Bio-Acoustic Section (WADC) for the use of an Air Force trailer which provided mobile laboratory and interviewing facilities. The trailer was located on one of the various flight lines in close proximity to both fighter and bomber maintenance crews. Ambient noise levels within the trailer were measured by a General Radio sound level meter from time to time; with minor exceptions, the ambient intramural noise of the test environment fell between 60 and 90 decibels. Ten men were selected by the Assistant Foreman of the particular hangar for testing and interviewing. He was asked to select these men in terms of the following criteria: 1) employment of two or more years on jet engine maintenance, 2) presence of frequently reported subjective symptoms related to "noise," or 3) lack of reported subjective symptoms related to "noise." The ten men, including the Assistant Foreman, thus selected proved to be extremely cooperative.

The testing and interviewing were carried out on an individual basis. Data were obtained from both direct and remote interviews. The latter took the form of the Cornell Medical Index Health Questionnaire which each man completed. The direct interview came at the end of the testing. It is felt that this order was favorable since it permitted the examiner to carry out the objective tests without knowledge of the worker's attitudes and/or subjective symptoms related to noise. The direct interview which was essentially open-ended in form, encouraged free discussion of the problem of "noise" and gave the examiner an important opportunity to clear up misunderstandings concerning such matters as the quality of individual performance on the tests, purposes behind the tests, and uses that would be made of the data.

Quantitative Findings

The objective tests employed were from a larger battery developed at the University of Chicago and for which adequate normative data were available (4,5). The tests consisted of the Halstead Tactual Performance Test, measurement of galvanic skin response under psychological stress,

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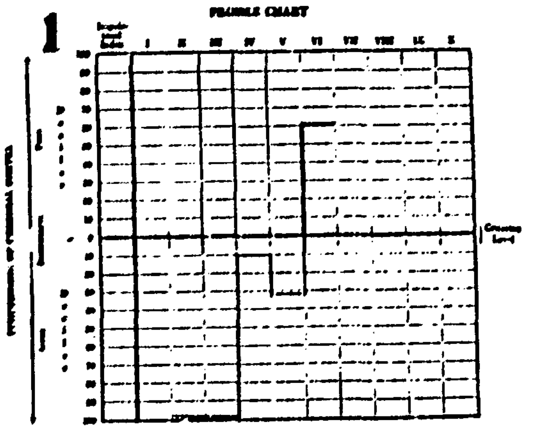
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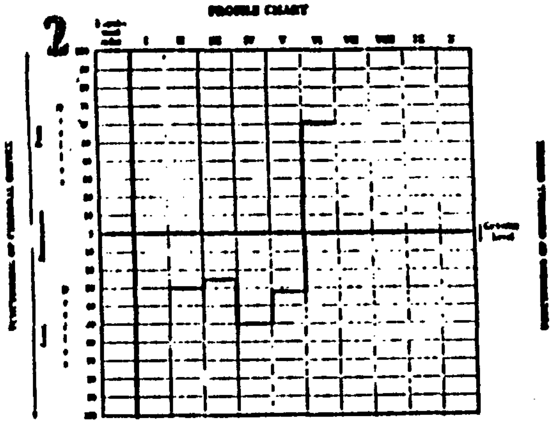
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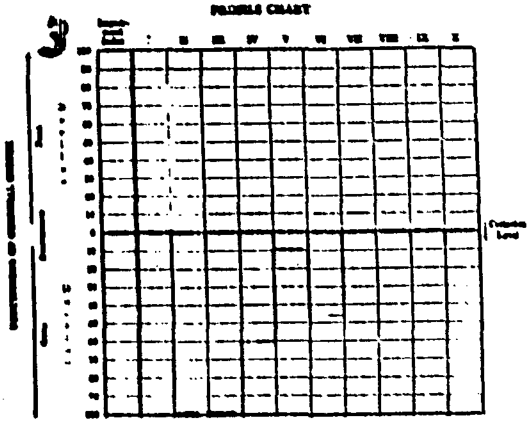
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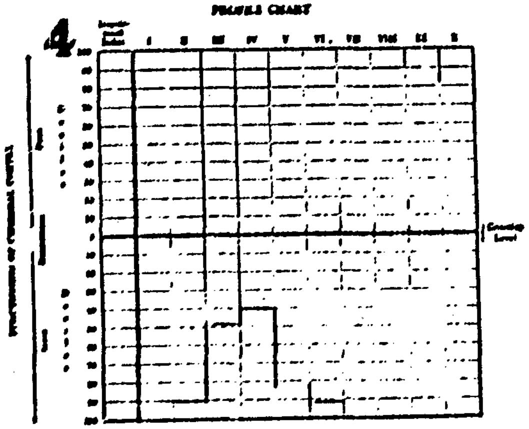
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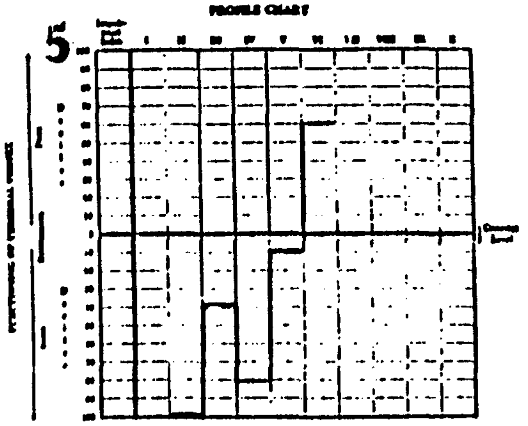
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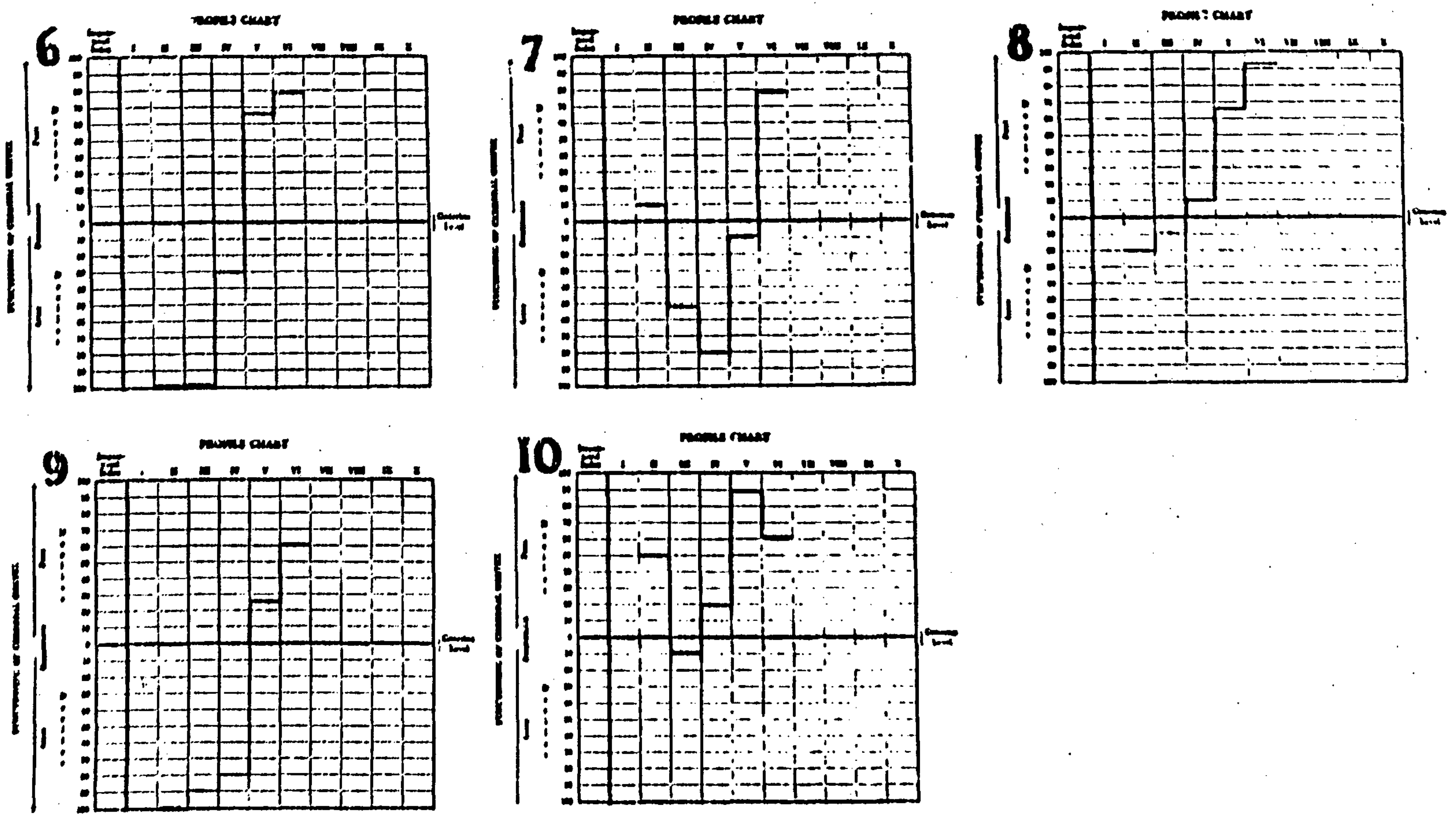

