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Evaluation of an Auditory Hazard Model Using Data from Human Volunteer Studies

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The auditory hazard assessment algorithm for the human ear computer model developed at the U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, was evaluated using data from human volunteer studies (conducted at Kirtland Air Force Base, Albuquerque, NM) sponsored by the U.S. Army Medical Research and Materiel Command, Ft Detrick, MD. Measurements of the exposure impulses made under the earmuffs of volunteers and the resulting temporary hearing losses were analyzed using the model. The model predictions were compared to the number of volunteers showing significant threshold shifts. For the six-impulse exposures, the model tended to predict more hazard than the human data showed. This over prediction of hazard at small numbers of impulses was exacerbated at larger numbers of impulses because of a rapid accumulation of predicted hazard with increasing numbers of impulses. The minimum phase procedure of the model for estimating the efficacy of hearing protection from real ear attenuation and insertion loss data was evaluated. The model predictions from the minimum phase calculations indicated higher risk than the measurements under the earmuffs. In general, the model hazard indications, from measured data and minimum phase calculations, were not in agreement with the results of the human studies.

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Introduction

The U.S. Army is currently using Military Standard (MIL-STD) 1474D (Department of Defense, 1997) to estimate the hazard associated with exposure to impulse noise. This standard uses peak pressure and a measure of effective duration (B-duration) to establish maximum safe conditions (Figure 1). This standard has been demonstrated to overestimate the hazard in human volunteer studies (Patterson et al., 1985; Patterson and Johnson, 1995, 1996 and 1998; Patterson, Mozo, and Johnson, 1993; Johnson and Patterson, 1992 and 1995 ; Patterson, Johnson, and Yelverton, 1996; Johnson, 1994 and 1998; Patterson et al., 1997; Chan et al., 2001).

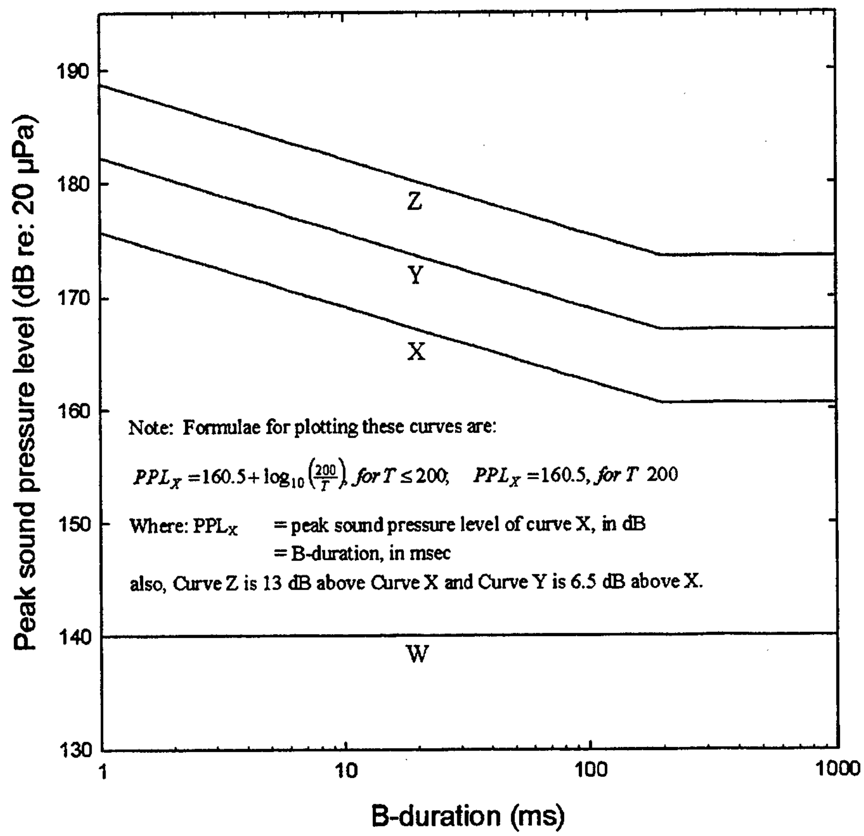

Figure 1. MIL-STD-1474D peak sound pressure levels and B-duration limits for impulse noise.

In an attempt to provide a better method to estimate the hazard from exposure to impulse noise, researchers at the U.S. Army Research Laboratory (ARL) developed a computer model, the auditory hazard assessment algorithm for the human ear (AHAAH). This model was designed to predict the risk of hearing loss resulting from exposure of humans to impulse noise (Kalb and Price, 1987; Price and Kalb, 1991 and 1998; Price, 1998a and 1998b). The model was initially developed for the cat auditory system and later adapted to become a model of the human auditory system. The model was designed to analyze digitized impulse pressure-time signatures to produce indications of the auditory hazard. It is capable of analyzing pressure-time signatures from measurements in the open with no human present, measurements at the entrance to the ear canal using a microphone mounted on a human head, and measurements at the eardrum position in a manikin head. The output data of the model have been called auditory hazard units (AHUs). The developers of the model suggest that 500 AHUs represent a maximum safe exposure for protection of 95 percent of an exposed population. For exposure to multiple impulses, the AHUs from each impulse are simply added.

The U.S. Army Medical Research and Materiel Command sponsored a series of human volunteer studies designed to establish new limits on the safe exposure of soldiers to the impulse noise produced by heavy weapons (Johnson, 1994 and 1998). These studies were conducted at Kirtland Air Force Base, Albuquerque, NM. Thus, they have come to be called the "Albuquerque studies." The results of these studies provide a large systematic database of the effects of impulse noise on humans. The number of volunteers in each study was large enough to estimate with high confidence whether 95 percent of the exposed population was adequately protected. The studies included exposure to four different pressure-time signatures, at seven intensity levels, and numbers of impulses that ranged from 6 to 100 impulses. The volunteers wore hearing protection during all exposures. Digital recordings of the exposure impulses were made in the open and under the earmuffs. Extensive audiometric evaluations of the volunteers were done before and after each exposure. The results of these human volunteer studies provide a database to evaluate the AHAAH model by comparing the AHUs calculated from the recorded pressure-time signatures with the confidence that 95 percent of the exposed population would be protected.

Methods

The Albuquerque Studies

The relevant methods used in the Albuquerque studies are summarized here. Additional details can be found in Johnson (1994).

Exposures

All of the exposure stimuli used in the human volunteer studies were produced by the detonation of explosive material. Three of the pressure-time signatures were typical of free-field blast waves. The 5-meter signature resulted from the explosion of a bare charge approximately 3 meters above the ground with the volunteers located 5 meters from a point under the charge. The 3-meter and 1-meter signatures resulted from the detonation of an explosive charge in the bottom of a vertical, 12-inch diameter, 3-meter long steel tube. The open end of this tube was the effective source for the impulse. The volunteers were located on a platform with their head (ear) height at the level of the open end of the steel tube. The distance from the center of the tube to the volunteer's ear was either 3 meters or 1 meter. All volunteers were seated on adjustable stools so that their head (ear) height above the ground or the platform floor was the same, independent of their stature height. The right ear was always oriented toward the effective source and was considered to be the test ear. The left ear was protected with both plugs and earmuffs (double protection) and the added protection of the head shadow. The fourth exposure condition was a reverberant exposure. The volunteers were seated inside a large steel enclosure. The explosives were detonated outside the enclosure near the opening of a steel tube that extended through the end wall into the enclosure approximately 2 meters. The open end of the steel tube was the effective source of the impulse noise.

For each distance, a matrix of possible exposures was established. The matrix consisted of seven peak-pressure levels with five (free-field) or three (reverberant) numbers of impulses (see below). The lowest peak-pressure level was chosen to be safe for more than six impulses using MIL-STD-1474D to rate the hazard. The highest level was at the threshold of nonauditory injury as established by animal studies of exposure to the same impulses. The peak-pressure levels were increased by approximately 3 dB from one level to the next level. The numbers of impulses were 6, 12, 25, 50, and 100 for the three free-field impulses and 1, 2, and 3 for the reverberant impulses. For all four types of impulses, the highest exposure level, Level Seven, was at the threshold of nonauditory injury for the smallest number of impulses. For all higher numbers of impulses, Level Six was the highest exposure level and was at or below the threshold of nonauditory injury for the highest number of impulses.

Threshold shifts

The volunteers were given a series of at least six baseline audiograms using an automated tracking procedure (Mozo et al., 1984) before any exposures. Before each exposure, an audiogram was obtained to verify that there was no change in baseline. After each exposure, audiograms were obtained starting at 2, 20 and 60 minutes postexposure. Right ears were tested first and constitute the primary data from the studies. The threshold shift (TS) at each frequency was calculated by subtracting the average baseline audiogram from the postexposure audiograms for each volunteer. When the TS at any audiometric frequency exceeded 25 dB, the hearing protector was considered to "fail" to provide adequate protection for the exposure condition that resulted in the excessive TS. When the TS at any audiometric frequency was between 15 and 25 dB, the hearing protector was considered a conditional failure at the level producing the TS. A failure was scored for the next higher level exposure condition. The conditional failure was used to protect the volunteers against TSs much larger than 25 dB. Only the TSs from the right ear were used in the scoring of failures. No significant TSs were observed in the left-ear tests.

Exposure sequences

Different groups of volunteers were exposed to the different distance conditions. Each volunteer was exposed to a sequence of exposures at one of the distances. Each exposure occurred on a different day. All volunteers were initially exposed to the smallest number of impulses at the lowest peak-pressure level. On succeeding exposure days, the exposure was increased in peak level for the smallest number of impulses until either the maximum level was reached or a failure was recorded at some level. If a failure (TS>25 db) occurred at some level, the next exposure was at two levels below the failure level and at the next higher number of impulses. If a conditional failure occurred, the next exposure was at one level below the conditional failure level and at the next higher number of impulses. Since the conditional failure resulted in a failure being scored at the next higher level, the two rules were effectively the same. If the volunteer reached Level Seven for the six impulse exposures without a failure, the next exposure was to the next higher number of impulses at Level Six. If no failures occurred, the number of impulses was increased on succeeding exposures. These rules were applied repeatedly until the volunteer reached the highest number of impulses for that exposure distance. These exposure sequence rules were devised to allow each volunteer to approach his failure level from a lower level or from a lower number of impulses.

Hearing protection

The volunteers wore hearing protection for all exposures. The first group of volunteers was exposed to the 5-meter distance wearing a talk-through earmuff on their right ears. Their left ears were protected both by earplugs and the earmuffs. The talk-through earmuff included an electronic circuit to pass low-level sounds from the outside to an earphone inside the earmuff. This circuit turned off automatically when the level outside the earmuff exceeded a preset threshold. The real ear attenuation at threshold (REAT) (ANSI S12.6-1984) of this earmuff with the talk-through circuit turned off is shown in Table 1. None of the volunteers in the first 5-meter study had TSs after any of the exposures using this earmuff. A second group repeated the 5-meter exposure conditions wearing the same earmuff that had been modified to have a leaky ear cup seal on the right ear cup (Figure 2). The real ear attenuation of the modified earmuff with the talk-through circuit turned off also is shown in Table 1. The modification to the earmuff reduced the attenuation and was intended to simulate a poorly-fitting earmuff. The modified earmuff was used for all exposure distances. As a result, data are available for the unmodified earmuff for the 5-meter exposure distance only. Data are available for the modified earmuff for all exposure distances.

Table 1.
Real ear attenuation in dB for the unmodified and modified earmuffs.

	Frequency in kHz								
Muff type	0.125	0.25	0.5	1.0	2.0	3.0	4.0	6.0	8.0
Unmodified	13.3	15.8	22.3	23.3	24.7	34.2	36.7	37.5	37.5
Modified	-0.3	-4.3	8.7	13.8	19.3	29.5	28.2	22.0	19.3

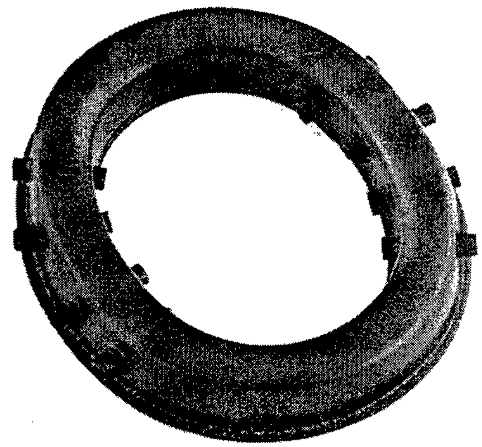

Figure 2. Photograph of the seal from the talk-through earmuff modified to simulate a poorly-fitting seal.

Summary of failures

Since none of the volunteers were actually exposed to all combinations of level and number of impulses, rules for filling in the matrix were adopted. It was assumed that TS would be monotonically increasing with level and number of impulses[1]. This assumption seemed reasonable based on human and animal studies (Hamernik, Patterson and Ahroon, 1998). Also, this assumption was supported by the result that every time a failure occurred, the two step decrease in level and one step increase in number resulted in a pass. All levels above a failure condition were scored as failures for that number of impulses. All levels below a pass were scored as a pass for that number of impulses. All numbers of impulses greater than a failure condition were scored as failures for that level. This prevented the volunteer from being exposed to a higher number at a level that had already resulted in a failure for a smaller number of impulses. The only exception to this rule was for a failure that resulted from a conditional failure. In this case, the failure at lower numbers of impulses was moved to higher levels if a pass occurred at higher numbers. This helped to reduce any bias introduced by the lower TS used to define conditional failures. Using these rules, the results of each exposure distance can be summarized as a matrix of the number of failures and the total number of volunteers (passes plus failures) for each combination of level and number impulses. Tables 2 through 6 contain the pass/fail results from the five groups of volunteers. Since some volunteers withdrew or were dropped from the study, the number of passes and the total number of volunteers were not the same for all combinations of level and number of impulses.

[1] The AHAAH does not assume that hazard increases monotonically with increasing level.

Table 2.

Number of failures, total number of volunteers, and confidence that 95 percent of the population would be protected by the unmodified earmuffs at the 5-meter distance.

Peak Pressure Level (dB)	Parameter	Number of impulses				
		6	12	25	50	100
173.2	Number of failures	0	0	0	0	0
	Total number	62	60	56	47	41
	Confidence	0.96	0.95	0.94	0.91	0.88
176.0	Number of failures	0	0	0	0	0
	Total number	62	60	56	47	41
	Confidence	0.96	0.95	0.94	0.91	0.88
179.2	Number of failures	0	0	0	0	0
	Total number	62	60	56	47	41
	Confidence	0.96	0.95	0.94	0.91	0.88
181.9	Number of failures	0	0	0	0	0
	Total number	62	60	56	47	41
	Confidence	0.96	0.95	0.94	0.91	0.88
184.0	Number of failures	0	0	0	0	0
	Total number	59	58	54	45	39
	Confidence	0.95	0.95	0.94	0.90	0.86
186.9	Number of failures	0	0	0	0	0
	Total number	58	56	53	44	39
	Confidence	0.95	0.94	0.93	0.90	0.86
189.5	Number of failures	0	NT	NT	NT	NT
	Total number	49	NT	NT	NT	NT
	Confidence	0.92	NT	NT	NT	NT

NT: Not tested.

Table 3.

Number of failures, total number of volunteers, and confidence that 95 percent of the population would be protected by the modified earmuffs at the 5-meter distance.

Peak Pressure Level (dB)	Parameter	Number of impulses				
		6	12	25	50	100
173.2	Number of failures	0	0	0	0	0
	Total number	59	57	57	57	57
	Confidence	0.95	0.95	0.95	0.95	0.95
176.0	Number of failures	0	0	0	0	0
	Total number	59	57	57	57	57
	Confidence	0.95	0.95	0.95	0.95	0.95
179.2	Number of failures	0	0	0	0	1
	Total number	59	57	57	57	57
	Confidence	0.95	0.95	0.95	0.95	0.79
181.9	Number of failures	0	0	0	1	1
	Total number	58	57	57	57	57
	Confidence	0.95	0.95	0.95	0.79	0.79
184.0	Number of failures	0	0	1	1	1
	Total number	57	57	57	57	57
	Confidence	0.95	0.95	0.79	0.79	0.79
186.9	Number of failures	0	1	1	1	3
	Total number	57	57	57	57	56
	Confidence	0.95	0.79	0.79	0.79	0.31
189.5	Number of failures	1	NT	NT	NT	NT
	Total number	56	NT	NT	NT	NT
	Confidence	0.77	NT	NT	NT	NT

NT: Not tested.

Table 4.
Number of failures, total number of volunteers, and confidence that 95 percent of the population would be protected by the modified earmuffs at the 3-meter distance.

Peak Pressure Level (dB)	Parameter	Number of impulses				
		6	12	25	50	100
Lost	Number of failures	0	0	0	0	0
	Total number	68	64	63	61	56
	Confidence	0.97	0.96	0.96	0.96	0.94
177.9	Number of failures	0	0	0	0	0
	Total number	68	64	63	61	56
	Confidence	0.97	0.96	0.96	0.96	0.94
180.9	Number of failures	0	0	0	0	0
	Total number	68	64	63	61	56
	Confidence	0.97	0.96	0.96	0.96	0.94
184.8	Number of failures	0	0	1	1	1
	Total number	68	64	63	61	56
	Confidence	0.97	0.96	0.83	0.82	0.78
187	Number of failures	2	2	2	3	4
	Total number	68	64	63	61	56
	Confidence	0.67	0.63	0.62	0.36	0.15
190.3	Number of failures	5	6	9	10	13
	Total number	68	64	63	59	49
	Confidence	0.12	0.04	0.00	0.00	0.00
193.2	Number of failures	5	NT	NT	NT	NT
	Total number	52	NT	NT	NT	NT
	Confidence	0.04	NT	NT	NT	NT

NT: Not tested.

Table 5.

Number of failures, total number of volunteers, and confidence that 95 percent of the population would be protected by the modified earmuffs at the 1-meter distance.

Peak Pressure Level (dB)	Parameter	Number of impulses				
		6	12	25	50	100
178.6	Number of failures	0	0	0	0	0
	Total number	65	60	58	49	42
	Confidence	0.96	0.95	0.95	0.92	0.88
181.3	Number of failures	0	1	1	1	1
	Total number	64	60	59	50	43
	Confidence	0.96	0.81	0.80	0.72	0.64
184.5	Number of failures	1	1	1	1	2
	Total number	63	59	58	49	43
	Confidence	0.83	0.80	0.79	0.71	0.36
187.8	Number of failures	1	2	2	3	3
	Total number	63	60	59	50	43
	Confidence	0.83	0.58	0.57	0.24	0.17
190.3	Number of failures	2	3	4	7	11
	Total number	63	60	59	53	49
	Confidence	0.62	0.35	0.17	0.00	0.00
193	Number of failures	2	6	8	10	16
	Total number	63	61	61	55	42
	Confidence	0.62	0.03	0.00	0.00	0.00
195	Number of failures	4	NT	NT	NT	NT
	Total number	59	NT	NT	NT	NT
	Confidence	0.17	NT	NT	NT	NT

NT: Not tested.

Table 6.

Number of failures, total number of volunteers, and confidence that 95 percent of the population would be protected by the modified earmuffs for the reverberant conditions.

