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Conference on Low Frequency Noise and Hearing

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THE EFFECTS OF HIGH LEVEL INFRASOUND

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INTRODUCTION

This paper will attempt to survey ~~our~~ THE current knowledge on the effects of relative high levels of infrasound on humans. While this conference is concerned mainly about hearing, some discussion of other physiological effects is appropriate. Such discussion also serves to highlight a basic question, "Is hearing the main concern of infrasound and low frequency exposure, or is there a more sensitive mechanism?". It would be comforting to know that the focal point of this conference is indeed the most important concern.

Therefore, besides hearing loss and auditory threshold of infrasonic and low frequency exposure, four other effects will be provided. These are performance, respiration, annoyance, and vibration.

AUDITORY THRESHOLD

A most common misconception about infrasound is that it cannot be heard. A glance at the results of various investigations[1,2,3] summarized in Figure 1 shows that infrasound can be heard (at least down to 1 Hz). Single frequencies of infrasound are not perceived as pure tones. Instead they are described as more of a chugging or motorboating sound. This leads one to the conclusion that what a person really hears is not a pure tone of infrasound, but instead the harmonics generated by the distortion from the middle and inner ear.

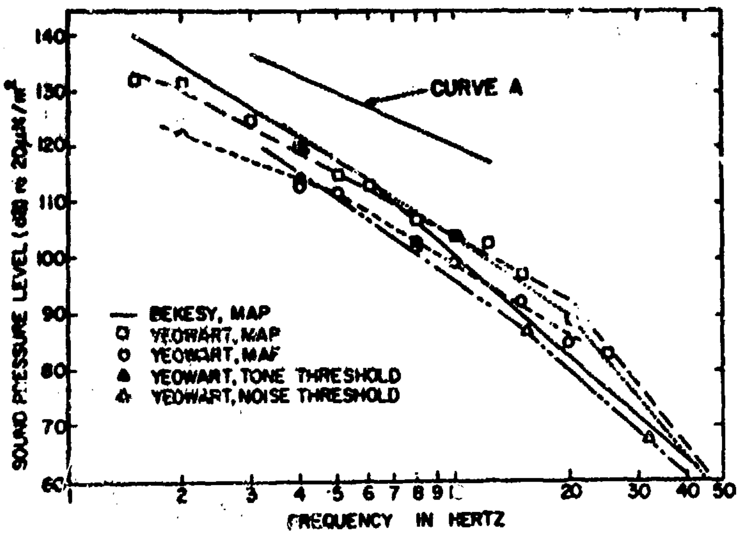

Figure 1. Hearing threshold levels for Minimum Audible Pressure (MAP), Minimum Audible Field (MAF), and for bands of noise. Curve A depicts the threshold of audibility due to middle ear distortion.

