Engine-Room Noise on Board Merchant Ships

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IN contemporary industrialised societies man has succeeded in controlling many aspects of his environment and in adapting many natural forces to meet his needs. Industrialisation has in some parts of the world largely solved economic problems by supplying man's need for food, shelter and clothing, and allowing free time for the enjoyments of modern life. Yet this advance has not been without its price, and existence in the ancient world or the Middle Ages, although the working day was often long and human life uncertain and short, might be viewed with a feeling of nostalgia for the relatively peaceful working and living environment of a pre-industrial society.

The original attitude of nineteenth century industrialism that the adverse aspects of industrial working environments must be accepted as part of the price of mechanised production has largely given way, and techniques for the adaptation of workplaces to provide a reasonably safe and agreeable environment for man are now systematically studied and applied in most developed countries.[1] Machinery guards protect workers against mutilation, insulation and thermal clothing against burns, adequate lighting and ventilation against eye-strain and lung damage, while heating, air conditioning, proper design of work benches, seats and machinery controls, and even colour harmonisation, sometimes add to the acceptability of the workplace. In contrast, however, the problem of noise has generally remained relatively untouched by efforts directed towards workers' safety, health and comfort, despite the importance of sound in a large number of work situations.

In 1961 the 19th Session of the Joint Maritime Commission of the I.L.O. turned its attention to the deleterious effects that noise

[1] See " Ergonomics : the Scientific Approach to Making Work Human ", in *International Labour Review*, Vol. LXXXIII, No. 1, Jan. 1961, pp. 1-33, and " Current Trends in Industrial Psychology ", ibid., Vol. LXXXII, No. 6. Dec. 1960, p. 586.

from machinery and equipment might have on the health of seafarers. In a resolution concerning the reduction of noise on board ship it proposed that the I.L.O. should study the question with a view to considering what further action might be taken to promote a solution of the problem.[1] The present article is offered as an introductory contribution towards the study of this question.

Generalities

The Study of Noise

Interest in the effect of noise on man (noise is currently defined as unwanted sound) can be traced back to the eighteenth century, or at least the mid-nineteenth century, when studies were made concerning hearing loss among blacksmiths and boilermakers. These and other early studies established the fact that cases of occupational hearing loss occurred not long after the beginnings of widespread industrialisation.

However, scientific investigation of industrial hearing loss and of the possibilities of noise reduction lagged far behind the investigation of other aspects of industrial working conditions, and before the Second World War little had been done by way of systematic analysis of the problem. For example the first study using audiometric techniques to measure hearing loss due to noise appears to have been made as late as 1937 [2], while the pioneer work on the reduction of noise in ships was published in 1938.[3]

In the late 1940s the scientific attention devoted to the effects of noise on man and to the possibilities of noise reduction began to increase, and in 1952 a Franco-Belgian review cited 435 publications in world medical literature devoted to the question. Since that time, however, the volume of world literature on noise has increased rapidly: a bibliography [4] published in 1955 lists over 2,336 publications on noise, and mentions an additional 1,500 references not set out, while current information files at the I.L.O. contain more studies, articles and documents on noise than on any other single safety and health problem (with radiation hazards and air pollution running closely behind).

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[1] I.L.O.: *Official Bulletin*, Vol. XLV, No. 1, Jan. 1962, pp. 40 and 71.

[2] C. C. Bunch: "The Neural Mechanism of Hearing: Nerve Deafness of Known Pathology or Etiology: Diagnosis of Occupational or Traumatic Deafness; Historical and Audiometric Study", in *Laryngoscope*, Vol. 47, Sep. 1937, pp. 615-691.

[3] R. S. Robinson: "Noise Reduction in Ships", in *Engineer* (London), 1938.

[4] Industrial Hygiene Foundation of America: *An Annotated Bibliography on Noise, Its Measurement, Effects and Control* (Pittsburgh, 1955).

These numerous publications, which range in specific subject matter from such questions as the main causes of escalator noise in the Moscow Underground to the problem of the singing propeller and control of people-noise in the community, may be divided into three general interrelated noise problems : the harmful effects of noise on man ; techniques of noise reduction and control ; and the measurement of noise. For convenience the question of noise on ships will be studied under these headings although it is clear that the problem is essentially one : for example to justify a necessarily expensive noise reduction programme the harmful effects of noise on man must be evaluated, and for both noise reduction and this evaluation an accurate system of noise measurement is required.

The Increase of Noise

The rapid increase in scientific publications concerned with noise since the 1950s is certainly a welcome development ; but the possibly equally rapid increase in the total quantity of noise produced by the world's human population would seem to call for less self-congratulation, and it is even arguable whether or not the rate of new publications on noise has kept pace with the rapidly growing loudness of our civilisation. The generalisation that noise increases with increasing mechanisation is not, however, necessarily true and, aside from the successful application of deliberate noise reduction programmes, a new technical development sometimes means less noise. For example, city noise has been reduced in some regions by the replacement of older tramways by quieter-running gasoline, diesel and propane buses.

The engine room of a merchant ship is not, however, one of the locations which demonstrate an exception to the generalisation and a great increase in noise level has resulted from the growing use of diesel propulsive machinery and the trend towards higher power and higher r.p.m. generated by lighter main propulsion engines installed in a smaller engine compartment. For example sound intensity in the engine room increased some ten times when low-speed diesels replaced the early opposed piston engine, and 100 times with the arrival of the high-speed, high-power diesel. Increase in sound energy has placed maritime enginemen among the groups of workers most exposed to high level noise, which include men working in heavy industry or in proximity to large internal combustion or jet engines.

What is Noise?

The two primary measurements of noise are the frequency, or the number of successive pressure waves per second (i.e. pitch—technically a measure of the effect of sound on man, not the sound itself) and the maximum pressure or force of these waves. Atmospheric pressure (which of course varies according to weather conditions and altitude) is, in the metric system, expressed in bars or dynes per square centimetre (1 bar=1 million dynes per sq. cm.) and measured with an instrument called a barometer. If a similar but more sensitive air pressure measuring device is placed near a sound source such as a ship's fog horn, it will fluctuate when the horn is sounded. The amount of this fluctuation shows the sound pressure and could also be measured in bars or dynes per square centimetre. At a distance of several hundred yards the pressure fluctuation caused by a small fog horn might be about 1 dyne per square centimetre or 1 microbar.[1] This measurement of sound in terms of dyne or microbar units is useful, but somewhat cumbersome for making comparisons and computations since, for example, the sound pressure near a powerful engine may be 200 microbars, which is 1 million times the sound pressure that is just audible to a very sensitive ear (0.0002 microbar). To ease the handling of this million-microbar range of sound pressure to which the human ear is sensitive it has become customary to express sound pressure by means of a logarithmic scale of only 130 units (decibels), whose use also facilitates the computation of sound pressure changes.[2]

The use of a sound pressure meter calibrated to give readings in decibels (dB) [3] makes it possible to compare the noise pressure level of various work environments. For example one of the many noise level studies concluded in recent years [4] reports average

[1] For a comprehensive explanation of the basic physics of sound see R. W. Young: "Physical Properties of Noise and Their Specification", in *Handbook of Noise Control* (New York, McGraw-Hill, 1957).

