FIELD EVALUATION OF HFD'S AT SURFACE MINING ENVIRONMENTS

By

George Durkt, Jr.[1]

ABSTRACT

A study was conducted to evaluate the effectiveness of circumaural hearing protection devices and their predictability when they were being worn by mine employees performing normal work duties. The method employed relied on a physical measurement of the noise reduction of the hearing protectors by utilizing two FM-wireless transmitting and receiving systems. One system measured the outside hearing protector noise level, the second system measured the inside hearing protector noise level. The noise level data of both systems was transmitted back to the corresponding receivers and was recorded onto a two-channel tape recorder. Three methods of evaluating hearing protector performance were explored and compared to the Environmental Protection Agency, Noise Reduction Rating (EPA NRR) values. They were, (1) - predicted National Institute for Occupational Safety and Health's (NIOSH). method #l values, (2) - field-calculated NIOSH #l values, and (3) - measured dBA reduction values, which was the arithmetic A-weighted differences between both microphone locations. A more detailed description of each method can be found in Appendix A. The majority of the data was obtained on operators of mobile strip equipment, such as bulldozers, front-end-loaders, and overburden drills. A total of 107 individual tests were conducted using 11 different hearing protectors. The results indicate that the amount of protection, which can vary significantly, is related either to the spectrum shape of the noise, or the C-weighted minus the A-weighted (C-A) value. This is consistent with other researchers that have used a similar approach,[1,2,3,4,5]. The field measured noise reductions were equivalent to the EPA NRR values when the **C-A** values were negative or approaching zero. When the C-A values increased, the measured noise reductions significantly decreased.

INTRODUCTION

In recent years, great emphasis has been placed on employee noise exposure. In controlling excessive noise, the most preferred solution has been to implement engineering controls on either the noise source, or the area where the employee is located. Typical

---

'Industrial Hygienist, Physical & Toxic Agents Division, Pittsburgh Safety and Health Technology Center.

examples would be machine enclosures, operator's booths, partial barriers, curtains, wall treatments, or combinations of these. These controls are considered permanent since they are intended to reduce or control the noise at all times, and for all personnel working in the particular area. However, noise controls of this type could become both complex and costly, depending on the situation.

As a result, there has been a general trend away from the more proven method of using engineering controls to the less proven technique of personal hearing protective devices. Personal hearing protectors are obviously easier to implement and considerably less expensive than engineering controls.

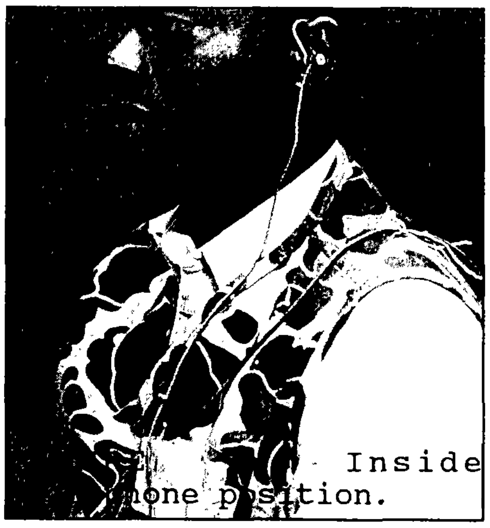
Because of this increase in usage, questions have been raised pertaining to their effectiveness, or more precisely, their effectiveness when worn in a working environment. Numerous articles technical papers have been written addressing this issues[6,7,8,9]. The general consensus is that hearing protector devices do not provide the attenuation claimed by their manufacturer.

This paper will attempt to answer the questions of HOW EFFECTIVE ARE HEARING PROTECTORS when they are being worn under normal working conditions and CAN THEIR EFFECTIVENESS BE PREDICTED?

The method used to investigate these questions was to physically measure the noise reduction of hearing protectors, using miniature microphones, and determine if a correlation existed between these results and the protectors advertised capabilities. It will be based on data obtained from both laboratory and field situations involving mining environments. The use of miniature microphones to evaluate hearing protectors is not a new approach. Several researchers have done this in the past with success[10,11,12].

METHODOLOGY

The instrumentation used in the evaluation was two (2) identical FM-wireless transmitting and receiving systems. Each transmitting system consisted of a miniature, l/4-inch dosimeter microphone connected to a pocket sized transmitter. Both transmitters were located on a vest, worn by the test subject. One of the systems utilized a miniature microphone, held in place with a plastic earpiece, under the earmuff next to one of the ear openings, figure 1. The other system, utilized a second miniature microphone that was taped to the outside of the earmuff, located on the same side as the inside microphone, figure 2. The microphones of both systems were acoustically matched.



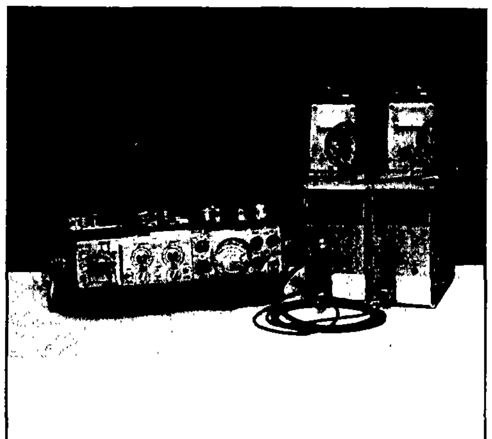


FIGURE 3- Data gathering system.

The corresponding receivers, which were located up to a distance of 500 feet and in line-of-sight, were connected to a two-channel tape recorder. This arrangement was considered the data gathering system, figure 3. Simultaneous tape recordings were made of both the outside and inside microphone locations, as the test subject worked.

By utilizing a wireless system, the test subjects were able to perform their normal work duties without the concern or danger of instrumentation cables impeding their movements. It also permits conducting measurements on operators of mobile equipment or workers who routinely travel by foot, or to monitor several areas within a building, such as mine preparation plants.

Unfortunately, the size of the microphones limited the evaluation, in that only circumaural (earmuff) type hearing protectors could be tested. In order to test the in-situ effectiveness of earplug protectors, other researchers have used a probe tube microphone inserted in the test subject's ear canal between the ear drum and the earplug protector[13]. This would have been both impractical and medically risky, while in a field environment. Furthermore, numerous researchers, examining non-mining, occupational environments, have consistently demonstrated degraded performance of earplug protectors when compared to the laboratory results[14,15,16,17,18,19]. The magnitude of degradation was dependent upon the type of earplug protector[14,16,18]. In addition to degraded attenuation, the variability increased substantially compared to laboratory evaluations[14,16,17,18]. Some of these tests yielded minimum attenuations, especially when projected to include at least 1 s.d.[14,17]. Calculating the protection afforded 84% of the population, based on the average attenuation and s-d., yielded amplification at a few frequencies. For the most part, the degradation for earplug protectors followed a trend similar to that for earmuffs [15,19]. In fact, some measurements yielded no attenuation for either type of protector [15]. When computing NRR values from field data on earplug protectors, it is not unusual to obtain negative NRR values. One study concluded that laboratory data better predicted field performance of earmuff protectors than earplugs [18]. Therefore, it is anticipated that the results and trends obtained for earmuff-type hearing protectors, can also be correlated to earplug protectors. However, the implementation of a good hearing conservation plan in conjunction with the use of personal hearing protection devices enhances the effectiveness of the HPDs [17].

METHODS OF EVALUATING HEARING PROTECTION DEVICES

At the present time the only nationally recognized method,for evaluating hearing protector devices is the American National Standards Institute (ANSI) Standard, S 12.6-1984 "Method For The Measurement of Real-Ear Protection of Hearing Protectors" [20]. It is a subjective test using human test subjects, under ideal laboratory conditions, to determine optimum real-ear-attenuation-at-threshold (REAT), for the following nine (9) specified one-third octave bands: 125,250,500,1000,2000,3150,4000,6300,8000 Hz.

Basically, the standard measures the hearing threshold of ten highly trained subjects, for both unoccluded (without hearing protector) and occluded (with hearing protector) conditions. The difference between the conditions is considered the hearing protector's attenuation capabilities. It is primarily an insertion loss measurement. The data is manipulated to yield an average and associated standard deviation (s.d.) for each of the nine test bands. These values are the hearing protectors REAT results.

The results are then incorporated into the Environmental Protection Agency (EPA), Noise Reduction Rating (NRR)[21] calculation which provides a single number estimate of the dBA noise reduction for that particular hearing protector. All hearing protectors sold in the United States are required by law to have their packages labeled with the calculated NRR value. The intent of the calculation was to develop a uniform method for the relative rank ordering of all hearing protectors, based upon their respective NRR values.

In our evaluation, four rating methods were used. Since the EPA NRR value is the only recognized numerical comparison available among all hearing protectors, we also included it as one of the rating methods.

The second method was the National Institute of Occupational Safety and Health's (NIOSH) calculation method #l, or LONG METHOD[22]. It is similar, in principle, to the EPA method in that it utilizes the manufacturer's advertized REAT results. It differs, however, in that it utilizes the actual noise spectrum levels and overall A-weighted noise level. It was designated as the PREDICTED NIOSH R-FACTOR, since the result is, in essence, a prediction of the hearing protectors effectiveness based on the manufacturer's REAT data.

The third method was again the NIOSH #l method, except that physically measured attenuation and s.d. results were substituted for the manufacturers REAT data. It was designated the MEASURED NIOSH R-FACTOR since the result is the actual measured protector' effectiveness.

The fourth, and final method was the arithmetic difference between the measured A-weighted noise level outside the protector and the measured A-weighted noise level inside the protector, after applying a 2 standard deviation (negative) adjustment to take into account the 95th percentile population.

A more detailed description of each method, including equations, can be found in Appendix A.

ANALYSIS

All tape recordings were analyzed for the noise spectra's linear dB content, using a a-channel real-time-analyzer (RTA), programmed for one-third octave band results. Both inside and outside microphone locations were analyzed simultaneously to eliminate any tracking errors. The laboratory evaluation recordings were analyzed at the nine (9) ANSI preferred one-third octave bands. Field evaluation recordings were analyzed for twenty-seven (27), one-third octave bands, from 25-10K Hz.

Analysis times varied, dependent upon the amount of taped data. Analysis of laboratory tests were conducted for the full duration of each individual test. For example, if a test was conducted for one (1) minute, that segment was analyzed for the full minute, and was considered one (1) sample.

Field evaluation tape recordings were approximately forty (40) minutes in length. There were occasions when the signal was interrupted by citizens band (CB) radios and interferences from large objects blocking the transmission path. When this occurred, that segment of tape was omitted from the analysis.

Each tape recording represented one test. It was generally divided into seven (7) equal length samples. The length of each sample varied between 2 to 5 minutes. The results were entered into a computer program, which computed the average attenuation and associated s.d. values at each test frequency for each test. The program also had the capability to utilize the resultant averages and s.d.'s to evaluate the hearing protectors, under the previously mentioned four methods.