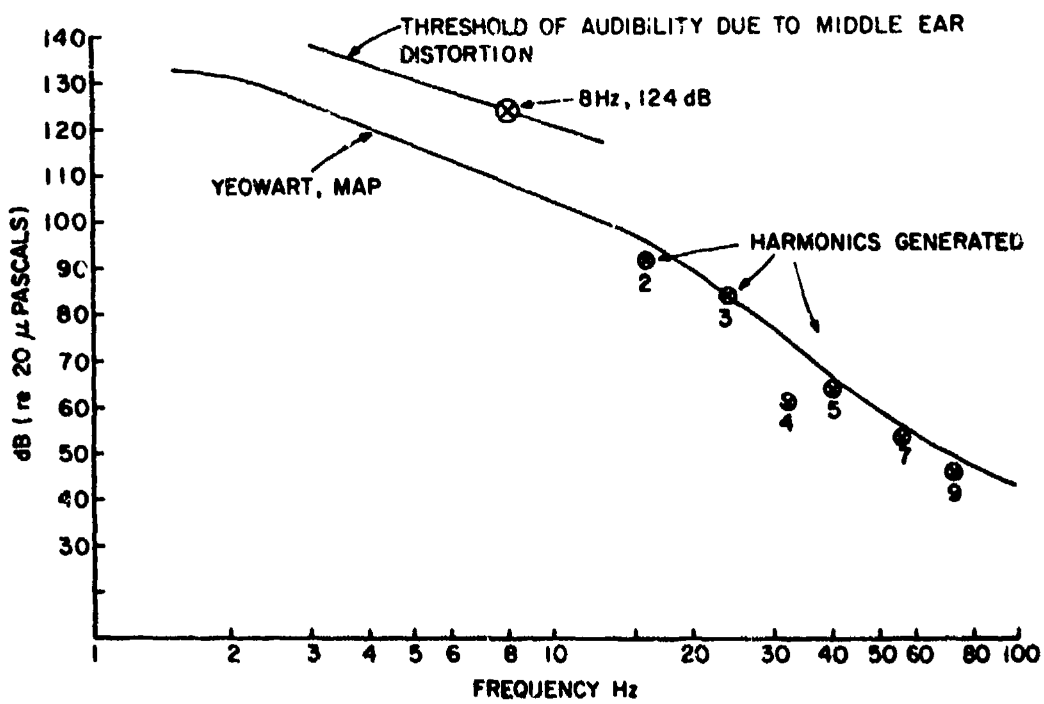

Figure 2. The Harmonics predicted due to middle ear distortion from a 8 Hz tone of 124 dB.

In our laboratory, we have investigated the possibility of known non-linearities of the middle ear causing infrasound to generate audible distortion. From just the middle ear non-linearities described by Kobrak[4], we can predict that infrasound should be audible by the time the levels reach the curve labeled A in Figure 1. For instance, a 8 Hz tone at 124 dB will produce harmonics due to the middle ear that lie on the audibility curve[5]. Figure 2 illustrates this example. Now if the audibility of infrasound is due to harmonic distortion, then it should be possible to mask the harmonics that are above 20 Hz. This is indeed the case. For instance a 7 Hz tone of 120 dB was easily masked in 5 out of 6 subjects if a 110 dB background noise (10-100 Hz) was presented[5]. A 10 Hz tone at 123 dB was detected by 3 of 6 subjects when it was added to the background noise shown in Figure 3. Often when analyzing noise in general, noise control engineers have blamed some bizarre effects on infrasound just because narrow band analysis showed that the highest Sound Pressure Level (SPL) was a narrow band in the infrasound region. The point I want to make here is that for most noises I'm aware of, it is not the infrasound that causes problems such as annoyance, chest vibration, etc., but audible frequencies about 20 Hz which are present in the noise.

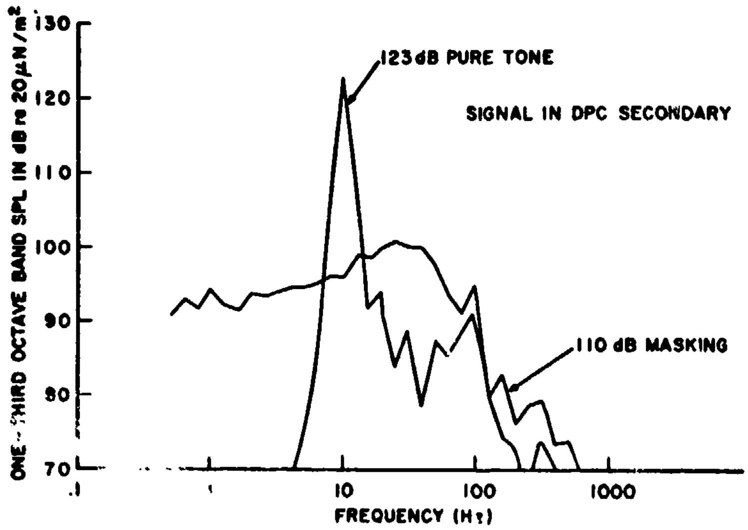

Figure 3. An overlay of both the one-third octave band analysis of a 110 dB background noise and a 123 dB 10 Hz tone. Only about one-half of the subjects could sense a difference between the combination of these noises and the background noise alone.

It can be noted that harmonic distortion could possibly cause levels of noise at higher frequencies that might be responsible for some Temporary Threshold Shift (TTS) at higher frequencies. This leads us into the next topic, the effect of infrasound on the auditory system.

HEARING LOSS

One of the more possible adverse effects of infrasound is the damage to the hearing organ. For exposures above 140 dB, TTS of the audiometric frequencies above 125 Hz of humans has been observed[6], although the frequencies above 1000 Hz seem to be the most sensitive. The TTS observed was usually small (less than 10 dB) and recovered rapidly. Figure 4 is a summary of results of various exposures to infrasound and the resulting TTS[6]. Recent whole body responses of 16 subjects to 142 dB at 7Hz for 15 minutes did not show statistically significant TTS.