Fig. 1a and 1b. Profile charts showing performance of jet engine maintenance workers on psychological tests for brain impairment.

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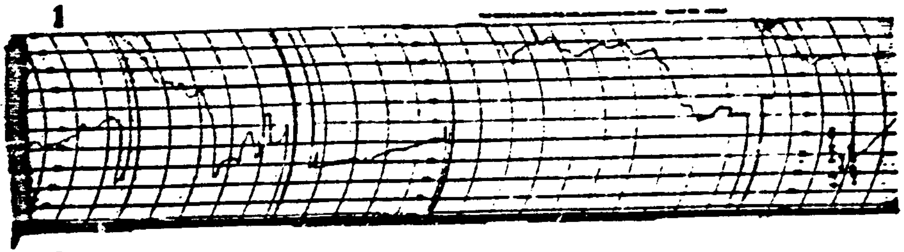

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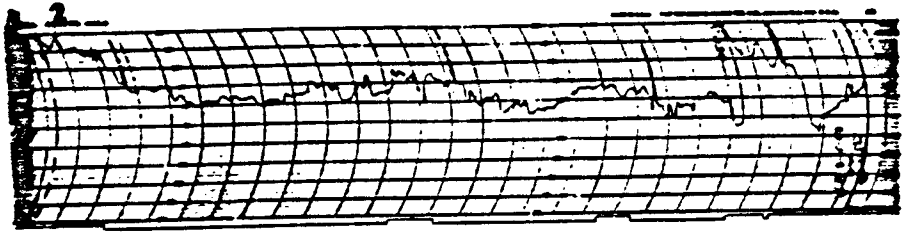

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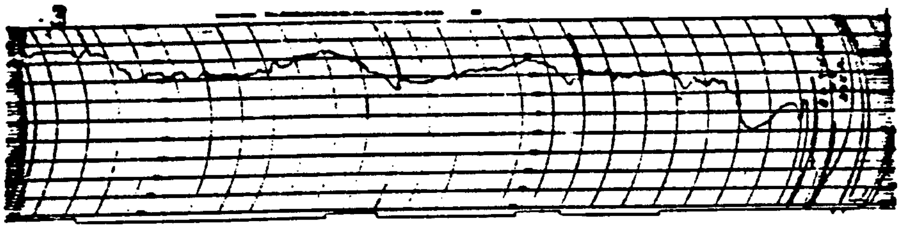