LABORATORY TESTS

The purpose of conducting laboratory tests was two-fold. The first being, to determine if the physical measurement method and data gathering system used in the field portion of the study would yield similar attenuation and s.d. results as reported by the ANSI procedure. The second was to compare and evaluate the results of the four ratings methods utilized, to determine if any trends were evident.

Seven (7) volunteers from within the Physical & Toxic Agents Division were used as test subjects. They were not selected based on ANSI criteria of audiometric testing since this was purely a physical measurement. Subjective input from the test subjects was not needed.
Eleven (11) earmuff-type hearing protectors were evaluated (10) were worn in the over-the-head (OH) position and one (l) was worn in the behind-the-head (BH) position. New hearing

protectors were chosen for this evaluation since the results were to be directly compared to the ANSI values. No specific

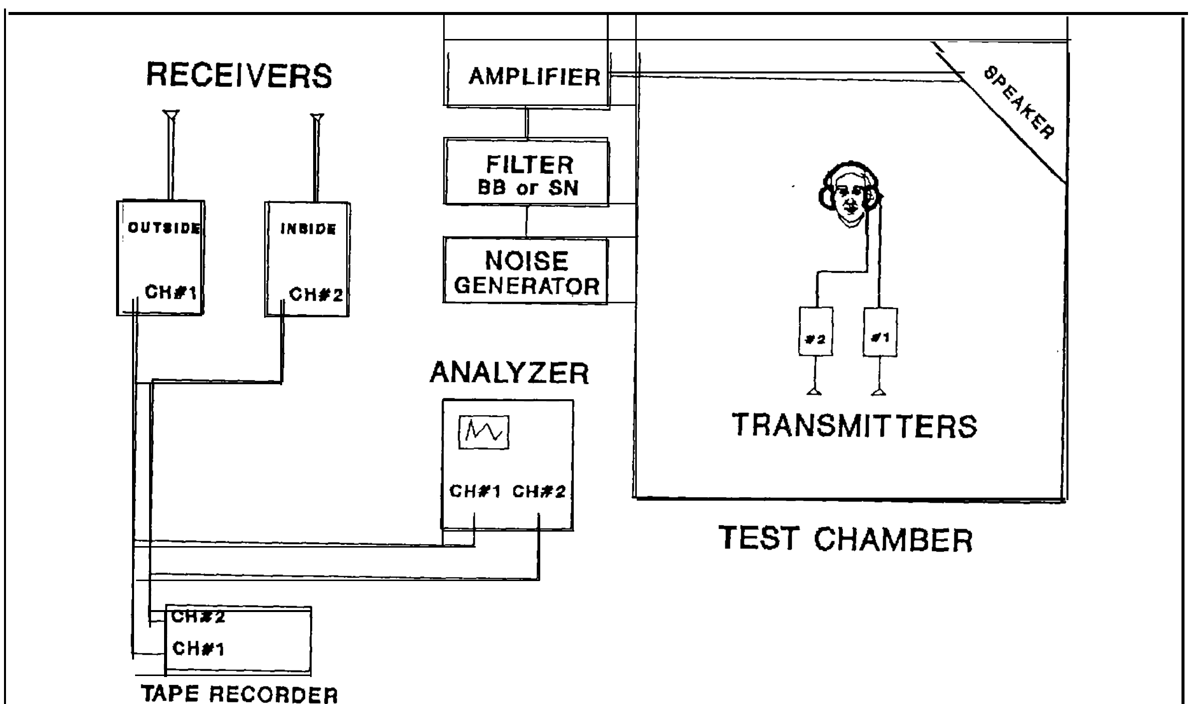


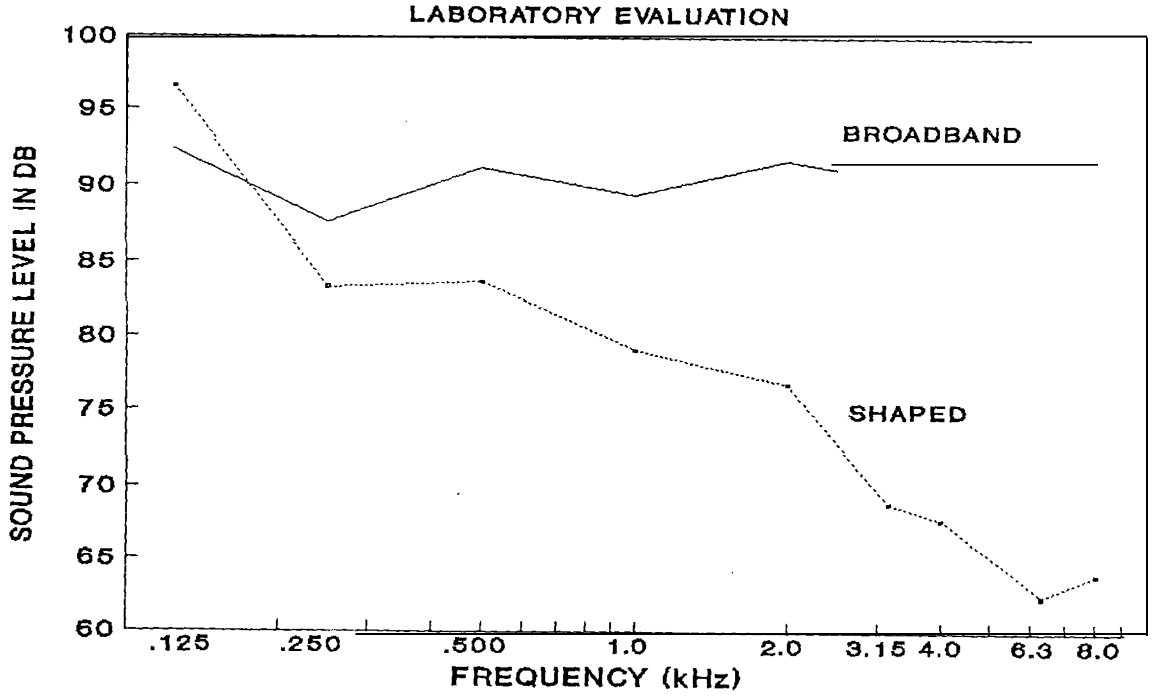
FIGURE 4 - SCHEMATIC OF LABORATORY SET-UP

instructions were given to the test subjects on fitting the protectors, except that the devices fit comfortably. The subjects were equipped with the transmitting portion of the data gathering system and seated inside a reverberant test chamber. None of the test subjects wore glasses during any testing session. Figure 4 is a schematic of the laboratory test set-up and instrumentation.

'In designing the laboratory tests, two (2) varying types of noise stimuli were used. The first was a flat, broadband (BB) spectrum exhibiting a very low (C-A) weighted value, (approaching 0). The second being a shaped noise (SN) spectrum with a large (C-A) weighted value, (approaching 10.0).

The broadband stimulus was electronically generated pink noise that was electrically filtered to yield a noise level of 90 dB in each one-third octave band between the frequency range of l00-8K Hz. The shaped stimulus was also filter generated noise, within the same frequency range. It corresponded to an average field spectrum compiled from past field noise investigations involving strip mining equipment. Figure 5, displays the two spectrums generated. Each noise spectrum had its own separate filter and

FIGURE 5 - BROADBAND & SHAPED SPECTRUMS
LABORATORY EVALUATION



was introduced into the test chamber via a speaker as a single noise source. Changing from the broadband to the shaped noise spectrum was accomplished by physically switching the appropriate noise filter output cable into the test chamber amplifying system.

Each test measurement was approximately one (l)-minute in duration with (3) repetitions each. This allowed for a maximum of 21 total tests per hearing protector for both the broadband and shaped noise stimuli. After each measurement, the subjects removed the hearing protectors from their ears and re-positioned them before the next measurement.

LABORATORY EVALUATION RESULTS

Figures 6 thru 16, (APPENDIX B), are graphical comparisons of the physically measured attenuation results to the advertized ANSI REAT data for each of the 11 hearing protectors. The results of each hearing protector are averaged for all test subjects as described in the ANSI standard.

The broadband results, essentially correspond to the REAT values (within 5 dB), in the frequency range of 500-8K Hz. The 125 and 250 Hz. results are not consistent with the REAT values. Generally, for these bands, the REAT values are larger.

The measured attenuation results of the shaped noise spectrum are nearly identical to the broadband data, in the frequency range of 125-2K Hz. There are significant differences above this range with the shaped spectrum yielding lower attenuation values.

The standard deviations, for each hearing protector, are comparable to the REAT results for both the broadband and shaped noise stimuli. This indicates the testing procedure was consistent and there was little variability between the test subjects.

The differences at the lower frequencies, for both noise stimuli, are comparable with the results of other researchers[23,24]. Their findings show.that during the REAT test, physiological noise produced by the inner ear's blood flow, and heart rate, is amplified by the presence of a hearing protector device. This amplification and masking raises the subjects minimum audible threshold in the occluded ear, at the lower frequencies.

The measured attenuation differences between the broadband and shaped noise stimuli are probably due to limitations of the inside data acquisition system's ability to accurately measure very low noise levels (<30 dB), in this frequency range. This was not considered to be a problem since the inside dBA noise level would be based on the entering predominant noise frequencies.

Table 1 lists the average results for the different rating methods for the broadband noise laboratory tests. These data were obtained by averaging across all test subjects. Generally, the rating method results are similar and indicate the hearing protectors performed closely to their published EPA NRR values. This is due to the following two reasons. The first being, broadband spectrum noise causes both the overall A and C-weighted noise levels to be essentially equal (as in the EPA NRR equation), with the dominating frequencies in the lK-8K range. The second, is that the frequencies that dominate the hearing protectors performance are also found in this same range, and have been shown to be comparable to the REAT values. Therefore, all the rating methods should be similar.

The PREDICTED NIOSH R-FACTOR values are highest because the ANSI REAT results at the higher frequencies are slightly larger than the physically measured results.

Table 2 lists the rating methods results of the shaped noise laboratory tests.