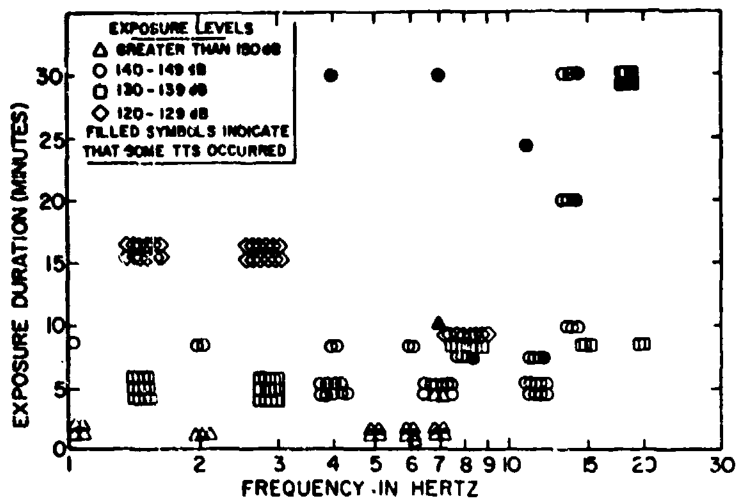

Figure 4. Conventional display of individual exposures recorded in our laboratory in terms of frequency and duration with levels as the parameter. Solid symbols indicate that some TTS was observed in the range of 125 Hz to 6000 Hz.

There is also the possibility of middle ear damage due to very intense infrasound. At 172 dB, exposures of 1 Hz (60 min), 4 Hz (15 min), and 8 Hz (7.5 min) all produced perforations of the tympanic membrane in chinchillas while exposures to 160 dB did not[6]. Histopathological investigation of the temporal bone of chinchillas exposed to such levels indicate major structural damage in the inner ear. Figure 5, prepared and interpreted by Dr. Lim of Ohio State University, illustrates such damage[7]. Endolymphatic hydrops and perforation of the saccular walls were common findings. This experiment has been repeated in greater detail and the final results will be reported this year. However, these structural changes seem to occur even at 160 dB, and the threshold of such effects may be as low as 150 dB for the chinchillas.

The chinchilla is probably more sensitive to infrasound than humans. There have been exposures of the auditory system in humans as high as 172 dB for less than 30 sec (1-8 Hz), 160 dB for 1 min (8 Hz) and 155 dB for several minutes (7 Hz). For these short times, no damage to the tympanic membrane or middle ear system occurred. However, the chinchilla results do indicate the need of caution in exposing humans to extremely intense (greater than 150 dB) levels of infrasound. This is in keeping with Tonndorf's reported scarring of the tympanic membrane of German submariners[8]. The exposure of men on snorkel subs constituted quite high infrasound exposures for long time periods. Unfortunately, the exact exposure level received by the men is unknown except that it is estimated to be considerably above 120 dB. It does not seem as clear to me as it has earlier, that the middle ear is the most sensitive part of the body. Nevertheless the middle ear certainly sets the physiological tolerance limit to infrasound due to pain. When we look at pain, we see that it is related to mechanical displacement of the middle ear system beyond its mechanical limits. Thresholds for pain as determined by Beksey and the Benox report[9] are summarized in Figure 4. There is some deviation in the data, but for the most part this depends on the type of stimulus used and interpretation of the sensations identified; the pain threshold, tickle threshold, or the touch threshold. Nevertheless, the pain threshold is probably the best indicator that we know at this time as to the physiological tolerance limit.