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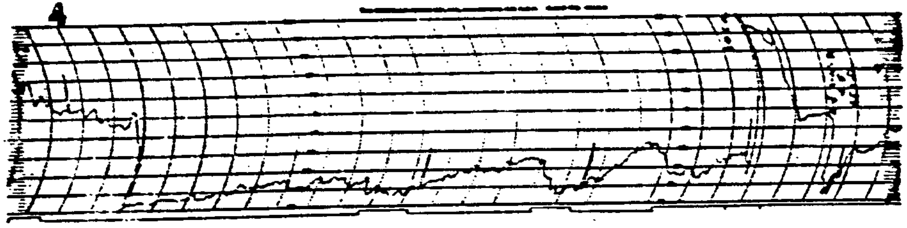

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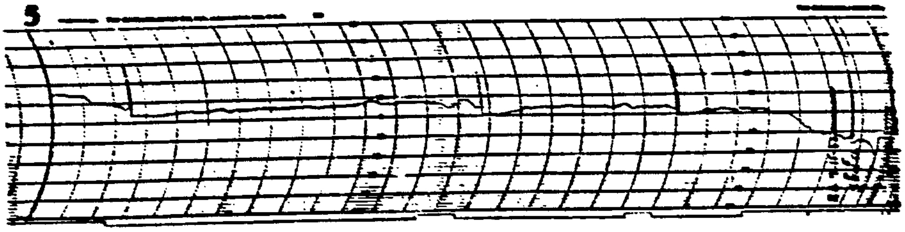

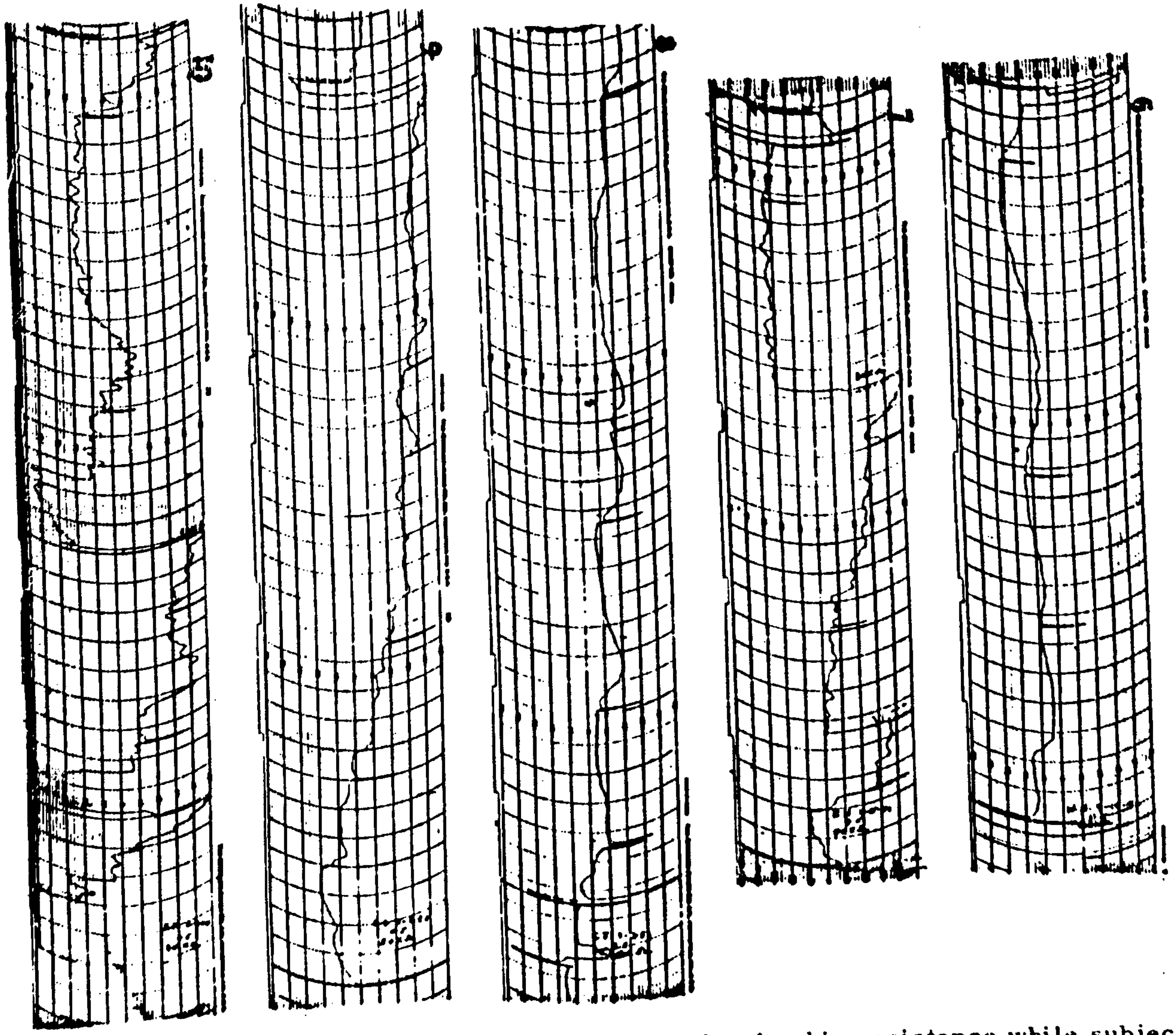

Fig. 2a and 2b. Tracings showing fluctuations in galvanic skin resistance while subjects were taking the Stress (Stroop) Test.

the University of Chicago Sound Discrimination Test, and measurement of critical fusion frequency.

The relative performance of each man tested is shown in the accompanying Profile Charts (cf. Fig. 1a and 1b). Each Profile Chart is based upon criterion scores which have been found to separate individuals with known impairment* of higher brain functions from normal control subjects at better than the one per cent level of confidence. Twelve year old children with I.Q.'s of 100 have obtained scores characteristic of the average normal adult on these tests. Scores which overlap those made by individuals with impairment of brain processes are charted in the upper half of the Profile Chart on a decile scale (with every tenth percentile indicated), whereas scores overlapping the controls are similarly charted below the midline, or criterion level. The scores which are here relevant to the Profile Charts were obtained from critical fusion frequency (II), average deviation in repeated settings of critical frequency (III), total time for three trials on the Tactual Form Board Test (IV), number of shapes accurately recalled from the experience of solving the board (V), and the number of shapes accurately located in the diagram made of the board (VI). These scores supply fifty per cent of the information obtained from the discriminating tests of the Halstead Battery. The galvanic skin response data and the sound discrimination test data will be discussed separately.