TABLE 1 - AVERAGE RESULTS FOR LABORATORY BROADBAND NOISE TESTS

HPD	SAMPLES	EPA NRR	PREDICTED NIOSH R-FACTOR	MEASURED NIOSH R-FACTOR	MEASURED DBA REDUCTION	MEASURED (C-A)
A	18	26.0	29.1	25.4	27.7	0.2
B	22	26.0	29.3	28.0	29.5	0.2
C	19	29.0	31.3	24.9	27.3	0.2
D	21	24.0	26.5	19.0	20.7	0.2
E	18	22.0	25.3	20.9	22.7	0.2
F	19	19.0	21.6	24.1	25.9	0.2
G	19	25.0	28.1	19.6	21.4	0.1
H	18	23.0	24.5	15.1	16.1	0.2
I		25.0	27.4	20.9	21.8	0.1
J	21	19.0	21.6	16.4	18.0	0.2
K	18	24.0	27.9	23.5	25.6	0.2
MEAN		23.8	26.6	21.6	23.3	0.2
s.d.		3.0	3.1	4.0	4.2	0.04

TABLE 2 - AVERAGE RESULTS FOR LABORATORY SHAPED NOISE TESTS

		EPA	PREDICTED NIOSH	MEASURED NIOSH	MEASURED DBA	MEASURED
A	18	26.0	20.4	12.9	12.2	10.6'
B	19	26.0	21.5	16.9	16.7	10.4
C	19	29.0	23.0	12.5	12.2	10.6
D	21	24.0	18.3	5.9	5.3	10.5
E	19	22.0	13.0	7.1	6.8	10.6
F	19	19.0	11.1	11.7	11.8	10.4
G	19	25.0	17.9	6.7	5.8	10.4
H	18	23.0	11.5	1.5	1.4	10.8
I	'22	25.0	14.9	7.6	7.7	10.8
J	21	19.0	10.4	1.9	1.2	11.2
K	18	24.0	13.5	8.7	8.6	10.9
MEAN		23.8	16.0	8.5	8.2	10.7
s.d.		3.0	4.5	4.7	4.8	0.3

These results, based on the use of a shaped spectrum indicate the hearing protectors do not perform as advertized. The results are significantly lower than the EPA NRR value. The reason for such large differences is the shaped noise spectrum causes the overall A and C-weighted noise levels to be significantly different (unlike the EPA NRR formula), with the dominating frequencies now in the 125-1K Hz range. The REAT attenuation values of hearing protectors in this range are usually lower than the higher frequency attenuation values. It has been previously demonstrated that these values are in general larger than what is actually measured. Therefore, the rating methods will yield results that are less than the EPA NRR values. The average PREDICTED NIOSH R-FACTOR method result is still somewhat larger because it utilizes the advertised REAT values.

FIELD EVALUATIONS

Field evaluations were conducted at ten (10) different mining locations. They were evenly divided between Metal/Nonmetal and Coal operations. All of the locations were surface operations, with the exception of one, which was an underground limestone mine. The same eleven (11) earmuff-type hearing protectors that were evaluated in the laboratory phase were re-evaluated here.

The machine operators were equipped with the data gathering systems. After all systems were properly calibrated, the machine operator was given a hearing protector that he placed on himself. As in the laboratory evaluation, the only instruction was to fit the protector so that it felt comfortable. This was considered a subject fit an a real world condition. He was then instructed to begin a normal days work. Via the telemetric link, simultaneous tape recordings were made for a period of approximately 40-minutes of both the inside and outside noise levels. The taping period consisted of both operational and idle work modes. Constant monitoring of the data gathering system and taping was conducted to assure proper operation.

The types of equipment and occupations studied are summarized in Table 3.

TABLE 3 - CATEGORIES AND DISTRIBUTION OF EQUIPMENT USED FOR FIELD STUDIES

	# OF STUDIES
MOBILE SURFACE EQUIPMENT:	
1. Bulldozer operator	4
2. Front-End-Loader operator	6
3. Overburden Drill operator	3
4. Overburden Drill helper	3
5. Dragline operator	1
6. Dragline oiler	1
7. Grader operator	1
8. Portable crusher operator	1
STATIONARY SURFACE EQUIPMENT:	
1. Crusher operator	1
2. Tipple operator	2
3. Panel operator	1
UNDERGROUND EQUIPMENT:	
1. Face Drill operator	1
2. Load-Haul-Dump operator	1

FIELD EVALUATION RESULTS

Figures 17 thru 27, (APPENDIX B), are the average field measured attenuation and s.d. results for the 11 hearing protectors evaluated. These results are similar to those from the shaped noise laboratory data at the lower and higher frequency bands. In the mid-frequency bands, the results are sometimes less than the laboratory data. The s.d.'s have generally increased. This was expected, since this portion of the evaluation was conducted on varying types of subjects, conditions, and equipment. Table 4 lists the average rating methods results for the field evaluations.

TABLE 4 - AVERAGE RESULTS FOR FIELD EVALUATION OF HEARING PROTECTORS

HPD	TESTS		EPA NRR	PREDICTED NIOSH R-FACTOR	MEASURED NIOSH R-FACTOR	MEASURED DBA REDUCTION	MEASURED (C-A)
A	8	mean	26.5	26.4	18.3	17.4	4.5
		s.d.	0.5	4.1	8.3	9.2	4.7
B	4	mean	26.0	24.9	18.8	17.6	6.7
		s.d.	0.0	4.8	7.1	7.6	5.7
C	10	mean	28.5	26.9	18.0	18.1	6.3
		s.d.	0.5	2.8	6.1	5.4	4.1
D	8	mean	22.1	19.8	13.8	12.3	5.9
		s.d.	1.5	1.2	6.1	5.5	2.8
E	8	mean	21i9	20.2	14.5	13.0	5.4
		s.d.	0.3	5.2	6.8	7.7	4.9
F	7	mean	19.0	17.7	18.3	16.7	5.3
		s.d.	0.0	4.4	5.8	5.7	3.7
G	11	mean	23.9	20.7	14.2	12.9	7.6
		s.d.	1.0	3.7	5.7	5.9	4.4
H	13	mean	23.0	16.7	14.7	15.2	8.4
		s.d.	0.0	5.1	6.8	5.8	4.4
I	16	mean	24.8	20.6	13.1	14.3	7.7
		s.d.	0.4	5.5	8.9	8.1	5.0
J	8	mean	18.6	16.8	14.0	13.3	6.6
		s.d.	0.5	3.0	6.9	6.6	4.0
K	14	mean	23.1	18.5	14.6	13.9	8.2
		s.d.	1.6	5.2	9.1	8.3	4.4
ALL	107	mean	23.6	20.5	15.2	14.7	6.9
		s.d.	2.8	5.5	7.6	7.3	4.6

The results of this table indicate the MEASURED DBA REDUCTION values are significantly lower than the advertized EPA NRR values. The average advertised EPA NRR value of the ll-hearing protectors was 23.6. The average MEASURED DBA REDUCTION value of 14.7, and the MEASURED NIOSH R-FACTOR value of 15.2 are both comparable. The average PREDICTED NIOSH R-FACTOR value was 20.5, or 3.1 dB less than the EPA NRR value. This was expected because of the physiological noise effect, previously mentioned. The average C-A value was 6.9 +/- 4.6 dB.

The large s.d.'s of the individual earmuffs reported for the MEASURED NIOSH R-FACTOR and MEASURED DBA REDUCTION results indicate there is significant variability within hearing protectors. The majority of variability appears to be due to the C-A values. This is evident in the C-A s.d.'s. Based on the laboratory tests, hearing protector effectiveness is a function of spectrum shape. To better illustrate this point, the data from this table has been separated into similar C-A values and listed in table 5. The results indicate that as the C-A value increases, the measured effectiveness of hearing protectors decreases. Due to the smaller C-A s.d.'s, the corresponding rating method s.d.l s now represent a more realistic variability between hearing protector and test subject fit.

TABLE 5 - AVERAGE RESULTS FOR FIELD EVALUATION OF HEARING PROTECTORS AS A FUNCTION OF C-A VALUE RANGES

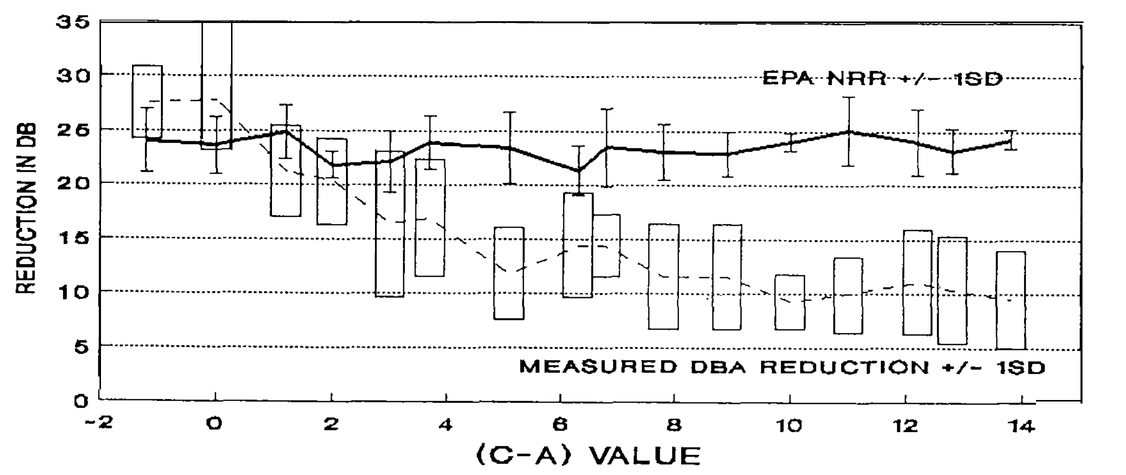
TESTS		EPA NRR	PREDICTED NIOSH R - FACTOR	MEASURED NIOSH R-FACTOR	MEASURED DBA REDUCTION	MEASURED (C-A)
7	mean	24.0	31.1	27.5	27.6	-1.2
	s . d	3.0	2.0	3.4	3.3	0.1
5	mean	23.6	28.5	29.2	27.8	0.0
	s . d	2.7	2.7	4.5	4.6	0.2
4	mean	25.3	27.8	22.0	22.4	1.2
	s.d.	2.6	2.1	4.3	3.9	0.3
3	mean	23.3	23.2	21.3	20.5	2.0
	s.d.	0.9	2.2	4.8	4.5	0.3
8	mean	22.1	21.4	17.3	16.4	3.0
	s . d	2.9	3.3	6.0	6.7	0.2
11	mean	23.9	22.4	18.7	16.9	3.7
	s.d.	2.5	2:6	4.3	5.4	0.3
9	mean	23.4	20.6	12.1	11.8	5.1
	s.d.	3.3	3.8	4.2	4.2	0.2
4	mean	27.3	18.6	16.9	14.4	6.3
	s.d.	2.3	1.4	4.8	4.8	0.2
4	mean	23.5	19.9	14.0	14.4	6.8
	s.d.	3.6	4.3	2.8	2.9	0.3
7	mean	23.1	19.2	13.4	11.6	7.8
	s . d	2.6	3.3	5.4	4.8	0.3
10	mean	22.9	18.7	11.1	11.6	8.9
	s.d.	2.1	2.3	5.9	4.8	0.3
3	mean	24.0	19.2	9.9	9.3	10.0
	s.d.	0.8	0.3	3.2	2.5	0.2
7	mean	25.1	19.6	9.4	10.0	11.0
	s . d	3.2	3.7	4.6	3.5	0.3
8	mean	24.0	17.5	12.2	11.1	12.2
	s.d.	3.1	4.1	5.6	4.8	0.2
IO	mean	23.2	15.5	10.5	10.4	12.8
	s.d.	2.1	2.3	5.4	4.9	0.2
7	mean	24.3	11.8	8.9	9.5	13.8
	s.d.	0:9	3.2	4.7	4.5	0.2

A comparison of the EPA NRR and the MEASURED DBA REDUCTION values, from the table, are shown in figure 28 for each of the C-A ranges. Included are the +/- 1 s.d. data points.

