INFLUENCE OF INSERTION/DONNING INSTRUCTION ON FREQUENCY-SPECIFIC SOUND ATTENUATION ACHIEVED WITH EAR CANAL CAPS AND EARMUFFS WITH IMPLICATIONS FOR INDUSTRIAL NOISE APPLICATION

by

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(ABSTRACT)

A study was conducted to determine the dependency of sound attenuation capabilities of earmuffs and earcaps on various application instruction techniques including: (1) no instruction, (2) no instruction with 70 dBA auditory feedback, (3) manufacturers' package instruction, (4) detailed instruction, and (5) modeled instruction. The hearing protection devices (HPDs) studied were: two earcaps (Willson #20 Sound-Ban, Flents #055 Peace & Quiet Headband), and four earmuffs (E-A-R model 1000, Siebe Norton In-

dustrial model 4540, Peltor H6A/v, and Willson 365A Sound Barrier). HPD comfort and wearer preferences were also assessed. Furthermore, typical excessive industrial machinery noises were sampled and analyzed across the 1/3 octave frequencies. Finally, an example is provided as to how these machinery noise spectra can be matched with HPD attenuation spectra to ascertain the protector which would afford optimal protection for a given noise situation.

Fifty subjects (twenty-five males and twenty-five females) participated in the experiment. Attenuation characteristics of the HPDs were evaluated utilizing the real-ear attenuation at threshold (REAT) method. A three-way mixed factorial design was used for data collection and analysis of attenuation results. Bipolar scales were used to assess individual HPD comfort, and the HPDs examined were ranked to obtain user preferences. In the analysis of attenuation results, analysis of variance (ANOVA) and pairwise comparisons were utilized to detect statistical significance. The comfort scales and ranking scores were evaluated using the Friedman one-way block design.

Attenuation results for the earmuffs and earcaps tested showed that they were much less susceptible than earplugs (from a previous study by Epps, 1984) to changes in user insertion/donning instruction technique and also not as dependent on user gender. The main effect of gender was not significant, and in general, any instruction was better than no instruction at all but the effects of those instructions did not differ significantly among each other. As

expected, there were main effect differences among the HPDs as to their attenuation capabilities, rated discomfort, and user preference. Because the main objective was on assessing donning instruction effects on HPD attenuation, the comfort/preference assessment was based on only a short (25 minutes) wearing time during the attenuation tests. Therefore, the comfort/preference ratings could likely vary given longer wearing periods and different work environments. All results found are discussed on the basis of the sample data obtained and conclusions drawn from these results should be limited to these experimental conditions and subsequent analyses, as actual attenuation achieved in practice may differ.

The example of HPD-machinery noise matching illustrates that the attenuation/spectral matching procedure may indeed be a feasible way of selecting optimal protection for workers.

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INTRODUCTION

Background

The many adverse effects of high intensity noise on humans have long been established. The dangers of industrial noise have aroused ever-growing concerns among industrial safety personnel and management alike. Permanent hearing loss, as evidenced by noise-induced permanent threshold shift (NIPTS), is one of the major direct effects of exposure to high noise levels. Evidence has shown that it is a pervasive problem and is one of the most severe, irreversible hazards threatening industrial workers. Its effect is compounded by a cumulative and insidious onset. These factors combine to make hearing protection and conservation imperative in modern industrial settings.

Miller (1978) indicated that there are more people suffering from occupational hearing loss than all other job-related diseases totalled. The effects of hearing deficiencies on the physical, psychological, and social well-being of humans are profound and far-reaching. Recent estimates reveal that 1.7 million workers aged between 50 and 59 have sufficient hearing loss to be granted compensation (Robinette, 1984). If only 10 percent of these workers successfully file claims, the cost would exceed $500 million. Sataloff (1984) estimated that the potential direct compensation costs may be over $20 billion. Worse yet, the number of workers

suffering from job-related hearing loss and the resulting compensations will likely soar unless more effective countermeasures are taken.

The importance of hearing conservation has been gradually recognized by industry. More, but still somewhat inadequate efforts are expended in hearing conservation programs. These programs generally include engineering controls and noise abatement, annual employee audiometric tests, special administrative measures, and the use of personal hearing protection devices (HPDs). HPDs remain popular as protective measures due to their low cost and ease of use/administration. Moreover, often times they represent the only feasible alternative available for protecting the workers.

Issues in Present Study

HPDs are known to vary substantially in their noise attenuation characteristics and utility (e.g., Edwards, Broderson, Green, and Lempert, 1983). The decision to select a specific hearing protector basically depends on its attenuation characteristics, the ambient noises which it must attenuate, comfort, cost, durability, and the HPD's effects on speech communication. The present study investigated the efficacy of selected HPDs (earmuffs and ear-canal caps) in relation to their respective attenuation characteristics achieved under various user insertion/donning in-

struction condition and to noise spectra emitted by different types of industrial machinery.

Attenuation characteristics of a hearing protector essentially depend on the design and construction material of the device and the application technique adopted by the wearer. HPD attenuation is generally reported by the manufacturer as a single number Noise Reduction Rating (NRR, in decibels) as required by the Environmental Protection Agency (EPA). The NRR represents the noise attenuation expected to benefit the wearer. While the NRR is based on weighted attenuation measurements in 1/3-octave frequency bands centered at 125 Hz (cycles-per-second) through 8000 Hz, its single-numbered representation depicts little about the actual attenuation characteristics throughout the frequency spectrum. Therefore, the comparisons between HPDs and the selection of HPDs for respective noises should be based on the protectors' attenuation characteristics across the noise spectrum, and not a single number rating.

In this research, a variety of industrial noises were sampled and 1/3 octave-analyzed for a frequency breakdown of the sound power distribution. Selected HPDs (four earmuffs and two earcaps) were evaluated and analyzed in the laboratory for their attenuation characteristics across the same frequency spectrum with respect to different insertion/donning instruction techniques. The matching of HPD spectral attenuation characteristics with the sound power distribution of a given noise was then possible. This latter effort

was to demonstrate a scientific, quantitative method for the selection of specific protectors for a particular noise problem, hopefully evidencing that hearing protectors can be accurately and optimally selected for use by workers who operate machinery with a known sound profile.

The NRR, and sometimes attenuation in decibels across frequencies, are provided by manufacturers on HPD packages. However, aiming at achieving optimal attenuation for comparison purposes, manufacturers' attenuation assessments are typically obtained using well-trained highly-motivated subjects, and an audiologist or knowledgeable individual to fit the HPD to the subject. This is not representative of what typically occurs in the actual industrial settings. In effect, for various reasons, the daily usage of HPDs is plagued by problems of motivation, improper application, misuses, abuses, and improper maintenance (Berger, 1982b; Edwards et al., 1983; Edwards, Hauser, Moiseer, Broderson, and Green, 1978; Regan, 1978; Riko and Alberti, 1981). Epps (1984) reported a significant main effect of insertion-instruction strategies on the noise attenuation capabilities of earplugs. Similar kinds of application-instruction strategies affecting the attenuation abilities of earmuffs and ear-canal caps were probed in this study. In addition, earmuff/earcap-induced discomfort and user acceptability were evaluated.

The ensuing sections of this introduction will expound on the effects of high-level noise on humans, the types of HPDs available,

how they attenuate noise, and factors influencing their effectiveness. The current methods of attenuation measurement and the results of recent research indicating actual protector attenuation in the workplace are then discussed. All the HPD-related issues will principally focus on earmuffs and earcaps. Later discussions on results and conclusions will incorporate comparison with findings on earplugs done in a parallel study at Virginia Tech (Epps, 1984).

EFFECTS OF INTENSE NOISE ON HUMANS

Anatomical Effects

Loud noise (e.g, above 80 decibels (dB)) triggers stapedius reflex (aural reflex) in which two sets of muscles are contracted to protect the ear. One set of muscles tightens the eardrum (tympanic membrane), and the other set draws the stirrup (stapes) away from the oval window of the inner ear. Since full aural reflex protection may take as long as 200 ms, the reflex is somewhat ineffective for the protection from high-level impulse noise. The eardrum can be ruptured by extremely high sound pressures which will result in a temporary loss of hearing and the possible hazard of ear infection. In most cases, the eardrum will heal, but the resulting scar formation may lower the sensitivity of the ear, especially for sounds of high frequency (Rossing, 1982, p.576).

On the other hand, ordinary exposures to moderately high level noise do not damage the eardrum as above but affect other anatomy. The primary site of injury in this case is the receptor organ of the inner ear (organ of Corti). The nature of damage ranges from distortion and partial destruction of hair (neural) cells to total destruction of the organ of Corti and degeneration of auditory neurons.

Two types of deafness, nerve deafness and conduction deafness, are typically delineated (e.g., Davis, 1957; McCormick and Sanders,

1982). Nerve deafness involves the damage or degeneration of the hair cells of the organ of Corti. The hearing loss is usually uneven, with greater loss in the higher frequency range. Nerve deafness is generally associated with aging (presbycusis) and continuous exposure to loud noise. This type of hearing loss is almost always irreversible.

Conduction deafness is caused by abnormal conditions in the outer or middle ear that affect sound transmission into the inner ear. These abnormal conditions include adhesions in the middle ear that prevent the vibration of the ossicles, infection of the middle ear, ear wax impregnation, or scars resulting from a perforated eardrum. Sudden, extremely loud noise might dislocate the ossicles and cause conduction deafness. This kind of deafness can sometimes be arrested or even improved through surgery, and the hearing loss is generally partial. Sound may still reach the inner ear via bone/body conduction. Conduction deafness can usually be somewhat compensated for with a hearing aid.

Physiological Effects

Sudden loud noises may produce startle responses including muscular reflex (e.g., eyeblink, facial grimace) and sympathetic reflex (e.g., pupil dilation, tachycardia, constriction of blood vessels, increase in breathing rate). These reactions may interfere with the normal functioning of the individual and may even cause accidents. Moreover, repeated exposure may induce chronic

syndromes such as cardiovascular disorders, ear, nose, and throat problems, gastrointestinal maladies, and equilibrium problems (e.g., Miller, 1974; Henderson, Salvi, and Hamernick, 1981). Experiments with animals have also demonstrated that intense noise can lead to such pathological changes as hypertrophy of the adrenal glands, fetal defects, brain damage, and sexual dysfunction (Rossing, 1982, p.581). However, the generalization of animal findings to humans should be considered with caution.

Psychophysiological Effects

Hearing loss. Exposure to loud noise for a relatively short period of time causes noise-induced temporary threshold shift (NITTS or TTS). The loss in sensitivity often occurs maximally around 4000 Hz. Moderate TTS normally recovers in about 16 hours. For a TTS of 35-40 dB, recovery takes days or weeks, and for a TTS above 50 dB, recovery may never be complete (Rossing, 1982, pp.571-575). Prolonged or frequently-repeated exposure may induce a permanent shift in hearing ability. The physiological basis of TTS is not yet fully understood. It is only known that the development and recovery of TTS is immune to the effects of drugs, time of day, hypnosis, or state of mind (Rossing, 1982). In general, low-frequency and intermittent noise produces less TTS.

Frequent excessive exposure produces noise-induced permanent threshold shift (NIPTS or PTS). This usually occurs when high level noise produces irreversible anatomical changes in the organ of

Corti and/or auditory neurons. PTS also occurs when sudden high level impulsive noise induces eardrum rupture and dislocation of the ossicles. It is believed that the early stages of PTS affect mainly frequencies between 2000 and 8000 Hz, and as a result ordinary speech (which is normally critical for understanding in the range of 1000-3000 Hz) may only be partially affected. Other frequencies will be affected as the disorder progresses. This explains why the onset of PTS often passes unnoticed by the victim. In conclusion, the following general statements can be made about noise-induced hearing loss (Melnick, 1979; Rudmose, 1957):

1. there exists a great variability in individual susceptibility to noise-induced hearing loss; this variability increases with increasing audiometric frequency and with increased duration in exposure;
2. studies of industrial hearing loss seem to indicate that men are more prone to the detrimental effects of excessive noise; however, controlled experimentation using normal-hearing young adults appears to show that there exists no innate sexual difference in susceptibility;
3. diseased conditions of the ear may aggravate or insulate the adverse effects of excessive noise on hearing, depending on the nature of the pathology;

4. the maximum effect of a particular noise exposure occurs at frequencies higher than the frequency spectrum of the offending noise;
5. the higher the frequency of the excessive noise (at least up to 6000 Hz), the greater the resulting threshold shift produced by similar sound pressure levels and durations;
6. NIPTS first appears in the region of 4000 Hz, relatively independent of the industrial noise spectrum; this may be due in part to the resonance of the outer ear and ear canal which amplifies sound pressure level at the eardrum in the 2000 to 4000 Hz zone by as much as 20 dB;
7. over time, for the same level of exposure NIPTS increases rapidly in the 3000 to 6000 Hz range and then slowly levels off; at lower frequencies (500, 1000, and 2000 Hz), NIPTS does not progress as rapidly, but it continues to increase throughout the time of exposure;
8. animal studies indicate that certain drugs and excessive noise act in a synergistic fashion to produce increased organic damage to the hearing apparatus; drugs such as kanamycin, neomycin, dihydrostreptomycin, quinine, and salicylic acid may as well produce similar synergistic effects in humans.

Social and Performance Effects

Speech communication and social interactions constitute important human activities. These may be compromised by noise-induced hearing loss which may lead to speech interference, misunderstanding, annoyance, and eventual isolation of the individual.

The effects of noise on performance are complicated. Past studies indicated that noise could either produce no effect (e.g., Gawron, 1982a), decremental effect (e.g., Broadbent, 1979), or improvement on performance effect (e.g., Gawron, 1982b). The particular effects of a given noise on performance depend on the characteristics of the noise and the nature of the task. In general, high level noise (over 95 dBA) will reliably produce detrimental effects on performance (Hockey, 1978). Loud noise induces the "funneling of attention" wherein the human focuses his/her attention on the most important aspects of the task (Broadbent, 1976). To the extent that other task-related aspects are neglected, loud noise is detrimental to performance. Broadbent also posited that excessive noise would produce increased confidence and increased variability in performance (evidenced by the performance "gaps"). Generally, steady noises below 90 dB do not appear to consistently affect performance, but intermittent noise can have deleterious effects. Complex, cognitive tasks, especially those involving short-term memory, are easily disrupted by moderately high level noise (70 to 80 dBA, Hockey, 1978). Noise with moderate intensity

around 1000 to 2000 Hz is more disruptive than low frequency noise. Noise is more likely to affect the accuracy of work than to reduce the total amount of work (Miller, 1974).

Also, noise appears to be related to human's misjudgement about the passage of time. Noise exposure may, as well, induce nervousness and anxiety syndromes which may in turn affect performance. Intermittent noises are most disturbing when the human has no control over the presentation of the noise (Glass and Singer, 1972). Poulton (1978) asserts that the effects of noise on performance are contingent upon (1) the masking of task-related auditory cues and inner speech, (2) distraction, (3) arousal, and (4) positive or negative transfer from performance in noise to performance in quiet. On the other hand, Broadbent (1979) contends that the deleterious effects of noise on performance are mainly due to "overstimulation " (overarousal).

INDUSTRIAL NOISE CONTROL

Given the many detrimental effects of excessive noise on humans and the potential costs of hearing loss liability cases, it is imperative for management to practice effective noise control and hearing protection. Bolt and Ingard's (1957) system concept depicts how industrial noise control should be enforced (Figure 1). Noise control measures can be directed toward the source, the path, or the receiver in decreasing order of preference. In general, the energy of sound can be reduced by spreading, deflection, absorption, or mere avoidance (e.g., shorter work shifts). Specific methods consist of: engineering measures (e.g., machine design, barriers, isolation), administrative measures (e.g., job assignment, rotation, work scheduling), and hearing protection devices (HPDs). Although the HPD should only be considered as an interim method in reducing excessive noise, it remains a widely-used method. This is essentially due to its low cost and ease of use/administration. Often times, it is also the only measure feasible for noise protection (e.g., as on an airfield).

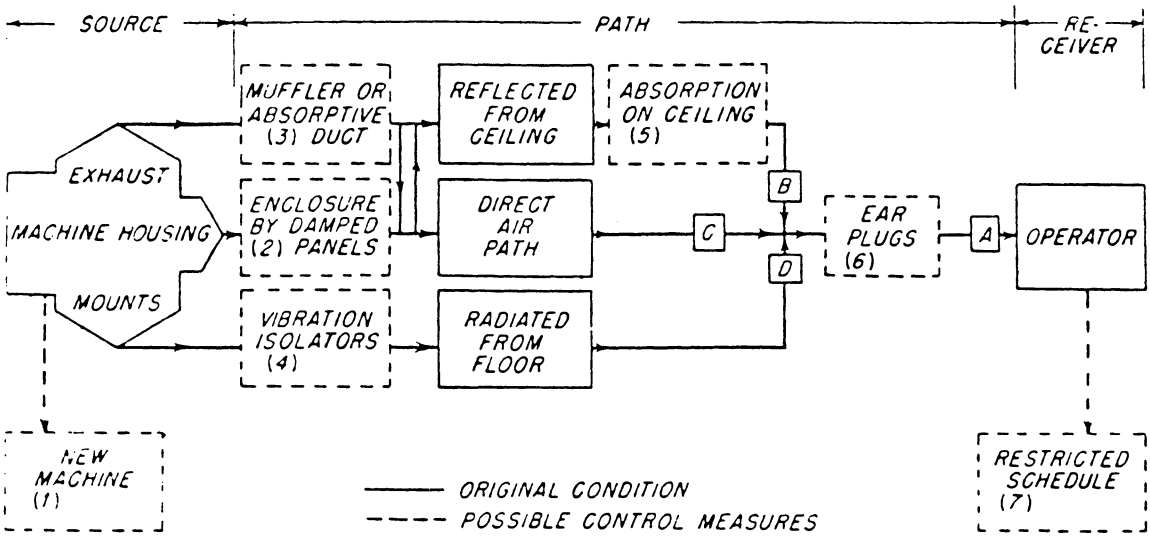

Figure 1. System approach to noise abatement (adapted from Bolt and Ingard, 1957).

HEARING PROTECTION DEVICES (HPDs)

HPD: Types

Four types of HPDs are currently available: (1) aural inserts (earplugs), (2) superaural devices (earcaps, canal-caps, or semi-inserts), (3) circumaural devices (earmuffs), and (4) helmets. These are briefly reviewed in the following sections.

Aural inserts. They will hereafter be referred to as "earplugs". When correctly inserted, earplugs provide high attenuation and they do not usually interfere with other devices worn by the workers such as eyeglasses and hard hats. They are among the most widely-used and accepted protectors in industry primarily due to their low cost and high protection realized for a wide variety of applications. However, their attenuation performance is also highly variable due to improper sizing and application (insertion) techniques.

There are three basic types of earplugs: custom-molded, premolded, and user-molded. A custom-molded earplug is a silicon or rubber insert that is made from a mold of the wearer's ear canal. It is the most expensive kind of earplug. The initial fit is precise and comfortable, and attenuation performance is high. But its effectiveness decreases over time with material degradation. It is more hygienic than a universal-fit plug in that the wearer does

not have to handle the portion of the plug that contacts the auditory canal.

Pre-molded earplugs are made from silicon, rubber, or mineral fiber. The silicon and rubber types usually have cones or multiple flanges that assist in holding the earplug in the ear canal. Rubber plugs may be supplied in multiple sizes and must be properly sized for each individual ear of the wearer (Botsford, 1972). Earplugs made of mineral fiber come in one "universal" size (i.e., one size fits most wearers). In general, pre-molded plugs are less expensive than custom-molded types. Both the custom-molded and pre-molded earplugs require regular cleansing (or disposal) and proper storage.

User-molded earplugs (also known as formable plugs) are molded by the wearer to fit each individual ear. They are normally of the disposable type, made of mineral fiber, waxed cotton, or foam polymer. Problems of material degradation and contamination over time are reduced because the plugs are intended to be disposed of after one or a few uses. Soft resilient materials used in some of these plugs may enhance wearer comfort and plug attenuation performance. In general, user-molded earplugs offer good noise attenuation and need little maintenance. Their increased long-term cost (because of the disposability) is usually balanced by the benefits gained. More industries are favoring disposable user-molded or disposable, universal-fit, pre-molded plugs. In partic-

ular, the disposable foam plugs and disposable mineral fiber plugs are quite popular.

Superaural devices. These devices will be referred to as earcaps. An earcap blocks the entrance to the ear canal by means of rubber/polymer caps supported by a compressioning headband or suspension from a hardhat. At times they can be worn as part of an earphone system.

Earcaps appear to depend less on sizing and application technique, therefore their attenuation performance may be somewhat less variable than that of earplugs. Earcaps are less affected by dirty conditions because, at least on some models, the wearer does not have to handle the caps directly. However, they do require regular maintenance and proper storage. Earcaps are smaller than earmuffs and interfere less with other devices worn on the head. However, as with earmuffs, they require some means of support, and this is more cumbersome than simply wearing earplugs. Their relatively high cost and lower attenuation capabilities virtually make them the least popular of all HPDs at present. (They also appear to be the least well-researched variety.)

Circumaural devices. These devices will be referred to as earmuffs in the ensuing discussion. An earmuff consists of two cups with cushions covering the entire outer ear and sealing against the head. The cups are held in place by a headband or they may be parts

of another headcovering (e.g., helmet or hard hat). Normally one size is made to fit all wearers. Beyond that, the cups may vary in weight, volume, area of cushion and construction material. Headbands may differ in construction material and mechanism for adjustment. Earmuffs with rotatable headbands (as with some earcaps) may be worn with the band in the above-the-head, behind-the-head, or under-the-chin positions, and different positions offer varying degrees of noise attenuation. Generally, wearing the headband in the above-the-head position provides the best attenuation, while under-the-chin and behind-the-head provide comparable protection (Gasaway, 1984).

Earmuffs cup cushions may be filled with foam, fluid (liquid or air), or a combination of foam and fluid (e.g., the Peltor muffs shown in Figure 5). In practice, the attenuation capabilities of the earmuffs depends on the construction and volume of the cups, the area of the cushion, the filler substance of the cushion, the type of covering for the cushion, and the adjustability and tension of the headband (Botsford, 1972; Savich, 1957; Zwislocki, 1957). Since almost anyone can be fitted satisfactorily with one-size earmuffs, their variability of performance is smaller than that of earplugs. Earmuffs are generally more durable, more effective in high noise levels (especially when the noise is of higher frequencies, i.e., greater than 1000 Hz). They are better for situations in which dirt is a problem, when the protector must be taken on and off frequently, or where HPD-monitoring is essential. In sum,

earmuffs are easier to apply and user compliance is usually easier to achieve.

Despite these merits, earmuffs have several disadvantages. Their average attenuation for frequencies below 1000 Hz is usually inferior to that of earplugs (Zwislocki, 1957). They are large and somewhat cumbersome, and they interfere with, and are affected by, almost everything worn on the head, including facial hair, such as sideburns and beards. Moreover, especially so for high-quality muffs, they are much more expensive than earplugs or even earcaps. Finally, earmuffs also require proper maintenance and their cushions need periodic cleansing and replacement.

Helmets. These headgear cover most of the head surface, and they are not commonly used for ear protection per se. Normally they combine hearing protection with protection of the head against cold or injury from impact trauma. They may also act as support for other devices such as intercommunication systems or earphones. Helmets are the largest, most cumbersome, and the most expensive of all HPDs. They have to be made in several sizes, and their industrial noise attenuation performance does not seem to excel significantly beyond that afforded by the earmuffs (Zwislocki, 1957). Therefore, helmets are used only when additional functions (e.g., protection from head injury and intercommunication) are needed besides hearing protection. Furthermore, because helmets cover a larger area of the head surface, they can provide additional at-

tenuation wherein sound transmission through the skull is reduced. This takes on considerable acoustic importance when attenuation at the ear approaches maximum and transmission through the bone/body becomes the limiting factor for attenuation. Especially when the ambient noise has considerable power at low frequencies in the spectrum, bone conduction may be a significant problem. Limiting factors of HPD attenuation will be covered in greater detail later in this section.

HPDs in combination. At certain frequencies, the combination of HPDs may or may not provide additional attenuation afforded by the best HPD alone (Berger, 1982a; Gorman, 1981). Hearing protectors generally attenuate sound by reducing air conduction to the ears. Helmets and earmuffs may reduce a certain amount of bone conduction. However, bone/body conduction threshold remains the ultimate limit for HPD attenuation. Studies of earplug-earmuff combinations showed that the total attenuation effect is not additive and is considerably less than the sum of the respective effects (Gorman, 1981; Zwislocki, 1957). There are four possible explanations for this: (1) the bone conduction threshold is decreased by the application of HPDs (Berger, 1982a), (2) sound may reach the ear through the mouth and the Eustachian (pharyngotympanic) tube, (3) the level of sound transmission through the skull and other parts of the body is reached, and (4) the vibration of earmuff may

be transmitted to the earplug via the flesh lining and the cartilaginous structures of the auricle (Zwislocki, 1957).

HPDs of the future. Major innovations may be expected in the area of "conditional" HPDs and "active" HPDs. An ideal hearing protector should give the wearer maximum protection possible against high-intensity noise, and yet allow low-level sounds to pass through. This is important for speech communication and auditory signal reception. Conditional (non-linear, amplitude dependent) HPDs will attenuate sound only when its intensity reaches beyond a certain cut-off level. This is exemplified by the "Gunfender" [Gundefender] amplitude sensitive earplug (Mosko and Fletcher, 1971; Shaw, 1981). This protector is a modified V-51R plug with a 0.025-inch (0.0635 cm) diameter opening into the ear canal. The combined opening and ear-canal volume act as a Helmholtz resonator for sounds of low intensity. These sounds pass through the earplug opening with laminar-flow (with low energy loss), while high-intensity sounds flow through with turbulence (with high dissipation of energy). Above 110 dB, the Gunfender is reported to be as effective as regular earplugs in attenuation performance. However, the Gunfender is only useful for protecting wearer from impulse noise such as gun fire (whereby it gets its name), and not from high-level steady noise.

More comprehensive protection may be provided by an active noise-reduction, signal-enhancement HPD (e.g., the DH-178

Artilleryman's Helmet built by the Gentex Corporation or the U.S. Army DH-132 Combat Vehicle Crewman's Helmet, Foreshaw and Cruchley, 1981). In such devices, the combination of an electronic microphone and amplifier actively counter high-intensity noise (above 85 dBA), while permitting lower level sounds to pass through. In its present design, the unit is bulky and cumbersome. However, these problems should be mitigated by future advances in electronic technology.

For the remainder of this literature review, the discussion will focus on earmuffs and earcaps, which are of immediate importance to the present research, and to a lesser extent on earplugs.

HPDs: Noise Attenuation

Human auditory sensation. The acoustical energy of sound impinging on the human body is conducted to the middle and inner ear via two pathways: air conduction and bone/body conduction. In air conduction, sound waves are collected by the pinna of the outer ear and propagated down the auditory canal. These waves cause vibration of the tympanic membrane, which then moves the ossicles of the middle ear (malleus, incus, stapes). The stapes impinges on the oval window causing fluid movement inside the cochlea. The fluid movement stimulates the hair cells of the organ of Corti within the cochlea. This stimulation generates nerve impulses which are conveyed via the eighth cranial nerve (the auditory nerve) to the

auditory center in the brain (Carlson, 1981, pp. 187-197). A secondary pathway for air conduction exists when sound is transmitted via the mouth and the Eustachian tube tube directly to the ossicular chain.

In bone/body conduction, primarily bodily tissues (especially those in the head) act as the medium of conduction of acoustical energy. Sound energy may be conducted via tissues (e.g., bone, cartilage) to the ear canal, tympanic membrane, or directly to the ossicles and cochlea. Bone conduction is specifically defined by Zwislocki (1957) as "an acoustical transmission channel to the inner ear that involves vibration of the bony structures other than the ossicles of the middle ear." Zwislocki further delineated three channels of bone conduction: (1) the elastic deformation of the skull leading to deformation of the middle and inner ear, (2) the vibration of the skull as a whole, and (3) the relative movement between the skull and the lower jaw. This last movement causes vibration of the cartilage of the ear canal, and airborne sound is produced which impacts on the eardrum. This route of transmission is known as the "osseotympanic" pathway. Sound energy may also be conducted, albeit ineffectively, via other parts of the body such as the chest and abdomen. All these bone/bodily conduction pathways together set the limit for passive HPD attenuation.

The difference between air conduction threshold and bone conduction threshold varies with the stimulus sound frequencies and with the listener. Botsford (1972) reported the bone conduction

threshold to be approximately 35 dB (at 1000 Hz) to 45 dB above the air conduction threshold. Zwislocki (cited in Berger, 1982a) estimated the open-ear bone conduction to be 40 dB to 65 dB (at 500 Hz) above the air conduction threshold. These numbers approximately define the limit of attenuation for the best possible passive HPDs.

The application of a hearing protector essentially produces a reduction (insertion loss) in airborne sound reaching the ear. The air conduction threshold should therefore increase appreciably. However, due to various reasons, the bone conduction threshold will decrease in the frequency range less than 2000 Hz. This effect is generally known as the occlusion or earplug effect (Berger, 1982a; Gorman, 1981). Irrespective of the HPDs used, sound can still reach the middle and inner ear in four ways: (1) through air leaks between the HPD and the ear or head, (2) by propagation through the protector itself, (3) through the vibration or resonance of the HPD as a whole body, and (4) via bone/body conduction (Berger, 1982a; Botsford, 1972; Zwislocki, 1957). In effect, these four factors define the practical limit for passive HPD attenuation.

Air leaks. For best results, an earplug or earcap must fit snugly in the ear canal and earmuff cushions must tightly fit the contour of the head area surrounding the pinna. Air leaks may occur, which generally decrease the attenuation at the ear, especially for low frequency sounds. Large leaks can readily nullify

noise attenuations. Typically, air leaks reduce attenuation by as much as 5 dB to 15 dB (Nixon, 1979).

HPD transmission. Various materials will differentially transmit sound waves according to frequencies. For example, mineral fiber will attenuate higher frequencies better than low frequencies. Transmission through the protector depends to a large extent on the type and thickness of the material used (Botsford, 1972). Generally, earplugs and earcaps will attenuate in a near-linear fashion from 125 Hz to 8000 Hz, with slightly better performance at the frequencies between 2000 Hz and 6000 Hz. Earmuffs afford better attenuation overall, and their attenuation generally increases with the frequencies of the sounds (e.g., it is often only 10 to 20 dB at low frequencies such as 125 to 500 Hz). But their attenuation for high frequency sounds is especially good (Botsford, 1972). The nonlinear relationship between earmuff attenuation and frequencies may be improved by the addition of one or more Helmholtz resonators (Zwislocki, 1957). Because of the large surface area of earmuff cups, sound transmission through the cup material and muff cushion may be significant. Material of high internal viscosity should be used as a filler for the cup cushion to reduce sound transmission. For similar reasons, a hard, rigid cup outer shell, usually of plastic, is also used.

HPD vibration. Due to the flexibility and compliance of the ear canal lining and human cutaneous tissues, earplugs can vibrate in a piston-like manner in the canal (Berger, 1982a). Likewise, an earmuff can vibrate against the head, acting as a mass/spring system. The resulting acoustical energy propagation will reduce the attenuation afforded by the HPDs.

Bone/body conduction. As mentioned before, since HPDs basically reduce air conduction of sound, bone/body conduction will eventually define the attenuation limit achievable by passive HPDs.

HPDs: Problems in Usage

Ideally, HPDs with the highest attenuation and lowest performance variation should be chosen. As previously mentioned HPD manufacturers are required by the EPA (Environmental Protection Agency) to label their packages with a single number Noise Reduction Rating (NRR), while the display of the attenuation characteristics across the 125 Hz to 8000 Hz frequency range is optional. These data must be obtained according to the ANSI S3.19-1974 standard. In real world usage, the attenuation afforded by the HPDs is highly variable and generally much lower than what is reported by the makers (Berger, 1982b). The following paragraphs address the problems associated with the daily usage of hearing protectors

which affect their attenuation performance (Berger, 1982a; Riko and Alberti, 1981; Zwislocki, 1957).

Motivation and acceptance. HPDs are often perceived as just an extra nuisance by workers. The worker may generate complaints related to discomfort, irritations, headache, speech interference, inability to detect important auditory signals, and other negative feelings (Royster and Holder, 1981). There exist numerous misconceptions about hearing protection in general and HPDs in particular (Berger, 1982c, 1982d, 1983c). Given these problems, the first hurdle that a personal hearing protection program has to overcome is the lack of motivation and acceptance. There do exist some recommendations in this vein, (e.g., Ritzky, 1984; Royster and Holder, 1981), but in general, the workers must be convinced of the adverse effects of excessive noise and the benefits (albeit inconvenience) of HPDs. All misconceptions must be clarified, and management must be understanding and supportive.

Proper placement technique. Industrial workers are often improperly or inadequately trained in the donning of HPDs. This may lead to air leaks, poor protection, discomfort, and possible resentment toward HPDs. For example, wearers often do not straighten the ear canal before inserting earplugs, therefore the plugs are not placed deep enough for a good seal. With user-molded earplugs, the workers may not form them correctly or may not hold foam plugs

in place long enough after insertion for them to expand and stabilize (Riko and Alberti, 1981).

Although earcaps appear to be easier to don than earplugs, few wearers realize that positioning the headband under the chin, over the head, or behind the head will provide different attenuation levels. Also, the front-back orientation of the cups is not apparent to some users. In addition, the wearer must realize the importance of correct alignment of the pod with the ear canal opening.

For earmuffs, again the positioning of the headband, and the orientation and adjustment of the cups will affect the attenuation. To ensure a tight seal and optimal attenuation, the band tension must be adequate, the pinna must be fully enclosed in the cups, the cup cushion must be in proper condition, and interfering eyeglasses and long hair must be removed or adjusted.

Proper fit. An earplug of the right size should be provided for each ear of an individual. An earplug that is too small will cause air leaks, while one that is too large will induce discomfort. Today, the sizing problem for earplugs has been solved somewhat by the development of universal-fit plugs.

Generally, one size of earmuffs or earcaps is made to fit all wearers. However, earcaps/earmuffs made by various manufacturers do differ in size, weight, and volume. The wearer must ensure that the pinnae are completely enclosed by the earmuffs and that the

cushions fit snugly to the head contour. Otherwise, air leaks and discomfort will ensue. Occasionally, certain head contours cannot be fitted by available earmuffs and some ear canals are unsuitable for any kinds of earplugs (Berger, 1982a). Such cases may then have to be dealt with on an individual basis. For instance, earmuffs may have to be provided to a person whose ear canals cannot be fitted with suitable earplugs.

Comfort. Comfort is one of the most important factors determining the effectiveness of a given HPD (Gasaway, 1984). An uncomfortable, albeit superb HPD may be worn incorrectly or possibly not at all. Royster and Holder (1981) reported that the major complaint associated with hearing protectors is that they may be uncomfortable. Sometimes, the better the fit of an HPD, the more uncomfortable it is (Berger, 1982a). A snug-fitting earplug will stretch the ear canal, and a tight-fitting earmuff will press against the head. Even though some wearers may adapt to the discomfort, it is often better to provide comfortable devices or different choices of protectors (Berger, 1982a).

Discomfort in earmuffs is usually attributed to the tension in the headband, the weight of the muff, and the size and design of the cups. It is also affected by high ambient temperature and humidity.

Readjustment. As the HPD-wearers move, talk, eat, and work, the HPDs may be dislocated and attenuation consequently reduced. Therefore, the wearers must constantly readjust the placement of HPDs if needed.

Percentage time worn. The cumulative energy theory indicates that noise-induced hearing loss is a function of the cumulative A-weighted noise exposure (Berger, 1982a). As per the OSHA standard, if the exposure level is increased by 5 dB, the exposure duration for an eight-hour working day must be reduced by one-half. The implication of this tradeoff relationship between time and dosage with regards to the protection provided by HPDs was discussed by Else (1973) and Berger (1982a). For instance, it was shown that if an HPD attenuates by 25 dB, wearing the device for only 95 percent of an eight-hour working day will give an equivalent protection of 20 dB. If worn 50 percent of the time, the equivalent protection drops drastically to 5 dB (Berger, 1982a) This illustrates how the intermittent use of an HPD quickly reduces the protection provided by the device.

Deterioration. The material and construction of hearing protectors degrade over time and with the frequency and environment of usage. Pre-molded earplugs may shrink and harden, and flanges may break off and crack (Riko and Alberti, 1981). Custom-molded plugs may crack, and earmuff cushions may harden, crack, or become

permanently deformed (Berger, 1982a). Headbands may lose their tension. Proper usage and maintenance will prolong the life of HPDs. Moreover, it is important to inspect and reissue protectors on a regular basis.

Durability. This is basically an economic factor which becomes important when large quantities of HPDs are used. However, it may also be an acceptability problem when durable protectors are more accepted and worn by the workers. Durability is closely related to the problem of deterioration. In general, earmuffs and earcaps should be able to survive a reasonable mechanical strain test, drop test, as well as humidity and temperature tests (Acton, 1977; Brinkmann and Serra, 1981).

Hygiene. Occasional ear infections are associated with the wearing of earplugs (Berger, 1982c; Riko and Alberti, 1981). Allergic reaction and local inflammation may also result, especially if the HPDs are not sanitized or replaced regularly. However, such incidences are not well-documented. The potential of hygiene problems can be reduced by proper application, maintenance, cleansing, and disposal of HPDs.

Abuse. Many protectors have been deliberately altered by workers for various reasons. Such reasons include discomfort, perspiration, pressure, pain, difficulty in speech communication,

and inability to hear important auditory signals (Riko and Alberti, 1981). Therefore, pre-molded plugs have been found with flanges cut-off or holes drilled into them. Custom-molded plugs have been found with canal inserts or with the external portions clipped down for comfort. Muffs found with holes and/or initials drilled or carved into them are common. These abuses greatly reduce the attenuation affordable by the HPDs. For these reasons, proper education of workers and adequate administration are deemed essential for effective personal hearing protection programs.

Communication. For wearers with normal hearing, HPDs usually improve speech communication when sound levels are greater than approximately 85 dBA (Acton, 1977; Berger, 1982c). However, especially over time with the use of HPDs, wearers forget the true "reference" background noise level and speak more softly. As a result, the speech communication between wearers of HPDs may be degraded. This problem can be alleviated by proper training and explanation to the users that donning HPDs makes one's own voice appear louder. For moderately to severely hearing-impaired wearers, HPDs may indeed degrade their speech communication even in high noise levels. Despite this, these individuals should still wear HPDs, otherwise, their hearing impairment would continue to deteriorate (Berger, 1982c; Foreshaw and Cruchley, 1981).

Some wearers may complain that with HPD use, machines and external auditory signals sound different. For instance, it is

sometimes important for machine tool operators to listen to auditory cues to determine the depth of cut, the presence of dull tools, the speed of cut, and the possible occurrence of anomalies in machine functioning. But individuals wearing HPDs may adapt to the new qualities of these sounds as heard through HPDs. In addition, since noise-induced TTS is averted, the workers will be able to hear the signals during their entire working shift.

HPD: ATTENUATION MEASUREMENT METHODS

From the preceding discussion it is clear that HPD attenuation capability is one of the important criteria for selection. In the past few decades, many different types of subjective and objective methods have been developed for the measurement of HPD attenuation, as shown in Table 1 (Berger, 1984).

Excellent reviews of such methods have been provided by Berger (1984), Epps (1984), and Nixon (1981) and will not be reiterated here. A few of the methods (e.g., the REAT method, the TTS method, and some objective methods) are popular, while others are rarely used. For instance, the REAT method has been adopted by the U.S., Canada, West Germany, Australia, and United Kingdom as standard. France uses the bone conduction method, while South Africa has adopted the binaural balance method.

Real Ear Attenuation at Threshold (REAT) Method

The REAT method of evaluating HPD attenuation is the most widely-accepted method. It has been adopted by U.S. government institutions (ANSI, EPA) as the basis for protector testing and resulting publications. As such, REAT attenuation test results often form the basis for HPD comparisons. For these reasons, the

TABLE 1

HPD Attenuation Measurement Methods (adapted from Berger, 1984)

A. SUBJECTIVE METHODS
   1. Real-Ear Attenuation at Threshold (REAT)
      a. Sound field REAT
         (ANSI Z24.22; ASA STD 1; BS 5108;
         ISO 4869)
      b. Headphone REAT
      c. REAT with hearing impaired subjects
   2. Above Threshold Procedures
      a. Masking
         (i) Sound field masking of earphone stimuli
         (ii) Sound field masking of bone conducted
              stimuli
      b. Loudness balance
         (i) air to air
         (ii) bone to air
      c. Midline lateralization
      d. Temporary Threshold Shift
      e. Effects on speech intelligibility
      f. Miscellaneous psychophysical methods
         (i) Cross modality loudness scaling
         (ii) Magnitude estimation
         (iii) Reaction time
   3. Subjective Comparison Methods
B. OBJECTIVE METHODS
   1. Acoustical Test Fixture (artificial head/ear)
   2. Microphone in real-ear
   3. Microphone in cadaver ear
   4. Tympanometry (aural-reflex threshold shift)

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present experiment utilized the REAT method (as in ANSI Z24.22-1957) for the assessment of HPD attenuations.

Two general methods of implementing REAT tests have been related by Berger (1984). These are methods which use either a sound field or a headphone test stimulus presentation technique.

Sound field REAT is probably the oldest and most common method of assessing HPD attenuation. It is also one of the most accurate test methods, and has thus been incorporated into the ANSI Z24.22, ANSI S3.19, and the most recent ANSI S12.6 standards. It can be used to evaluate different kinds of HPD. This method is based on psychophysical testing procedures for the determination of absolute hearing threshold and threshold shift. A subject is first assessed for his/her hearing threshold at a certain test frequency in dBA with unoccluded (no HPD) ears. The HPD is then applied to the subject (both ears occluded) and the subject is retested for auditory threshold at the same frequency. The difference in the occluded and unoccluded thresholds is the attenuation (insertion loss) of the HPD at that particular frequency (Berger, 1984). This procedure is repeated for several frequencies across the 125 Hz to 8000 Hz range. Sound field REAT requires very low ambient noise levels and a special acoustical test environment and equipment. Thus, it may be difficult to implement in field settings. Typically it is assumed that attenuation results obtained by the REAT method are generalizable to high noise levels (the linearity assumption).

That is, the dB reduction achieved at low intensity levels will hold for high intensity levels as well.

The REAT method may also be performed using a circumaural headphone in lieu of an acoustical test environment. This helps to alleviate equipment and background noise problems. Of course, this method is only applicable to the evaluation of earplugs. Sound field REAT and headphone REAT have been shown to provide equivalent data as long as the headphone results are appropriately corrected (Michael, Kerlin, Bienvenne, Prout, and Shampan, 1976).

One major problem with all REAT methods relates to physiological noises (Anderson and Whittle, 1971). These are "internal" noises generated by the normal functioning of the body. They include sounds caused by air flow (breathing), blood flow, and muscle/bone activities such as eyeblinks. Such noises incur a masking effect on the test tones in the occluded-ear conditions. This generally results in spurious responses, inflation of the occluded hearing threshold, and exaggeration of the measured HPD attenuation. For example, this inflation may amount to 6 dBA in the 125 Hz to 500 Hz range (Anderson and Whittle, 1971).

Another potential problem occurs only with earplugs. The insertion of the earplug may push ear wax into the auditory canal (impaction), and this will also result in inflated attenuation (Epps, 1984).

Furthermore, standard subjective measurement procedures such as REAT are not amenable for the examination of the variation of

HPD attenuation with increasing sound levels (linearity assumption), neither do they permit the evaluation of the attenuation of impulse noises nor the characteristics of nonlinear amplitude-sensitive hearing protectors (Martin, 1981). However, the REAT method remains the most widely-used and accepted method of determining frequency-specific HPD attenuation in the United States.

ANSI Z24.22-1957 (R1971)

This standard is the original standard derived by ANSI for the assessment of HPD attenuation and it incorporates the REAT method. The procedure entails a human subject seated in a directional sound field in an anechoic or near-anechoic environment. Using pure tones as the test stimuli, the subject is assessed for open-ear hearing threshold (in dBA) at seven test frequencies: 125, 250, 500, 1000, 2000, 4000, and 8000 Hz. The HPD is then applied by the subject to both ears, while listening to a 70 dBA background noise. After appropriate adjustment, the background noise is turned off and the subject is tested for the occluded-ear hearing thresholds (in dBA) at the same seven test frequencies. The difference between three (or more) occluded-ear threshold measurements (ascending, descending, ascending) and three (or more) unoccluded threshold measurements (ascending, descending, ascending), for ten (or more) subjects, determines the attenuation (in dBA) at each of the seven test frequencies.

ANSI S3.19-1974

In this standard, the REAT method was modified in an attempt to better reflect the "real world" situation. Test stimuli composed of 1/3 octave-band (OB) test tones are used instead of pure tones. Tests are performed in a semi-reverberant room instead of an anechoic/near-anechoic environment. Furthermore, a uniform nondirectional sound field is utilized in lieu of a directional sound field.

According to this standard, the subject is seated in a semi-reverberant room with three loudspeakers which create a diffuse sound field. One loudspeaker is placed on the surface of each of the three major planes (i.e., the ceiling-floor plane and two opposing wall planes). The subject is first tested for unoccluded-ear hearing threshold at nine 1/3 OB test frequencies centered at: 125, 250, 500, 1000, 2000, 3150, 4000, 6300, and 8000 Hz. The HPD of interest is then applied to both ears. The subject is then assessed for occluded-ear auditory thresholds at the same nine 1/3 OB tones.

Again, the difference between three (or more) pairs of occluded and unoccluded thresholds for ten (or more) subjects determines the HPD attenuation (in dB) at each of the nine 1/3 OB frequencies.

In addition to the primary sound field REAT method for most all HPDs, the ANSI S3.19 standard also specifies a supplemental physical method for earmuffs which is particularly useful for assessing muff attenuations at higher than threshold levels. This

is an objective (rather than psychophysical) method using an acoustical test fixture (artificial head/ear). A microphone is placed inside the artificial ear to assess sound pressure levels (SPLs). The algebraic difference in SPL (in dB) for each test frequency with and without the HPD on the dummy head is considered to be the attenuation. This method is superior to the REAT method in that attenuation at high noise levels can be accurately measured. However, it entails the tentative assumption that results generated by this method are applicable to humans. (No human variability is accounted for in any way.)

ANSI S12.6-1984

A recent renewal of ANSI S3.19 has been proposed and published in ANSI S12.6-1984. The two standards essentially utilize identical procedures except the new proposal aims at obtaining optimal performance values of HPDs which "may not usually be obtained under field conditions." By employing similar optimal procedures, a reliable "rank-ordering" of protectors would be obtained. The important subject-related procedures for attaining such a goal include an experimenter-supervised fit of HPDs for best attenuation. (However, no actual manipulation of the protector by the experimenter is allowed.) Moreover, once the actual audiometric testing is in progress, no further manipulation of the HPD is permitted. This standard is not designed to address real-world HPD

performance (Berger, 1985). This is contrary to most of the issues explored by the present study. For this reason and also to avoid redundancy, the following discussion will center around the two earlier standards.

Comparing the REAT Method of ANSI S3.19 and ANSI Z24.22

In theory, the use of a diffuse audiometric test sound field (ANSI S3.19) reduces the diffraction effects around the subject's head (Martin, 1977). Likewise, the use of 1/3 octave-band (OB) test tones instead of pure tones also diminishes such diffraction effects. Moreover, the possibility of pure-tone resonances occurring within an earmuff or earplug is reduced.

In practice, however, the mean attenuation results of tests using the two different standard procedures have been found to be almost identical (Berger, 1982f; Martin, 1977; Waugh, 1974). But for frequencies of 1000 Hz and above, there is some difference in standard deviations between the two measurement procedure (Martin, 1977). The ANSI S3.19 method generally produces less variable results.

Inter-laboratory (ANSI S3.19-qualified) variability of results have been investigated by Berger and Kerivan (1982). The overall results indicate significant variations among laboratories. For instance, the results for two earplugs (E-A-R, V51-R) showed at-

tenuations at the 1/3 OB test frequencies to differ by as much as 13 dBA for the V51-R and 9 dBA for the E-A-R plugs.

The intra-laboratory and inter-laboratory findings suggest that acceptable attenuation results can be obtained by either method. Apparatus available for the present study was most amenable to the ANSI Z24.22 standard, therefore it was adhered to for the earcap and earmuff attenuation tests.

The Psychophysical Method

Both the ANSI S3.19 and ANSI Z24.22 utilize the psychophysical method of minimal changes (method of limits) first developed by Fechner (Chaplin and Krawiec, 1979, p.41) for the presentation of acoustic stimuli to human subjects. In this method, a certain frequency tone is presented to the subject in a series of ascending and descending trials about the subject's auditory threshold. The "true" threshold is estimated by the average of all ascending and descending trials. This method tends to avert errors due to habituation and expectation. Habituation error occurs when the subject responds to a nonexistent tone by sheer reflex. Expectation error is due to incorrect response which is the result of motivation or heightened anticipation. Both of these errors tend to decrease the apparent hearing threshold of the subject. They are averted in this method by varying the descending and ascending trials and by selecting random beginning dB levels for trials.

HPDs: ATTENUATION NUMERICAL REPRESENTATION

According to the previously-discussed ANSI standards, the attenuation characteristics of an HPD are determined by its attenuation and standard deviation of attenuations at the seven test tones or nine 1/3 OB test frequencies. However, in practice, judgement and comparison of attenuation are difficult. These tasks are simplified if the above frequency-specific attenuation characteristics are quantified into a single number rating, although spectral information is hidden. Numerous attempts have been made to incorporate standard deviations across frequencies, representative ambient noises, and safety factors into attenuation values to derive a single number factor (Michael, 1981). The goal has been to represent the attenuation afforded by an HPD with a number which would indicate the amount of protection received by the majority of wearers.

No less than eleven single number ratings have been proposed since 1970 (Berger, 1982e). They differ in assumptions, methods, and results. A good single number factor scheme should provide an appropriate compromise between under-protecting a minority and over-protecting a majority of users in most environments (Berger, 1982e). The EPA has chosen to use the Noise Reduction Rating (NRR) as the single number rating. Its labeling is required on all HPD packages, while reporting the attenuations and standard deviations

in the 125 Hz to 8000 Hz range is not compulsory (EPA Part 211, 1984).

Berger (1982e) gave an illustration of how NRR is computed (Table 2). The NRR is the difference between the overall C-weighted sound level of a flat-by-octaves noise spectrum and the A-weighted noise levels at the ear while the hearing protector is worn. The mean attenuation value used incorporates a two-standard deviation reduction factor. This correction ensures that the attenuation values used in the calculation are actually attainable by the majority (98 percent) of wearers who correctly wear their HPDs. This adjustment supposedly accounts for wearer variation in HPD fit, sizing, or other factors. It does not account for misuse or abuse of the HPDs. Furthermore, a safety factor of 3 dB is subtracted from the overall C-weighted sound level to take into consideration possible variations in the spectra of actual industrial noises versus the test sound stimuli.

It is obvious from the example that the larger the attenuation and the smaller the standard deviation measured at each frequency, the larger will be the NRR. As has been mentioned before, manufacturers employ optimal procedures to evaluate their HPDs. The results are close to optimal attenuation with small standard deviations. The resulting NRRs may reflect possible attainable attenuation, but only under the best situations. In actual usage, however, the protection afforded by such HPDs is considerably less (Berger, 1982a). The primary reasons for this include differences

TABLE 2

An Illustration of NRR Derivation (adapted from Berger, 1982e)

Octave Band Frequency (Hz)	125	250	500	1000	2000	4000	8000
1. Hypothetical noise spectrum OB† sound levels (pink noise)	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	(level assumed is not significant)						
2. C-weighted OB sound levels unprotected ear	99.8	100.0	100.0	100.0	99.8	99.2	97.0
3. Overall C-weighted sound level (logarithmic sum of the seven OB sound levels in step 2)	108.0 dBC						
4. A-weighted OB sound levels unprotected ear	83.9	91.4	96.8	100.0	101.2	101.0	98.9
5. E-A-R™Plug mean attenuation	29.6	31.3	34.1	34.0	35.5	41.4*	39.6**
6. E-A-R™Plug standard deviations x2	6.4	6.6	4.2	4.6	5.4	3.9*	4.8**
7. Protected A-weighted OB sound levels [Step 4 - Step 5 + Step 6]	60.7	66.7	66.9	70.6	71.1	63.5	64.1

8. Overall A-weighted sound level under the protector (effective exposure) -- 76.0 dBA (logarithmic sum of the seven OB sound levels in step 7)

9. NRR = Step 3 - Step 8 - 3 dB††
   NRR = 108.0 - 76.0 - 3 = 29 dB

† OB-Octave band

†† This is a correction (safety) factor to protect against over estimating the device's noise reduction because of possible variations in the spectra of actual industrial noises.

