Active Noise Reduction (ANR) in Hearing Protection: Does it Make Sense for Industrial Applications?

E-A-R 01-16/HP

E. H. Berger, M.S.

E•A•R / Aearo Company
E•A•RCAL^{SM} Laboratory
7911 Zionsville Road
Indianapolis, IN 46268-1657
phone: 317-692-1111
fax: 317-692-3116
email:eberger@compuserve.com

February 26, 2002

Version 1.9

An invited paper for a special discussion session presented at the 27th Conference of the National Hearing Conservation Association, Dallas, TX
Spectrum Supplement 1, 20

E•A•RCAL^{SM} Laboratory is accredited by the National Institute of Standards and Technology, National Voluntary Laboratory Accreditation Program, for the measurement of attenuation of hearing protection devices re ANSI S3.19-1974 and ANSI S12.6-1997. NVLAP Laboratory Code 100374-0.

ACTIVE NOISE REDUCTION (ANR) IN HEARING PROTECTION: DOES IT MAKE SENSE FOR INDUSTRIAL APPLICATIONS?

E. H. BERGER, E-A-R / AEARO COMPANY
7911 Zionsville Rd., Indianapolis, IN 46268-1657; eberger@compuserve.com

ABSTRACT

Active noise reduction (ANR) is a much-heralded technology that would seem to offer interesting promise for enhancing the degree of noise attenuation provided by conventional passive hearing protection. For over 20 years researchers, especially those in the military, have been aggressively pursuing development of ANR, yet its application to industrial noise exposures where employees are mobile and exposed to varying noise sources has been limited, and for good reasons. Nevertheless many hearing conservationists seek ANR devices as though they were the Holy Grail, capable of solving the nastiest of noise exposure problems. This paper will explore the gains available in the best ANR earmuffs developed to date, and compare the protection provided by conventional and ANR devices worn in 300 typical industrial environments, including some predominantly low-frequency noise exposures. In terms of reduction in the overall A-weighted noise levels, it will be shown that in all but a small percentage of industrial environments, a conventional earmuff will provide essentially equivalent protection. This may be surprising especially in light of the dramatic auditory effect one can perceive when switching an ANR earmuff on and off in a low-frequency dominated noise. An explanation for this discrepancy is provided. The reader is encouraged to review an accompanying paper by D. Gauger of Bose Corporation (Gauger, 2002) that describes valid and useful applications for ANR hearing protection technology, primarily in general aviation and military environments.

INTRODUCTION

Conventional passive hearing protection is a relatively mature technology that has undergone approximately one-half century of evolution since the end of World War II. Of more recent development has been the design of noise-canceling circuitry that can be incorporated into hearing protectors to sense the sounds that pass through the hearing protector, invert them in phase, and rebroadcast them via an earphone to provide active noise reduction. It is natural to presume that with today's advanced electronic devices, passive protection could be improved upon by such noise-canceling circuitry in hearing protection devices (HPDs) especially for earmuffs, if not also earplugs. Noise-cancellation devices, commonly referred to as active noise reduction (ANR) HPDs, have been the subject of much research and many claims.

As ANR developments have continued, not only are analog devices being produced, but digital systems as well. Naturally, hearing conservationists in their quest for maximum protection in severe noise environments have been prone to turn to this electronic technology expecting that it would have much to offer. The purpose of this paper is to provide them guidance for the typical industrial application, namely an employee freely moving through an industrial space, not constrained to a vehicle or instrument panel, with no readily available source of electrical power except for batteries, and with no built-in communication systems in his or her HPDs. Although ANR earplugs are currently under development, the focus of this paper will be on ANR earmuffs since the devices which are commercially available today are only of that variety.

For a general discussion of ANR systems the reader is encourage to turn to Casali and Berger (1996) and Gauger and Sapiejewski (1999) as listed in the references.