[2] The decibel unit is also useful because the human ear, generally following the logarithmic law of growth, senses sound increases in a manner corresponding more closely to the decibel scale than to the absolute sound energy of a sound pressure increase.

[3] The approximate sound pressure level in decibels and sound pressure in microbars for a few common sound sources are set out below:

Sound level in dB	Sound pressure in microbars	Sound source
120	200	(Threshold of pain) Pneumatic drill Auto horn at 3 feet
100	20	Inside aircraft—Noisy factory
80	2	Office with tabulating machines—Radio at high volume
60	0.2	Conversational speech at 3 feet Average office—Residential kitchen
40	0.02	Library—Whisper
20	0.002	Quiet church—Soundproof room
0	0.0002	(Threshold of hearing)

[4] M. Assemat: "Niveaux d'intensité sonore relevés dans les établissements industriels de Normandie", in *Premier colloque international sur le bruit* (Paris, Institut national de sécurité, 1959), p. 164.

global noise levels up to 90 dB in various working locations in a sugar refinery ; of 89 dB in a plastics plant ; of 85 dB in a spinning factory, and so on. A similar investigation concerned sound pressure levels in a railway locomotive plant [1] and produced equally high or higher decibel readings. It was found that a riveter was subjected to an average global noise of 80 to 95 dB, a forge worker to 96 dB, and engine test-stand workers to 105 to 110 dB. The highest work environment noise rating of 125 dB went to workers riveting inside locomotive boilers. Studies of noise in ships' engine rooms have also disclosed extremely high sound pressure levels at operating stations near main propulsion machinery.[2] The three highest recorded were from a free piston engine at 113 dB, a converted 1,200 h.p. 240 r.p.m. submarine engine at 112 dB and a normal 2,500 h.p. 420 r.p.m. diesel at 111 dB. Another study [3] reports global noise levels ranging between 100 dB and 110 dB in various locations in the engine room on two cross-channel vessels. The highest noise level was an ear-splitting 126 dB in a high-frequency band in an insulated generator room.

To sum up, industrialisation has resulted in numerous noisy occupations and the engine crew man on board a merchant vessel is one of the chief sufferers. It might be added that the sea-going worker has the added handicap of being unable to escape completely from his working environment as can, for example, the metal worker who, after an eight-hour shift, exchanges the clang of a drop-hammer for the quieter clatter of a city apartment or suburban home ; the seafarer is forced to remain within vibration range of the same engines which fill his ears with sound during working hours.

Harmful Effects of Noise on Man

The harmful effects of noise on man are those which damage the auditory system itself and those which have deleterious effects on other parts of the human organism. These non-auditory effects of noise are multiple and real, but nevertheless difficult to assess. It has been shown that high-level noise produces psychic stress causing continuous muscle tension [4]; an increase in pulse and

[1] V. Raymond, P. Chavasse, G. Saulnier and H. Nickles : " La prospection du bruit dans un établissement industriel type ", ibid., p. 95.

[2] A. Carré and Y. Lebec : " Bruits et vibrations dans les compartiments des machines des bâtiments modernes ", in *Revue de médecine navale* (Paris), Vol. XIII, No. 3, 1958, p. 250.

[3] R. Cook and N. Fleming : " Some Aspects of Noise Reduction in Merchant Ships ", in *Joint Meeting of the Institute of Marine Engineers and The Royal Institution of Naval Architects* (London, 1963), pp. 4, 5.

[4] H. Gopfert : " Über die Muskelanspannung des Menschen bei Lärmeinwirkung ", in *Kampf dem Lärm* (Munich), Vol. 7, No. 2, Apr. 1940, pp. 37-39.

respiration rates and in blood pressure [1]; and changes in endocrine and other glandular secretions [2] which, in experiments subjecting pigs to an intense noise, have been sufficient to cause the death of the animal.[3] However, with a less intense sound, below the 130 dB level, adaptation of the affected organs normally follows the noise-induced reaction.[4] The psychological consequences of these profound initial physical reactions varies considerably with the individual and is difficult to measure or to associate with a certain noise level. Discomfort, ill humour, lack of well-being and anger against the source of the noise, consciously or unconsciously, are normal reactions of high-noise workers; their ability to do demanding physical work is impaired [5], their morale is lowered [6] and a decrease in working efficiency because of more frequent momentary errors and lapses has been established in laboratory experiments and in actual work situations.[7] Many other more complex and psychological reactions (such as the worker deciding to leave his employment without consciously knowing the reason for his decision, difficulties in inter-personal relations on the job and at home, insomnia, emotional instability and so forth) are frequently postulated, but cannot be considered as experimentally established.

Exploration of the non-auditory or general effects of noise is still in its initial stage and includes too many unknown factors to support generalisations concerning the effects on man of a high-level noise environment. The auditory effects, however, are known, and within the last two decades it has been clearly established that continuous exposure to high-level noise somewhere in the sound pressure area above 80-85 dB, where loud-voiced conversation is difficult, causes permanent and incurable loss of hearing through the damage and destruction of inner-ear structures.

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[1] GOETHE: " Der Lärm in der Schiffahrt ", in *Hansa*, Vols. 6 and 7, Feb. 1960, pp. 359-360.

[2] A. ANTHONY: " Changes in Adrenals and Other Organs Following Exposure of Hairless Mice to Intense Sound ", in *Journal of the Acoustic Society of America*, Vol. 28, No. 2, 1954, pp. 270-274.

[3] Pierre BUGARD: " Les effets extra-auditifs du bruit ", in *Premier colloque international sur le bruit*, op. cit., p. 75.

[4] A. GLORIG: " The Problem of Noise in Industry ", in *American Journal of Public Health and the Nation's Health* (New York), Vol. 51, No. 9, 1962, p. 1343.

[5] GOETHE, op. cit.

[6] J. G. FELTON and C. SPENCER: " Morale of Workers Exposed to High Levels of Occupational Noise ", in *American Industrial Hygiene Association Journal* (Baltimore), Vol. 22, No. 2, Apr. 1941. pp. 136-147.

[7] D. E. BROADBENT and E. A. J. LITTLE: " Effects of Noise Reduction in a Work Situation ", in *Occupational Psychology* (London), Vol. 34, No. 2, 1960, pp. 133-148.