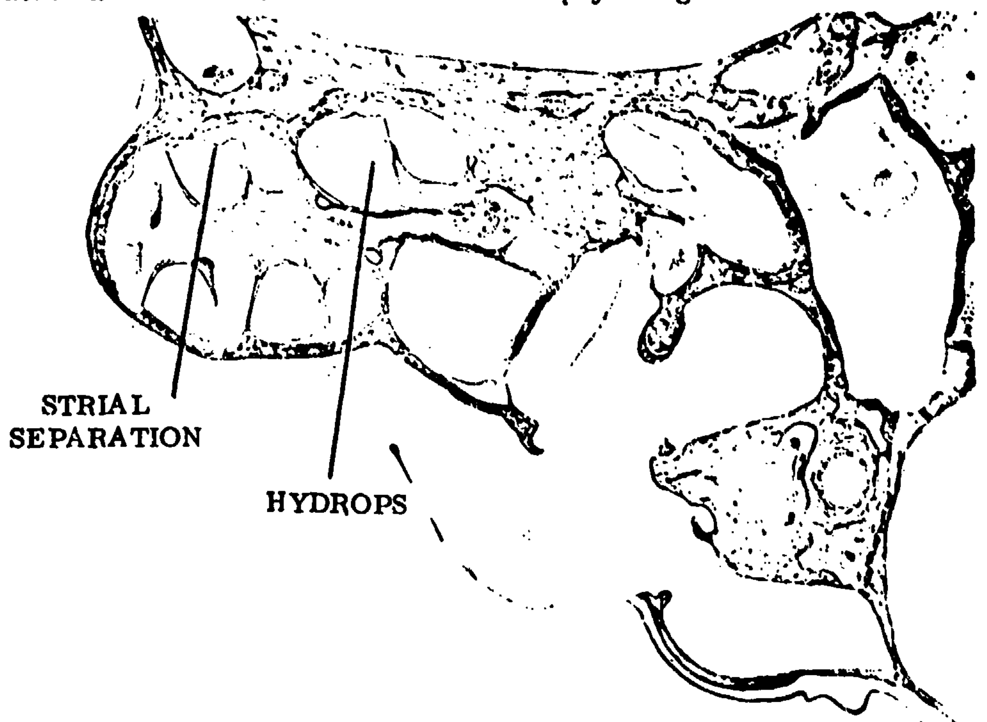

Figure 5. Structural changes due to exposure of 170 dB at 8 Hz for 10 min and 30 min exposures to levels of 153 dB to 166 dB from 12 to 30 Hz by Dr. Lim[7]

Also in Figure 6 is a range of the threshold of pressure buildup due to whole body exposures. This pressure sensation in the middle ear first starts from about 127 to 133 dB and is one of the most consistent findings in our infrasound exposures with humans[5,9,10]. The sensation does not necessarily become more intense as the SPL is raised and has been relieved temporarily by valsalva[10,11]. This pressure sensation can be explained in terms of a rectification effect caused by the eustachian tube and differs little from what one would feel during a 50 or 100 meter altitude change[12].

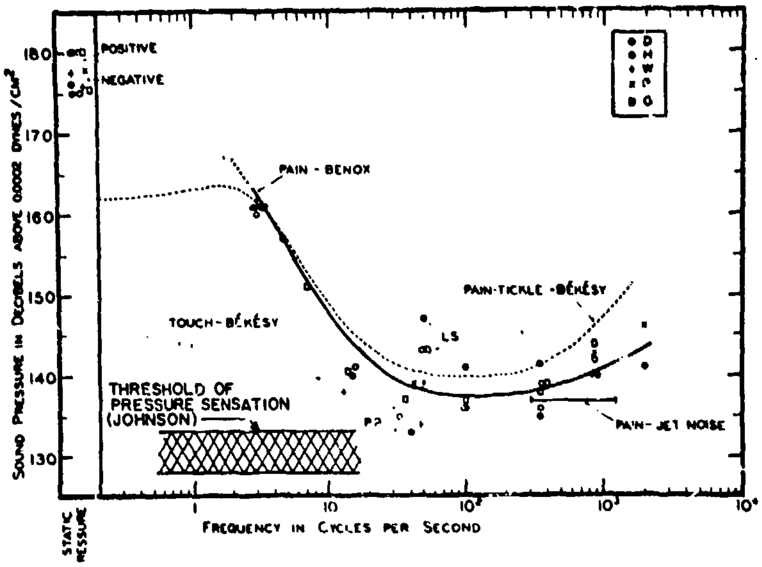

Figure 6. Thresholds of pain, tickle and pressure sensations.