* Numerical average of the 3000 Hz and 4000 Hz data

** Numerical average of the 6000 Hz and 8000 Hz data

in training, motivation, and utilization. In the laboratory situations, the test subjects are well-instructed and generally motivated. Comfort is not usually a problem for short test periods, and there exists minimal movement and of course, no HPD deterioration during the tests.

As a result of the discrepancy between optimal and actual effects, various proposals have been voiced to "derate" the reported NRR. Berger (1983d) suggested a reduction of 10 dB from the published NRR. OSHA (1983) has recently developed a derating guideline for weighing the benefits of noise control engineering against those of personal hearing protection. The guideline stipulates that a 50 percent derating scheme should be used.

Berger (1983b) summarized the OSHA-approved methods for estimating HPD adequacy (Table 3).

The Octave-Band method is the most accurate, followed by the NRR method and the Adjusted NRR method (Berger, 1983d). Berger also remarked that both the NRR methods are practical and suitable, provided the manufacturer's NRR is appropriately derated (e.g., by 10 dB) to reflect the real world attenuation. An HPD is acceptable for use only if it is shown to be adequate by any one of these methods. The OSHA regulations require that employers must provide HPDs to the workers whose TWA (Time Weighted Average) exposure is above 90 dB, and also to workers whose TWA exposure is 85 dB if they already have a standard threshold shift (STS) of hearing. STS is said to have occurred when changes in hearing acuity, relative to

TABLE 3

Summary of OSHA-approved Methods for Estimating HPD Adequacy (adapted from Berger, 1983b)

Technique	Description
Octave-Band Method * Long Method * NIOSH Method 1 *	Mean attenuation less 2 s.d. is subtracted from workplace noise levels at each frequency from 125 Hz - 8 kHz. Resultant values are A-weighted and summed to yield estimated dBA exposure.
NRR Method ** NIOSH Method 2 **	dBC (workplace noise level or TWA) - NRR = dBA (estimated protected exposure)
Adjusted NRR Method *** NIOSH Method 3 ***	dBA (workplace noise level or TWA) - (NRR - 7) = dBA (estimated protected exposure)

* Three alternative names for the same technique.

, * The two methods are identical except for minor mathematical differences which result in NRRs being approximately 0.5 dB less than the corresponding NIOSH methods.

the baseline audiogram, exceed 10 dB or more at 2000, 3000, and 4000 Hz in either ear (Berger, 1983a). The method of assessing the TWA exposure of workers is shown in Table 4 (Berger, 1983a). Therefore, in general, wearing an adequate protector should satisfy the condition: dBC - NRR $\leq$ 85dB OR dBA - (NRR - 7) $\leq$ 85 dB.

It has been estimated that a full 90 percent of the noise spectra in industry falls below 105 dBA, and that the vast majority of such noises do not require NRR values of 25-30 dB (Bilsom, 1984). Furthermore, low frequency noise environments are rare and HPDs generally are biased toward the attenuation of high frequencies. Therefore, it may be the case that in certain situations, workers using HPDs may in fact be "over"-protected. Over-protection is undesirable if it leads to the choice of a less comfortable or a less durable protector, one that is more expensive, or an HPD which drastically interferes with speech communication or perception of important auditory signals. In sum, the NRR only serves as one guideline, the selection of an HPD should take into consideration factors in actual usage as well as HPD comfort and durability. If misused, the NRR only gives the users a false sense of security, and skirts the problems of training and motivation.

The following discussions outline some of the research which has attempted to simulate "real world" attenuation in the laboratory, and those studies which probe into the attenuation of HPDs as worn in the actual work settings. Epps (1984) presented a similar review concentrating on earplugs; The current discussion fo-

TABLE 4

Estimating the TWA Exposure of Workers (adapted from Berger, 1983a)

TABLE I

Abbreviated version[9] of Table G-16a for computation of employee noise exposure.

Sound Level (dBA)	Permissible Time (hrs.)
80	32
85	16
90	8
95	4
100	2
105	1
110	0.5
115	0.25
120*	0.125*
125*	0.063*
130*	0.031*

* Exposures above 115 dBA are not permitted regardless of duration (see Table G-16), but should they exist, are to be included in computation of the noise dose.

TABLE II

Abbreviated version[9] of Table A-1 for conversion from Dose to TWA.

Dose (%)	TWA (dBA)*
10	73
25	80
50(action level)	85
75	88
100 (PEL)	90
115	91
130	92
150	93
175	94
200	95
400	100

* Values rounded to the nearest dB. The exact conversion from Dose to TWA is given by:

$$TWA = 16.61 \log_{10}[D/100] + 90$$

DOSE (D) = $100[C_1/T_1 + C_2/T_2 + \ldots + C_n/T_n]$

where C_n is the time exposed at a specific level and T_n is the time permitted at that level.

EXAMPLE(1): Workday consists of 7 hours exposure to a constant level of 95 dBA; D = [7/4] = 175%

EXAMPLE(2): Workday consists of 1 hour @ 95 dBA
2 hours @ 90 dBA
4 hours @ 85 dBA

D = 100[1/4 + 2/8 + 4/16] = 75%

cuses on earmuffs and earcaps while a corresponding review on earplugs can be found in Epps (1984).

HPDs: LABORATORY ESTIMATES OF ACTUAL ATTENUATION

The NAL Study

Various attempts have been made to simulate real world usage of HPDs in laboratories, and the resulting attenuations were estimated. Waugh of the National Acoustic Laboratories (NAL) in Australia attempted such a study on 75 earmuffs and 19 earplugs (cited in Berger, 1982b). The HPDs were first subjected to physical tests such as vibration, impact, and temperature cycling, then the attenuations were measured. The attenuations were assessed in accordance with the ANSI Z24.22 standard and the data corrected to 1/3 octave-band values. Subjects were given only the manufacturers' insertion-instructions and they received very little experimenter supervision. The overall results of the NAL study indicated significantly lower mean attenuations and higher standard deviations than the data published by the manufacturers.

User-fitted

Alberti, Riko, Abel, and Kristensen (1979) reported a study on 88 workers (mostly miners and steelworkers) who were undergoing evaluation for compensation for noise-induced hearing loss. These workers were asked to bring their own HPDs and fit them on themselves for attenuation tests in the laboratory. In all, 71 earplugs

and 17 earmuffs were evaluated. This research again represented an attempt to simulate real world HPD usage in the laboratory. Attenuations were determined by the sound field REAT method with narrow-band tones centered at 125, 250, 500, 1000, 2000, 3000, 4000, and 6000 Hz. The muffs and most plugs produced comparable attenuation at high frequencies, although the muffs afforded less attenuation at low frequencies. These findings were similar to those in previous controlled laboratory studies. However, in all cases the mean attenuation was significantly lower, while the standard deviation was higher, than figures published by the manufacturer.

Similar research was pursued by Abel, Alberti, and Riko (1981). The research involved 347 workers (again miners and steelworkers) who had worked in potentially hazardous noise environments for 5 to 20 years. Test procedures were identical to the Alberti et al. (1979) study. Six types of plugs (210 in total) and four different muffs (137 in total) were tested. In general, the Alberti et al. (1979) findings were repeated in this later study.

The discrepancy between actual achieved attenuation and manufacturer's estimated attenuation is obvious. This can at least in part, be attributed to improper application of HPDs by workers and poor protector care and maintenance.

Audiologist/Experimenter Application vs. Subject Application

The importance of proper training in HPD application for wearers has been verified indirectly by experiments comparing the attenuation results of audiologist/experimenter application versus novice subject application. Abel et al. (1981) reported an average increase of 7 or 8 dB across test frequencies when HPDs were fitted by an audiologist. These values are 3 to 4 dB less than the manufacturers' specifications.

In a recent study using the E-A-R user-molded plug, Berger (1981) investigated the effects of user insertion versus experimenter insertion on HPD attenuations. Sixty-five subjects, of which 55 percent had some experience inserting the earplug, participated in the research. The REAT method in ANSI S3.19 was utilized to assess protector attenuation. Subjects were first tested in the experimenter-insertion condition, then they were given E-A-R foam plugs along with package instructions and detailed written instructions. Next, the subjects were asked (in the second test) to insert the plug with no experimenter supervision. Attenuations were again estimated using the same REAT method.

Similar to the Abel et al. (1981) findings, Berger's (1981) attenuation results for the experimenter-insertion condition were comparable to the manufacturer's data. Variations in attenuations (between the experimenter-insertion and manufacturer's data) across frequencies were always less than 3 dB. Attenuation results from the subject-insertion condition were significantly lower than man-

ufacturer's data, especially in the 125 Hz to 1000 Hz range. These results are very close to that of the NAL, with slightly better attenuations across all frequencies with the subject-insertion condition in the Berger study. This slight improvement may be attributed to the addition of detailed written instructions given to the subjects and the familiarity of 55 percent of the subjects with the earplug insertion technique. No similar study has been attempted on earmuffs or earcaps.

HPD Application Instructions

Findings of the aforementioned research have shed some light on the importance of proper HPD application and application instructions. The quality of application instructions may be the single most significant factor affecting the attenuation of HPDs in actual workplaces. Poor noise attenuation may result from insufficient instruction and/or lack of wearer training by personnel involved in hearing conservation programs. Application training in industry ranges from no instruction at all to face-to-face demonstrations (Mellard, Doyle, and Miller, 1978).

The most important aspects of application instruction concern its completeness and understandability (Epps, 1984). The completeness of manufacturer's package instruction is normally limited by the space provided. Application instructions for earplugs are generally printed on the package; those for earmuffs and earcaps

are usually made available in a separate leaflet accompanying the HPDs. Instructions printed on a separate leaflet pose a special problem. The page may be lost or simply ignored. Some of the instructions have poor quality or too small print, while other may overwhelm the user with extraneous materials such as advertisement and construction information. Some instructions are quite inconspicuous, and the application steps may be oversimplified.

Epps (1984) mentioned there are three basic problems associated with some manufacturer's instructions. First, some written instructions are of a letter-point size of 9 or less. These letters may be difficult to read, especially for workers with visual acuity problems or for those working under poor lighting. Printing the instructions on a flexible plastic package also reduces readability. Secondly, high quality line drawings are not often utilized adequately. Good quality line drawings can mitigate problems due to illiteracy, multi-linguality of the workforce, and poor sentence structure and length. Line drawings should be of high quality, good clarity, and should describe the meaningful sequence of application steps. Lastly, most current package instructions do not provide the wearer with feedback. Such instructions never explicitly inform the user how the HPD should look or feel when correctly fitted, or how to tell if the attained seal is adequate.

A few more comments about package instructions can be added to this list. Few, if any, manufacturers' instructions incorporate explicit and conspicuous warnings about the adverse effects of im-

proper fitting on protector attenuation. Fewer still mention the deleterious consequences of improper care and maintenance.

Regarding nondisposable HPDs, two separate sets of instructions should be provided. One set of instructions concerns proper application procedures. The other set relates correct care and maintenance of the HPDs. In most cases, however, the two distinct sets of information are intermingled and presented in package instructions. This way of presentation may confuse the users and undermine their appreciation of the importance of proper maintenance.

Package instructions vary a great deal in quality and in the amount of information furnished. Worse still, relentless competitions have instigated manufacturers to resort to words and phrases which might be misleading. For instance, a phrase such as "EFFECTIVE ANY WAY YOU WEAR IT" may undermine the user's adherence to package instructions and provide them with an inflated sense of security.

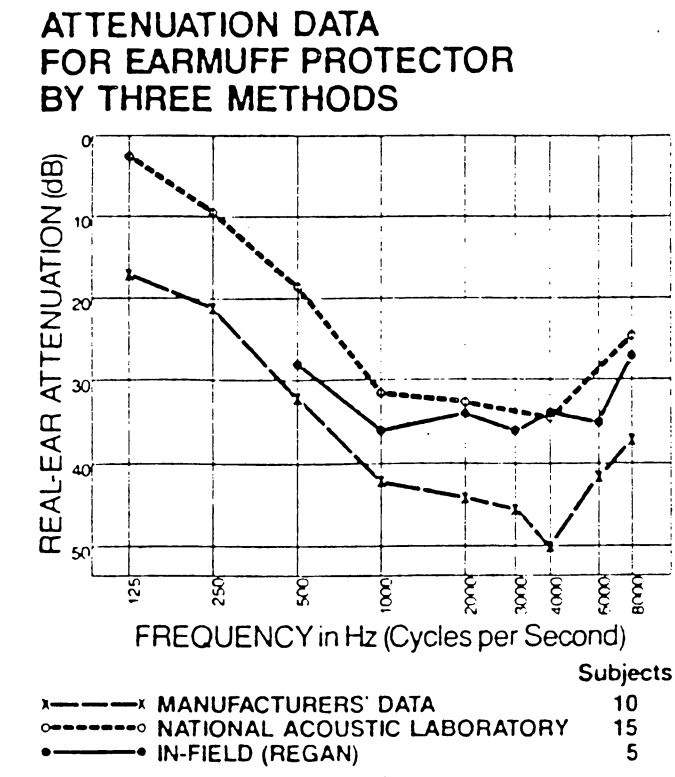
Given the importance of application instructions and the problems associated with some manufacturer's package instructions, it is surprising to find that hitherto only one study (Epps, 1984) has been done to compare the efficacy of different instruction techniques. Epps classified five instruction techniques for earplug insertion according to the information presented and strategy of instruction. The effects of instruction procedures on attenuation performance were confirmed. In general, model in-

struction produced best performance, followed by detailed instruction, manufacturers' package instruction, auditory feedback (a background reference noise) only, and no instruction at all. Attenuation afforded increased over twofold from no instruction to model instruction. More interestingly, the main effects of instruction strategies were differentially affected by some earplug designs. An example is Willson's EP-100 plug. It performed better with the auditory feedback than with package instructions. This indicates that some HPD designs are more susceptible to variations in application instructions, and optimal application instruction procedures are more important for some HPD designs. On the other side of the coin, such designs are probably more vulnerable to wearer misuses in the real world in the absence of proper instruction. The present study utilized similar instruction strategies to investigate their effects on the attenuations of earmuffs and earcaps.

HPDs: IN-FIELD ESTIMATES OF ACTUAL ATTENUATION

Attempts have been made to assess the attenuation of HPDs as they are worn in the actual workplace. In all of these studies, which will be discussed in the ensuing paragraphs, measurement facilities were established at the plant sites and subjects were brought in directly from their workplace. Although workers were aware that they might be subjects, they did not know the exact time of testing, and special precautions were taken to insure that they did not readjust their protectors once they were notified as subjects. One might argue that the mere knowledge that they will be tested would lead the workers to fit the HPD more carefully, and the resulting attenuations would still not reflect the "true" real world usage of HPDs. With this caution in mind, one can examine these studies for possible insights.

Early works in this area were performed by Regan (1978). All testing and evaluation procedures were done in a mobile unit located outside a plant site. The equipment and procedures were in compliance with ANSI Z24.22-1957. Subjects were brought in at random times and the occluded-ear thresholds followed by the unoccluded-ear thresholds were obtained. Test frequencies centered at 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz were used. In all, three types of earplugs and one muff were examined. Attenuation results indicated that a malleable sponge insert provided the best per-



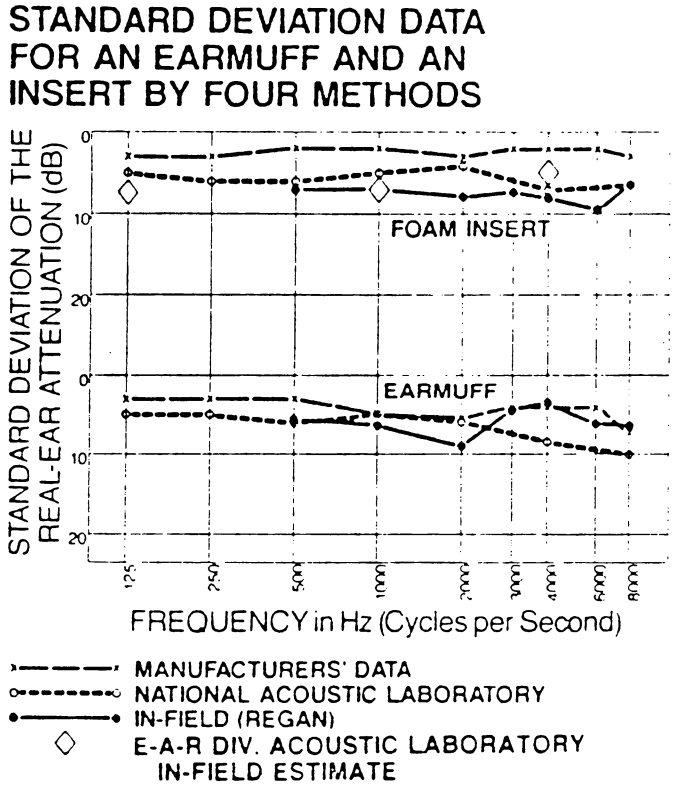


Figure 2. Results comparison of three approaches to HPD attenuation measurement (adapted from Berger, 1982b).

formance, followed by the earmuff, non-malleable rubber plugs, and custom-fitted plugs. These attenuations were significantly lower, and the standard deviations higher, than the corresponding values published by manufacturers. Regan's data generally agree with the NAL results mentioned earlier (Figure 2). For earmuffs, the agreement is within 4 dB across frequencies except at 500 Hz where the NAL data were much lower.

Several other field studies have been performed on earplugs (Edwards, Broderson, Green, and Lempert, 1983; Edwards, Hauser, Moiseev, Broderson, and Green, 1978; Padilla, 1976). In these three studies, nearly one thousand workers were measured using the headphone REAT method. In 1976, the National Institute for Occupational Safety and Health (NIOSH) funded a study to develop on-site instrumentation and procedures for earplug evaluation that would be consistent with ANSI S3.19-1974 test results. This resulted in the creation of the EAL (Environmental Acoustics Laboratory) field method (Michael et al., 1976). This method utilizes the headphone REAT procedure and corrects the field data, using linear equations, to values that would have been obtained in the laboratory had the ANSI S3.19 standard been followed. The EAL method is not designed to replace the ANSI S3.19 standard, but rather to simplify the in-field measurement of earplug attenuations. Several large-scale studies were made possible using this method (Edwards et al., 1978; Edwards et al., 1983).

Since the EAL method utilizes headphone REAT procedures, it is not applicable to the assessment of earmuffs and earcaps. A comparable methodology that is as convenient and can generate results consistent with ANSI S3.19 data has yet to be developed for earmuffs and earcaps. Further, user-molded earplugs have gained in popularity due to their low cost and convenience. Earmuffs are still popular in many work settings (e.g., heavy equipment operations, mines, cold areas). However, the usage of the earcap has dwindled (e.g., statistics cited in Gasaway, 1984). For all these reasons, real world study of earmuffs and earcaps is scant.

Goff and Blank (1984) attempted to use the objective method of a microphone in a human ear to estimate the actual protection afforded by earmuffs in mining situations. An internal microphone was placed inside the muff to measure the noise level reaching the ear. An external microphone was worn by the worker on the shoulder to measure the outside noise level at the same time. The difference between the two microphone readings indicated the noise reduction provided by the earmuff. A total of 40 workers and five different muffs were studied. Actual measured noise reduction ranged from 1 dBA to 25 dBA with a mean value of 14 dBA. Almost all (except two) of the real world data were lower, and in general considerably less, than the laboratory estimates. The authors also revealed that the muffs provided good attenuations at higher frequencies (above 1000 Hz). At lower frequencies, earmuff attenuations are relatively poor and amplification of noise may occur at 80 to 315 Hz.

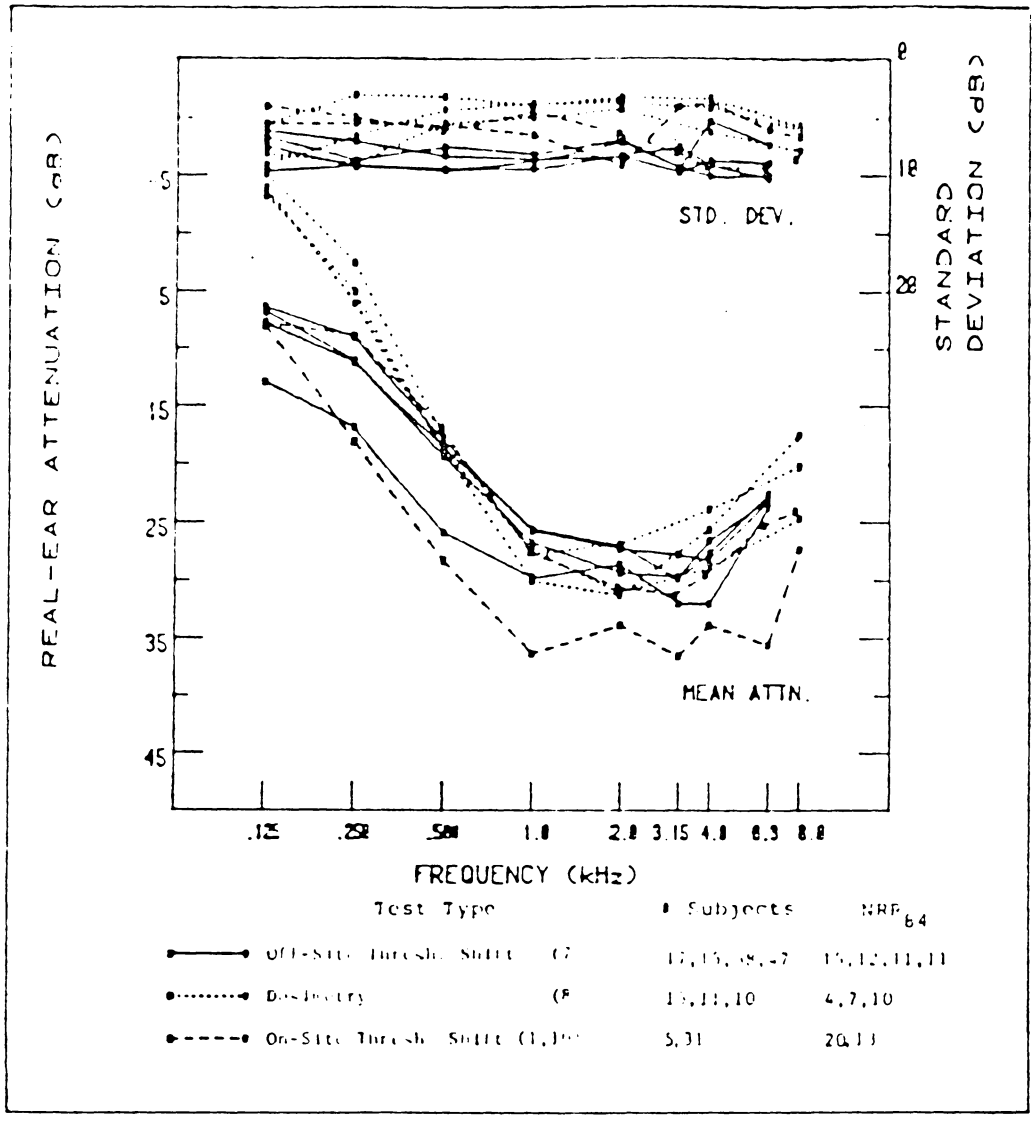


Figure 3. Real world performance of eight earmuffs evaluated by three methods (adapted from Berger, 1983d).

Berger (1983d) summarized the results of five real world studies on earmuffs, and compared the labeled NRR with the "Real World NRR" (RWNRR84). The calculation of the RWNRR84 is essentially similar to the EPA NRR, with the exception that only one standard deviation, and not two, is subtracted from the attenuation values. RWNRR84 is supposed to be a single number rating reflecting in-field protection for 84 percent of the wearers. The summary of results is shown in Table 5 and Figure 3.

The large discrepancy between labeled NRR and RWNRR84 is evident. This is an interesting summary because even though various brands of earmuffs were studied by different researchers using dissimilar methods, the attenuation data for the individual earmuffs were very similar (Figure 3). Furthermore, once again the in-field attenuations were lower, and standard deviations higher, than those reported by the manufacturers.

All in all, as concluded by Berger (1982b):

1. Manufacturers' laboratory data overrate the real world performance of HPDs. For a comfortable HPD, manufacturers' laboratory data can indicate the optimal protection obtainable by a conscientious, well-trained user. For an uncomfortable protector, the actual attenuation afforded may be much lower.

TABLE 5

Summary of Labeled vs. Real World Performance (adapted from Berger, 1983d)

	# of Subjects	Labeled NRR_{98}	RW NRR_{84}	a
Foam Plug	280	29	11	18
Custom Molded	391	14	6	8
Willson EP100	95	15	3	12
V-51R	296	23	2	21
MSA Accu-Fit	13	14	2	12
Norton Com-Fit	18	26	7	19
Bilsom Fiberglass	148	22	3	19
Ear Plugs (Average)	**1241 (Total)**	**20**	**5**	**15**
David Clark	17	23	15	8
Safety Supply #258	15	22	12	10
Hellberg MK-IV (Cap Model)	58	23	11	12
MSA MK IV	62	23	8	15
Welsh 4530	5	25	20	5
Genrl Muffs	101	22	14	8
AO 1720	11	25	7	18
Glendale 900	10	22	10	12
Bilsom UF-1	31	22	13	9
Ear Muffs (Average)	**310 (Total)**	**23**	**12**	**11**
Grand Average	**1551 (Total)**	**22**	**9**	**13**

a - Column 2 minus column 3

2. Laboratory simulation of actual usage (e.g., the NAL study) can generate useful insights into the actual attenuation in the real world.

In-field measurement may indicate the actual attenuation of HPDs. However, it does not reveal factors affecting the poor attenuation levels. Variables such as application technique, worker motivation, proper HPD fit, and wearing time cannot be controlled. Via adequate experimental manipulation and control, laboratory estimates probably offer the best alternative for quantifying the attenuation capabilities of HPDs, especially so that they can be compared against each other on a relatively common scale.

HPD COMFORT

Protector comfort may be the single most important factor determining the effectiveness of the HPD in the workplace. This is because an uncomfortable HPD will not be worn for long even though it may have superb attenuation capabilities. Furthermore, discomfort associated with the wearing of HPDs is the most frequent complaint lodged by users. Royster and Holder (1981) interviewed nurses, audiometrists, OSHA inspectors, and other personnel involved in the industrial hearing conservation programs to assess HPD problem areas. Results showed that a full 39 percent of the respondents regarded general discomfort as the major problem with hearing protectors. Despite these findings, comfort is much more infrequently evaluated than attenuation per se.

Flugrath and Tuberville (1972) performed the first study on this issue, evaluating the subjective comfort associated with the wearing of earplugs. They asked five males to rank six different earplugs on several criteria: comfort, ease of insertion and withdrawal, and how well the plug stayed in position after insertion. The earplugs tested included three solid, flexible, pre-formed rubber plugs, two liquid-filled plugs, and one user-molded plug. Results indicated that multiple-flange rubber plugs were least uncomfortable, but no statistical analysis was performed.

Savich (1981) postulated that the comfort provided by earmuffs depends upon the ear cushion seal against the head and the overall design of the muff. The ear cushion seal is contingent upon four factors: the clamping force of the muff, the adjustment of the muff, the softness of the cushion, and the weight of the muff (usually less than 200 grams). Savich then asked mine workers to classify eleven types of earmuffs for comfort as satisfactory, good, or very good. Larger surface area (against the head) was found to be a significant factor in enhancing comfort.

In a similar study (Damongeot, Tisserand, Krawsky, Grosdemange, and Lievin, 1981), the physical characteristics of 29 earmuffs were correlated with a subjective global comfort rating. Contrary to common belief, the weight of earmuffs had minimal influence on global comfort. The tightness of the spring (application force per unit of separation) and the adaptation pressure to local contour were important factors affecting the discomfort of HPDs. Also found to be moderately significant were the total application force on the cups and the average application pressure (force per unit cup cushion area). Heat was suggested as a probable candidate. However, the authors contended that thermal measurements taken did not allow discrimination between the HPDs.

Epps (1984) derived a comfort index (CI) for each of five earplugs using the semantic differential scales developed by Osgood, Suci, and Tannenbaum (1957). Six different scales were found to be significantly correlated with a general

COMFORTABLE/UNCOMFORTABLE scale and were therefore included in the CI together with the COMFORTABLE/UNCOMFORTABLE ratings. The six scales were: SOFT/HARD, SMOOTH/ROUGH, SHARP/ROUNDED, SHALLOW/DEEP, TIGHT/LOOSE, and PAINFUL/PAINLESS. The CI was found to be successful in differentiating between comfortable and uncomfortable plugs. Due to the success and demonstrated validity of Epp's comfort index, a similar approach will be employed in the proposed study to evaluate the comfort of earmuffs and earcaps.

RESEARCH OBJECTIVES

As discussed previously, the actual attenuation afforded by earmuffs and earcaps may be contingent upon the type of HPDs (both design and material), application technique, comfort, condition of the HPDs, amount of body movement, motivation of the wearer, anthropometric variations in head geometry (e.g., bizygomatic breadth, that is, the distance between the cheeks), head surface covering (hair, skin, and flesh layer), and the presence of any head gear (e.g., helmets, spectacles).

Selection of an ideal HPD must also take into consideration the ambient noise characteristics. For instance, earmuffs are typically quite good for midband energy noises (primarily around 1000 Hz). If the ambient noises are basically of low frequencies (e.g., 125-250 Hz), then a foam or pre-molded earplug may be preferred (Berger, 1983d). This kind of protector/noise spectrum matching may be performed to provide augmented protection for needed workers.

The present research investigated the effects of several of the aforementioned factors on earplugs/earmuffs/earcaps attenuation and selection. The specific aims were to:

1. sample and spectrally-analyze several representative excessive industrial noises;

2. experimentally determine the attenuation capabilities of selected earmuffs and earcaps in relation to different application instruction techniques;
3. assess the wearer comfort and preference for each earmuff and earcap; and
4. based on the data from (1) and (2), provide an example for optimal protector/noise spectra matching.

This process was aimed at yielding information for the selection and implementation of HPDs for various noise environments and determining the influence of different wearer application instruction strategies on the noise protection capabilities achieved with various HPDs.

EXPERIMENTAL METHOD AND DESIGN

Industrial Noise Sampling

Noises created by the following machines were measured, recorded, and spectrally-analyzed across the 1/3 octave frequency bands at local machine shops: vibro-energy finishing mill, numerical-control (NC) drilling machine, manual notcher, contour saw, engine lathe, band saw, sand blaster and dust collector, foundry furnace, ton press, surface grinder, and pedestal grinder. Their noise spectra and floor configuration at machine sites are shown in Appendix A (in alphabetical order).

Noise sampling method. The field method for the measurement of sound pressure levels specified in ANSI S1.13-1971 was adhered to as much as possible. Whenever possible, machine noises were assessed in-situ via a rectangular array of microphone positions. The smallest possible imaginary rectangular parallelepiped that would just enclose the source was noted for reference purpose. The microphone positions were then specified with respect to the parallelepiped. Four primary measuring points were located on the mid-planes, X meter(s) from each of the four sides of the parallelepiped. An additional noise measurement was taken at the operator's position.

For small sources whose maximum linear dimension (MAX) is less than 0.25 m , X is four times the MAX. For most sources whose MAX is equal to or greater than 0.25 m, X is one meter (3.28 feet). For large sources (or for sources that produce higher levels at greater distances than at one meter), X would be increased (e.g., two meters).

In most cases, the preferred height (h) of the microphone above the ground plane is 1.5 m (5 feet). Otherwise, h = H/2 (where H is the height of the parallelepiped), but not less than 0.25 m. For a microphone at standing operator's position, h is 1.63 m (64 inches); while for a microphone at a seated operator's position, h is 74 cm (29 inches) above the sitting surface.

The sound pressure level of machine noises were analyzed across the 1/3 octave bands recommended in the USAS S1.6-1967 standard, and recorded in the forms as shown in Appendix B. All SPL measurements were performed using a Larson-Davis Type I (ANSI Precision) Sound Level Meter with a 1.25 cm (0.5 inch) pressure response microphone directed at 0 degree toward the source. The complete noise sampling documentation is shown in Appendix B.

SPLs obtained at each microphone position were corrected for ambient noises and their average across different microphone positions for various frequencies were plotted as closed circles in the graphs of Appendix A. On the other hand, open circles indicated SPLs which were indistinguishable from background noise (when the machine SPL and ambient SPL differed by three dB or less). For each

particular source, the corrected SPLs from all primary microphone positions for a certain 1/3 octave frequency were averaged using the formula:

$$\bar{L} = 10 \log_{10} \left[\frac{1}{N} \sum_{i=1}^{N} 10^{0.1 L_i} \right]$$

The averaged SPLs were plotted in the format as specfied in ANSI S1.13-1971. These plots are intended to be "matched" with HPD attenuation results to ascertain which HPD will provide the maximum noise spectrum protection for respective machine noises.

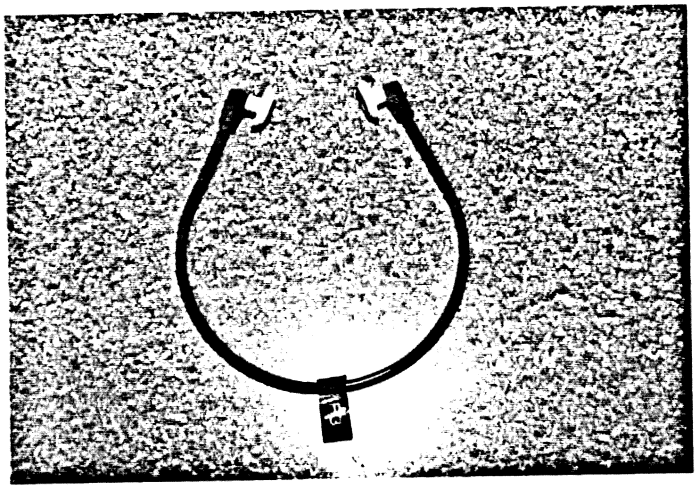
HPD Review and Selection

In preparation for the experiment, a review and subsequent selection of specific HPDs was performed. The following vendors were contacted and their products were considered for investigation: Adco Hearing Conservation, Airco, American Allsafe, American Optical, Aural Research, Aural Technology, Bilsom International, Curtis Safety Products, David Clark, E-A-R, Earmark, Eastern Safety Equipment, Emtech, Erb Safety, Fibre-Metal, Flents Products, Glende Optical, Global Marketing, Hearing Control, H.E. Douglas Engineering Sales, H.S. Leight & Associates, Hocks Laboratories, Inco, Insta-Mold Prosthetics, Mediprint, Midland Optical, Mine Safety Appliances, Mddex-Metric, Peltor, Plasmed, Pulmosan

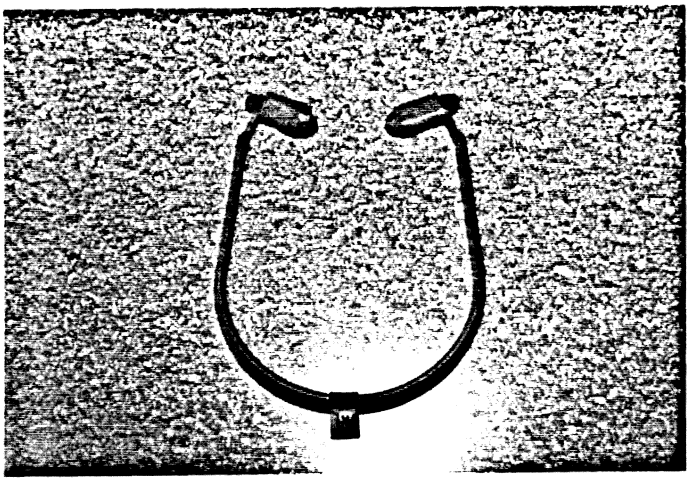
Safety, Saleco, Safety Direct, Sellstrom, Siebe Norton, Tasco, Telex Communications, and Willson Safety Products.

Four earmuffs and two earcaps were selected for the study. The earmuffs were selected on the basis of volume (large/small), cushion area (large/small), headband type, cushion filler type (foam/fluid), and adjustment mechanism. Earcaps were picked according to cap material (soft/hard) and headband type.

For selection purposes, the emphasis was on diversity of HPD style and construction, so that the interaction of different types of HPDs and instructions could be assessed. These HPDs were selected to represent as many attributes of HPDs as possible which were available on the present market. The emphasis was on design and instruction and not on manufacturer or vendor. The selected earcaps were Willson #20 Sound-Ban and Flents #055 Peace & Quiet Headband, and the four earmuffs were E-A-R model 1000, Siebe Norton Industrial model 4540, Peltor H6A/v, and Willson 365A Sound Barrier. The chosen earcaps are shown in Figure 4, and the earmuffs in Figure 5. An attribute comparison matrix for the four earmuffs appears in Figure 6. The apparatus and set-up for assessing the clamping force exerted by individual earmuff are shown in Figure 7. All force measurements for earmuffs were done using a Dial Push-Pull Force Gauge (Chatillon Model DPP - 200 N). The clamping force of each earmuff was measured and documented so that its possible relationship with attenuations and subjective comfort could be examined. It has been suggested that a larger clamping force



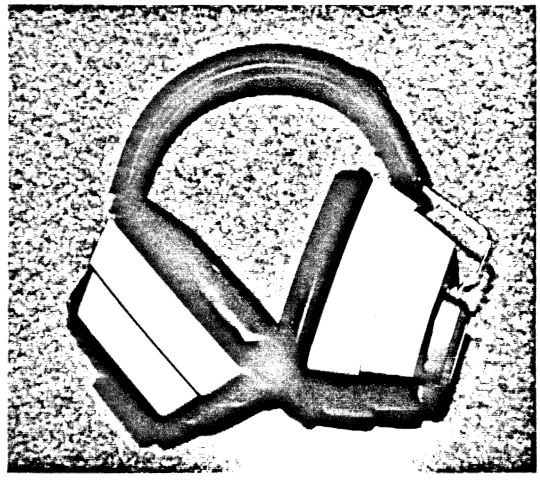
Flents #055 Headband



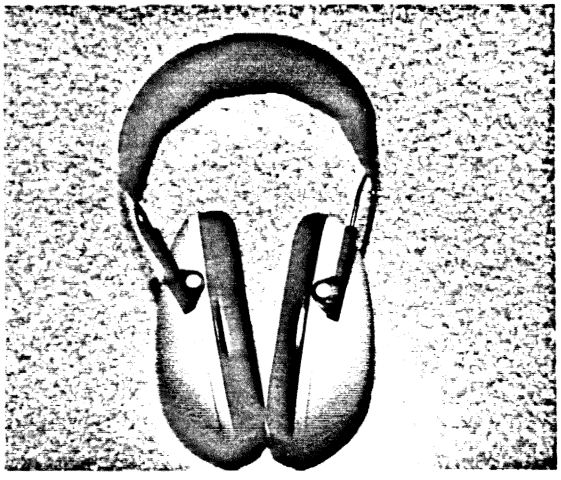
Willson #20 Sound-Ban

Figure 4. Earcaps included in the study.

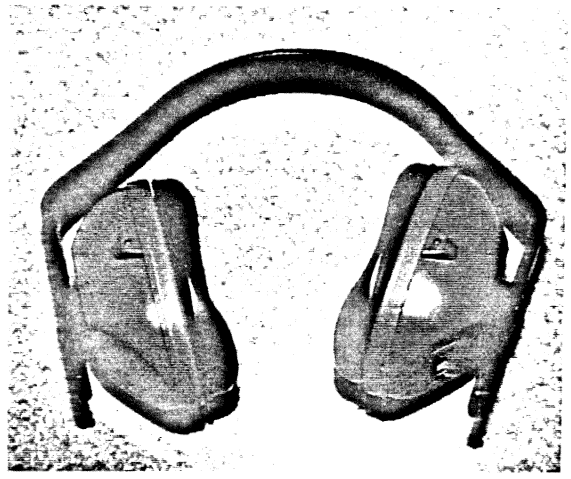
EAR Model 1000



Siebe Norton Model 4540



Peltor Model H6A/v



Willson Model 365A

Figure 5. Earmuffs included in the study.

	EAR 1000	Norton 4540	Peltor H6A/v	Willson 365A
Cushion Filler	Foam	Foam	Liquid & Foam	Liquid
Padded Headband	None	None	Yes	None
Weight	204.1 g 7.2 0z	309.0 g 10.9 oz	164.4 g 5.8 oz	311.8 g 11.0 oz
Cup Volume (ml)	151	178	126	207
Cushion Area (at 14.35 cm; in sq. cm)	25.55	48.39	35.87	33.29
Clamping Force (at 14.35 cm; in N)	13.0	26.0	12.4	14.0
Cup Depth (cm)	4.3	5.7	3.8	5.0

Figure 6. Attribute comparison of the four earmuffs.

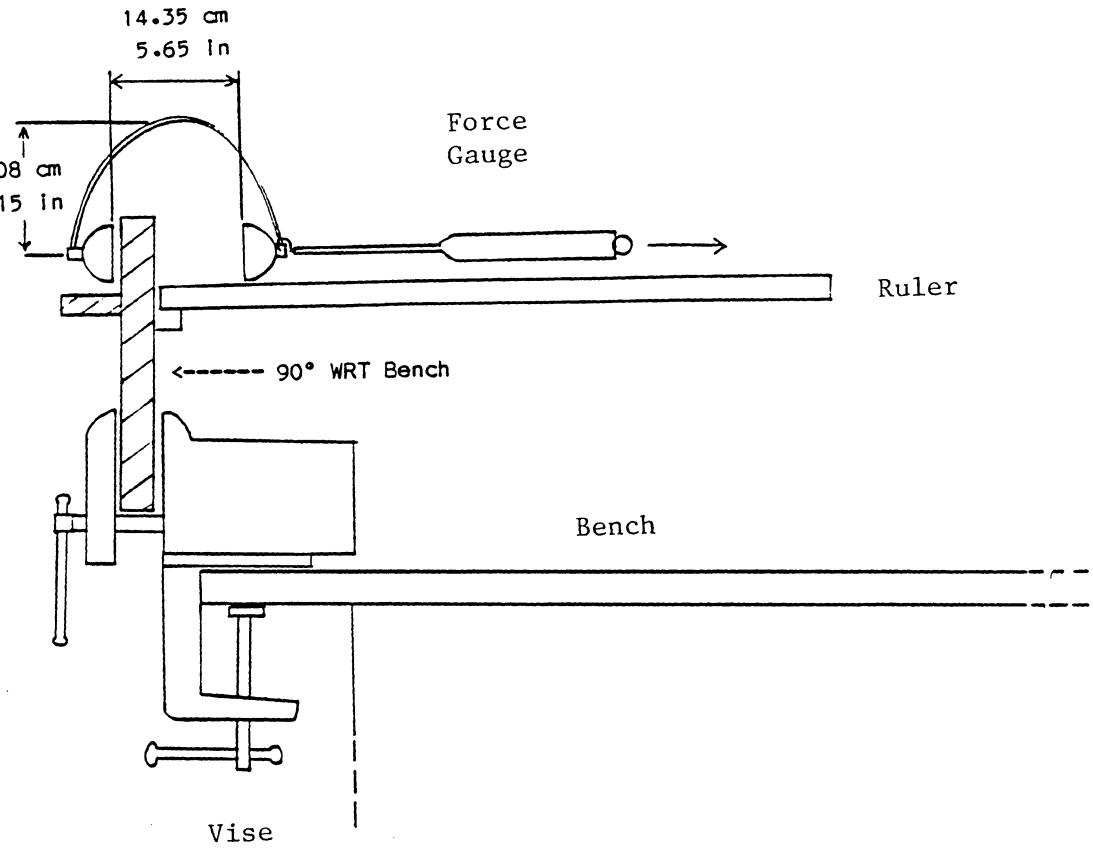


Figure 7. Apparatus and set-up for measuring clamping force of earmuffs.

may be associated with increased attenuation (which provides a tighter seal around the ears) and also increased discomfort.

As shown in Figure 4, the earcaps included the Flents and Willson caps. The Flents cap comprised a hollow flexible headband with minimal clamping force. Its noise-blocking apparatus consisted of a solid black end nut (one on each side) with a soft flange cushion designed to cover over the ear canal opening. The Willson cap had a solid plastic headband possessing a certain amount of clamping force. Its noise-blocking device comprised two end pods made of soft solid rubber designed to be inserted some distance into the ear canal. The pods shaped like earplugs but they were larger in size.

Subjects

Twenty-five females and twenty-five males were drawn from the Virginia Tech community to serve as paid volunteer subjects. An equal number of males and females were assigned to each experimental cell (as shown in Figure 8). The mean age (standard deviation) of the females was 21.08 (1.29) years and that of the males was 21.92 (1.55) years. The experimental procedures and subject's rights were explained to the participants beforehand and they were given an informed consent document (Appendix C) to read and sign before being allowed to participate.

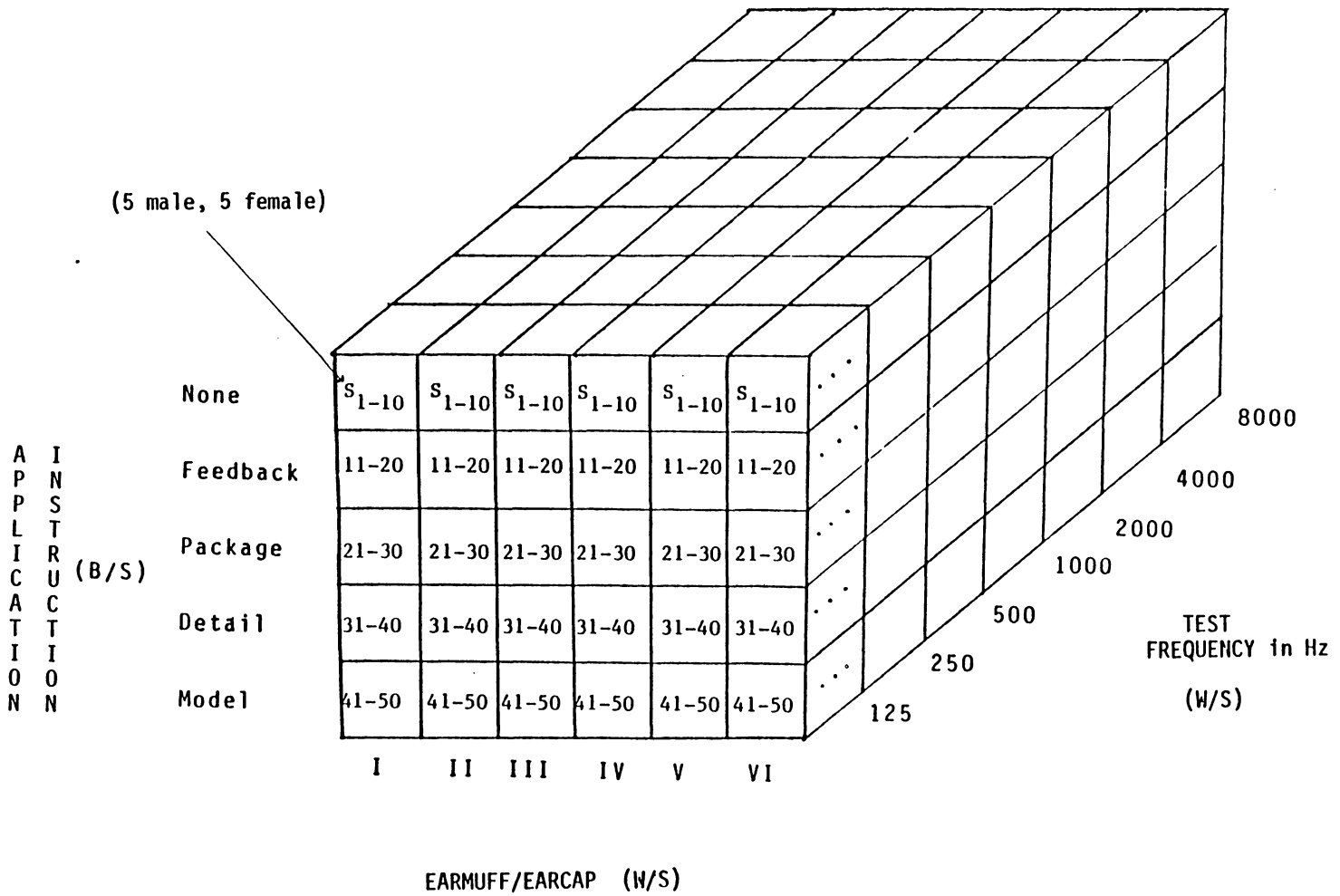


Figure 8. Experimental design matrix with independent variables and subject assignment.

Requirements for participation included: (1) subject had no or very limited prior experience with HPDs, (2) subject had not participated in previous HPD or audiological threshold experiments, (3) subject had no otopathic disorders (e.g., tinnitus, excessive ear wax), (4) subject had normal hearing as determined by an audiometric hearing threshold test (specified in the procedures section), and (5) subject had no beard or long sideburn which might have interfered with earmuff seal. Subjects wearing eyeglasses were told to remove their glasses during the experiment.

Experimental Test Facility

This study utilized an experimental facility existing in the Auditory Systems Laboratory at Virginia Tech which complies with ANSI Z24.22-1957. The facility is composed of a test booth, audiometer, power amplifier, frequency equalizer, loudspeaker, and subject's chair (Figure 9).

Test booth. The booth was designed and constructed to attenuate ambient noise during testing and to create a near-anechoic test environment. The outside dimensions of the chamber are approximately 1.82 x 1.82 x 2.44 meters (6 x 6 x 8 feet). The structure is made of wood framing with thick chipboard on the outside. A near-anechoic interior was achieved by placing thick fiberglass

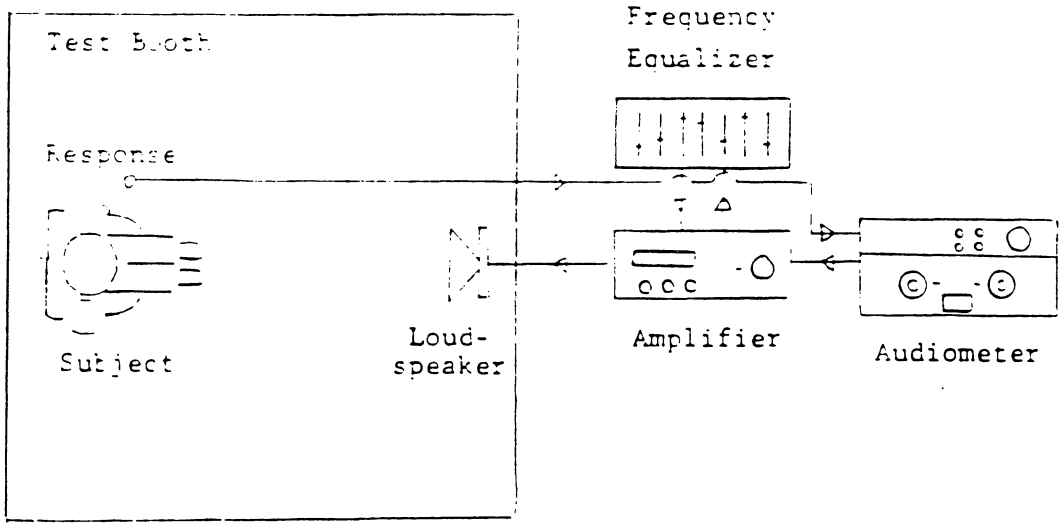


Figure 9. Block diagram of Virginia Tech audiometric test facility.

insulation between the framework and lining on all six interior surfaces with a polyurethane foam skin for sound absorption.

A ventilation system is provided for fresh air flow and cooling. Two sound baffles are used together with a variable speed, 100 cubic-feet-per-minute (CFM) fan. The system is capable of completely replacing the air in the test booth within three minutes. To minimize extraneous noise, the ventilation system was turned on only during intermissions between hearing tests. Lighting in the booth is provided by a 30-watt flourescent bulb located at the center of the ceiling. The lighting fixture emits no audible noise.

Audio instrumentation. The test signal presentation system consisted of a Beltone 114 Clinical Audiometer, a Scott 458A Integrated Stereo Amplifier, a Realistic 31-2000A Frequency Equalizer, and an Infinity RS-9B two-way loudspeaker. These components were used in integration to present pulsed, pure tones at the seven octave frequencies at sound levels below open-ear thresholds and above occluded-ear thresholds. A brief description of each component in the system follows.