Peak Pressure Level (dB)	Parameter	Number of impulses		
		1	2	3
164.5	Number of failures	0	0	0
	Total number	64	59	59
	Confidence	0.96	0.95	0.95
167.5	Number of failures	0	0	0
	Total number	63	59	59
	Confidence	0.96	0.95	0.95
171	Number of failures	0	0	0
	Total number	63	59	59
	Confidence	0.96	0.95	0.95
175	Number of failures	0	0	0
	Total number	61	59	59
	Confidence	0.96	0.95	0.95
179.5	Number of failures	0	0	0
	Total number	61	59	59
	Confidence	0.96	0.95	0.95
182.5	Number of failures	0	0	0
	Total number	59	59	59
	Confidence	0.95	0.95	0.95
184	Number of failures	0	NT	NT
	Total number	59	NT	NT
	Confidence	0.95	NT	NT

NT: Not tested

The number of failures and the total number of volunteers were used to calculate the confidence that 95 percent of the population wearing a given hearing protection would not show a significant TS when exposed to each combination of level and number of impulses (Patterson et al., 1997). The following equation was used to calculated the confidence levels:

$$c = 1 - \sum_{i=0}^{n} \binom{N}{N-i} (0.95)^{N-i} (0.05)^{i}$$

where: c is the confidence that 95 percent of a population is protected
N is the total number
n is the number of failures

The percent confidence values are shown in Tables 2 through 6 for each of the groups of volunteers. These confidence values are the results that were compared to the model hazard indicator. All groups started with at least 59 volunteers, which gives at least 95 percent confidence that 95 percent of the population is protected if there are no failures. The confidence value is affected by both the number of failures and the total number of volunteers. As the number of failures increases, the confidence decreases. As the total number of volunteers decreases, so does the confidence.

Pressure-time signatures

Pressure-time signatures were measured by bare gauges for all exposure conditions. These were designated the free-field gauges since they measure the impulse noise at the nominal head position without a person present. They were located at the same distance from the source and at the same height above the ground as the volunteers' heads. In addition, gauges were placed under the earmuffs for a subset of the volunteers. For the 5-meter, modified earmuffs, recordings were made under the earmuffs worn by the three principal investigators. For all other conditions, up to six volunteers were fitted with the under-the-earmuff gauges. In all cases, these gauges were taped to the side of the head with the sensing element at the entrance to the ear canal. The complete set of pressure-time signatures recorded during the under-the-earmuff measurements had been screened for recording artifacts (Patterson et al., 1997). These pressure-time signatures were analyzed using the AHAAH model to produce the AHUs.

The model calculations

The AHAAH model allows for AHUs to be calculated from both the free-field recordings and the under-the-earmuff recordings. The recordings from under the earmuffs provide the most direct data for the evaluation of the model's performance since this analysis requires no assumptions about the hearing protection. Approximately 12 pressure-time signatures from each combination of intensity and number of rounds were used in the analysis if that many were available. To analyze the under-the-earmuff recordings, the "ear canal entrance" option was chosen for the model input. The recorded pressure time signatures were scaled, baseline levels were adjusted, start points were set and the record lengths were adjusted as needed using the model data preparation features. The resulting pressure-time signatures then were analyzed using the model's analysis features. The peak-pressure level under the earmuffs and the AHUs using both the warned and unwarned analysis options were calculated from each record. For the warned calculation, the model representation assumed that the middle ear muscles were contracted prior to the impulse arrival. For the unwarned calculation, the model representation assumed the middle ear muscles were contracted in response to the incoming impulse. For each exposure level and distance, the average peak-pressure level under the earmuff, the average warned AHUs, and the average unwarned AHUs were calculated. The average AHUs were an estimate of the single impulse hazard for each level of each distance. These estimated single impulse AHUs at each level were then multiplied by the numbers of exposure impulses to produce a matrix of estimated total AHUs for all combinations of exposure level and numbers of impulses for each exposure distance.

The model also was capable of estimating the pressure-time signatures under a hearing protector using REAT data and a minimum-phase filter assumption to estimate the hearing protector transfer function. The recordings from the free-field gauges were analyzed using the REAT values shown in Table 1 and the "minimum-phase earmuff" feature of the model. This produced a set of estimated under-the-earmuff pressure-time signatures that were analyzed in the same way the measured under-the-earmuff recordings were analyzed. Since the levels measured under the earmuffs suggested a nonlinear growth (Patterson et al., 1997), a set of level-dependent insertion losses collected using a physical ear attenuation or microphone-in-real-ear (MIRE) (ANSI S12.42-1995) procedure was calculated from the octave-band spectra of the free-field impulses and the impulses measured under the earmuffs at each level. The attenuation values at 3.0 and 6.0 kHz were interpolated since the data available for these calculations were at octave intervals. The MIRE values shown in Tables 7 through 10 were used to analyze the recordings from the free-field gauges using the minimum-phase feature of the model to predict the under-the-earmuff signatures. Using these values should account for any level dependent changes (non-linearities) in the earmuff attenuation. The MIRE-estimated signatures were analyzed the same way as the measured data.

Table 7.
Insertion loss in dB (MIRE) for the unmodified earmuffs at the 5-meter distance for the seven exposure levels used in minimum-phase calculations.

Level	Frequency in kHz								
	0.125	0.25	0.5	1.0	2.0	3.0	4.0	6.0	8.0
1	6.0	10.9	22.6	24.4	25.5	26.4	27.2	26.8	26.4
2	8.6	10.7	22.0	24.8	25.5	26.4*	27.2*	26.8*	26.4*
3	11.0	9.8	21.0	25.9	25.5	26.4*	27.2*	26.8*	26.4*
4	10.8	10.1	18.9	23.6	29.0	29.1	29.2	29.6	29.9
5	9.8	7.9	14.6	20.6	26.0	25.8	25.6	25.7	25.8
6	10.9	8.6	15.0	21.4	24.1	25.9	27.8	28.5	29.1
7	7.6	7.5	11.3	16.4	22.7	24.5	26.2	23.5	20.8

* Estimated from Level 1 since data were not available.

Table 8.
Insertion loss in dB (MIRE) for the modified earmuffs at the 5-meter distance for the seven exposure levels used in minimum-phase calculations.

Level	Frequency in kHz								
	0.125	0.25	0.5	1.0	2.0	3.0	4.0	6.0	8.0
1	2.3	0.4	14.6	12.4	22.7	23.4	24	21.1	18.3
2	3.5	1.1	13.5	11.8	22.9	23.8	24.6	23.2	21.7
3	4.9	2.1	10.4	15.4	20.3	22.6	24.8	23.8	22.8
4	4.5	1.3	11.7	14.1	18.1	18.9	19.6	17.4	15.1
5	5.4	4	12.8	15.9	18.5	18.8	19	19.5	19.9
6	3.3	4	6.3	14.5	18.8	18.3	17.8	18.2	18.5
7	7.4	5.1	9.4	14.7	18.8	17.3	15.9	16.4	16.9

Table 9.
Insertion loss in dB (MIRE) for the modified earmuffs at the 3-meter distance for the seven exposure levels used in minimum-phase calculations.

Level	Frequency in kHz								
	0.125	0.25	0.5	1.0	2.0	3.0	4.0	6.0	8.0
1	ND	ND	ND	ND	ND	ND	ND	ND	ND
2	3.2	2.5	14.9	18.1	20	22	23.7	22	20
3	0.9	1.3	11.8	17.4	18.4	19.1	19.8	20.7	21.5
4	3.8	6.4	13.9	17.7	18.4	19.4	20.5	23	25.4
5	4.5	7.8	13.2	16	16.6	17.7	18.8	20.2	21.6
6	5.1	5	12.7	16.9	18.8	20	21.1	22.8	24.4
7	5.3	6.4	13.5	19.7	22.3	23.1	23.9	24.6	25.3

ND: No data available at this level.

Table 10.
Insertion loss in dB (MIRE) for the modified earmuffs at the 1-meter distance for the seven exposure levels used in minimum-phase calculations.

Level	Frequency in kHz								
	0.125	0.25	0.5	1.0	2.0	3.0	4.0	6.0	8.0
1	0.3	1.2	10.1	11	18	21.2	24.5	25.2	25.8
2	-0.2	2.1	10.6	12.4	18.9	20.4	22	22.9	23.8
3	0.7	2.6	12.4	13.4	22.1	22.9	23.6	23.5	23.4
4	0.7	2.5	13.6	15.7	21.1	21.9	22.7	20.9	19.1
5	2.5	6.1	14.6	16.8	22.7	24.2	25.6	25.3	24.9
6	ND	ND	ND	ND	ND	ND	ND	ND	ND
7	ND	ND	ND	ND	ND	ND	ND	ND	ND

ND: No data available at this level.

Results and discussion

Peak levels under the earmuffs

Figures 3 and 4 show the peak levels measured under the unmodified and the modified earmuffs as a function of the peak levels outside the earmuffs for the 5-meter exposure distance. These figures provide insight into the linearity of the growth of the peak levels under the earmuffs. Figures 3 and 4 also show the peak levels estimated under the earmuffs using the minimum-phase REAT calculation and the minimum-phase MIRE calculation. Ideally, the peak level under the earmuff should increase linearly with the peak level outside. For the 5-meter distance, the growth is close to linear for both the modified and unmodified earmuffs. For the unmodified earmuffs at the 5-meter distance, the REAT model prediction is approximately 2 dB lower than the measured data at all levels. The apparent slight departure from linearity seen in the measurement data at the higher levels is also in the REAT minimum-phase model predictions. Since the REAT values are the same at all levels, the hearing protection is linear for the REAT model predictions. The slight departure from linearity must result from something other than a non-linearity of the earmuffs. For the modified earmuffs at the 5-meter distance, the REAT model prediction is about 6 to 7 dB higher than the measured data. The MIRE model prediction is only about 2 dB higher than the measured data. The MIRE-estimated peak levels show a greater departure from linearity than the measured data or the REAT-estimated levels. This may be a result of level dependent instability in the MIRE estimates of the attenuation values.

Figure 5 shows the peak levels measured under the earmuffs and the minimum-phase model predictions as a function of the peak levels outside the earmuffs for the 3-meter exposure distance. The REAT model predicted levels are about 9 dB higher than the measured levels. The MIRE model predicted levels are about 5 dB higher than the measured levels. As with the

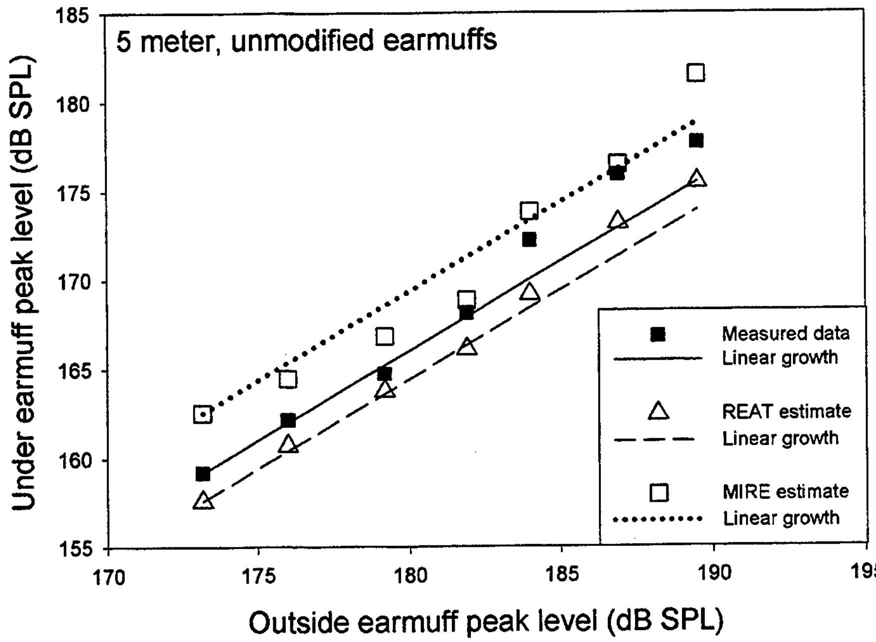

Figure 3. Peak levels under the unmodified earmuffs as a function of the peak levels outside the earmuffs, 5-meter exposure condition.

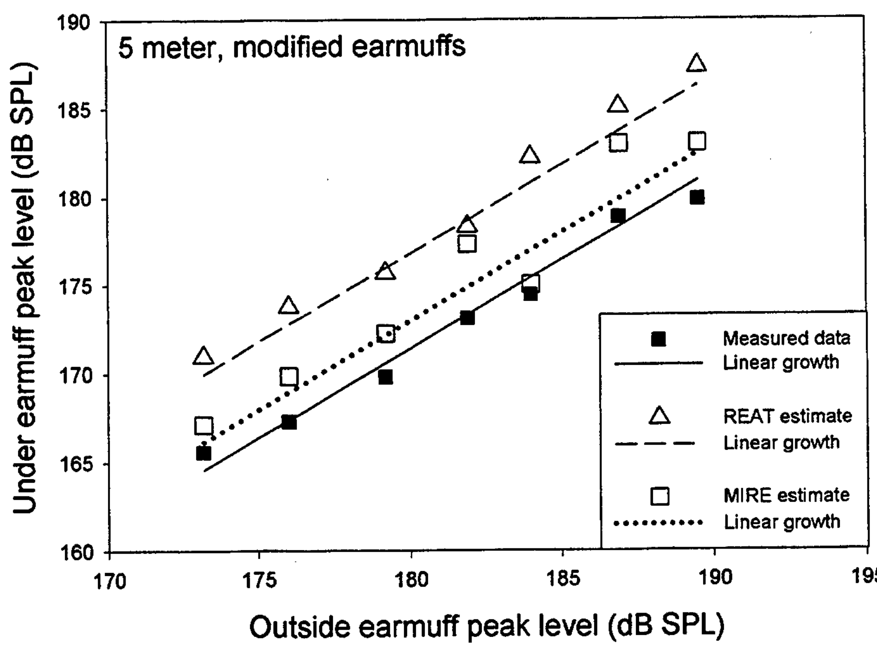

Figure 4. Peak levels under the modified earmuffs as a function of the peak levels outside the earmuffs, 5-meter exposure condition.

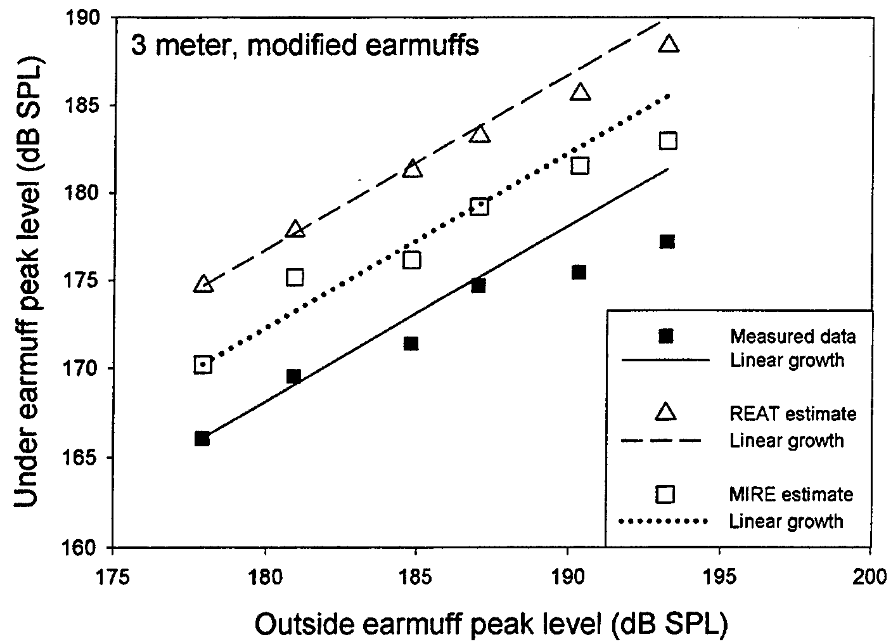

Figure 5. Peak levels under the modified earmuffs as a function of the peak levels outside the earmuffs, 3-meter exposure condition.

5-meter distance, the slight departure from linearity is seen in both the model predictions and the measured data. The highest two levels show slightly more of a departure from linearity than the lower five levels.

Figure 6 shows the peak levels measured under the earmuffs and the model predictions as a function of the peak levels outside the earmuffs for the 1-meter exposure distance. The REAT model-predicted levels are about 6 to10 dB higher than the measured levels. The MIRE model predicted levels are about 5 to7 dB higher than the measured levels. For the measured data, there appears to be a large departure from linear growth. The model predicted results show a slight departure from linearity. There were no free-field data from the highest two levels to use for the minimum-phase estimates of the under-the-earmuff levels using the model. However, there is a clear trend for the measured data to depart from linearity more than the REAT predicted results. Thus, the hearing protector was likely providing increasing attenuation with increasing levels at the 1-meter distance.

Figure 7 shows the peak levels measured under the earmuffs as a function of the peak levels outside the earmuffs for the reverberant condition. The levels measured under the earmuffs show a generally linear growth with no indication of a reduced peak at the highest exposure levels. No outside the earmuff data were available to calculate the minimum-phase model predictions.

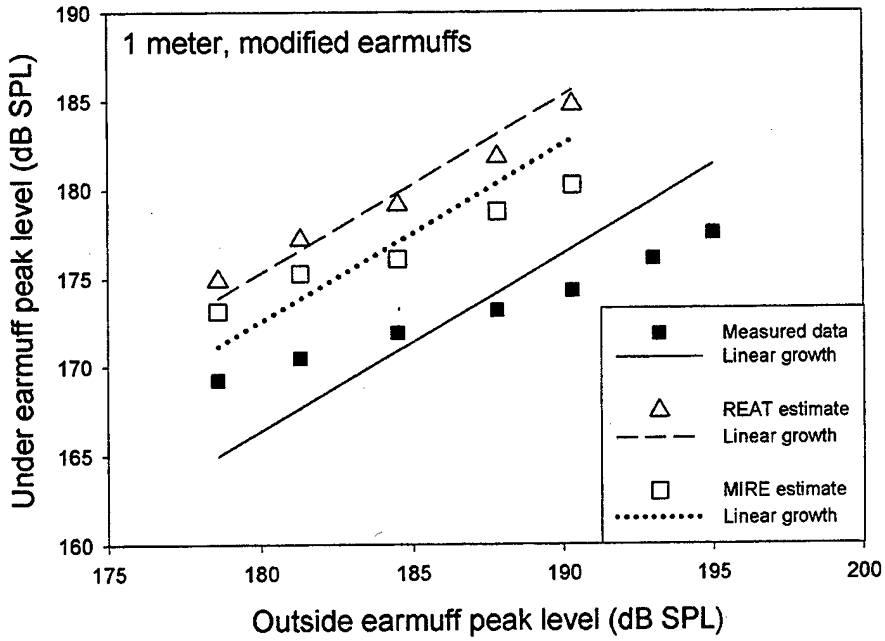

Figure 6. Peak levels under the modified earmuffs as a function of the peak levels outside the earmuffs, 1-meter exposure condition.