Sound, which is essentially a succession of pressure waves excited by a vibrating surface, moving through a medium such as water or the atmosphere, enters human perception by way of the outer ear, and passes through the external canal to impinge on the surface of the ear drum. The successive pressure impacts, with their variations of frequency and pressure, are transmitted and controlled by a system of three small bones across the middle ear to the window of the inner ear, where they are imparted to the liquid-filled spiral canal of the cochlea. The flexible coverings of the windows at either end of the spiral canal allow pressure waves to move back and forth through the enclosed fluid, which in turn produces a fluid wave in a second canal enclosed inside the larger external spiral canal. This second fluid wave is sensed by the auditory organ of Corti by means of a series of projecting hair cells and the harp-like pitch discrimination fibres of the basilar membrane, and nerve impulses are transmitted to the auditory area of the cerebral cortex by the auditory nerve system. The " place " theory holds that interpretation of the fluid waves into sound sensation is carried out on the spot by the organ of Corti, while the " telephone " theory holds that a pattern of stimuli is transmitted to higher nerve centres for interpretation. In any event, although the structure and functioning of the outer and middle ear are relatively well understood, the functioning of the inner ear and especially of the organ of Corti, remains largely unknown.[1]

It is this inner ear, however, that is affected by continual high levels of noise, and recent studies show that exposure to noise produces an inner-ear lesion which may vary from a degenerative process in the hair cells to complete destruction of the organ of Corti. The precise etiology of permanent noise-induced hearing loss is not understood but, in general, over-stimulation by noise for a long period produces a change in the metabolic processes in the cells of the organ of Corti, which in turn causes permanent damage to the cell structure.[2] Although no relationship has been clearly established [3] it has been suggested that permanent hearing loss is the residual loss after repeated daily temporary hearing loss from which there has been incomplete recovery.[4] A comparison of the pattern of typical temporary hearing loss [5] with measurements of permanent hearing loss would tend to bear out this theory.

[1] For a summary of the effects of noise on hearing see A. Glorig : *Noise and Your Ear* (New York, Grune and Stratton, 1958), pp. 31-34.

[2] Ibid., p. 112.

[3] Wayne Rudmose : " Hearing Loss Resulting from Noise Exposure ", in *Handbook of Noise Control*, op. cit.

[4] A. Glorig : " The Problem of Noise in Industry ", loc. cit.

[5] B. Kylin : " Temporary Threshold Shift and Auditory Trauma Following Exposure to Steady-State Noise—An Experimental and Field Study ", in *Acta Oto-Laryngologica* (Stockholm), Vol. 51, No. 6, Supp. 152, Apr. 1960.

The extent of permanent noise-induced hearing loss, as might be expected, varies with the individual ; normal ears in a steady, high-level noise environment will suffer a loss of auditory sensitivity, but ears that are highly sensitive will suffer inner-ear lesions within a short period. Although no medical treatment is possible for loss of hearing, there is often a slight recovery after a long period away from the noisy environment. On the other hand, continued exposure to noise after hearing loss has begun results in further and sometimes accelerated loss of sensitivity to sound.[1]

Thus noise-induced hearing loss is a subtle process, which often takes place without the worker becoming aware of the diminution in auditory sensitivity until lesions in the organ of Corti have reached an advanced stage. One of the reasons for this is that the first hearing loss normally takes place in the 4,000 cycles per second (c/s) frequency range which, although human hearing responds to sounds between about 16 and 16,000 c/s, is above the conversational range (500-2,000 c/s) and may go unnoticed or ignored for some time. The fact that noise-induced loss of hearing tends to start with sounds at about 4,000 c/s is probably due to the fact that the ear is more sensitive in this area, can perceive lower-energy sounds and therefore is more subject to the constant fatigue from continuous noise which may lead to hearing loss. An additional consequence of this greater sensitivity is that higher frequency noises tend to be more destructive for the inner-ear structure.

Hearing loss is usually measured by the extra amount of sound pressure that is required to make a pure tone barely audible to the person with impaired hearing. For example if, in order to produce a sensation of hearing at a certain frequency, an individual ear needs 10 dB more sound pressure level than the normal threshold of hearing, the ear is said to have a 10 dB hearing loss at that frequency.[2] The general frequency pattern which is characteristic of noise-induced hearing loss (but not of other types of hearing loss such as that produced by age) may be illustrated by two examples taken from case studies of hearing loss among ships' engine-room personnel.[3] One worker, a 52-year-old engineman with 10 years' service, showed a loss of 20 dB or less in the conversational range

[1] M. Lawrence : " The Importance of Individual Differences in Noise-induced Hearing Loss ", paper presented to the Meeting of the Minnesota Academy of Occupational Medicine and Surgery, March 1962.

[2] For a summary of pure tone audiometric technique see A. Glorig and D. J. Harris : " Audiometric Testing in Industry ", in *Handbook of Noise Control*, op. cit.

[3] Mario Ameli : *Effetti del Rumore e delle Vibrazioni sul Personale di Macchina delle Navi a Propulsione Meccanica* (Genoa, Istituto di Medicina del Lavoro dell'Università di Genova, 1961), pp. 64-67.

of frequencies, which would be normal considering age, but a 65-70 dB loss at 4,000 cycles per second. A second worker, a 32-year-old engineman with 4 years' service, showed a 25 dB loss at 500 c/s, 30 dB loss at 1,000 c/s, 40 dB loss at 2,000 c/s but showed a 65-70 dB loss at 4,000 c/s.[1] If high noise level exposure continues, the large hearing loss in the 4,000 range may be expected to extend toward the conversational frequencies.

The measurement of hearing loss in decibels, however, whether a single frequency or an average of several frequencies is used, does not necessarily present an accurate picture of the individual loss of ability to hear conversation. This is because ability to hear complex speech sounds does not correspond exactly to the ability to hear the single frequencies used in pure-tone audiometry and also because the individual may develop lip-reading techniques which mask his hearing loss. Research is now being carried on into new methods of accurately assessing loss of discrimination in conversational speech.

Although the exact nature of the damage caused by noise to the auditory system has been analysed only since the 1940s the eighteenth and nineteenth century studies mentioned above show that such damage has been recognised since the industrial revolution put men in high-noise working environments. It has been only within the last 15 years, however, that workers' compensation schemes have begun in some countries to provide money payments to workers who have suffered noise-induced loss of hearing. In 1959, 18 countries were reported to have legislative provisions covering such hearing loss [2] and seven others provide

[1] The scale of degrees of hearing loss below relates average decibel loss at 500, 1,000 and 2,000 c/s to a general description of the impairment.