(i) Beltone 114 Audiometer. This device was used as a pure tone generator, pulsing network, calibrated attenuator, and pure tone on-off switching device. This unit was able to produce pure tones at seven frequencies: 125, 250, 500, 1000, 2000, 4000, and 8000 Hz, within 3.0 percent of the indicated frequency (Beltone Special Instruments, 1983). Sound intensity was adjusted with a

dial. The dial was calibrated in one dB increments with detents at 5 dB steps. The attenuator linearity was within 3 dB over a 120 dB range. There were no audible transients for pulsed tones, and the rise and decay times of tones were 0.04 ms. Pulsed on-time was 230 ms and off-time was 300 ms. The average cycle time and duty cycle were about 530 ms and 43 percent, respectively. Total harmonic distortion was less than 0.03 percent and the noise level was greater than 70 dB below pure tone sound intensity levels.

The Beltone also had the capability of remote subject response. This was achieved by a subject response switch and experimenter's console subject response indicator. The switch was a quiet, momentary contact, pushbutton. Two-way communication between the subject and experimenter was made possible through an audiometer console-to-test booth intercom system.

(ii) Scott 458A Amplifier. This device was used to amplify pulsed, pure tone sounds for free field presentation in the test chamber. Its linearity was within 1 dB over the 20-20000 Hz audible range. The total harmonic distortion was 0.03 percent, and the signal-to-noise ratio exceeded 70 dB (Scott, 1983).

(iii) Frequency Equalizer. The pure tone signals from the amplifier were next passed through the equalizer. This allowed the audio system to compensate for any nonlinearity in the audiometer, amplifier, loudspeaker, and sound-field characteristics of the test booth. In this study, a Ross R-31M 31 band 1/3 octave equalizer was employed. The dB output range was again 24 (±12), and the in-

strument's linearity was within 3 dB from 5 Hz to 65 KHz. Total harmonic distortion was less than 0.1 percent over the 5 Hz to 65 KHz range (Ross, 1985).

(iv) Infinity RS-9B Loudspeaker. The two-way loudspeaker was used to present test tones to the subject in the booth. The orientation of the loudspeaker was such that the axis was horizontal and directed toward the ear level of the subject's head. The loudspeaker comprised a two-speaker vertical configuration of one 15.24 cm (6 inch) low-midrange polypropolene drivers and one 2.54 cm (1 inch) tweeter driver.

Facility Calibration

Facility calibration was performed using the Larson-Davis Type 1 (ANSI Precision) Sound Level Meter with a 2.54 cm (1.0 inch) random incidence microphone and 18 m (50 feet) microphone extension cable. The microphone was placed 70 cm (28 inches) above the sitting plane of the chair (which represents the mean sitting height of the 50 percentile U.S. male and female population), at the approximate center of the subject's head, at a 70 degree angle incident to the loudspeaker. All calibration procedures were performed with the door to the test booth closed and the flourescent light on.

The sound levels incident on the subject's ears were then calibrated using the minimum audible field (MAF) curve (Robinson

and Dadson, 1956). The MAF threshold dB level of each pure test tone was designated as the 0 dB hearing threshold level (HTL). The relationship between the absolute dB level and the dB HTL is shown in Table 6.

All baseline calibration was done at 40 dB HTL. Thus, the actual dB level as measured by the sound level meter was 40 + 22 = 62 dB at 125 Hz, 40 + 13 = 53 dB at 250 Hz, and so forth.

The calibration procedure was an iterative process of adjusting the amplifier volume control and the seven attenuators on the equalizer, until the desired dB levels were obtained across the seven test frequencies. Next, each test tone level was varied from 30 dB HTL to 70 dB HTL, in 5 dB steps, in order to ascertain that the system behaved linearly within each test frequency. The results (in dB) are shown in Table 7, and it was demonstrated that the readings gave accurate indications of the dB levels at the subject's head position. The facility was checked for correct calibration prior to each subject during the experiment.

Experimental Design

As shown previously in Figure 8, a mixed, three-way factorial design was used for data collection and analysis. The three factors were: instruction technique, HPD type, and pure tone test frequency. Instruction technique was a between-subjects factor with five levels (no instruction, no instruction with auditory feedback,

TABLE 6

Relationship between Absolute dB and dB HTL (adapted from Epps, 1984)

	Test Tone (Hz)						
	125	250	500	1000	2000	4000	8000
dB	22	13	7	6	2	-3	8
dB HTL	0	0	0	0	0	0	0

TABLE 7

Audio System Linearity Across Sound Intensity and Frequency

Test Tone (Hz)	dB Setting on Attenuator								
	30	35	40	45	50	55	60	65	70
125	51.9	57.0	62.0	66.7	71.8	76.8	81.5	86.0	89.5
250	42.9	48.0	53.0	57.7	62.8	67.9	72.9	77.8	82.7
500	36.8	41.9	47.0	51.7	56.9	61.9	66.9	71.9	76.8
1000	35.8	40.9	46.0	50.7	55.9	60.9	65.8	70.9	75.7
2000	32.0	37.0	42.0	46.6	51.8	56.8	61.7	66.5	71.3
4000	27.0	32.0	37.0	41.5	46.8	51.9	56.7	61.7	66.7
8000	37.8	43.0	48.0	52.6	57.8	62.9	67.9	72.9	77.7

manufacturer's package instruction, detailed instruction, and instruction by model). HPD type was a within-subject variable with six levels (four earmuffs and two earcaps). Test tone frequency was a within-subject variable with seven levels: 125, 250, 500, 1000, 2000, 4000, and 8000 Hz.

Each subject was assigned one instruction technique and tested with all protectors at all seven frequencies. By making instruction technique a between-subjects variable, systematic training effects of subjects were minimized. Five males and five females were assigned to each cell, therefore sex was a blocking factor. Furthermore, subjects were matched according to their audiometric hearing levels. Subjects were divided into five equal groups based on their pre-experimental assessment of hearing thresholds (see section titled "Experimental Procedures"). Each group was comprised of five males and five females. One male and one female from each group were randomly assigned to each one of the five instruction techniques. This practice helped minimize possible differences in measured HPD attenuations due to individual hearing sensitivity.

To reduce possible order and learning effects, a Youden Square design was employed for the ordering of HPD presentation (Figure 10). In similar vein, the presentation of the seven test tones was ordered by a Youden Square (Figure 11).

HPD comfort, for the wearing time during the test procedures, was assessed for each protector with a series of bipolar scales

		Subjects									
		1	2	3	4	5	6	7	8	9	10
	1	1	2	3	4	5	4	5	6	1	2
	2	2	3	4	5	6	5	6	1	2	3
HPD	3	6	1	2	3	4	3	4	5	6	1
order	4	3	4	5	6	1	6	1	2	3	4
	5	5	6	1	2	3	2	3	4	5	6
	6	4	5	6	1	2	1	2	3	4	5

HPD: 1 = EAR Muff
2 = Flents Cap
3 = Norton Muff
4 = Peltor Muff
5 = Willson Cap
6 = Willson Muff

Figure 10. Youden Square for HPD presentation.

		HPD Order					
		1	2	3	4	5	6
	1	1	2	3	4	5	6
	2	2	3	4	5	6	7
Frequency	3	7	1	2	3	4	5
Order	4	3	4	5	6	7	1
	5	6	7	1	2	3	4
	6	4	5	6	7	1	2
	7	5	6	7	1	2	3

Frequency: 1 = 125 Hz, 2 = 250 Hz, 3 = 500 Hz, 4 = 1000 Hz, 5 = 2000 Hz, 6 = 4000 Hz, 7 = 8000 Hz

Figure 11. Youden Square for Frequency presentation.

(Appendix D). Subjects were also asked to rank each protector according to: (1) discomfort, (2) ease of application, (3) general preference, and (4) projected preference for an eight-hour wearing time (Appendix E).

Experimental Procedures

Each of the participants attended two sessions. The subjects were screened (checked for the required qualifications) in the first session. During the second session, data were collected on the effects of instruction technique on HPD attenuations, HPD comfort ratings, and rankings.

Session one: Subject screening. Subjects were first asked to read an informed consent form (Appendix C). Any subject-initiated questions were answered by the experimenter, provided that the answer did not bias the experiment. The subject then signed the consent form if he/she agreed to participate. (All subjects chose to do so.)

To ensure that the participants had limited experience with HPDs, had never participated in a similar kind of study, had no known hearing problems, and did not suffer from otopathic disorders, they were requested to complete the questionnaire shown in Appendix F. Then eligible subjects were tested for normal hearing in accordance with the ANSI S3.21-1978 (Methods for Manual Pure-

Tone Audiometry) standard. Each subject was tested for left and right ear hearing thresholds at 125, 250, 500, 1000, 2000, 4000, and 8000 Hz. The average of three consecutive ascending thresholds, determined at each test frequency using a five pulse duration, equaled the mean estimate of hearing threshold at that frequency. Five complete on-off tone cycles were presented in each trial. Time between pulses and between trials were varied, but it always exceeded three seconds. Audibility was assumed when a subject responded on or before the fourth pulse. Subjects were considered to have normal hearing if hearing threshold was not more than 20 dBA for 125, 2000, 4000, and 8000 Hz, and not more than 15 dBA for 250, 500, and 1000 Hz.

At the conclusion of session one, eligible subjects were scheduled to return for the experimental session. In order to minimize incidence of noise-induced temporary threshold shift (TTS) during the interim period before the actual experiment, a reminder (shown in Appendix G) to avert TTS was given to each subject.

Session two: Effects of instruction strategies on attenuation - Application instruction condition. The second session lasted about three and one-half hours, during which HPD attenuation data, comfort ratings, and ranking responses were collected. Five males and five females received one type of instruction for each hearing protector. General, pre-test instructions common to each instruction condition are shown in Appendix H and are discussed below,

while specific instructions for each condition are shown in Appendices I and J.

(i) No instruction. Subjects were asked to don the HPDs with no accompanying instruction. This represented an attempt to simulate real world situations when workers are provided with hearing protectors without any instructions.

(ii) No instruction with auditory feedback. Subjects were asked to fit the HPDs without instruction. However, in this case a 70 dBA white noise was presented over the loudspeaker to help the wearers adjust for a good seal. This attempted to mimic real world cases where the wearers of hearing protectors are left with no instruction, and may rely on background noises to adjust for a good seal.

(iii) Manufacturer's package instruction. Subjects were provided with the complete HPD package together with the manufacturer's instruction. They were asked to don the HPDs in accordance with that instruction. This attempted to imitate real world situations where the workers are furnished with manufacturer's instruction as their only guide. These instructions are shown in Appendix I.

(iv) Detailed instruction. Manufacturers' instructions were modified and augmented with detailed written and pictorial presentations to derive the detailed instructions. The detailed instructions followed the proper application logic and were of such a length that they could be put on or inside HPD packages. This

instruction technique was an attempt to improve upon the manufacturer's package instruction which may be over-simplified and sometimes confusing. Furthermore, the detailed instruction for each HPD still consisted of a paper form that could be included with HPDs. Such instructions are shown in Appendix J.

(v) Model instruction. A face-to-face demonstration of proper application procedures was given to the subject. The subject first observed the experimenter donning each HPD once. Verbal instructions similar to the detailed instructions described previously were given to the subject during the demonstration. The subject then applied the HPD while the experimenter repeated the instruction. The subject was allowed to ask questions regarding proper HPD application. The experimenter answered these questions and provided verbal feedback concerning the subject's technique and correct HPD placement. Then the subject donned the HPD for a second time, after which attenuation tests were performed. This instruction technique attempted to simulate the optimal instruction possible when the wearer has proper feedback and hands-on experience for correct HPD application.

Session two - Procedures. The experimental protocol is shown in Table 8. A brief, verbal summary of the session was initially provided to the subject. Any questions regarding the session were answered by the experimenter provided the answers would not bias the experiment. Then the subject was assessed for open-ear hearing

threshold. A head positioning device was used to align the subject's head so that it was horizontal and facing the loudspeaker. The subject was reminded to avoid any head movement. A practice trial was given to acquaint the subject with the psychophysical method of limits. Once it was apparent that the subject understood the procedure, the open-ear thresholds were then determined for the test frequencies of 125, 250, 500, 1000, 2000, 4000, and 8000 Hz.

A standard psychophysical procedure was used to obtain the open-ear (and the subsequent occluded-ear) thresholds:

1. Each test frequency was presented in a pulsed tone through the free-field sound system. Trials were of five pulse duration. Time between trials was varied randomly from two to five seconds. Two ascending and two descending thresholds were estimated for each of seven pure tones.
2. The initial level for a chosen tone was -10 dB HTL. A test tone was then presented at this level. If no response was elicited, the level was increased in 10 dB HTL steps until the subject responded. Audibility was assumed when the subject responded on or before the fourth of five pulses.
3. The initial tone level for the first descending threshold was set between 5 and 15 dB HTL above the level of the first response. The tone level was decreased by 2.5 dB HTL steps until the subject did not respond, and the lowest level of response was recorded.

TABLE 8

Summary of Test Procedures: Session Two

EVENT NUMBER	EVENT/MEASUREMENT
1	Open-ear threshold practice at 1000 Hz
2	First Open-ear threshold at seven test frequencies
3	Apply HPD for a given instruction technique
4	Occluded-ear threshold at seven frequencies
5	Subjective HPD comfort rating
6	Remove HPD
7	Break period
8	Repeat events 3 to 7 for remaining HPDs
9	Second Open-ear threshold at seven test frequencies
10	Overall HPD preference rankings
11	Debrief and pay subject

4. The initial tone level for the first ascending threshold was then set at 5 to 10 dB HTL below the descending threshold. The tone level was increased by 2.5 dB HTL steps until the subject responded. This level was then noted as the ascending thresh-

5. The ascending and descending trials were repeated one more time, and the average of the four trials was taken as the estimated open-ear threshold at that particular frequency.

Next, the subject was given the general directions concerning his/her assigned instruction technique. Again, the general directions for the five instruction strategies are shown in Appendix H. For all except the no instruction group, the subject was also shown an information sheet saying:

> THE HEARING PROTECTORS WE WILL BE TESTING TODAY ARE ALL USED IN INDUSTRY TO PROTECT WORKERS FROM LOUD NOISE. THE AMOUNT OF NOISE THAT A PROTECTOR BLOCKS IS DETERMINED BY HOW GOOD THE "PROTECTOR SEAL" IN (OR AROUND) THE EAR OPENING IS.

To acquaint the subject with bipolar scales, directions for completing the scales and examples were shown to the subject prior to the attenuation tests. These directions appear in Appendix K. Then the subject was asked to don the first HPD as indicated ac-

cording to the instructions provided. Again, for all but the no instruction group, a reminder was presented to the subject:

> TAKE A MOMENT TO SEE HOW THE HEARING PROTECTION DEVICE (HPD) FEELS.
> IF YOU DO NOT FEEL THAT YOU HAVE ACHIEVED A "GOOD HPD SEAL," PLEASE RE-APPLY OR ADJUST THE DEVICE.

After the subject had donned the HPD, a one-minute stabilization (waiting) time followed. Occluded-ear thresholds were then determined for the HPD across the seven test frequencies. The occluded-ear thresholds were ascertained using the same standard procedures as for open-ear estimation previously discussed.

Next, while still wearing the HPD, the subject was asked to rate the comfort afforded by the protector, for the period of time worn. Then the HPD was removed and the subject was allowed a three-minute break.

The procedure was then repeated for the rest of the HPDs. Finally, all HPDs were ranked by the subject in order of comfort, ease of wearing, general preference, and estimated preference for an eight-hour wearing time. Subject's open-ear thresholds across the seven frequencies were assessed one more time to detect possible changes due to fatigue, learning, and so on. The average of the pre- and post-experiment open-ear thresholds was used in the calculation of HPD attenuations. As dictated by the REAT procedure,

the difference between the occluded-ear and open-ear thresholds represented the attenuation of the HPD (in dB) at a particular test frequency.

At the completion of the experiment, the subject was debriefed and any questions he or she may have had were answered. The subject was then paid and allowed to leave.

RESULTS

The data analysis consisted of four parts: HPD (earmuffs and earcaps) attenuation in relation to HPD type, application-instruction technique, and test frequency; HPD comfort index (CI) analysis; HPD rankings analysis; and examination of industrial machinery noises. Parametric statistical techniques were employed in the analyses of HPD attenuation results, while nonparametric procedures were used in the CI and ranking analyses. Most of the parametric analyses were done on the IBM 370 computer (with 3084 processor) using the Statistical Analysis System (SAS, 1985). The majority of nonparametric procedures were performed on the same computer utilizing the Virginia Tech Nonparametric Statistics Package (NPSP; Pirie, 1983).

HPD Attenuation: Primary Analysis

This analysis was aimed at: (1) determining the effects of various application instructions and different HPDs on attenuation, (2) determining the susceptibility of HPD-type and design to instruction, and (3) assessing HPD attenuations across the 125 to 8000 Hz frequency range.

Data comprised ten attenuation values (in dB, one for each subject) for every instruction/HPD/frequency combination (exper-

imental cell). Each attenuation value was the difference between the occluded (HPD-on) and the unoccluded (open-ear) hearing thresholds. The occluded thresholds were based on the mean of two ascending and two descending thresholds. The unoccluded thresholds were determined by the mean of four ascending and four descending thresholds.

First, an overall analysis of variance (ANOVA) was performed on the mixed-factors design. Instruction technique was a between-subjects factor (with 5 levels), test frequency was a within-subject factor (7 levels), and HPD was also a within-subject factor (with 6 levels). The primary ANOVA results are shown in Table 9. All main effects were shown to be significant (instruction, F (4,45) = 6.15, p = 0.0005; HPD-type, F (5,225) = 162.05, p = 0.0001; frequency, F (6,270) = 404.95, p = 0.0001). However, significant interaction effect comprised only HPD-by-frequency (F (30,1350) = 77.81, p = 0.0001). These results are further expounded and their respective loci of significance identified by pairwise comparisons (using Newman-Keuls Sequential Range Tests) in subsequent sections. (Note: An alternative method for ANOVA analysis incorporating the ordering effects of HPD and frequency presentation is addressed in Appendix L.) All results found are discussed only on the basis of the sample data obtained and conclusions drawn from these results should be limited to these experimental conditions and subsequent analyses, as actual attenuation achieved in practice may differ.

TABLE 9

ANOVA Summary Table for the Primary Analysis of Earmuff/ Earcap Attenuation

Source	df	SS	F	p
Between-subjects				
Instruction (I)	4	5382.85	6.15	0.0005
Subjects S/I	45	9844.77		
Within-subject				
HPD-type (H)	5	43503.20	162.05	0.0001
H x I	20	788.78	0.73	0.7881
H x S/I	225	12080.59		
Frequency (F)	6	132643.69	404.95	0.0001
F x I	24	1630.03	1.24	0.2035
F x S/I	270	14740.15		
H x F	30	39884.09	77.81	0.0001
H x F x I	120	2355.40	1.15	0.1385
H x F x S/I	1350	23065.46		
Total	2099	285919.01		

HPD-by-frequency interaction. The significant earmuff/earcap-by-frequency interaction (F (30,1350) = 77.81, p = 0.0001) was addressed using Newman-Keuls tests to isolate one set of multiple comparisons. Differences between the HPDs at each of seven test frequencies were examined to determine the level of protection afforded by each HPD across the 125 to 8000 Hz range. These results are important for matching a specific HPD to noise spectra.

Results of the Newman-Keuls test for the earmuff/earcap-by-frequency interaction are displayed in Table 10. These results indicate that, at 125 Hz, the Willson cap afforded superior attenuation to all other earcaps/earmuffs. The Willson muff, EAR muff, and Flents cap were the second best, while Norton and Peltor muffs provided comparable protection. However, the attenuation results of the Flents cap and Norton muff were not significantly different.

For 250 Hz tones, the Willson muff provided the greatest attenuations, followed by the Norton muff. Even though the Willson cap and EAR muff were not significantly different from each other in terms of protective capability, the Willson cap provided better attenuation than both the Peltor muff and Flents cap. Finally, the EAR muff attenuated better than the Flents cap.

Tones at 500 Hz were reduced most by the Norton muff, followed by the Willson muff. EAR and Peltor muffs provided the third best protection against these tones, while the Willson cap was fourth over the Flents cap.

TABLE 10

Results of the Newman-Keuls Test for the Earmuff/Earcap-by-Frequency Interaction: Differences Between Earmuffs/Earcaps by Frequency *

Alpha Level=0.05 df=1350 MS=17.09 n=50

125 Hz

Mean	HPDs			
15.35	Willson cap	A		
10.15	Willson muff	B		
8.95	EAR muff	B		
8.68	Flents cap	B	C	
6.64	Norton muff		C	D
5.81	Peltor muff			D

250 Hz

Mean	HPDs			
18.62	Willson muff	A		
16.46	Norton muff	B		
13.98	Willson cap	C		
12.27	EAR muff		C	D
11.22	Peltor muff			D E
9.22	Flents cap			E

500 Hz

Mean	HPDs		
28.92	Norton muff	A	
26.38	Willson muff	B	
22.14	EAR muff	C	
21.53	Peltor muff	C	
13.32	Willson cap	D	
8.39	Flents cap	E	

1000 Hz

Mean	HPDs		
35.45	Norton muff	A	
35.26	Willson muff	A	
30.48	EAR muff	B	
29.18	Peltor muff	B	
10.08	Willson cap	C	
7.29	Flents cap	D	

(cont'd)

* means (mean attenuations in dB) with the same letter are not significantly different at $p < 0.05$

TABLE 10 (cont'd)

Results of the Newman-Keuls Test for the Earmuff/Earcap-by-Frequency Interaction: Differences Between Earmuffs/Earcaps by Frequency *

Alpha Level=0.05 df=1350 MS=17.09 n=50

2000 Hz

Mean	HPDs	
36.79	Willson muff	A
36.40	Peltor muff	A
35.94	EAR muff	A
33.41	Willson cap	B
33.13	Norton muff	B
18.78	Flents cap	C

4000 Hz

Mean	HPDs	
33.13	Peltor muff	A
32.93	EAR muff	A
32.89	Willson cap	A
30.34	Willson muff	B
27.67	Norton muff	C
17.28	Flents cap	D

8000 Hz

Mean	HPDs	
32.96	EAR muff	A
32.60	Willson cap	A
29.35	Willson muff	B
28.55	Norton muff	B
25.03	Peltor muff	C
23.05	Flents cap	D

* means (mean attenuations in dB) with the same letter are not significantly different at $p < 0.05$

At 1000 Hz, the Norton and Willson muffs afforded the best attenuation, followed by the comparable performance of EAR and Peltor muffs. Lastly, the Willson cap proved to be better than the Flents cap at 1000 Hz.

The Willson, Peltor, and EAR muffs provided the greatest amount of noise reduction at 2000 Hz. These were followed by the Willson cap and the Norton muff, while the Flents cap was the least capable at this frequency.

At 4000 Hz, the Peltor, EAR, and Willson cap were distinguished from all others as the best protectors. They were followed by the Willson muff, Norton muff, and the Flents cap. The differences among them were all significant.

Results at 8000 Hz revealed that the best protection was afforded by the EAR muff and Willson cap. Willson and Norton muffs gave the next best attenuation, while the Peltor muff was decidedly better than the Flents cap.

It is apparent from these interaction results that there is no one best muff/cap across all frequencies. Each HPD excelled in one or a few frequencies range. However, the performance of the Willson muff appeared to be among the best over all frequencies.

Instruction main effect. The main effect of instruction technique was significant, F (4,45) = 6.15, p = 0.0005. Newman-Keuls tests were performed on the instruction main effect to isolate the exact loci of significance, and the results are shown in Table

11. The differences in attenuations attained among instructions by model, detailed, noise feedback, and manufacturer's package were not significant. No instruction, however, consistently provided the least attenuation. Therefore, it is apparent that with any instruction at all, the noise attenuation was significantly improved, no matter what the instruction strategy was.

HPD main effect. The main effect of HPD type was significant, with F (5,225) = 162.05, p = 0.0001. It must be noted that the earmuffs/earcaps main effect findings are confined by the significant HPD-by-frequency interactions. Although the study was not aimed at determining main effect differences among HPDs, as they can be surmised from manufacturer-provided NRR and spectral data, it was possible to analyze the HPD main effect (collapsed across instruction and frequency) for this sample. Newman-Keuls pairwise comparisons were performed to isolate the loci of significance. The comparison results are shown in Table 12. In general, the Willson muff yield superior attenuation to the EAR muff, Peltor muff, Willson cap, and Flents cap. The Norton muff and the EAR muff provided better attenuations than the Peltor muff, Willson cap, and Flents cap, in order of significant noise attenuation performance differences. Earcaps generally offer less attenuation than earmuffs and this is borne out by the ordering of the means for the earmuff/earcap main effect.

TABLE 11

Results of the Newman-Keuls Test for the Instruction Technique Main Effect

Alpha Level=0.05 df=45 MS=218.77 n=420

Mean *	Instruction	
24.85	Model	A
22.80	Detailed	A
22.69	Feedback	A
22.46	Package	A
19.82	None	B

* means (attenuations in dB) with the same letter are not significantly different at $p < 0.05$

TABLE 12

Results of the Newman-Keuls Test for the Earmuff/ Earcap Main Effect

Alpha Level=0.05 df=225 MS=53.69 n=350

Mean *	HPDs		
26.67	Willson muff	A	
25.59	Norton muff	A	B
25.14	EAR muff		B
23.68	Peltor muff		C
20.86	Willson cap		D
13.21	Flents cap		E

* means (attenuations in dB) with the same letter are not significantly different at $p < 0.05$

Frequency main effect. The main effect of test tone frequency was significant, F (6,270) = 404.95, p = 0.0001. Again, this effect should be examined in the context of interaction effects of frequency with other variables, such as the effects of HPD-by-frequency discussed earlier. The Newman-Keuls comparison results for frequency main effect involving earmuffs and earcaps are shown in Table 13. Considering the earcaps and earmuffs attenuations together, protection afforded at 2000 Hz was the best. These HPDs provided second best attenuations at 4000 and 8000 Hz. Then noise protection tapered off in the following order: 1000, 500, 250, and 125 Hz, with significant differences between each.

HPD Attenuation: Secondary Analysis of Gender Block

The primary analysis of the three-way (instruction by HPD by frequency) model was expanded to incorporate the gender block as a between-subjects factor. An overall ANOVA on the resultant four-way 5 x 6 x 7 x 2 (gender block) model was performed, and the results shown in Table 14. The main effect of gender was highly insignificant, F (1,40) = 0.09, p = 0.7675, while the frequency-by-gender interaction was significant, F (6,240) = 2.63, p = 0.0174, and therefore explored further. The three-way interaction of HPD-by-frequency-by-gender was also slightly significant, F (30,1200) = 1.56, p = 0.028, however it is of minimal practical significance, and its interpretation is difficult. For these rea-

TABLE 13

Results of the Newman-Keuls Test for the Frequency Main Effect (Earmuffs/Earcaps)

Alpha Level=0.05 df=270 MS=54.59 n=300

Mean *	Frequency	
32.41	2000 Hz	A
29.04	4000 Hz	B
28.59	8000 Hz	B
24.62	1000 Hz	C
20.11	500 Hz	D
13.63	250 Hz	E
9.26	125 Hz	F

* means (attenuations in dB) with the same letter are not significantly different at $p < 0.05$

TABLE 14

ANOVA Summary Table for the Gender Block Analysis of Earmuff/Earcap Attenuation

Source	df	SS	F	p
Between-subjects				
Instruction (I)	4	5382.85	5.71	0.0010
Gender (G)	1	20.88	0.09	0.7675
I x G	4	400.94	0.43	0.7893
Subjects S/IxG	40	9422.95		
Within-subject				
HPD type (H)	5	43503.20	156.91	0.0001
H x I	20	788.78	0.71	0.8122
H x G	5	136.89	0.49	0.7828
H x I x G	20	853.79	0.77	0.7477
H x S/I x G	200	11089.92		
Frequency (F)	6	132643.69	430.19	0.0001
F x I	24	1630.03	1.32	0.1500
F x G	6	809.82	2.63	0.0174
F x I x G	24	1596.92	1.29	0.1676
F x S/I x G	240	12333.41		
H x F	30	39884.09	78.25	0.0001
H x F x I	120	2355.40	1.16	0.1306
H x F x G	30	795.72	1.56	0.0280
H x F x I x G	120	1881.60	0.92	0.7085
H x F x S/I x G	1200	20388.14		
Total	2099	285919.01		

sons, this effect was not probed further. Significance levels of interaction and main effects investigated in the primary analysis appeared to remain relatively unchanged with the incorporation of the gender factor to the model. Therefore, only gender-related effects were explored further.

Frequency-by-gender interaction. The interaction effect of frequency with gender for earmuffs/earcaps was significant at $F(6,240) = 2.63$, $p = 0.0174$. A Newman-Keuls test was performed to isolate any significant differences between males and females at each of seven test tone frequencies. Differences between male and female attenuation means for each test frequency for earmuffs and earcaps are shown in Table 15. At all but 4000 Hz, the attenuations provided by earmuffs/earcaps to male and female subjects were essentially the same. Only at 4000 Hz, the earmuffs/earcaps afforded better protection for male subjects than for females.

Open-ear threshold analysis. As is evident from the ANOVA results, the gender effect was not significant. The absence of significant differences in HPD attenuation between males and females might be attributed to possible differences in open-ear thresholds, among other reasons which could not be empirically studied in this case. Differences in open-ear hearing thresholds might augment or nullify possible effects due to factors such as gender. Therefore, an additional analysis was performed to deter-

TABLE 15

Results of the Newman-Keuls Test for the Frequency-by-Gender Interaction: Differences in Gender by Test Frequency (Earmuffs/Earcaps) *

Alpha Level=0.05 df=240 MS=51.39 n=150

125 Hz			250 Hz			500 Hz		
Mean	Gender		Mean	Gender		Mean	Gender	
9.3	Female	A	14.0	Female	A	20.6	Female	A
9.2	Male	A	13.2	Male	A	19.6	Male	A

1000 Hz			2000 Hz			4000 Hz		
Mean	Gender		Mean	Gender		Mean	Gender	
25.3	Female	A	33.1	Female	A	30.3	Male	A
24.0	Male	A	31.8	Male	A	27.8	Female	B

8000 Hz		
Mean	Gender	
28.9	Male	A
28.3	Female	A

* means (attenuations in dB) with the same letter are not significantly different at $p < 0.05$

mine whether actual differences in open-ear hearing thresholds between males and females did in fact exist. A mixed, two-way factorial design, with gender as a between-subjects variable and frequency as a within-subject variable, was explored. ANOVA results (Table 16) unveiled no significant difference in open-ear hearing thresholds between males and females. Both the main effect of gender, F (1,48) = 0.03, p = 0.8631, and the gender-by-frequency interaction F (6,288) = 0.77, p = 0.5938 were not significant.

HPD Attenuation: Secondary Analysis on NRE/NRR84

In previous discussions, HPD attenuations were collapsed in a linear fashion across frequencies except where test frequency was included in the analysis as a separate variable. The Noise Reduction Rating (NRR) mentioned earlier represents an attempt to better reflect HPD attenuation over frequencies by a single number. In calculating an NRR, the attenuation data at each octave frequency is A-weighted and reduced by two standard deviations. The weighted attenuations are then collapsed across frequency and further reduced by a safety factor of three dB (see Table 2). It was therefore decided to further examine the HPD attenuation data of the present study by deriving single-number attenuation ratings similar to the NRR.

For each combination of instruction technique and HPD type, two single-number ratings were developed. They comprised the Noise

TABLE 16

ANOVA Summary Table for the Open-Ear Hearing Thresholds

Source	df	SS	F	p
Between-subjects				
Gender (G)	1	25.34	0.03	0.8631
Subjects S/G	48	8527.73		
Within-subject				
Frequency (F)	6	120182.67	54.25	0.0001
F x G	6	286.59	0.77	0.5938
F x S/G	288	17857.31		
Total	349	46860.47		

Reduction Estimate (NRE) and the Noise Reduction Estimate for the 84th percentile (NRR84, same as RWNRR84). The NRE is simply an NRR without the two standard deviation and 3 dB safety factor reduction. NRR84 is similar to the NRR except one, instead of two, standard deviation is subtracted from the attenuations. As mentioned earlier, the one standard deviation adjustment has been proposed as a reasonable estimate for single number rating of real world HPD attenuation performance (Berger, 1983d). Therefore, in making comparison with the reported NRRs, the NRR84s were used instead of adjusting the manufacturers' NRRs. The calculated NREs together with the NREs reported by manufacturers' for earmuffs and earcaps are displayed in Table 17, and the NRR84s were shown in Table 18.

NRE calculations showed that attenuations attained using the manufacturers' package instructions was, on average, 7 dB less than the manufacturers' reported NRE. Furthermore, none of the earmuffs/earcaps tested reached the manufacturers' NREs using <u>any</u> of the instruction conditions. The NRR84 results demonstrated a greater separation between the manufacturers' data and the experimental findings. Attenuations achieved by using the manufacturers' package instructions, for example, was on average across HPDs close to 8 dB below the manufacturers' claim. Deprived of any application instructions, a subject may receive 10 dB on average, across HPDs, less protection than that reported by the manufacturers. These indications are, however, inconclusive in that no further statistical analysis was possible due to incomplete data

TABLE 17

Results of the Noise Reduction Estimate (NRE) Calculations for Earmuffs/Earcaps *

HPD TYPE	None	Feedback	Package	Detail	Model	MEAN
	INSTRUCTION TECHNIQUE					
EAR muff (NRE=31.4)**	25.5	25.3	24.8	26.4	26.8	25.8
Flents cap (NRE=23.4)**	10.1	12.6	12.7	12.8	16.4	12.9
Norton muff (NRE=33.3)**	24.3	27.1	25.8	26.6	29.0	26.6
Peltor muff (NRE=27.3)**	22.9	23.7	23.9	24.5	24.8	24.0
Willson cap (NRE=29.0)**	14.2	16.6	18.1	15.7	19.8	16.9
Willson muff (NRE=34.0)**	27.0	29.3	28.1	28.6	31.0	28.8
MEAN (NRE=29.7)**	20.7	22.4	22.2	22.4	24.6	

* NRE calculated from study results
** reported NRE

TABLE 18

Results of the Noise Reduction Estimate for the 84th Percentile (NRR84) Calculations for Earmuffs/Earcaps *

HPD TYPE	None	Feedback	Package	Detail	Model	MEAN
	INSTRUCTION TECHNIQUE					
EAR muff (NRR=24)**	18.3	19.3	18.6	19.5	20.5	19.2
Flents cap (NRR=17)**	2.2	4.5	4.3	6.3	9.7	5.4
Norton muff (NRR=25)**	14.8	20.1	18.0	18.0	22.4	18.7
Peltor muff (NRR=20)**	14.6	17.4	17.4	17.6	16.9	16.8
Willson cap (NRR=22)**	5.1	9.1	9.3	9.3	13.6	9.3
Willson muff (NRR=26)**	18.2	21.8	20.0	20.7	24.2	21.0
MEAN (NRR=22.3)**	12.2	15.4	14.6	15.2	17.9	

* NRR84 calculated from study results
** reported NRR

available (e.g., the total number of subjects participating in manufacturers' HPD tests was not known). As a result, the above comparisons were based only on visual examination of the NRE and NRR84 data.

Comfort Index Analysis

A comfort index (CI) analysis was performed to: (1) determine which of the semantic differential scales were indicative of earmuffs/earcaps comfort and were therefore were valid measures, and (2) develop a single-number comfort index associated with each HPD, based only on the selected scales from (1). It should be noted that all comfort ratings were based on the subjects' wearing of the HPDs for approximately 25 minutes during the tests. Longer wearing periods might alter comfort ratings.

Scale correlations for earmuffs/earcaps. Subject responses on the semantic differential scales were coded into a 1 to 7 numerical range (see Appendix D). Since COMFORT was the hypothetical construct of interest, each scale was correlated (using the nonparametric Spearman Rank Correlation Coefficient) separately with the COMFORTABLE/UNCOMFORTABLE scale. The rationale was that any differential scale showing a significant correlation with the COMFORTABLE/UNCOMFORTABLE scale might be eliciting specific sensations or feelings associated with COMFORT. Nonparametric corre-

lation coefficients were used because the data were of ordinal scale, and the assumption of normal distribution of data, which is important for parametric procedures, was very likely violated in this case. In sum, 22 semantic differential scales were correlated with the COMFORTABLE/UNCOMFORTABLE scale, and the results are shown in Table 19. All significant scales (at $p < 0.05$) together with the COMFORTABLE/UNCOMFORTABLE scale were incorporated in the CI calculations.

Comfort Index (CI) for earmuffs/earcaps. Again, the CI was the sum of the coded responses for the twenty-one scales for each subject under each HPD. Thus, each HPD had a total of 50 CIs. Each scale had a possible score of 1 to 7. As a result, for each subject, the most comfortable HPD would have a CI of 21, while the most uncomfortable HPD could score a possible CI of 147 (21 x 7).

The nonparametric Friedman one-way block design was utilized for the CI analysis. The factor of interest was HPD type with 6 levels and the blocking factor was subjects (50 levels). The main effect of HPD was significant, $S(5) = 82.96$, $p < 0.001$, based on the chi-square large sample approximation (Hollander and Wolfe, 1973). Multiple comparisons (using the Wilcoxon Signed Rank test) were performed to locate the loci of significance and the results are shown in Table 20. This analysis indicated that Peltor, Willson, and EAR muffs were rated as more comfortable than the Norton muff and the two earcaps. The Norton muff was rated more

TABLE 19

Results of Spearman Correlation Values for Twenty-two Bipolar Scales with the Uncomfortable/Comfortable Scale (Earmuffs/Earcaps)

Scale	r
Soft/Hard	-0.62 *
Rough/Smooth	0.50 *
Loose/Tight	-0.31 *
Shallow/Deep	-0.18 *
Heavy/Light	0.05
Small/Large	0.23 *
Thick/Thin	-0.08
Simple/Complex	0.15 *
Symmetrical/Asymmetrical	-0.18 *
Delicate/Rugged	0.17 *
Strong/Weak	-0.25 *
Cold/Hot	-0.19 *
Expensive/Cheap	-0.44 *
Annoying/Pleasing	0.87 *
Valuable/Worthless	-0.47 *
Cumbersome/Convenient	0.54 *
Good/Bad	-0.74 *
Restrictive/Nonrestrictive	0.44 *
Painful/Painless	0.84 *
Open/Blocked	-0.48 *
Full/Empty	0.15 *
Uncomfortable Pressure/ No Uncomfortable Pressure	0.79 *

* significant at $p < 0.05$, using the Spearman correlation coefficient

TABLE 20

Results of Nonparametric Comparisons of Earmuffs/Earcaps Comfort Index (CI) Using the Signed Rank Test *

Rank Sum **	HPD	
128.5	Peltor muff	A
135.0	Willson muff	A
141.0	EAR muff	A
164.0	Norton muff	B
222.5	Flents cap	C
259.0	Willson cap	D

* rank sums with the same letter are not significantly different at $p < 0.05$

** a low rank sum value indicates a more "comfortable" HPD

comfortable than either of the earcaps, while the Flents cap was judged to be more comfortable than the Willson cap. Therefore, in general, the muffs were more preferred than earcaps in terms of comfort.

Comfort/Preference Rank Analysis

The four earmuffs and two earcaps were eventually ranked by each subject on four criteria: (1) amount of discomfort, (2) ease of application, (3) general preference, and (4) projected preference for an eight-hour wear time. Each group of rankings was analyzed separately via a nonparametric Friedman one-way block design. Overall significant findings were further pursued by a series of pairwise comparisons (using the Signed Rank test) on each ranking to locate the loci of significance. It must again be emphasized that these rankings were based on the subjects' exposure to the various HPDs during the relatively short experimental sessions.

Discomfort. Based on the Friedman test, the earmuffs/earcaps main effect was significant, S (5) = 133.2, $p < 0.001$. Results of pairwise comparisons are shown in Table 21. Results showed that the HPDs were perceived to be increasingly uncomfortable in the following order: Peltor muff, EAR muff, Willson muff, Norton muff, Flents cap, and Willson cap. Again, the earcaps were judged to be more uncomfortable than the muffs.

TABLE 21

Results of Nonparametric Comparisons of Earmuffs/Earcaps Ranks Based on Discomfort Using the Signed Rank Test *

Rank Sum **	HPD	
83	Peltor muff	A
129	EAR muff	B
155	Willson muff	C
186	Norton muff	D
222	Flents cap	E
275	Willson cap	F

* rank sums with the same letter are not significantly different at $p < 0.05$

** a high rank sum value indicates a more "uncomfortable" HPD

Ease of application. The main effect of earmuffs/earcaps was significant, S (5) = 74.87, $p < 0.001$. Results of pairwise comparisons on ease of application are given in Table 22. The Peltor and Willson muffs were judged to be the easiest to put on. However, the difference between the Willson and EAR muffs was not significant, and subjects perceived the Willson and EAR muffs easier to apply than the Norton muff, Flents cap, and Willson cap. In turn, the Norton muff was ranked as easier to wear than either of the caps. Both the caps were judged to be most difficult to apply.

General preference. Results of earmuffs/earcaps comparison indicated significant main effect of HPD type, S (5) =145.51, $p < 0.001$. Table 23 shows the findings of pairwise comparisons on the preference ranks. The Peltor and EAR muffs were found to be most preferred by the subjects. The rest of the HPDs were, in order of decreasing preference: Willson muff, Norton muff, Flents cap, and Willson cap. The earcaps were again ranked lowest, in this case on general preference.

Eight-hour wearing time. In ranking their preference for HPDs for an eight-hour wearing time, subjects had to base their estimates on their limited experience with the HPDs during the study. Therefore, this was a projected ranking only and not based on actual

TABLE 22

Results of Nonparametric Comparisons of Earmuffs/Earcaps Ranks Based on Ease of Application Using the Signed Rank Test *

Rank Sum **	HPD	
122	Peltor muff	A
127	Willson muff	A B
150	EAR muff	B
183	Norton muff	C
221	Flents cap	D
247	Willson cap	D

* rank sums with the same letter are not significantly different at $p < 0.05$

** a low Rank Sum value indicates that an HPD was "easy" to apply

TABLE 23

Results of Nonparametric Comparisons of Earmuffs/Earcaps Ranks Based on General Preference Using the Signed Rank Test *

Rank Sum **	HPD	
98	Peltor muff	A
113	EAR muff	A
142	Willson muff	B
178	Norton muff	C
247	Flents cap	D
272	Willson cap	E

* rank sums with the same letter are not significantly different at $p < 0.05$

** a low rank sum value indicates a more "preferred" HPD

eight hours of experience with the device. The main effect of earmuffs/earcaps type on projected eight-hour wearing time preference was significant, S (5) =145.09, $p < 0.001$. Nonparametric pairwise comparisons as shown in Table 24 unveiled a very clear-cut pattern. The order of preference for an eight-hour wear time is as follows: Peltor muff, EAR muff, Willson muff, Norton muff, Flents cap, and Willson cap. The differences among them were all significant. Again the muffs fared better than the caps.

Result Comparisons with a Sister Study on Earplugs

As has been mentioned before, a comparable study utilizing similar procedures and probing the effects of instructions on earplug attenuation was accomplished by Epps (1984). The methodological similarities between Epps' and the present study enabled the following comparison and contrasting of the findings on earplugs and earmuffs/earcaps.

Comparison of attenuation results of earplugs and earmuffs/earcaps is presented in Table 25. Several conspicuous differences were evident between earplugs and earmuffs/earcaps. Effects which were significant for earplugs but not for earmuffs/earcaps include the gender main effect, HPD-by-instruction interaction, and the HPD-by-gender interaction. In general, other significant effects were comparable.

TABLE 24

Results of Nonparametric Comparisons of Earmuffs/Earcaps Ranks Based on Eight-Hour Wearing Time Preference using the Signed Rank Test *

Rank Sum **	HPD	
87	Peltor muff	A
113	EAR muff	B
154	Willson muff	C
189	Norton muff	D
233	Flents cap	E
274	Willson cap	F

* rank sums with the same letter are not significantly different at $p < 0.05$

** a low rank sum value indicates a more "preferred" HPD

The interaction of earplug with interaction was significant, F (16,180) = 2.85, p = 0.0004. In general, significant differences were detected between the five earplugs for each of the instruction techniques and between the five instruction techniques for each earplug type. For instance, results indicated that the Willson earplug provided better attenuations under model, detailed, and noise feedback instructions than under package and no instructions. The findings of the present study suggested strongly, however, the absence of similar interaction effect for earmuffs and earcaps.

The instruction technique by model was revealed as the superior technique for earplug application instruction over noise feedback, manufacturer's package, and no instructions (F (4,45) = 7.70, p = 0.0001). Furthermore, no instruction provided less attenuation than package, feedback, and detailed instructions. For earmuffs and earcaps, however, it was revealed that any one type of instruction technique was superior to no instruction at all.

The HPD-by-frequency interaction results (F (24,1080) = 7.04, p = 0.0001) in general concurred with the notion that earplugs (versus earmuffs) provide greater attenuation for lower frequency tones (below 500 Hz). Earmuffs are generally quite good for attenuating noise of higher frequencies (above 500 Hz). These trends were borne out by the results described herein. Furthermore, earcaps (especially so with the plug-like Willson cap) provide better protection at lower (below 250 Hz) and higher (above 4000 Hz) frequencies. In general, based on this study's findings the

TABLE 25

Summary Table Comparing Attenuation Findings on Earplugs and Earmuffs/Earcaps (Epps, 1984 and the Present Study)

		HPDs	
		Earplug	Earmuff/Earcap
EFFECTS	I	F (4,45) = 7.70 p = 0.0001 *	F (4,45) = 6.15 p = 0.0005 *
	H	F (4,180) = 15.06 p = 0.0001 *	F (5,225) = 162.05 p = 0.0001 *
	F	F (6,270) = 291.86 p = 0.0001 *	F (6,270) = 404.95 p = 0.0001 *
	G	F (1,40) = 6.69 p = 0.0134 *	F (1,40) = 0.09 p = 0.7675
	H x I	F (16,180) = 2.85 p = 0.0004 *	F (20,225) = 0.73 p = 0.7881
	H x F	F (24,1080) = 7.04 p = 0.0001 *	F (30,1350) = 77.81 p = 0 .0001 *
	H x G	F (4,160) = 2.69 p = 0.0331 *	F (5,200) = 0.49 p = 0.7828
	F x G	F (6,240) = 2.80 p = 0.0118 *	F (6,240) = 2.63 p = 0.0174 *

Effects: H = HPD I = Instruction
F = Frequency G = Gender

* significant at $p < 0.05$

earmuffs afforded better overall attenuation, followed by earplugs and earcaps. However, HPD attenuations should be viewed in the context of the significant HPD-by-frequency interactions in both the earplug and earmuff/earcap studies.

The interaction effect of earplug with gender was significant, F (4,160) = 2.69, p = 0.0331. Further analyses revealed that for the twenty-five females who participated in the experiment, the EAR earplug provided better attenuation than the Tasco, Bilsom, and Flents plugs. The Flents earplug was revealed as inferior in attenuation capability to the other four earplugs. For male subjects, the EAR was also superior to the Flents, Tasco, and Bilsom earplugs. Only the Flents earplug was sensitive to the gender factor, providing better attenuation for males than females. Once again, such interaction effect was strongly denied for earmuffs and earcaps.

The main effect of gender was also significant for earplugs (F (1,40) = 6.69, p = 0.0134). Again, the main effect of gender is restricted by the earplug-by-gender and frequency-by-gender interactions. In general, males received significantly higher attenuation than females for earplugs. In contrast, for earmuffs and earcaps, the gender effect was not significant.

The earplug NRE calculations indicated results similar to that found for earmuffs/earcaps. First, the attenuation achieved using the manufacturers' package instructions was, on average, 16 dB less than the reported NRE. Second, no one earplug tested attained the level of attenuation reported by the manufacturers. The NRR84

calculations unveiled a wider disparity between the experimental attenuation results and the manufacturers' reported attenuation. The attenuation achieved by the no instruction group is over 23 dB less than the reported attenuation for the earplugs. In addition, the manufacturers' package instruction resulted in over 17 dB attenuation less than manufacturers' reports.

By comparing the NRE and NRR84 findings for earplugs and earmuffs/earcaps, it is evident that even though none of the HPDs tested attained the same attenuation levels proclaimed by the manufacturers, the experimental results for earmuffs/earcaps corresponded closer to the manufacturers' numbers.

The separate ranking procedures and the different setup of bipolar scales for earplugs and earmuffs/earcaps precluded any feasible comparisons between the earplug and earmuff/earcap ranks and comfort indices.

Examination of Industrial Machinery Noises

In general, the machinery noises can be grouped into (1) spectra with noise power concentrated in higher frequency ranges, (2) spectra with noise power concentrated in lower frequency ranges, and (3) relatively uniform broadband spectra. Group one includes the pedestal grinder, contour saw, and the sand blaster. Group two comprises the dust collector and the blast furnace. Group three consists of the engine lathe, surface grinder,

sand blaster with dust collector, cutoff saw, manual notcher, 27-ton press, NC drilling machine with controller, and the vibro-energy finishing mill. The spectra plots and the floor configurations at machine sites are displayed in Appendix A.

DISCUSSION AND CONCLUSIONS

The present research accomplished its goals of (1) determining the attenuations of various earmuffs and earcaps across frequency as affected by different instruction techniques, (2) assessing wearer comfort and preference by using a refined subjective measurement technique, and (3) sampling various excessive machinery noises and providing an example of matching the optimal hearing protector to individual high-level noises.

HPD Attenuations

HPD attenuations will be discussed in light of: instruction effects, HPD design, gender effect, and single-number ratings. Again, earplug and earmuff/earcap results will be compared and contrasted.

Application instructions. Results of the earplug attenuation (Epps, 1984) indicated that there exist substantial differences among instruction techniques for achieving effective attenuation with earplugs. The magnitude of earplug protection was greater than a twofold increase from no instruction to model instruction.

The large gain in earplug attenuation associated with more intensive instruction may hint that, in hearing conservation pro-

grams, by instituting a program which included a five-minute demonstration of correct earplug insertion (similar to the modeling condition in this study), earplug attenuation gain might increase tremendously. Also, the actual demonstrations might not require a trained audiologist, as earplug insertion procedures are relatively easy to learn and demonstrate. Classroom-type instruction sessions or even audio-visual instruction might be given in lieu of individual model demonstration. However, the nature of the instruction media differs, and further research is needed to clarify their relative efficiency. For instance, audio-visual aids alone may deprive the learner of performance feedback and hands-on experience.

On the other hand, the present study clearly demonstrated that earmuff/earcap attenuation was not nearly as dependent on application instructions as earplugs. This is perhaps the most important finding of the present study because it indicates that user insertion/donning instructions are much more critical to the success of protection afforded by earplugs than earmuffs and earcaps. The data revealed that, in general, earmuffs and earcaps were much more resilient than earplugs to changes in instruction techniques. Table 9 and Table 11 indicate that even though any one type of instruction was better than no instruction at all, the differences in attenuations achieved by diverse instructions were not significant. This hints that in some practical cases where inadequate application instruction is unfortunately the norm, then earmuffs

and, possibly earcaps, might be a better choice over earplugs. However, since adequate instruction is easy to achieve, given a little extra planning, effort, and motivation, as demonstrated by Epps' study on earplugs, narrowing the choice on earmuffs/earcaps may be unnecessary. With this premise, the choice of using a particular HPD-type would be better based on other criteria such as the particular problem noise, cleanliness of work environment, or personal preference. Nevertheless, the important point to remember is that earplug-type is quite sensitive to variation in instruction technique, while earmuffs and earcaps are more resistant to changes in instruction-type, as inadequate instruction is always better than none at all. It should also be stressed that the complete lack of instruction is clearly contraindicated for both earmuffs and earcaps as well as for earplugs.