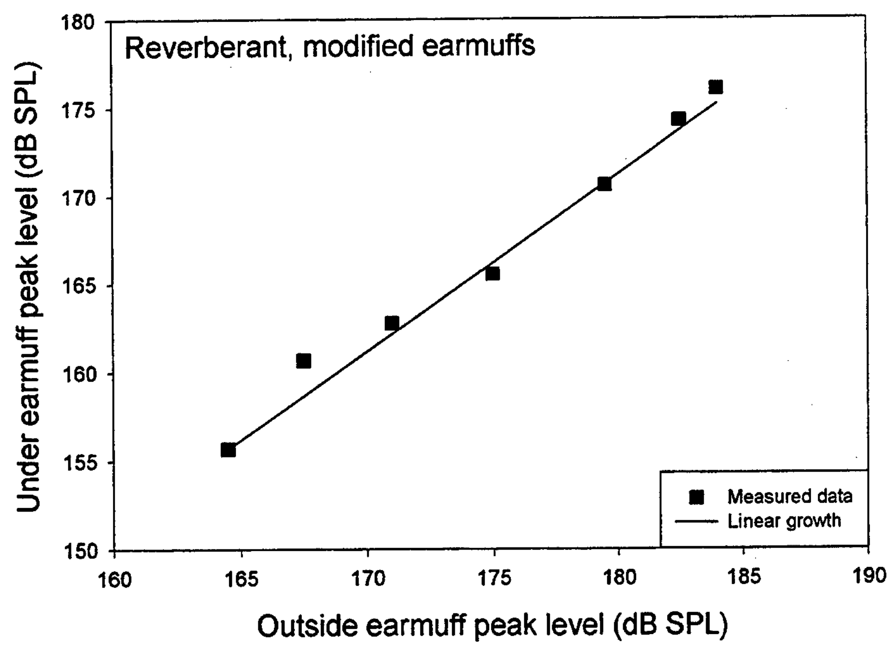

Figure 7. Peak levels under the modified earmuffs as a function of the peak levels outside the earmuffs, reverberant exposure condition.

AHUs from under-the-earmuff data

AHUs were calculated using the pressure-time signatures measured under the earmuffs, the REAT-estimated pressure-time signatures, and the MIRE-estimated pressure-time signatures. The AHUs calculated from the signatures measured under the earmuffs provide the most direct evaluation of the model's hazard prediction accuracy without the additional assumptions concerning the hearing protector attenuation. The evaluations using the REAT and MIRE-estimated signatures provide insight into how well the minimum-phase hearing protector calculations predict the effective exposures. For most applications of the model to real world exposures, only the REAT-estimated exposures will be available since measurements under protection are difficult and rare. All of the analyses included both the warned and unwarned functions of the model.

AHUs as a function of exposure level

The unwarned AHUs for six impulses as a function of the peak-pressure level outside the earmuffs are shown in Figures 8 through 11 for the four free-field exposure distances. For the unmodified earmuffs at the 5-meter distance, the AHUs calculated from the under-the-earmuff measurements, the REAT estimates, and the MIRE estimates show a monotonic increase with increasing exposure level. Note that the AHUs exceed 500 for the highest exposure level for the measured data and the highest three exposure levels for the MIRE estimates. This indicates that significant TSs should have been observed at these levels, but no TSs were observed for the six impulse exposures with the unmodified earmuffs. For the modified earmuffs at the 5-meter distance, the AHUs from the measured data show no trend across the exposure levels. The AHUs exceed 500 for the lowest level, the third level, and the highest two levels. The REAT estimate AHUs show a monotonic increasing function of exposure level and all exceed 1500. The MIRE estimate AHUs show a monotonic increasing function of exposure level except for the highest level and all exceed 1000. Again, significant TSs should have been observed throughout the six-impulse exposure series but were not. For the modified earmuffs at the 3-meter distance, the AHUs from the measured data show no trend across the exposure levels. The AHUs exceed 500 for all exposure levels. The AHUs from both the REAT and MIRE estimates show a nonmonotonic trend of exposure level and all exceed 1500. For the modified earmuffs at the 1-meter distance, the AHUs from the measured data show a nonmonotonic trend across the exposure levels. The AHUs exceed 500 for all exposure levels. The AHUs from both the REAT and MIRE estimates show a monotonic increasing function of exposure level and all exceed 1500. For both the 3-meter and the 1-meter exposure distances, the model calculations indicate that significant TSs should have been observed at the lowest exposure levels. Again, this is not in agreement with the data.

Each impulse was preceded by a countdown that was audible to the volunteers. The investigators were aware that this countdown might affect the results of the studies through voluntary contractions of the middle ear muscles (Johnson, 1994). To investigate this possibility, a no-countdown study was conducted using volunteers who had already completed the main study. The exposure sequence was repeated without the countdown. The results indicated that

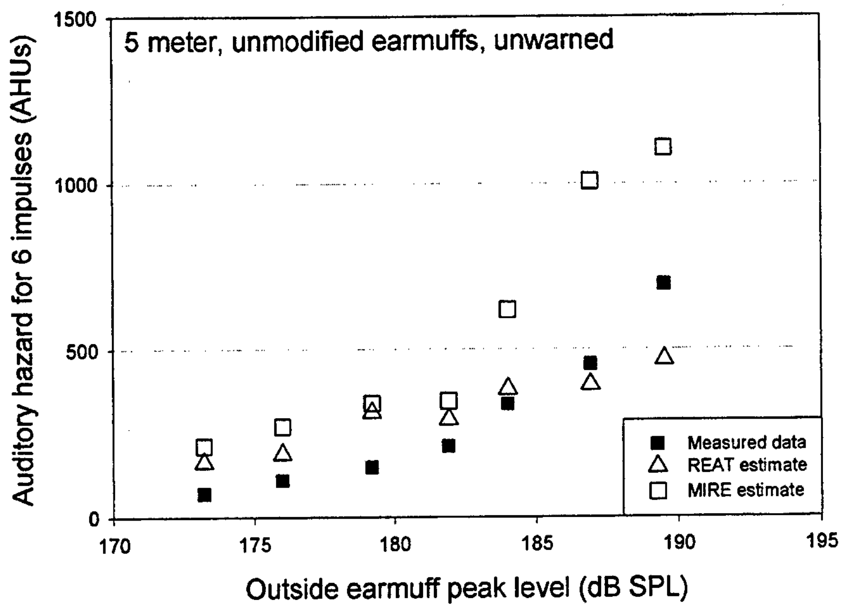

Figure 8. Unwarned auditory hazard units for six impulses calculated from pressure-time signatures under the unmodified earmuffs as a function of the peak levels outside the earmuffs, 5-meter exposure condition.

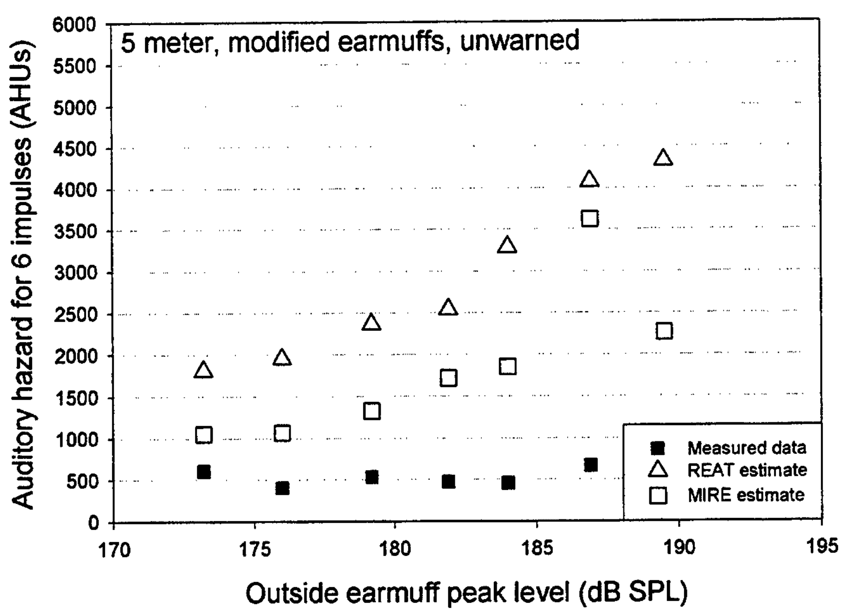

Figure 9. Unwarned auditory hazard units for six impulses calculated from pressure-time signatures under the modified earmuffs as a function of the peak levels outside the earmuffs, 5-meter exposure condition.

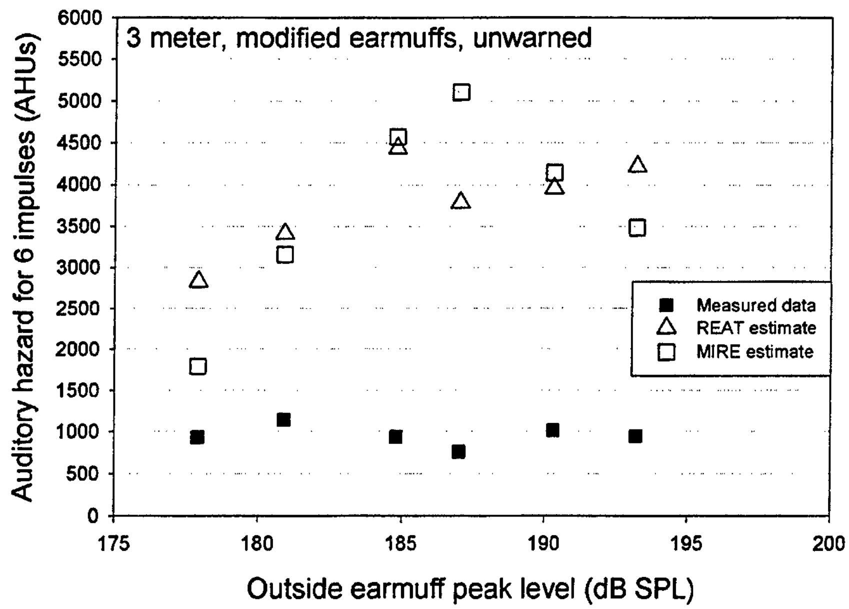

Figure 10. Unwarned auditory hazard units for six impulses calculated from pressure-time signatures under the modified earmuffs as a function of the peak levels outside the earmuffs, 3-meter exposure condition.

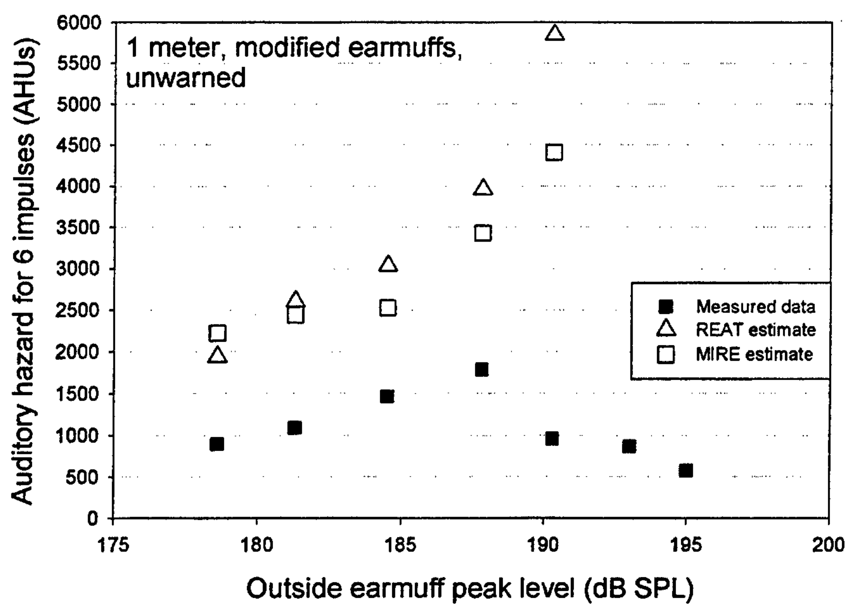

Figure 11. Unwarned auditory hazard units for six impulses calculated from pressure-time signatures under the modified earmuffs as a function of the peak levels outside the earmuffs, 1-meter exposure condition.

the countdown had no effect on the threshold shifts. The participants did not like the exposures without the countdown and many dropped out. However, there is no evidence that the volunteers' middle ear muscles were in a warned state at the time the impulses arrived. Thus, the most appropriate model calculation was the unwarned analysis.

The warned AHUs for six impulses as a function of the peak-pressure level outside the earmuffs are shown on Figures 12 through 15 for the four free-field exposure distances. For the unmodified earmuffs at the 5-meter distance, the AHUs calculated from the under-the-earmuff measurements, the REAT estimates, and the MIRE estimates generally show a monotonic increase with increasing exposure level. None of the AHUs exceed 500 for any of the exposure levels for the measured data, the REAT estimates, and the MIRE estimates. This finding is in essential agreement with the TS data. For the modified earmuffs at the 5-meter distance, the AHUs from the measured data show no trend across the exposure levels. The AHUs do not exceed 500 for any of the levels. The REAT estimated AHUs show a monotonic increasing function of exposure level, and all exceed 500 except for the lowest exposure level. The MIRE-estimated AHUs show a monotonic increasing function of exposure level except for the highest level. The highest four exposure levels exceed 500. The measured calculations are in essential agreement with the TS data; but, the REAT and MIRE analyses are not. For the modified earmuffs at the 3-meter distance, the AHUs from the measured data show no trend across the exposure levels. The AHUs do not exceed 300 for all exposure levels, indicating that no significant TSs should have been observed. The TS data indicate that the highest two levels did produce significant shifts. The AHUs from both the REAT and MIRE estimates show a nonmonotonic trend of exposure level and all exceed 500. Again this is not consistent with the TS data. For the modified earmuffs at the 1-meter distance, the AHUs from the measured data show a nonmonotonic trend across the exposure levels. The AHUs do not exceed 500 for all exposure levels. The TS data show a monotonic increasing number of significant shifts. The AHUs from both the REAT and MIRE estimates show a monotonic increasing function of exposure level and all except 1 exceed 500. These results are inconsistent with the TS shift data.

Figure 16 shows the single impulse AHUs for both the unwarned and the warned calculations for the reverberant exposures with the modified earmuffs. Both show a nonmonotonic trend with increasing exposure level. The AHUs for the fifth exposure level for the unwarned calculation exceed 500. No significant TSs were observed at any level. There were no signatures from outside the earmuffs to use for the REAT and MIRE minimum-phase estimates of the under-the-earmuff pressure-time signatures.

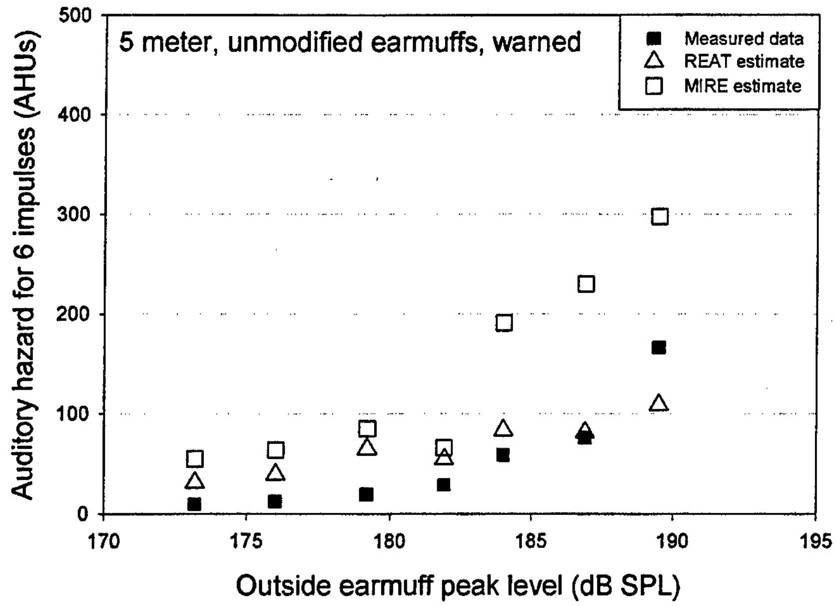

Figure 12. Warned auditory hazard units for six impulses calculated from pressure-time signatures under the unmodified earmuffs as a function of the peak levels outside the earmuffs, 5-meter exposure condition.

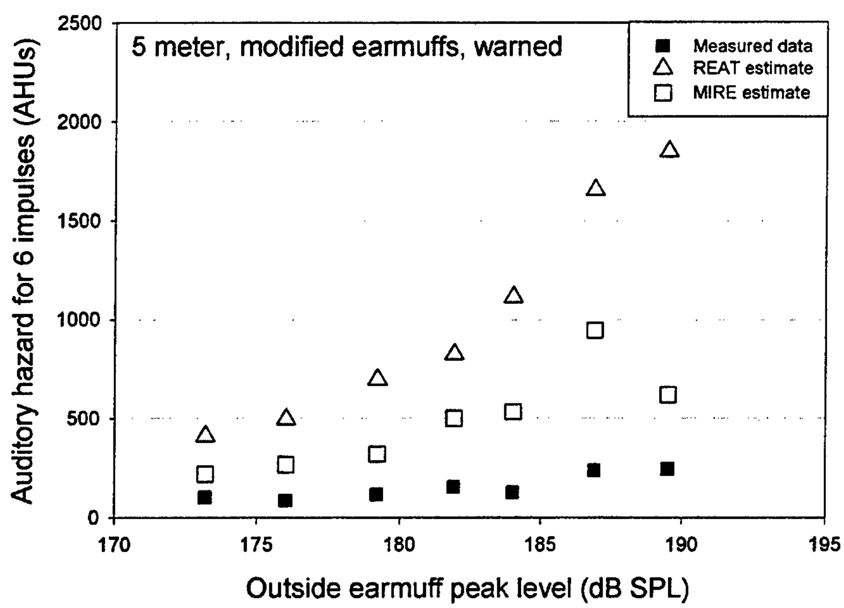

Figure 13. Warned auditory hazard units for six impulses calculated from pressure-time signatures under the modified earmuffs as a function of the peak levels outside the earmuffs, 5-meter exposure condition.

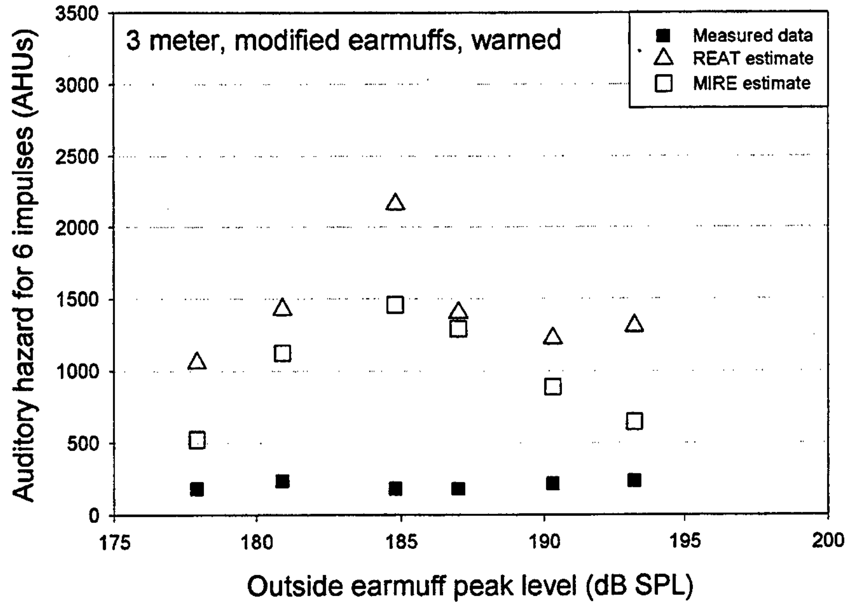

Figure 14. Warned auditory hazard units for six impulses calculated from pressure-time signatures under the modified earmuffs as a function of the peak levels outside the earmuffs, 3-meter exposure condition.