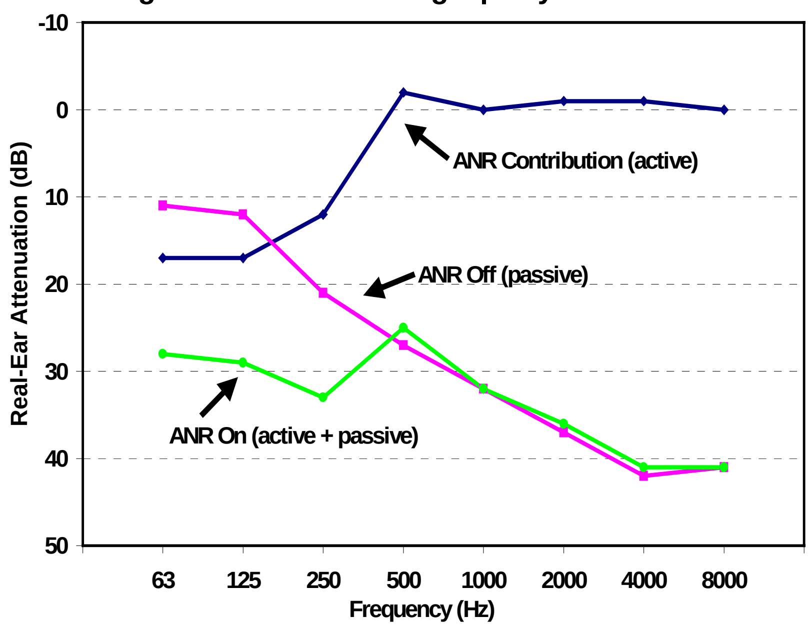
MATERIALS

The Earmuff

I have been asked on a number of occasions to evaluate ANR systems and have also reviewed numerous studies in the literature. Based upon my experience, a single prototype ANR system that was measured in our laboratory was selected as it represents one of the highest attenuating ANR earmuffs evaluated to date.

Real-ear attenuation at threshold (REAT) was measured for this device turned off as well as for a conventional earmuff using a similar sized and shaped cup, but lacking the ANR components. The laboratory-measured NRR of the conventional earmuff was approximately 26 dB. Additionally, microphone-in real ear (MIRE) measurements on a group of subjects were recorded for the ANR earmuff in the on and off conditions in order to estimate the degree of active noise reduction.[1] The active reduction was added to the REAT values to estimate the total noise reduction provided by the ANR when turned on.[2] The data for the ANR earmuff are presented in Figure 1. Notice that up through approximately 400 Hz ANR provides useful gains with a peak performance of nearly 20 dB at 63 Hz and 125 Hz. However, at 500 Hz there is a small net loss in performance and essentially no effect at the higher frequencies.

Figure 1: Attenuation of high-quality ANR earmuff



---

[1] REAT cannot be used to evaluate the attenuation provided by ANR devices because they create broadband residual noise that is audible in a very quiet test chamber. This creates masking in the occluded condition that would spuriously elevate the measured attenuation values.

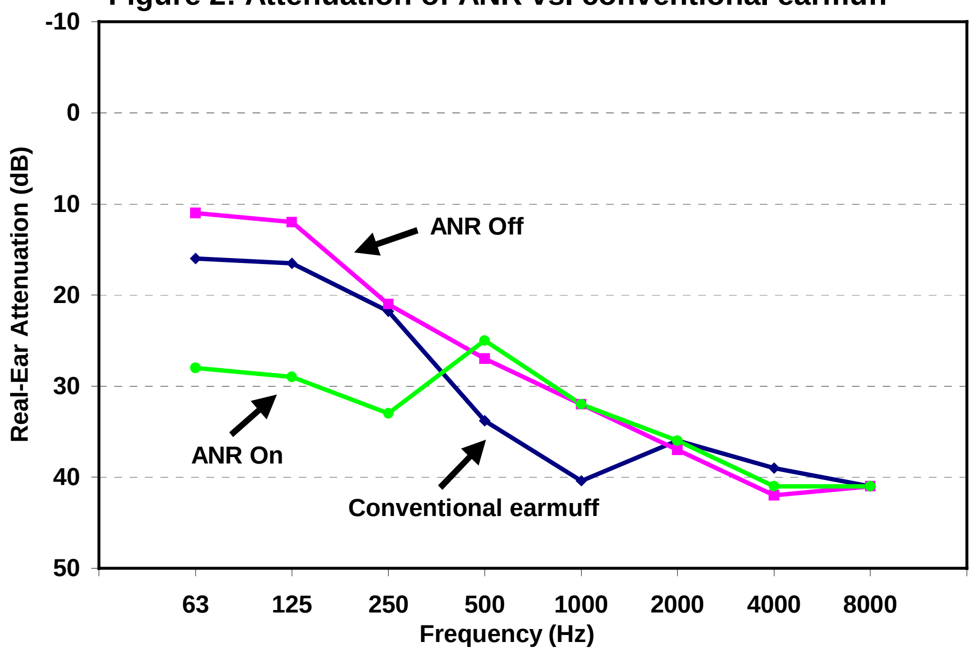
[2] In this paper REAT values were utilized for the passive attenuation estimate for both earmuffs. The active performance of the ANR device was estimated by adding the MIRE values to the REAT. One could also argue that one should base all the measurements on MIRE data (for both the passive and active modes) since it is well documented that at low frequencies REAT values are spuriously elevated due to physiological noise masking (Berger and Kerivan, 1983). The error is approximately 3 dB @ 125 Hz for the muffs evaluated herein, which would cause the performance of the ANR earmuffs to look slightly more favorable in the subsequent analyses, but would not materially effect any of the conclusions. REAT was selected since those values are more commonly reported in general hearing conservation practice.