Within each HPD-type, some brands of a particular type may be more susceptible to changes in instruction. In general, Epps (1984) demonstrated that for all five earplug designs tested, the model and detailed instruction techniques provided the highest attenuation levels and the no instruction technique provided the least attenuations. However, the attenuations of certain earplugs were differentially affected by various instructions. For instance, the Willson EP-100 plug performed better with the auditory feedback than package instructions. As related by Epps, a possible explanation of this result concerns the small amount of information contained in the manufacturer's instruction. As a result of this,

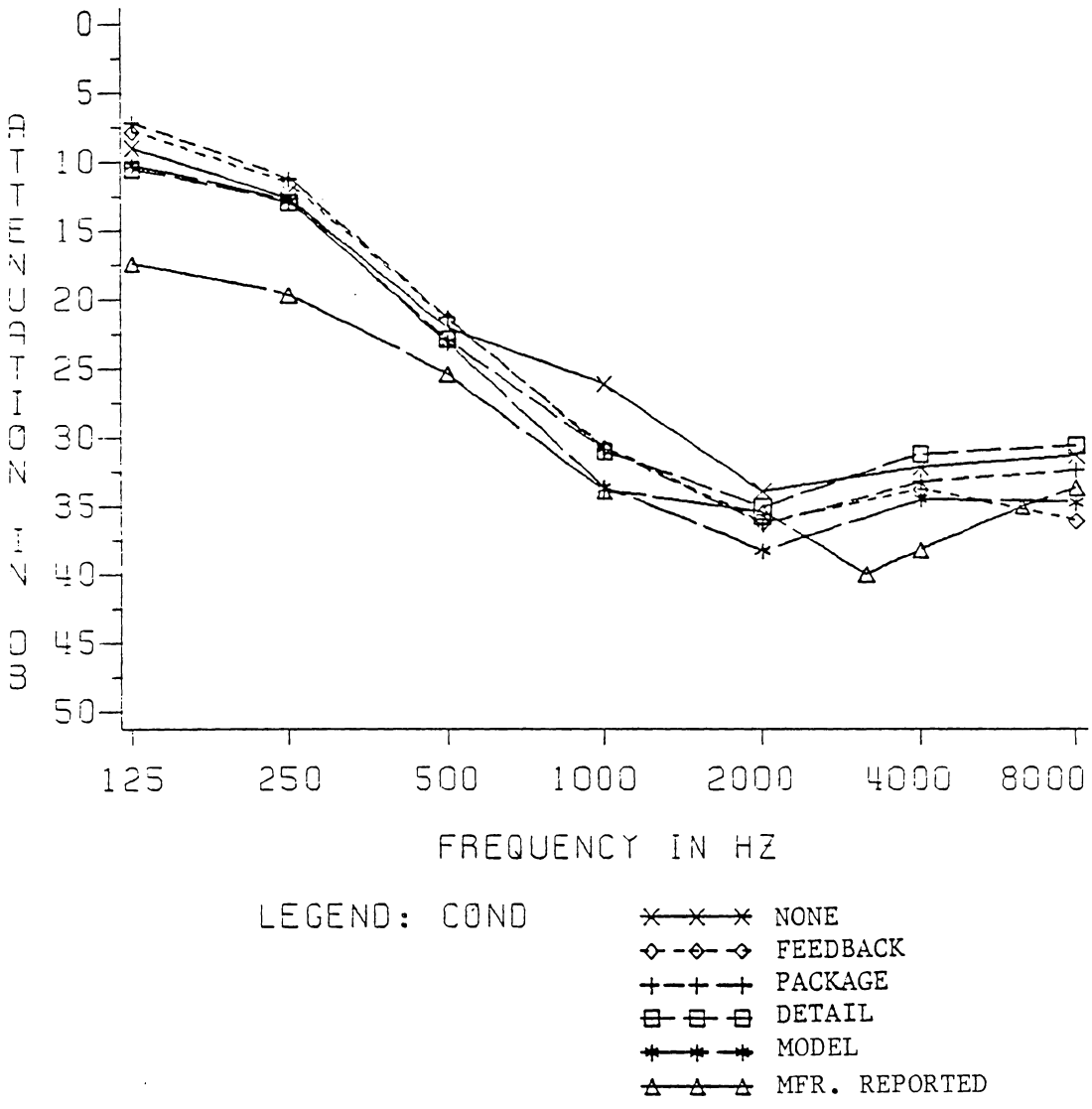


Figure 12. Attenuation characteristics of EAR muff model 1000 at each instruction technique.

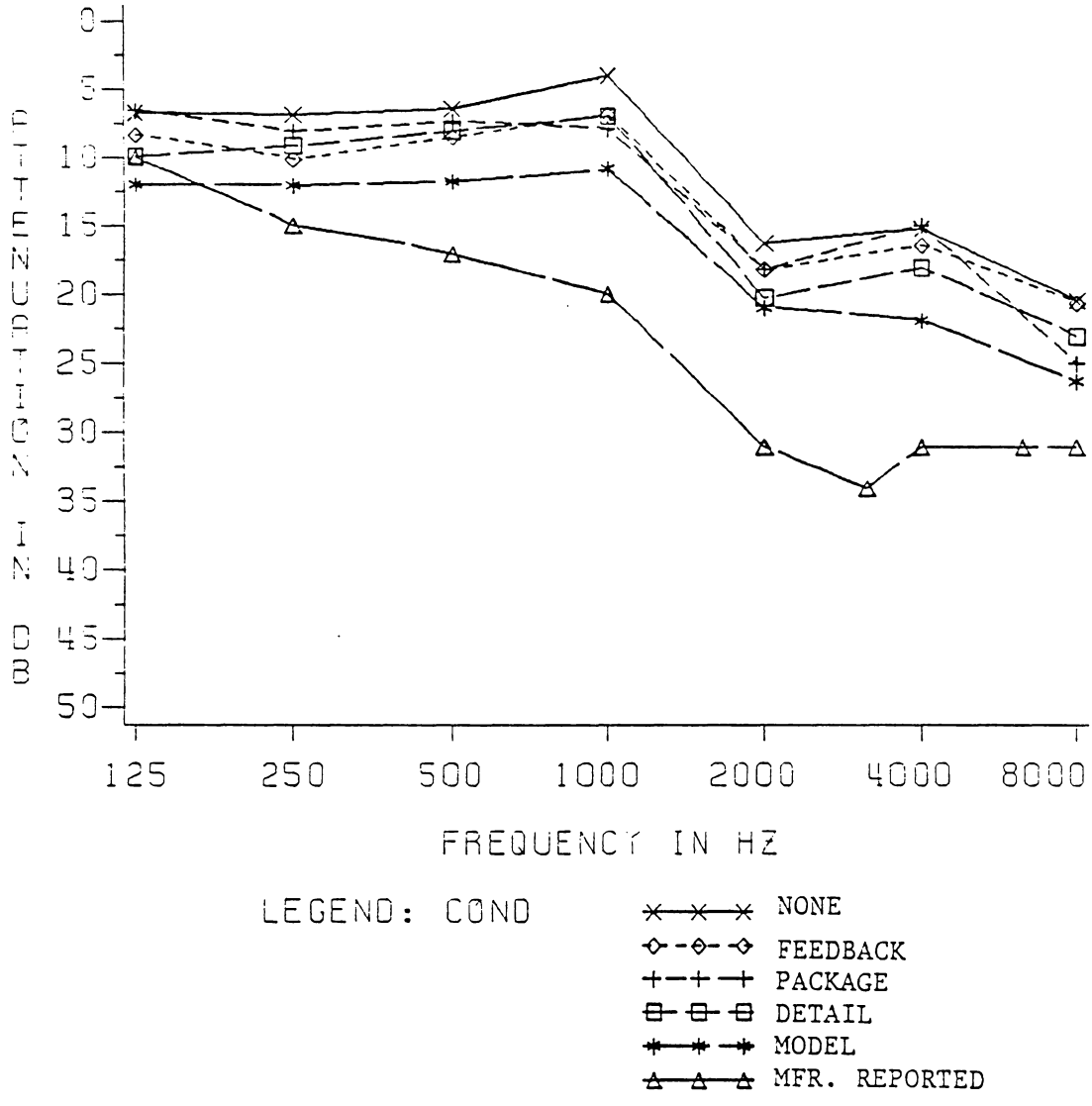


Figure 13. Attenuation characteristics of Flents earcap model #055 at each instruction technique.

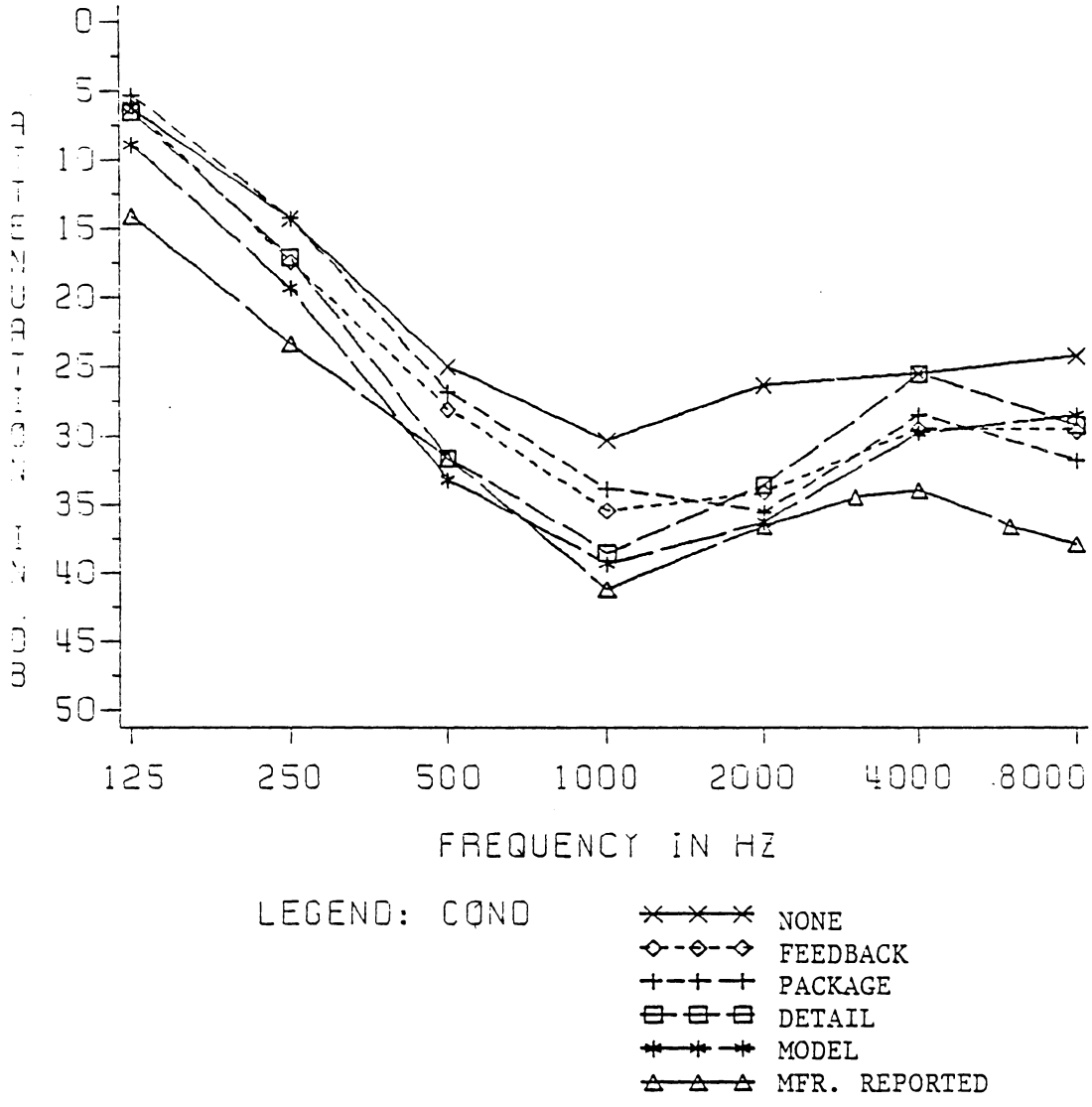


Figure 14. Attenuation characteristics of Norton muff model 4540 at each instruction technique.

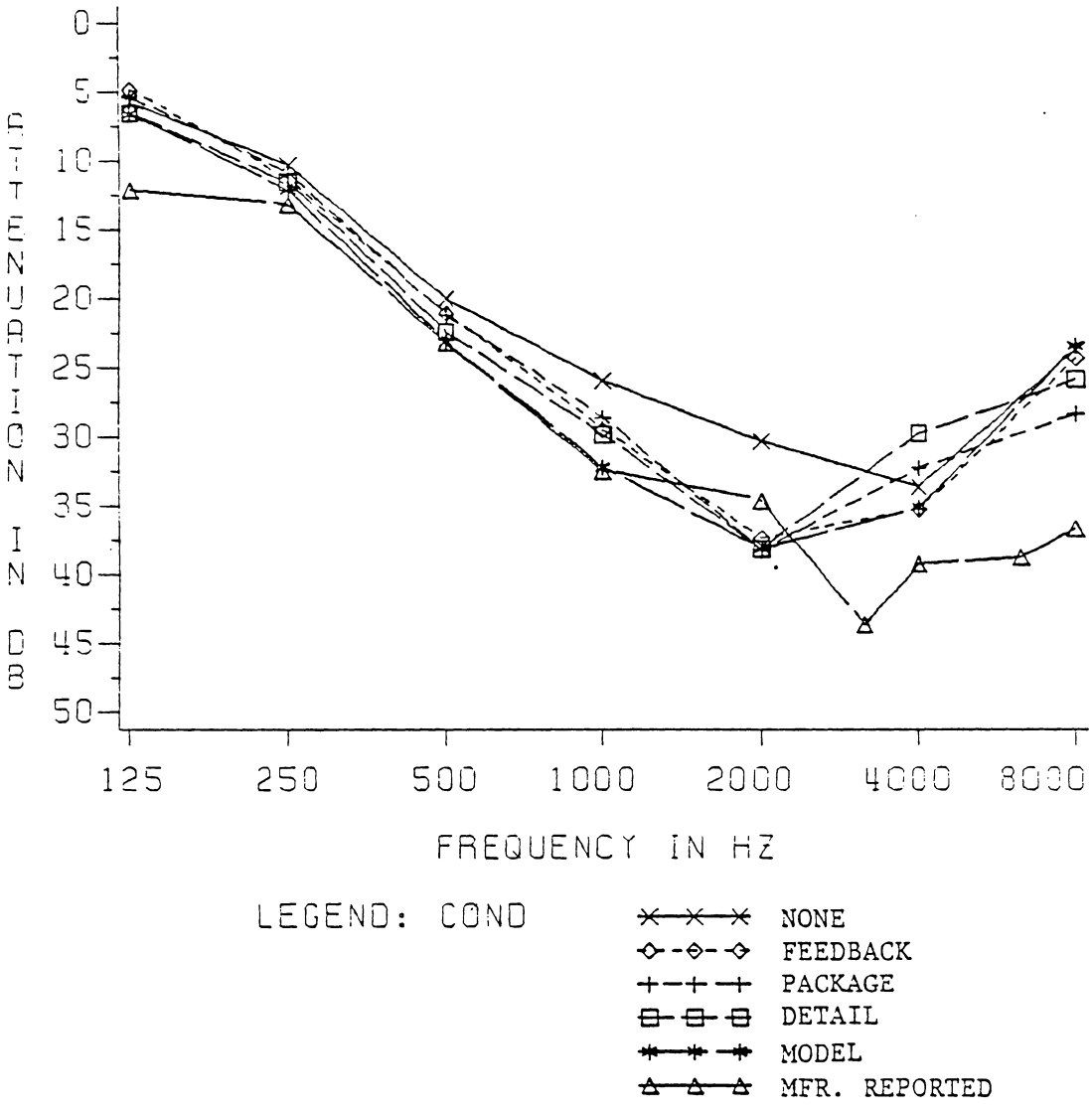


Figure 15. Attenuation characteristics of Peltor muff model H6A/v at each instruction technique.

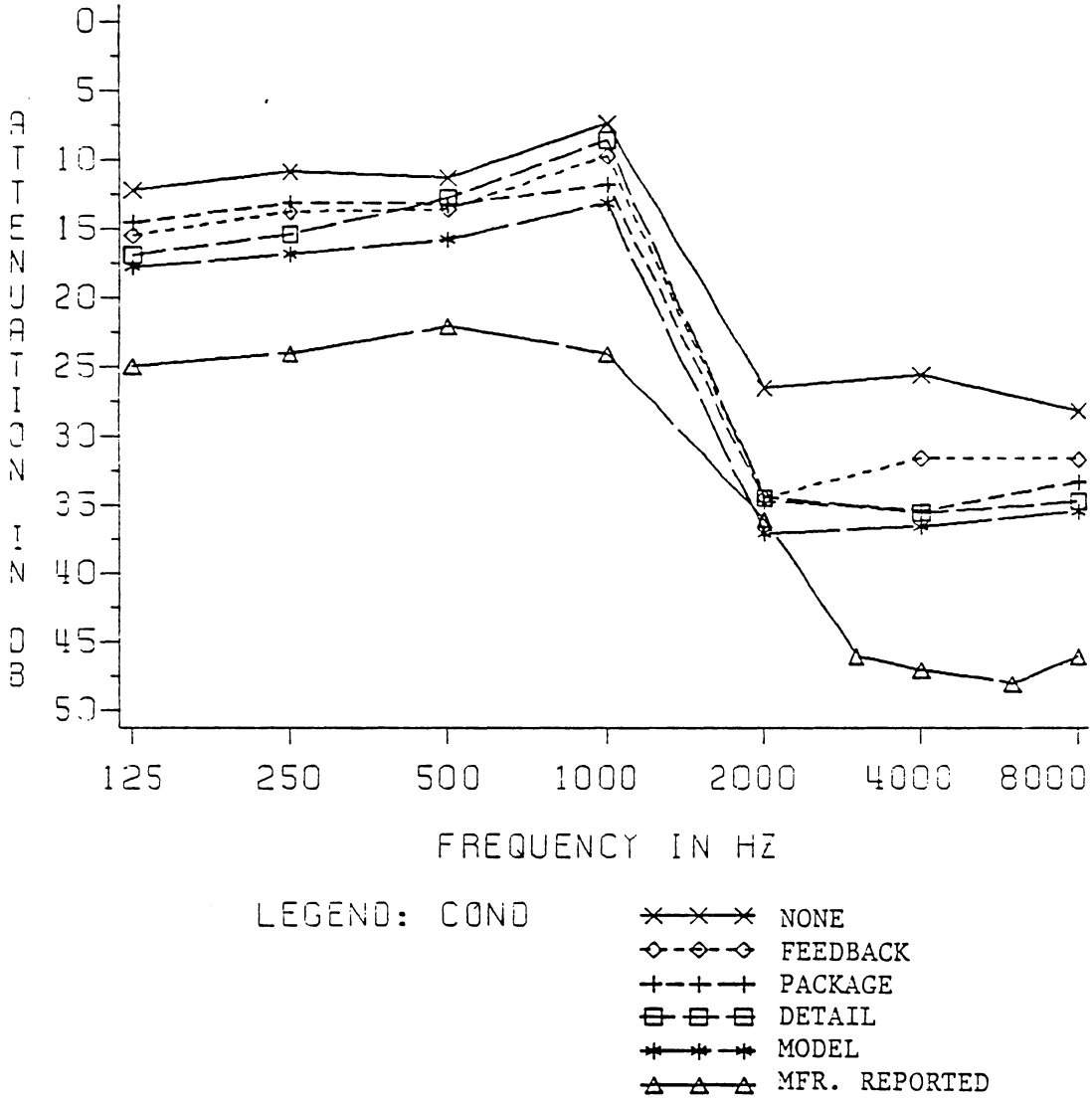


Figure 16. Attenuation characteristics of Willson earcap model #20 at each instruction technique.

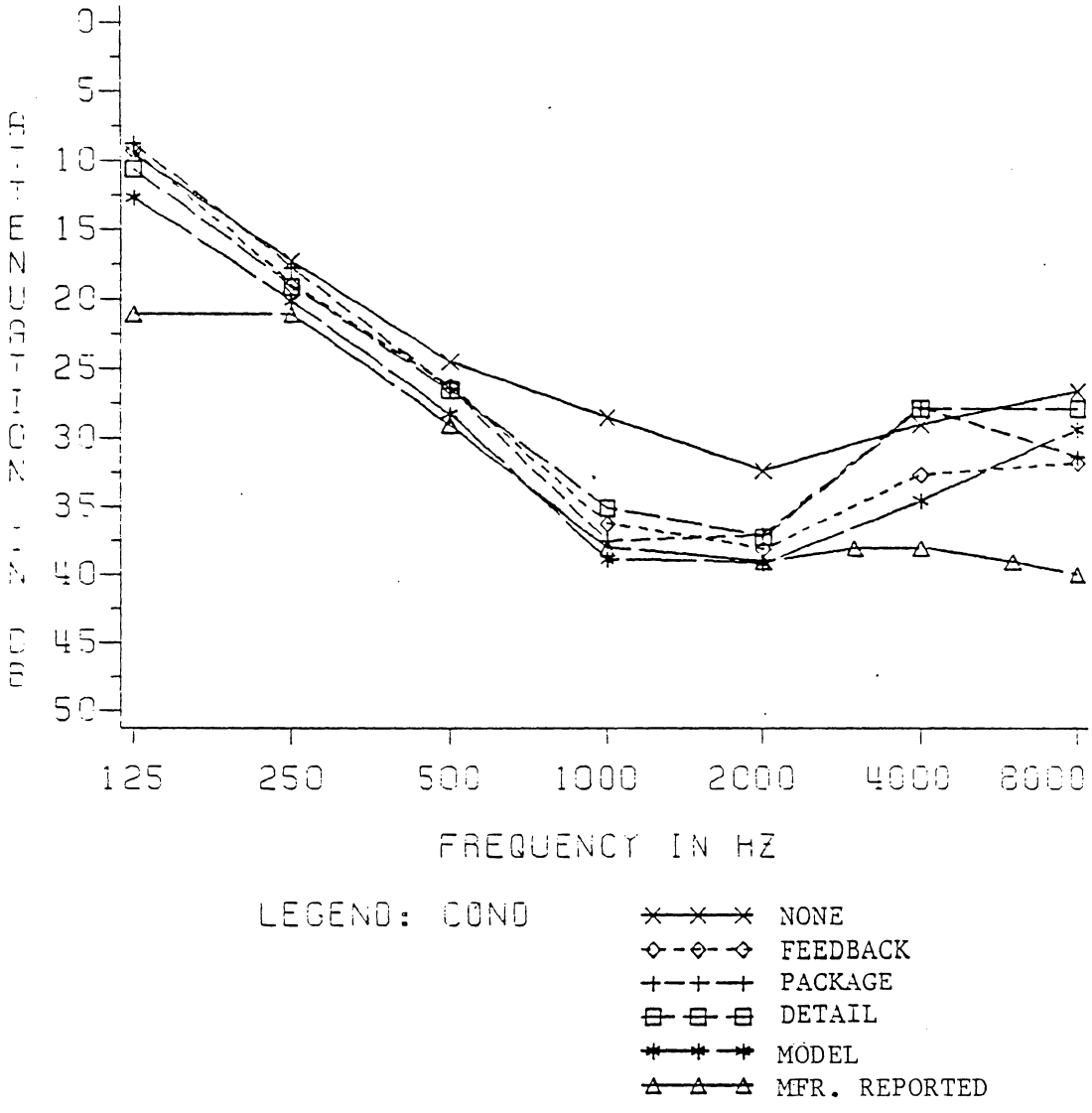


Figure 17. Attenuation characteristics of Willson muff model 365A at each instruction technique.

workers may receive less protection by following manufacturers' instructions than by strictly relying on environmental noise in the workplace as an earplug-seal feedback mechanism.

On the contrary, the results of attenuation tests in this study indicate that variations in instruction technique do not differentially affect different earmuff/earcap attenuation performance. Thus, individual earmuff/earcap designs were less sensitive to differences in instruction. This can be determined in Figures 12 through 17 wherein:

NONE = no instruction
FEEDBACK = no instruction with auditory feedback
PACKAGE = manufacturer's package instruction
DETAIL = detailed written instruction
MODEL = instruction by model
MFR. REPORTED = manufacturer's reported attenuation.

In general, for each earmuff/earcap, the like pattern of attenuations was evoked by different instructions (except for the ineffective no instruction condition), and the magnitude of attenuations afforded via various instructions were in comparable order across HPDs.

Though not the focus of the study, the determination of which earmuff/earcap achieved the best protection can be surmised from Table 9 and Table 12. The pairwise comparison results on signif-

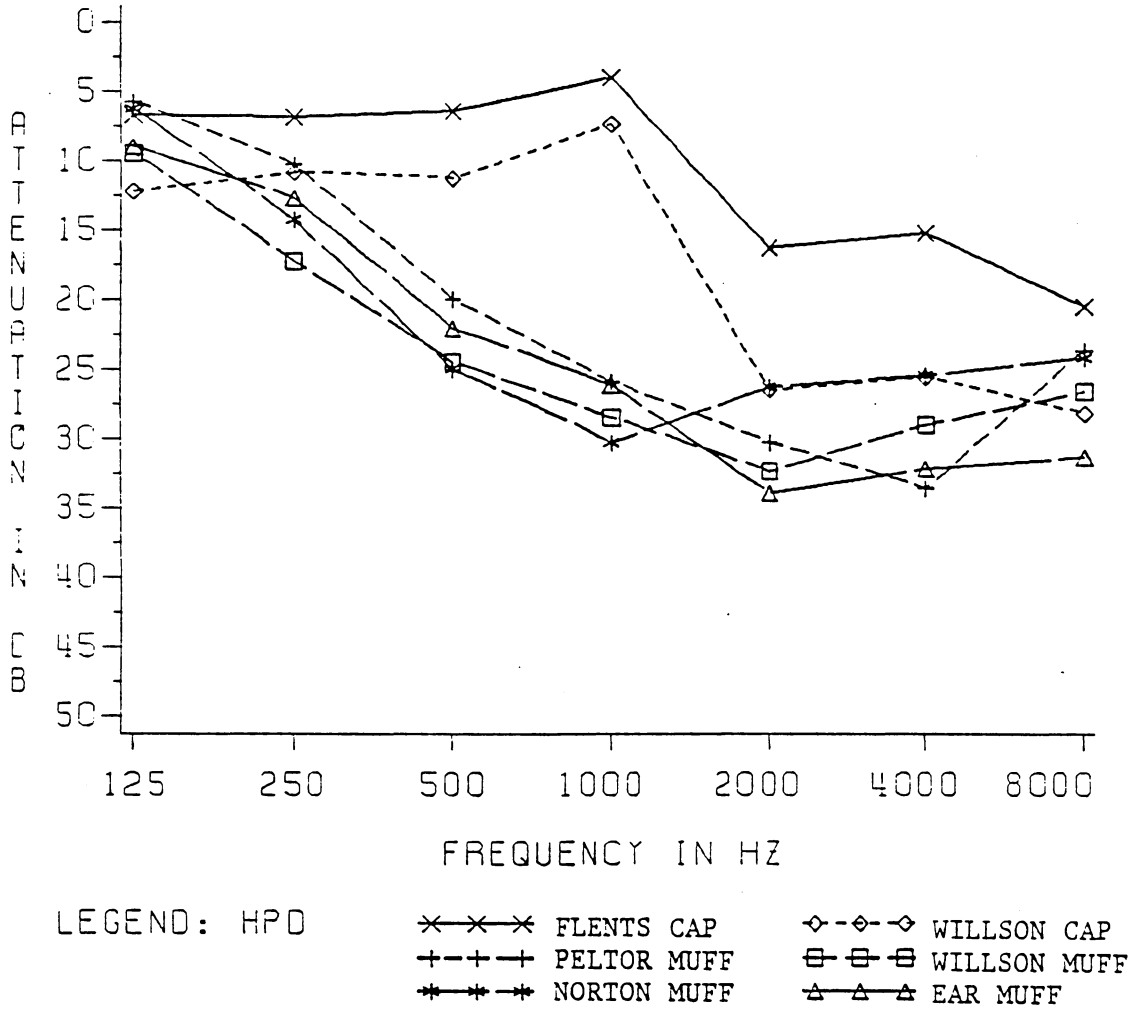


Figure 18. No instruction: Earmuff/earcap attenuation characteristics.

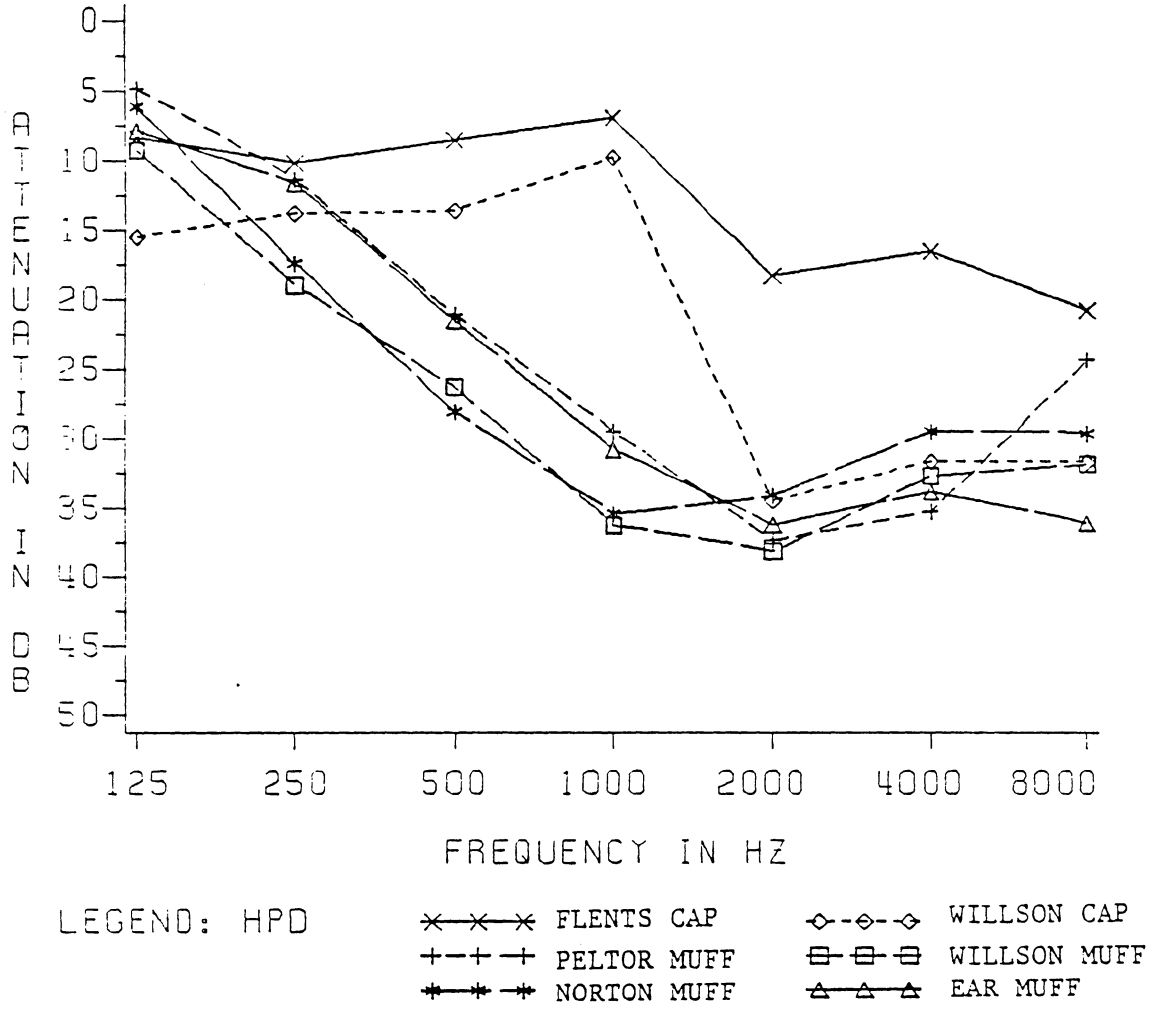


Figure 19. No instruction with auditory feedback: Earmuff/earcap attenuation characteristics.

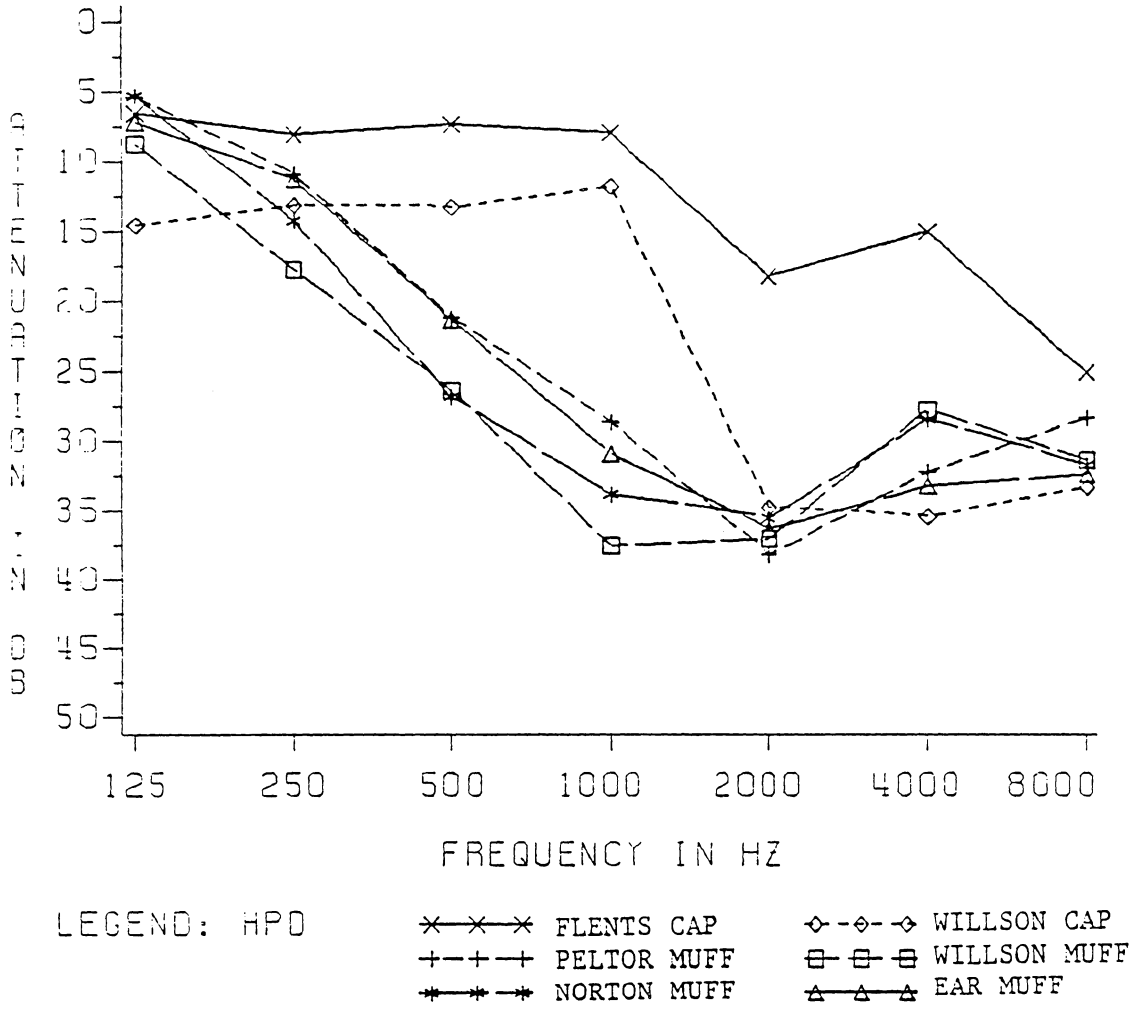


Figure 20. Manufacturer's package instruction: Earmuff/earcap attenuation characteristics.

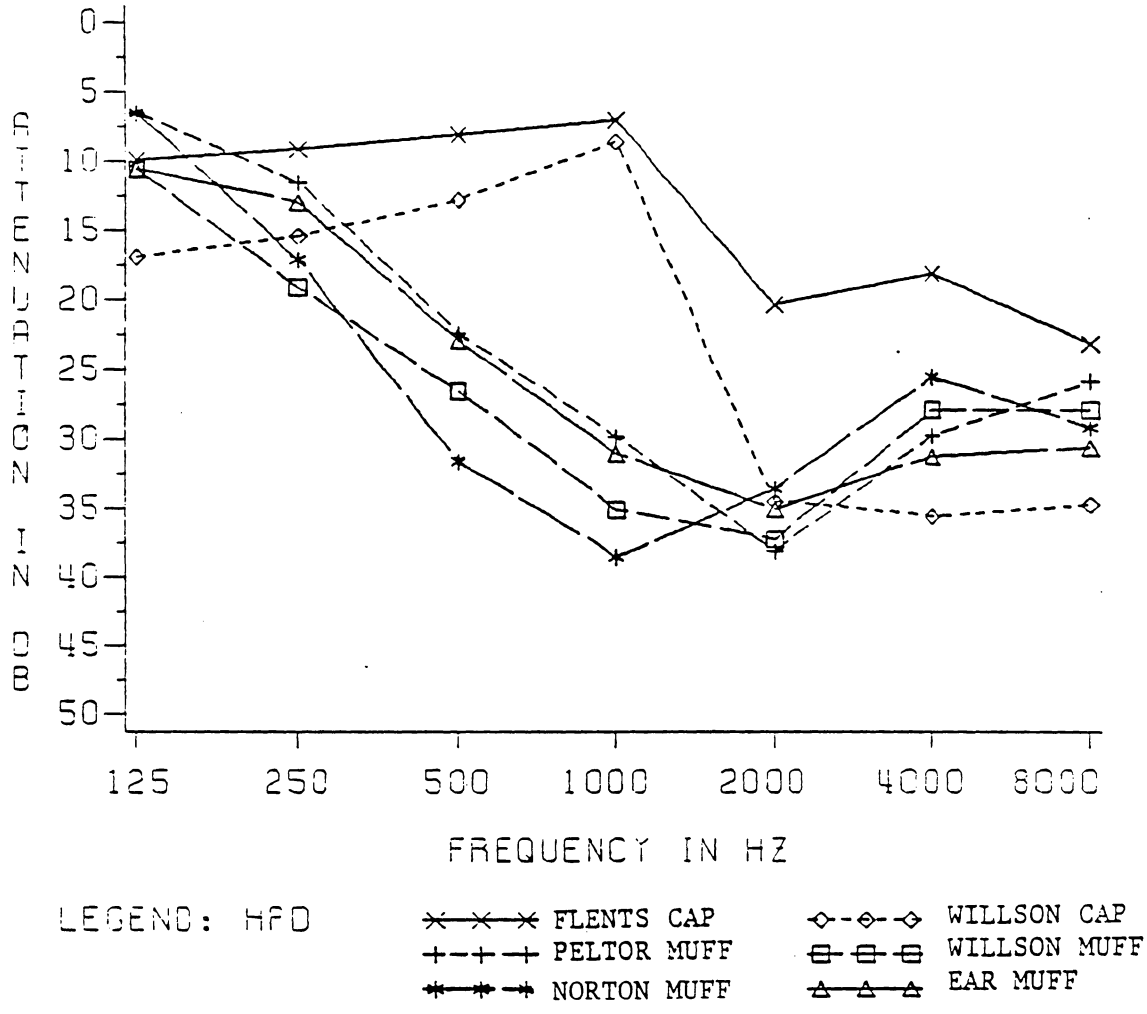


Figure 21. Detailed instruction: Earmuff/earcap attenuation characteristics.

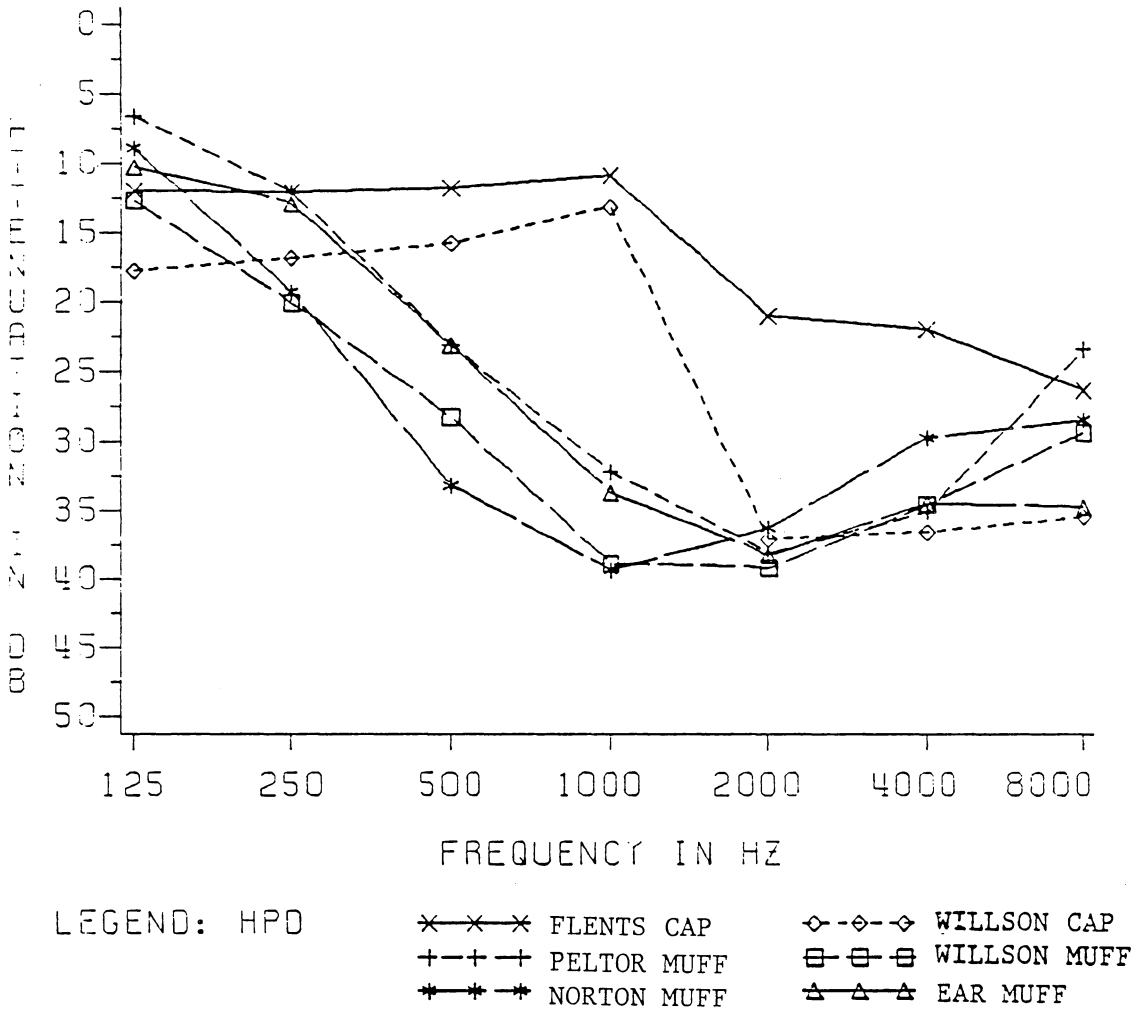


Figure 22. Instruction by model: Earmuff/earcap attenuation characteristics.

icant HPD-by-frequency and HPD main effects showed that the Willson muff was in general among the best across all frequencies. The Norton muff was among the best at all but 125 and 4000 Hz. The Flents cap provided the least attenuations at all frequencies but 125 Hz. This is not to criticize any of the protectors because they are designed to be used in different noise intensity levels and for different applications. Therefore, differences in their attenuation capabilities as demonstrated here, would be fully expected. The attenuations of the various HPDs as achieved with each instruction technique are presented in Figure 18 through 22.

Comparing the overall results of this and Epps' (1984) sample of earplugs and earmuffs/earcaps, it can be seen that in general the earplugs provide better attenuations at lower frequency ranges (below 250 Hz). Above that range, the sample earmuffs are generally better. One exception was the Willson muff, which demonstrated good attenuations at low frequencies even when compared with earplugs.

Gender. Gender related analyses on earplugs (Epps, 1984) revealed that males generally achieved better attenuation, across earplugs, than females (about a 4.5 dB difference). In addition, males received superior attenuation when compared to females across all frequencies tested.

Epps speculated that the substantially greater attenuation that males received, relative to females, may at least in part attributable to ear canal anthropometric differences. That is, fe-

males typically have ear canals of much smaller diameters than males. Since universal-fit earplugs, such as those tested in Epps' study, may be designed for the "average" ear canal size, many females may have trouble inserting the earplugs completely, resulting in lower attenuation values. Epps further posited that this result may be important to the administrator of a hearing protection program who must protect a work force of both males and females from harmful environmental noise.

Although Epps did not find any significant difference between the open-ear hearing thresholds of males and females, he cautioned that the different interpretation of instructions and variations in psychophysical task ability between sexes, among other possibilities, may have contributed to the overall gender differences.

Epps further found that the only earplug which showed a significant difference between males and females was the Flents' wax cotton plug. He postulated that the relatively large size of the Flents earplug and the force needed to seal the earplug within the ear canal may have contributed to the substantial gender difference (8 dB).

Compared to findings on earplugs, once again, the earmuffs/earcaps were shown in this experiment to be robust to the influence of gender factor. As shown in the gender ANOVA summary (Table 14), almost none of the aforementioned gender effects in earplugs were significant for earmuffs/earcaps. The only significant finding was that male subjects received better attenuation

at 4000 Hz (Table 15). A plausible explanation for this isolated frequency-specific effect is difficult. Again, comparison of open-ear hearing abilities between the males and females did not disclose any significant difference, and possible explanation seems to lie elsewhere.

These findings have direct bearing on the selection of HPDs for the prospective user population. In general, the attenuation afforded by earmuffs and earcaps was shown to be less dependent (than earplugs) on gender. For this reason, earmuffs and/or earcaps may be a safer HPD-choice for unknown or large user population, if good and adequate attenuation is important. Furthermore, administrators of hearing conservation program should convey the important information to wearers about such possible differences in attenuation due to sex.

Single number ratings. As stated before, the single number ratings were calculated to consider the A-weighted scale and standard deviations in the comparison of HPDs. Among the earmuffs/earcaps, the Willson muff gave the best attenuations based on visual examination of the means. Overall, the Willson muff appears to provide over 4 dB more attenuation than the EAR plug (the best in Epps' study) according to the mean values.

As previously mentioned, the NRR84 is NRE adjusted by one standard deviation and a 3 dB safety factor, thus compensating for variations among individuals and ambient noise characteristics.

On the NRR84 measure, the Willson muff again afforded the most attenuation among the earmuffs/earcaps examined, based on perusal of the means. The NRR84s indicated that, in general, the earmuffs provide most protection in terms of noise reduction.

These results also comfirmed the differences between experimentally-obtained NRRs and manufacturers' reported NRRs.

HPD Comfort

As discussed previously, HPD discomfort is among the most common excuses for workers not wearing their hearing protectors. Therefore, the aim of the earmuff/earcap comfort analysis was to define possible bipolar scales which would be sensitive to perceived HPD comfort, and to combine the significant scales into a single-number comfort index. Again, all comfort ratings were based on the approximately 25-minute wearing period for the experiment, and ratings may change given longer wearing time.

In comparing the earmuffs/earcaps, the Peltor, Willson, and EAR muffs were found to be most comfortable (Table 21). Even though the present study was not aimed at pinpointing the contributory attributes affecting HPD comfort, it can be speculated that the Peltor muff has a high rating because it is compact, smooth-fitting, with a moderate clamping force and a padded wide headband. Its ear cushion filler is liquid plus foam. The Willson muff is compact and simple, with liquid-filled cushions and a relatively wide

headband. The EAR muff is also compact, with a relatively wide headband, light-clamping force and soft-foam cushions. Invariably, subjects in this study did not find the earcaps comfortable. It can be speculated that objects with a certain amount of clamping force in the ear canals and which fill the rims of the canals are likely to be uncomfortable. Interestingly, the weight of the HPDs tested did not seem to affect the subjective feeling of comfort (see Table 19). This concurs with Damongeot et al.'s (1981) findings that the weight of earmuffs had minimal influence on global comfort.

HPD Ranks

As explained previously, subjects were asked to rank the earmuffs/earcaps, on four criteria: (1) comfort, (2) ease of application, (3) general preference, and (4) preference for an eight-hour wearing time. Overall results for the comfort rankings of earmuffs and earcaps were similar to the CI results except that this time the Peltor muff was significantly ranked the best among all earmuffs and earcaps, the EAR muff was considered to be more comfortable than the Willson muff, Norton muff, Flents cap, and Willson cap, all of which were significantly different from each other. Major grievances voiced by subjects against the two earcaps included: (1) in general, a foreign body exerting a certain amount of clamping force on ear opening was uncomfortable, (2) a good noise-blocking seal was hard to achieve with earcaps; furthermore,

good seals were easily dislocated by head or body movement, and (3) the dangling headband amplified skin- (or object-) contact noises (the "stethoscopic" effect).

In general, the Peltor muff was judged to be the easiest to put on (Table 22). Both the earcaps were decidedly the hardest to don. Earcaps require that the ear pods or cushions be adjusted to the right angle of the ear canal, and the amount of inserting force must be correct to obtain an adequately good seal without causing undue pain or discomfort.

Epps (1984) found that, for general preference, the EAR and Willson earplugs were preferred over the Bilsom plug even though the Bilsom was rated highest on both insertion ease and comfort rankings. Epps believed that this may indicate that the general preference rankings were based on criteria other than just comfort and ease of insertion. For example, the general preference ranking may have also incorporated a "sound blocking capability" criterion. It is interesting to note that the two most preferred earplugs were those that attenuated noise the best in the study (i.e. EAR, Willson).

For the earmuffs/earcaps, the choice of preferred HPDs approximately followed the comfort and easy-on rankings. The Peltor and EAR muffs were the most preferred (for both general preference and eight-hour wearing preference) and the Flents and Willson cap the least preferred. The Willson muff was also well-liked, even though not as much as the Peltor and EAR. However, it must be borne

in mind that the attenuation capability of the Willson muff was superior to both of those earmuffs according to the tests in this study. Accounting all the scores (attenuation, comfort, easy-on, and both preference measures) the better HPDs are the Willson, EAR, and Peltor muffs. Among them, choice of a particular HPD should be contingent upon other factors such as the specific noise application problem, personal preference, HPD durability, and economic reasons.

Effects of Earmuff Attributes on Attenuation and Comfort

Several of the earmuff attributes were quantified and measured as shown in Figure 6. It was possible to perform a post-hoc regression analysis to determine the association between earmuff attenuation (and subjective feeling of comfort) and several quantitative attributes (weight, cup volume, cushion area, cup depth, and clamping force). The mean NRE across different instruction techniques for a particular earmuff was taken to represent the overall average attenuation of the muff. Likewise, the comfort index (CI) was used to reflect the average subjective feeling of comfort toward each earmuff (a smaller CI indicated a more comfortable muff). Regression analyses were performed to reveal any significant dependency of NRE and CI on the five different attributes of earmuffs. In each case, simple, one-factor, linear regressions were performed using the SAS package. Despite the fact

that only four data points were available (not much statistical power), the results might hopefully provide some inkling as to which attributes were significantly related to NRE and CI, which would have direct bearing on HPD design. However, multiple regression was precluded because more data points were deemed necessary.

Results of the one-factor regressions are shown in Table 26. The regression of NRE on volume was significant, F (1,2) = 78.37, p = 0.0125, (NRE = 16.9750 + (0.0563)Volume), and differences in cup volume of earmuffs accounted for 97.51 percent of the total variance in attenuation. Despite the small statistical power available in this case, the results were quite significant. Thus, it can be tentatively concluded that earmuff attenuation is positively related to cup volume (the larger the cup volume, the better the attenuation afforded). It may be the case that the sound-wave impedance imposed by the air volume contained in the larger cups accounted for the higher attenuation. However, it must be cautioned that if a larger sample size was available (therefore greater statistical power), other attributes might be revealed as significant factors in affecting earmuff attenuation as well.

Result of the regression of CI on clamping force indicated a borderline significant positive relationship (greater clamping force in the earmuff headband was associated with increased discomfort), F (1,2) = 19.41, p = 0.0478, (CI = 104.931 + (2.2749)Force). The difference in earmuff headband clamping force accounted for 90.66 percent of the variation in subjective feeling

TABLE 26

Results of Simple Regressions of NRE and CI on Various Earmuff Attributes

	NRE			CI		
	F	p	r^2	F	p	r^2
Weight	6.87	0.12	0.7744	1.11	0.4021	0.3575
Cup volume	78.37	0.0125*	0.9751	0.24	0.6708	0.1084
Cushion area	0.00	0.9564	0.0019	1.83	0.3088	0.4777
Clamping force	0.09	0.7985	0.0406	19.41	0.0478*	0.9066
Cup depth	1.64	0.3289	0.4504	4.99	0.1552	0.7137

* significant at $p < 0.05$

of comfort toward earmuffs. Again, a larger sample size may unveil other significant factors.

In sum, the results seemed to indicate that larger cup volume is related to higher muff attenuation, and that greater clamping force in the headband is associated with increased discomfort. This may have ramification for the design of earmuffs to achieve optimal attenuation while maintaining comfort. No other attributes measured were found to be related to either perceived comfort or achieved attenuation according to this small sample. Again, it should be noted that the attenuation comparison is based on a small sample, further verify the importance of such attributes as they have bearing on achieved attenuation and comfort. It is imperative that such a comparison be performed using empirical techniques to aid in future HPD design.