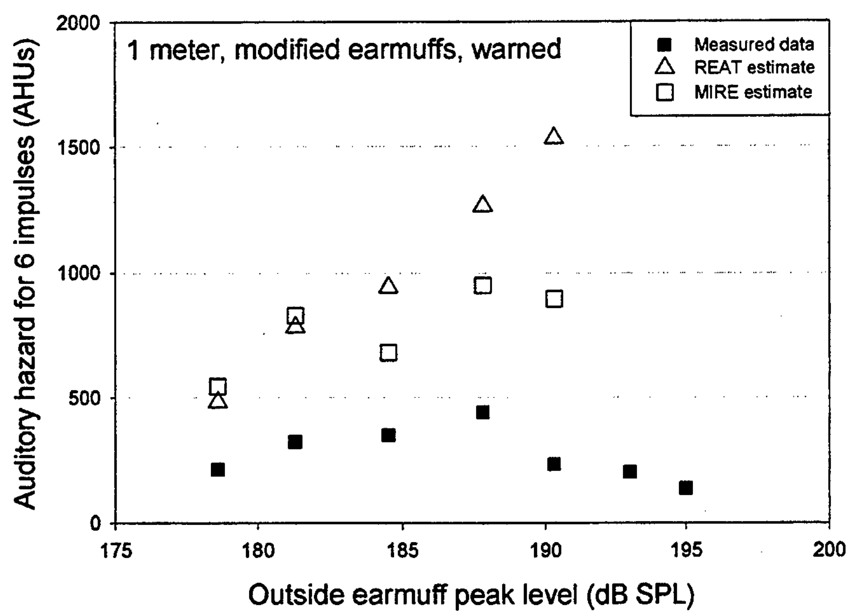

Figure 15. Warned auditory hazard units for six impulses calculated from pressure-time signatures under the modified earmuffs as a function of the peak levels outside the earmuffs, 1-meter exposure condition.

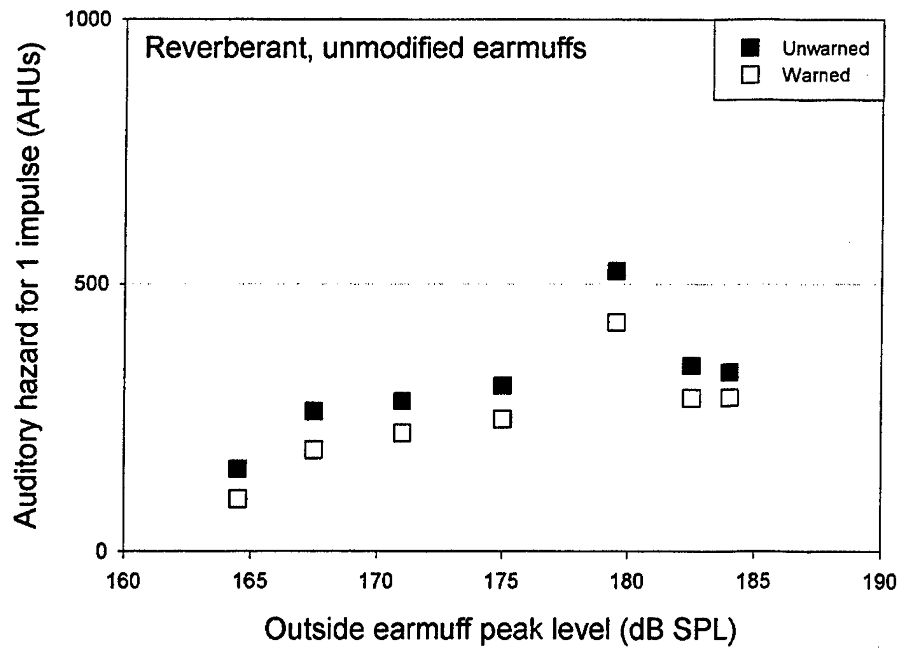

Figure 16. Warned and unwarned auditory hazard units for one impulse calculated from pressure-time signatures under the modified earmuffs as a function of the peak levels outside the earmuffs, reverberant exposure condition.

If the model were a good predictor of the auditory hazard, all of the AHU values should show a monotonic increasing function of exposure level. This is clearly not the case for either the measured data or the minimum-phase estimates. The minimum-phase REAT estimates should have matched the measured data for the conditions where the hearing protector behaved linearly. This was generally not the case. The minimum-phase MIRE estimates should have matched the measured data. This also was not the case.

Confidence level as a function of AHUs from the under-the-earmuff measurements

The confidence that 95 percent of the exposed population would be protected as a function of the AHUs calculated from the under-the-earmuff measurements using the unwarned analysis feature is shown in appendix A, Figures A-1 through A-5, for the five exposure groups. The confidence values were taken from Tables 2 through 6. The model's developers have suggested that 500 AHUs be used as the limit of exposures for protection of 95 percent of the exposed population. This limit is depicted as a vertical line in each figure. For the 5-meter exposures, we would expect that all of the data points for the unmodified earmuffs (Figure A-1) would fall below the 500-AHU limit, since there were no significant TSs in any of the exposure conditions. For the 5-meter exposures with the modified earmuffs (Figure A-2), we would expect most of the data to fall below the 500-AHU limit with the conditions showing a single failure to be near the 500-AHU limit. Only the 100-impulse, Level-Six exposure condition might have been expected to exceed the limit. There are many more data points above the limit in both 5-meter exposure distance data sets than would be expected, if the model were predicting the hazard accurately. The 3-meter and the 1-meter data (Figures A-3 and A-4) show a scattering of data points with no systematic relationship between the AHUs and the confidence that 95 percent of the population was protected. There are extremely large (20,000) AHUs for conditions where the confidence level is 95 percent and AHUs barely above 500 for conditions where the confidence is about 5 percent (i.e., the confidence that 95 percent of the population is not protected is 95 percent). The reverberant exposure data (Figure A-5) should have all been below 500 AHU also, since there were no significant TSs for this exposure condition. Nearly half the data are above the 500-AHU limit.

Figure 17 shows a composite of the data from all exposure conditions using the unwarned calculation. Note the tendency for the 50 and 100 impulse data to fall at the higher AHUs. This is a result of the rapid growth of AHUs with increasing numbers of impulses. The 50 percent confidence level is the point at which it is equally as likely that 95 percent of the population is or is not protected. Therefore, we should expect that the confidence level should be above 50 percent for AHUs less than 500 and be below 50 percent for AHUs above 500. That is, there should be a transition from high confidence to low confidence near 500 AHUs. There is no obvious trend for this crossover in confidence level at any AHU value. In fact, there is a lack of any systematic relationship between AHUs and the confidence that 95 percent of the population was protected. There are a number of high confidence data points below 500 AHUs. This is a result of the study design that required each exposure distance to start with several exposures that were considered safe by MIL-STD-1474D, which is known to be conservative.

To quantify the predictive power of the AHUs, the data were classified into a two-by-two prediction matrix (Model Prediction Safe/Unsafe by Exposure Classification Safe/Unsafe). An exposure condition was predicted to be safe for 95 percent of the population if the AHUs were less than 500 for that condition. An exposure condition was predicted to be unsafe if the AHUs were greater than 500. The data were classified as safe or unsafe exposures using two approaches. The first was the 50-50 criterion. If the confidence that 95 percent of the population was protected was greater than 50 percent, the condition was classified as a safe exposure. If the confidence was less than 50 percent, the condition was classified as an unsafe exposure. This is a symmetric criterion for separating the data that uses all 138 data points. The second approach, a 90-10 criterion, was more restrictive. Only conditions which indicated high confidence that 95 percent of the population was protected were classified as safe. The cut off for high confidence was 90 percent confidence. The symmetric criterion for unsafe was then taken to be 10 percent confidence that 95 percent of the population was protected (90 percent confidence that 95 percent of the population was not protected). This eliminated all the data that fell between these two confidence levels, leaving 91 data points.

The number of conditions predicted to be safe and classified as safe was divided by the total number of conditions classified as safe and converted to a conditional percentage. The number of conditions that were predicted to be unsafe and classified as safe were divided by the total number classified as safe and converted to a conditional percentage. These two percentages sum to 100 percent. Analogous calculations were done for the predictions with respect to conditions classified as unsafe. Table 11 shows the conditional percentage prediction matrix for the 50-50 criterion for classifying safe conditions. The overall percent correct prediction was 33 percent. The model correctly classified all unsafe conditions. However, it was able to achieve this by falsely classifying 79 percent of the safe conditions as unsafe. Table 11 also shows the prediction matrix for the 90-10 criterion for safe conditions. The overall percent correct prediction for the 90-10 criterion was 38 percent. The model still correctly classified all unsafe conditions. However, it also falsely classified 70 percent of the safe conditions as unsafe. These are very high false unsafe rates.

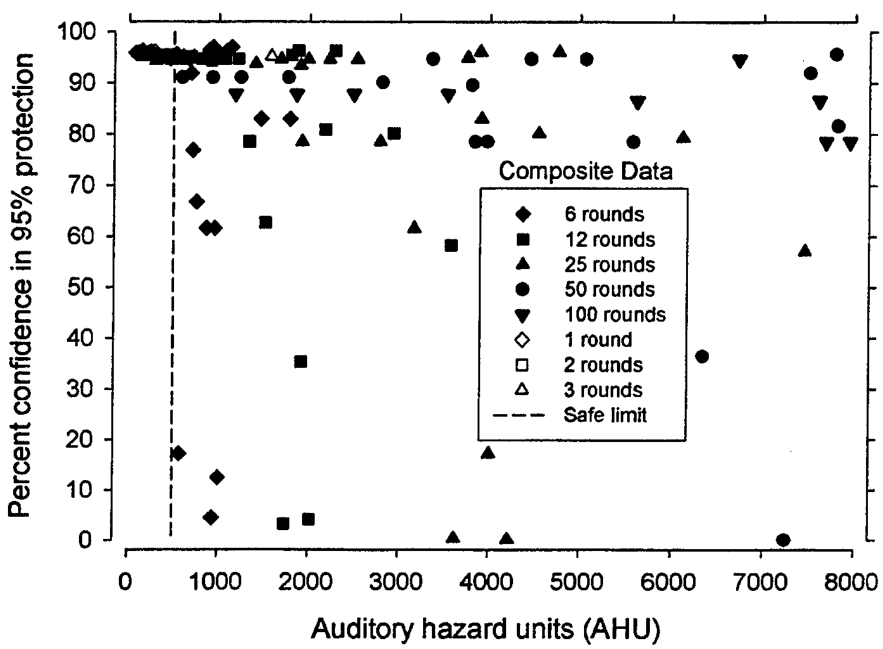

Figure 17. Composite percent confidence that the earmuffs provide adequate protection for 95 percent of the population as a function of unwarned auditory hazard units calculated from pressure-time signatures measured under the earmuffs, all exposure conditions.

The high rate of false unsafe predictions can be mitigated by raising the AHU limit for predicting safe conditions. Table 11 shows the prediction matrix using a 1000-AHU limit and the 50-50 criterion for safe conditions. The percent correct prediction rises to 51 percent. The percent false unsafe prediction drops to 56 percent. This is achieved at the cost of raising the false safe indication to 10 percent. Table 11 shows the prediction matrix using the 1000-AHU limit and the 90-10 criterion for safe conditions. The percent correct prediction rises to 63 percent. The percent false unsafe prediction drops to 41 percent. The false safe indication is still 9 percent.

Table 11.
Percent model predictions of safe and unsafe exposure conditions using under-the-earmuff measurement data from all exposure distances.

Model ear state	AHU limit	Classification Criterion	Model Prediction	Classification Safe	Classification Unsafe	Percent correct
Unwarned	500	50-50 confidence	Safe	21	0	33
			Unsafe	79	100	
Unwarned	500	90-10 confidence	Safe	30	0	38
			Unsafe	70	100	
Unwarned	1000	50-50 confidence	Safe	44	10	51
			Unsafe	56	90	
Unwarned	1000	90-10 confidence	Safe	59	9	63
			Unsafe	41	91	
Warned	500	50-50 confidence	Safe	61	29	62
			Unsafe	39	71	
Warned	500	90-10 confidence	Safe	74	27	73
			Unsafe	26	73	
Warned	138	50-50 confidence	Safe	18	0	30
			Unsafe	82	100	
Warned	138	90-10 confidence	Safe	26	0	35
			Unsafe	74	100	

The confidence that 95 percent of the exposed population would be protected as function of the AHUs, calculated from the under-the-earmuff measurements using the warned calculation is shown in Appendix A, Figures A-6 through A-10, for the five exposure groups. The confidence values are the same as those used for the unwarned evaluation. The 500-AHU limit is depicted as a vertical line in each figure. For the 5-meter exposures, we would expect that all of the data points for the unmodified earmuffs (Figure A-6) would fall below the 500-AHU limit, since there were no significant TSs in any of the exposure conditions. For the 5-meter exposures with the modified earmuffs (Figure A-7), we would expect most of the data to fall below the 500-AHU limit with the conditions showing a single failure to be near the 500-AHU limit. Only the 100 impulse, Level-Six exposure condition might have been expected to exceed the limit. There are many more data points above the limit in both 5-meter exposure distance data sets than would be expected, if the model were predicting the hazard accurately. The 3-meter and the 1-meter data (Figures A-8 and A-9) show a scattering of data points with no systematic relationship between the AHUs and the confidence that 95 percent of the population was protected. There are large (4000) AHUs for conditions where the confidence level is 95 percent and AHUs below 500 for conditions where the confidence is about 5 percent (i.e., the confidence that 95 percent of the population is not protected is 95 percent). The reverberant exposure data (Figure A-10) should have all been lower than 500 AHU also, since there were no significant

TSs for this exposure condition. However, there are a significant number of data points above the 500-AHU limit.

Figure 18 shows a composite of the data from all exposure conditions using the warned calculation. Compared to the unwarned calculations, the AHUs are smaller. There is still a lack of any systematic relationship between AHUs and the confidence that 95 percent of the population was protected. However, the warned calculation resulted in a number of data points showing low confidence in 95 percent protection with AHUs below 500. These are exposure conditions, for which there is high confidence that the protection was not adequate, that would be incorrectly categorized as acceptable by the model calculations.

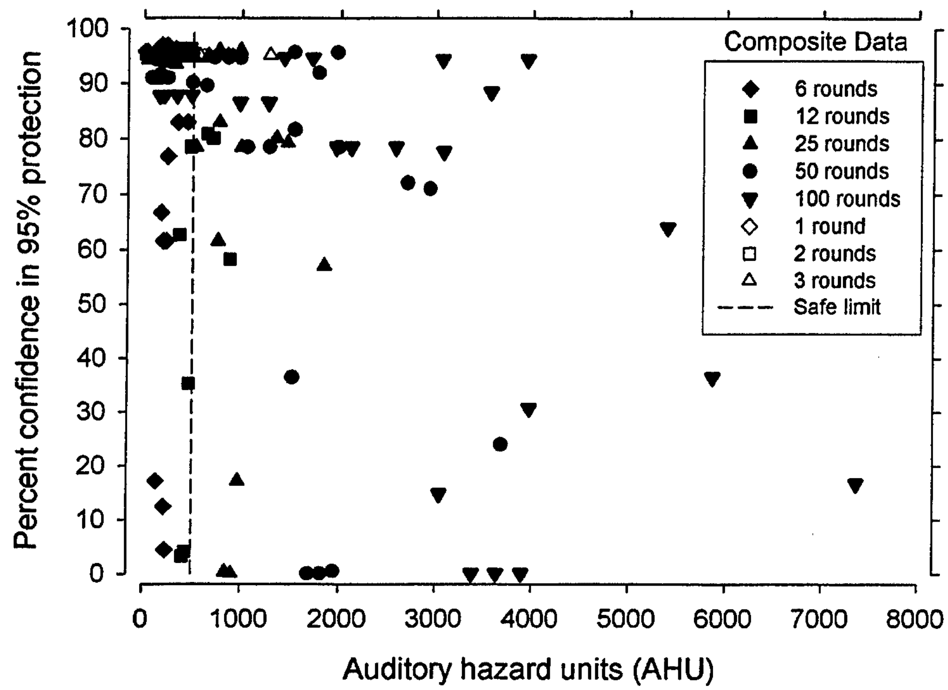

Figure 18. Composite percent confidence that the earmuffs provide adequate protection for 95 percent of the population as a function of warned auditory hazard units calculated from pressure-time signatures measured under the earmuffs, all exposure conditions.

As with the unwarned calculations, the data were separated into a two-by-two prediction matrix. The 500-AHU limit was used as an indication that an exposure condition was predicted to be safe for 95 percent of the population. An exposure condition was predicted to be unsafe if the AHUs were greater than 500. The data were classified as safe or unsafe exposures using the 50-50 criterion and the 90-10 criterion. Table 11 shows the prediction matrix for the 50-50 criterion for safe using the warned AHUs. The overall percent correct prediction was higher, at 62 percent, than for the unwarned AHUs. In the case of the warned calculations, the model failed to correctly classify all unsafe conditions. The false safe rate reached 29 percent. However, the rate for falsely classifying the safe conditions as unsafe was only 39 percent. Table 11 shows the prediction matrix for the 90-10 criterion for safe conditions. The overall percent correct prediction for the 90-10 criterion was 73 percent. The model still incorrectly classified 27 percent of the unsafe conditions as safe, while it falsely classified 26 percent of the safe conditions as unsafe. These are very high false safe rates. Ideally, all unsafe conditions should be correctly classified.

To reduce the false safe predictions, it was necessary to reduce the AHU limit from 500 to 138. This is the highest limit that allows for no false safe predictions using the warned analysis. Table 11 shows the prediction matrix for the 50-50 criterion for safe using the warned AHUs and the 138-AHU limit. The overall percent correct prediction was 30 percent. Using the lower limit, the model correctly classified all unsafe conditions. The false unsafe rate reached 82 percent. Table 11 shows the prediction matrix for the 90-10 criterion for safe using the 138-AHU limit. The overall percent correct prediction for the 90-10 criterion was 35 percent. The model correctly classified all of the unsafe conditions, while it falsely classified 74 percent of the safe conditions as unsafe. Reducing the safe exposure limit to eliminate false safe predictions significantly degrades the overall predictive performance of the model.