In Figure 2 the ANR and conventional earmuff are compared. The ANR device performs very well up through 250 Hz but at the important frequencies of 500 and 1000 Hz where the active circuitry provides no advantage or even a net loss, the performance is inferior to a good conventional earmuff. At and above 2 kHz, where ANR neither adds nor detracts from performance, the conventional and ANR earmuffs are essentially identical. This is because the act of putting the ANR components into the earmuff cup degrades its passive performance. The active performance, which is nonexistent at and above 500 Hz (see Figure 1), is unable at those frequencies to provide an offsetting gain.

The Noises

The noise data base used for the analysis was based upon three studies published in the literature. In 1953 Karplus and Bonvallet published a set of 579 representative occupational noise spectra. In 1975 NIOSH selected a subset of 100 that were intended to provide a representative index of U. S. industry (Kroes et al., 1975). Those have been the “gold standard” of noise spectra, but today they are nearly 50 years old. In 1969 a similar exercise was conducted and published in which 615 South Australian spectra were recorded (McQueen et al., 1969). And in the late 1980s and early 1990s the exercise was repeated yet again in New Zealand (Backshall, 2000).

Figure 2: Attenuation of ANR vs. conventional earmuff

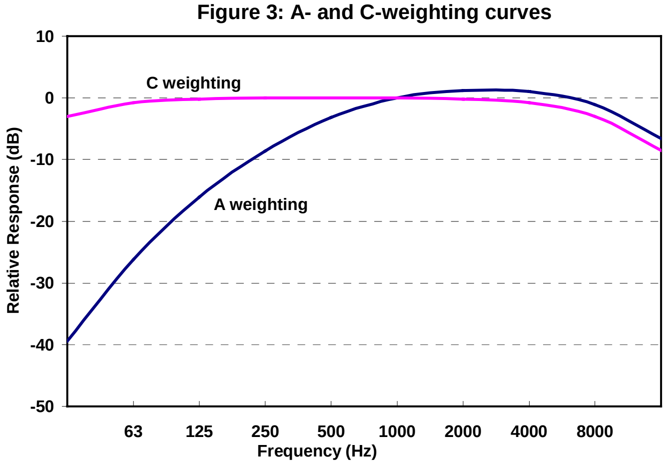


Previously Berger (2000) has examined these data bases and found a general similarity, although the South Australian noises cover a broader range of spectral values and include a greater proportion of noise with high-frequency energy. For this study a quasi-random subset of 100 of the South Australian and 100 of the New Zealand noises were combined with the 100 NIOSH noises to produce a set of 300 noises with which to work.