HPD and Machinery Noise Matching

As noted by Berger (1983d), the examination of the mean attenuation of a hearing protector at the individual 1/3 octave-bands provides the ability to make a gross match between the device and the target noise. For example, in the presence of significant low frequency (125-250 Hz) ambient noise, an earmuff type of HPD would generally be a poor choice and a foam or a pre-molded earplug might be better. On the other hand, if significant midband energy is present (around 1000 Hz), then an earmuff might be preferred. Also,

within each HPD-type, a certain design may be more appropriate for a particular noise type. Therefore, by matching the transparencies provided in the pouch at the end of this report showing individual HPD attenuations across frequencies with the machinery noise spectra (Appendix M), one might be able to better decide the proper choice of hearing protector for each ambient noise. For instance, it can be seen that the attenuations of the EAR muff matches closely with the noise spectrum of the sand blaster and therefore might be an optimal protector. However, as cautioned by Berger (1983d), one must realize that assigning particular HPDs to particular jobs in a plant (based on spectrum shapes) may be difficult. The choice of HPDs may be compounded by personal preference and shifting of protectors across machines, sites and work shifts. But in cases when the right match of protector and ambient noise represents the only way of achieving sufficient noise spectrum protection, the matching procedure is fruitful and safety personnel as well as workers should be advised of the significance of such a procedure.

NEGATIVE ATTENUATIONS

If HPDs are designed to provide any protection at all, the attenuations afforded should, of course, always be positive, as a negative attenuation, in effect, represents sound amplification. That is to say the worker should always "hear less" after he or she dons a hearing protector. In the present study, however, fourteen (out of 2100) attenuations were found to be of negative value. This small percentage (0.7%) may be attributable to chance, spurious responses, experimenter error, REAT assumption of threshold level to intense noise level linearity, etc., but nevertheless, its occurrence should be considered further. A negative attenuation value evidences that at certain times the wearer heard "more" with the protector on.

The breakdown of cases of negative attenuations according to individual factors (HPDs, instructions, and test frequencies) are shown in Table 27. Three questions are of interest here: (1) is 14 out of 2100 significant? (e.g., was this number of occurrences due to "chance"?) (2) within each factor, are there any significant differences among the number of cases across levels? (And if there are any, can the experimenter pinpont the locus(i) of significance?) (3) is a specific number of cases significantly different from zero? Given the small probability (0.7%) of the occurrence of negative attenuation, it is highly probable that its occurrences

were due to measurement errors, among other possibilities. Unfortunately, given the type and amount of data at hand, there appear to be no rigorous statistical tests available to better answer these questions. An attempt is made, though, to venture some conditional analyses.

Conditional tests using the binomial probability distribution were used to compare the counts of negative attenuation across various levels in a given factor. Count of negative attenuation was considered to be a binomial random variable, and the tests were "conditional" upon a given total occurrence of 14 cases. The basic question was: Given a total of 14 occurrences of negative attenuation, what is the probability of 8 (the maximum observed) or more occurring in any one of the 6 HPDs, 6 or more in any one of the 5 instruction conditions, 5 or more in any one of the 7 test frequencies (refer to Table 27)? Notice that this is a conditional test of:

$$H_o: P_1 = P_2 = P_3 = \ldots = P_i$$

given an observation of 14 total counts. The largest number in each factor condition was used to test the hypothesis.

For <u>instruction technique</u>, six incidences of negative attenuation were associated with manufacturer's package instruction.

$$p\{ \geq 6 \text{ in any one instruction condition } \}$$

TABLE 27

Breakdown of Number of Negative Attenuations for Each Factor

Instruction:		HPD:		Frequency:	
package	6	Flents cap	8	125	5
none	5	Willson cap	4	1000	5
detail	2	Willson muff	2	250	2
noise	1	EAR muff	0	500	1
model	0	Norton muff	0	8000	1
		Peltor muff	0	2000	0
				4000	0
Total:	14		14		14

$$= 5 \sum_{j=6}^{14} \left[\begin{matrix} 14 \\ j \end{matrix} \right] \left[\frac{1}{5} \right]^{j} \left[\frac{4}{5} \right]^{14-j}$$

$$= 0.2195$$

Thus, the null hypothesis was not rejected in this case, and it was concluded that there was no significant difference among the counts of negative attenuation within different instruction conditions.

For HPDs, the largest number of negative attenuations occurred with the Flents earcap (8).

$$p\{ \geq 8 \text{ in any one HPD} \}$$

$$= 6 \sum_{j=8}^{14} \left[\begin{matrix} 14 \\ j \end{matrix} \right] \left[\frac{1}{6} \right]^{j} \left[\frac{5}{6} \right]^{14-j}$$

$$= 0.0042$$

So the null hypothesis was strongly rejected, and it was concluded that if all HPDs are equivalent, it is highly unlikely that 8 out of 14 negative incidences would occur in one HPD. Thus, one can tentatively conclude that the Flents cap might indeed be associated with more incidences of negative attenuations.

Among the various test frequencies, most incidences of negative attenuation occurred at 125 and 1000 Hz (5).

$$p\{ \geq 5 \text{ in any one frequency } \}$$

$$= 7 \sum_{j=5}^{14} \binom{14}{j} \left(\frac{1}{7}\right)^{j} \left(\frac{6}{7}\right)^{14-j}$$

$$= 0.273$$

For this reason, the null hypothesis was not rejected, and it was concluded that there exist no significant differences among the counts of negative attenuations across frequencies.

The reason why there were more negative attenuations associated with the Flents earcap is not readily apparent. The noise-blocking apparatus of the Flents cap is comprised of a small central hard plastic core and a surrounding flap of soft rubber/plastic (called a "cap cushion") for adapting to the ear canal opening. If the angle of the cap cushion is not aligned properly with the ear canal opening, a slit remains between the inside and outside of the cushion. This is potentially one of the reasons why the Flents cap consistently provided the lowest attenuation among the devices studied. How this phenomenon would relate to the negative attenuations is not known. The negative attenuations occurred in 8 different subjects (of 50), and their pre- and post-experiment open-ear hearing threshold disparity never exceeded 6 dB (only one

case over 5 dB). Therefore, changes in hearing sensitivity over time would not likely be the culprit. It must be emphasized again, however, that these discussions are somewhat tentative as the findings were not backed by rigorous statistical analyses, due to the small sample of negative attenuations. This phenomenon must be further investigated before any firm conclusions can be drawn.

It is most probable that negative attenuations have occurred in other experiments involving HPDs. For one reason or another they were not usually discussed. The clarification of this problem certainly has important bearing on the design of future HPDs and on the design and implementation of hearing conservation programs. Notice that most incidences of negative attenuations occurred with one particular device (possibly an implication for design changes), and none with modeled instruction (an indication of the importance of adequate instruction for proper HPD application). The reader is again cautioned, however, that these findings are far from conclusive and one must be judicious in generalizing from them. More research is needed to target the reasons behind negative attenuation, and to determine its repercussion on HPD design and application.

RECAPITULATION AND RECOMMENDATIONS FOR FUTURE RESEARCH

For the given experimental procedures and the samples of subjects and HPDs tested, the following conclusions can be drawn from the present study:

1. In general, the attenuation achieved with the earmuffs and earcaps tested is much less susceptible to variations in insertion/application instruction techniques than that achieved with the earplugs investigated in Epps (1984).
2. Any of the instruction conditions resulted in significant attenuation improvement with earmuffs and earcaps over no instruction at all.
3. The achieved attenuation of earmuffs and earcaps tested is quite resistant to the gender difference, which is not the case with earplugs.
4. Various HPDs evoked markedly different comfort and preference ratings by the subject wearers. Some HPD designs were consistently more preferred.
5. Earmuff cup volume was found to be positively related to the amount of earmuff attenuation (larger volume, higher attenuation). The clamping force exerted by the earmuff headband was shown to be positively related to the degree of perceived discomfort (more force, higher rated discomfort).

6. HPD attenuation/noise spectra matching appears to be an objective, quantitative, and a feasible method of identifying the optimal hearing protector for a given noise situation.

It must again be emphasized that these findings are not absolute conclusions. Their generalization to real world situations has yet to be validated. Single event and time series study delineating the immediate and long-term effects of different application instruction techniques on achieved attenuation, learning transfer, and retention of application techniques by workers should also be examined.

It was shown in this study and a prior study (Epps, 1984) that attenuation afforded by selected earplugs was affected by gender differences, while the same effect was almost absent for the earmuffs and earcaps tested. This finding must be further validated and the reason behind the difference between earplug and earcap/earmuff susceptibility to gender effects must be more fully explained.

A more comprehensive study should be performed to identify the various design attributes of HPDs and their effects on the attenuation, perceived comfort, and preference of different types of HPDs. This has important bearing on the design and construction of a more desirable HPD in terms of achieved attenuation and comfort provided. The results of the present study hint that cup volume and clamping force of earmuffs are critical factors.

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APPENDICES

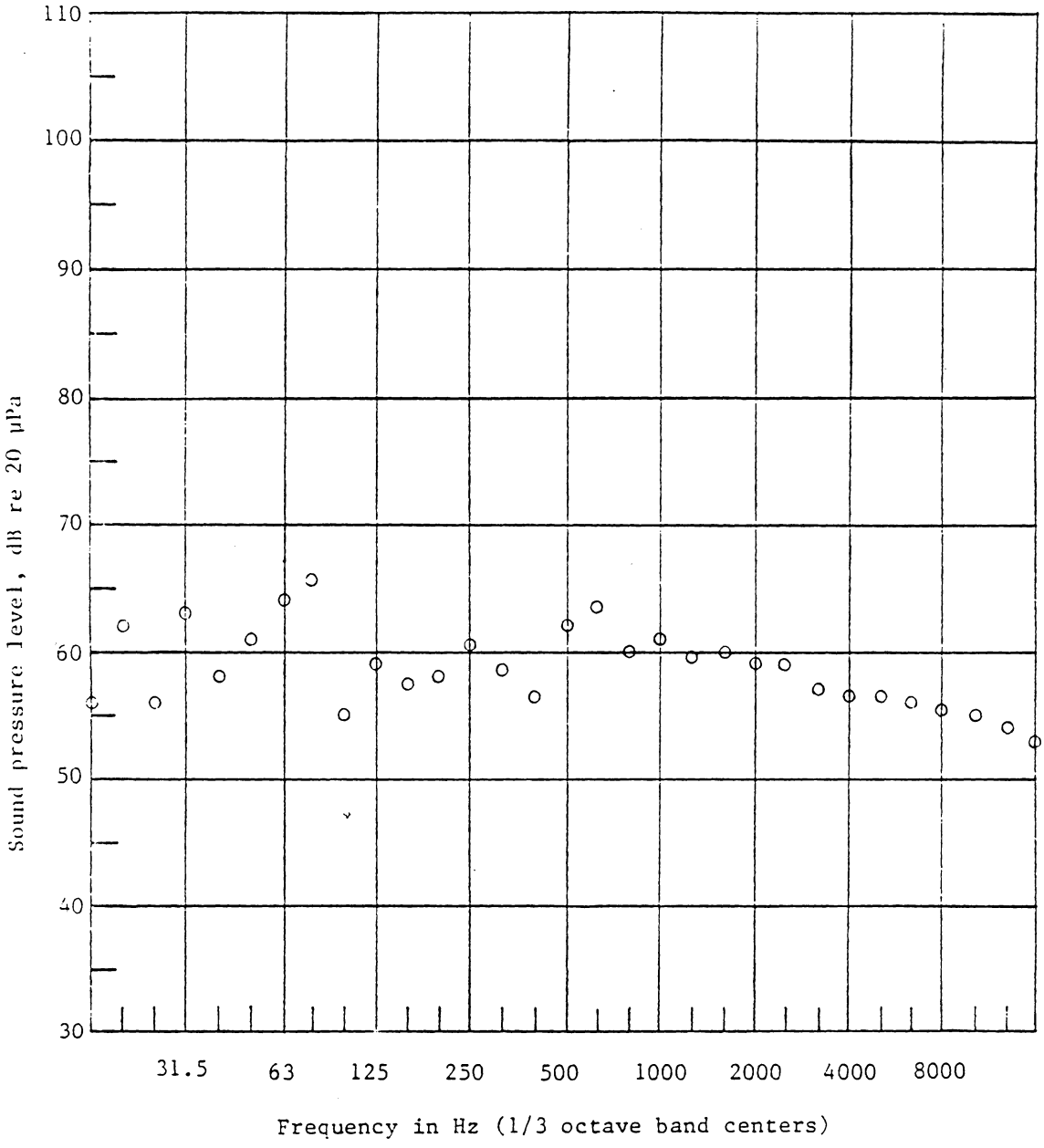
APPENDIX A

Machinery Noise Spectra with Measurement Situation (Floor Configuration) Schemation

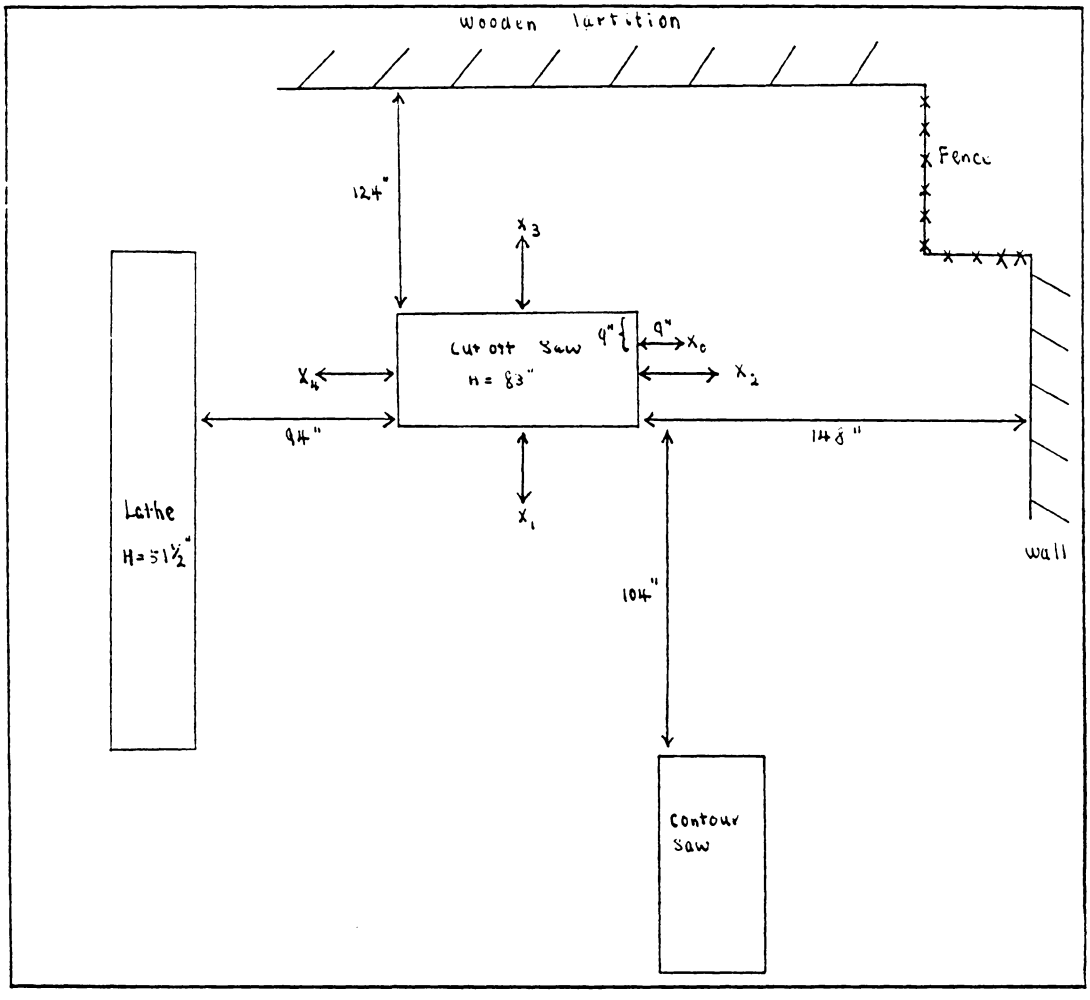
The following conventions were used in the graphs and diagrams presented. Refer to pages 71-73 in text for further discussion of measurement procedures.

1. All SPLs used Re. 20 $\mu N/m^2$.
2. Unless stated otherwise, a microphone position was located on the mid-plane of, and one meter (three feet) away from the side of the parallelepiped (see text). The top of the microphone was 1.5 m (5 feet) above the ground.
3. X_0 denotes the microphone at the operator's position, and X_1 , X_2 , X_3 , and X_4 show other microphone positions.
4. Closed circles in noise spectrum graphs denote machine SPLs which were adjusted for ambient noise levels. Open circles indicate uncorrected machine SPLs (they could not be differentiated from background SPLs; i.e. the difference was less than or equal to 3 dB; ANSI S1.13-1971).
5. Linear SPLs were measured using the "slow" response on the Larson-Davis Model 800-B sound level meter. Peak SPLs were estimated utilizing the "peak hold" response. Only linear SPLs were corrected for ambient noise levels (when the difference was within 4 - 15 dB), while peak SPLs were not adjusted.
6. The noise measurement environment comprised a dropped ceiling with acoustic tiles, concrete floor, and cinder-block walls. (The only exception was in the foundry where the furnace was

located, where there was no dropped ceiling, and the concrete floor was covered with soft sand.)

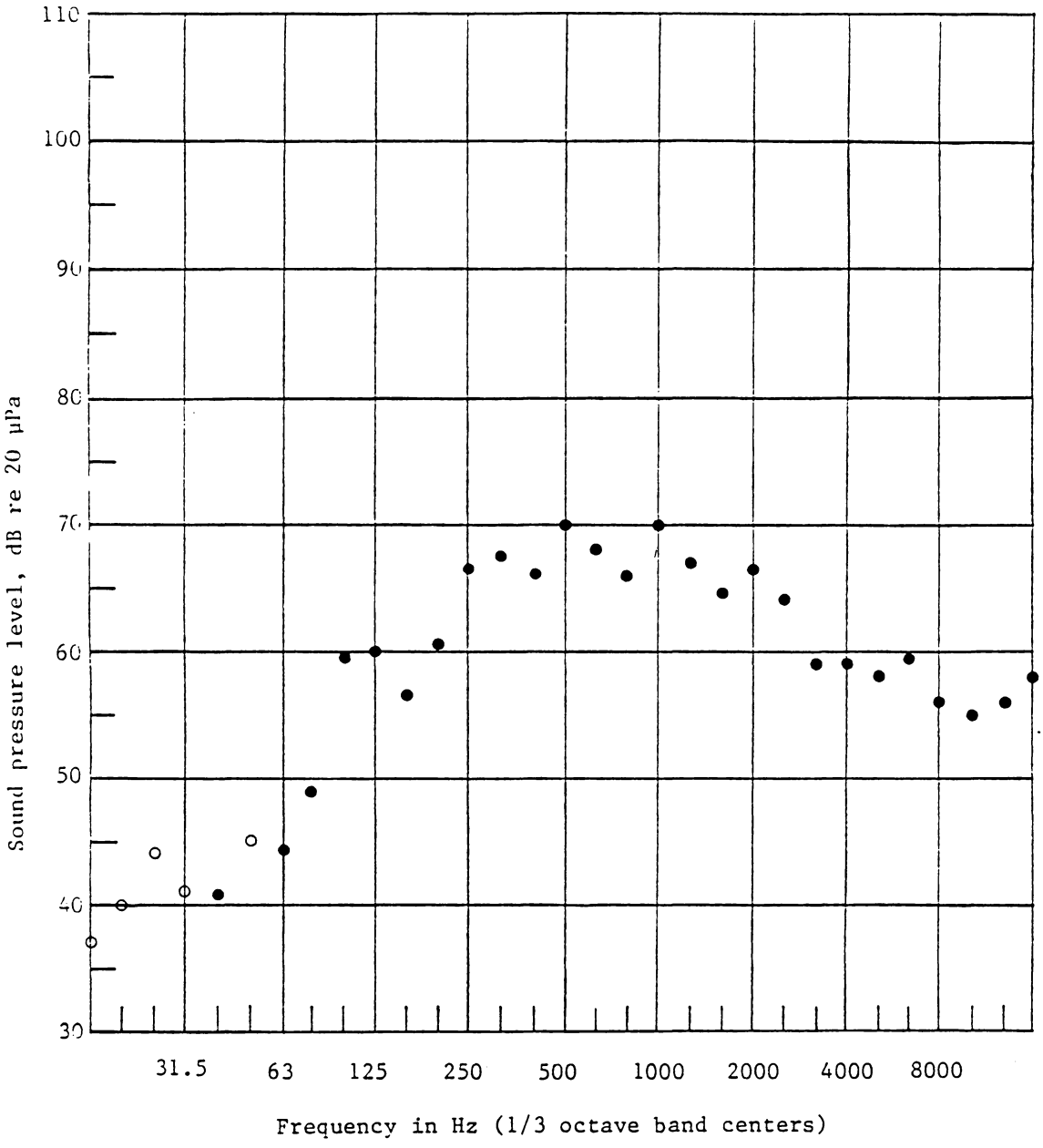


1/3 OB Noise Spectrum for general background noise of a motor machine shop, single microphone position, linear sound pressure level

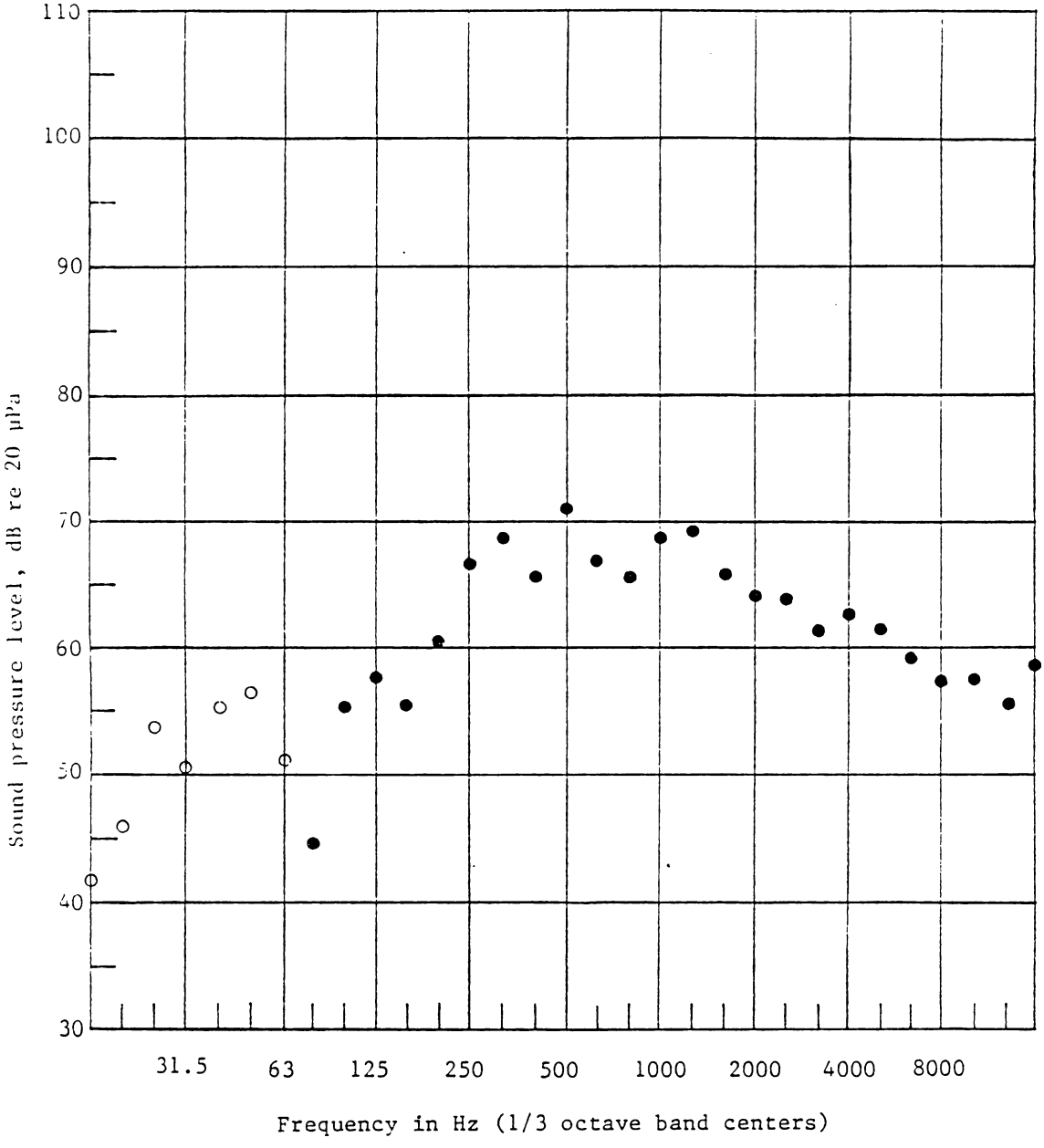


Marvel Metal Band Saw Model No. 8
Measurement Conditions:
Operating speed - normal
Tool - blade 7 teeth per inch, water coolant
Work material - Aluminum plate 1/4 inch thick

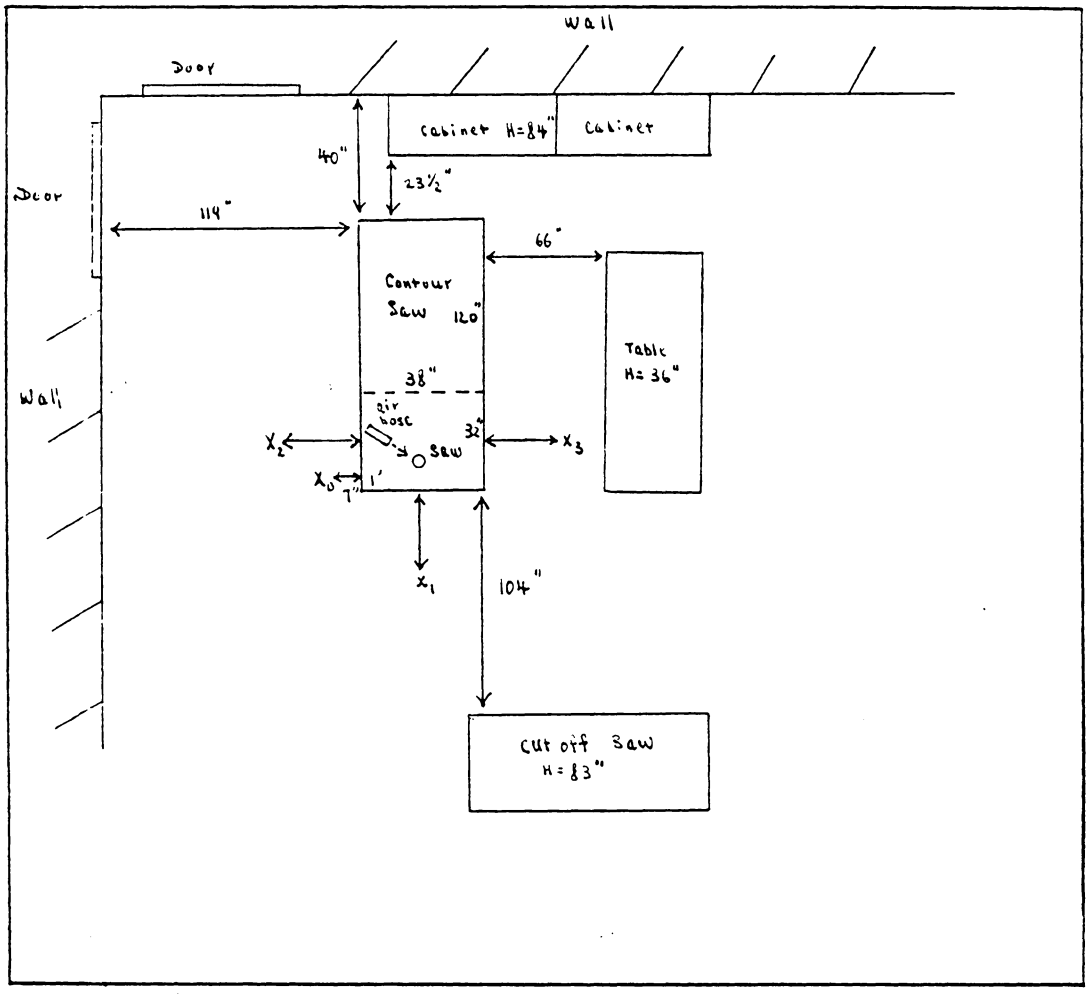
(noise spectrum on following page(s))



1/3 OB Noise spectrum for band saw, operator's position, linear sound pressure level

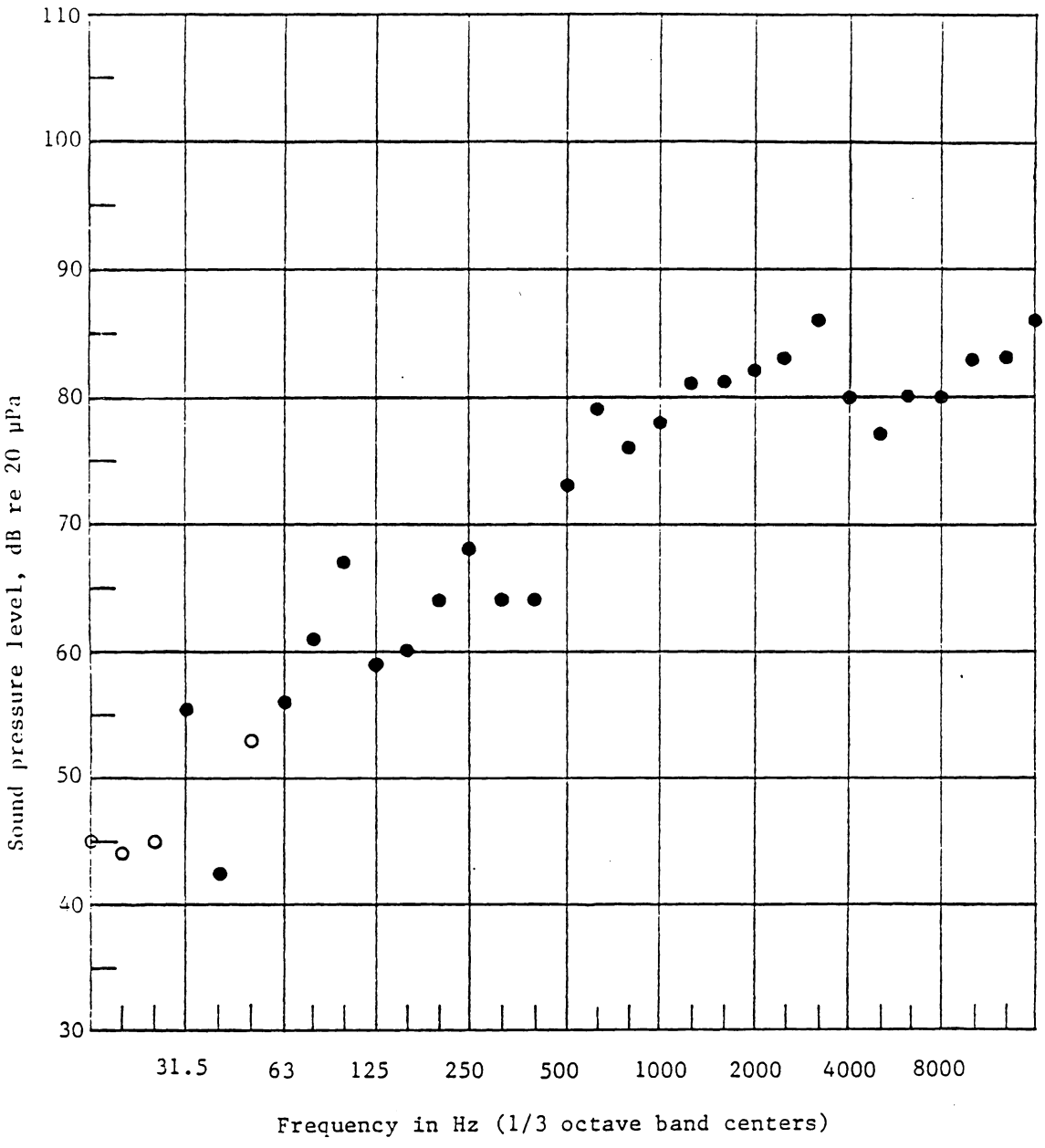


1/3 OB Noise spectrum for band saw, average four microphone positions, linear sound pressure level

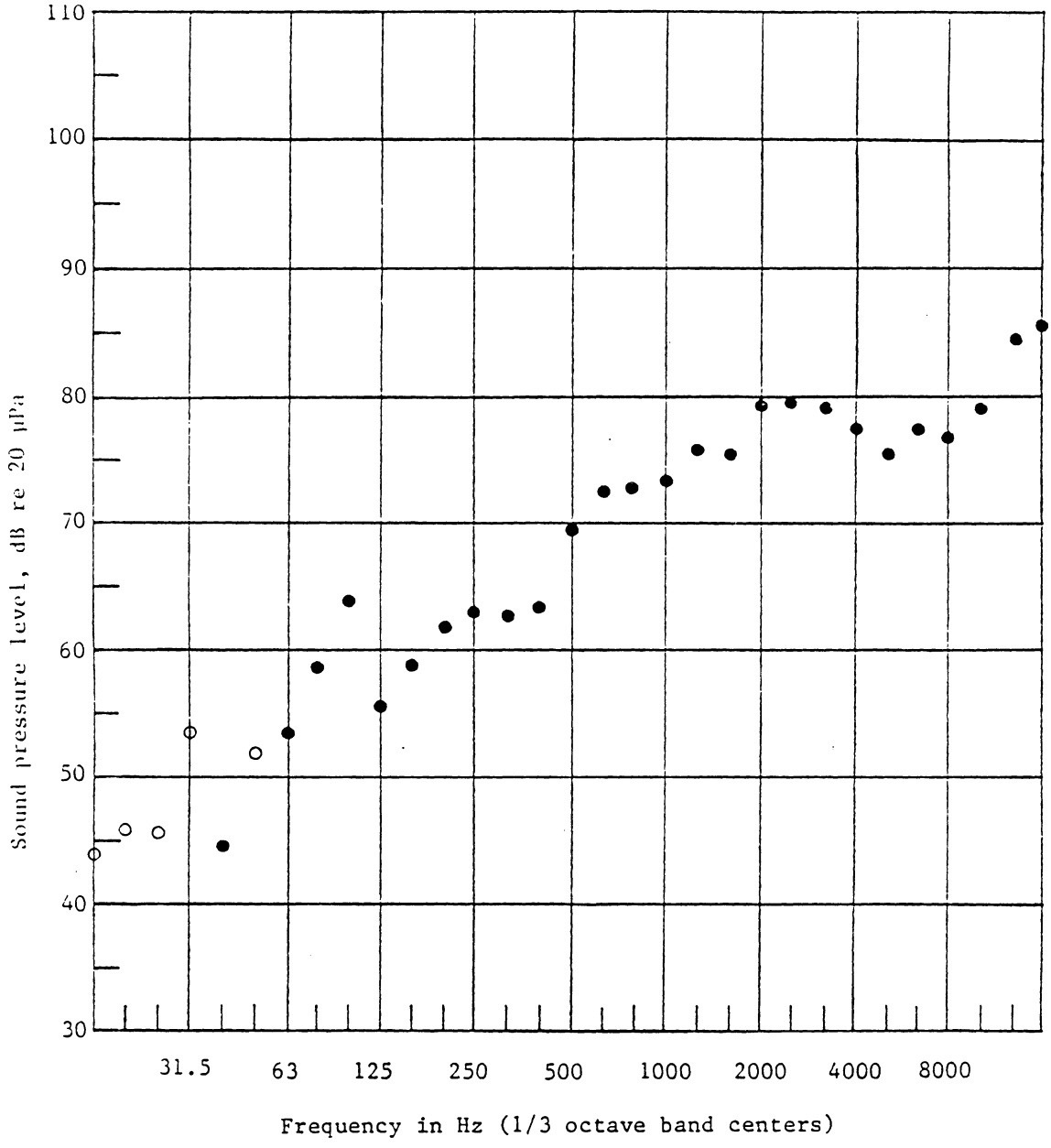


Peerless Contour Saw Model 3600 MS
Measurement Conditions:
operating speed - 750 ft. per minute
Tool - fine tooth blade, air hose clear
Work material - clear plexiglass 1/4 inch thick

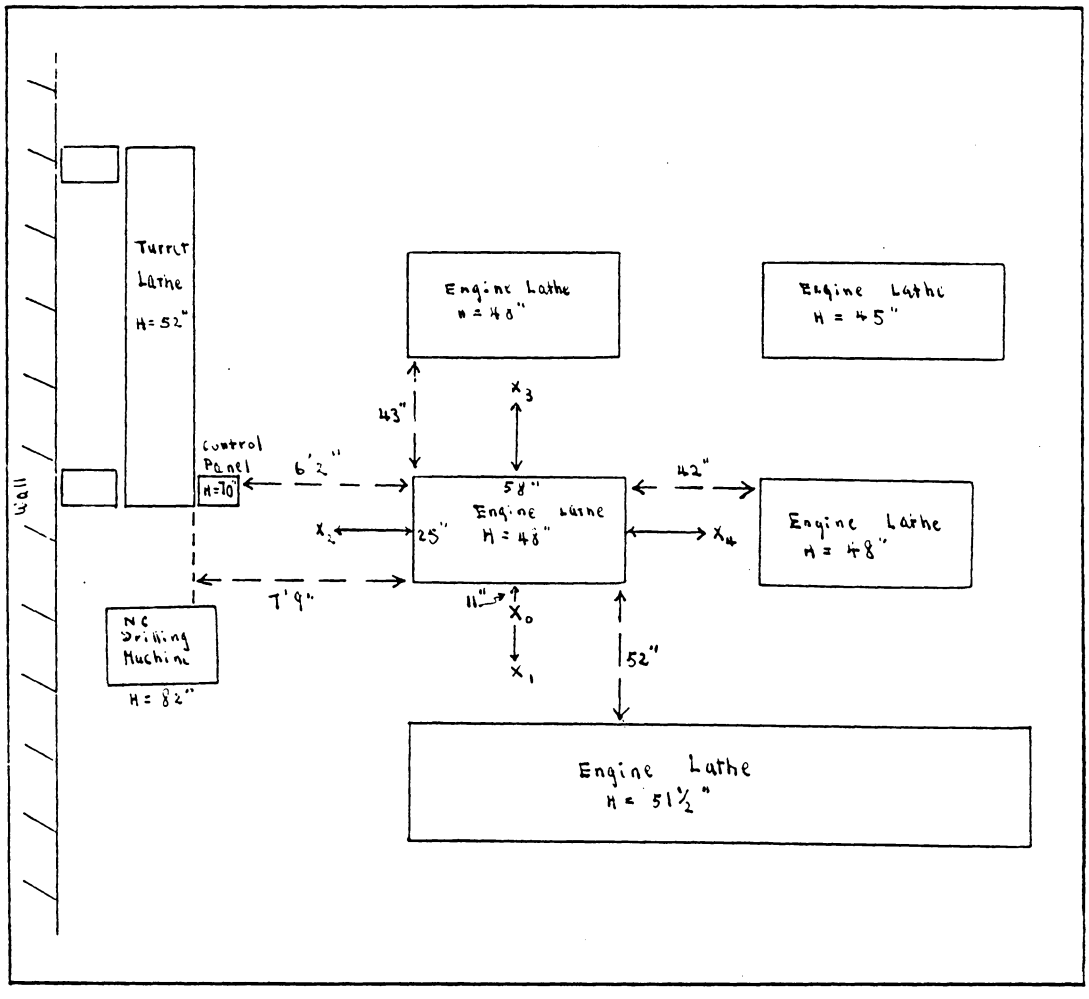
(noise spectrum on following page(s))



1/3 OB Noise spectrum for contour saw, operator's position, linear sound pressure level

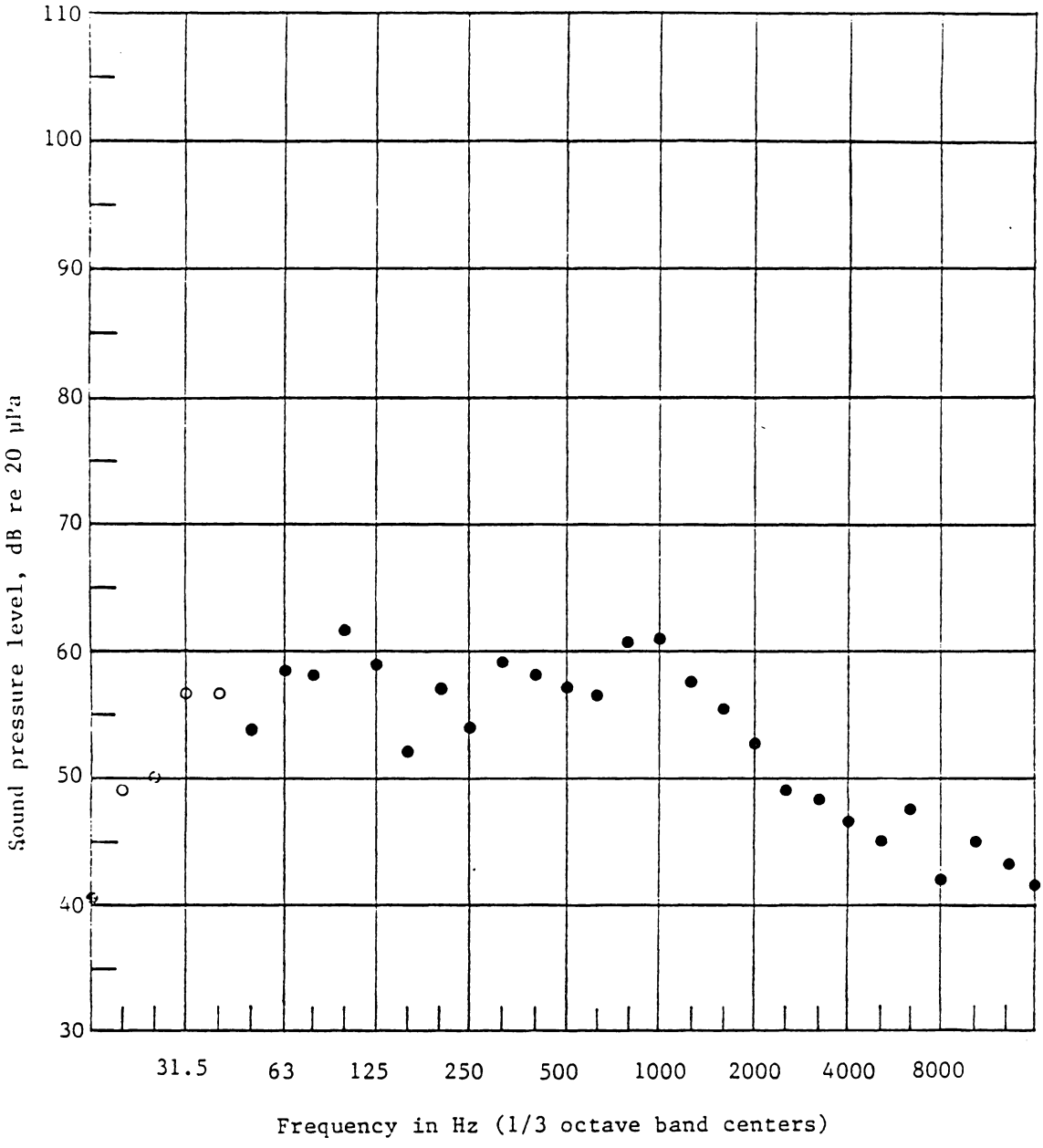


1/3 OB Noise spectrum for Contour saw, average three microphone positions, linear sound pressure level

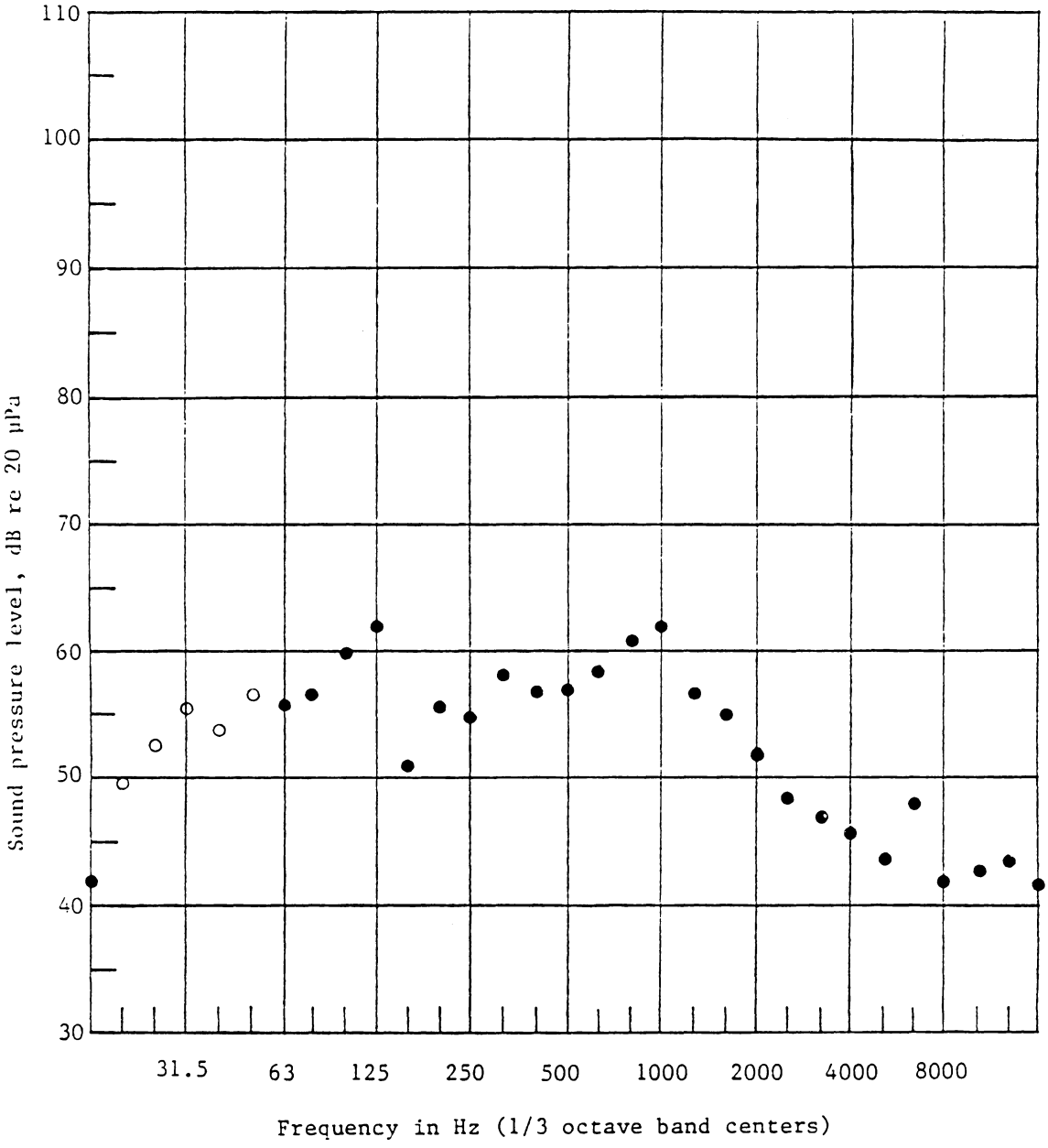


Monarch Engine Lathe Model 10-inch EE
Measurement Conditions:
Operating speed - 400 rpm
Tool - high-speed steel
Work material - cold-roll steel

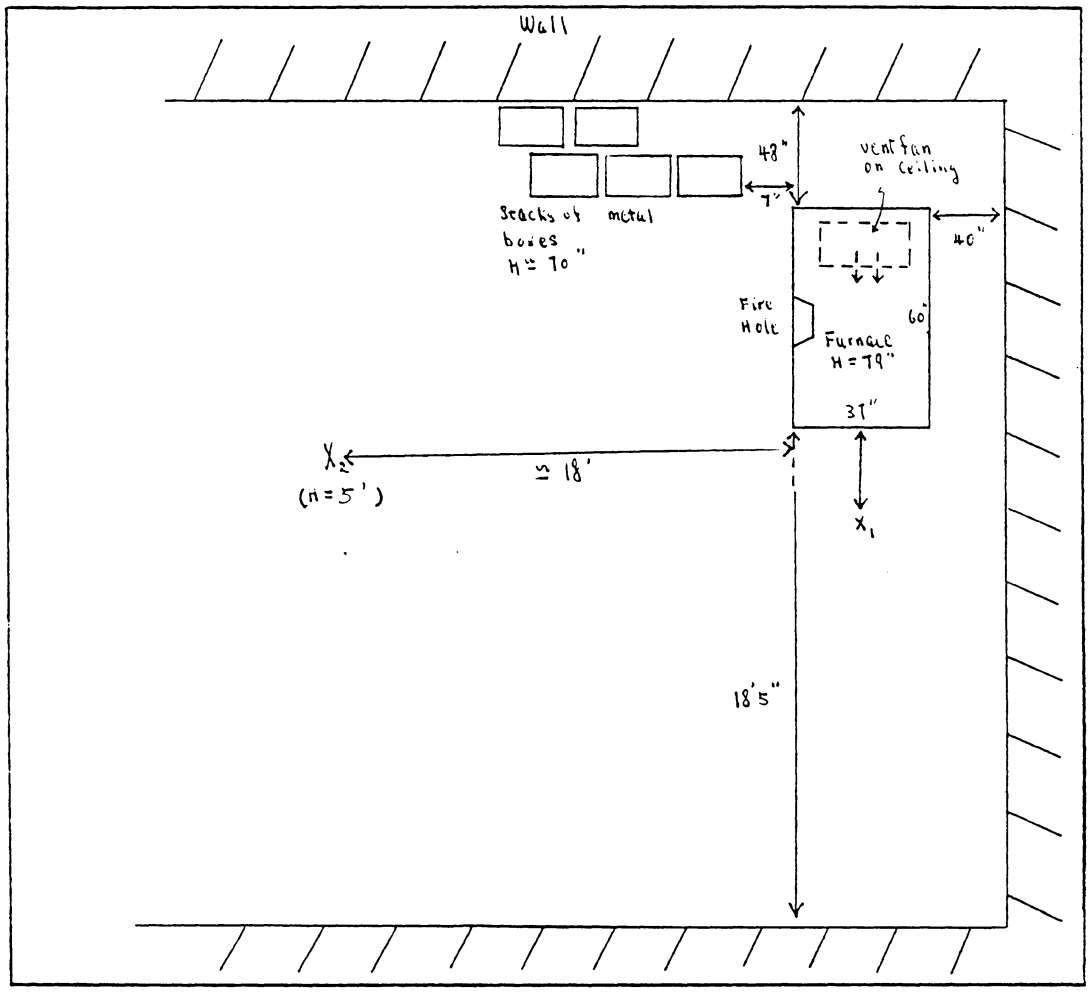
(noise spectrum on following page(s))



1/3 OB spectrum for engine lathe, operator's position, linear sound pressure level