Neither the unwarned nor the warned calculations produce results that organize the confidence levels that 95 percent of the population would be protected. To add some perspective to how well a predictor of auditory hazard might organize the confidence level data, the peak-pressure levels outside the earmuffs adjusted by 3 times the base 10 logarithm of the number of impulses was used as a hazard indicator. Figure 19 shows the percent confidence that 95 percent of the population would be protected as a function of this indicator. There is a clear trend for the confidence level to drop as the indicator increases, crossing the 50 percent confidence between 190 and 195 dB. Using 190 dB as a conservative limit for defining safe exposures, two-by-two prediction matrices for safe and unsafe exposure conditions were determined using both the 50-50 criterion and the 90-10 criterion. Table 12 shows the conditional percentage prediction matrix for the 50-50 criterion for classifying safe conditions. The overall percent correct prediction was 88 percent. The indicator correctly classified all unsafe conditions. It was able to achieve this while falsely classifying only 15 percent of the safe conditions as unsafe. Table 12 also shows the prediction matrix for the 90-10 criterion for safe/unsafe. The overall percent correct prediction for the 90-10 criterion was 97 percent. The indicator still correctly classified all unsafe conditions. However, it falsely classified only 4 percent of the safe conditions as unsafe. This analysis is not intended to promote the adjusted peak level as a hazard indicator. Rather it is intended to show that the data are sufficiently orderly that the model could have performed much better if it were a good indicator of auditory hazard.

Table 12.
Percent predictions of safe and unsafe exposure conditions using the peak level + 3 × $\log_{10}(N)$ as the predictor variable from all exposure distances.

dB limit	Classification Criterion	Prediction	Classification Safe	Classification Unsafe	Percent correct
190	50-50 confidence	Safe	85	0	88
		Unsafe	15	100	
190	90-10 confidence	Safe	96	0	97
		Unsafe	4	100	

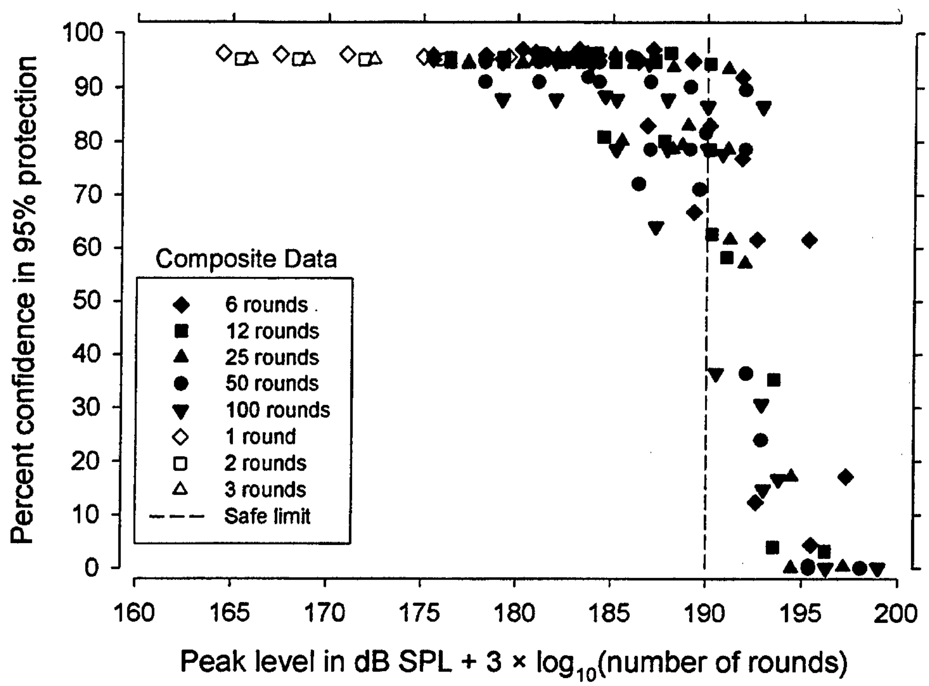

Figure 19. Composite percent confidence that the earmuffs provide adequate protection for 95 percent of the population exposed to all the exposure conditions as a function of the exposure peak level plus 3 × $\log_{10}$(number of impulses).

Confidence level as a function of AHUs from the REAT-estimated pressure –time signatures

The confidence that 95 percent of the exposed population would be protected as a function of the AHUs calculated from the REAT estimates of the under-the-earmuff signatures using the unwarned calculation is shown in appendix B, Figures B-1 through B-4, for the four free-field exposure groups. REAT calculations were not performed for the reverberant exposures. The confidence values were again taken from Tables 2 through 6. The 500-AHU limit is shown as the vertical line. The patterns of data are similar to the patterns noted for the measured signatures except that the AHUs were typically larger for the REAT-estimated signatures.

Figure 20 shows a composite of the data from all exposure conditions using the unwarned REAT calculation. There is a lack of any systematic relationship between AHUs and the confidence that 95 percent of the population was protected for the REAT-estimated data.

As with the measured signatures, the REAT-estimated data were separated into a two-by-two prediction matrix. The 500-AHU limit was used as an indication that an exposure condition was predicted to be safe for 95 percent of the population. An exposure condition was predicted to be unsafe if the AHUs were greater than 500. The data were classified as safe or unsafe exposures using both the 50-50 criterion and the 90-10 criterion. Table 13 shows the conditional percentage prediction matrix for the 50-50 criterion for classifying safe conditions. The overall percent correct prediction was only 22 percent. The indicator correctly classified all unsafe conditions. It falsely classified 91 percent of the safe conditions as unsafe. Table 13 also shows the prediction matrix for the 90-10 criterion for safe conditions. The overall percent correct prediction for the 90-10 criterion was 24 percent. The indicator correctly classified all unsafe conditions. However, it falsely classified 85 percent of the safe conditions as unsafe. These false unsafe rates are even higher than the rates for the measured signatures because of the overall increase in the REAT-estimated AHUs for all of the exposure conditions.

The high rate of false unsafe classifications can be mitigated by raising the AHU limit for safe conditions. Table 13 shows the prediction matrix using a 3900-AHU limit and the 50-50 criterion for safe conditions. The percent correct prediction rises to 49 percent. The percent false unsafe prediction drops to 59 percent. This is achieved while maintaining no false safe indications. Table 13 also shows the prediction matrix using the 3900-AHU limit and the 90-10 criterion for safe conditions. The percent correct prediction rises to 62 percent. The percent false unsafe prediction drops to 43 percent. There are no false safe indications. This is the best percent correct achievable for the REAT-estimated data without false safe predictions.

The confidence that 95 percent of the exposed population would be protected, as function of the AHUs calculated from the REAT estimates of the under-the-earmuff signatures using the warned calculation is shown in Figures B-5 through B-8 for the four free-field exposure groups. REAT calculations were not performed for the reverberant exposures. The confidence values were again taken from Tables 2 through 6. The 500-AHU limit is shown as the vertical line. The patterns of data are similar to the patterns noted for the measured signatures using the warned calculations, except that the AHUs were typically larger for the REAT-estimated signatures.

Table 13.
Percent model predictions of safe and unsafe exposure conditions using REAT-estimated under-the-earmuff data from all free-field exposure distances.

Model ear state	AHU limit	Classification Criterion	Model Prediction	Classification Safe	Classification Unsafe	Percent correct
Unwarned	500	50-50 confidence	Safe	9	0	22
			Unsafe	91	100	
Unwarned	500	90-10 confidence	Safe	15	0	24
			Unsafe	85	100	
Unwarned	3900	50-50 confidence	Safe	41	0	50
			Unsafe	59	100	
Unwarned	3900	90-10 confidence	Safe	57	0	62
			Unsafe	43	100	
Warned	500	50-50 confidence	Safe	26	0	36
			Unsafe	74	100	
Warned	500	90-10 confidence	Safe	41	0	47
			Unsafe	59	100	
Warned	1200	50-50 confidence	Safe	42	0	50
			Unsafe	58	100	
Warned	1200	90-10 confidence	Safe	57	0	62
			Unsafe	43	100	

Figure 21 shows a composite of the data from all exposure conditions using the warned REAT calculation. As with the unwarned analysis, there is a lack of any systematic relationship between warned AHUs and the confidence that 95 percent of the population was protected for the REAT-estimated data.

As with the measured signatures, the warned REAT data were separated into a two-by-two prediction matrix. The 500-AHU limit was used as an indication that an exposure condition was predicted to be safe for 95 percent of the population. The data were classified as safe or unsafe exposures using both the 50-50 criterion and the 90-10 criterion. Table 13 shows the prediction matrix for the 50-50 criterion for safe conditions. The overall percent correct prediction was 36 percent. The indicator correctly classified all unsafe conditions. It falsely classified 74 percent of the safe conditions as unsafe. Table 13 shows the prediction matrix for the 90-10 criterion for safe conditions. The overall percent correct prediction for the 90-10 criterion was 47 percent. The indicator correctly classified all unsafe conditions. However, it falsely classified 59 percent

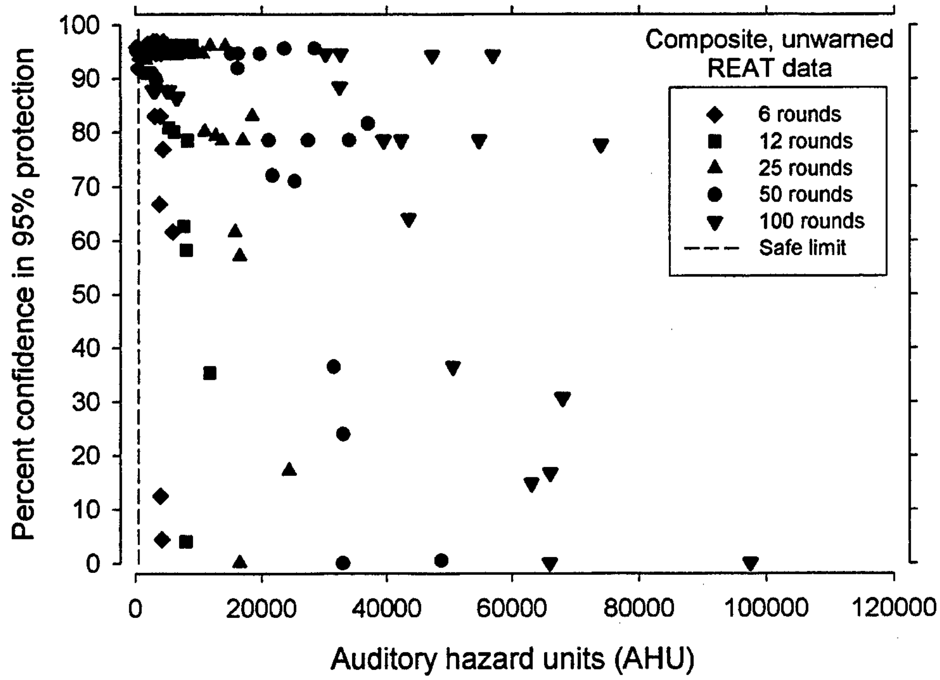

Figure 20. Composite percent confidence that the earmuffs provide adequate protection for 95 percent of the population as a function of unwarned auditory hazard units calculated from pressure-time signatures under the earmuffs, estimated from real ear attenuation data, all exposure conditions.

of the safe conditions as unsafe. As with the unwarned REAT calculations, the overall increase in AHUs contributed to the high false unsafe predictions when the 500-AHU limit is used.

Table 13 shows the prediction matrix using a 1200-AHU limit and the 50-50 criterion for safe conditions. The percent correct prediction rises to 50 percent. The percent false unsafe prediction drops to 58 percent. This is achieved while maintaining no false safe indications. Table 13 also shows the prediction matrix using the 1200-AHU limit and the 90-10 criterion for safe conditions. The percent correct prediction is 62 percent. The percent false unsafe prediction remains at 43 percent. There are no false safe indications. This is the best percent correct achievable for the warned REAT-estimated signatures without false safe predictions.

The performance of the model is no better using the REAT estimates than using the measured signatures. The overall increase in AHUs from the REAT estimates contributes to the poor performance of the model.

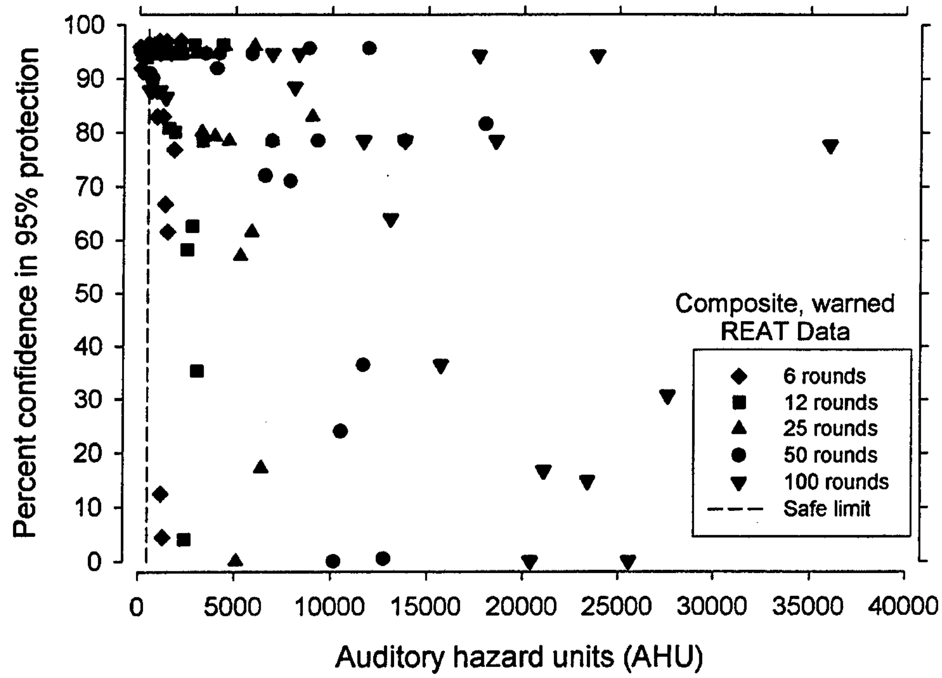

Figure 21. Composite percent confidence that the earmuffs provide adequate protection for 95 percent of the population as a function of warned auditory hazard units calculated from pressure-time signatures under the earmuffs, estimated from real-ear attenuation data, all exposure conditions.

<u>Confidence level as a function of AHUs from the MIRE-estimated pressure–time signatures</u>

The confidence that 95 percent of the exposed population would be protected as function of the AHUs calculated from the MIRE estimates of the under-the-earmuff signatures, using the unwarned calculation, is shown in appendix C, Figures C-1 through C-4, for the four free-field exposure groups. The confidence values were again taken from Tables 2 through 6. The 500-AHU limit is shown as the vertical line. The patterns of data are similar to the patterns noted for the measured signatures, except that the AHUs were typically larger for the MIRE-estimated signatures.

Figure 22 shows a composite of the data from all exposure conditions using the unwarned MIRE calculation. There is a lack of any systematic relationship between AHUs and the confidence that 95 percent of the population was protected for the MIRE-estimated data. As with the measured signatures, the unwarned MIRE data were separated into a two-by-two prediction matrix. The 500-AHU limit was used as an indication that an exposure condition was predicted to be safe for 95 percent of the population. An exposure condition was predicted to be unsafe if the AHUs were greater than 500. The data were classified as safe or unsafe exposures using both the 50-50 criterion and the 90-10 criterion. Table 14 shows the conditional percentage prediction matrix for the 50-50 criterion for classifying safe conditions. The overall percent correct prediction was only 19 percent. The indicator correctly classified all unsafe conditions. It falsely classified 95 percent of the safe conditions as unsafe. Table 14 also shows the prediction matrix for the 90-10 criterion for safe conditions. The overall percent correct prediction for the 90-10 criterion was 18 percent. The indicator correctly classified all unsafe conditions. However, it falsely classified 92 percent of the safe conditions as unsafe. These false unsafe rates are even higher than the rates for the measured signatures. This is due to the overall increase in the unwarned MIRE AHUs for all the exposure conditions.

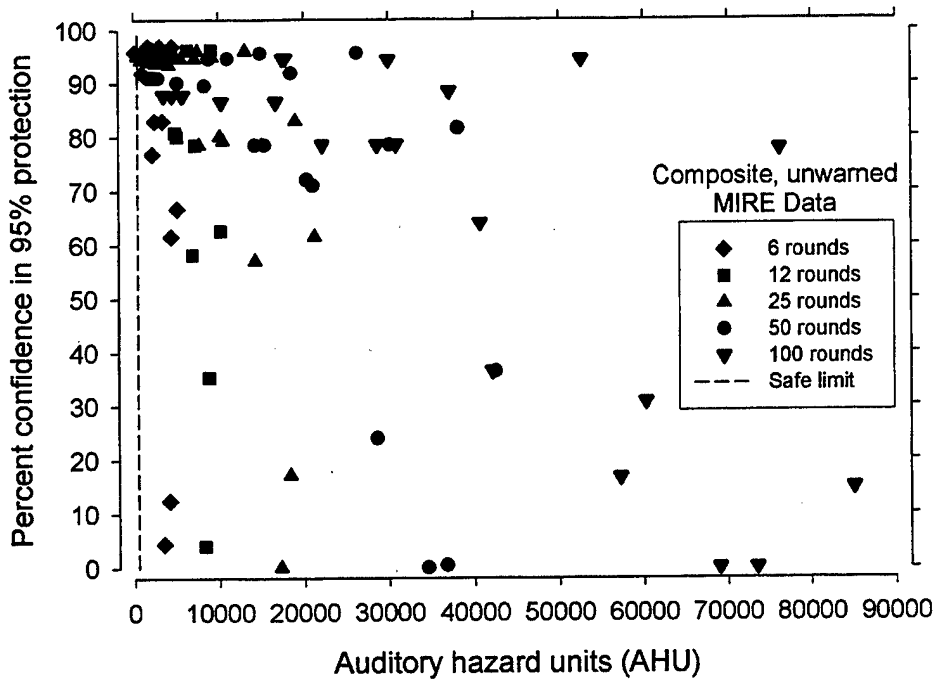

Figure 22. Composite percent confidence that the earmuffs provide adequate protection for 95 percent of the population as a function of unwarned auditory hazard units calculated from pressure-time signatures under the earmuffs, estimated from physical-ear attenuation data, all exposure conditions.

The high rate of false unsafe classifications can be mitigated by raising the AHU-limit for safe conditions. Table 14 shows the prediction matrix using a 3485-AHU limit and the 50-50 criterion for safe conditions. The percent correct prediction rises to 48 percent. The percent false unsafe prediction drops to 61 percent. This is achieved while maintaining no false safe indications. Table 14 also shows the prediction matrix using the 3485-AHU limit and the 90-10 criterion for safe conditions. The percent correct prediction rises to 62 percent. The false unsafe prediction drops to 43 percent. There are no false safe indications. This is the best percent correct achievable for the unwarned MIRE data without false safe predictions.