ANALYSIS OF RESULTS

Results of both the laboratory and field evaluations indicated that the advertized EPA NRR value does not provide an accurate

FIGURE 28 - FIELD COMPARISON OF EPA NRR AND MEASURED DBA REDUCTION VALUES



estimate of a hearing protector's effectiveness in all noise environments. The MEASURED DBA REDUCTION method, however, did provide an accurate and simple method to describe protector effectiveness, when the MEASURED NIOSH R-FACTOR is used as the basis for comparison. In addition, it was determined that a hearing protectors effectiveness was also a function of a noise spectrums C-A value.

Utilizing these three variables, a procedure was devised to relate the actual effectiveness of a hearing protector to the EPA NRR value using a CORRECTION FACTOR. This correction can be subtracted from the EPA NRR value to obtain an estimate of the actual performance of the hearing protector.

This can be expressed in the algorithm:
FACTOR

$$[DBA(reduction) - EPA\ NRR] = Y + X(C-A) \quad (5)$$

where: [DBA(reduction) - EPA NRR] = amount of measured effectiveness compared to the advertised EPA NRR value. It is designated as the CORRECTION FACTOR.

Y = Y axis intercept

x = Slope of regression line

C-A = Description of spectrum shape

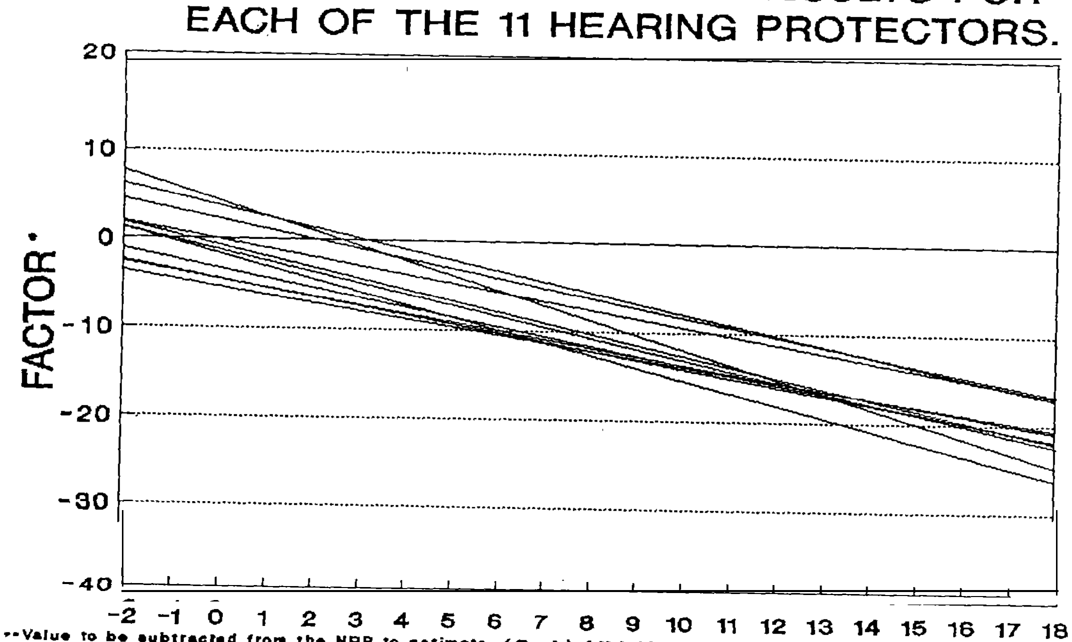
Table 6 lists the field calculated CORRECTION FACTOR regression equations for the 11 hearing protectors and their corresponding R-squared values, again for a 95% confidence limit.

TABLE 6 - CORRECTION FACTOR REGRESSION EQUATIONS FOR FIELD RESULTS

HPQ	FIELD TESTS	EPA NRR	CORRECTION FACTOR = Y + X(C-A)	R-SQUARE
A	8	26	= -5.27 - 0.85(C-A)	0.19
B	4	26	= -0.55 - 1.19(C-A)	0.81
C	10	29	= -4.29 - 0.97(C-A)	0.54
Q	8	24	= -4.44 - 0.91(C-A)	0.17
E	8	22	= -1.56 - 1.37(C-A)	0.72
F	7	19	= 3.83 - 1.16(C-A)	0.56
G	11	25	= -3.17 - 1.04(C-A)	0.52
H	13	23	= 0.13 - 0.94(C-A)	0.50
I	16	25	= -1.29 - .1.19(C-A)	0.54
J	8	19	= 2.03 - 1.11(C-A)	0.47
K	14	24	= 4.29 - 1.64(C-A)	0.80
COMBINED	107	23.6	= -1.18 - 1.11(C-A)	0.46

The results of the table show the regression slopes are all negative, indicating that, as the C-A value increases, the hearing protectors effectiveness decreases. The Y-intercept is centered around 0. Figure 29 graphically depicts the individual equations.

FIGURE 29 - FIELD REGRESSION RESULTS FOR EACH OF THE 11 HEARING PROTECTORS.



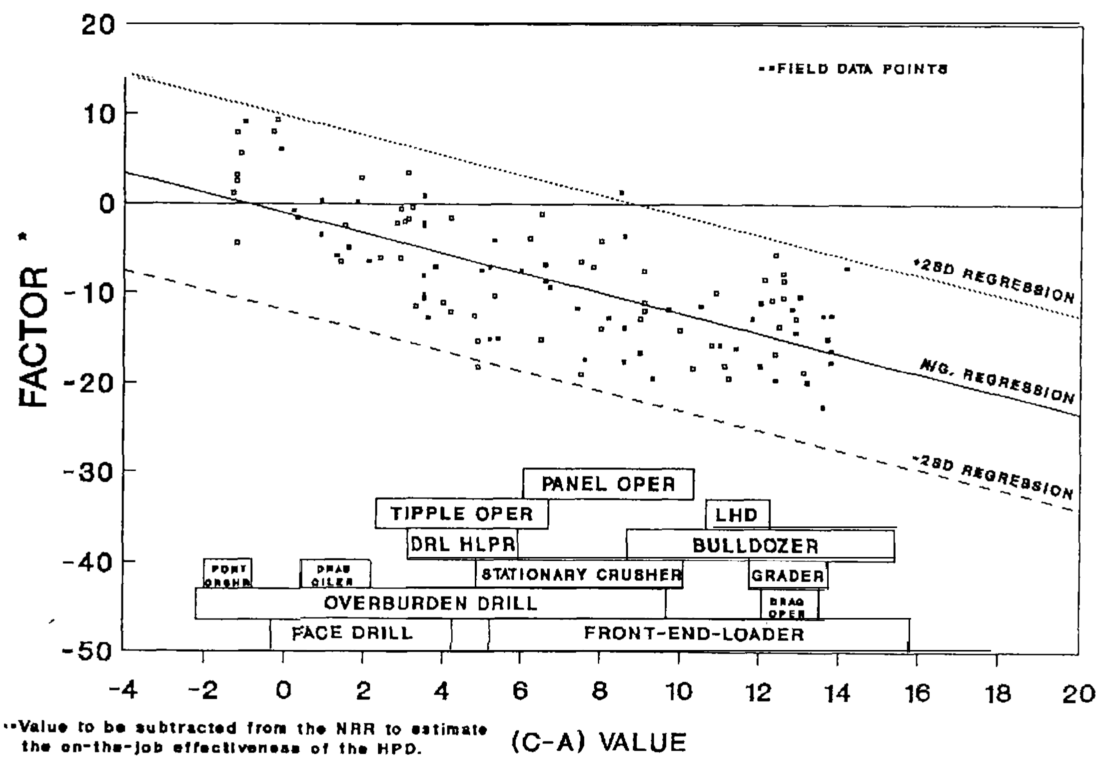
**Value to be subtracted from the NRR to estimate the effectiveness of the HPD, based on the averaged field data for that particular HPD.

It is apparent from the figure the regression lines are not parallel. Many of them intersect each other. This is an indication that the hearing protectors do not perform uniformly 'or according to their NRR rating. If that were the case, the higher rated protectors would outperform the lower rated ones.

Figure 30 is a plot of the regression line through the data set, along with the upper and lower bounds for the 95th percentile. The data fit within 95% of these bounds. Included in the figure are +/- 2 s.d. ranges for the C-A data, along the X-axis, for the field equipment encountered. The most apparent feature is the range of variation at each C-A value. For example, at a C-A value of 7, the CORRECTION FACTOR ranges from $2 to a -20. This indicates a hearing protectors effectiveness could fall within a range of 22 dBA.

The range of C-A values for several of the equipment types complicates matters further. For example, front-end-loaders have a C-A value range of approximately 5 to 15.7. Taking into account the best (+2 s.d.) and the worst (-2 s.d.) case conditions, based on the regression lines, a +5 or -30 dB could be applied to a hearing protectors NRR value. This is a significant difference.

FIGURE 30 - FIELD FACTOR VALUES



It should be noted that the EPA, in principle, acknowledges that low frequency noise has an effect on HPD performance. The EPA suggests when a noise environment is dominated by low frequency noise (i.e., 500 Hz. or less), the NRR value be subtracted from the overall C-weighted noise level rather than the A-weighted noise level. This value is then considered to be the approximated A-weighted noise level that is entering the wearers ear. As has been described earlier, low frequency noise causes the C-weighted noise level to be larger than the A-weighted level. Thus, when the NRR is subtracted from the C-weighted level the resultant value will be larger than if the A-weighted level were used. This in effect reduces the NRR value by a factor equivalent to the C-A value.

EXAMPLE:
Where:
NRR = EPA NRR value of HPD
dbAout = A-weighted outside level
dBCout = C-weighted inside level
dbAin = A-weighted inside level

NRR = 20
dbAout = 90
dbCout = 100
dbAin = 70

CASE #l:
Assume the predominant noise is above 500 Hz.

(dbAout - NRR) = approximated inside A-weighted level
90 - 20) = 70 dbAin

CASE #2:
Assume the predominant noise is below 500 Hz.)

(dbCout - NRR) = approximated inside A-weighted level
(100 - 20) = 80 dbAin

In CASE #l, the approximated dbAin noise level is 70 dBA and the HPD retains its 20 NRR value. However, in CASE #2, the approximated dBAin noise level is now 80 dBA or 10 dBA higher. In essence, the NRR value was reduced by 10 dBA, which is equivalent to the C-A value for this example.

The comparison of this EPA procedure to the average field regression line results is comparable.
It can be seen that diesel equipment, including dozer, front-end-loader, dragline, grader, and load-haul-dump vehicles exhibit primarily high C-A values, centered around 11.9. This was expected since diesel engines are known to generate low frequency noise. The average drilling equipment is found in the low C-A value range of 3.5. This was also expected since drills generate

high frequency noise due to the drill steel impacting on internal chuck assemblies.

All of these results indicate that hearing protector effectiveness is primarily a function of spectrum shape. Determining the C-A value for a particular piece of equipment will sufficiently describe that equipment's frequency content.