It is apparent from inspection of the Profile Charts (cf. Fig. 1b) that some of the men tested overlap significantly in their test performances a reference group known to have impairment of higher brain functions. The fact that two men have no scores in the upper zone (higher brain impairment) and that three additional men have only one score in the upper or impairment zone provides an internal control group on the testing procedures and environment. While test results were obtained on members of the study group for use as control data, it is felt that considerations of test sophistication, educational background, etc., makes such data of little value as a control for maintenance workers. It is probably significant that five of the ten men examined have two or more scores which fall in the impairment zone. It is of particular interest that gross or borderline impairment is present in all five on the memory scores of the Tactual Performance Test (V and VI). From interviews, it was learned that many of the critical inspections made by these men, especially for night flights, are tactual rather than visual in character. The possibility must be considered that the loss of tactual information in these maintenance men is somehow related to the human error factor which appears to be responsible for some airplane crashes, both military and civilian (see recently declassified material on air accidents).

It should be noted that the signs of impairment of higher brain functions obtained in five of the ten men do not necessarily represent recent alterations, or for that matter alterations associated with a high level noise environment. Their presence in a group of men who have the responsibility

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* The term impairment is used to avoid the implication of irreversible structural changes suggested by such terms as "deterioration" or "damage."

individually and collectively for highly technical and frequently esoteric maintenance operations can scarcely be regarded as desirable from the standpoint of efficiency and safety of ground and flight operations.

The data for the sound discrimination test present no evidence of impairment of sense-organ or central nervous system function in the men tested. This test provides a measure of auditory flutter fusion frequency (A.F.F.) which is in many ways analogous to visual critical flicker fusion frequency (C.F.F.). Samples of uninterrupted and interrupted white noise are presented successively to the subject's ear through a pair of headphones connected to a Magnecorder tape recorder. The rate of interruption of the white noise samples increases gradually throughout the test, thus making discrimination from the uninterrupted samples progressively more difficult. The point in the test where discrimination breaks down provides a "threshold" for auditory flutter. It has been found that the total number of errors on the test establishes individual differences in this "threshold" reasonably well. It is not yet known how this function is related to auditory acuity. The average number of errors made by the ten subjects was 6.7. For the five men whose scores on other tests are suggestive of mild impairment of higher brain processes, the average number of errors was 5.4. For the men without such signs of impairment, the average number of errors was 8.0. Since no audiograms were obtained on any of these men this inversion of test performance on A.F.F. cannot be interpreted. It does indicate, however, that the men who showed other signs of impairment were probably basically cooperative in taking the test battery.

The technique for measuring galvanic skin response was identical with that described by Halstead, Van Bortel and Kirsner (5). The method involves direct graphic and continuous recording of the galvanic skin response during the administration of a mildly stressful psychological test known as the Stroop Test.

The Stroop Test consists of three cards which the subject is asked to read. In card one the subject is requested to read rapidly 100 color names from a card. Only four color names are involved, the words "red," "green," "yellow," and "blue." These are presented in white on a black background in random order. In the case of card two, the subject is asked to name rapidly aloud the colors of 100 colored dots presented in random order on a black background. The dots are the same four colors named in card one. These first two cards are not intended to frustrate the subject, but to establish two mental sets in performance. Card three presents a conflict of the sets established in cards one and two. It is similar to card one, except that each of the 100 words is printed in a color other than that named by the word. For instance, the word "red" may be printed in green, yellow, or blue, but never in red. The subject is told to name rapidly the color in which the word is printed, that is, he must name the physical colors rather than read the words. The frustrating qualities of this task are evidenced by explosive verbalizations, anger at errors in performance, agitated body activity, etc. Some subjects block completely on the task for short intervals. All individuals who completed the task reported some frustration.

The data for initial skin resistance (in ohms), minimal skin resistance, and the difference interval in seconds between the time required for cards two and three of the Stroop Test (stress score) are shown in Table I. No attempt will be made to provide here a detailed analysis of the galvanic skin response data (see tracings in Fig. 2a and 2b). Certain general impressions are in order. In the first place the median initial skin resistance of the ten subjects is 32.5k ohms. In one instance it was higher than 100,000 ohms. While it cannot be stated that the level of 32.5k ohms is definitely abnormally high, there is reason to suspect that it is. It might be noted that high skin resistance is commonly reported in myxedema, duodenal ulcer and schizophrenia (6). Several of the GSR records present evidence of dissociation between autonomic discharge and the various levels of psychological stress induced by the Stroop Test. This kind of dissociation has been observed to occur in brain disease and in metabolic disorders. The examiner is willing to entertain the notion that something associated with the work environment of these men is critically stressful to them and that they can show no further degree of arousal to more ordinary forms of psychological stress. He is well aware of the controversial status of GSR measurements in the literature and regards the present observations based upon this indicator as suggestive but quite preliminary.

Cornell Medical Index Health Questionnaire

The Cornell Medical Health Questionnaire consists of 195 questions bearing upon somatic and mental health. The average number of "yes" responses obtained from the five individuals with scores indicating no brain impairment was 19.6 (range 3 to 51). For the five men with signs of impairment, the average number of "yes" responses was 21.4 (range 9 to 48). The last page of the questionnaire is devoted to neuropsychiatric (NP) questions. The average number of "yes" responses to the NP questions in the impairment group was 4.8 (range 0 to 15). There is no reliable difference in the number of subjective complaints, either somatic or mental, between the two groups.