Class	Hearing loss in dB	Description of impairment
A. Normal	Under 15	No difficulty with faint speech
B. Near normal	15 to 30	Has difficulty only with faint speech
C. Mild impairment	30 to 45	Has difficulty with normal speech, but not loud speech
D. Serious impairment	45 to 60	Has difficulty even with loud speech
E. Severe impairment	60 to 90	Can only hear amplified speech
F. Profound impairment	Over 90	Cannot understand even amplified speech
G. Total loss of hearing	—	—

Prepared by the Committee on Hearing of the National Research Council, National Bureau of Standards, United States. Circular 534, 2 Mar. 1953.

[2] Austria, Bolivia, Bulgaria, Colombia, Costa Rica, Czechoslovakia, Denmark, Ecuador, Finland, Federal Republic of Germany, Honduras, Italy, Italian Somalia, Japan, Mexico, Norway, Sweden and U.S.S.R. See E. Hellen : " Exposé introductif ", in *Premier colloque international sur le bruit*, op. cit., p. 237.

general coverage which in some cases includes noise-induced hearing loss.[1]

A series of investigations conducted in 1957-58 [2] undertook a comparison between the noise levels at various workplaces in the engine rooms of a number of ships and the hearing loss of the enginemen working on board these vessels. The investigators were fortunate in having available the health records, including hearing test diagrams, of the enginemen prior to their service on board the vessels studied, so that the effects of auditory damage from this particular source could be largely isolated. The soundmeter used in the study measured the over-all sound pressure level (decibels) of the noise at engine control stations, and also the level within high, middle and low frequency bands.[3]

On board an opposed-piston steam-driven ship dating from before the Second World War the over-all noise at the engine control post was 91 dB, with 81 dB in the high frequency range. The audiograms of the engine-room crew showed no hearing loss which exceeded the normal loss of auditory sensitivity attributable to age.

On a newer, 180 r.p.m. diesel the average over-all noise level at the control post was considerably higher at 112 dB, with 118 to 120 dB in the high frequency band. Eleven enginemen working on board this vessel, who had normal or above normal hearing when coming on board, were examined, and all were found to have substantial hearing loss of varying degrees of gravity. For example a 30-year-old engineman with 44 months on board showed an 85 dB loss in one ear at 4,000 c/s (where noise-induced hearing loss first appears) and a loss of about 40 dB in both ears in the 2,000 c/s (conversational) frequency range. He also complained of a buzzing in his ears, which usually disappeared after a month's rest ashore. For older seafarers the loss of hearing set in sooner, and a 53-year-old engineman showed a hearing loss beginning at 1,000 c/s after only 17 months on board. However, some younger men were more susceptible to damage to the inner-ear structures and one 29-year-old engineman had a 40 dB loss at 4,000 c/s after only eight months on board.

At the engine control post on a free-piston vessel the average over-all sound pressure level was 113 dB, with 98 dB in the high

[1] Australia, Brazil, Canada, Indonesia, New Zealand, Turkey and United States. Ibid.

[2] A. Carré and Y. Lebec, op. cit., p. 250; F. Baron, A. Carré and Y. Lebec: "Audition chez le personnel des machines à bord des navires", in *Annales d'oto-laryngologie* (Paris), Vol. 75, No. 9, 1958, p. 601; and A. Carré: "Bruit des machines des navires modernes", in *Premier colloque international sur le bruit*, op. cit., p. 214.

[3] Between 6,400 and 1,600 c/s, 1,600 and 400 c/s and 400 and 100 c/s.

frequencies. The enginemen with over a year on the ship had varying degrees of hearing impairment, which was usually beginning to enter the conversational range, while men with less time on the ship still retained their normal hearing.

In general the examiners found that the typical noise-induced hearing loss on these high-noise-level vessels began with a substantial loss at 4,000 cycles, after sometimes as few as eight months on board. After 15 months the 4,000 c/s loss usually increases to 60 dB and begins to extend laterally towards the conversation frequency range of 500-2,000 c/s. After 65 months in a high-noise-level engine room all of the previously normal enginemen tested showed serious loss of ability to understand normal speech.[1]

The latent period of damage, before hearing loss in the conversational range appears, was observed to be shorter—in one case, only 14 months—than the two- or three-year period postulated for high-noise-level industrial workers. This rapid evolution of noise-induced hearing loss was attributed to the continuity of the noise during watches in the tightly enclosed engine compartment and to the vibrations which, transmitted through the hull to the crew's quarters, continue to shake their inner-ear organs, during off-duty hours, at the same frequency as during direct exposure to high noise-levels in the engine room.

Noise Reduction on Ships

The same advances in engineering techniques that have made possible the more powerful, lighter, higher speed and noisier engines now installed on ships have also taken place in the area of applied acoustics, thus making shipboard noise control more possible. Some industrial processes, such as those involving cutting, abrasion or impacts, are not readily amenable to noise reduction measures but shipboard engine noise can, at the present stage of the engineering arts, be reduced ; and it has been said that " with regard to the present status of the noise problem on ships . . . knowledge of causes and treatments is now sufficient to provide loudness levels not exceeding about 65 phons [2] in the accommodation and 95 phons in the engine room, the matter being one of business economics rather than engineering skill ".[3]

[1] These results are also generally supported by Mario Ameli, op. cit., and by R. F. Nauton *(American Speech and Hearing Association Annals, Chicago, January 1962)*, who reported hearing loss among 384 of 500 enginemen examined.

[2] A phon is approximately numerically equal to a decibel in the middle frequency range.

[3] W. K. Wilson : " The Noise Problem on Board Ship ", in *Marine Engineer and Naval Architect*, Vol. 79, No. 951, Jan. 1956, pp. 3-10, and No. 952, Feb. 1956, pp. 58-62.

The sources of noise in a ship's engine room are both the main propulsion machinery (steam turbine, diesel, free piston generator or steam piston) and the auxiliary engines (electrical generators, fuel and water pumps, compressors, fans, blowers and superchargers). Coming directly from the engines, the many-pitched vibrations caused by moving parts, the dull explosive roar of fuel burning in cylinders or boilers, the high frequency whine of turbines, the high-pitched squeals of reduction gears, the grind of moving parts in contact and the insistent rumble of intake air create a complex noise which assails the human ear through most of the range of hearing, while the enclosure of the engines in the tight metallic box of the engine compartment adds reflected air-borne sound to the total noise level. In addition, vibrations travel through the engine mountings and connections to bulkheads and decks, which pass them on to the engine-room air.

As we have seen, not all of the complex of noise in the engine-room is of equal importance to hearing conservation, and it is in the middle and high frequencies that noise reduction is most necessary, for higher sound levels may be tolerated at the lower frequencies. Unfortunately, it is in this middle and high frequency range that sound level peaks on certain installations occur. For example reduction gears (which are the highest noise source for steam turbine engines) have been measured at 102 and 110 dB at 850 c/s, and scavenge-air blowers and air charges, the highest noise components on diesels, are sometimes up to 118 dB in the 1,600-6,400 c/s band. It is to these and other similar principal high-level noise sources that effective noise reduction measures should be directed, since reduction of a secondary or minor source of noise lowers the over-all or peak levels only insignificantly.