SUMMARY

The results of this evaluation have shown that the protection provided by a hearing protector varies, depending for the most part on the type of noise spectrum present in the mining environment. They attenuate best at the higher frequencies. Lower frequency noise is not as easily attenuated because of inherent physical characteristics such as frequency wavelength and materials of construction. It has been demonstrated that subjective ANSI REAT attenuation results at 125 and 250 Hz., generally over-estimate the hearing protectors effectiveness when compared to physically measured attenuations. This anomaly results from the masking of the test subjects occluded threshold of hearing by physiologically generated noise. The physically measured attenuations for frequencies above 250 Hz. better approximate the ANSI REAT results. The over-estimation in the first two ANSI test bands causes a problem when incorporating these values into the PREDICTED NIOSH 61 method formula, especially when the spectrum used is dominated by low frequency noise. The resultant value significantly over-estimates the hearing protectors advertized NRR value when compared to both the MEASURED NIOSH #l, and DBA REDUCTION values. However, when a predominately high frequency spectrum is substituted into the same formula, the PREDICTED NIOSH #l resultant value becomes essentially equal to, or slightly greater than the advertized NRR value. It also corresponds well with both the MEASURED NIOSH #l and DBA REDUCTION results.

The numerical difference between the physically measured dBA reduction level and the EPA NRR value is considered to be an adjustment or CORRECTION FACTOR value. Utilizing both the C-A and CORRECTION FACTOR values, a relationship was developed which shows that as the C-A value increases, the effectiveness of the hearing protectors decreases. The equation derived is:

$$\text{CORRECTION FACTOR} = -1.18 - 1.11(C-A)$$

This is an "average" relationship for the hearing protectors evaluated in the field evaluation. Unfortunately, based on the results from figures 29 and 30, the amount of effectiveness varied significantly among the protectors. It was demonstrated that for any C-A value, the predicted hearing protector effectiveness, for a 95% confidence limit, lie within a 22 db range. The range of C-A values for different equipment types also varied significantly and compounded the prediction even further.

Attempting to predict a hearing protectors performance with a great degree of certainty appears to be minimal. The variability of the ANSI REAT results for hearing protectors and wearer fit are too numerous to quantify and control. The only valid conclusion that can be stated is that hearing protector effectiveness cannot be described by a single rating value, and is predominantly dependent upon the noise environments spectrum shape.

Variables such as head and jaw movement, sweating, glasses, long hair, headband tension, and size of the hearing protector were not investigated in the evaluation. Several papers have been published which explored these areas [25, 26]. Their results indicate that hearing protector performance could be increased by being aware of how noise leaks can occur and taking the time to correct these deficiencies.

APPENDIX A

The following is a listing of the numbering designations used throughout all 4 methods.

Subscript	Frequency
j=l	125 Hz
2	250 "
3	500 "
4	1000 "
5	2000 "
6	3150 "
7	4000 "
8	6300 "
9	8000 "

METHOD #l: EPA NRR CALCULATION

The EPA NRR is a numerical value which is intended to approximate the amount of noise reduction anticipated from wearing a particular hearing protector. It utilizes the manufacturers advertized ANSI REAT results, it assumes noise levels of 100 dB per test band, and it subtracts an additional 3 dB for unknown spectral differences. The amount of protection is based on the "assumed overall dBC noise level".

The basic equation is:

$$EPANRR = dBA(out)-dBA(in) \qquad (1)$$

Where :

dBC(out)=Overall C-weightednoise level outside the HPD.
dBA(in) =Overall A-weightednoise level inside the HPD.

$$dBc(out) = 10LOG\left[\sum_{j=1}^{5} 10^{(L_j+C_j/10)} + 10^{(L_7+C_7/10)} + 10^{(L_9+C_9/10)}\right] \qquad (1a)$$

$$dBA(in) = 10LOG\left[\sum_{j=1}^{5} 10^{(Q_j/10)} + 10^{(Q_6/10)} + 10^{(Q_7/10)}\right] \qquad (1b)$$

Where:

$$Q_j = L_j + A_j - ATTN_j + 2SD_j$$
$$Q_6 = L_7 + A_7 + [(ATTN_6 + ATTN_7)/2] + SD_6 + SD_7$$
$$Q_7 = L_9 + A_9 + [(ATTN_8 + ATTN_9)/2] + SD_8 + SD_9$$

Where:
L,=outsidenoise level for the jth frequency band.
A,=A-weighted correction for the jth frequency band.
ATTNj=ANSIAttenuation value for the jth frequency band.
SO,=ANSI Standard Deviation value for the jth frequency band.

When equation (1) is used according to the EPA policy, the term (Loj) is equal to 100 dB per test band. This in turn forces the term (dBCo), or equation (la), to become a constant value equal to 107.9 dBC.

APPENDIX A

This calculation is basically describing a hearing protectors performance when worn in a noise environment that produces a flat spectral shape. It would be very difficult to find a real-life work environment which exhibits this type of continual frequency distribution.

METHOD #2: PREDICTED NIOSH #l or LONG METHOD CALCULATION

This method is considered a more precise calculation to predict the amount of noise reduction from wearing a particular hearing protector. Like the NRR calculation, the NIOSH #l method also uses the manufacturers advertized ANSI REAT results. However, they differ in that the NIOSH method utilizes the actual noise spectrum and overall A-weighted noise level, rather than the "assumed" overall C-weighted noise level. In this form, it is a "PREDICTION" calculation.

Its basic equation is:

$$PREDICTED\ NIOSH\ R\text{-}FACTOR = dBA(out) - dBA(in) \qquad (2)$$

Where:

dBA(out)=Overall A-weightednoise level outside the HPD.
dBA(in)=Overall A-weightednoise level inside the HPD.

$$dBA(out) = 10LOG\left[\sum_{j=1}^{5} 10^{(L_j+A_j/10)} + 10^{(L_7+A_7/10)} + 10^{(L_9+A_9/10)}\right] \qquad (2a)$$

$$dBA(in) = 10LOG\left[\sum_{j=1}^{5} 10^{(Q_j/10)} + 10^{(Q_6/10)} + 10^{(Q_7/10)}\right] \qquad (2b)$$

Where:

$$Q_j = L_j + A_j - ATTN_j + 2SD_j$$
$$Q_6 = L_7 + A_7 + [(ATTN_6 + ATTN_7)/2] + SD_6 + SD_7$$
$$Q_7 = L_9 + A_9 + [(ATTN_8 + ATTN_9)/2] + SD_8 + SD_9$$

Where:

L_j=*outside noise level for the jth frequency band.*
A_j=*A-weighted correction for the jth frequency band.*
$ATTN_j$=*ANSI Attenuation value for the jth frequency band.*
SD_j=*ANSI Standard Deviation value for the jth frequency band.*

A drawback to using this method is that on-site octave band noise analysis must be done. This entails using more sophisticated equipment other than a standard sound level meter (SLM) or personal noise dosimeter.

APPENDIX A

METHOD #3: MEASURED NIOSH #l CALCULATION

This is identical to method #2, except that physically measured hearing protector attenuation and s.d. results are substituted into equation (2b) for the manufacturers data.

Its basic equation is:

$$MEASVREDNIOSHR\text{-}FACTOR = dBA(out) - dBA(in) \qquad (3)$$

Where:

dBA(out)=Overall A-weighted noise level outside the HPD.
dBA(in)=Overall A-weightednoise level inside the HPD.

$$dBA(out) = 10LOG\left[\sum_{j=1}^{5} 10^{(L_j+A_j/10)} + 10^{(L_7+A_7/10)} + 10^{(L_9+A_9/10)}\right] \qquad (3a)$$

$$dBA(in) = 10LOG\left[\sum_{j=1}^{5} 10^{(Q_j/10)} + 10^{(Q_6/10)} + 10^{(Q_7/10)}\right] \qquad (3b)$$

Where:,

$$Q_j = L_j + A_j - Msrd\ ATTN_j + 2Msrd\ SD_j$$
$$Q_6 = L_7 + A_7 + [(Msrd\ ATTN_6 + Msrd\ ATTN_7)/2] + Msrd\ SD_6 + Msrd\ SD_7$$
$$Q_7 = L_9 + A_9 + [(Msrd\ ATTN_8 + Msrd\ ATTN_9)/2] + Msrd\ SD_8 + Msrd\ SD_9$$

Where:

L_j=outside noise level for the jth frequency band.
A_j=A-weighted correction for the jth frequency band.
Msrd $ATTN_j$=Measured Attenuation value for the jth frequency band.
Msrd SD_j=Measured Standard Deviation value for the jth frequency band.

The results of this method is the standard by which the other three methods will be compared against.

METHOD #4: PHYSICALLY MEASURED DBA NOISE REDUCTION

This method is the arithmetic difference between the A-weighted noise level measured inside and outside of a hearing protector.

The basic equation is:

$$MEASURED\ dBA\ REDUCTION = [dBA(out) - dBA(in)] - 2SD \qquad (4)$$

Where:

dBA(out)=AverageMeasured outside A-weightednoise level (4a)
dBA(in)=AverageMeasuredinsideA-weightednoise level (4b)
SD=StandardDeviation for number of samples.

This equation accounts for several important variables, in one simple noise measurement. It accounts for the hearing protectors attenuation values, the noise spectrum shape, and the fit of the protector on the test subject, including noise leaks.
The decision to reduce the average attenuation value by 2 s.d.'s was used to include 95 percent of the population.