In interpreting the medical significance of "yes" responses on the Cornell Medical Index, Doctors Brodman, Lorge, Erdmann and Wolff, following their study of a sample of more than 20,000 individuals, found the CMI to be sensitive in detecting both somatic and emotional disturbances. In the manual which supplies information concerning admininstration and interpretation of the CMI, the authors state: "The entire form is examined to determine the number of 'yes' answers. A serious disorder is to be suspected when more than 25 items are so marked. The distribution of 'yes' answers is noted. If the 'yeses' are chiefly in one or two sections, the patient's medical problem probably is localized. If scattered throughout the four pages of the CMI the medical problem is likely to be diffused, usually involving an emotional disturbance. In relation to the patient's emotional status, 'yes' answers on the last page are important. Here are questions about the patient's moods, feelings, attitudes, and behavior. More than two or three 'yes' answers on the last page suggest psychological disturbances."

Table I

WRIGHT-PATTERSON AIR FORCE BASE MAINTENANCE PERSONNEL

				FLICKER				GSR		TACTUAL FORM BOARD						CORNELL	
Sub-ject	Age	Yrs. Ex-posed	Yrs. Educ.	C F F	Dev.	Sound Discrim.	Stress Score	Init. Resis.	Min. Resis.	Time	Time	Time	Total	Mem.	Loc.	Tot.	N.P.
A.B.	42	6	9	39.0*	±2.7*	10†	53	100K†	35K	5'51	4'36	4'05	14.5	7	2*	3	0
W.P.	42	7	12	22.2	±.8	8	55	40K	-	3'55	3'58*	3'21	11.2	7	2*	12	3
E.D.	27	2.5	14	30.2	±2.7*	6	55	25K	-	5'49	3'27	1'07	10.4	6	6	24	4
H.J.	31	8	12	27.3	±1.0*	9	92†	35K	30K	6'00	4'55	1'29	12.4	9	8	51†	17†
R.A.	50	10	15	38.0*	±8.5*	7	70	20K	-	3'28	3'01	1'59	8.5	6	2*	8	0
W.H.	34	8	10	32.2	±6.2*	3	80†	20K	-	5'55	4'49	2'15	13.0	4*	1*	9	0
R.W.	30	6	12	20.5*	±1.0	3	40	40K	25K	4'08	2'23	1'55	8.4	6	1*	10	0
C.T.	43	10	12	21.5	±.7	8	100†	25K	-	6'00	4'26	5'32*	16.0*	4*	0*	48†	15†
R.S	49	3	8	29.7	±1.8	5	70	30K	25K	3'49	2'13	1'59	6.0	5*	2*	17	1
R.F.	47	7	10	17.5*	±.7	7	48	35K	-	6'46	7'55*	1'47	16.5*	3*	2*	23	4

* Abnormal

† Probably abnormal

Direct Interview

The direct interview required approximately fifteen minutes and was carried out immediately upon completion of the test battery for each man. Only one of the ten men admitted to no particular distress associated with noise. This man boasted that he didn't use ear plugs. While he falls in the unimpaired group from the standpoint of the Impairment Index, it is of interest that he had the highest error score of all on the auditory flutter frequency (Sound Discrimination Test). In general, the direct interview yielded data which suggest that (a) nine of the ten men have trouble sleeping, and (b) have difficulties relaxing when they get home, (c) most of them tend to tune the television or radio too loud for their wife's or friend's listening comfort, and (d) most complain of a gradual reduction in libido which is quite possibly premature for their age. Should the reductions of libido prove to be a stable finding, it would provide supportive evidence for the existence of a chronic stress syndrome among some of the maintenance workers. Most of the men interviewed expressed the belief that they tended to be irritable and short tempered in their social relations and especially with their wives and children. Nine of the ten men admitted frankly that they disliked the noise. There was common agreement among them that it was "bad enough before," but the introduction of the afterburner makes it "just plain hell to be around." Several of the men who were ex-servicemen with combat area experience compared the afterburner to an 88 millimeter shell going off right beside them.

It should be noted that there are several factors which might contribute to high situational anxiety level in these maintenance workers. It is my opinion that one such factor arises from the nature of the jet airplane from the standpoint of materials. The slender fusilage and thin skin of the jet fighter plane, for example, offer no visual assurance that it can safely contain the tremendous concentrations of energy known to be present from the noise and vibration. By contrast, the heavy breech and rifle of an 88 mm. gun provide visual assurance that it can contain its inner forces. As one worker put it, "I always feel that damned thing is going to blow up." Another anxiety-producing factor arises from the genuine hazard of many of the maintenance operations. The men feel a constant threat from the danger of burns, explosions, falls, suction from the intakes, fatal fires from ruptured high pressure fuel lines, and accidental setting off of live ammunition. However, most commonly verbalized by the men was the fear that they might make a mistake and send up a plane that would cost a pilot his life. The degree of personal identification with the total flight operation as well as with the individual pilot creates an unusual degree of loyalty and morale among this group of workmen which may tend to reduce absenteeism and symptomatic complaints.* There are in many ways very close similarities between the flight line and the battle line (7). While it is true

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* A similar factor of hyper-motivation was noted by the author in flight deck crews of the aircraft carriers Wasp and Coral Sea. Less than ten per cent of ship personnel is privileged to be up (on deck) when "things are going on".

that the stresses involved take a somewhat different form under the two conditions of survival, it is quite possible that biologically speaking the two conditions may be fundamentally more alike than different. There is, of course, one fundamental difference which may operate against the civilian maintenance worker. There is no provision for rotational relief from the environmental stresses at the flight line comparable to the policies of rotation of personnel at the fighting line.

Health Questionnaire Data Obtained on the Carrier Wasp

Through the cooperation of Comdr. Johns, Air Officer of the Wasp, the Cornell Medical Index Health Questionnaire was administered to forty-one members of the flight-deck operating personnel. These men included crew captains, crew members, and one landing officer. As a group they constituted a sample of the total flight deck personnel involved directly in the critical operations of launching and recovering aircraft. In carrying out their routine duties they were all directly exposed to the highest sound levels which occur from flight deck operations. The questionnaire was administered to the group in one sitting. The purpose of the questionnaire was explained to the men in general terms by Comdr. Harrington. I then instructed them in detail concerning procedures in filling out the questionnaire. Comdr. Harrington, Dr. Neff, who was present, and I share the view that the men cooperated fully in completing the questionnaire. This view was strengthened by the material obtained in personal interviews conducted on an individual basis with approximately one-half of the group.