A decrease of noise at its source, and especially at these high-level sources, has been shown to be the most effective means of noise reduction. Such a measure as the more accurate cutting of reduction gear teeth is reported in one example to have reduced the over-all sound-level by 13 phons and in another by 18 phons. Similar (if less spectacular) reductions in noise may be obtained by reducing the weight and improving the balance of moving parts and increasing the weight and rigidity of stationary parts. The noise of turbo-superchargers, which have a high-pitched whine with a dominant frequency equal to the number of blades on the supercharger impeller multiplied by the impeller r.p.m., has been minimised by selecting the number of impeller blades on the wheel so that the dominant frequency falls outside the 3,000-5,000 c/s range to which the ear is most sensitive, and by using various types of sound-absorbing lining in the supercharger air intake.[1] Other types of silencer for air intakes and exhausts have also proved effective on a variety of other installations, such as the intake of free-piston gas generators.[2] The isolation of particularly noisy components, such as scavenge-air blowers, high-speed generators and reduction gears, by acoustic hoods has also proved a valuable technique of noise reduction.[3] Metal parts of the hood, however, must not touch any part of the component being masked, and metal pipes crossing through the hood must have flexible connections or the vibrations will be fully transmitted to the outside. An example has been cited of a substantial noise reduction effected by removing the bolts from the reduction gear case cover and replacing them by a number of wooden match-sticks which, being relatively elastic, did not transmit the reduction gear vibrations to the cover.[1] Another technique is to isolate engine vibrations by means of elastic engine mountings, which diminish the noise energy transmitted from the engines through the ship's structure to bulkheads and other broad metal surfaces from which it could be radiated as airborne noise. All these methods have been shown to be highly effective. On the other hand, the possibility of reducing engine-room noise by sound-absorbent lining in the engine compartment has proved to be a disappointment, since this lining at best has been found only to double the absorption of reverberant noise[4], which would mean only a 3 dB noise-level decrease in the reflected noise, the direct noise remaining the same. Measurements in similar vessels with and without sound-absorbent lining have shown almost identical noise-levels.[5]

Most of the noise reduction techniques considered above may be more effectively employed at the design stage, and their application to existing vessels may in some cases be limited, although enclosure of noisy components, use of intake silencers and so forth may still be carried out. However, on board vessels which continue to have an intolerably high level of noise after every effort has been made to reduce it at the source, other measures of noise protection (as distinct from noise reduction) must be considered. One method of personal protection is the use of ear plugs inserted in the auditory canal, and ear muffs that cover the exterior of the ear as does a

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[1] WILSON, op. cit., p. 12.

[2] R. COOK and N. FLEMING, op. cit., pp. 10-12.

[3] Ibid., and A. J. KING : " Reduction of Internal-Combustion Engine Noise by Enclosure ", in *Symposium on Engine Noise and Noise Suppression* (London, Institution of Mechanical Engineers, 1958).

[4] R. S. DODSON and E. G. BUTCHER : *Investigations of the Noise from the Diesel-engine Installations in a Cross-Channel Motor Vessel,* British Ship Research Association Report 94 (1952) ; see also COOK and FLEMING, op. cit.

[5] Idem : *Observations of the Noise of the Exhaust Systems of Two Motor Ships,* British Ship Research Association Report 97 (1952).

radio head-set. These ear protectors are capable of reducing the sound level reaching the inner ear by as much as 25-35 dB [1] but a great deal depends on an accurate fit, and effectiveness may vary from one work situation to another. Although muffs are easier to fit than plugs their sound attenuation is somewhat less. The use of ear protectors, however, is not always accepted by crews and the hot, oily atmosphere of the engine room, as well as the length of time that the protectors would have to be worn, have been raised as objections to their widespread use.

Another method of individual protection is the periodic examination of enginemen whose hearing is unusually sensitive to noise and those who have already begun to experience hearing loss in its early stages.

The most effective means of noise protection appears at present to be the local screening of working posts from the general engine-room noise by a double-glazed enclosed control cabin or a " sentry box " lined with sound-absorbent material.[2] This system has been used on a number of new vessels [3] and could perhaps with modifications be more extensively adopted.

Noise in the crew's quarters, unlike that in the engine room, where direct airborne noise is the principal component, is primarily caused by main propulsion engine vibrations transmitted through the ship's structure. These vibrations may be reduced by isolation of the main engine vibrations with rubber, plastic or other flexible engine mountings and connections, or by isolation of the accommodation space from the ship's structure by rubber- or felt-mounted walls and flooring. Also the crew's quarters may be located amidships and yet farther away from the engines if these are placed three-quarter aft or aft, other considerations permitting this design.

Noise on the navigation bridge may be reduced by better location of engine ventilation, diminution of structure-borne noise and relocation of auxiliary machinery.

The Measurement of Noise

Since it is clear that physical injury to the auditory system results from high engine-room noise levels, and since sufficient progress in adapting the engine room to the men who work there has been made to permit a substantial reduction in, or at least a

[1] J. Zwislocki : " Ear Protectors ", in *Handbook of Noise Control,* op. cit.

[2] Cook and Fleming, op. cit., p. 12 ; and Carré, op. cit., p. 215.

[3] In France, Germany, Japan and Sweden.

screening from, excessive sound pressure levels, it might seem reasonable to open the question of the establishment of international maximum noise level standards.

It might be argued on the one hand that it is too early in the development of noise measurement techniques and basic scientific knowledge to attempt to set an industrial noise standard [1], and on the other that, in view of the technological progress which has been made, conditions in ships' engine rooms should not be allowed to continue to become worse, but should be improved. In any event the establishment of precise maximum noise standards is a problem of considerable difficulty which, first of all, requires the adoption of a satisfactory noise measurement system.

The objective system of sound measurement which we have been using thus far in this article and which measures sound in decibels of sound pressure level and cycles per second of the sound pressure waves, is not completely satisfactory from a human or subjective point of view, especially if a single decibel value is used to express the over-all noise level. An interrelation of complex sounds can produce a subjective response which does not correspond exactly with the objective frequency and sound pressure level. For example, we have seen that the ear is more sensitive to sounds near the frequency of 4,000 c/s (the high tones of a violin) and sounds in this area would seem louder to a normal listener than others at higher or lower frequencies but with exactly the same mechanically measured sound pressure level.