When examining a large noise database it is helpful to find simplified ways of characterizing the data. Normally researchers have used the A-weighted and C-weighted sound levels as suitable metrics. Since

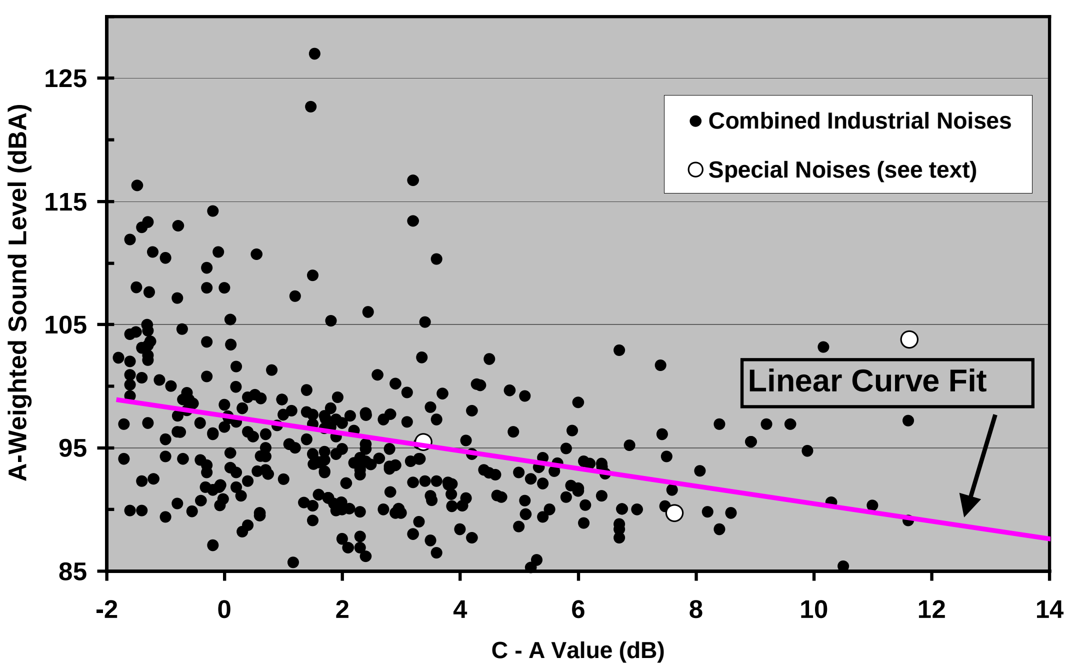
A weighting rolls off the low frequency energy and C weighting does not, as shown in Figure 3, the C-A value is a good indicator of the proportion of low-frequency energy present in the spectrum. A-weighted sound levels are plotted vs. their corresponding C-A values in Figure 4 and a commonly observed relationship emerges. More intense noises contain a higher proportion of high-frequency energy, as indicated by their lower C-A values. It is noted that noises with C-A values of greater than or equal to 5 dB rarely exhibit noise levels exceeding 100 dBA.

Figure 3: A- and C-weighting curves



In addition to the 300 noises, three additional noises were selected for illustrative purposes and are also plotted (large open symbols) in Figure 4. The noises consist of the "Typical Noise," an industrial noise from a glass factory with substantial low-frequency content, and an Air Force spectrum from Johnson and Nixon (1974). The Typical Noise as defined by Tobias and Johnson (1978) was intended, as the name implied, to be a representative industrial noise for purposes of analyzing HPD performance. It has a C-A value of 3 dB and is very close to pink in nature. By comparison the mean and median C-A values of the 300 noises used herein are 2.5 and 1.9 dB respectively. The glass factory noise was selected by the manufacturer of the prototype ANR earmuff used in this study as an environment in which ANR products would be anticipated to provide advantageous performance. The Air Force spectrum was one of the 50 spectra (#43) reported by Johnson and Nixon that had the greatest preponderance of low-frequency energy. It has been previously utilized to demonstrate the advantages of ANR designs for military operations (Nixon et al., 1992).