PERFORMANCE

From the time Gavreau[13] first stated that weak infrasound could affect the balance or equilibrium mechanism in the ear, produce fatigue, induce nausea, etc., there have been a number of contradictory results. Various authors have suggested that infrasound can make you drunk[14,15] and adversely affect human performance. Even levels from 105 dB to 120 dB can supposedly affect reaction time, and thus are equivalent to a drunken state. Nevertheless, the experimentation done by Dr. Stan Harris, myself, and others in our laboratory during the past 6 years still indicates infrasound below 130 dB should be quite innocuous. The work by Borredon[16], who found a 130 dB, 7.5 Hz infrasound stimulus presented for a period of 50 min had negligible affect on human reaction time, also supports this contention. As I presented to the 1973 Paris Colluiquium on Infrasound, animal studies conducted in our laboratory yielded no results that would suggest any adverse effects at levels below approximately 160 dB[12,17]. Similarly, informal observations of human subjects exposed to infrasound suggested levels greater than 160 dB might be necessary to produce adverse effects. We then used nystagmography and a rail test of equilibrium to measure human responses to infrasonic stimulation objectively[18]. Nystagmus was not produced at intensity levels to 155 dB, and decrements in rail task performance were not observed at levels at 140 dB.

As these experiments did not absolutely prove that cognitive performance was not degraded, the cognitive performance of 40 subjects was measured by Dr. Harris during exposure to infrasound in three experiments[19]. In experiment 1, 12 subjects performed a serial search task while exposed for 15 min to each of four experimental conditions; 65 dB ambient noise, a low-frequency noise at 110 dB (see the 110 dB masking noise of Figure 3), a 7 Hz tone at 125 dB plus the ambient noise, and the 125 dB tone plus the low frequency noise. The second experiment was the same as the first except a Complex Counting Task was used and the exposure duration was increased from 15 to 30 min. In the third experiment eight female and eight male subjects were used. The Complex Counting Task was again used and the subjects were exposed for 15 min to 110 dB low frequency noise alone (see Figure 3) or with low frequency noise and 125 dB tone at 7 Hz, 132 dB at 7 Hz, or 142 dB at 7 Hz.

There were no decrements in performance revealed by analysis of variance in any of the three experiments. As with previous studies, there were no spontaneous comments from any of the subjects that would indicate they felt "drunk." Six subjects reported they were distracted by infrasound at the 142 dB level because of pressure in the ear, vibration, or inability to concentrate; however, corresponding degradation of performance was not measured for them as a group. It seems unlikely that any of these symptoms was caused by a direct stimulation of the vestibular system of our subjects, particularly, since there were no reports of vertigo, symptoms of motion sickness, or any illusionary movements of the visual field. While this experiment was not designed to note changes in auditory threshold, there was not statistical difference pre - post test thresholds in the normal audiometric range of 500 to 6000 Hz.

The lack of performance decrements from these experiments again support the contention that infrasound criteria proposed in the Paris Colloquium are reasonable[20]. There may be tasks that will show significant changes due to infrasound, but we have about given up looking for them.

RESPIRATION

One of the first studies accomplished by our laboratory was a short range program to confirm 140 dB would not jeopardize the mission of the crew of the Apollo rocket[11]. In the infrasound range, exposures of four experienced human subjects to discrete frequencies of as high as 151-153 dB were obtained for as long as 90 sec[11]. At these levels the subjects could feel the abdominal wall and chest wall moving. These sensations increased above 145 dB and at the 150-153 range the limit of voluntary tolerance was reached for the low frequency (above 10 Hz) exposures. This was due to the subject reporting a tickling and choking sensation in the throat, which led to the coughing response. The cause of this coughing reaction is most certainly the result of the oscillating air movement in the throat due to the pressure fluctuation. This air is undoubtedly drying the mucous membrane in this area, leading to tickling and choking sensations. This pressure oscillation can be increased such that infrasound can provide a means of artificial respiration. As I mentioned in the Colloquium at Paris, with the anesthetized animals respiration rate decreases once a SPL of 166 dB is reached. At 171 to 173 dB, respiration normally ceases for the larger dogs[12,21]. The explanation of this phenomenon is that air molecules are being exchanged between the ambient air and the lungs of the dog since each pressure fluctuation causes a density change of 10%. Thus infrasound at 172 dB serves to ventilate artifically the dog's lungs. The frequency range for which I have found this effect is 0.5 to 8 Hz, and it is interesting to note that below 1 Hz the chest is virtually motionless. This phenomenon was recently reverified for animals paralized with drugs; however, the practical use of this method of artificial respiration has not been developed.