The confidence that 95 percent of the exposed population would be protected as function of the AHUs calculated from the MIRE estimates of the under-the-earmuff signatures, using the warned calculation, is shown in appendix C, Figures C-5 through C-8, for the four free-field exposure groups. The confidence values were again taken from Tables 2 through 6. The 500-AHU limit is shown as the vertical line. The patterns of data are similar to the patterns noted for the measured signatures using the warned calculations except that the AHUs were typically larger for the MIRE-estimated signatures.

Table 14.
Percent model predictions of safe and unsafe exposure conditions using MIRE-estimated under-the-earmuff data from all free-field exposure distances.

Model ear state	AHU limit	Classification Criterion	Model Prediction	Classification Safe	Classification Unsafe	Percent correct
Unwarned	500	50-50 confidence	Safe	5	0	19
			Unsafe	95	100	
Unwarned	500	90-10 confidence	Safe	8	0	18
			Unsafe	92	100	
Unwarned	3485	50-50 confidence	Safe	39	0	48
			Unsafe	61	100	
Unwarned	3485	90-10 confidence	Safe	57	0	62
			Unsafe	43	100	
Warned	500	50-50 confidence	Safe	23	0	34
			Unsafe	77	100	
Warned	500	90-10 confidence	Safe	36	0	43
			Unsafe	64	100	
Warned	645	50-50 confidence	Safe	32	0	42
			Unsafe	68	100	
Warned	645	90-10 confidence	Safe	49	0	54
			Unsafe	51	100	

Figure 23 shows a composite of the data from all exposure conditions using the warned MIRE calculation. As with the unwarned analysis, there is a lack of any systematic relationship between warned AHUs and the confidence that 95 percent of the population was protected for the MIRE-estimated data.

As with the measured signatures, the data were separated into a two-by-two prediction matrix. The 500-AHU limit was used as an indication that an exposure condition was predicted to be safe for 95 percent of the population. The data were classified as safe or unsafe exposures using both the 50-50 criterion and the 90-10 criterion. Table 14 shows the prediction matrix for the 50-50 criterion for safe conditions. The overall percent correct prediction was 34 percent.

The indicator correctly classified all unsafe conditions. It falsely classified 77 percent of the safe conditions as unsafe. Table 14 shows the prediction matrix for the 90-10 criterion for safe conditions. The overall percent correct prediction for the 90-10 criterion was 43 percent. The indicator correctly classified all unsafe conditions. However, it falsely classified 64 percent of the safe conditions as unsafe. As with the unwarned MIRE calculations, the overall increase in AHUs contributed to the high false unsafe predictions when the 500-AHU limit is used.

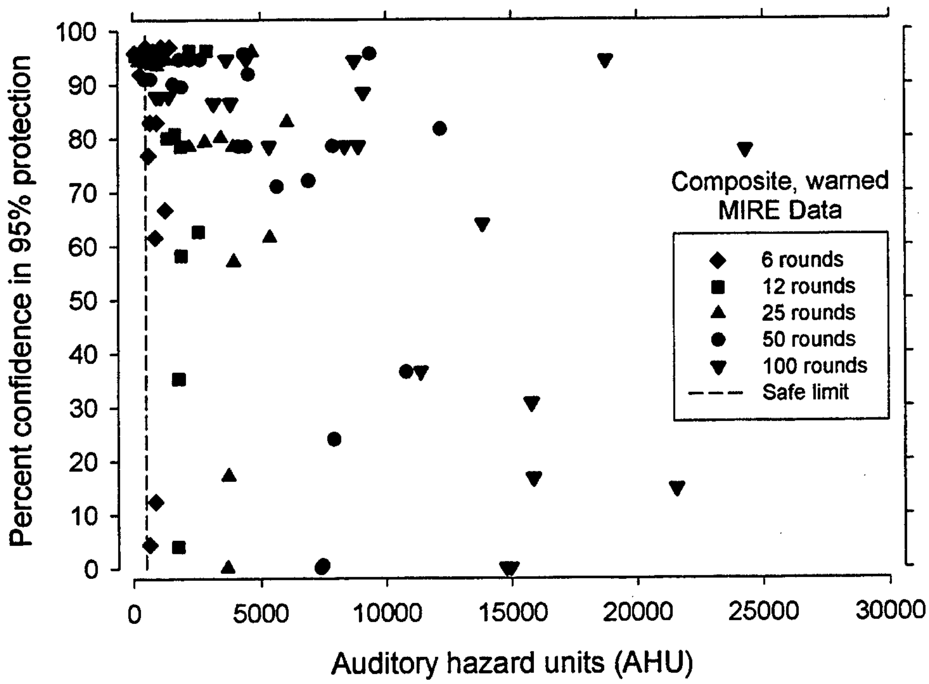

Figure 23. Composite percent confidence that the earmuffs provide adequate protection for 95 percent of the population as a function of warned auditory hazard units calculated from pressure-time signatures under the earmuffs, estimated from physical-ear attenuation data, all exposure conditions.

Table 14 shows the prediction matrix using a 645-AHU limit and the 50-50 criterion for safe conditions. The percent correct prediction rises to 42 percent. The percent false unsafe prediction drops to 68 percent. This is achieved while maintaining no false safe indications. Table 14 also shows the prediction matrix using the 645-AHU limit and the 90-10 criterion for safe conditions. The percent correct prediction is 54 percent. The percent false unsafe prediction remains at 51 percent. There are no false safe indications. This is the best percent correct achievable for the warned MIRE-estimated signatures without false safe predictions.

The performance of the model is no better using the MIRE estimates than using the measured signatures or the REAT estimates. The overall increase in AHUs using the MIRE estimates contributes to the poor performance of the model.

Number-level trading relation

Number-level trading rules take the form:

$$Limit = Level + R \times Log(N / N_0)$$

Where: *Limit* is a constant (maximum safe exposure)
Level is a peak-pressure level or energy level in dB
R is the trading relation constant
N is the number of impulses
N_0 is a reference number, commonly = 1

MIL-STD-1474D uses R = 5; equal energy uses R = 10. In Figure 24, R = 3 was used to align the data. Patterson et al. (1997) found R = 3 fit the confidence level data best for several hazard indicators. Chan et al. (2001) found R = 3.44 fit the human data from the same studies. The value of R is an indication of how fast the hazard indicator grows with increasing numbers of impulses relative to the exposure level. The AHUs are additive across multiple impulse exposures and are directly proportional to the number of impulses. This causes the AHUs to increase rapidly with increasing numbers of impulses. To evaluate the trading rule for the AHAAH model, a pressure-time signature measured under the modified earmuffs from each free-field distance was selected such that the unwarned AHUs were approximately 100. This implied that five rounds should be the maximum number-of-safe exposures for each signature. These signatures were scaled by ±10 and ±20 dB using the scaling feature of the model. This resulted in five signatures that spanned a 40 dB range for each exposure distance. These were analyzed for both unwarned and warned AHUs, and the corresponding allowable number of impulses for each scaled signature. The logarithm of each allowable number of rounds divided by the largest of the five is shown in Figure 24 for the unwarned analysis and in Figure 25 for the warned analysis. The unwarned AHU data are close to the R = 25 line for all three distance conditions. For reference, R = 10, R = 5, and R = 3 lines are shown. These results indicate that the unwarned AHUs increase much faster with increasing numbers of impulses than the actual hazard. The warned analysis resulted in an R = 18. This is still larger than is indicated by the human data, which is more consistent with an R = 3.

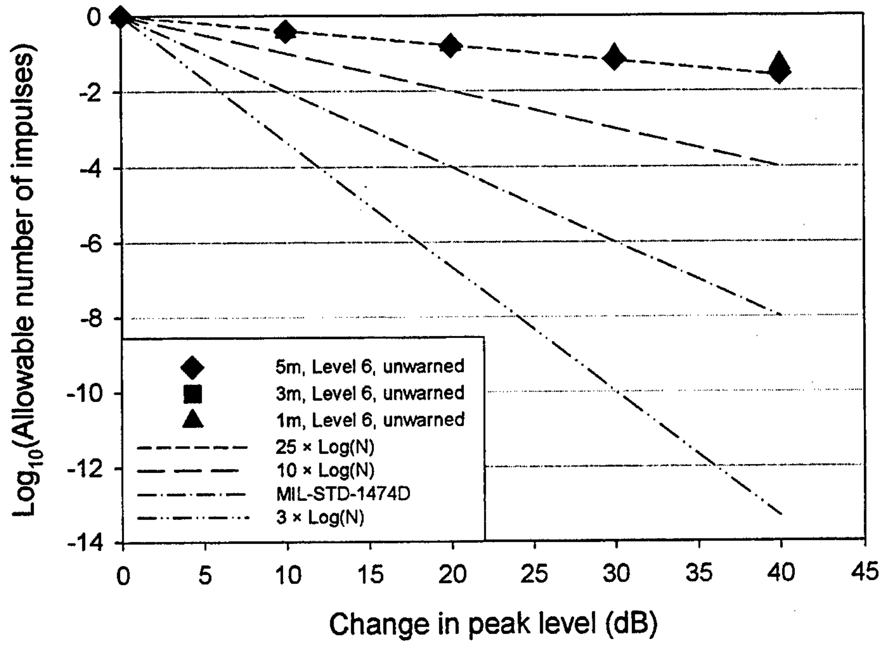

Figure 24. The logarithm of the ratio of each allowable number of rounds to the largest of the five, unwarned analysis.

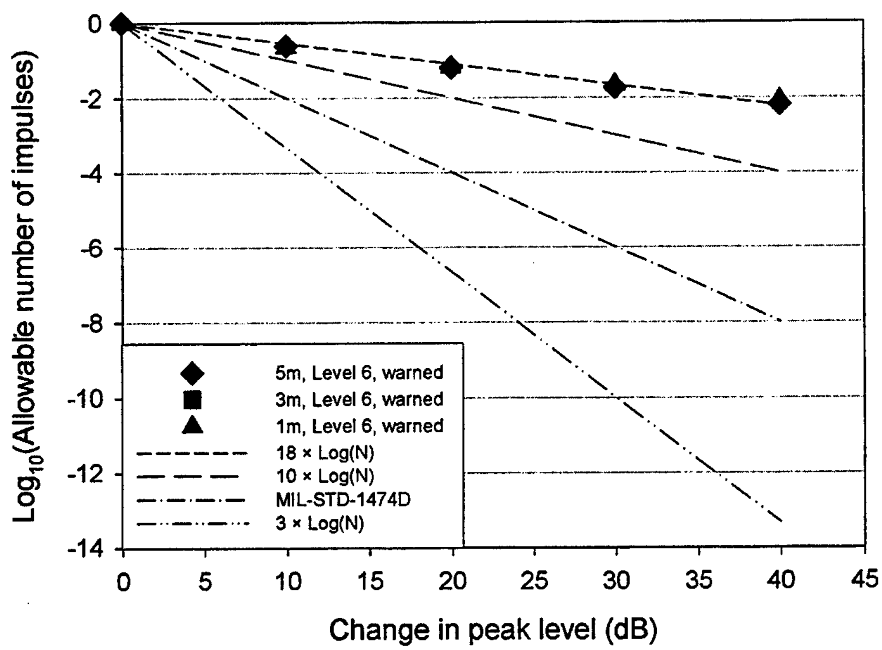

Figure 25. The logarithm of the ratio of each allowable number of rounds to the largest of the five, warned analysis.

Conclusions

The auditory hazard assessment model index of hazard (AHUs) was not in general agreement with the results of the Albuquerque human volunteer studies conducted for the U.S. Army Medical Research and Materiel Command. It overestimated the hazard in many cases when the unwarned middle ear analysis feature of the model was used. It underestimated the hazard in a number of cases when the warned middle ear analysis feature was used. Some exposures for which there was high confidence that the exposures were not safe were predicted to be safe using the warned middle ear analysis. There was a general lack of a systematic relationship between the calculated AHUs and the confidence that 95 percent of the exposed population would not show a significant threshold shift. The minimum-phase estimates of exposure under the earmuffs showed large deviations from the measured levels under the earmuffs. Neither the REAT nor the MIRE minimum-phase calculations resulted in accurate predictions of the auditory hazard. The indicated hazard increased much too fast with increases in number of impulses.

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Appendix A

Figures showing confidence in 95 percent protection as a function of AHUs calculated from measurements of under the earmuff pressure-time signatures.

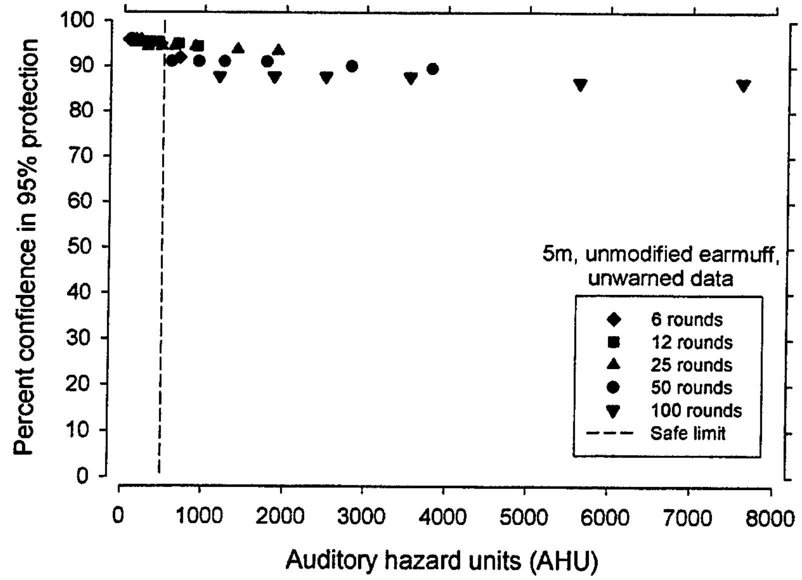

Figure A-1. Percent confidence that the unmodified earmuffs provide adequate protection for 95 percent of the population as a function of unwarned auditory hazard units calculated from pressure-time signatures measured under the earmuffs, 5-meter exposure condition.

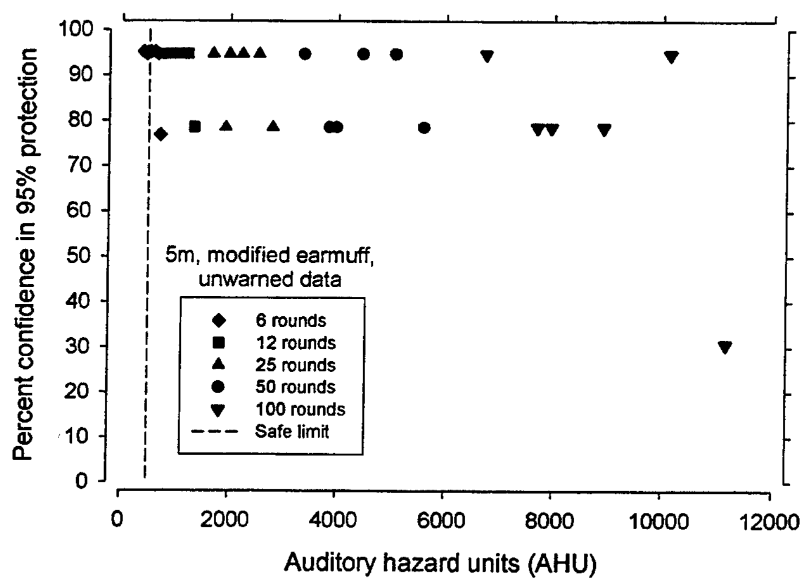

Figure A-2. Percent confidence that the modified earmuffs provide adequate protection for 95 percent of the population as a function of unwarned auditory hazard units calculated from pressure-time signatures measured under the earmuffs, 5-meter exposure condition.

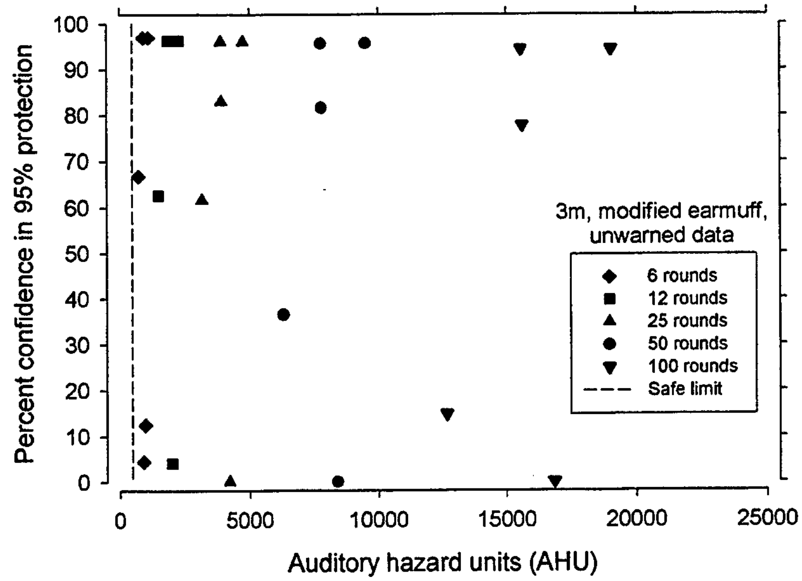

Figure A-3. Percent confidence that the modified earmuffs provide adequate protection for 95 percent of the population as a function of unwarned auditory hazard units calculated from pressure-time signatures measured under the earmuffs, 3-meter exposure condition.

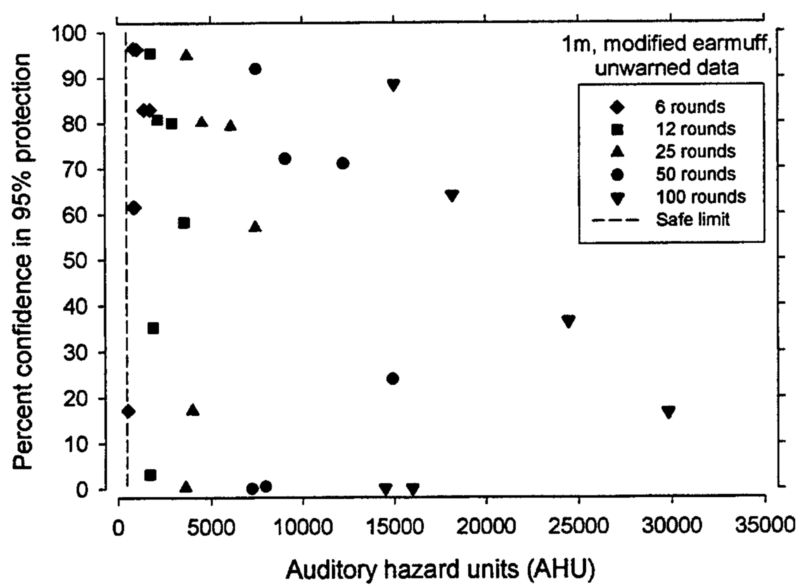

Figure A-4. Percent confidence that the modified earmuffs provide adequate protection for 95 percent of the population as a function of unwarned auditory hazard units calculated from pressure-time signatures measured under the earmuffs, 1-meter exposure condition.