In the subjective measurement of sound, pitch is the equivalent of frequency, and loudness (the observers' impression of the strength of an auditory sensation) is the equivalent of sound pressure. Two scales of loudness are in general use, the units being the phon and the sone respectively.[2]

These subjective sound measurement scales come closer to the essential problem, which is the effect of the sound pressure waves on man, but they have the practical disadvantage that a delicate laboratory investigation is required for each measurement. For example the technique adopted in one phon scale measurement of engine-room noise was to make extensive recordings of a ship's engine room, which were reproduced in a laboratory and measured by a group of 30 normal listeners against standard tones.[3] To

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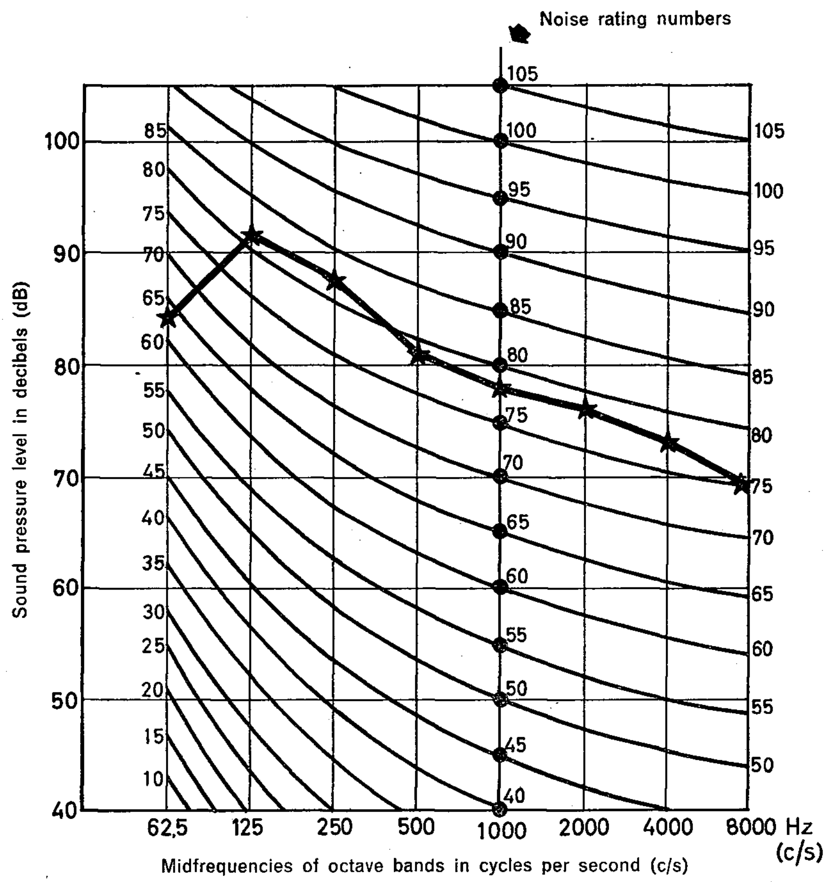
[1] For example see E. ABRAHAMSON and J. W. E. PETTERSEN : " Übersicht über die Schiffslärmbekämpfung in den Skandinavischen Ländern ", *Det Norske Veritas* (Oslo), Report No. 60, 1960.

[2] International Organisation for Standardisation Recommendation R 131 : *Expression of the Physical and Subjective Magnitudes of Sound of Noise* (1959). Also British Standard 3045 : *The Relation between the Sone Scale of Loudness and the Phon Scale of Loudness Level* (1958).

[3] R. COOK and N. FLEMING, op. cit., p. 6.

avoid such involved techniques and to provide a noise measuring system that would be practicable and would also register sound on a subjective scale, the sound level meter was developed. This meter automatically gives extra weight to frequencies where the ear is more sensitive, and for any given noise provides an over-all sound level reading in phons. An instrument of this type has been specified by the German Standards Institution (D.I.N.) and is widely used in the Federal Republic.[1] It has been found, however, that the effect of complex noises is more subtle than was anticipated and when several different levels of noise are mixed with a wide

FIGURE 1. NOISE RATING CURVES [1]



[1] From drawing No. 8606/1 prepared by a Working Group of the I.S.O. Technical Committee on Acoustics, June 1961, Helsinki, Finland.

[1] Deutsche Industrie-Norm No. 5045.

distribution in various octaves, there is often a considerable difference, as high as 10-15 phons, between the D.I.N. meter reading in phons and the loudness level in phons as measured by human listeners.[1]

The present trend is to abandon the attempt to construct a simple instrument for the measurement of subjective loudness and instead to use the objective measurement of sound in decibels and cycles per second, but to attach more significance to the composition of the noise (that is, the sound pressure levels at various frequencies) than to the over-all sound pressure reading. Various similar methods of rating noise levels have been proposed and the International Organisation for Standardisation is considering the standardisation of one of these methods by which noise would be rated by means of a series of curves, such as shown in figure 1.

The sound pressure level of the noise in question would be measured in decibels at the different frequencies indicated and compared with the noise rating curves to obtain an over-all noise rating number. For example the complex noise spectrum plotted in figure 1 shows a sound pressure level of 84 dB at 62.5 c/s, and 92 dB at 125 c/s, but would have a noise rating of 85 dB since it is entirely below the 85 dB rating curve. This and other noise rating systems give higher frequencies of the same sound pressure a relatively high noise rating number since higher-frequency noise is louder, more annoying and more harmful to the human ear. If this I.S.O. proposal or some similar method can furnish a satisfactory method of noise evaluation, other problems in the setting of specific industry noise standards may be considered.

Setting Noise Standards

On an international level the question of noise prevention has already been dealt with by the I.L.O. which, in addition to an early study on the effects of noise [2], and provisions in model health and safety codes [3], has adopted a Recommendation [4] that, among other matters, " all appropriate measures should be taken by the employer . . . to eliminate or reduce as far as possible noise and vibrations which constitute a danger to the health of workers ".

[1] E. Lübcke : " Lärmbekämpfung in Betrieben ", in *Die Berufsgenossenschaft* (Bielefeld), No. 3, 1960, p. 90.

[2] I.L.O. : *Workers' Hygiene. Encyclopaedia of Hygiene, Pathology and Social Assistance* (Geneva, 1930).

[3] Idem : *Model Code of Safety Regulations for Industrial Establishments, for the Guidance of Governments and Industry.* (Geneva, 1949), Rule 229, article 1. Also idem : *Safety and Health in Dock Work* (Geneva, 1958), article 428.

[4] Protection of Workers' Health Recommendation, 1953 (adopted by the 36th Session of the International Labour Conference), article 2*(h)*.

The International Conference on Safety of Life at Sea has touched upon the safety aspect of noise and has adopted a recommendation urging the study of methods of reducing machinery and equipment noise on ships' navigation bridges.[1] The International Organisation for Standardisation is now considering recommended noise limits for traffic and for industry.[2] An international meeting on noise, held in France [3], considered maximum noise recommendations, and noise limit problems were also discussed at a tripartite international conference of the European Productivity Agency in Zürich in 1959.