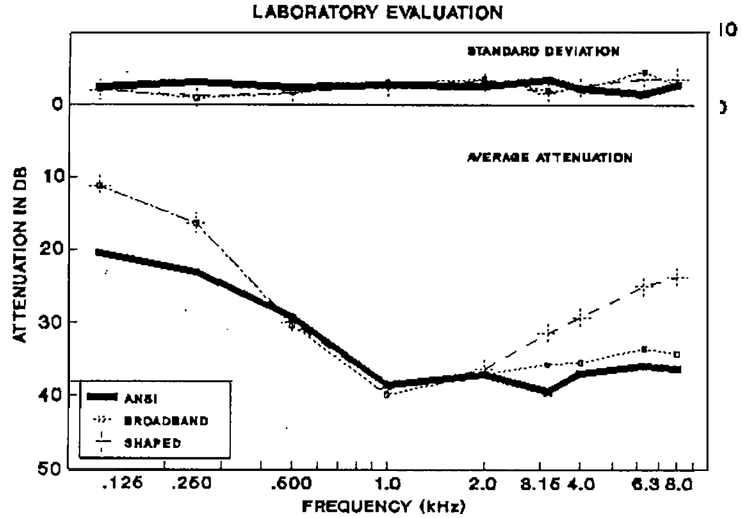


FIGURE 6 - HPD "A" ATTENUATION RESULTS
LABORATORY EVALUATION

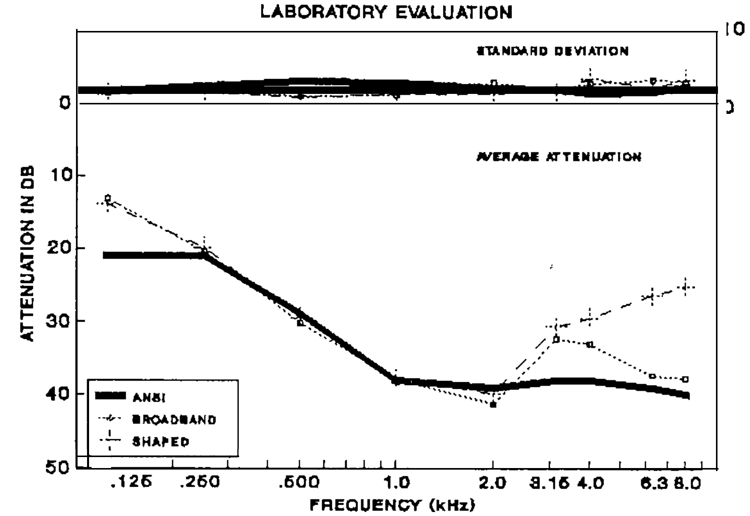


FIGURE 7 - HPD "B" ATTENUATION RESULTS
LABORATORY EVALUATION

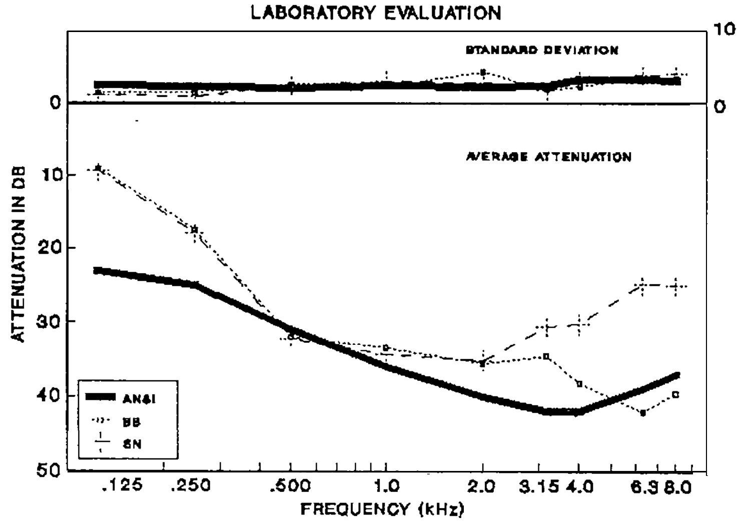


FIGURE 8 - HPD "C" ATTENUATION RESULTS
LABORATORY EVALUATION

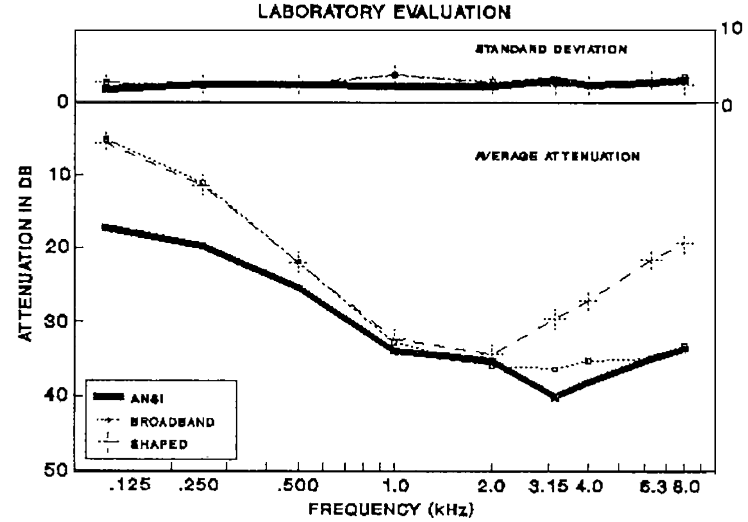


FIGURE 9 - HPD "D" ATTENUATION RESULTS
LABORATORY EVALUATION

FIGURE 10 - HPD "E" ATTENUATION RESULTS
LABORATORY EVALUATION

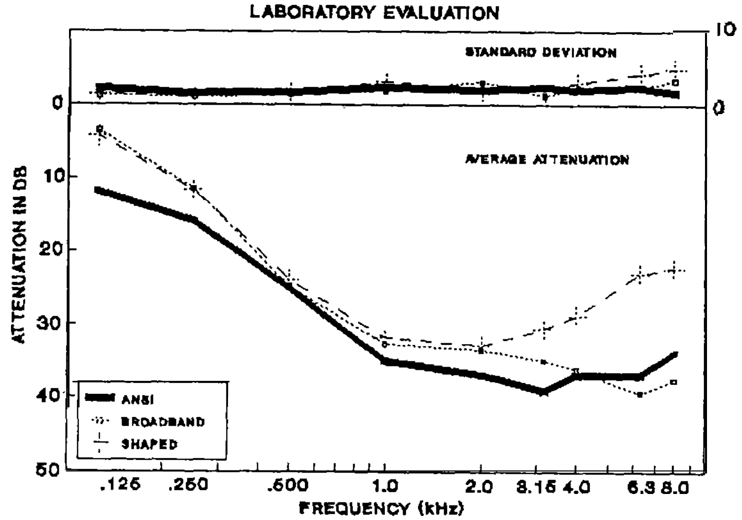


FIGURE 11 - HPD "F" ATTENUATION RESULTS
LABORATORY EVALUATION

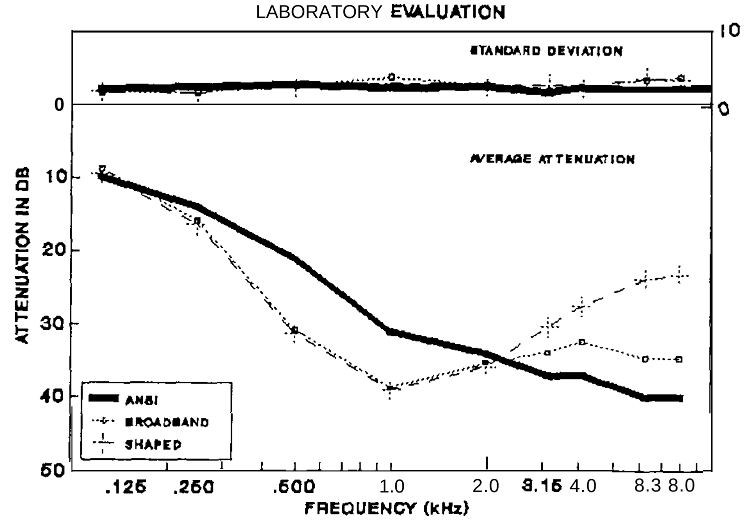


FIGURE 12 - HPD "G" ATTENUATION RESULTS
LABORATORY EVALUATION

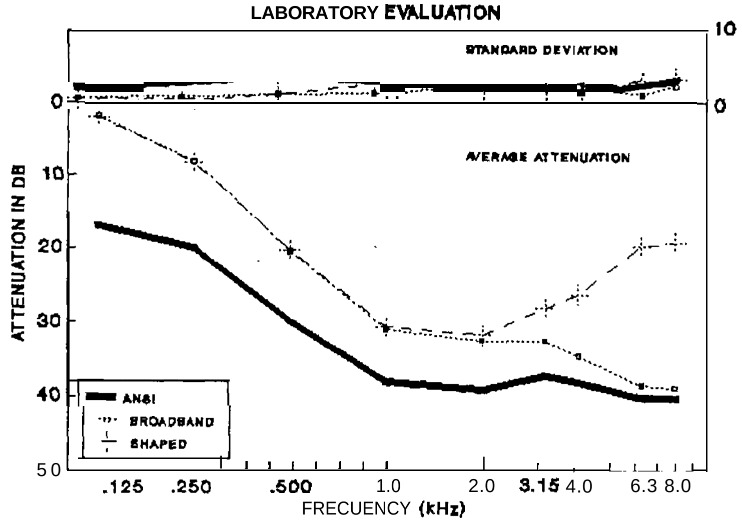


FIGURE 13 - HPD "H" ATTENUATION RESULTS
LABORATORY EVALUATION

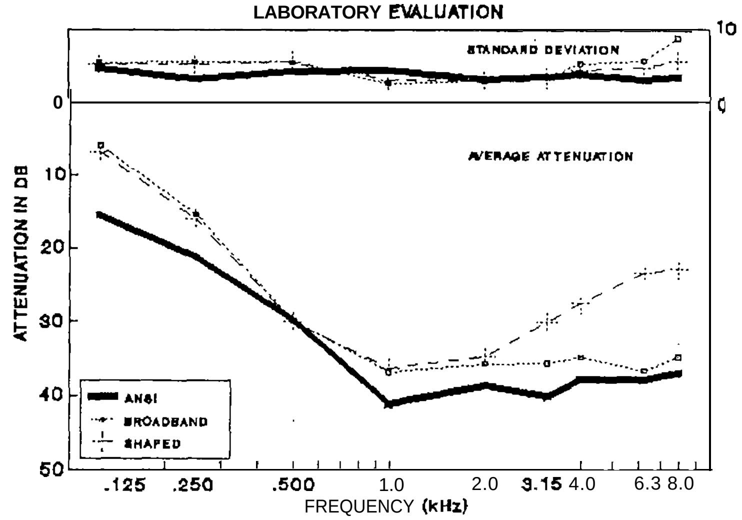


FIGURE 14 - HPD "I" ATTENUATION RESULTS

LABORATORY EVALUATION

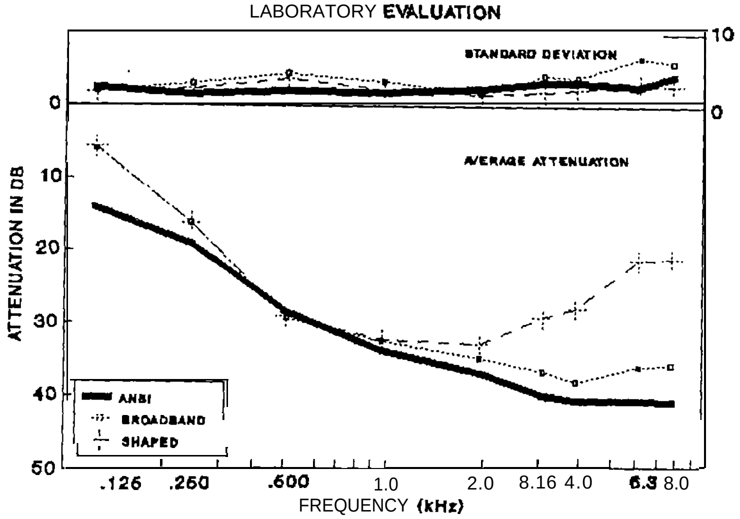


FIGURE 15 - HPD "J" ATTENUATION RESULTS

LABORATORY EVALUATION

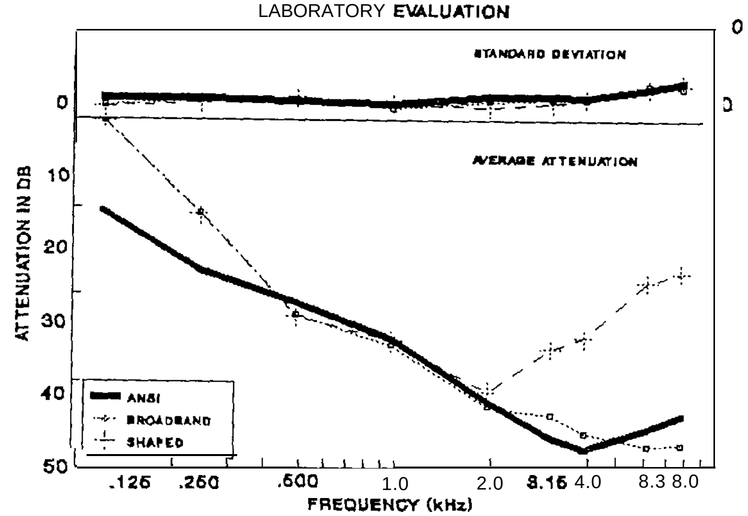


FIGURE 16 - HPD "K" ATTENUATION RESULTS

LABORATORY EVALUATION

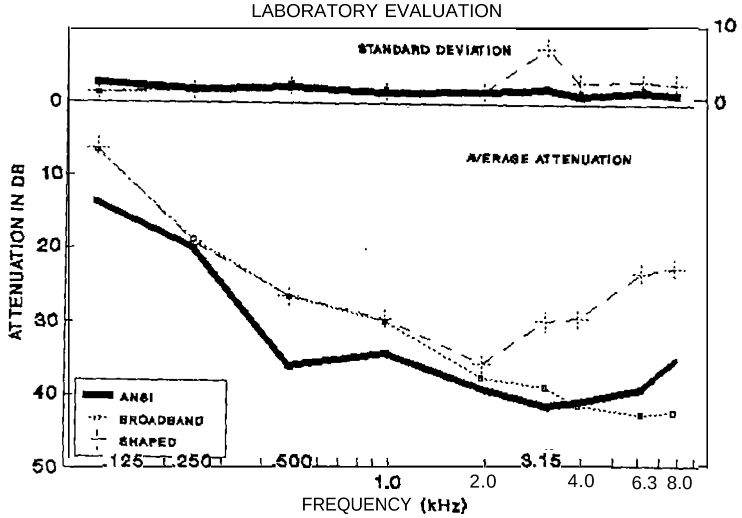


FIGURE 17 - HPD 'A' ATTENUATION RESULTS
FIELD EVALUATION

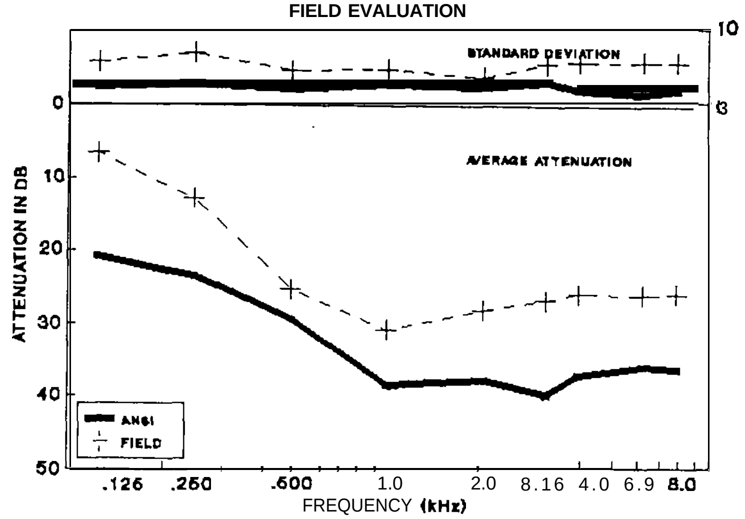


FIGURE 18 - HPD "B" ATTENUATION RESULTS
FIELD EVALUATION

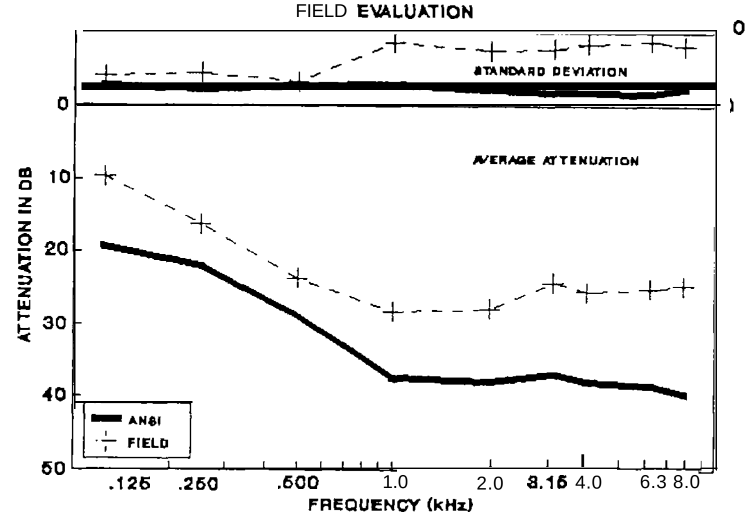


FIGURE 19 - HPD "C" ATTENUATION RESULTS
FIELD EVALUATION

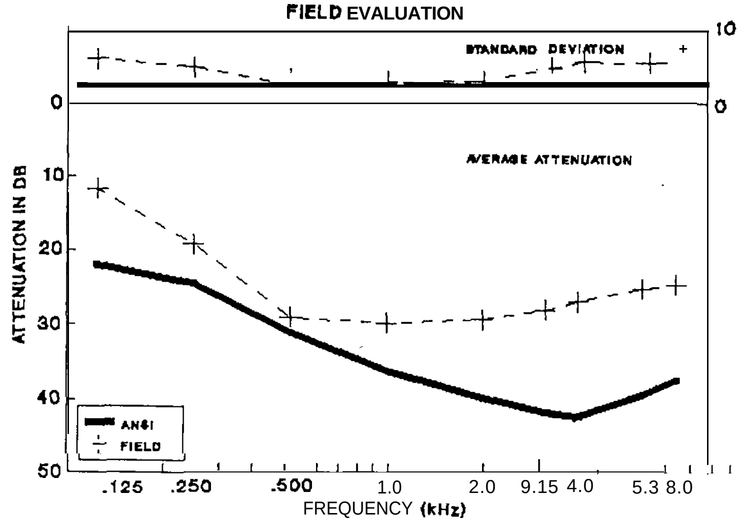


FIGURE 20 - HPD "D" ATTENUATION RESULTS
FIELD EVALUATION

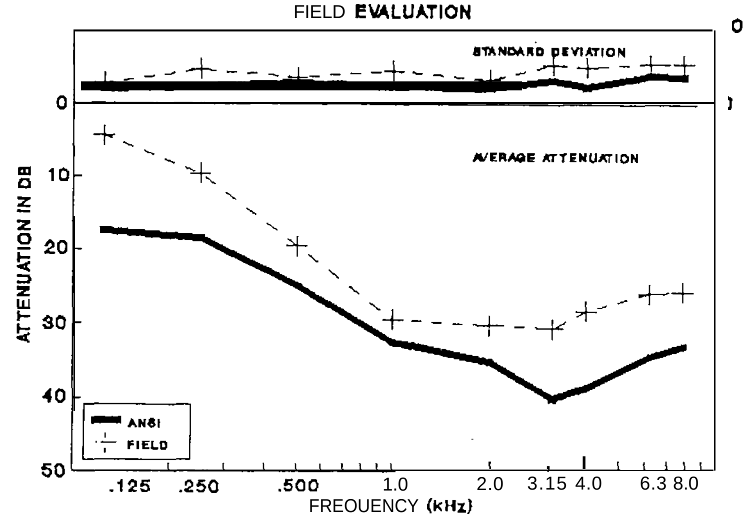


FIGURE 21 - HPD "E" ATTENUATION RESULTS
FIELD EVALUATION

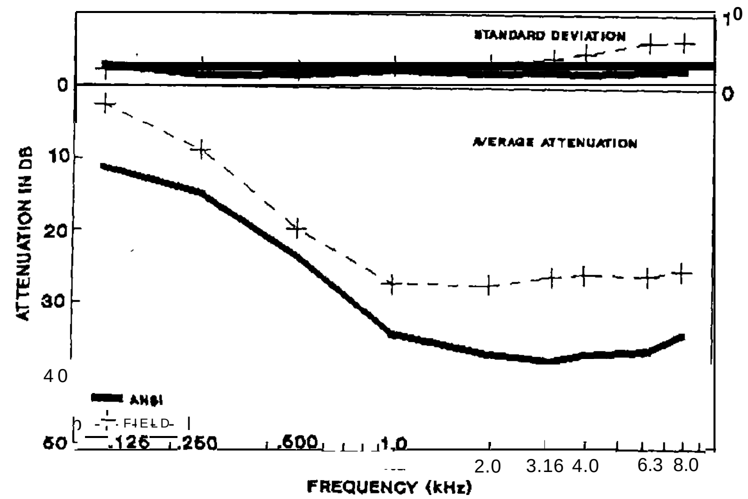


FIGURE 22 - HPD "F" ATTENUATION RESULTS
FIELD EVALUATION

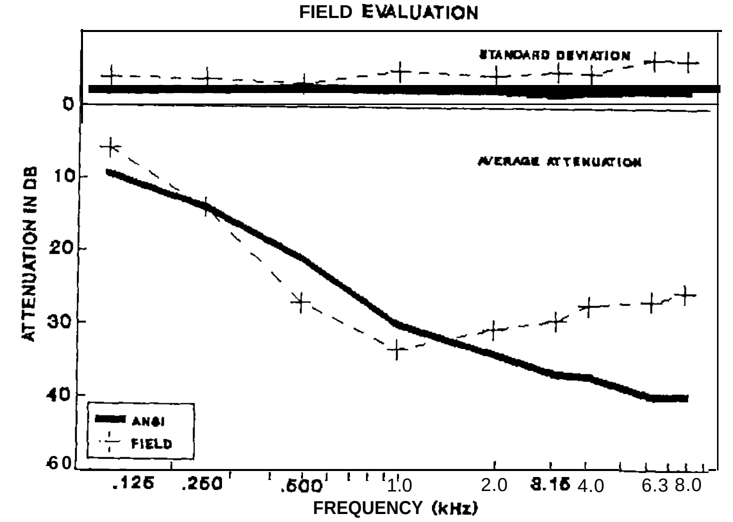


FIGURE 23 - HPD "G" ATTENUATION RESULTS
FIELD EVALUATION

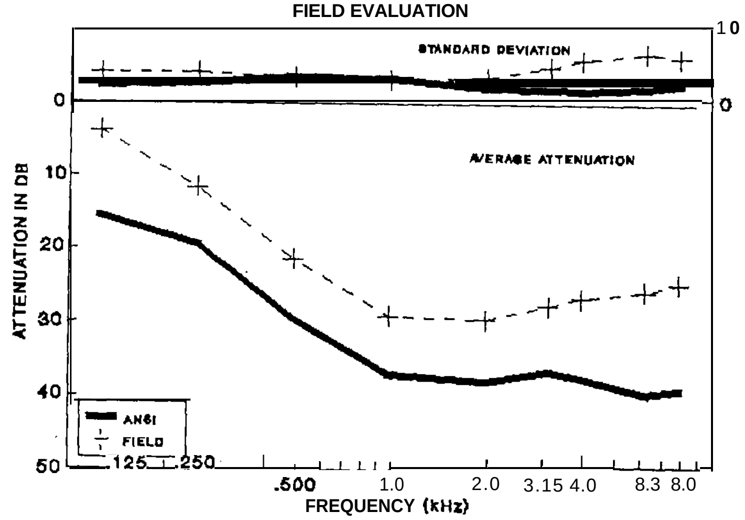


FIGURE 24 - HPD "H" ATTENUATION RESULTS
FIELD EVALUATION

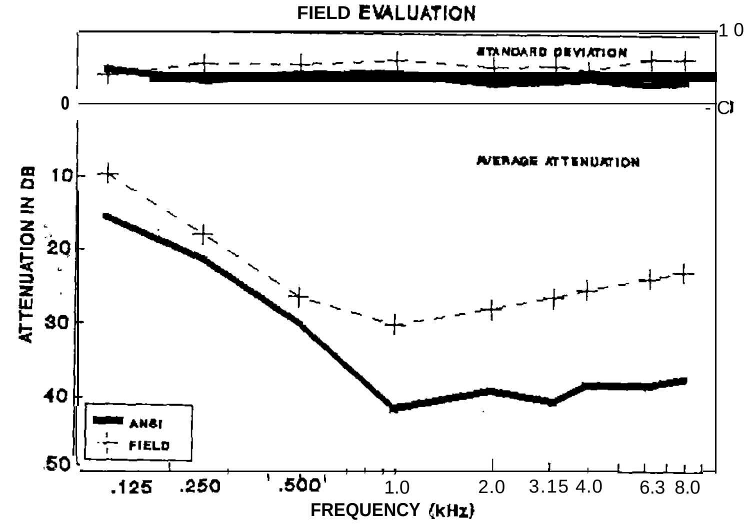


FIGURE 25 - HPD 'I' ATTENUATION RESULTS

FIELD EVALUATION

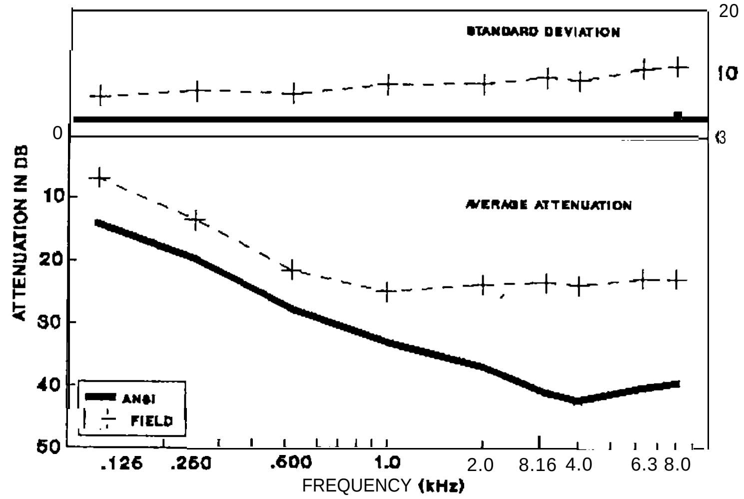


FIGURE 26 - HPD "J" ATTENUATION RESULTS

FIELD EVALUATION

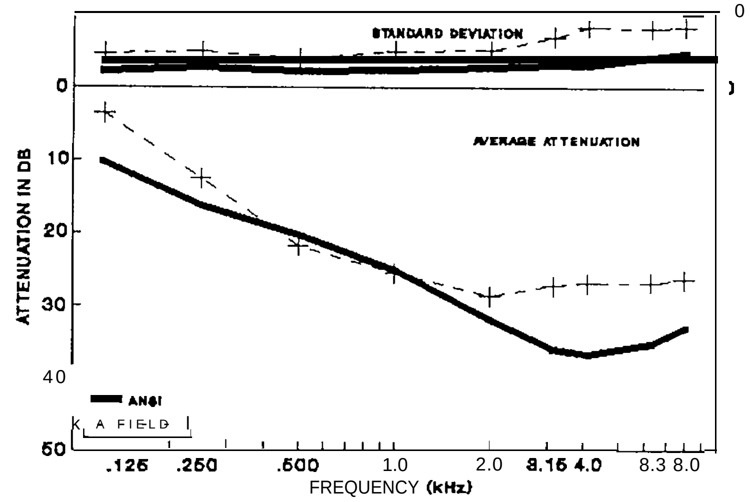
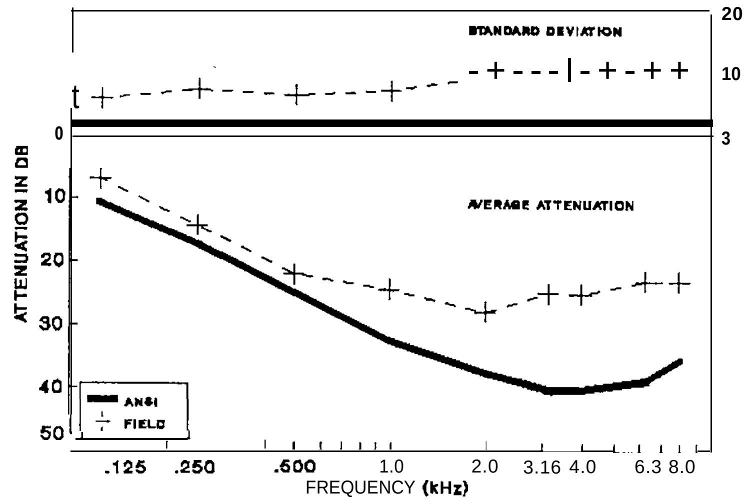


FIGURE 27 - HPD "K" ATTENUATION RESULTS