An item analysis made of the 195 questions presented in the questionnaire revealed certain results of interest. In the first place, those items of the somatic section of the questionnaire which were answered affirmatively by ten or more of the forty-one individuals appear to be related to the shipboard environment and activities of the respondents (e.g., eating lots of candy bars, intense sweating, etc.). Perhaps the most interesting exception to this generalization is to be noted in the response to item No. 88 (see appendix). To the question, "Were you ever knocked unconscious ?", twenty-four of the forty-one men replied in the affirmative.

There is a strong suggestion provided by the questionnaire that the flight deck personnel included individuals with mild or even severe neurotic symptoms. The questions bearing directly on this appear on the last page of the questionnaire (questions 145-195). In standardizing the questionnaire Dr. Harold Wolff and his associates found that four or more "yes" responses on this neuropsychiatric section are sufficient to direct attention to possible neurotic involvement of the responding individual. Three individuals presented questionnaires indicating rather marked evidence of psychoneurosis. One had 41 "yes" responses in the neuropsychiatric section, the other two had scores of 33 and 27. It was found by checking the sick bay calls of all respondents to the questionnaire that whereas the average individual had made less than three-tenths sick bay calls during the preceding six months, the above three men had averaged four calls to the sick bay during the preceding six months. The person with 41 "yes" responses on the neuropsychiatric section referred to above was second from the top in number of sick bay calls with four visits. Should the proportion of three out of 41 men, or approximately 7 per cent of the significan questionnaires, and frequent sick bay visits be confirmed by further investigations, the Cornell Medical Index Health Questionnaire would appear to be a useful screening tool to the flight surgeon in monitoring the mental and physical health of flight deck personnel. Since the questionnaire requires no more than 30 minutes for any convenient-sized group, it would be possible to obtain such information at an early stage of the training of all operating personnel with repetition at reasonable intervals of time.

The observations presented above must be viewed in terms of future levels of stress for operating personnel which are likely to arise. Ship operations as a whole, and flight deck operations in particular, depend for their smooth execution on highly complex teamwork. Defect in these operations is reflected specifically in the loss of or damage to men and machines. These restricted losses take their toll in the least expendable commodity of the carrier, which is time. The temporal interval in critical launching and recovery procedures is the index of effectiveness and safety of the system as a whole. It is now well established that one circumstance where past performance fails to predict future performance of human operators is the intrusion of cryptic biological stress (3,4,8).

Discussion

Although test results comparable to those obtained at Wright Field are not available from the carrier personnel, the questionnaire data strongly suggest that the flight-deck personnel includes some individuals with either mild or severe neurotic symptoms. There is at present no way of estimating their incidence among shipboard personnel. Furthermore, there is no way of knowing how long neurotic tendencies have been operative in these individuals. This limitation is equally present in our Wright Field data. The evidence obtained there strongly suggests to this investigator that some of the men who have the responsibility for critical maintenance of expensive aircraft have some impairment of higher brain functions. Present methodology permits no conclusion as to when this impairment arose. That the impairment may be of some consequence in the particular job environment becomes apparent by the fact that among the behavioral consequences is loss of tactual information. Many critical inspections of the plane are made in a dense sound field on a tactual basis. The foreman of one hangar crew estimated that 80 per cent of all critical maintenance adjustments for night flight are made on a tactual basis. It is equally important to note that some men with equal exposure to the stress of noise exhibit no such losses. In this connection it is of interest to examine the neurotic potential of these men in comparison with those who have undergone some impairment. Case No. 8 (see Figs. 2 and 4) is a 43 year old man who has had ten years of experience with jet engines. His test results suggest that he has undergone rather severe alterations in higher brain functioning. Examination of his health questionnaire revealed the presence of strong neurotic tendencies. For comparison, case No. 4 (see Figs. 1 and 3) is a 31 year old man who has had eight years of experience with jet engines. His test results revealed no impairment of higher brain functions. His health questionnaire, however, revealed the presence of neurotic tendencies of the same magnitude as in the preceding case. From our past experience with the battery of tests employed we would judge that age is not the significant factor. In a discussion of this problem Dr. Hudson Hoagland expressed the view that the age differential here would not be reflected in adrenal functioning. Obviously it would be of great value to make intensive studies of the adrenal responses to stress in two groups of men similar to the above two cases. The first task is to detect these men by behavioral techniques. They should then be described as completely as possible by neurological and electroencephalographic technique, by psychiatric interviews, by detailed physical examinations, and in terms of their neurohumoral reactions to experimental stress. Detailed job analysis of the men should be carried out. This would reduce, if not eliminate, the possibility that occupational mismatching was a significant factor.

It is well established that the organism reacts to certain environmental stresses by an elaborate chain of neural and humoral events. The successive links in the chain from cerebrum to the adrenal glands have been examined closely in recent experiments and are now fairly well understood. On the other hand the feedback loop from the adrenals to the brain is essentially obscure. Removal of both adrenal glands in man results in death unless maintenance therapy with cortisone or its equivalent is instituted promptly. This radical shift from a demand-type of regulation supplied by the adrenals to availablity of adrenal steroids on a forced feeding basis is compatible with good biological homeostasis, both in terms of somatic and mental functions. The adequate response to physical stress in the bilaterally adrenalectomized individuals calls into question many of our basic assumptions concerning the role of these structures in mediating biological adaptation to the environment (10).

In spite of much progress that has been made in recent years at teasing out neurohumoral factors in biological adaptation, much work remains to be done before reliable indicators of stress tolerance in man will be forthcoming. It is probable that if we are to expedite the appearance of such indicators, it will be necessary to undertake long and short range studies which are so designed that they will permit description of results in terms of neural, extraneural and personality-determined disturbances in regulations. More specific suggestions toward this goal will be found elsewhere in this report.