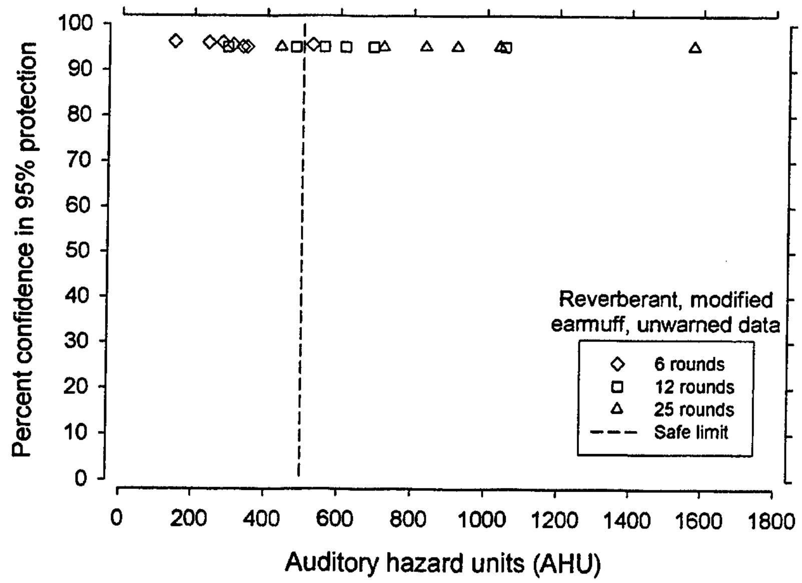

Figure A-5. Percent confidence that the modified earmuffs provide adequate protection for 95 percent of the population as a function of unwarned auditory hazard units calculated from pressure-time signatures measured under the earmuffs, reverberant exposure condition.

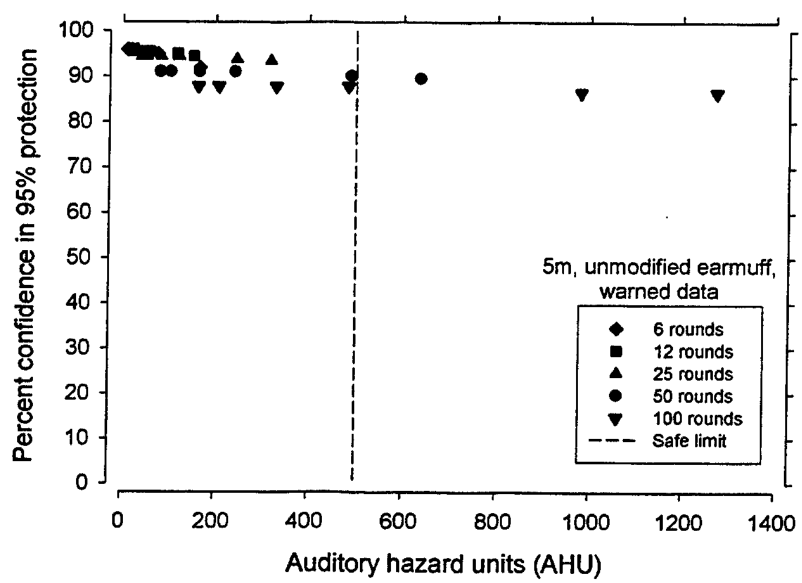

Figure A-6. Percent confidence that the unmodified earmuffs provide adequate protection for 95 percent of the population as a function of warned auditory hazard units calculated from pressure-time signatures measured under the earmuffs, 5-meter exposure condition.

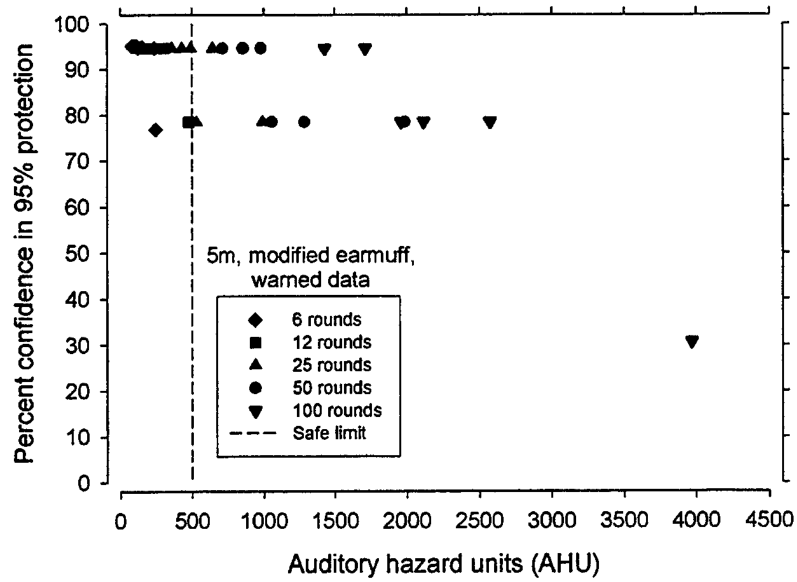

Figure A-7. Percent confidence that the modified earmuffs provide adequate protection for 95 percent of the population as a function of warned auditory hazard units calculated from pressure-time signatures measured under the earmuffs, 5-meter exposure condition.

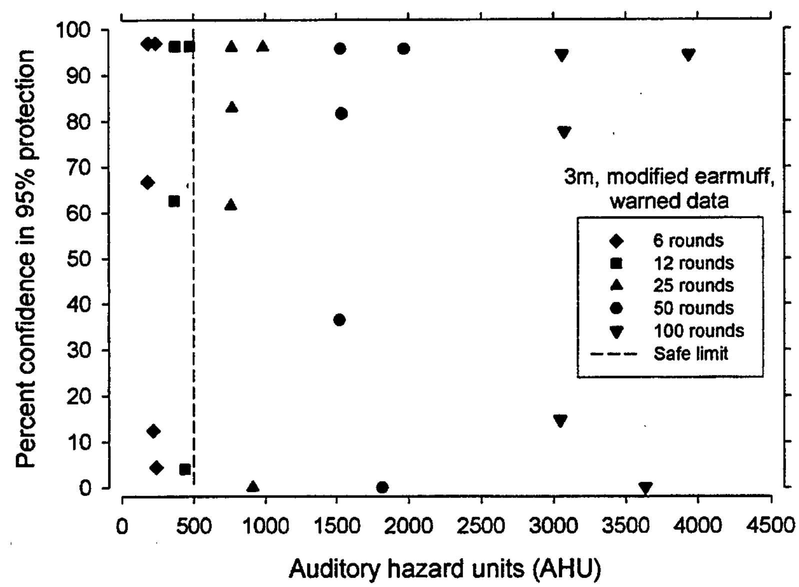

Figure A-8. Percent confidence that the modified earmuffs provide adequate protection for 95 percent of the population as a function of warned auditory hazard units calculated from pressure-time signatures measured under the earmuffs, 3-meter exposure condition.

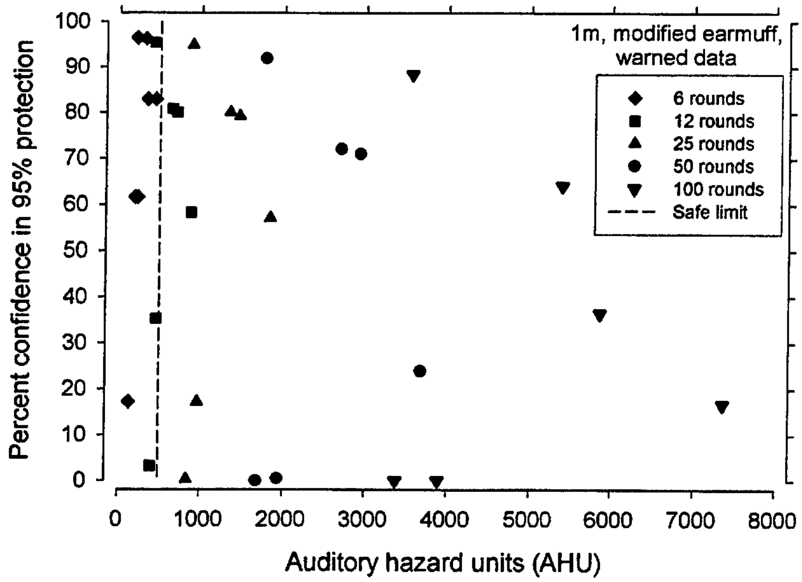

Figure A-9. Percent confidence that the modified earmuffs provide adequate protection for 95 percent of the population as a function of warned auditory hazard units calculated from pressure-time signatures measured under the earmuffs, 1-meter exposure condition.

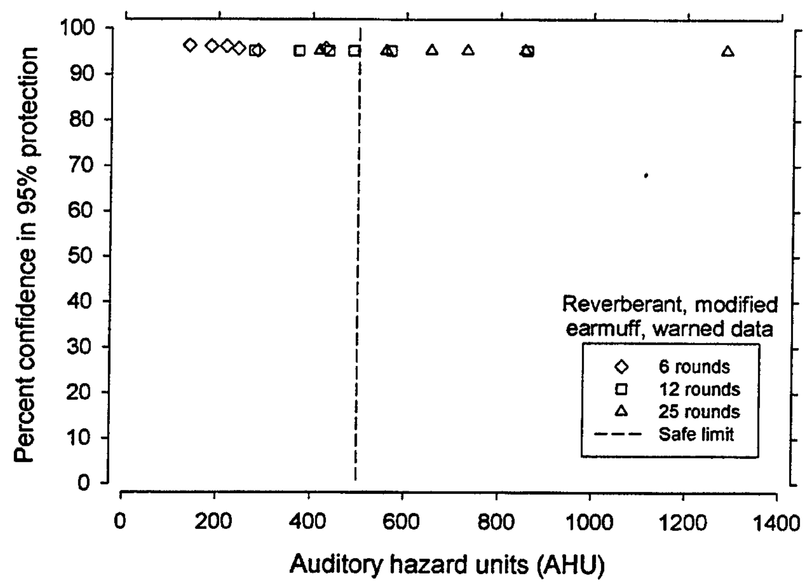

Figure A-10. Percent confidence that the modified earmuffs provide adequate protection for 95 percent of the population as a function of warned auditory hazard units calculated from pressure-time signatures measured under the earmuffs, reverberant exposure condition.

Appendix B

Figures showing confidence in 95 percent protection as a function of AHUs calculated from REAT estimates of under the earmuff pressure-time signatures.

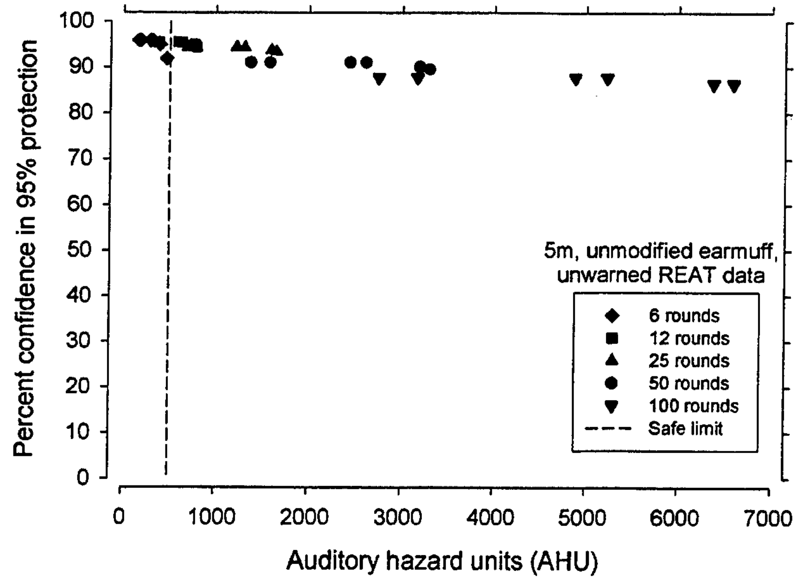

Figure B-1. Percent confidence that the unmodified earmuffs provide adequate protection for 95 percent of the population as a function of unwarned auditory hazard units calculated from pressure-time signatures under the earmuffs, estimated from real-ear attenuation data, 5-meter exposure condition.

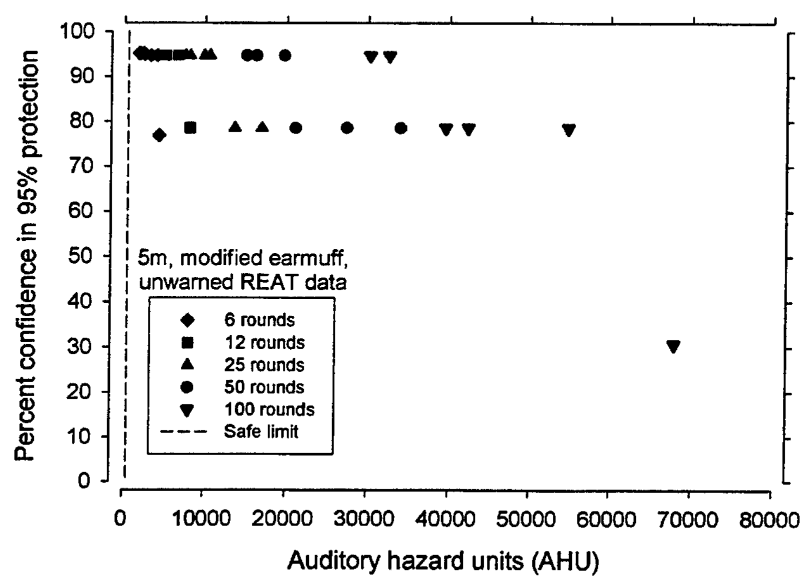

Figure B-2. Percent confidence that the modified earmuffs provide adequate protection for 95 percent of the population as a function of unwarned auditory hazard units calculated from pressure-time signatures under the earmuffs, estimated from real-ear attenuation data, 5-meter exposure condition.

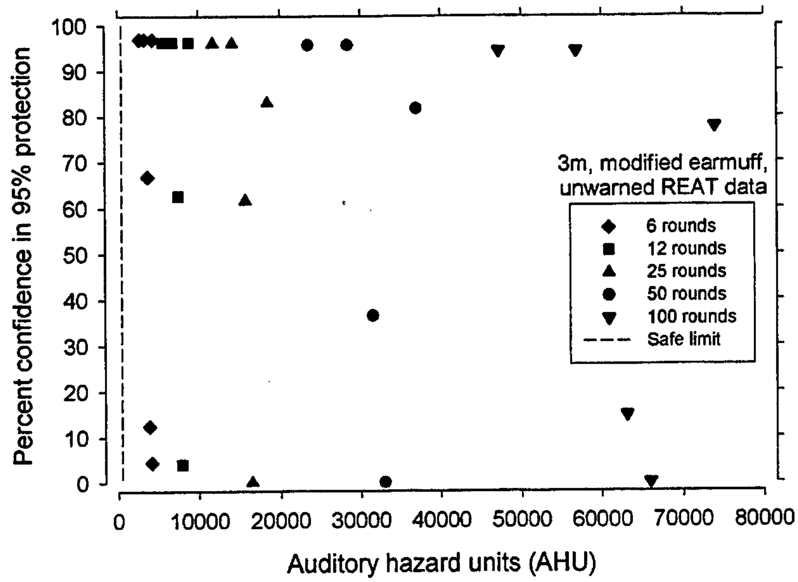

Figure B-3. Percent confidence that the modified earmuffs provide adequate protection for 95 percent of the population as a function of unwarned auditory hazard units calculated from pressure-time signatures under the earmuffs, estimated from real-ear attenuation data, 3-meter exposure condition.

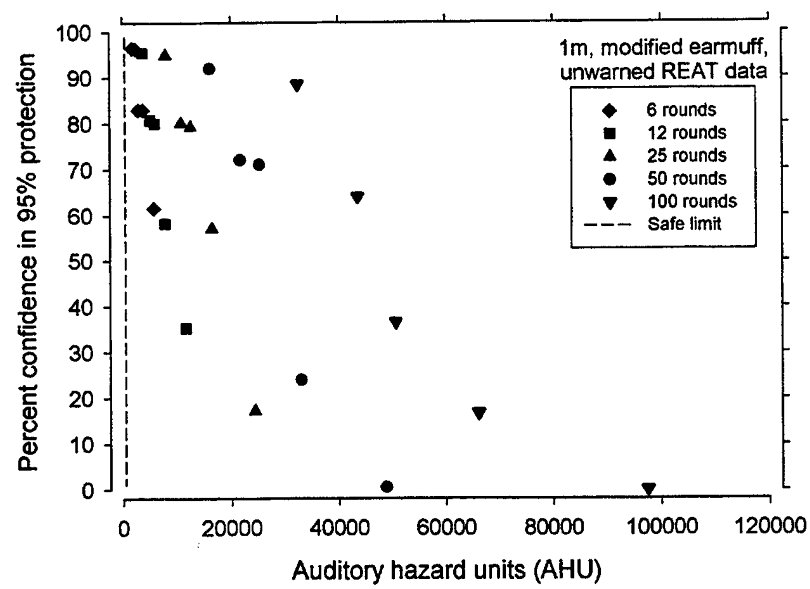

Figure B-4. Percent confidence that the modified earmuffs provide adequate protection for 95 percent of the population as a function of unwarned auditory hazard units calculated from pressure-time signatures under the earmuffs, estimated from real-ear attenuation data, 1-meter exposure condition.

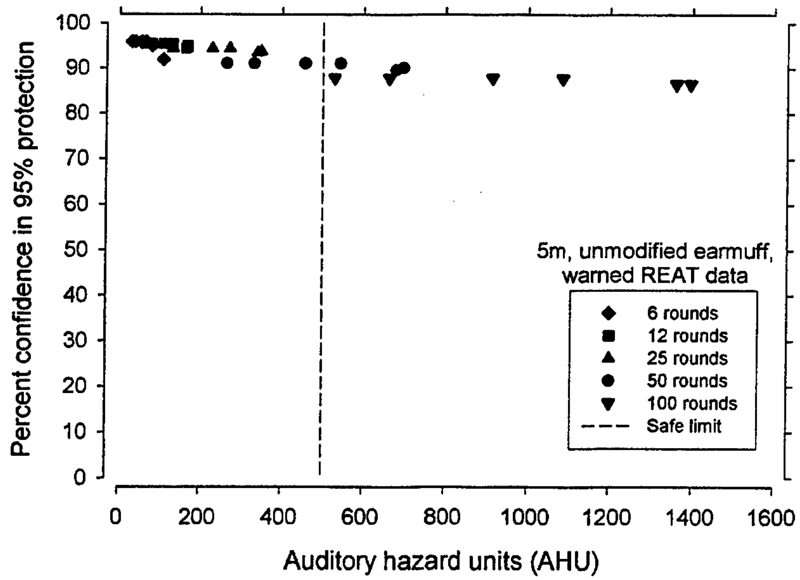

Figure B-5. Percent confidence that the unmodified earmuffs provide adequate protection for 95 percent of the population as a function of warned auditory hazard units calculated from pressure-time signatures under the earmuffs, estimated from real-ear attenuation data, 5-meter exposure condition.