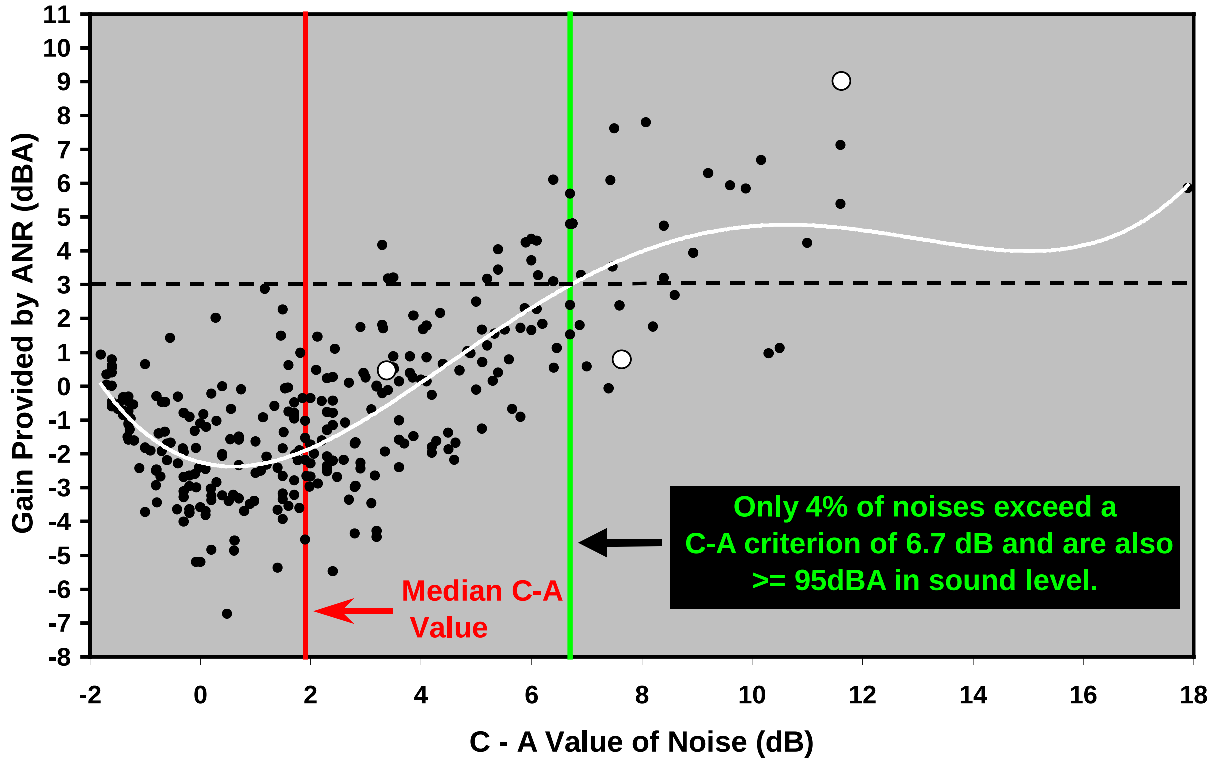
Figure 4: A-Weighted Sound Level vs. C-A Value



ANALYSIS

The performance of the high-quality ANR earmuff and the good conventional earmuff were evaluated using an octave-band computational procedure in the 303 noises described above. The values are plotted in Figure 5 in terms of the overall noise-reduction advantage provided by the ANR earmuff, versus the C-A value of the noise. For the median C-A value of 1.9 dB the ANR earmuff generally provides a net loss in protection. As the noise spectra include more low-frequency energy the ANR devices provide useful gains. If one presumes that a 3-dB net gain is the minimum desirable amount required to justify purchase of an ANR system, then a C-A value of approximately 6.7 dB must be exceeded as shown by the intersection of that value on the abscissa with the 4th order curve fit of the 300 data points (see black curve in Figure 5). This occurs for only 10% of the 300 noises. If one considers how many of those noises exceed a value of 95 dBA wherein one might require the extra protection provided by ANR, the number of appropriate applications drops to only 4% of the 300 representative noises.

Figure 5: Gains Provided by ANR Earmuff in 303 Noises



The unweighted spectra of the three special noises depicted in Figure 5 (large open symbols) are shown in Figure 6 along with their corresponding unweighted (dBL) and C-A values. This provides an indication of the relationship between spectrum shape/slope and C-A. In the accompanying graph, Figure 7, the spectra have been A weighted. Except for the Air Force noise that still peaks in the 125 - 250 Hz range, A weighting has shifted the peak of the other two spectra into the range between 500 and 2000 Hz. This indicates that those octave-band levels are the ones that predominantly influence the damaging noise exposure, and hence the ones that are most in need of attenuation. Since ANR performance is lacking in that frequency range, it would not be expected to be beneficial in such environments.