Personnel selection techniques can be expensive and useless unless significant parameters for selection can be established. It is very probable from both the Wright Field data and the carrier interviews that great individual differences exist in aversions to noise. Some men at both installations stated that the noise did not bother them once they got used to it (periods ranging from one week to six months). It seems reasonable to expect that a wise selection program could help to maximize human tolerance for noise as an environmental stress. At the present stage of our ignorance, however, there is no useful clue as to what to select for and what to select against. With the likelihood of increased stress associated with the introduction of more powerful engines, it would seem desirable to undertake early intensive investigation aimed at clarification of the significant neural, extra-neural and personality factors which bear upon "tolerance" or healthy adaptation to noise stress.

Conclusions

1. Complaints of tiredness, irritability, insomnia, and possibly some reduction in libido, have been encountered in civilian maintenance workers who are intermittently exposed to the noise levels close to jet aircraft. There is, however, no objective evidence to date that intermittent exposure to present sound levels of approximately 140 db is physiologically fatiguing per se to young military men who are otherwise in good physical and mental health. This may simply mean that proper methodologies have not yet been applied.
2. Evidence was obtained which may indicate the existence of a marginal "stress" syndrome in some civilians who work without ear protection and who have the responsibility for executing critical maintenance operations on jet aircraft. This syndrome is reflected in certain tests of higher brain functions. The impairment of function detected thus far includes loss of information through the tactual route. This loss of information could be significant at the present time since many critical ground maintenance adjustments (especially in night operations) are carried out chiefly on a tactual basis.
3. Neurotic tendencies, as operationally defined, were detected with almost equal frequency in men who demonstrated impaired test performance and in men who did not show signs of impairment. This exploratory study yields no evidence as to whether the presence of such neurotic tendencies bears upon work effectiveness.
4. The present findings are indecisive as to whether the observed impairment is reversible, and whether it is attributable to primary central nervous system effects of exposure to noise, to cryptic brain injuries, or to secondary involvement of the CNS via a neuro-humoral stressing mechanism.
5. Carefully designed investigations, aimed at clarification of the effects of neurosis, central nervous system effects, and neurohumoral effects in influencing biological adaptations to environmental high-level noise fields, should be initiated at once. These investigations should include both short and long term studies and should encompass both field and laboratory aspects.

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XIII

SUMMARY

1. Overall noise levels of 130 to 140 db (re .0002 dyne/cm^2) are found in places where personnel must work near the vicinity of common types of jet planes now in use. For engines with afterburners these levels reach as high as 140 to 150 db. As more powerful jet engines are developed noise levels will increase. It would appear that any increase in thrust by an increase in exhaust velocity or by scaling up the engine in size while maintaining the exhaust velocity will result in an increase in acoustic power which will at least be proportional to the thrust increase. If any gain is to be made on the problem of reducing noise at the source, it can be done only by paying special attention to the noise producing properties of engines. Present estimates indicate that the prospects for a large decrease in acoustic output are not too bright.

In general the plane pilot is well protected from exhaust by his cockpit and canopy and by his earphones. Also to a great extent he travels ahead of the noise of his plane's power plant. It may be, however, that some occupants of future aircraft will be in sound fields that are too high for complete safety and effective communication unless some provision for their protection is incorporated in future aircraft design. At present and for the immediate future it is the maintenance crews and particularly certain members of the deck crews of carriers who suffer most seriously from intense sound.

2. Pain in the ears begins to be felt at about 140 db sound pressure level (overall). The threshold is about the same for all frequencies from 15 to at least 2000 cps. Below 15 cps it is increased to 179 db for "static pressure." Jet engine exhaust noise reaches the pain threshold. The pain is most probably generated in the middle ear. Permanent and temporary loss of hearing due to exposure to excessive acoustic stimulation is based on damage to the sensitive receptors in the inner ear. The threshold for aural pain is considerably above the level of stimulation necessary for damage to hearing. Thus aural pain does not give adequate warning of cumulative damage to hearing from repeated exposures to sound levels below the threshold of pain. Increase in sound level above 140 db causes rapid increase in the severity of the pain and will force personnel to employ ear protectors of some sort at levels only slightly above those encountered at present.

3. Levels of 130-140 db overall, commonly encountered near jet engines are far above the level that causes permanent hearing loss if ears are exposed repeatedly over a period of years. Some permanent injuries to hearing are undoubtedly being incurred by men now working around jet planes. At present sound levels, consistent use of available insert-type ear defenders will practically eliminate these injuries.

Sound pressure produced by jet engines with afterburners are very close to the level which can cause irreversible damage to the unprotected ear at a single brief exposure. Brief exposure without ear protection to the noise of a jet engine at full military speed without afterburner causes a temporary hearing loss which may last for 24 hours or more. Ear defenders of the insert-type such as the V-51R, if properly fitted, reduce temporary hearing loss and provide the best known protection against permanent damage to the ear from noise levels currently encountered.

Over-the-ear protectors that have been tested in the past do not give as good protection as the insert-type of ear defenders. Over-the-ear protectors are particularly poor for frequencies below 1000 cps.

4. There are definite unavoidable limits to the amount of protection that can possibly be achieved by any earplug, earmuff or combination of the two. This limit is theoretically determined by the difference between the threshold to air-conducted sound and the threshold to sound absorbed by bone and other tissue of the body and transmitted directly to the inner ear. At frequencies below 1000 cps the elasticity of the skin lining the ear canal determines the practical limit for attenuation obtainable with insert-type earplugs. Above 1000 cps the attenuation actually provided by earplugs reaches the limit set by the fact that sound reaches the inner ear not only by air-conduction but also by bone-conduction. These considerations show that little improvement can be expected from changes of the material, shape or fit of insert-type earplugs.