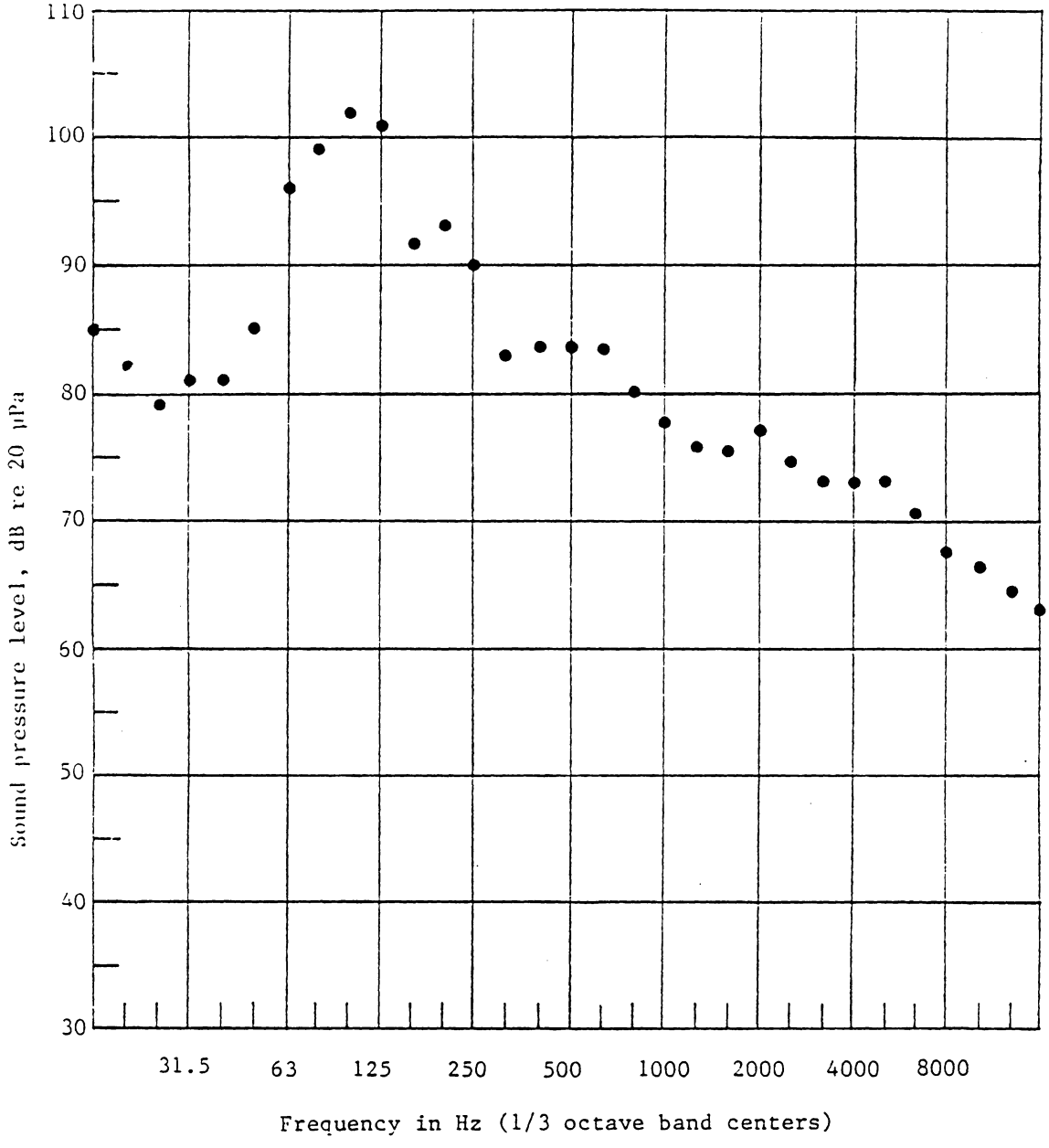


1/3 OB Noise spectrum for engine lathe, average four microphone positions, linear sound pressure level

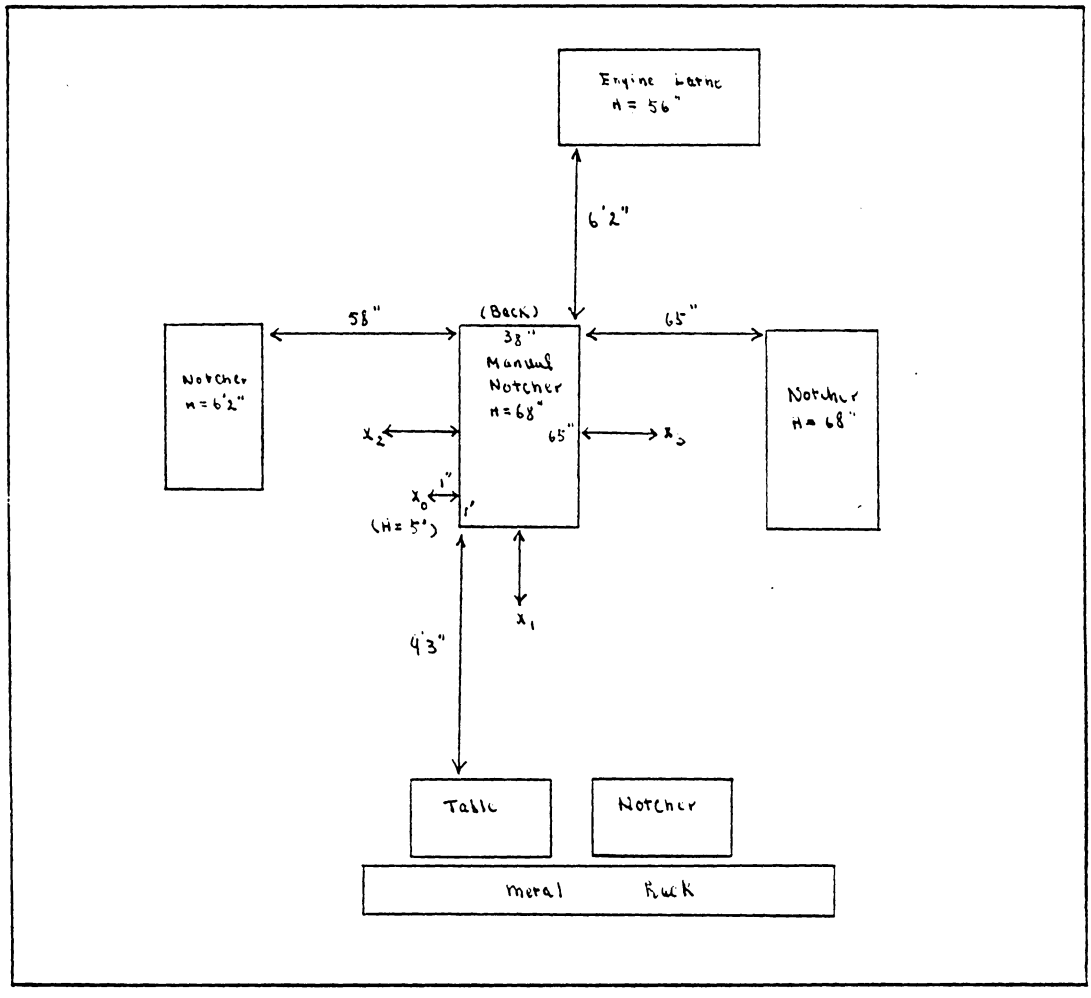


Revecon Furnace and Ventilation Fan Model 320-500
Measurement Conditions:
Fuel - #2 heating oil (17 PSI)

(noise spectrum on following page(s))

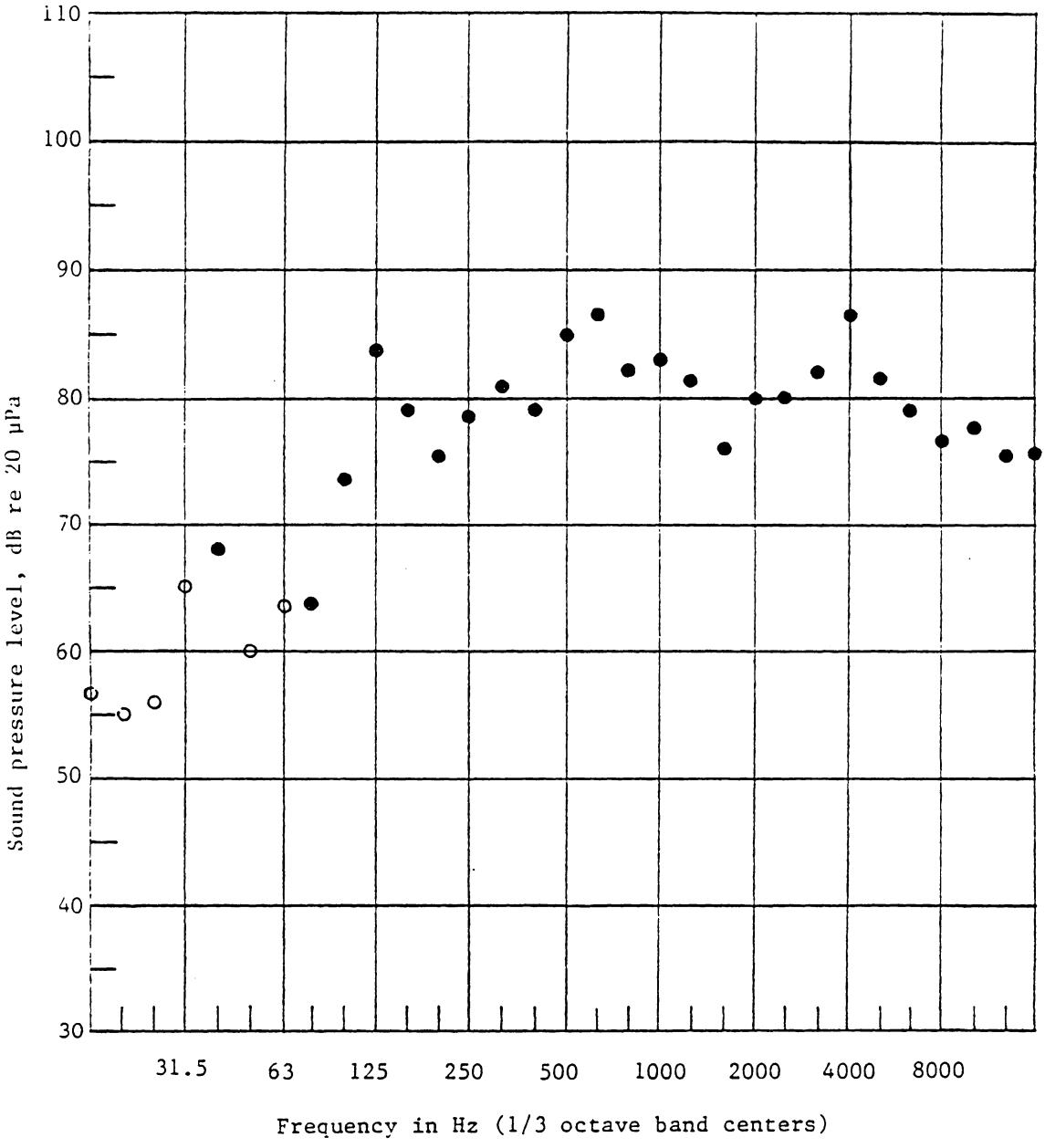


1/3 OB Noise spectrum for furnace and ventilation fan, single microphone position, linear sound pressure level

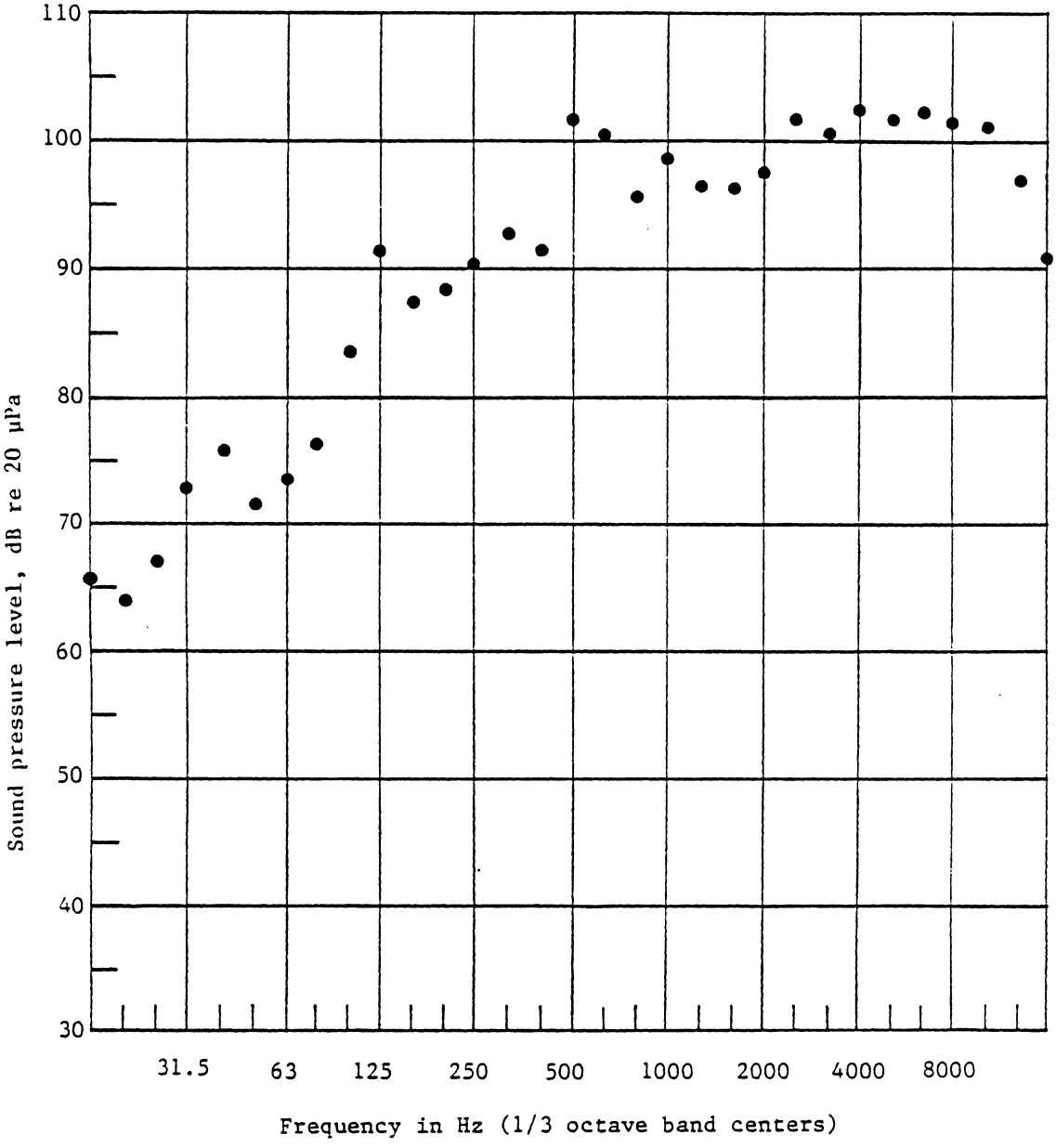


V & O Manual Notcher (5 ton) Model V & O -410 No. 1
Measurement Conditions:
Operating speed - 280 strokes per minute
Tool - carbide die
Work material - M27 - 025 steel

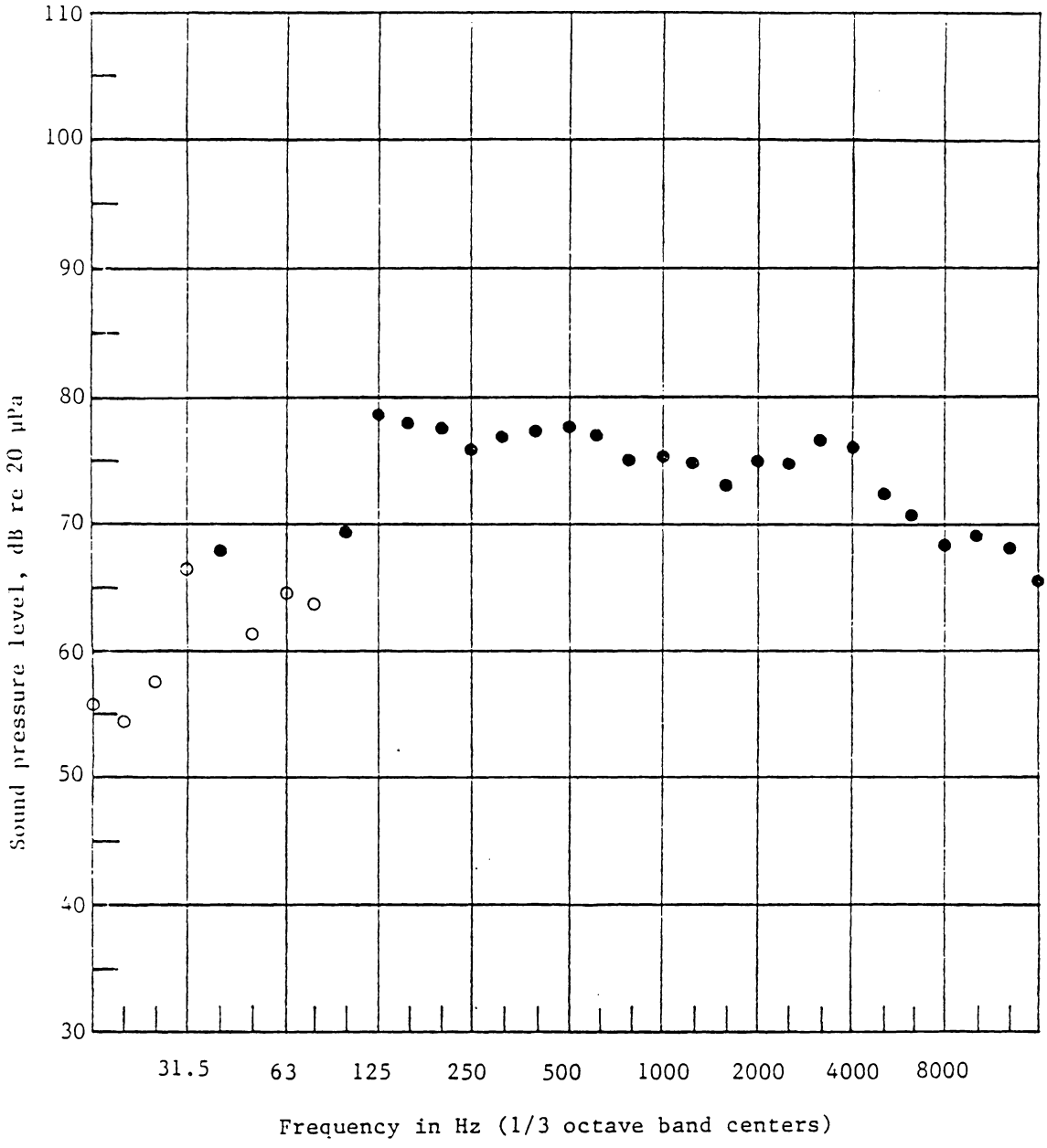
(noise spectrum on following page(s))



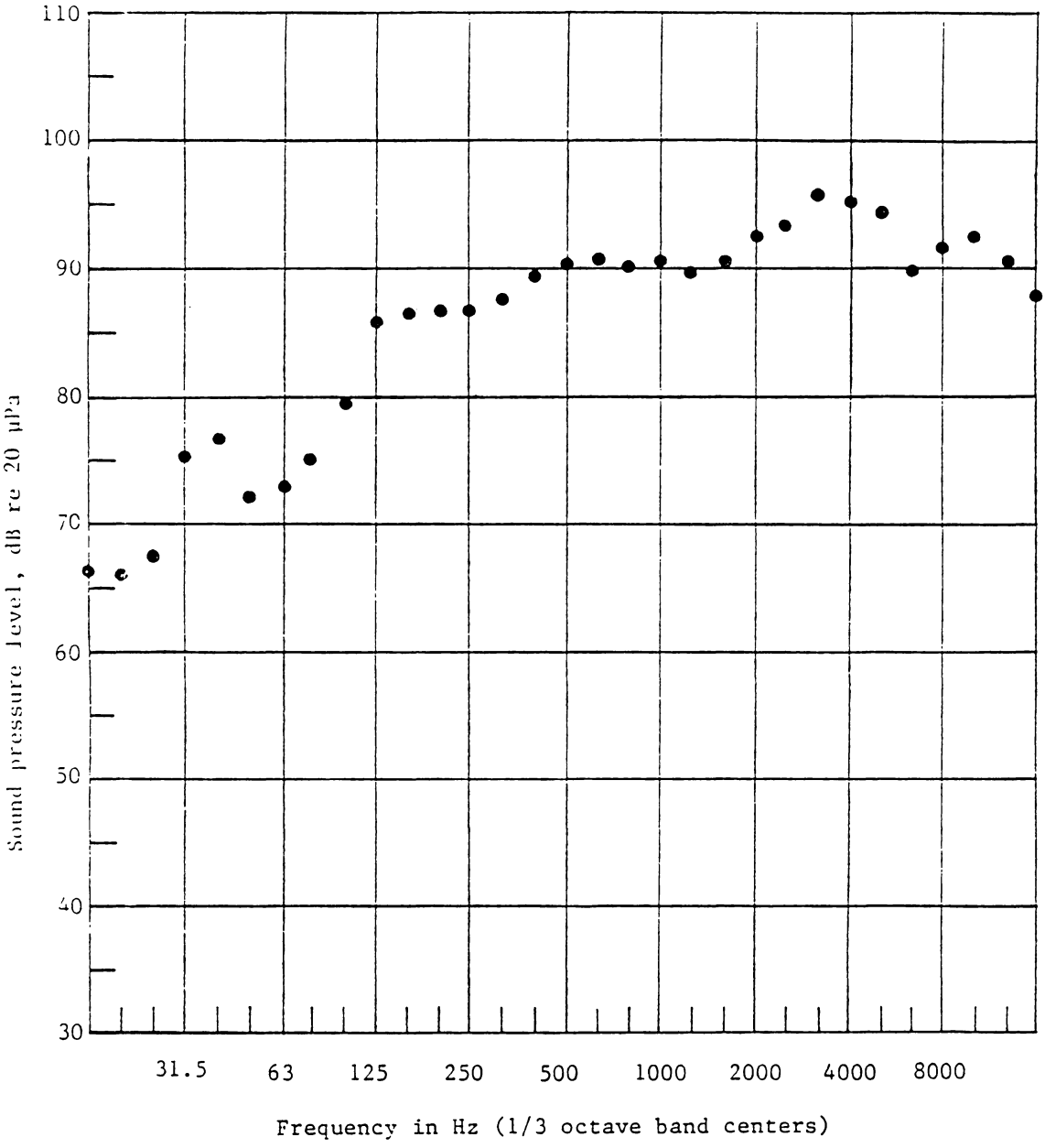
1/3 OB Noise spectrum for manual notcher, operator's position, linear sound pressure level



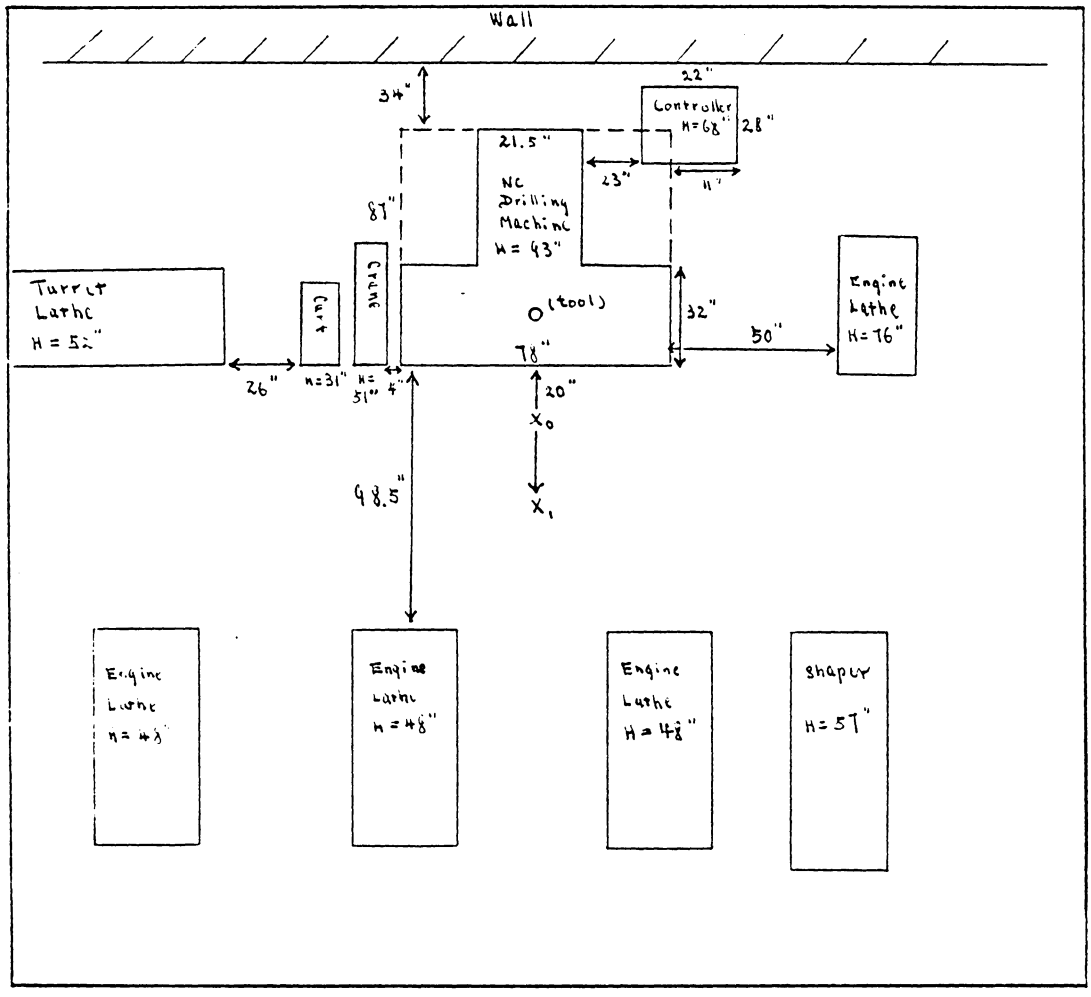
1/3 OB Noise spectrum for manual notcher, operator's position, peak sound pressure level



1/3 OB Noise spectrum for manual notcher, average three microphone positions, linear sound pressure level

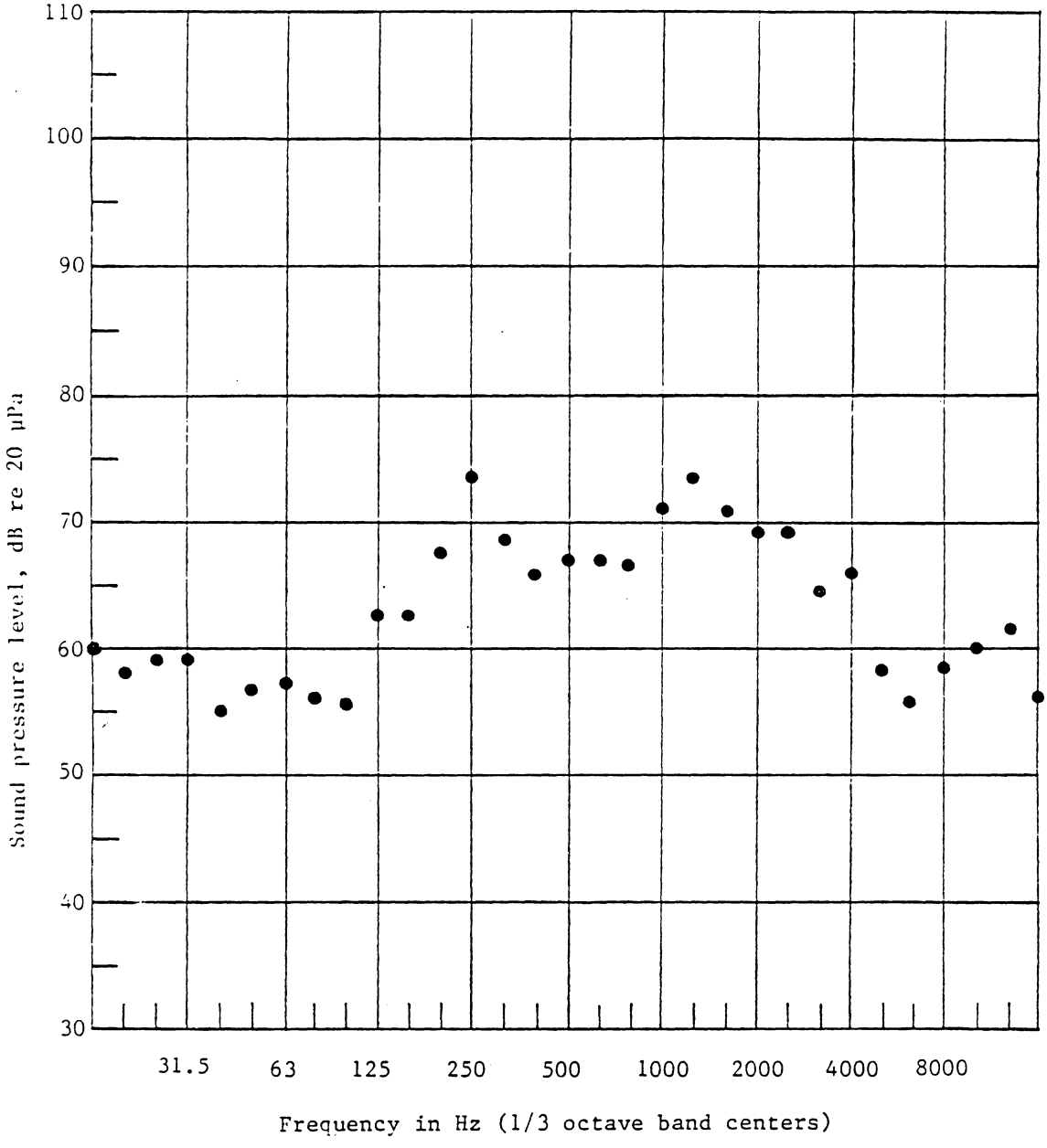


1/3 OB Noise spectrum for manual notcher, average three microphone positions, peak sound pressure level

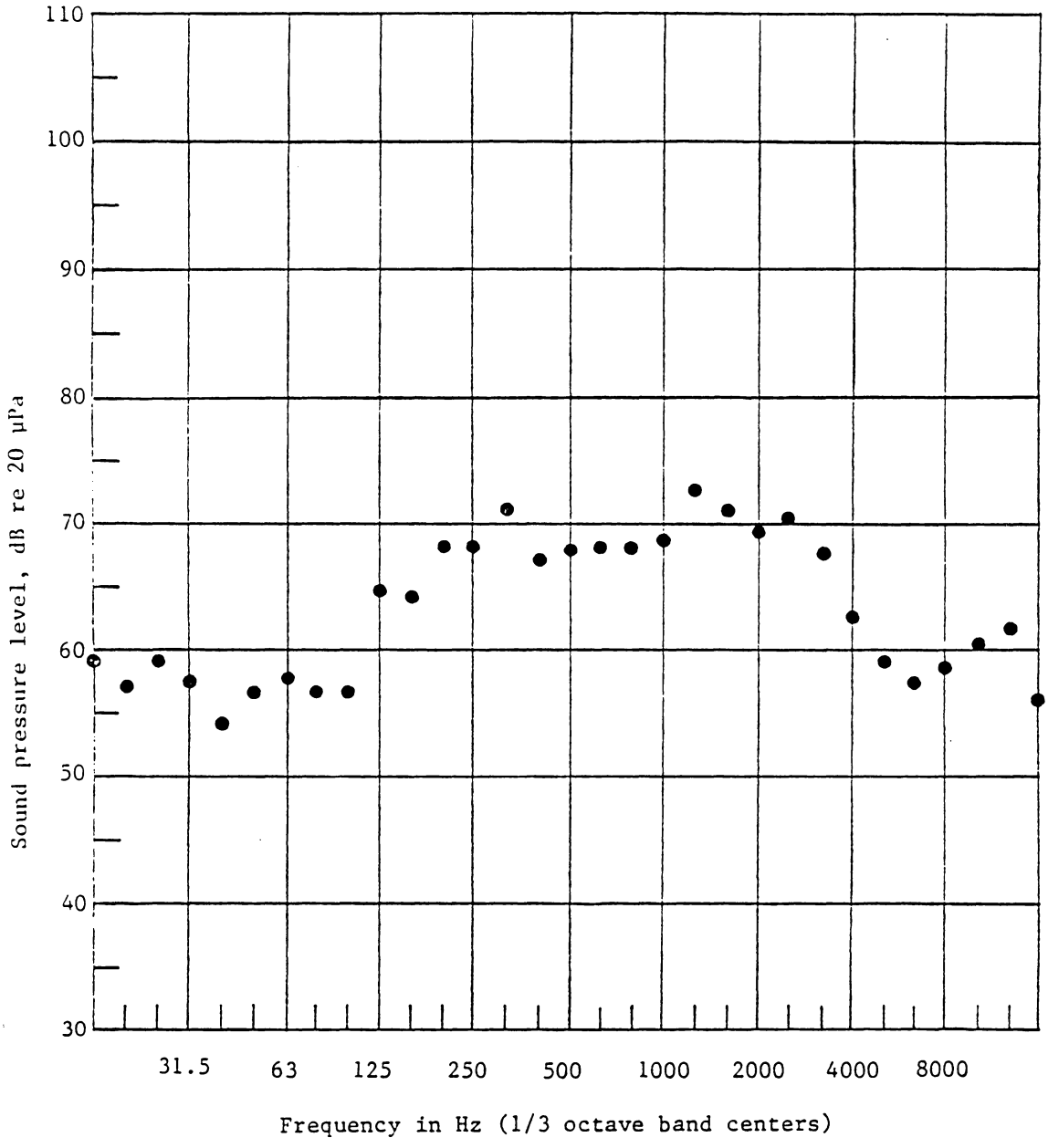


Pratt & Whitney NC Drilling Machine and Controller Model C
Measurement Conditions:
Operating speed - 290 rpm
Tool - one inch high speed steel end mill
Work material - Aluminum plate 3/4 inch thick

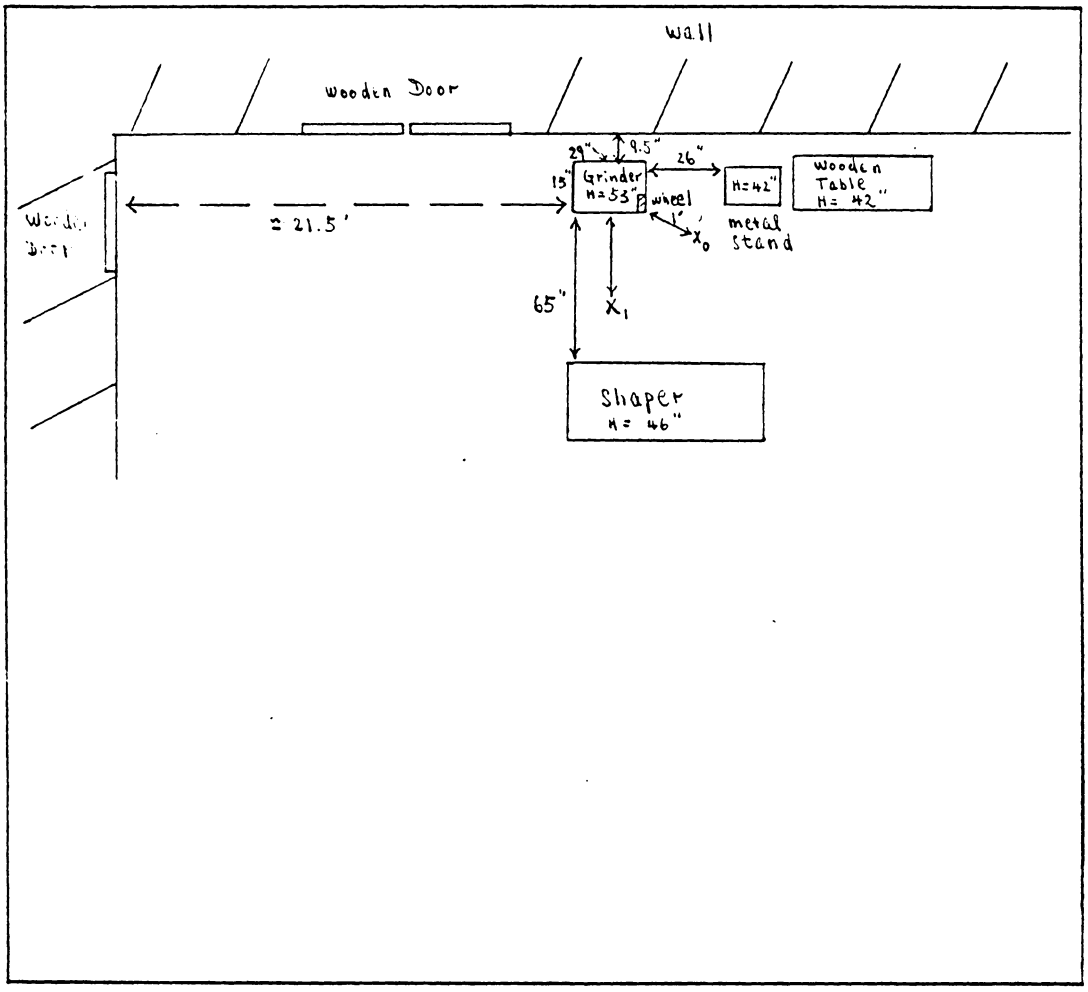
(noise spectrum on following page(s))



1/3 OB Noise spectrum for NC drilling machine and controller, single microphone position, linear sound pressure level

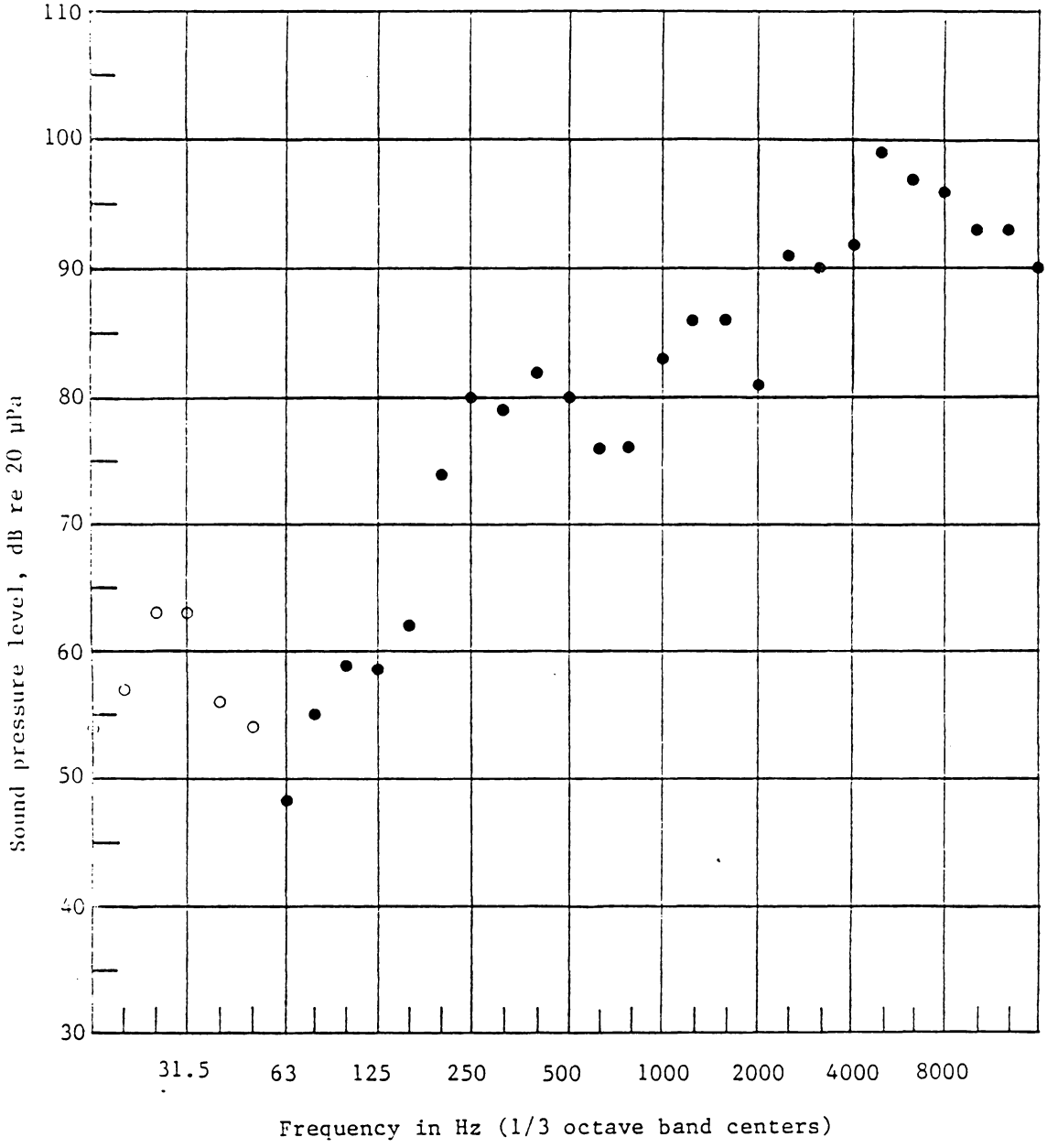


1/3 OB Noise spectrum for NC drilling machine and controller, operator's position, linear sound pressure level

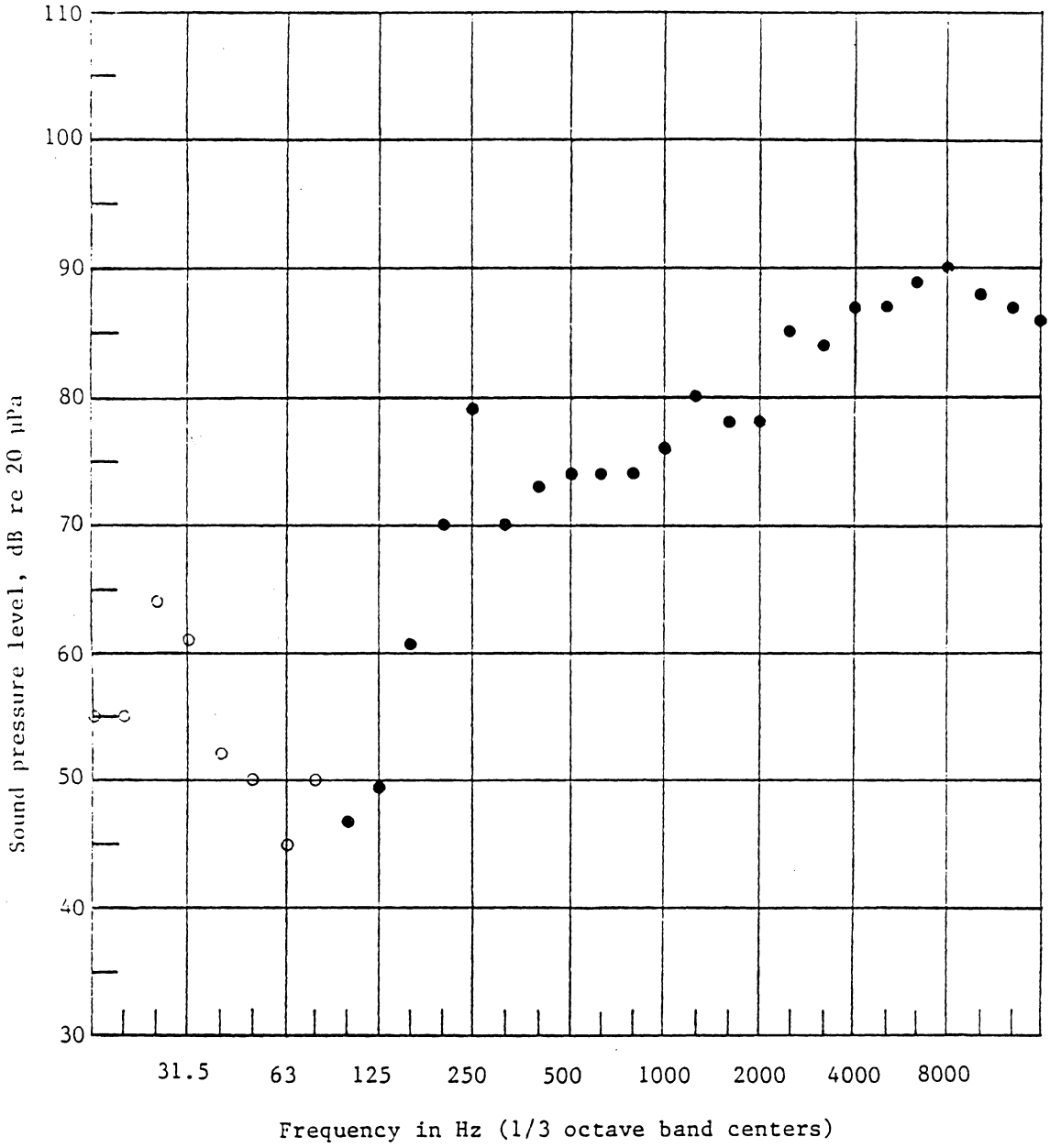


Hisey - Wolf Pedestal Grinder Model 4
Measurement Conditions:
Operating speed - 1750 rpm
Tool - Aluminum oxide grinder wheel
Work material - steel plate

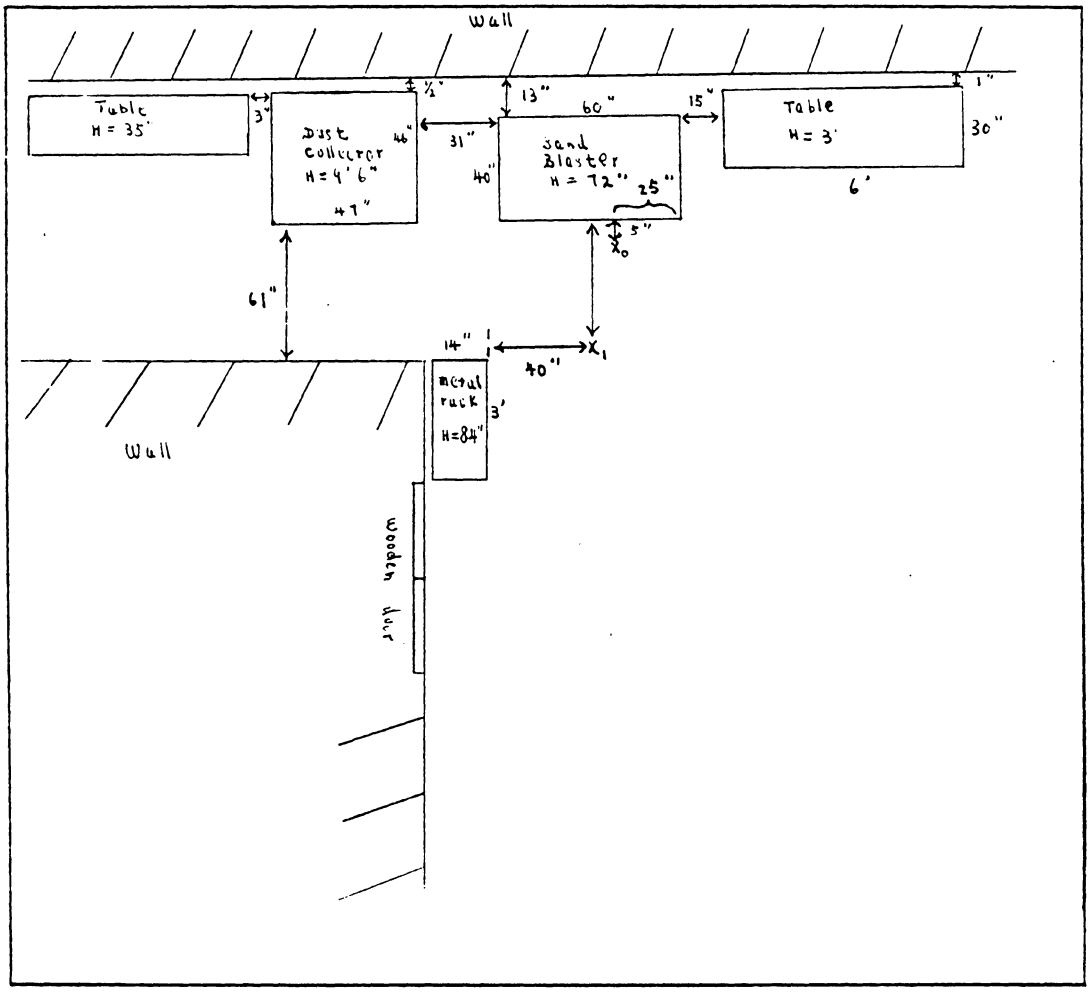
(noise spectrum on following page(s))



1/3 OB Noise spectrum for pedestal grinder, operator's position, linear sound pressure level

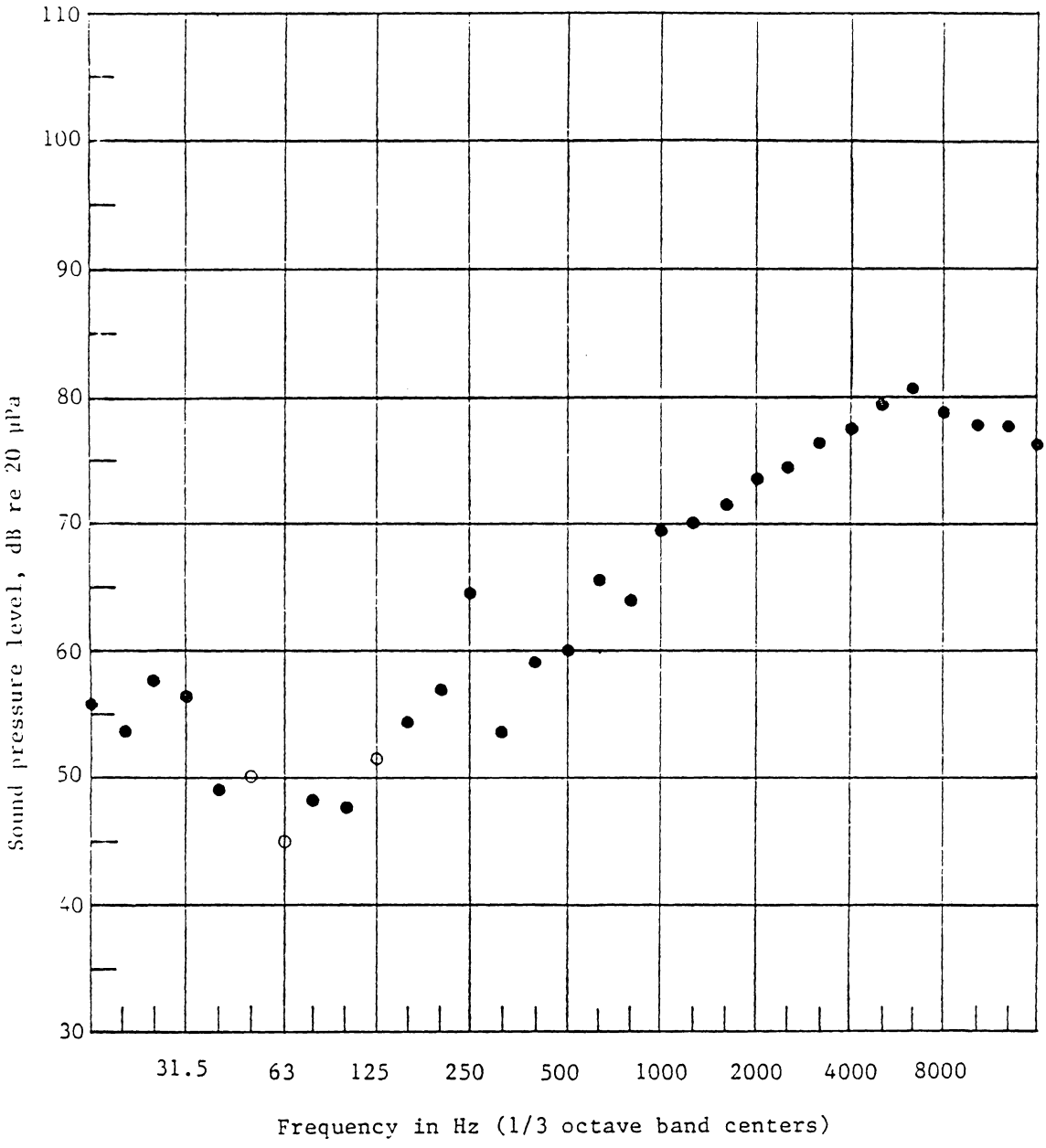


1/3 OB Noise spectrum for pedestal grinder, single microphone position, linear sound pressure level