ANNOYANCE

From a practical viewpoint, the greatest effect infrasound may have with respect to the general health and welfare is via all those many factors that make up the annoyance response. I am convinced people in general do not like to hear or feel infrasound. However, it is clear that infrasound should not annoy a person is it cannot be heard or sensed. Thus, the threshold curves of Yeowart should serve as the threshold of any human annoyance. Using this concept, a general annoyance criteria has been developed in Figure 7. The most sensitive curves of Yeowart are shown in Figure 1. Unfortunately, there are differences in the audibility of tones versus bands of noise as well as difference in Minimum Audible Pressure and Minimum Audible Field. Thus Figure 7 has a cross hatched range in which the infrasound may first be audible.

In keeping with the U.S. Environmental Protection Agency's suggested yearly Ldn of 55 dB as the value for audible sounds required to protect public health and welfare, it should be appropriate to equate the corresponding loudness curves for the Ldn of 55 dB to the loudness of infrasound. Whittle[22] et al, have the necessary loudness curves and the 45 phon curve (which is roughly approximate to an Ldn of 55) is estimated from their data. This is also drawn in Figure 7 for SPLs less than 120 dB. Note that there is relatively little difference between the threshold curves and the 45 phon equal loudness curve. This illustrates the fact, unlike noises in the 100 to 1000 Hz range, the effects of infrasound can go from absolutely nothing to quite severe with relatively little change in Sound Pressure Level.

However, there are other important factors which should serve as a rationale for limiting exposure of uncontrolled population to levels above 120 dB. The main consideration is with respect to the annoying rattling of buildings or even damage to such structures. It is interesting to note that around Cape

Kennedy, 120 dB was used as the upper limit for short term exposures of people or communites in the vicinity of the large rocket launch sites[23]. After 18 years of experience, this level seems to still be valid. Another reason for choosing 120 dB as the upper limit is the phenomenon of the middle ear pressure. The 120 dB value provides a 7 dB cushion against this disturbing phenomenon.

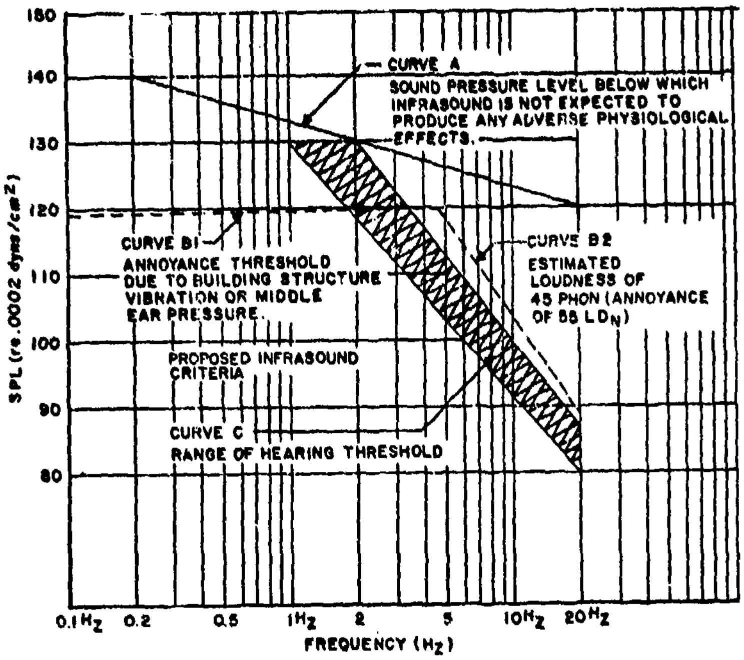

Figure 7. Various criteria proposed for infrasound exposure. Curve A first presented at Colloquium on Infrasound, Paris

In a recent CHABA publication, "Guidelines for Environmental Impact Statements,"[24] the infrasound limits for uncontrolled populations for 1 min or less was suggested as:

less than 120 dB. . . . . 0.1 Hz to 5 Hz

less than 120 dB - 30 log $\frac{f}{5}$ . . 5.0 Hz to 20 Hz

These levels are reduced by (10 log t) dB, where t is the total time and is between 1 and 100 minutes. Exposures longer than 100 min should use the 100 min limit. In other words, exposures 20 dB less than the 1 min criteria should be regarded as having no impact, regardless of exposure time. The 20 dB down point, incidently, basically insures that the infrasound is inaudible.