The typical noise with its C-A value of 3 dB is close to the median C-A value for the all of the noises, 1.9 dB. For this noise, as would be anticipated from the preceding discussion, there is no advantage provided by ANR. Surprisingly, there is also no beneficial effect of ANR in the glass factory noise with its C-A of 8 dB, which demonstrates that ANR will not necessarily be advantageous in all low-frequency emphasized noises. Finally, in the Air Force spectrum with its C-A of 12 dB, there is a large gain in attenuation of nearly 9 dB with the ANR design. However, the Air Force noise is not a typical industrial spectrum but rather was measured in an operational aircraft.

Figure 6: Spectra of the three special noises

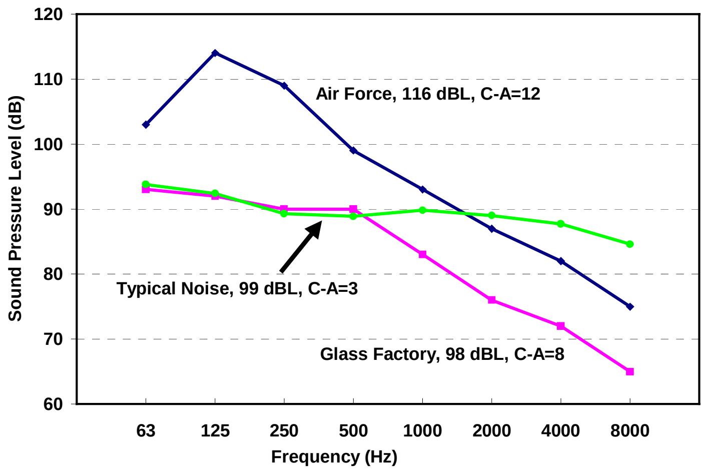
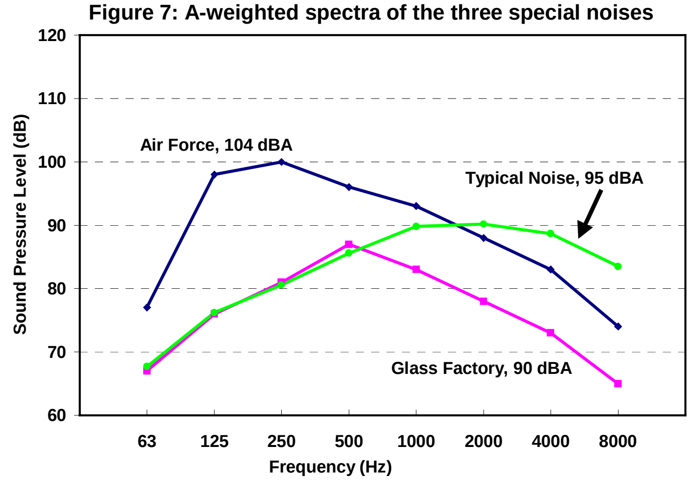


Figure 7: A-weighted spectra of the three special noises



DISCUSSION

The question addressed in this paper was whether today's best ANR designs provide useful benefits in typical industrial noise environments. For analysis we selected a high-quality ANR earmuff and compared it to the performance of a good conventional earmuff in 300 representative industrial noise environments. It was found that in only 10% of those environments was there a net gain of at least 3 dB in terms of overall A-weighted noise reduction provided by ANR. However, when one further considers if such a gain is needed, i.e. is the environmental noise high enough in level to warrant a concern for additional noise reduction, it is found that in only 4% of environments is that the case. In fact if one presumes that a conventional earmuff should be adequate up to 100 dBA 8-hour exposures and a concern for extra protection would only be warranted above that level, then the number of situations in which ANR might be considered drops to 1%.