FIELD EVALUATION



BIBLIOGRAPHY

l.Botsford, J.h., (1973). "How to Estimate dbA Reduction of Ear protectors, "Sound and Vibration , November, pp. 32-33.

2.Johnson, D.L., and Nixon, C.W., (1974). "Simplified Methods for Estimating Hearing Protector Performance," Sound and Vibration, June 1974, pp. 20-27.

3.Cluff, G.L., Campbell, J., and Tellis, D., (1978). "Quick Procedure for Determining Effectiveness of Hearing Protectors," Sound and Vibration 18(5), pp. 24-25.

4.Lundin, R., "Three Methods for Calculating the Attenuation Index of a Hearing Protector - A Presentation and a Comparison. S-26050. Billesholm, Sweden: Bilsom AB, 1987.

5.Behar, A., "The High, Medium, and Low Method - A better Noise Reduction Rating?," Am. Ind. Hyg. Assoc. J., (51), December 1990, pp. 659-662.

G.Shaw, E.A.G. (1979). "Hearing Protector Attenuation: A Perspective View," Appl. Acoust. 12, pp. 139-157.

7.Sutton, G.L., and Robinson, D.W., (1981). "An appraisal of Methods for Estimating the Effectiveness of Hearing Protectors," J. of Sound Vib. 77,1, pp.79-91.

8.Goff, R.J., and Blank, W.J. (1984). "A Field Evaluation of Muff-Type Hearing Protection Devices, " Sound and Vibration 18(10), 16-22.

S.Behar, A. (1985). "Field Evaluation of Hearing Protectors," Noise Control Engineering Journal, Vol. 24, No. 1, pp. 13-18.

lO.Stewart,K.C., and Burgi, E.J. (1979). "Noise Attenuation Properties of Earmuffs Worn by Miners, Volume I: Comparison of Earmuff Attenuation as Measured by Psychophysical and Physical Methods," Final Report Volume 1 on Contract No. JO188018, Univ. of Pittsburgh, Pittsburgh, Pa.

ll.Rood, G. M. (1982). "The In-Situ Measurement of the Attenuation of Hearing Protectors by the Use of Miniature Microphones," in <u>Personal Hearing Protection in Industry</u>, edited by P. W. Alberti (Raven, New York), pp. 175-198.

12.Pehringer, J.L., and Preves, D.A. (1983). "The Use of Sub-Miniature Probe Microphones to Determine the Attenuation of Earmuff Hearing Protectors, "Noise & Vibration Control, Vol.14 No.2, pp. 49-53.

13.Liu, C., Pekkarinen, J., and Starck, J., (1989). "Application of the Probe Microphone Method to Measure Attenuation of Hearing Protectors Against High Impulse Sound Levels," Applied Acoustics. 27, pp.13-25.