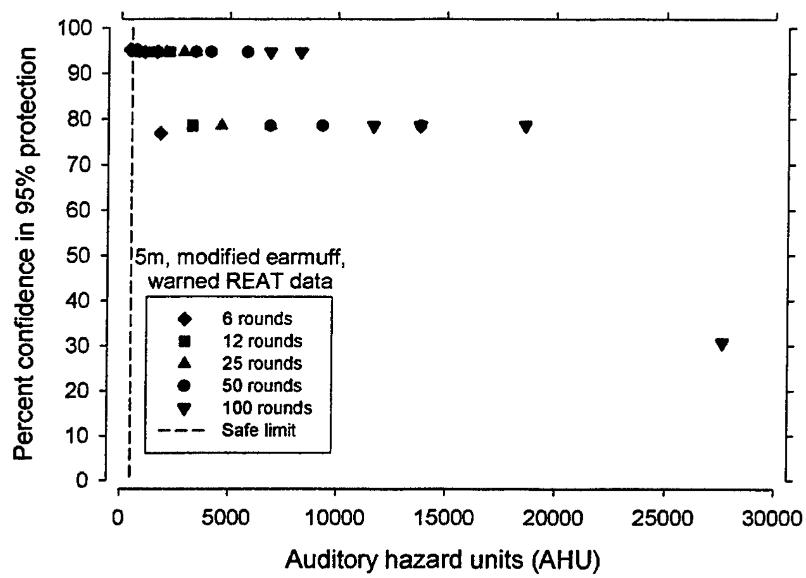

Figure B-6. Percent confidence that the modified earmuffs provide adequate protection for 95 percent of the population as a function of warned auditory hazard units calculated from pressure-time signatures under the earmuffs, estimated from real-ear attenuation data, 5-meter exposure condition.

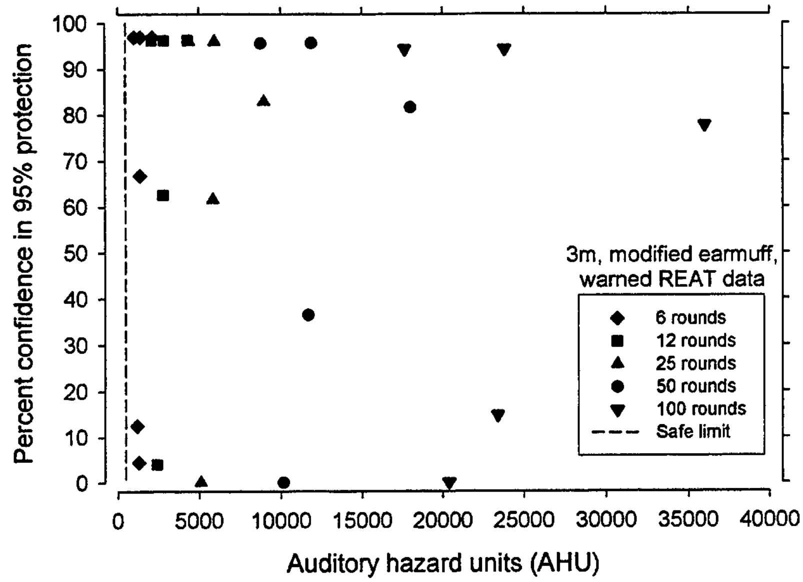

Figure B-7. Percent confidence that the modified earmuffs provide adequate protection for 95 percent of the population as a function of warned auditory hazard units calculated from pressure-time signatures under the earmuffs, estimated from real-ear attenuation data, 3-meter exposure condition.

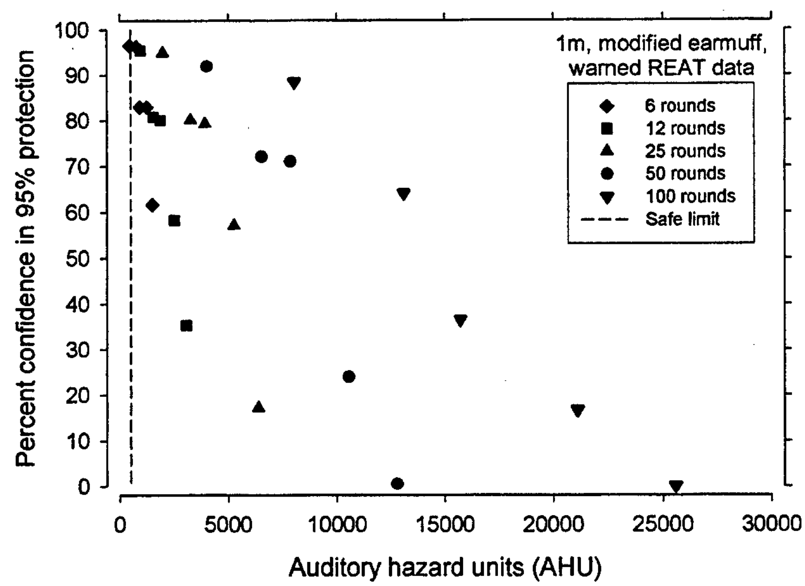

Figure B-8. Percent confidence that the modified earmuffs provide adequate protection for 95 percent of the population as a function of warned auditory hazard units calculated from pressure-time signatures under the earmuffs, estimated from real-ear attenuation data, 1-meter exposure condition.

Appendix C

Figures showing confidence in 95 percent protection as a function of AHUs calculated from MIRE estimates of under the earmuff pressure-time signatures.

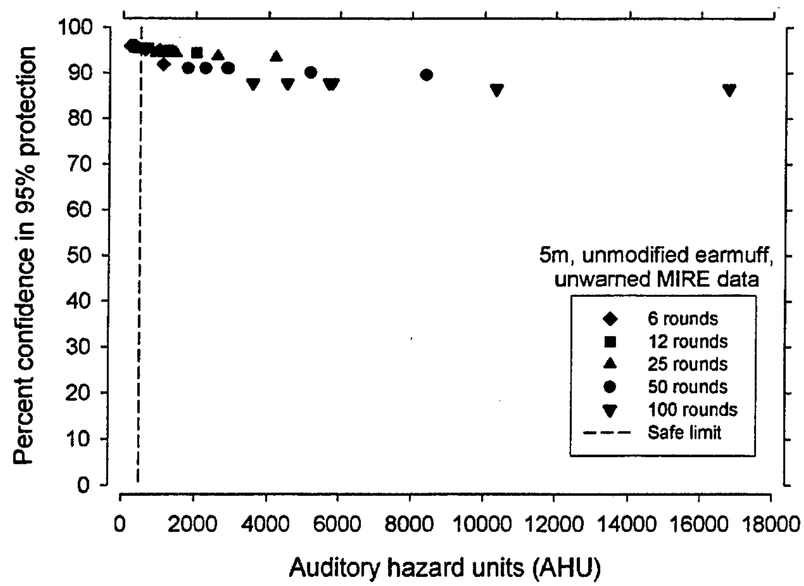

Figure C-1. Percent confidence that the unmodified earmuffs provide adequate protection for 95 percent of the population as a function of unwarned auditory hazard units calculated from pressure-time signatures under the earmuffs, estimated from physical-ear attenuation data, 5-meter exposure condition.

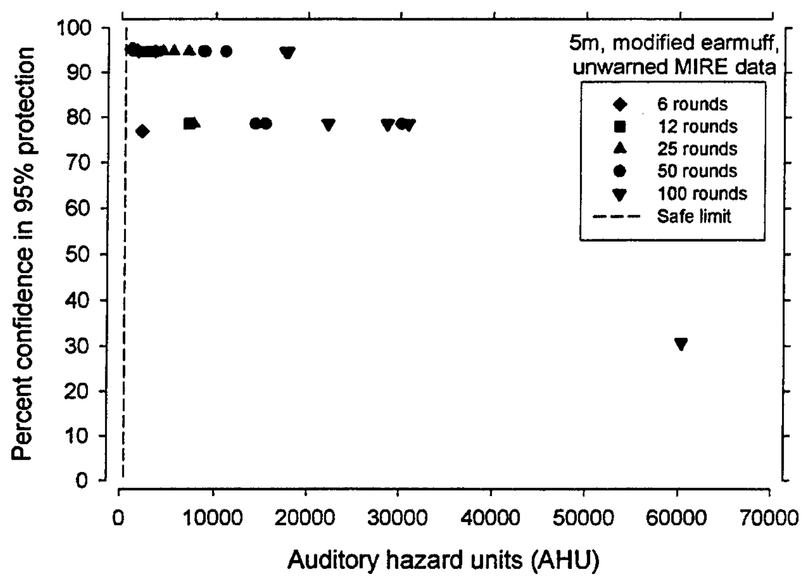

Figure C-2. Percent confidence that the modified earmuffs provide adequate protection for 95 percent of the population as a function of unwarned auditory hazard units calculated from pressure-time signatures under the earmuffs, estimated from physical-ear attenuation data, 5-meter exposure condition.

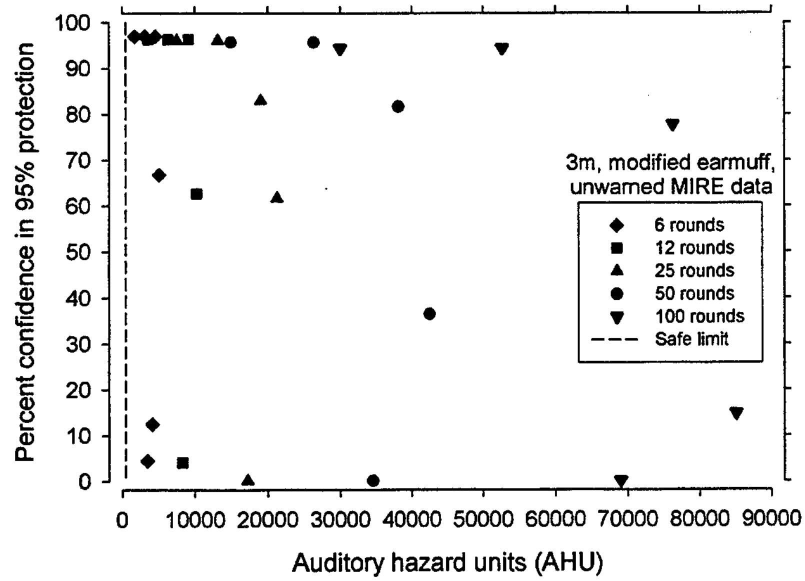

Figure C-3. Percent confidence that the modified earmuffs provide adequate protection for 95 percent of the population as a function of unwarned auditory hazard units calculated from pressure-time signatures under the earmuffs, estimated from physical-ear attenuation data, 3-meter exposure condition.

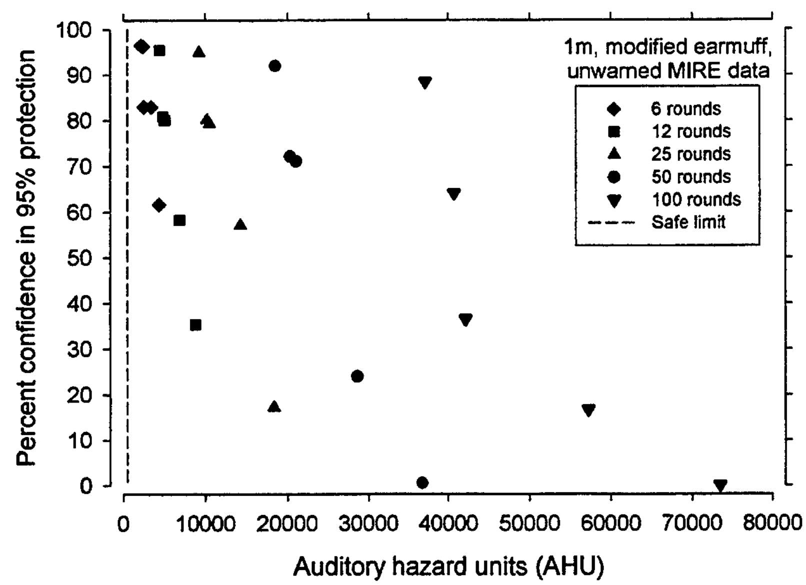

Figure C-4. Percent confidence that the modified earmuffs provide adequate protection for 95 percent of the population as a function of unwarned auditory hazard units calculated from pressure-time signatures under the earmuffs, estimated from physical-ear attenuation data, 1-meter exposure condition.

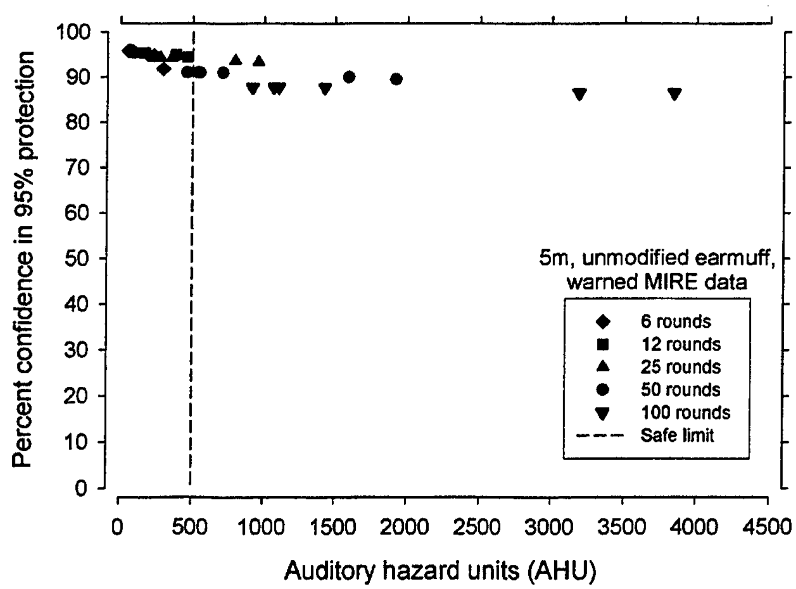

Figure C-5. Percent confidence that the unmodified earmuffs provide adequate protection for 95 percent of the population as a function of warned auditory hazard units calculated from pressure-time signatures under the earmuffs, estimated from physical-ear attenuation data, 5-meter exposure condition.

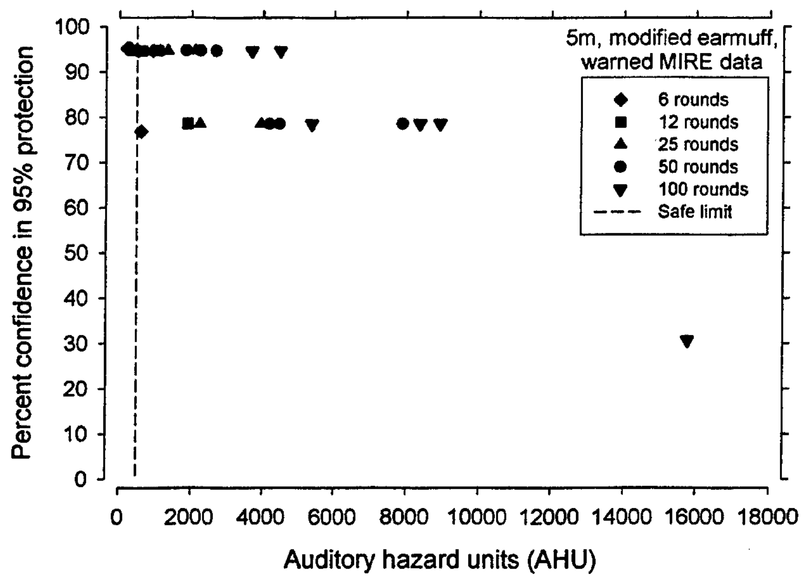

Figure C-6. Percent confidence that the modified earmuffs provide adequate protection for 95 percent of the population as a function of warned auditory hazard units calculated from pressure-time signatures under the earmuffs, estimated from physical-ear attenuation data, 5-meter exposure condition.

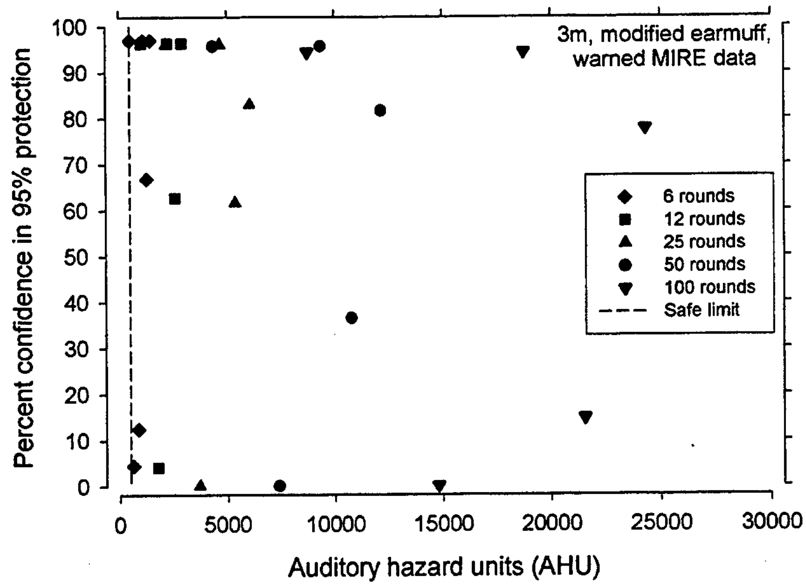

Figure C-7. Percent confidence that the modified earmuffs provide adequate protection for 95 percent of the population as a function of warned auditory hazard units calculated from pressure-time signatures under the earmuffs, estimated from physical-ear attenuation data, 3-meter exposure condition.

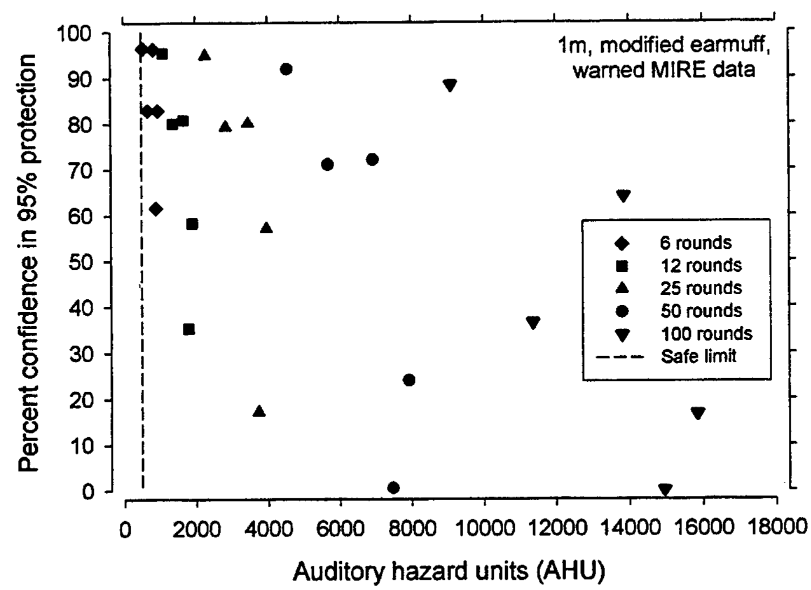

Figure C-8. Percent confidence that the modified earmuffs provide adequate protection for 95 percent of the population as a function of warned auditory hazard units calculated from pressure-time signatures under the earmuffs, estimated from physical-ear attenuation data, 1-meter exposure condition.