Good wearable earmuffs (over-the-ear protectors) alone do not provide as adequate protection as good earplugs. Earmuffs alone are better than no protection, but they must fit snugly. Reliance should not be placed on earmuffs alone.

Protection of the entire head by means of a rigid helmet does not appear feasible for several reasons, particularly because sound conducted to the ear through the tissues from stimulation of the body other than the head does not require much higher levels than those that give rise to bone reception by the head.

5. In many current operational situations, voice communication is severely handicapped because of interference by noise. By utilizing standard communication procedures, special phraseology, and well designed equipment, some communication by voice can be continued in these situations.

Even with the best possible procedures and protection of the ears from ambient noise, voice communication is impossible in some operational situations. Recourse to visual signals or other forms of person-to-person communication are therefore necessary.

6. Man's sense of his position in space (orientation) is derived from the integrated action of several sense organs, especially the non-auditory portion of the inner ear (labyrinth), the eyes and muscle sense and touch from feet, legs, body and neck. Any one of these can be spared without very serious reduction in overall performance, particularly if there has been opportunity to become accustomed to the loss. More serious disturbances come from conflicting information from two or more of

these sense organs or from false stimulation of one of them by unusual means, such as direct stimulation of the labyrinth by sound. Such stimulation begins a little below the threshold for auditory pain (about 135 db) in a frequency range centering about 1000 cps. The physiological and practical significance of this stimulation should be assessed by further studies. Symptoms of nausea and vomiting, nystagmus, shifting of the visual field, feelings of forced movements and staggering and falling are known to be closely associated with abnormal or excessive stimulation of the organs for orientation, and such symptoms have been reliably reported as the result of exposure to jet engine noise at present power levels. Such disturbances are much like motion sickness and they may become more serious in susceptible individuals as sound levels are further increased. The undesirable effects on orientation and the symptoms of nausea can be alleviated by earplugs at currently encountered noise levels.

7. In the narcotized animal, overall sound levels of 133-137 db (siren) cause stimulation of the reticular activating system of the brain stem as the result of bombardment presumably entering the CNS over the eighth nerve.

In the awake human subject, EEG changes consisting of alpha blockade and generalized cortical desynchronization occured when ear defenders were removed and stimulation was presumably sufficient to activate the vestibular portion of the eighth nerve. The threshold for this effect lies in the neighborhood of 135 db overall sound level.

The activation of central neural mechanisms, presumably via the eighth nerve, causes increase in deep tendon reflexes in some individuals during exposure to overall noise levels of 134-136 db (jet engine). This effect was not observed in persons wearing ear protectors.

There is reason to surmise that stimulation of the reticular activation system in the brain resulting from exposure to high noise levels might well mobilize the adrenal stress mechanism. These CNS changes could well account for changes in muscle tone, incoordination, difficulties in ocular orientation, nausea and vomiting and possibly errors in judgment which have been reported. The noise stimulation might also precipitate seizures in epileptic patients.

Although data are not available at noise levels above 145 db, it is possible that the increasing labyrinthine stimulation would cause definite and marked central nervous dysfunction of the same kind as those described but in greater degree, including major defects in the sphere of complex integrative function.

All of the CNS effects observed thus far at noise levels currently encountered appear to be mediated over the eighth nerve and can be prevented in part at least by use of ear defenders. At higher noise levels ear defenders may not be effective and polysensory bombardment from other sensory modalities may accentuate the functional changes minimally present at 135-140 db.

There is reason to believe that, in addition to mechanical methods of noise attenuation, pharmacological means of affording protection to the CNS may be developed, possibly through the use of anti-cholinergic drugs.

8. Studies of psychomotor performances in noise conducted by Harvard Psycho-Acoustic Laboratory and Iowa University during World War II were made under well stabilized conditions and on highly practiced tests. Maximum noise levels were 115 db (overall). The experimental subjects, in spite of annoyance, were able to perform about as well in noise as in a more quiet environment. Very little experimentation has yet been done to measure the effects upon psychomotor performance of noise at levels above 115 db. Exploratory experiments conducted at Wright Field in noise at levels up to 140 db and under less well stabilized and uniform conditions than those of earlier studies cited above gave the following results:

(a) There was a tendency toward increased time necessary to accomplish a relatively complex psychomotor task.
(b) Subjects more frequently forgot or neglected to follow instructions.
(c) There was an urge to work hurriedly and get out of the noise situation.

The results of these preliminary experiments were in no sense conclusive. They do suggest that in wide-band noise such as that of a jet engine, the first signs of interference with psychomotor performance are beginning to appear at overall intensity levels of 130 to 140 db. With increased noise levels (150-160 db) much more severe breakdown in performance is to be expected unless further protective measures are taken.

9. Complaints of tiredness, irritability, insomnia and reduction in libido were encountered in men who were repeatedly exposed to noise while working around jet aircraft. Excepting the auditory system there is, however, no objective evidence to date other than such verbal reports, that intermittent exposure to currently encountered sound levels (below 140 db) produces physiological fatigue in young men who are otherwise in good physical and mental health. This may simply mean that proper methodologies have not yet been applied to detect the fatigue effects.

From the examination of a very small number (10) of maintenance men who had been repeatedly exposed to noise over a period of years, evidence was found which suggests the presence in some of these individuals of a marginal stress syndrome. This syndrome is reflected as decrement in scores made on tests of higher mental function. The chief impairment of function noted in this small sample of men was loss of information from tactual cues. Although the evidence is slight, and the cause of the impairment cannot be directly attributed to noise exposure, these results cannot be overlooked because of the great importance of the tactual sense to the maintenance man. For many maintenance adjustments (especially in night operations) tactual cues alone are used.

The Cornell Medical Index Health Questionnaire was used in collecting information about maintenance men on the flight line at Wright Field and about members of the plane and deck crew of the U.S.S. Wasp. Only a very cursory attempt was made to correlate the responses given on the questionnaire with actual behavior such as [illegible] or by complaints of fatigue. Nevertheless, [illegible] such as the Cornell Questionnaire might be [illegible] cerned with medical aspects of exposure to [illegible]