14.Alberti, P.W., Riko, K., Abel, S.M., and Kristensen R. (1979). "The Effectiveness of Hearing Protectors in Practice," Journal of Otolaryngology 8(4), pp. 354-359.

15.Abel, S.M., Alberti, P.W., and Riko, K., "User Fitting of Hearing Protectors: Attenuation Results" in Personal Hearing Protection in Industry, edited by P.W. Alberti (Raven, New York), pp. 315-322.

16.Crawford, D.R.,and Nozza, R.J. "Field Performance Evaluation of Wearer-Molded Ear Inserts", presented at The American Industrial Hygiene Conference in Portland, OR., May 1981.

17.Edwards, R.G., and Green, W.W. (1987). "Effect of an Improved Hearing Conservation Program on Earplug Performance in the Workplace,"Noise Control Engineering Journal. 28(2), pp. 55-65.

18.Casali, J.G., and Park, M. (1991). "Laboratory versus Field Attenuation of Selected Hearing Protectors," Sound and Vibration 25(10), 28-38.

19.Regan, D.E., "Real Ear Attenuation of Personal Ear Protective Devices Worn in Industry," Ph.D. dissertation, Kent State University 1975.

20.ANSI (1984). ANSI S12.6-1984, "Method for the Measurement of the Real-Ear Attenuation of Hearing Protectors" (Acoustical Society of America, New York).

21."Noise Labeling Requirements for Hearing Protectors", Federal Register 42:190(Sept. 1979). pp.56139-56147.

22.National Institute for Occupational Safety and Health: "List of Personal Hearing Protectors and Attenuation Data", U.S. Dept. H.E.W. Publication No.(NIOSH) 76-120. Cincinnati, Ohio:National Institute for Occupational Safety and Health, September 1975.

23.Anderson, C.M.B., and Whittle, L.S. (1971). "PhysiologicalNoise and the Missing 6 dB," Acustica 24,261-272.

24.Berger, E.H., and Kerivan, J.E., "Influence of Physiological Noise and the Occlusion Effect on the Measurement of Real-Ear Attenuation at Threshold",J.Acoust. Soc. Am., 74(1), (1983), 81-94.

25.Action, W.I., and Lee, G.L. and Smith, D.J.,(1979).[1]'Short Communication: Effect of Head Band and Pressure on Comfort of Ear Muffs," Ann. Occup. Hyg. Vo1.19, pp. 357-361. Pergamon Press. Printed in Great Britain.

26.Berger, E-H., and Mitchell, 1.(1989). "Measurement of the Pressure Exerted by Earmuffs and its Relationship to Perceived Comfort," Applied Acoustics. 27, pp.79-88.