Although in most industrial countries the number of conferences, meetings and publications on the question of noise prevention and noise limits is substantial, only a few national regulations for noise prevention or limitation have been adopted. All these regulations have been in effect only since 1945 or later, and contain only general provisions similar to those of the I.L.O. Recommendation already mentioned.[4]

The U.S.S.R. has adopted some tentative maximum noise level standards [5], and the Shipowners' Mutual Accident Insurance Association of the Federal Republic of Germany has established specific maximum noise levels as an insurability requirement.[6] These insurance regulations also provide, however, that tolerance should be allowed for the imprecisions of noise measurement and that if the expense of noise reduction for a noise source exceeding the maximum level is unreasonable, only partial noise reduction is required and ear protectors may be provided instead.

In general, however, the approach to maximum noise regulations has been considerably more tentative than to the provisions, now

[1] International Conference on Safety of Life at Sea, London, 1960. Recommendation No. 49.

[2] Working Group 7 of the I.S.O. Technical Committee on Acoustics has been charged with the study of specific noise limits for traffic noises, and Working Group 8 with industrial and residential noise limits.

[3] Premier colloque international sur le bruit, organised by the Institut national de sécurité in Paris in 1959.

[4] E. Hellen, op. cit., pp. 237-240.

[5] *Tekhnika Bezopasnosti i Proizvodstvennaya Sanitariya. Sbornik Postanovlenii i Pravil* (1960), p. 250. These standards provide that those responsible should take all possible measures to see that noise is reduced below 90-100 dB in frequencies up to 350 c/s ; 85-90 dB between 350 and 800 c/s, and 75-85 dB above 800 c/s, and a list of measures for noise reduction at the source is set out in the tentative regulation. If noise reduction is not possible, prophylactic measures, such as lowering the time of exposure, providing ear protectors and periodical medical examinations, should be taken.

[6] *Kampf dem Lärm* (Munich), Vol. 9, No. 1, Feb. 1962, pp. 16-17. The following maximum noise levels are specified in D.I.N.-phons for vessels begun after 1 May 1961 : prolonged exposure in engine rooms, 90 ; short exposure in engine rooms, 100 ; the bridge, radio room and crew accommodation, 60. For other ships the D.I.N.-phon values are 95, 105 and 70 respectively.

fairly widespread, concerning payment of compensation once injury has occurred. The reason for this is that it is one thing to say, for example, that an injurious noise level in ships' engine rooms is not permitted and another to fix a specific maximum intensity level; this latter necessarily involves an accurate and workable system of measurement, the specification of noise levels implying a risk of physical damage to the normal human ear and a judgment as to the practicability of noise reduction in the particular industry.

In discussing specific noise level limits, a distinction must be made between maximum noise levels intended to preclude physical damage to the auditory system, those intended to permit speech communication, and those intended to permit work without excessive annoyance. It is the first noise level limitation—for the conservation of hearing—which is of more immediate concern and towards which standard-setting attempts should first be directed. There is, moreover, insufficient experimental data upon which noise annoyance standards could be based, and too many unknown factors contribute to the non-auditory effects of noise on man to permit a specific analysis. This is not the case, as we have seen, in reference to the auditory effects of noise, and experimental data have established that any prolonged exposure to continuous over-all noise levels of about 80-90 dB will gradually impair the workers' hearing ability.[1]

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[1] Numerous investigations, for example those listed below, have experimental results which suggest a level near 80-90 dB, depending on the frequency, above which noise-induced hearing loss occurs:

90 dB:

D. Höger: " Le bruit dans l'industrie ", in *Revue de médecine préventive* (Zürich), Vol. 6, No. 5, May-June 1961, pp. 174-183.

W. Ermisch, G. Haydn and H. Wittgens: " Statistische Untersuchungen an 2.415 Lärmarbeitern der Deutschen Bundesbahn ", in *Der ärtzliche Dienst D.B.* (Darmstadt), Vol. 22, Nos. 7-8, July-Aug. 1961, pp. 239-246.

86 dB:

J. Huguet and J. E. Fournier: " L'audition des ouvriers exposés au bruit en fonction de l'âge et du temps passé à l'atelier ", in *Archives des maladies professionnelles* (Paris), Dec. 1961, pp. 711-717.

85-89 dB:

B. Kylin: " Temporary Threshold Shift and Auditory Trauma following Exposure to Steady-State Noise—an Experimental and Field Study ", op. cit.

85 dB:

A. A. Arkadevski: " Gigieniceskoe normirovanie nepreryvnogo Vysokochastotnogo shuma ", in *Gigiena i sanitariya* (Moscow), No. 2, Feb. 1962, pp. 25-28.

A. Glorig, W. W. Dixon and J. Nixon: *Damage Risk Criteria and Industrial Deafness* (New York, Grune & Stratton, 1962).

80 dB:

R. Chocholle: " Les limites acceptables de bruit ", in *Premier colloque international sur le bruit*, op. cit., p. 84.

These and further investigations also show that hearing loss is affected not only by the over-all noise level but also by the frequency composition or spectrum of the noise (higher frequency noise, it will be remembered, is more harmful), the duration of exposure in the working day, and the total duration of exposure in the working life. In establishing the maximum noise levels which can be allowed without damage to the ear, all four factors must be considered, but noise to which a worker is not continuously exposed or which is intermittent should not be placed on the same footing as steady-state noise.[1] Although ships' engine-room noise is among the most severe it is not one of the most difficult for which to set maximum noise levels for the conservation of hearing ; this is because the general noise level is constant and continuous throughout the working day, except for those occasions when extremely noisy machinery has to be checked.

As pointed out above, it is now generally considered that the frequency distribution or spectrum of noise can be best evaluated by a curve similar to those shown in figure 1, by which the sound pressure in decibels is related to an octave band. In this system the sound pressure level above which there is a risk of damage to the ear is set out for each octave rather than by a single over-all decibel, phon or sone figure. A large number of investigators in various countries using this system of expression have developed diagrammatic curves which set out the results of their experiments as to the level of sound pressure at differing frequencies above which damage to the auditory system occurs.[2] Although, as might be expected, no two investigators have reached exactly the same conclusions, there is a large measure of agreement as to the area

[1] The equal energy theory of noise exposure (which is based on the concept discussed previously that permanent hearing loss is composed of the residual loss resulting from partial recovery from daily temporary hearing losses) holds that total exposure may be computed by the addition of partial exposures, and would assume for example that if exposure times were cut by half the allowable intensity could be doubled. This may apply to longer exposure times, but probably not to brief exposures. A. R. Jones and F. W. Church : " A Criterion for Evaluation of Noise Exposure ", in *Industrial Hygiene Journal*, Dec. 1960, p. 483.