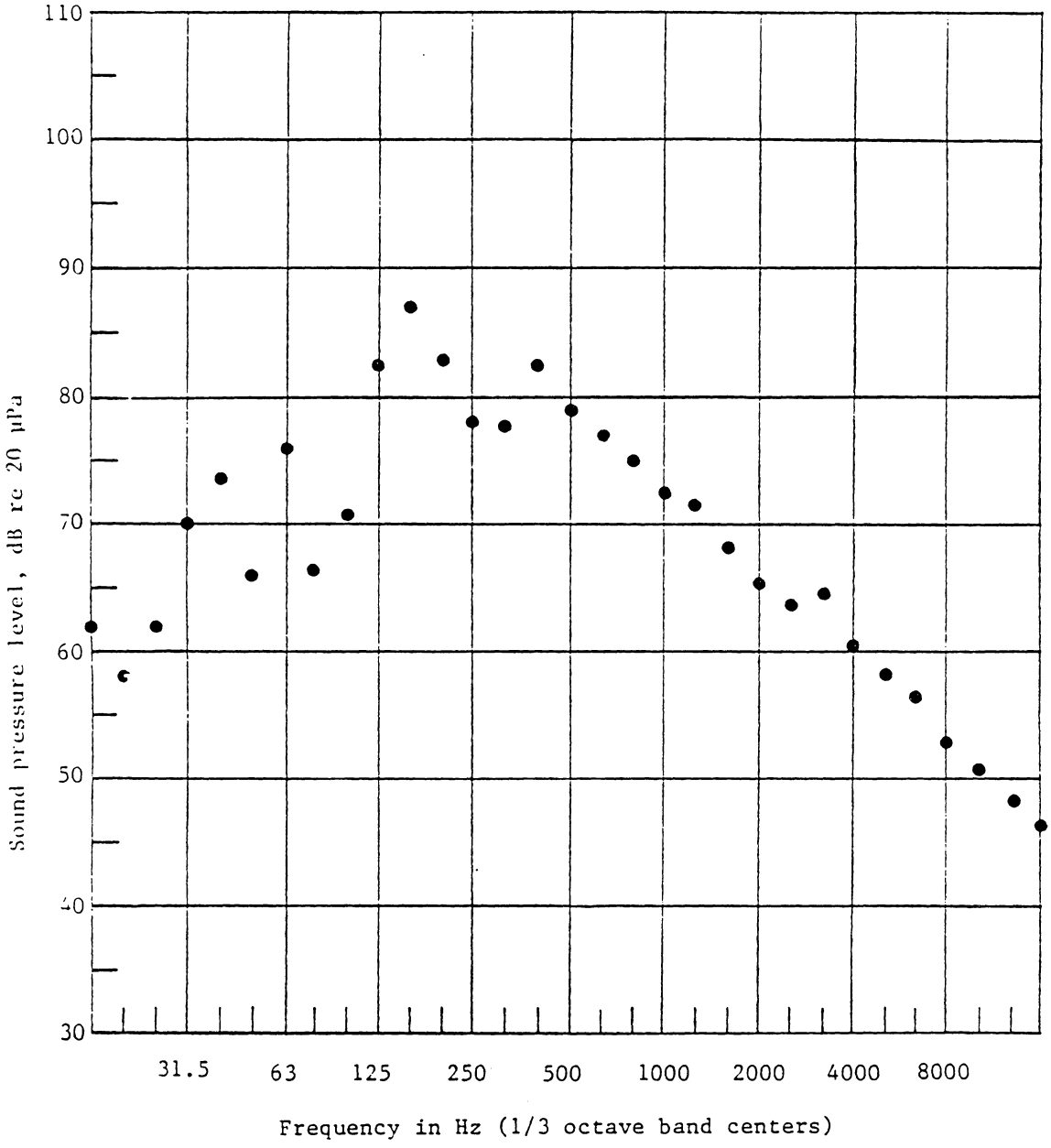


Pangborn Sand Blaster and Dust Collector Model size 200-CN
Measurement Conditions:
Operating condition - 60 PSI
Tool - Steel grit
Work material - Cast iron

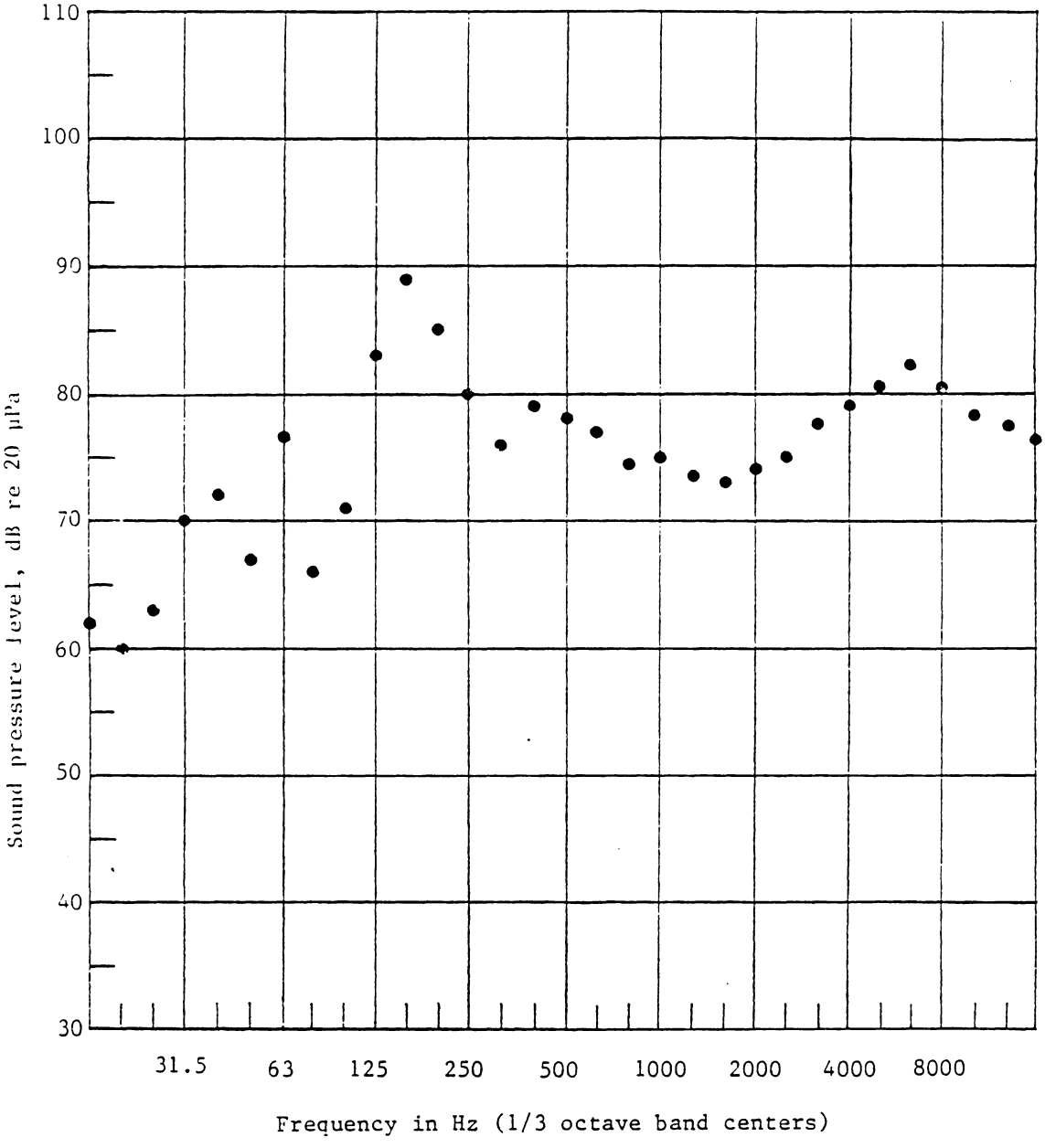
(noise spectrum on following page(s))



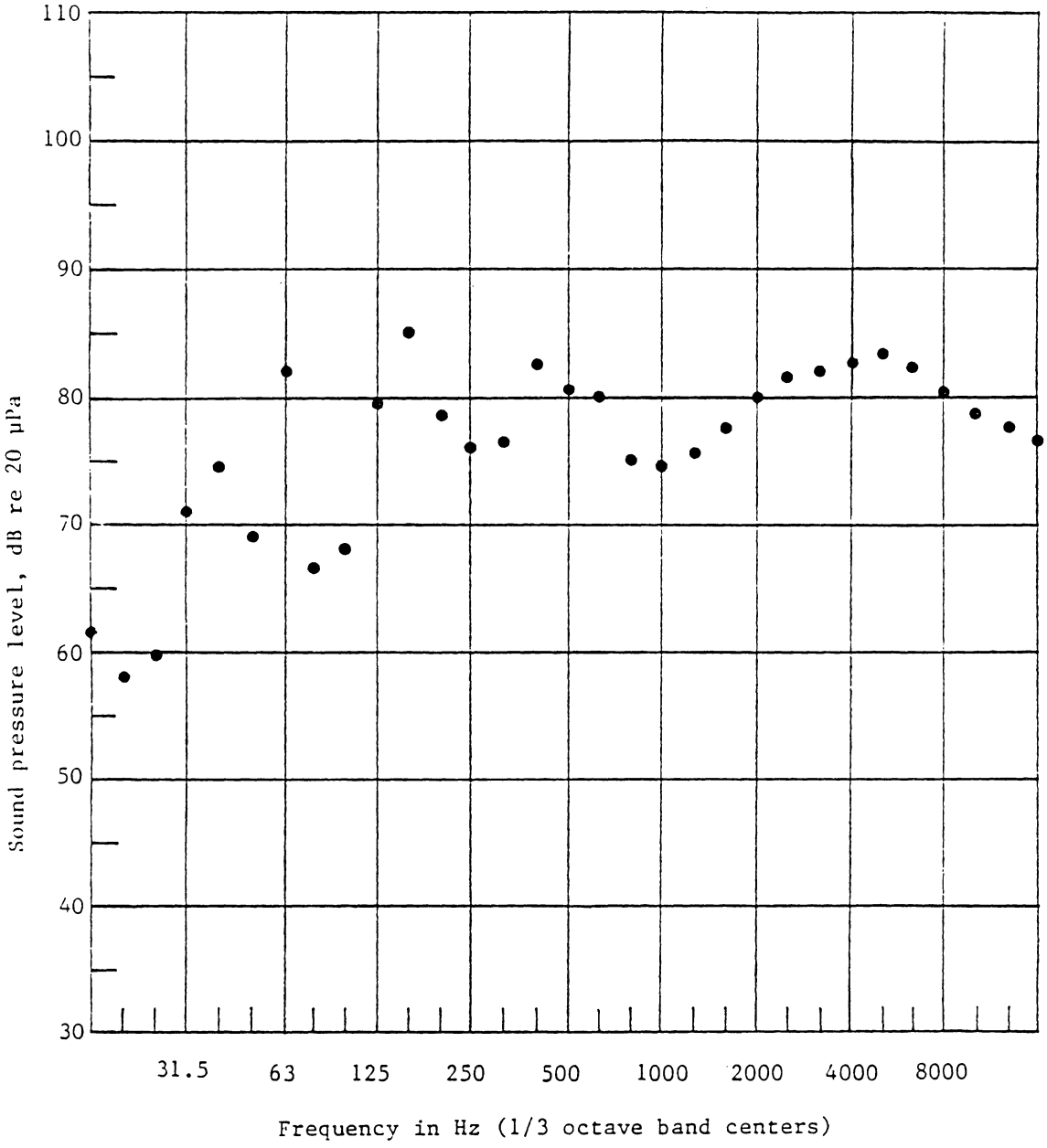
1/3 OB Noise spectrum for sand blaster alone, operator's position, linear sound pressure level



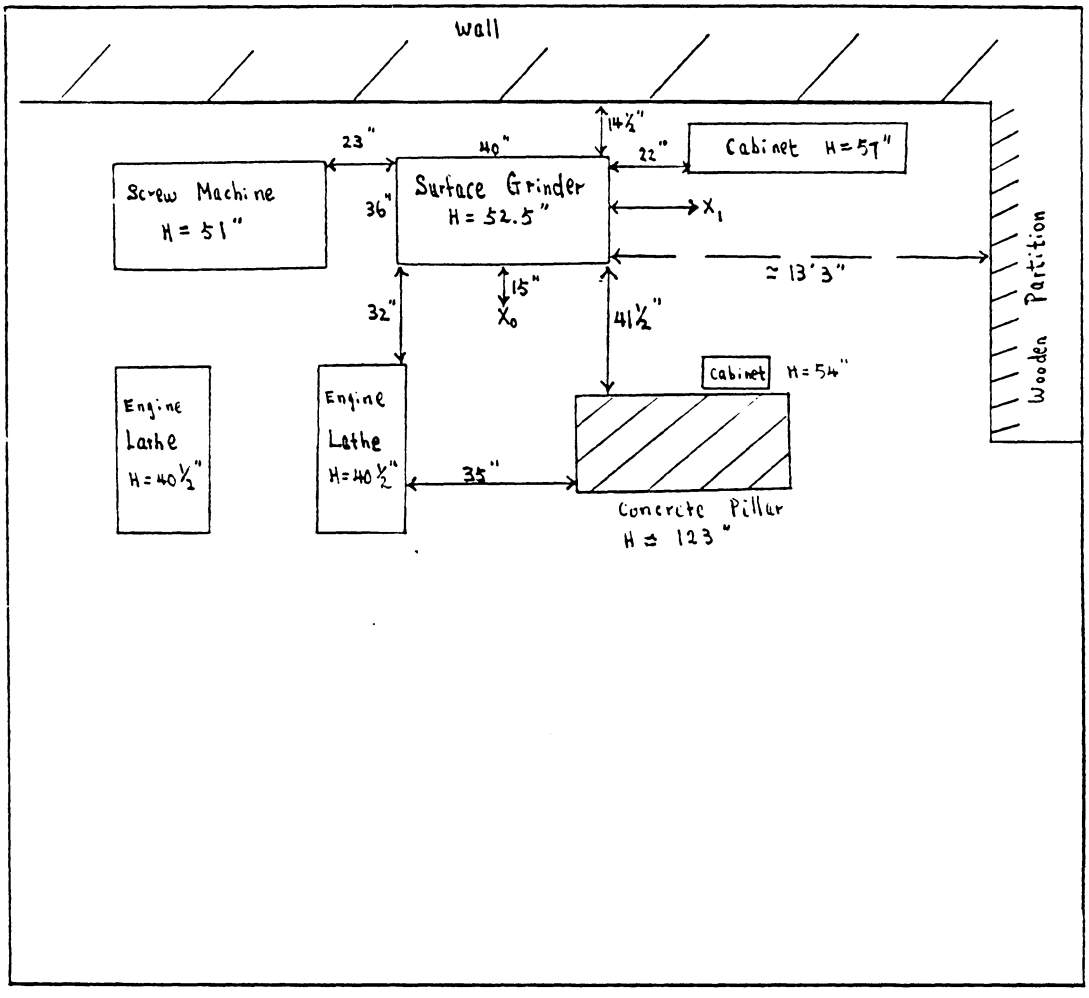
1/3 OB Noise spectrum for dust collector alone, operator's position, linear sound pressure level



1/3 OB Noise spectrum for sand blaster and dust collector, operator's position, linear sound pressure level

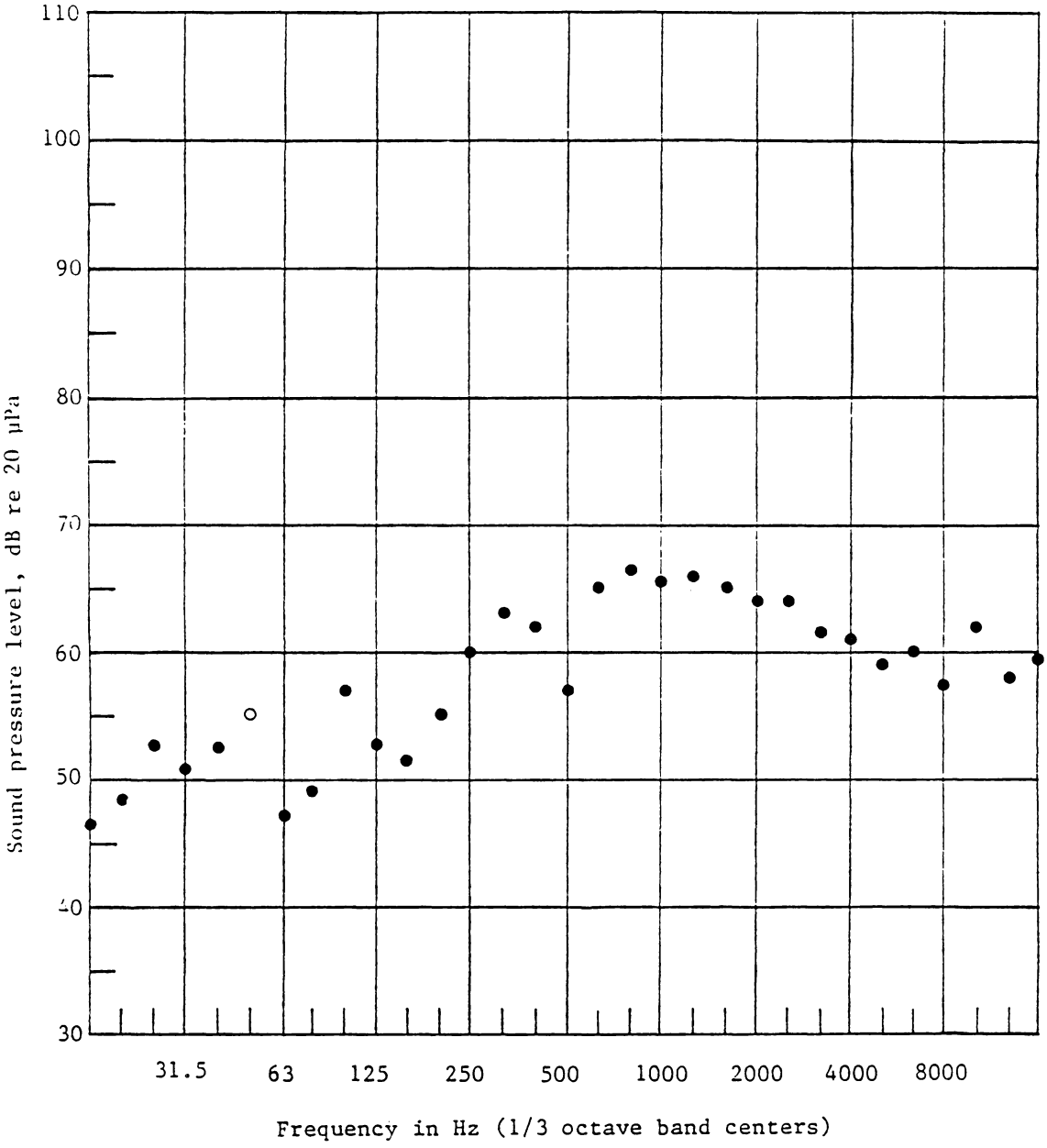


1/3 OB Noise spectrum for sand blaster and dust collector, single microphone position, linear sound pressure level

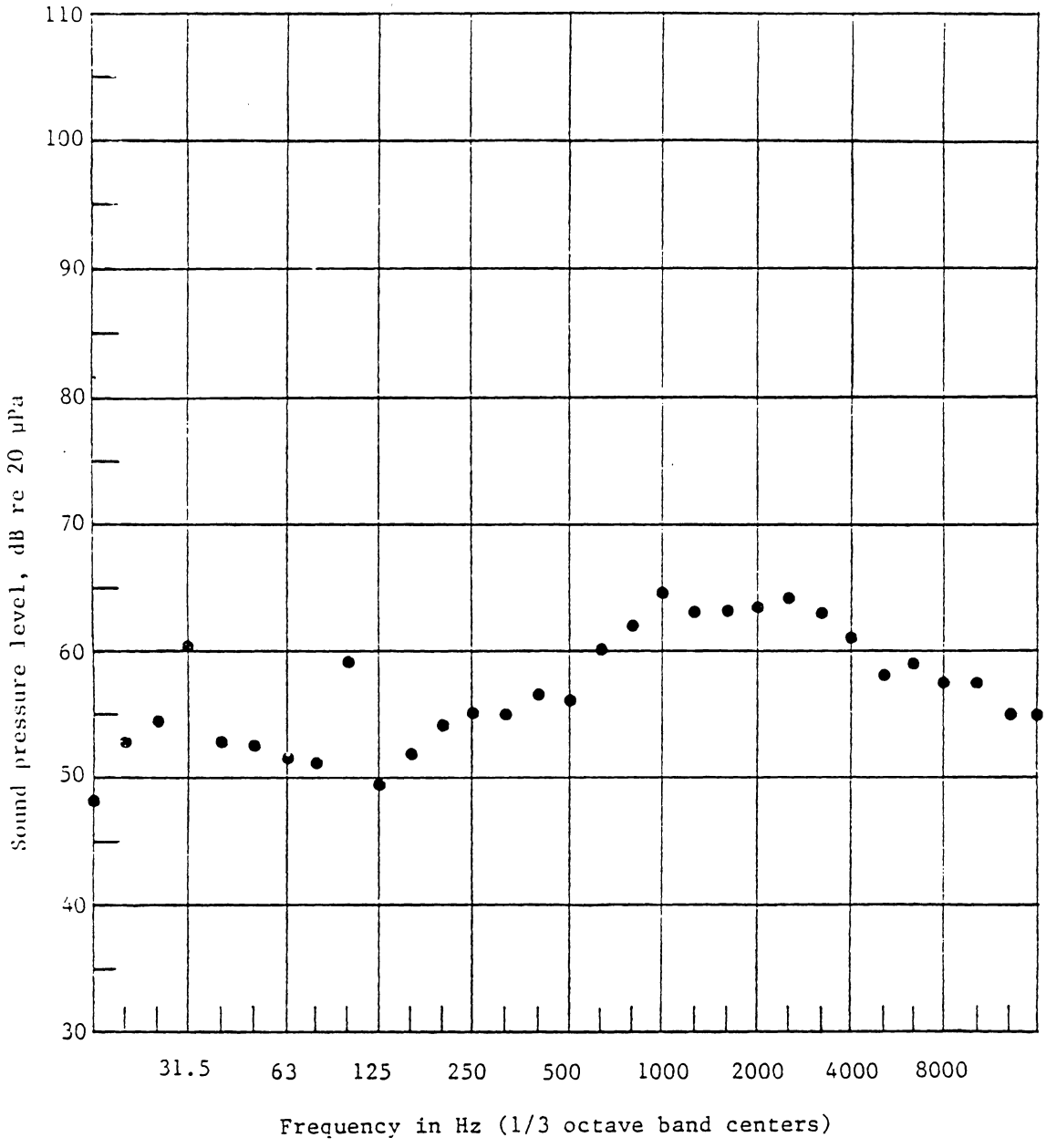


Norton Surface Grinder Model NAS 19/5
Measurement Conditions:
Operating speed - 2900 rpm
Tool - Aluminum oxide grinding wheel
Work material - Carbon steel

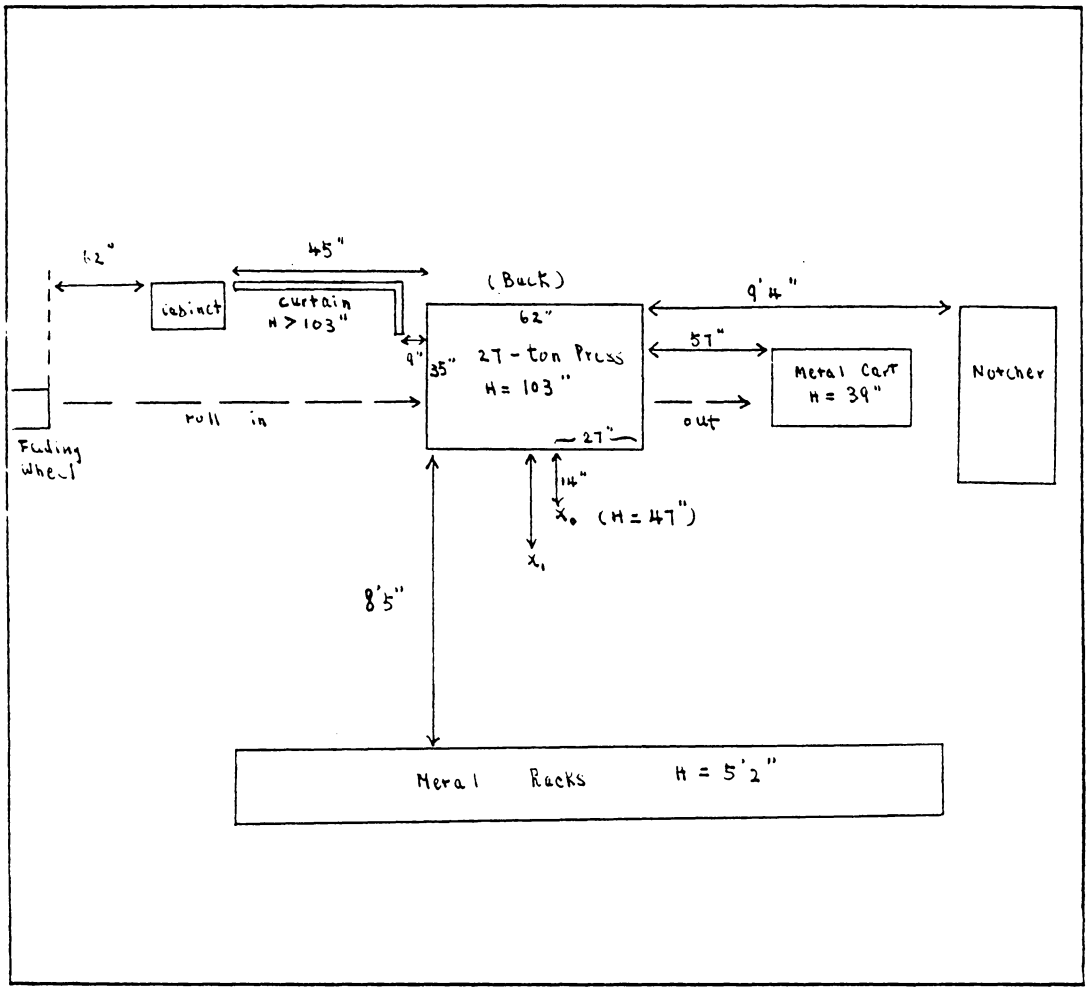
(noise spectrum on following page(s))



1/3 OB Noise spectrum for surface grinder, operator's position, linear sound pressure level

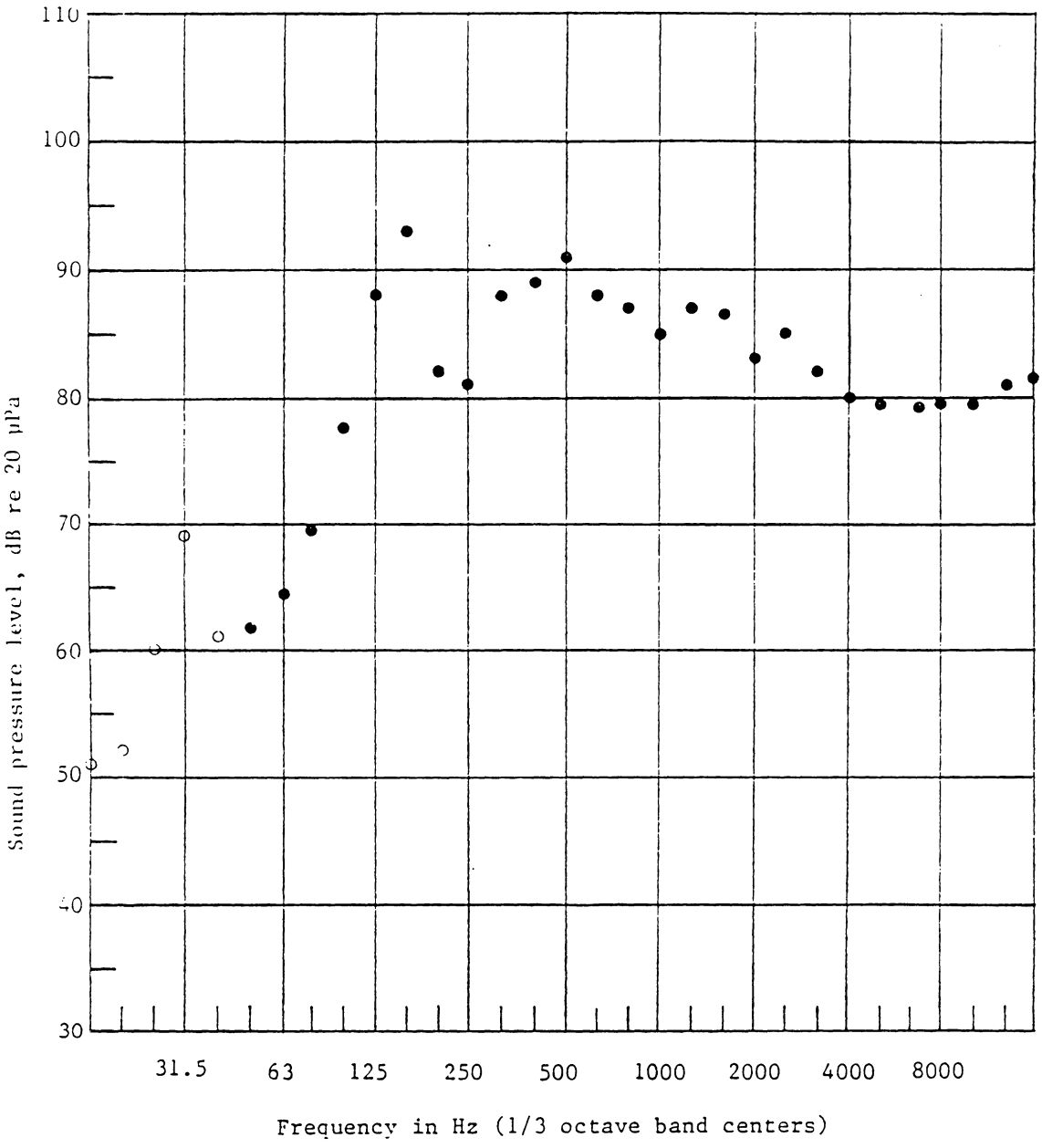


1/3 OB Noise spectrum for surface grinder, single microphone position, linear sound pressure level

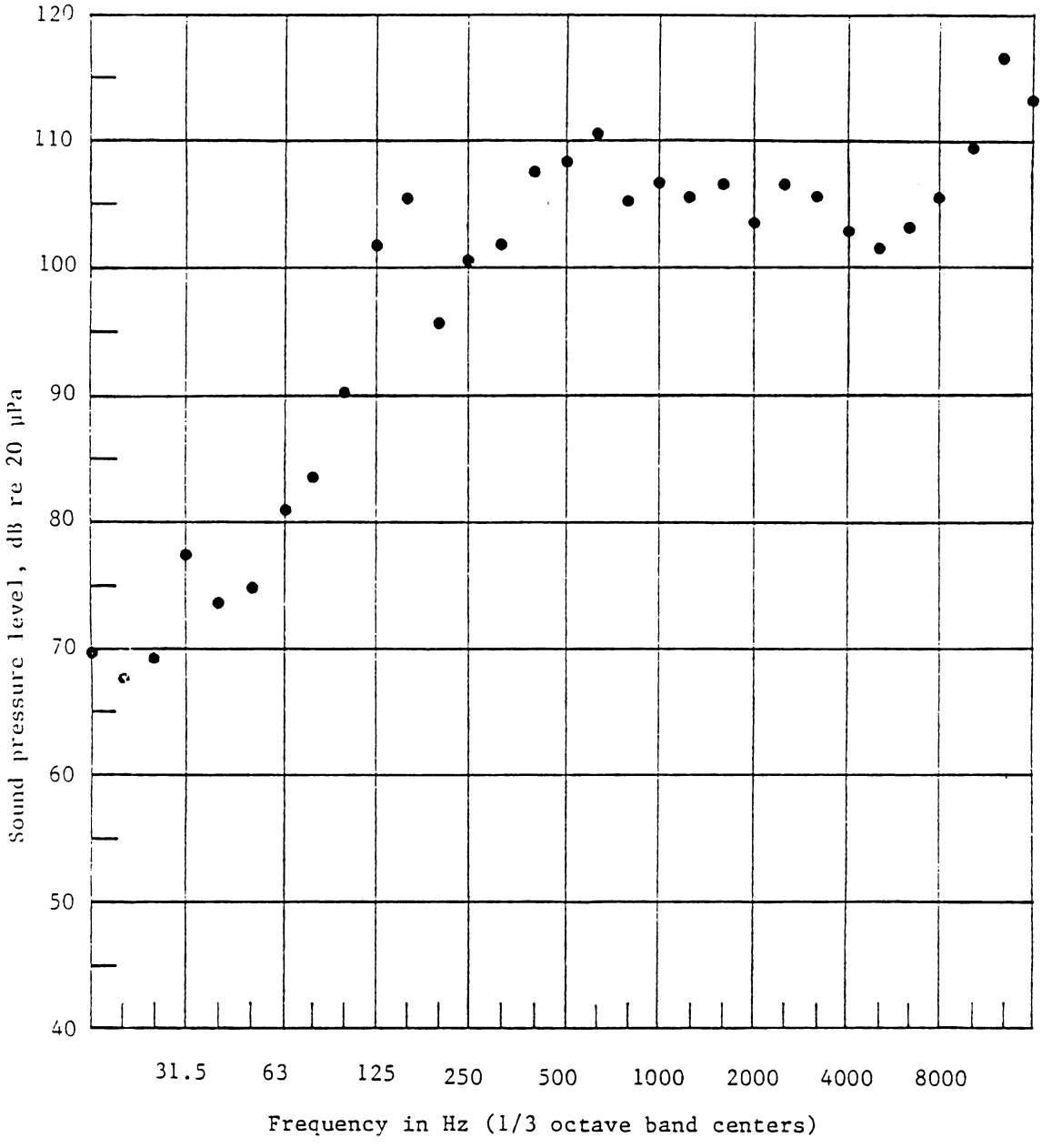


L & J 27 - Ton Press Model W-27
Measurement Conditions:
Operating speed - 126 strokes per minute
Tool - high speed steel
Work material - steel plates 0.018 inch thick

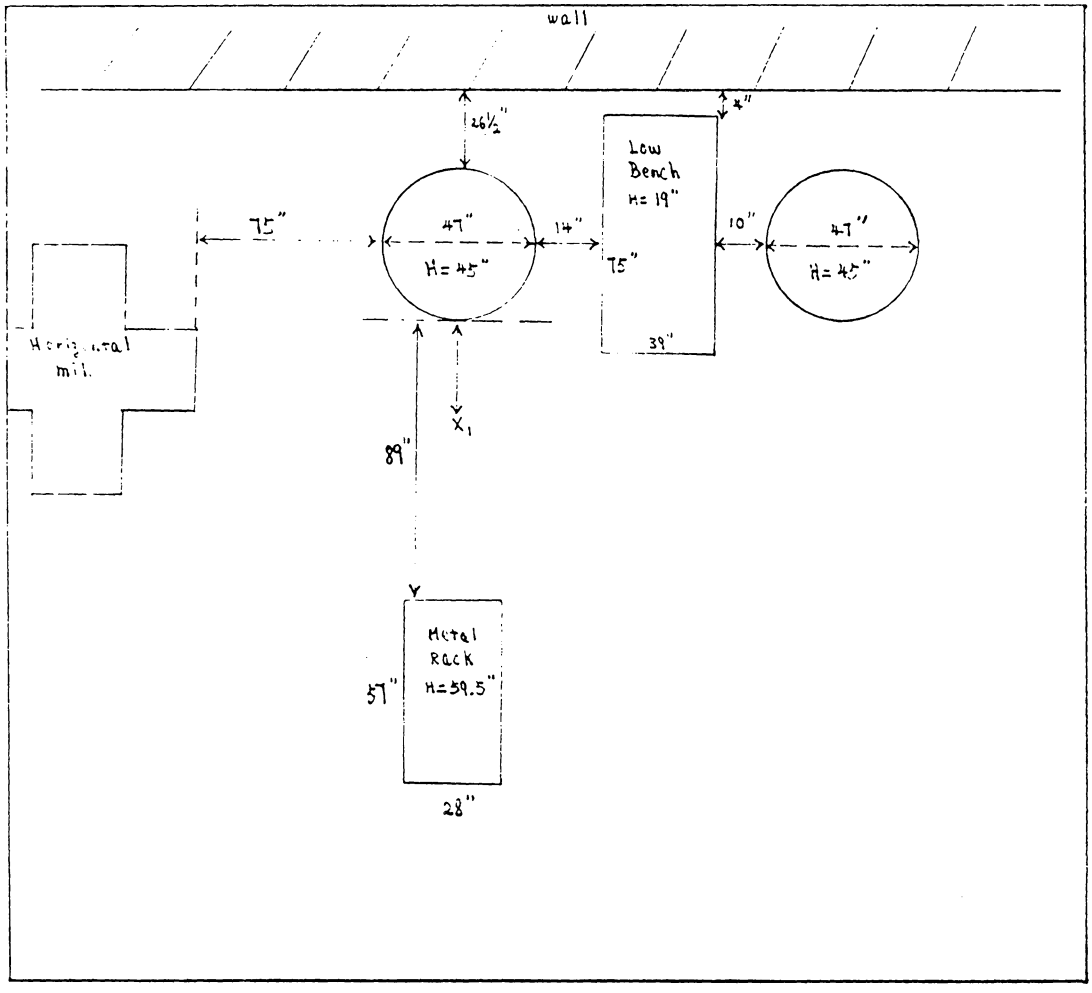
(noise spectrum on following page(s))



1/3 OB Noise spectrum for 27 - ton press, single microphone position, linear sound pressure level

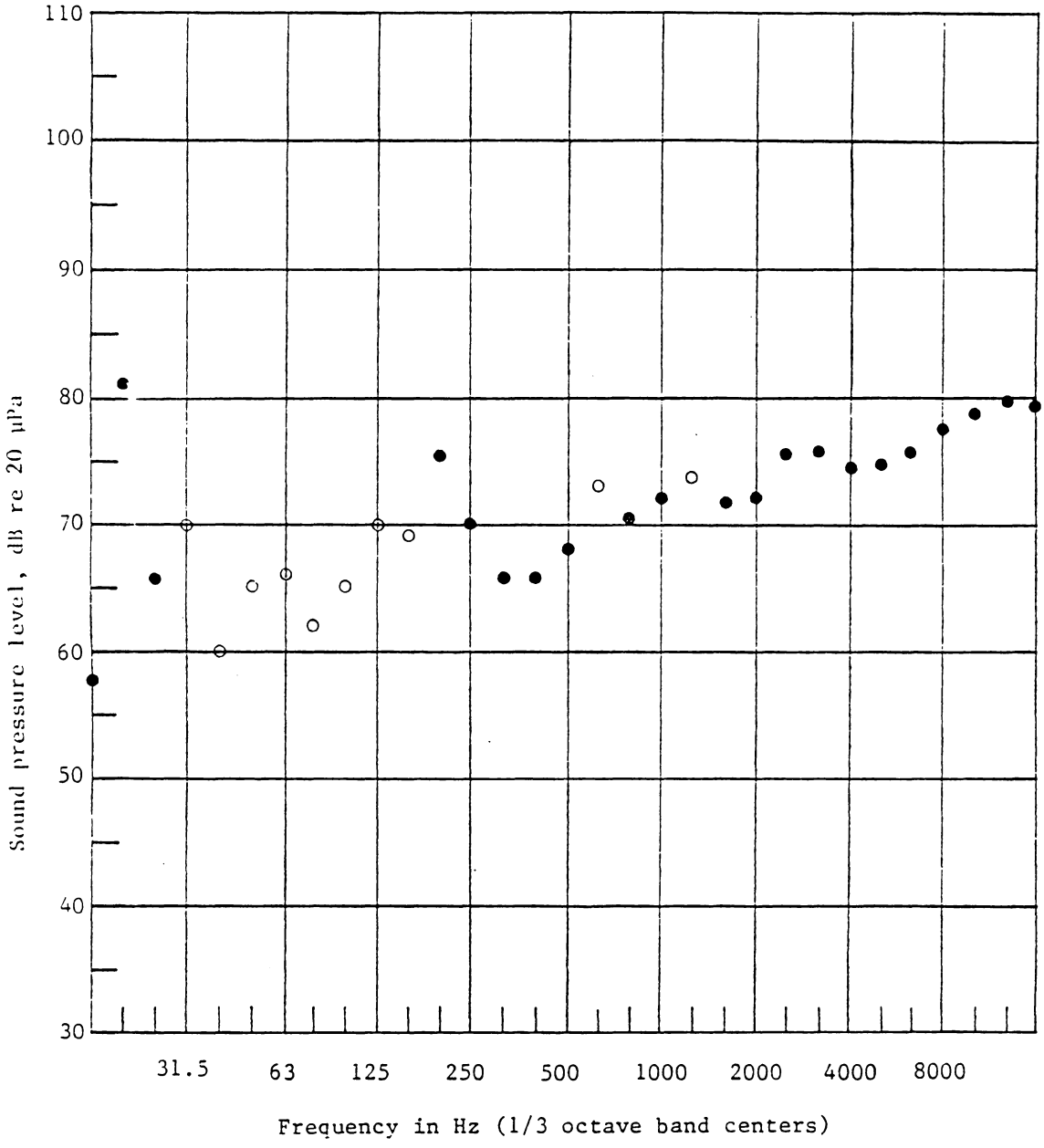


1/3 OB Noise spectrum for 27 - ton press, single microphone position, peak sound pressure level



SWECO Vibro - energy Finishing Mill (Vibrating Deburrer) Model FMD71-R
Measurement Conditions:
Operating speed - 1200 rpm
Tool - ceramic tumbling media
Work material - none

(noise spectrum on following page(s))



1/3 OB Noise spectrum for vibro-energy finishing mill, single microphone position, linear sound pressure level

APPENDIX B

Noise Sampling Documentation Forms

SOUND SURVEY

OBSERVER(S):

DATE/TIME:

SITE/PLANT AREA:

MACHINE/SETTING:

Type: _____

Model: _____ Manufacturer: _____

Description: _____

_____

TEST CONDITIONS:

Environment: _____ Indoor/Outdoor: _____

Background SPL: _____

Machine Running Free: _____ With Load: _____

Operating Speed as Tested: _____ Tool: _____

Type of Workpiece/Material: _____

Location of Machine in Room: _____

Room Size: _____

Distance from Machine to Microphone: _____

Reflecting Plane Composition: _____

Distance of Mic from Reflecting Plane: _____

Temperature: _____ Humidity: _____

Bar. Pressure: _____ Wind Speed: _____

Other Remarks: _____

INSTRUMENTATION:

Microphone: _____

Sound Level Meter: _____

Octave Band Analyzer: _____

Calibrator: _____

Sound Recorder: _____ Cable: _____

Other: _____

_____

SPL MEASUREMENT DATA SHEET:

Noise Source: _____
Mic Location/Orientation: _____
Sound Level/Sound Pressure Level (dB), Re 20 μN/m²

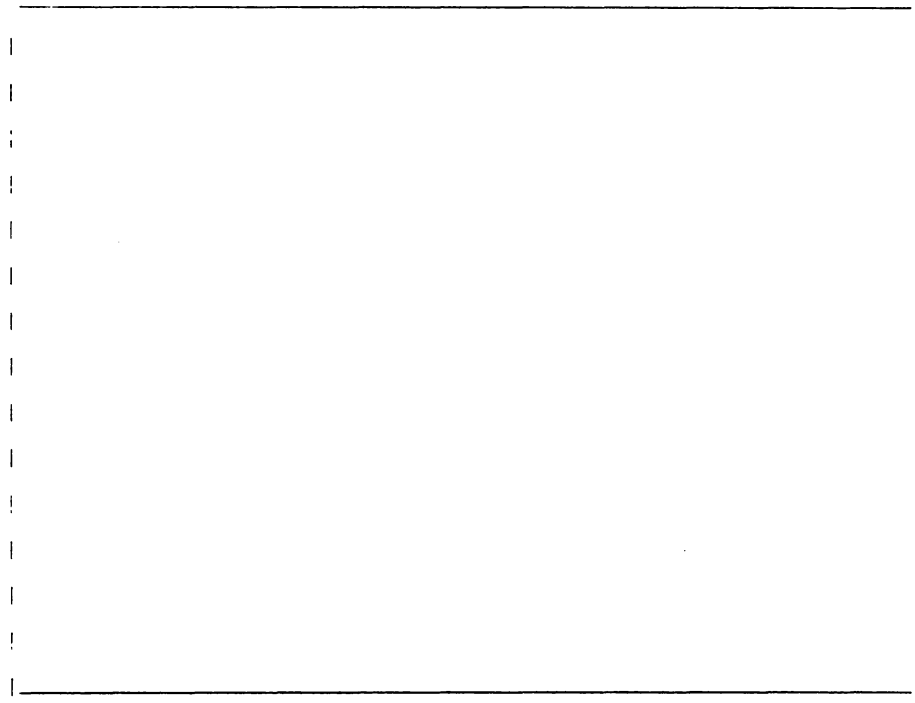
Overall SPL (Fast/Slow):	dBA	dBC	dBLin	Peak
Run Free				
Run Loaded				
Background				

Spectral SPL (Fast/Slow):

1/3 OB Ct.(Hz)	Bkg	L	P			1/3 OB Ct.(Hz)	Bkg	L	P		
* 16						630					
20						800					
25						* 1000					
* 31.5						1250					
40						1600					
50						* 2000					
* 63						2500					
80						3150					
100						* 4000					
* 125						5000					
160						6300					
200						* 8000					
* 250						10000					
315						12500					
400						* 16000					
* 500											

*: Preferred frequencies for one octave center (Hz)
Bkg: Background SPL L: Linear P: Peak

Sketch Showing Mic Positions (X), Orientation of the Machine, and Operator(s) Position:



SUMMARY OF SPL MEASUREMENTS:

Noise Source. _____

Sound Level/Sound Pressure Level (dB), Re 20 μN/m²

$$\bar{L} = 10 \log_{10} \left[\frac{1}{N} \sum_{i=1}^{N} 10^{0.1 L_i} \right]$$

1/3 OB Ct.(Hz)	Mic	Mic	Mic	Mic	- L	1/3 OB Ct.(Hz)	Mic	Mic	Mic	Mic	- L
* 16						630					
20						800					
25						* 1000					
* 31.5						1250					
40						1600					
50						2000					
* 63						2500					
80						3150					
100						* 4000					
* 125						5000					
160						6300					
200						* 8000					
* 250						10000					
315						12500					
400						* 16000					
* 500											

*: Preferred frequencies for one octave center (Hz)
Note: SPLs corrected for ambient noises are used

APPENDIX C

Informed Consent

The purpose of this experiment is to investigate the sound attenuation (protection) of hearing protectors (earmuffs and earcaps). The experiment will be conducted over two sessions. In the first session, you will be given a hearing test and asked to fill out a short questionnaire. During the second session, you will be asked to don six different types of hearing protectors while following specific instructions. After putting on each protector, you will be given an audiometric test in order to collect attenuation data.

At no time during the experiment will you be exposed to harmful noise levels or be in any danger associated with the study. There may be possible slight discomfort associated with the "feel" of certain kind of protectors. At any time during the sessions, you may discontinue participation for any reason. However, you will be paid only for the portion of time you have completed. Of course, the experimenters involved would like for you to complete the study.

Some protectors may be difficult to fit or adjust. If so, simply do your best and follow any instructions you may be given. At any time during the experiment, feel free to ask the experimenter questions. If a particular question should bias the outcome of the experiment, the answer may be withheld until after the end of your data collection.

The data that are collected from your participation in this experiment will be treated anonymously; that is, your name will not be connected with your data in any way.

The duration of the combined sessions will be approximately three and one-half hours. You will be paid $3.50 per hour for your participation.

After you have completed the two sessions, please refrain from discussing the experiment with other individuals who might be future subjects, until after September 30, 1985. Persons with prior knowledge of the experiment before participation might bias the experimental results.

The research team is comprised of Mr. Siu-Tong Lam, M.S. candidate, IEOR Department, and Dr. John G. Casali, Director of the Auditory Systems Lab, IEOR Department. They can be contacted at the address and phone number below.

Auditory Systems Laboratory
Department of IEOR
Room 169 Whittemore Hall
Virginia Tech
Blacksburg, VA 24061

As a participant in this experiment, you have certain rights. The purpose of this sheet is to describe these rights to you and to obtain your written consent to participate.

1. You have the right to discontinue participating in the study at any time for any reason. If you decide to terminate the experiment, inform a member of the research team and he will pay you for the portion of time you have spent.

2. You have the right to inspect your data and to withdraw it from the experiment if you feel that you should. In general, data are processed and analyzed after all subjects have cmpleted the experiment. In this experiment, the investigators can supply you with some qualitative information immediately following the experiment. Subsequently, all the data are treated with anonymity. Therefore, if you wish to withdraw your data, you must do so immediately after your participation is completed.

3. You have the right to be informed as to the overall results of the experiment. If you wish to receive a synposis of the results, include your address (three months hence) with your signature below. If after receiving the synposis, you would then like further information, please contact the Auditory Systems Laboratory and a full report will be made available to you.

The faculty and graduate student member of the research team sincerely appreciate your participation. They hope that you will find the experiment a pleasant and interesting experience. If you have any questions about the experiment or your rights as a participant, please do not hesitate to ask. The investigators will try to answer them, subject only to the constraint that the results will not be pre-biased by a detailed answer.

Your signature on the next page indicates that you have read and understood your above stated rights as a participant, and that you agree to participate.

Auditory Systems Laboratory
Department of IEOR
Virginia Tech
Blacksburg, VA 24061

Name: _____

_____

Address: _____

_____

_____

Signature: _____

(Indicating that you have read your rights and wish to participate in the experiment.)

APPENDIX D

Bipolar Scales

While you are still wearing the hearing protection devices, please rate them on the following descriptive scales.

Make your judgements based on your feelings toward the devices While you are wearing them.

SOFT ____:____:____:____:____:____:____ HARD

ROUGH ____:____:____:____:____:____:____ SMOOTH

LOOSE ____:____:____:____:____:____:____ TIGHT

SHALLOW ____:____:____:____:____:____:____ DEEP

HEAVY ____:____:____:____:____:____:____ LIGHT

SMALL ____:____:____:____:____:____:____ LARGE

THICK ____:____:____:____:____:____:____ THIN

SIMPLE ____:____:____:____:____:____:____ COMPLEX

SYMMETRICAL ____:____:____:____:____:____:____ ASYMMETRICAL

DELICATE ____: ____: ____: ____: ____: ____: ____ RUGGED

STRONG ____: ____: ____: ____: ____: ____: ____ WEAK

COLD ____: ____: ____: ____: ____: ____: ____ HOT

EXPENSIVE ____: ____: ____: ____: ____: ____: ____ CHEAP

ANNOYING ____: ____: ____: ____: ____: ____: ____ PLEASING

VALUABLE ____: ____: ____: ____: ____: ____: ____ WORTHLESS

CUMBERSOME ____: ____: ____: ____: ____: ____: ____ CONVENIENT

GOOD ____: ____: ____: ____: ____: ____: ____ BAD

RESTRICTIVE ____: ____: ____: ____: ____: ____: ____ NON-RESTRICTIVE

While you are still wearing the hearing protection devices, please rate them on the following descriptive scales.

Make your judgements based on how <u>you feel</u> with the devices on.

PAINFUL ____:____:____:____:____:____:____ PAINLESS

OPEN ____:____:____:____:____:____:____ BLOCKED

UNCOMFORTABLE ____:____:____:____:____:____:____ COMFORTABLE

FULL ____:____:____:____:____:____:____ EMPTY

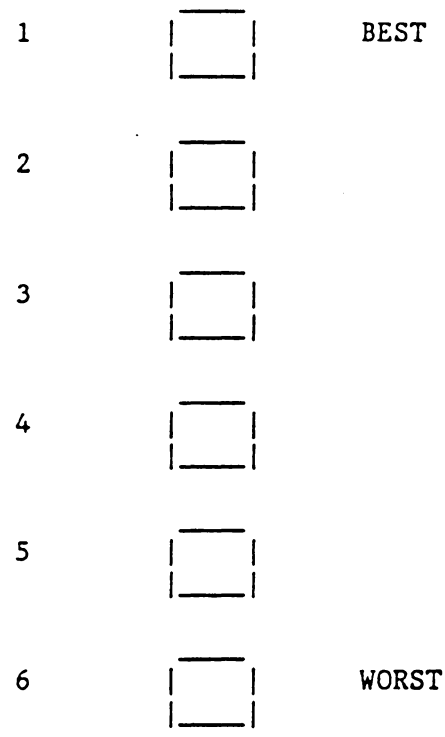
UNCOMFORTABLE PRESSURE ____:____:____:____:____:____:____ NO UNCOMFORTABLE PRESSURE

APPENDIX E

Ranking Scales

Please rank the six hearing protection devices based on how easy they were to put on. The BEST device is the one which you feel was the easiest to put on and adjust. The WORST device is the one which you feel was the most difficult to put on and adjust.

Place the corresponding identification letters of each device in the appropriate box.



Please rank the six hearing protection devices based on the amount of discomfort associated with the wearing of each type. The BEST device is the one which you feel caused the LEAST discomfort. The WORST device is the one you feel caused the MOST discomfort.

Place the corresponding identification letters of each device in the appropriate box.