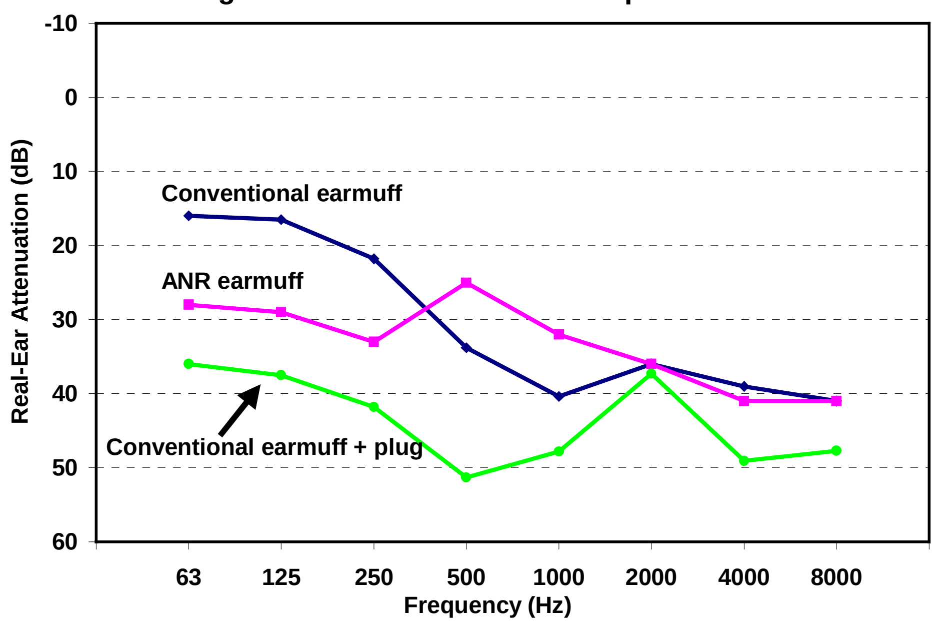
Furthermore, the 4% value may be an overestimate. Although the 300 noises used herein were selected to represent industrial spectra, whether or not they represent a valid statistical sample, i.e. whether the proportion of noise levels represented in this data base is a good reflection of industry today is open to question. For example, OSHA utilized a sampling procedure to estimate the prevalence of noise levels in U. S. industry (OSHA, 1981). No spectral data were available but A-weighted values were provided. In Table 1 the distribution of levels is compared for the 300 noises and the OSHA values. Notice that the OSHA noises have a substantially smaller proportion of noises above 95 dBA, suggesting that if that data base is more representative of industry than are the 300 noises, then even the 4% estimation for environments in which ANR is useful, may be an overestimate.

Table 1 - Distribution of A-weighted levels in two groups of representative noises

Exposure level (dBA)	*300 Noises*	*OSHA Noises*
85-90	14	44
90-95	39	32
95-100	26	15
>100	19	9

Another question that sometimes arises regarding ANR is whether it is beneficial if one needs to provide the maximum attenuation possible. The data in Figure 8 bear on that question, by comparing the attenuation for a conventional earmuff and an ANR earmuff to that obtained with the conventional earmuff worn in conjunction with a well-fitted foam earplug. Clearly the completely passive system consisting of the dual protection substantially outperforms the ANR earmuff at all frequencies except 2 kHz. Preliminary data on the performance of an ANR earmuff worn in conjunction with a foam earplug suggest that it provides only a small additional gain at the lowest frequencies over a conventional earmuff worn in conjunction with a high-attenuation earplug.

Figure 8: ANR earmuff vs. dual protection



Besides noise attenuation, additional factors limit the environments in general industry in which ANR will be the optimal choice. One must consider that an ANR earmuff generally costs upwards of $175 per pair, versus about $15 for a conventional earmuff, that it requires regular battery replacement or recharging, is more susceptible to damage, and will weigh more than a conventional earmuff. Thus, when considering an ANR earmuff for use in general industry an octave-band computation of the comparative effectiveness of the ANR and conventional earmuff is recommended in order to be sure that substantial gains in protection will be provided.