[2] For example—

Katsuki (Japan), 95 dB between 100 and 200 c/s ; 90 dB between 200 and 3,200 c/s ; 85 dB between 3,200 and 6,400 c/s.

Kryter (United States) : 110 dB below 75 c/s, 100 dB between 75 and 150 c/s ; 98 dB between 150 and 300 c/s ; 95 dB over 300 c/s.

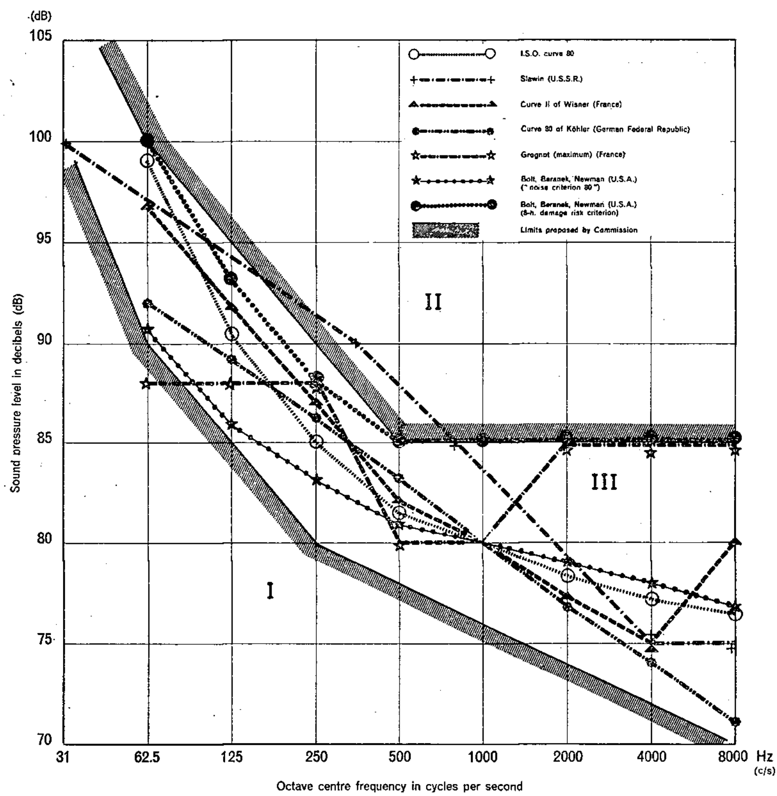
Kock (Federal Republic of Germany) : 96-100 phon below 1,000 c/s, 85-90 phon between 1,000 and 4,000 c/s ; 96-100 phon between 4,000 and 6,000 c/s.

Society of Safety Engineers (Austria) : 95-100 phon below 1,000 c/s ; 85-90 phon between 1,000 and 2,000 c/s ; 95-100 phon over 2,000 c/s.

See B. Schneider : " Einige Probleme der Begründung und Anwendung von Grenzwerten höchstzulässiger Produktionsgeräusche ", in *Zeitschrift für ärztliche Fortbildung* (Jena), Vol. 54, No. 2, 1960.

in which the noise level becomes harmful to the auditory system. The technical committee for the study of noise of the French Ministry of Health recently conducted a study of various proposed noise level limitations [1], some of which are set out in figure 2.

FIGURE 2. COMPARISON OF DIFFERENT CURVES SHOWING THE MAXIMUM BEARABLE NOISE LEVELS BY OCTAVE BANDS



For comparison the I.S.O. curve 80, taken from figure 1, has been added, as has a noise curve from the U.S.S.R. Safety and Health Regulations.[2]

[1] Reported in *Travail et sécurité* (Paris), No. 6, June 1961, pp. 182-183.

[2] A slightly but not substantially different U.S.S.R. curve was reported in United States Atomic Energy Commission : *Information Bulletin No. 86* (1958), p. 2.

It will be noted that figure 2 shows three clearly defined zones :

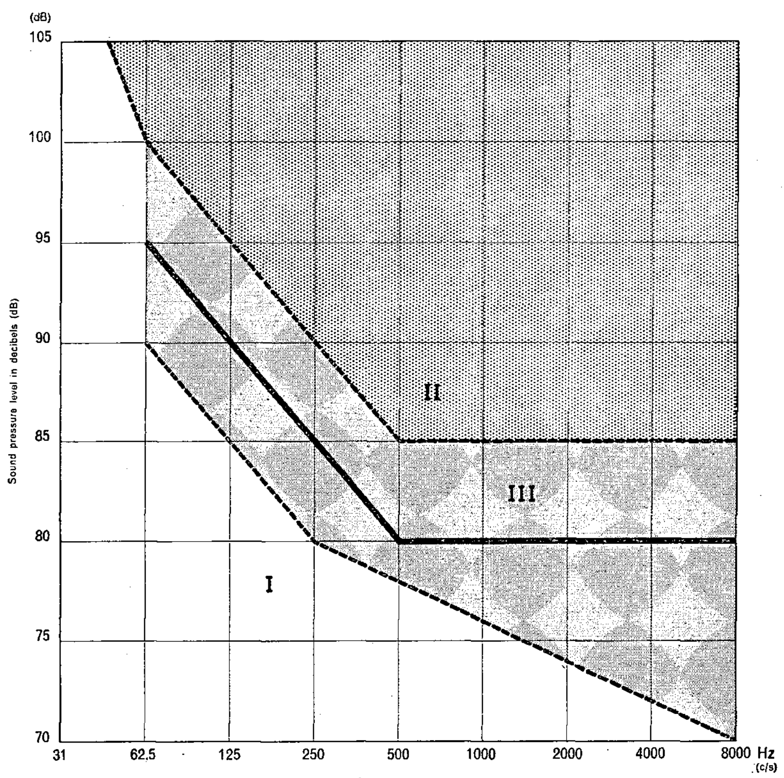
I. The zone below the lowest curve, i.e. with values less than those given by the most pessimistic authors, in which the noise levels, even if annoying, can be considered as harmless.

II. The zone above the highest curve, which is considered dangerous by all the authors.

III. The zone between the two curves, where there is a presumption of danger.

Instead of selecting a single curve as the most accurate statement of the noise level above which ear damage occurs, the committee decided upon the average curve shown by the solid line in figure 3 as the recommended maximum noise level for French industry.

FIGURE 3. MAXIMUM ACCEPTABLE NOISE LEVEL CURVE RECOMMENDED BY THE COMMITTEE FOR THE STUDY OF NOISE (FRANCE)



Whether this or some other method of noise evaluation or limitation is used, and whatever the techniques of noise reduction at the source or of individual protection that are employed to reduce noise to the determined limits in ships' engine-rooms and elsewhere, the suppression of harmful noise levels is one of the major tasks yet to be accomplished in order to provide the workers of our industrial civilisation with the safe and healthy environment to which they are entitled.