One practical method for reducing the annoyance due to infrasound was first suggested by Gavreau[13], and later by Westin[25]. Gavreau reported relief of the problems of infrasound was gained by masking the infrasound with high intensity sound such as music. This strategy certainly is in keeping with our experience that infrasound can be easily masked by higher frequency sounds. In fact, Figure 2 is a good example of such a strategy. Of course, care is required in order to insure the "cure is not worse than the bite."

VIBRATION FROM INFRASOUND

There are some definite similarities between whole body infrasound exposure and vibration exposure in that for both exposures it is the compressible air spaces which determine the resonances of the body. Although the force acts on all the body masses when sitting on a vibrating surface, it is the action of the abdominal mass, which moves in and out of the rib cage compressing the air in the lungs, which causes tolerance limiting resonance at 4 - 8 Hz[23]. Infrasound, because of the long wave length versus body size, acts uniformally on the whole body. Displacement of tissue primarily occurs if air is displaced or compressed, and the main air enclosures of importance in the body are the lungs and the middle ear. Low frequency sound and infrasound will act simultaneously on the abdomen, chest walls, and mouth, all of which will affect the lungs. This uniform pressure will cause the system to act much stiffer than if the stimulus is unidirectional vibration. This is why the main thorax/abdominal resonances to sound are in the 40 to 60 Hz range[23]. Such resonances have been measured by Leventhall[26] at Sound Pressure Levels as low as 105 dB, and if anyone sees the movie "Earthquake" (the Sound Pressure Level was measured as high as 120 dB in the 60 - 100 Hz region). The effect of such resonances are quite obvious. I would emphasize, however, that such resonances at these relative low sound pressure levels are in the low frequency range above 20 Hz, not in the infrasound range. Our experiments do indicate subjects do sense vibration of the abdomen or chest once the infrasound levels reach 132 dB or above in the frequency range of 4 to 20 Hz[10,19]. Interestingly, none of the four subjects exposed to 144 dB at 2 Hz or 1 Hz sensed any vibration.

CONCLUSIONS

This review emphasized those facts which, in my view, were the most pertinent. Fortunately, the present state of knowledge is more extensive than can be written in a few pages. The reader should be aware of other review articles, the better of which are the chapters of von Gierke and Parker, one of which is in a recent book on infrasound edited by Tempest[27] and the other in the Handbook of Sensory Physiology[28]. A review of the exaggerations of the effects of infrasound is provided by reference 29 while Westin provides a somewhat different viewpoint[25]. A short summary of the effects of infrasound is shown in Table 1.

Returning to the initial question concerning the importance of hearing loss from infrasound, the answer is a qualified yes. The auditory system does appear to be the most sensitive system with respect to direct physiological damage. Curve A of Figure 7 still seems reasonable, although I expect there is a moderate safety factor in this curve. However, exposures high enough to threaten the auditory system are somewhat rare. From the practical viewpoint, therefore, annoyance is the main factor that dictates permissible levels of infrasonic exposure. Unfortunately, little work has been accomplished on this problem. Our laboratory is continuing research on the effects of infrasound on hearing in the 150 dB to 170 dB range. I know of no one actively pursuing the annoyance question. In my opinion, annoyance provides one of the more timely research topics for infrasound.

AUDITORY THRESHOLD	Infrasound is audible down to 2 Hz, but loses tonal quality at 16 Hz. Infrasound is easily masked by low frequency noise.
HEARING LOSS	A small amount of TTS has occurred for exposures longer than 20 min, but generally a level below 150 dB is not expected to produce adverse results if exposure duration is less than 30 min.
PERFORMANCE	The threshold level of performance decrements has not been reached. No decrements, except for speech interference, have been found at levels below 142 dB.
RESPIRATION	Definite effect once 166 dB is reached. Artificial respiration can occur for .5 Hz - 8 Hz once 172-173 DB is reached.
ANNOYANCE	A definite problem. The threshold is probably the same level as the threshold of audibility.
VIBRATION	Approximately 132 dB from 4-20 Hz.
WHOLE BODY EFFECTS . . .	Start noticing adverse subjective effects past 150 dB. Tolerance limit not reached. Middle ear pressure buildup starts at 130 dB as well as voice communication modulation.

Table 1. Summary of thresholds where various effects should occur.

This paper is a compilation of AMRL-TR-76-17, AMRL-TR-77-51, and Research Memo, "Exposure of Four Chinchillas to Infrasound."

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