In applications beyond general industry, however, there are situations wherein ANR provide valuable performance benefits. These are generally found in general aviation and certain military environments. In those applications communications are usually integral to the circumaural device and thus ANR is not simply being implemented for additional noise reduction, but is also important for optimizing speech and signal transmission in high-level low-frequency dominated noises. A companion paper by D. Gauger describes those situations, and the concomitant benefits of ANR in great detail (Gauger, 2002).

Finally, let's return to a comment raised in the abstract, namely the dramatic auditory benefit one perceives when switching on and off an ANR system in a low-frequency dominated noise. A large benefit is heard because one is comparing the effect of attenuation values represented by the ANR-off and ANR-on curves in Figure 2. However, as was discussed at the top of page 3 the mere act of equipping an earmuff cup with ANR components degrades its performance, which if the ANR is to be useful, must be more than offset by the electronic circuitry. Therefore a fair comparison of the auditory merits of ANR is to compare the sound of a similar-sized conventional earmuff (which of course lacks those components) to the ANR-on condition, as shown by the conventional earmuff vs. ANR-on curves in the same figure. Clearly much less of a difference is perceived in this situation, especially if the noise had any important audible contributions above 250 Hz. This latter type of demonstration can only be effectively accomplished by creating a pre-recorded auditory demonstration in which sample noise spectra are filtered to simulate the attenuation provided by the two conditions.

So when you take an ANR earmuff for a "test drive" you may enjoy the experience of switching it on and off and hearing the low-frequency energy disappear, but don't be fooled, the actual benefits compared to conventional earmuffs are much less spectacular.

REFERENCES

1. Backshall, D. (2000). Personal communication of previously unpublished data.
2. Berger, E. H. (2000). "Proposal for a Grading Scheme for CSA Standard Z94.2, Hearing Protectors, " E-A-R Technical Rept. E-A-R 00-22/HP, Indianapolis, IN.
3. Berger, E. H. and Kerivan, J. E. (1983). "Influence of Physiological Noise and the Occlusion Effect on the Measurement of Real-Ear Attenuation at Threshold," J. Acoust. Soc. Am. 74(1), 81-94.
4. Casali, J. G. and Berger, E. H. (1996). "Technology Advancements in Hearing Protection Circa 1995: Active Noise Reduction, Frequency/Amplitude-Sensitivity, and Uniform Attenuation," Am. Ind. Hyg. Assoc. J. 57(2), 175-185.
5. Gauger, D. (2002). "Active Noise Reduction (ANR) and Hearing Protection: Where It's Appropriate and Why," Spectrum Suppl. 1, 19.
6. Gauger, D. and Sapiejewski, R. S. (1999). "ANR Headphones: Past and Present," Spectrum Suppl. 1, 16, p. 23.
7. Johnson, D. L. and Nixon, C. W. (1974). "Simplified Methods for Estimating Hearing Protector Performance," Sound and Vibration 8(6), 20-27.
8. Karplus, H. B. and Bonvallet, G. L. (1953). "A Noise Survey of Manufacturing Industries," Ind. Hyg. Qtrly., December, 235-263.
9. Kroes, P., Fleming, R., and Lempert, B. (1975). "List of Personal Hearing Protectors and Attenuation Data," National Institute for Occupational Safety and Health, U.S. Dept. of HEW, Rept. No. 76-120, Cincinnati, OH.
10. McQueen, G. H., Cameron, A. J., King, R. B., Mannam, J., Reilly, R. N., Stafford, R. G., and Wilson, K. J. (1969). "Good Health," Occup. Health Branch, Dept. of Public Health, Adelaide, Australia.
11. Nixon, C. W. and McKinley, R. L. (1992). "What Can Active Noise Reduction Headsets Do for You?," in Proceedings, Hearing Conservation Conference, Off. Eng. Serv., Univ. Kentucky, Lexington, KY, 107-110.
12. OSHA (1981). "Occupational Noise Exposure; Hearing Conservation Amendment," Occupational Safety and Health Administration, 29CFR1910.95 Fed. Regist. 46(11), 4078-4181.

13. Tobias, J. V. and Johnson, D. L. (1978). "The Typical Noise: First Step in the Development of a Short Procedure for Estimating Performance of Hearing Protectors," J. Acoust. Soc. Am. 63(1), 207-210.