1 ____ BEST

2 ____

3 ____

4 ____

5 ____

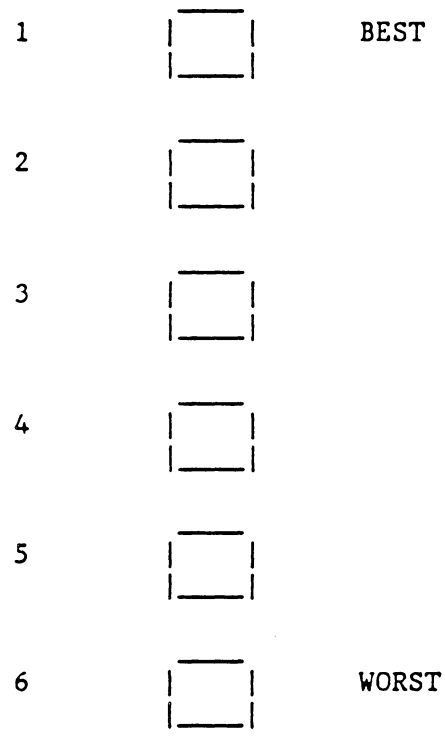
6 ____ WORST

Please rank the six hearing protection devices based on your preference as for wearing the devices.

The BEST device is the one which you most prefer to wear.

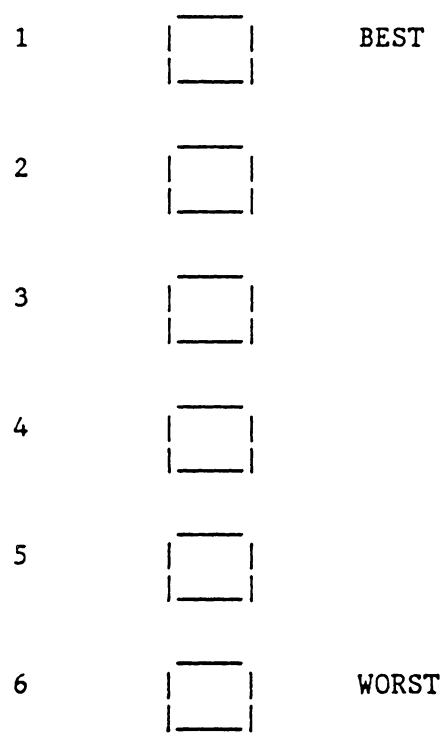
The WORST device is the one which you least prefer to wear.

Place the corresponding identification letters of each device in the appropriate box.



Please rank the six hearing protection devices as if you were asked to wear each type for an eight-hour day. The BEST device is the one which you would choose first (most prefer) to wear for an eight-hour day. The WORST device is the one you would choose last (least prefer).

Place the corresponding identification letters of each device in the appropriate box.



APPENDIX F

Pre-experimental Questionnaire

(1) Have you ever used hearing protectors either at work or at home for protection from loud noise?

_____ Yes _____ No

(2) Have you ever participated in an experiment which included hearing threshold testing? This does not include audiometric testing by medical personnel.

_____ Yes _____ No

(3) Do you have any of the following problems?

_____ Tinnitus (Ringing in the ears)

_____ Allergies/infections which affect your hearing

_____ Excessive ear wax

_____ Common cold/influenza/and like syndromes

_____ Other (Please specify)

_____

(4) Have you ever had excessive ear wax removed by a physician?

_____ Yes _____ No

If yes, how recent was the last treatment? _____

APPENDIX G

Reminder For Averting Temporary Threshold Shift (Given to Subjects)

A VERY IMPORTANT REMINDER:

When you return for the experimentation session, it is most important that you do not have any temporary loss of your normal hearing abilities. Temporary hearing loss is very common due to exposure to loud noise (e.g., loud music) and to certain health-related conditions such as common cold and influenza. Any reduction in normal hearing will cause our experimental results to be compromised. Therefore your normal hearing will need to be reaffirmed before the experiment can begin. If a temporary hearing loss has occurred since your last test, it will be necessary to reschedule you or perhaps not include you in the experiment. This will cause unnecessary inconvenience to yourself and to the experimenter alike. Therefore, please try your best to avoid temporary hearing loss by staying away from loud noise for at least 48 hours before the experiment. We very much appreciate your understanding and cooperation in this regard.

APPENDIX H

General Application Instructions

(NO INSTRUCTION)

During this session you will be given four earmuffs and two earcaps. When one hearing protector is given to you, please don (place) it to the best of your ability over your ears. Notify the experimenter when you are ready to begin the test.

Please maintain your posture and remain absolutely still during the experiment. Any head or body movement will greatly affect the outcome of the experiment. If you wear eye-glasses (contact-lenses excepted), please remove them during the tests.

(NO INSTRUCTION WITH AUDITORY FEEDBACK)

During this session you will be given four earmuffs and two earcaps. The experimenter will play a background noise through a loudspeaker in front of you to aid you in adjusting the protector for a good seal. While listening to the background noise, don (place) the protector on your ears. Adjust or re-fit the protector until the background noise seems lowest in volume. Take as much time as you need. Notify the experimenter when you feel that you have obtained the most reduction in noise possible and are ready to begin the test.

Please maintain your posture and remain absolutely still during the experiment. Any head or body movement will greatly affect the outcome of the experiment. If you wear eye-glasses (contact-lenses excepted), please remove them during the tests.

(MANUFACTURER'S PACKAGE INSTRUCTION)

During this session you will be given four earmuffs and two earcaps with the individual manufacturer's instruction for donning (placing) each on your ears. Carefully read the directions for fitting the protector completely one time. Don the protector to the best of your ability, while re-reading the manufacturer's instructions. Take as much time as you need. Notify the experimenter when you are ready to begin the test.

Please maintain your posture and remain absolutely still during the experiment. Any head or body movement will greatly affect the outcome of the experiment. If you wear eye-glasses (contact-lenses excepted), please remove them during the tests.

(DETAILED INSTRUCTION)

During this session you will be given four earmuffs and two earcaps along with instructions for donning (placing) each on your ears. One protector and accompanying instructions will be given to you at one time. Carefully read through the instructions completely once. Don the protector over your ears to the best of your ability, while re-reading the written step-by-step procedures and pictures. Take as much time as you need. Notify the experimenter when you are ready to begin the test.

Please maintain your posture and remain absolutely still during the experiment. Any head or body movement will greatly affect the outcome of the experiment. If you wear eye-glasses (contact-lenses excepted), please remove them during the tests.

(MODELED INSTRUCTION)

During this session you will be given four earmuffs and two earcaps. The experimenter will be showing you a step-by-step procedure for fitting each type of protector. When the fitting procedure is performed, you should carefully observe the technique while listening to any verbal instructions. Then don (place) the hearing protector on your ears to the best of your ability, following the step-by-step procedure closely. (The experimenter will be giving you verbal instructions as you don the protector.) You may ask the experimenter questions concerning the application technique. Take as much time as you need. Notify the experimenter when you are ready to begin the test.

Please maintain your posture and remain absolutely still during the experiment. Any head or body movement will greatly affect the outcome of the experiment. If you wear eye-glasses (contact-lenses excepted), please remove them during the tests.

APPENDIX I

Manufacturers' Package Instructions

E·A·R™ MUFF

IMPROPER FIT OF THIS DEVICE WILL REDUCE ITS EFFECTIVENESS IN ATTENUATING NOISE. CONSULT THE INSTRUCTIONS FOR PROPER FIT.

1. With the headband over-the-head, pull the earcups down to fully enclose the ears. The two halves of the headband may be slid apart or together to adjust for a snug, comfortable fit, that provides maximum quiet. (FIGURE 1) This will result when the cushions exert equal pressure around the ears.

FIGURE 1

2. The band may be rotated for use behind-the-head or under-the-chin. In these positions the band should normally be slid together for best fit. (FIGURE 2) For better support and long term wearing comfort, an optional crown strap is available.

FIGURE 2

3. Best performance will be obtained when the cushions seal tightly against the head. Pull hair back and out from underneath the cushions as much as practical. Eyeglass temples should fit close to the head and be as thin as possible (items such as pencils should not be stored under the cushions). Caution: Bending or reshaping the headband will cause a loose fit and allow noise to leak in under the earmuff.

FIGURE 3

Manufacturer's HPD - application instructions for EAR Muff Model 1000

Flents®

DIRECTIONS FOR USING Peace & Quiet® Headband

1. Your Peace & Quiet Headband is designed to be worn under the chin only — will not interfere with eyeglasses and other headgear.
2. Hold the band below each ear cushion.
3. Simply swivel end caps slightly forward to match the angle of your ear canal.
4. Gently push the soft cushion into place until your voice sounds hollow.
5. Your Peace & Quiet Headband is in place, ready to provide hours of comfortable, effective personal hearing protection.
6. All material is non-toxic and easy to clean with soap and water.
7. Replacement ear cushions (#056 white) and end caps (#057 black) are available.

Improper fit of this device will reduce its effectiveness in attenuating noise. Consult instructions for proper fit.

Manufacturer's HPD - application instructions for Flents earcap model #055

Norton Industrial Earmuff MODEL 4540

INSTRUCTIONS FOR USE:

1. Extend head-band to maximum "open" position.
2. Place one cup over each ear making sure area marked "Top" is up.
3. Swivel head-band to desired position.
4. Compress head-band to position when earcups feel most comfortable and snug.
5. When hearing protection is no longer needed, simply spread earcups apart and remove from ears.
6. Store in original plastic bag or other suitable clean dry location.

CAUTION:

1. Do not BEND, or change any part of the head-band, cups, cup liners or ear seals.
2. Inspect before each use for worn, cracked, broken, or missing parts . . . especially the ear seals.
3. Replace worn or damaged parts if available. If not available, replace entire earmuff. (Use *only* Norton replacement parts.)
4. Some spectacle temples or hair underneath the earcup seals may reduce the effectiveness of any earmuff. It is recommended that spectacles with temples causing the least interference with muffs be used.
5. Clean regularly with mild soap and warm water only.
6. Use only Norton replacement parts to insure the Noise Reduction Rating (NRR).

"Improper fit of this device will reduce its effectiveness in attenuating noise. Consult the enclosed instructions for proper fit."

Manufacturer's HPD - application instructions for Norton muff model 4540

Hearing Protectors

• INSTRUCTIONS FOR USE •

INSTRUCTIONS FOR USE:

(a) Put the soft headband over the head and lower earcups by pulling down properly. Cover ears for maximum attenuation.

(b) When using our backband unit, put the backband of the hearing protector behind the head and properly cover ears for maximum attenuation.

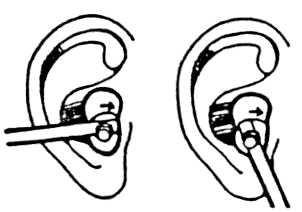
Improper fit of this device will reduce its effectiveness in attenuating noise. Consult instructions for proper fit.

Manufacturer's HPD - application instructions for Peltor muff model H6A/v

WILLSON™
SAFETY PRODUCTS

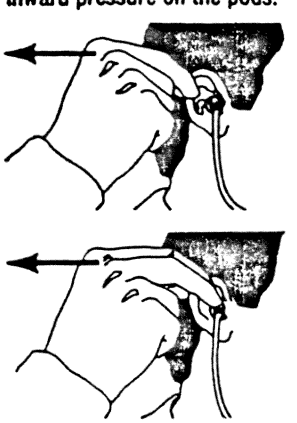
FIT AND CARE INSTRUCTIONS

1. Turn headband to desired position, then adjust pods so arrow is on top pointing forward when positioned in ear.



2. Place pods in ear, grasp pods (not cap nut) and work them forward and into ear until ear canal is completely covered.

3. Then, grasp ears and pull out and back while applying *slight* inward pressure on the pods.



4. To clean ear pods, wash with soap and warm water or disinfectant, and rinse thoroughly.

"Improper fit of this device will reduce its effectiveness in attenuating noise. Consult the enclosed instructions for proper fit."

Manufacturer's HPD - application instructions for Willson earcap model #20

INSTRUCTION SHEET
WILLSON™ SOUND BARRIER® EAR MUFFS MODELS #365 AND #365A
LES SERRE-TÊTE ANTIBRUIT "SOUND BARRIER" DE WILLSON #365 ET #365A
SORDINAS ®SOUND BARRIER ®WILLSON MODELOS #365 y #365A

FITTING INSTRUCTIONS

For **MAXIMUM HEARING PROTECTION**, it is essential that the Willson Sound Barrier protector be properly positioned and adjusted to obtain the correct fit.

Headband adjustment and ear cup positioning can be accomplished by the following steps:

1. Place headband in desired position (over the head, under the chin, or behind the head) and determine if the ear cups are properly positioned. Your ears must be inside the ear cups with the cushions resting against your head. If the muffs feel comfortable and secure, no adjustment is necessary.

2. If the muffs do not feel comfortable and secure (ear cups not positioned properly), merely slide the cups up or down as required.

3. Please note that if the #365 or #365A is worn behind the head or under the chin, additional support may be obtained by using the optional nylon strap (Part No. EM196). This strap may be easily attached to the slotted strap supports on each #365 or #365A ear cup and, when placed over your head, will prevent ear cup slippage when the Sound Barrier protector is worn during very active work operations.

When using crown strap, make certain strap is positioned over the ear cushions as shown.

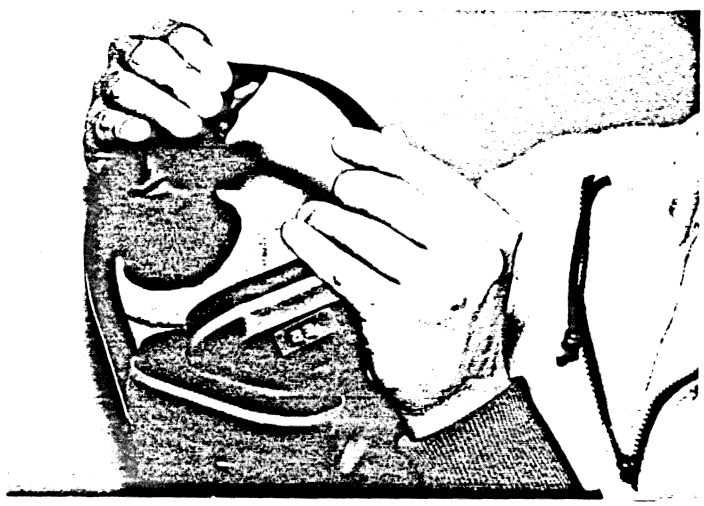
"Improper fit of this device will reduce its effectiveness in attenuating noise. Consult the enclosed instructions for proper fit."

Manufacturer's HPD - application instructions for Willson muff model 365A

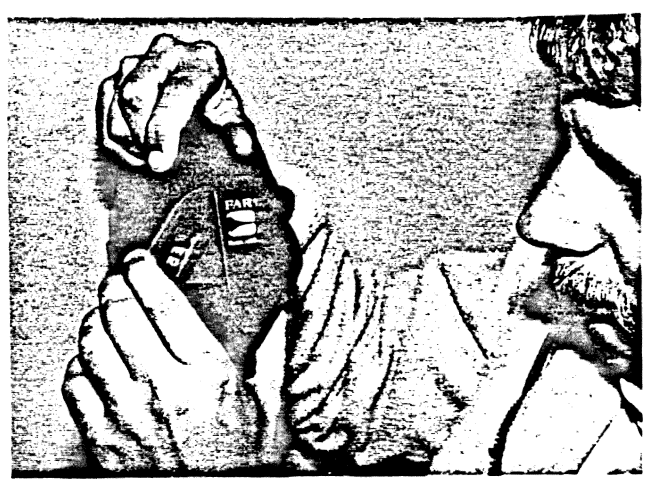
APPENDIX J

Detailed Instructions

E-A-R MUFF 1000



STEP 1. Grasp the black plastic headband on each side next to the red earcups and slide the two halves of the headband apart and then back together again. Notice how the headband is adjustable by this sliding action. Now make sure that the two halves of the headband are slid together fully.



STEP 2. Rotate each earcup so that it is in-line (longways) with the headband.

STEP 3. Arrange your hair so that it is away from your ears as much as possible. By holding one earcup in each hand, pull the earcups slightly apart and place the earcups over the ears with the headband located over the top of your head. Perform this by pulling the two earcups down (simultaneously) to fully enclose the ears while the headband is pressing against the top of your head.

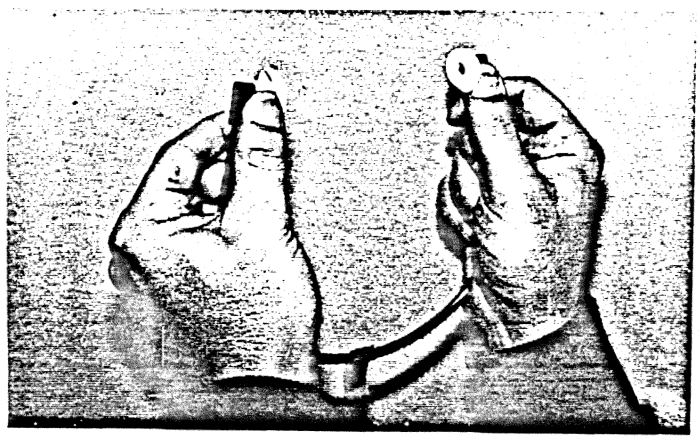
STEP 4. To the extent possible, pull your hair out from underneath the earmuff cushions so that it will not interfere with the "seal" between the cushions and your head.

STEP 5. Now that you have the earmuff on, you should adjust it for maximum comfort and a snug fit. First, rotate the headband to the desired position over the head. Then compress or expand the headband until the earmuff cushions are against (touching) your head completely around your ears. Perform this by sliding the two halves of the headband together or apart. The cushions should be slightly compressed against your head, exerting equal pressure around the ears. By sliding the headband and swiveling the earcups, adjust the earcups to the position that they feel most comfortable and snug. Now you should again pull your hair back and out from underneath the earcup cushion as much as possible.

STEP 6. Put your hands in your lap and take a moment to see how the muff feels. If you do not feel that you have achieved a good noise-blocking seal, or the muff is uncomfortable, re-apply the muff by returning to STEP 1. However, realize that the muff should feel snug on your head (but not painfully tight) to obtain a good noise-blocking seal.

FLENTS HEADBAND 055

STEP 1. Arrange your hair so that it is behind and away from your ears as much as possible. Be sure that there is no hair over the openings of your ears.



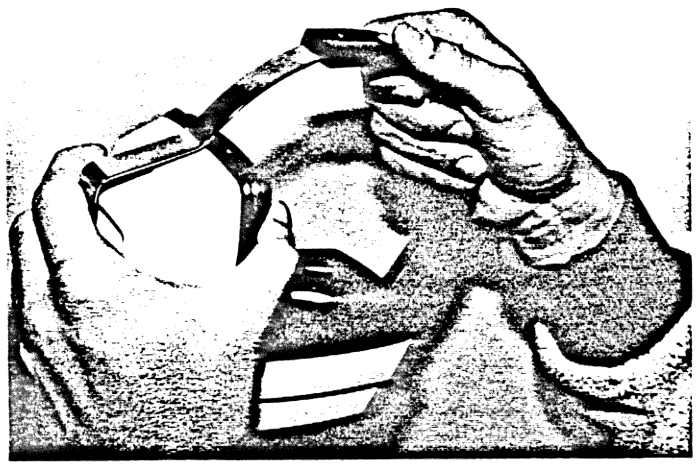
STEP 2. Make sure that the black endcaps on the orange headband are pointed so that the white ear cushions face each other. If not, swivel the black endcaps until the cushions face

STEP 3. With the ear cushions at the top and the headband below, grasp the band on each side just below the black endcaps using the thumb and forefinger. Spread the band by pulling it apart slightly. With the headband located under your chin, place one cushion over the opening of each ear.

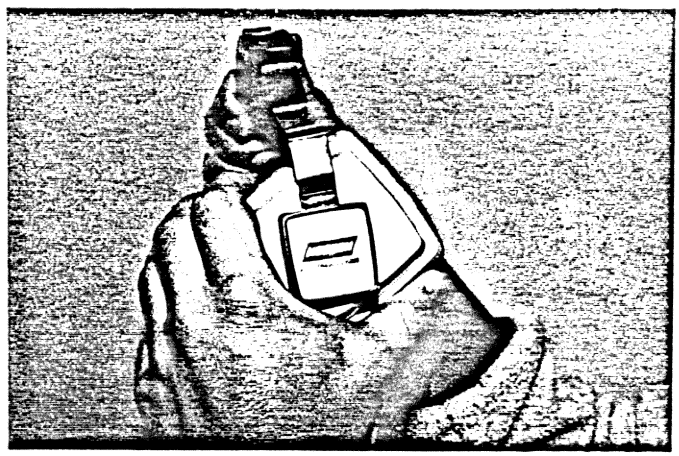
STEP 4. Now that you have the protector on, you should adjust it for maximum comfort and a snug fit. First, swivel the black endcaps forward or backward so that the ear cushions are adjusted to the angle of your ear canal. Next, gently push on the two black endcaps until the ear cushions seal in place. You may need to adjust the ear cushions (by swiveling and/or pushing them gently) several times until you have achieved a good noise-blocking seal in each ear.

STEP 5. Put you hands in your lap and take a moment to see how the protector feels. If you do not feel that you have achieved a good noise-blocking seal, or the protector is uncomfortable, re-apply the protector by returning to STEP 1. However, realize that the ear cushions should feel snug in your ears (but not painfully tight) to obtain a good noise-blocking seal.

NORTON MUFF 4540



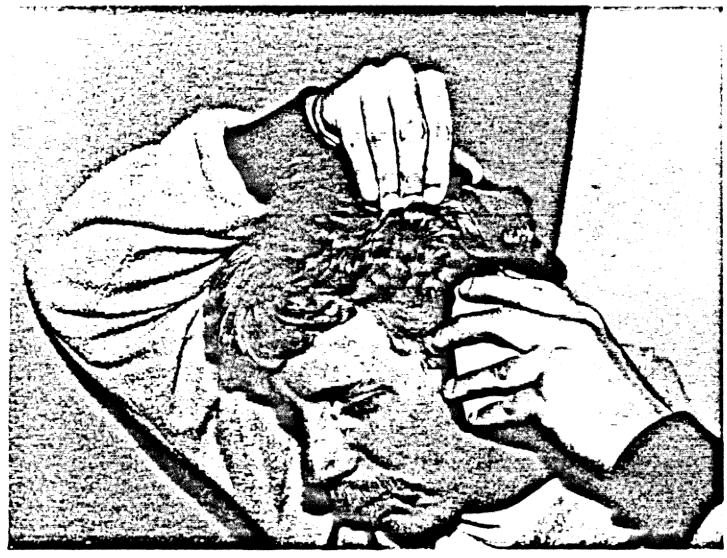
STEP 1. Grasp either white earcup in one hand and the black plastic headband sheath with the other hand. Pull the earcup away from the headband as far as it will go to extend the headband fully. Repeat this procedure for the remaining earcup. Make sure the headband is fully extended on each side.



STEP 2. Swivel each earcup through its click positions until the word "Top" on the earcup is facing up (toward the headband).

STEP 3. Arrange your hair so that it is away from your ears as much as possible. By holding one earcup in each hand, pull the earcups slightly apart and place one earcup over each ear with the headband located over the top of your head.

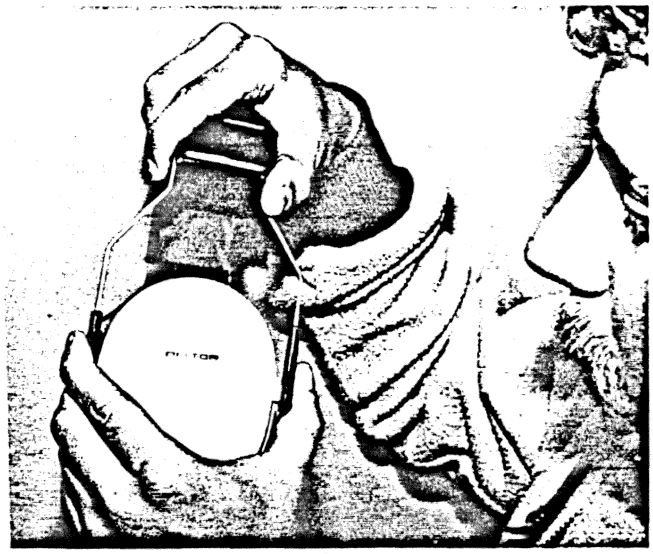
STEP 4. To the extent possible, pull your hair out from underneath the earmuff cushions so that it will not interfere with the "seal" between the cushions and your head.



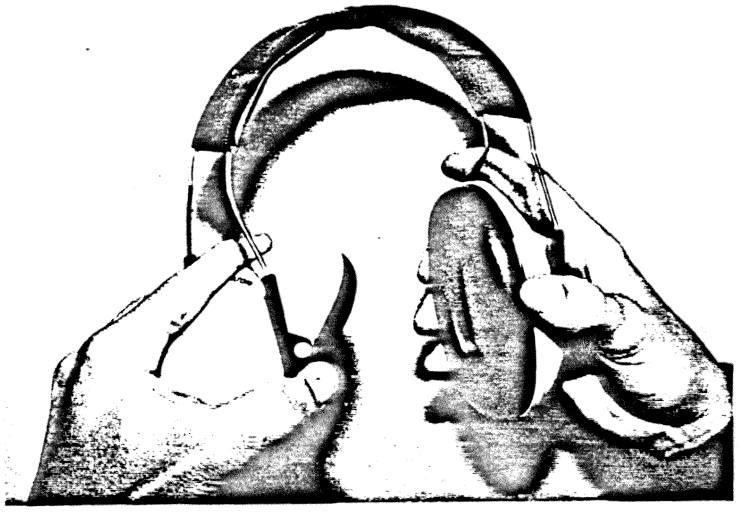
STEP 5. Now that you have the earmuff on, you should adjust it for maximum comfort and for a snug fit. First, rotate the headband to the desired position over the head. Then compress the headband until the earmuff cushions are against (touching) your head completely around your ears. Perform this by pushing the metal part of the headband up into the plastic headband sheath on both sides. The cushions should be slightly compressed against your head, exerting equal pressure around the ears. Next, note that the earcups can swivel both around and across your ears. While holding the headband in place with one hand, use your other hand to adjust the earcups to the position that they feel most comfortable and snug. Now you should again pull your hair back and out from underneath the earcup cushions as much as possible.

STEP 6. Put your hands in your lap and take a moment to see how the muff feels. If you do not feel that you have achieved a good noise-blocking seal, or the muff is uncomfortable, re-apply the muff by returning to STEP 1. However, realize that the muff should feel snug on your head (but not painfully tight) to obtain a good noise-blocking seal.

PELTOR MUFF H6A/V

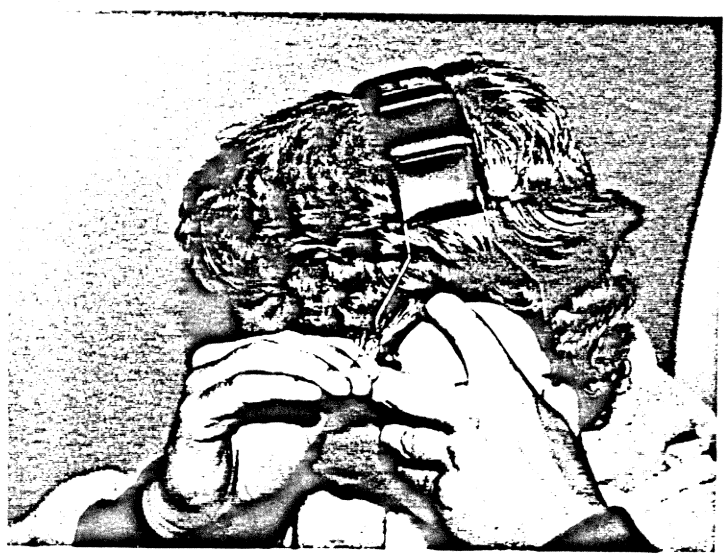


STEP 1. Grasp either earcup by its swivel joints in one hand and the adjacent side of the black padded headband in the other hand. Push the earcup toward the headband so that the black plastic earcup "sleeves" are up as far as they will go on the wire headband. Repeat this procedure for the remaining earcup.

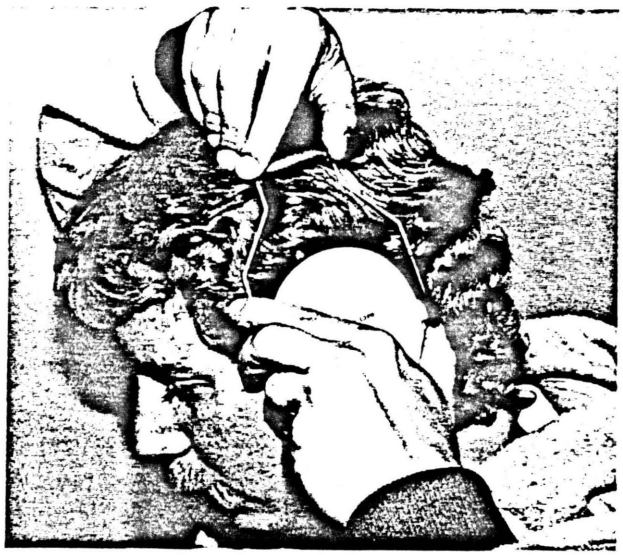


STEP 2. Rotate the earcups on their swivel joints so that the black earcup cushions are facing each other.

STEP 3. Arrange your hair so that it is away from your ears as much as possible. By holding one earcup in each hand, pull the earcups slightly apart and place one earcup over each ear with the headband located over the top of your head. Lower each earcup so that it fully covers the ear by pulling the earcup down on the wire headband.



STEP 4. To the extent possible, pull your hair out from underneath the ear-muff cushions so that it will not interfere with the "seal" between the cushions and your head.

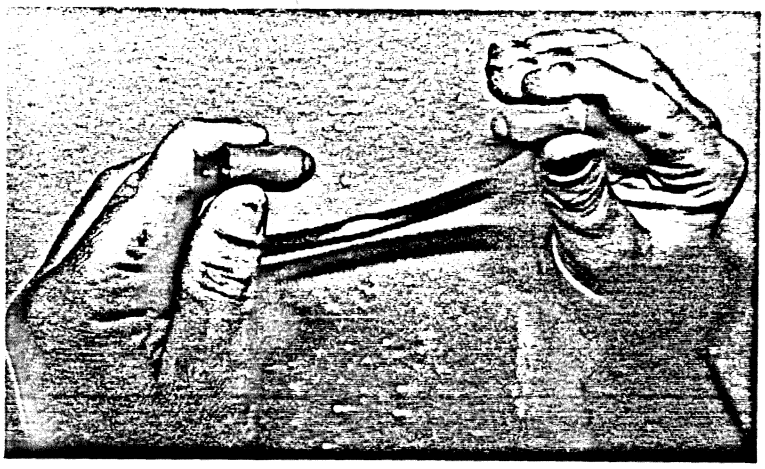


STEP 5. Now that you have the earmuff on, you should adjust it for maximum comfort and a snug fit. First, be sure that the earmuff cushions are against (touching) your head completely around your ears. If not, slide the earcups up or down on the wire headband until they are at the proper height. The cushions should be slightly compressed against your head, exerting equal pressure around the ears. Now you should again pull your hair back and out from underneath the earcup cushions as much as possible.

STEP 6. Put your hands in your lap and take a moment to see how the muff feels. If you do not feel that you have achieved a good noise-blocking seal, or the muff is uncomfortable, re-apply the muff by returning to STEP 1. However, realize that the muff should feel snug on your head (but not painfully tight) to obtain a good noise-blocking seal.

WILLSON SOUND-BAN 20

STEP 1. Arrange your hair so that it is behind and away from your ears as much as possible. Be sure that there is no hair over the openings of your ears.



STEP 2. Grasp the headband such that the blue ear pod labeled "R" is in the right hand and the pod labeled "L" is in the left hand. With the headband at the bottom and the pods above, grasp the right pod between thumb and forefinger and turn it such that the arrow on the pod is on top, pointing forward. Repeat for the left pod.

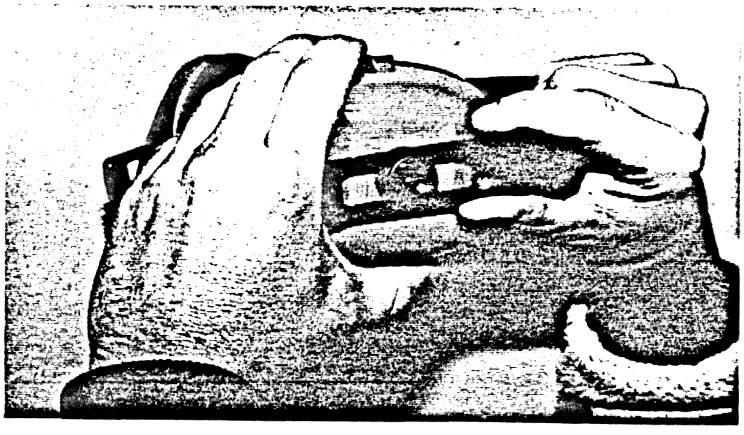
STEP 3. With the pods at the top and the headband below, grasp the band on each side just below the pods using the thumb and forefinger. Spread the band by pulling it apart slightly. With the headband located under your chin, place the pod labeled R in the right ear and the pod labeled L in the left ear.

STEP 4. Now that you have the headband on, you should adjust it for maximum comfort and a snug fit. First, grasp each pod between thumb and forefinger and adjust it forward and into the ear until the ear opening is completely covered.

Next, grasp the top of one ear, gently pull the ear out (away from the head) and back while applying slight inward pressure on the pod until it seals in place. Repeat for the remaining ear pod. You may need to adjust the ear pods several times using this procedure until you have achieved a good noise-blocking seal in each ear.

STEP 5. Put your hands in your lap and take a moment to see how the headband feels. If you do not feel that you have achieved a good noise-blocking seal, or the headband is uncomfortable, re-apply the headband by returning to STEP 1. However, realize that the ear pods should feel snug in your ears (but not painfully tight) to obtain a good noise-blocking seal.

WILLSON MUFF 365A

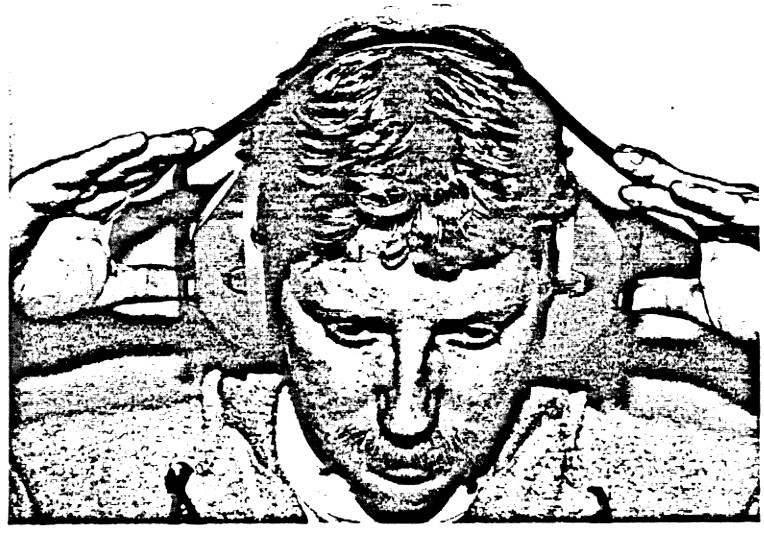


STEP 1. Grasp either blue earcup in one hand and the black plastic headband in the other hand. Slide the stud attaching the cup to the headband until the stud is centered in the slot in the headband. Repeat this procedure for the remaining earcup.

STEP 2. Rotate each earcup so that it is in-line (longways) with the headband.

STEP 3. Arrange your hair so that it is away from your ears as much as possible. By holding one earcup in each hand, pull the earcup slightly apart and place one earcup over each ear with the headband located over the top of your head.

STEP 4. To the extent possible, pull your hair out from underneath the ear-muff cushions so that it will not interfere with the "seal" between the cushions and your head.



STEP 5. Now that you have the earmuff on, you should adjust it for maximum comfort and for a snug fit. First, rotate the headband to the desired position over the head. Then, make sure that the earmuff cushions are against (touching) your head completely around your ears. If not, adjust the earcup positions by sliding the studs up (or down) the headband. The cushions should be slightly compressed against your head, exerting equal pressure around the ears. Now you should again pull your hair back and out from underneath the earcup cushions as much as possible.

STEP 6. Put your hands in your lap and take a moment to see how the muff feels. If you do not feel that you have achieved a good noise-blocking seal, or the muff is uncomfortable, re-apply the muff by returning to STEP 1. However, realize that the muff should feel snug on your head (but not painfully tight) to obtain a good noise-blocking seal.

APPENDIX K

Bipolar Scale Instructions

After each hearing protection device (HPD) is tested, you will be asked to judge them on a series of descriptive scales. Your judgements should be based on how a certain type of HPD feels to YOU.

Here is an example of how to use the scales:

If you feel that wearing a certain type of device is VERY CLOSELY RELATED to one end of the scale, you should place your check-mark as follows:

GOOD __X_:____:____:____:____:____:____ BAD

or

GOOD ____:____:____:____:____:____:__X_ BAD

If you feel that wearing a certain type of device is QUITE CLOSELY RELATED to one end of the scale, you should place your check-mark as follows:

GOOD ____:__X_:____:____:____:____:____ BAD

or

GOOD ____:____:____:____:____:__X_:____ BAD

If you feel that wearing a certain type of device is ONLY SLIGHTLY RELATED to one end of the scale, you should place your check-mark as follows:

GOOD ____:____:__X_:____:____:____:____ BAD

or

GOOD ____:____:____:____:__X_:____:____ BAD

The DIRECTION toward which you check, of course depends upon which of the two ends of the scale seem to be more characteristic of how the device feels while you are wearing it.

If your feeling of wearing a certain type of hearing protection device is NEUTRAL between the ends of the scale, or the scale is COMPLETELY IRRELEVANT, you should place your check-mark as follows:

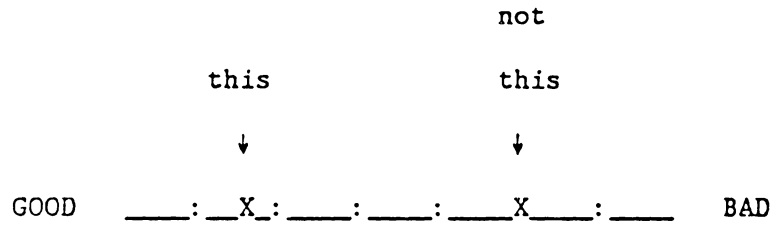
GOOD ____:____:____:__X_:____:____:____ BAD

****

IMPORTANT

********** **********

(1) Place your check-marks in the MIDDLE of the spaces, not on the boundaries:



(2) Be sure you check each scale and do NOT omit any scales.

(3) Never put more than one check-mark on a single scale.

(4) Do not look back and forth through the items. Make each item a SEPARATE and INDEPENDENT judgement.

(5) Indicate your ACTUAL, IMMEDIATE, and FIRST impressions.

APPENDIX L

An Alternative Method for Analyzing HPD Attenuations

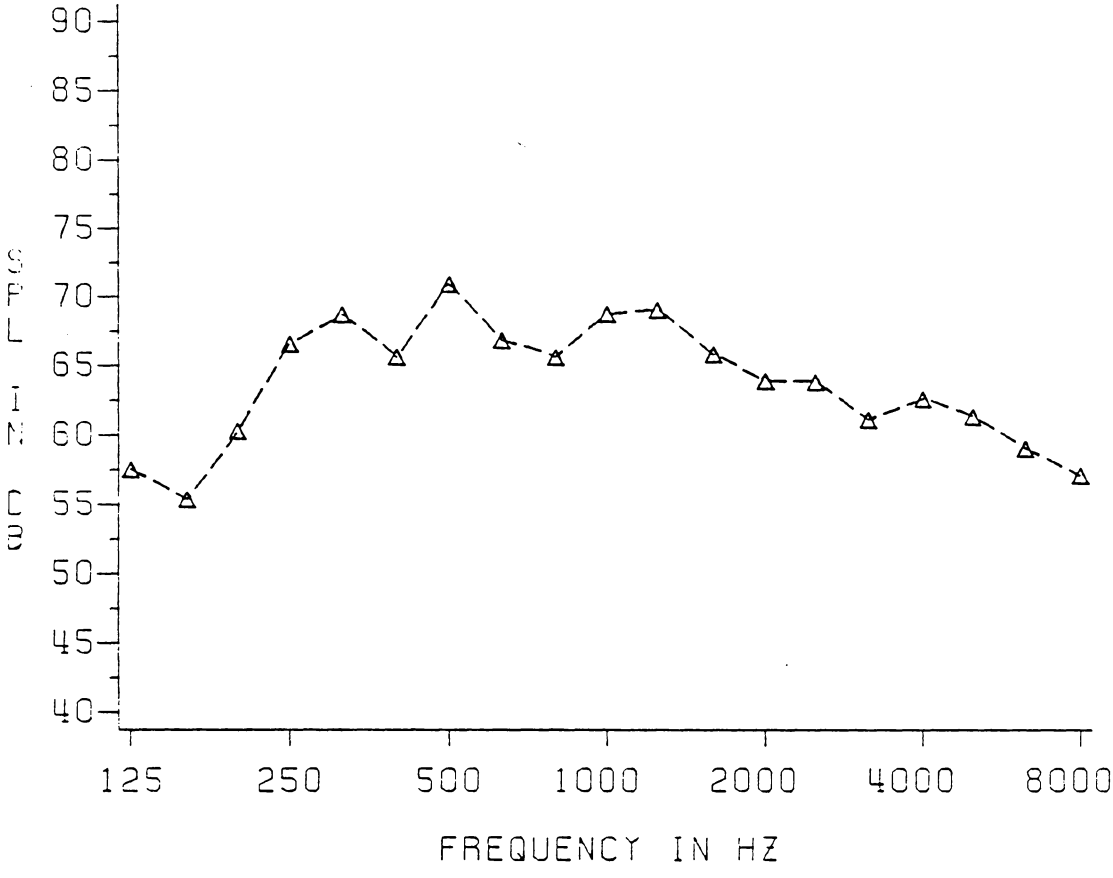
ANOVA Summary Table for an Alternative Analysis of Earmuff/Earcap Attenuation (Using Type III SS)

Source	df	SS	F	p
Instruction (I)	4	5382.85	51.40	0.0001
HPD type (H)	5	43040.02	328.77	0.0001
Frequency (F)	6	127969.43	814.61	0.0001
Gender (G)	1	20.88	0.80	0.3720
Subjects S/IxG	40	9422.95	9.00	0.0001
HPD Order	5	318.10	2.43	0.0329
Frequency Order	6	94.18	0.60	0.7309
H x I	20	787.44	1.50	0.0702
F x I	24	1630.03	2.59	0.0001
G x I	4	400.94	3.83	0.0042
G x H	5	115.63	0.88	0.4928
G x F	6	809.82	5.16	0.0001
G x F x H	60	40404.57	25.72	0.0001
residual	1913	50086.66		
Total	2099	285919.01		

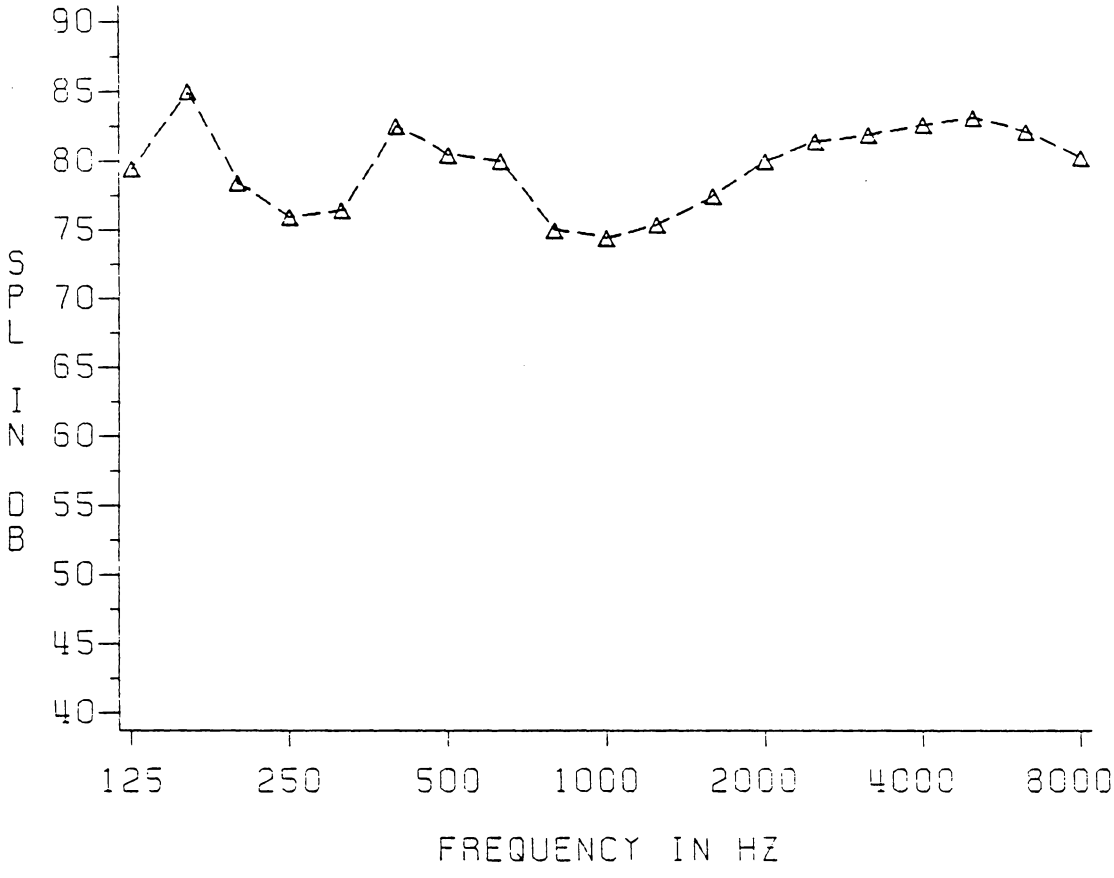
APPENDIX M

Graphs and Transparencies for Noise Spectra Matching

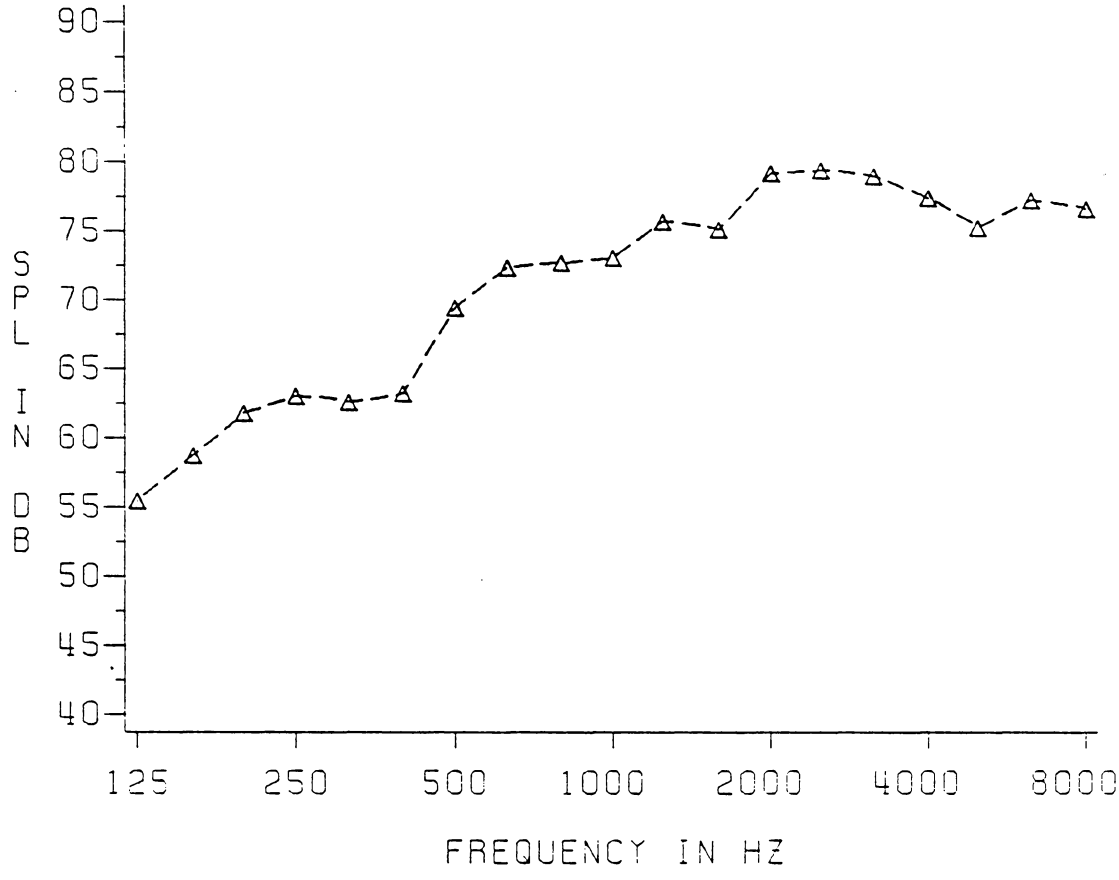
Transparencies of HPD spectral attenuations enclosed in the pouch at the back of this report are intended to overlain on top of each of the machine noise spectra provided on the following pages. This procedure can be used to identify the optimal HPD for (which best matches) a given noise spectrum. A discussion of this procedure appears in the text on pages 161-162.



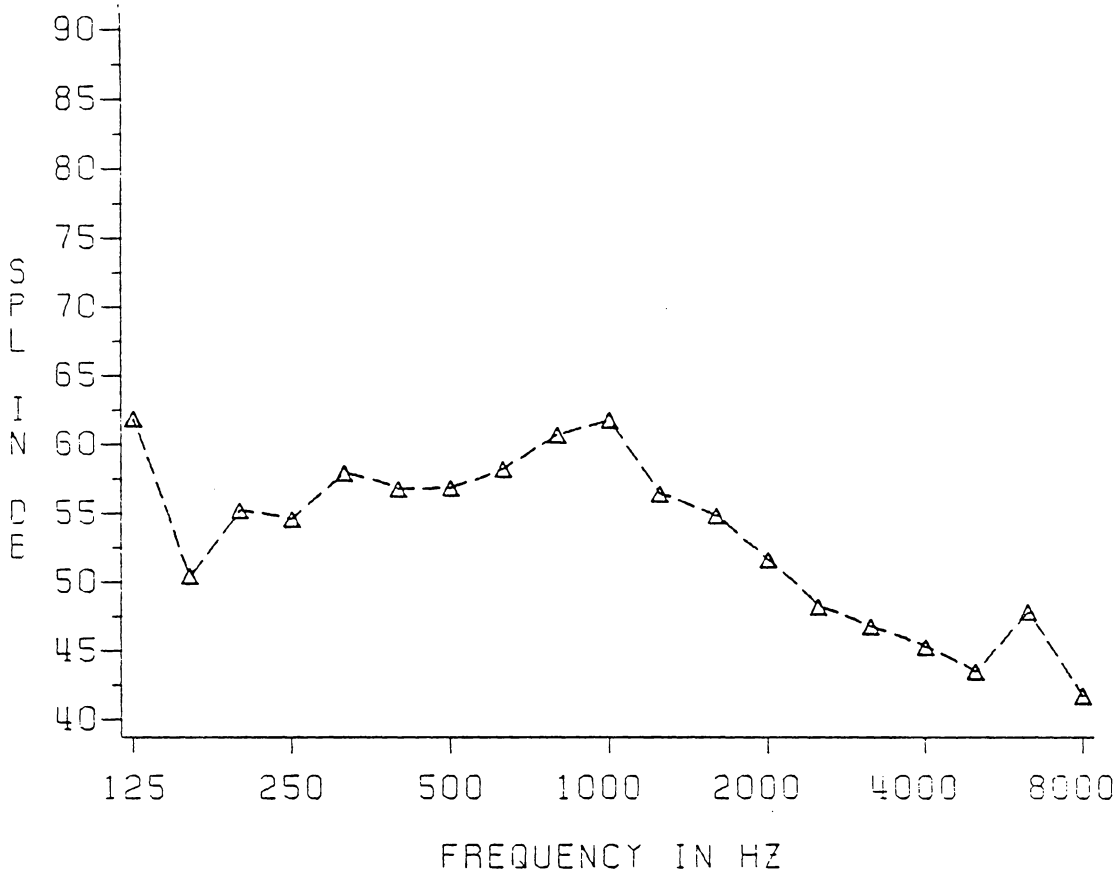
1/3 OB Noise spectrum for band saw, average four microphone positions, linear SPL (to be used for HPD matching)



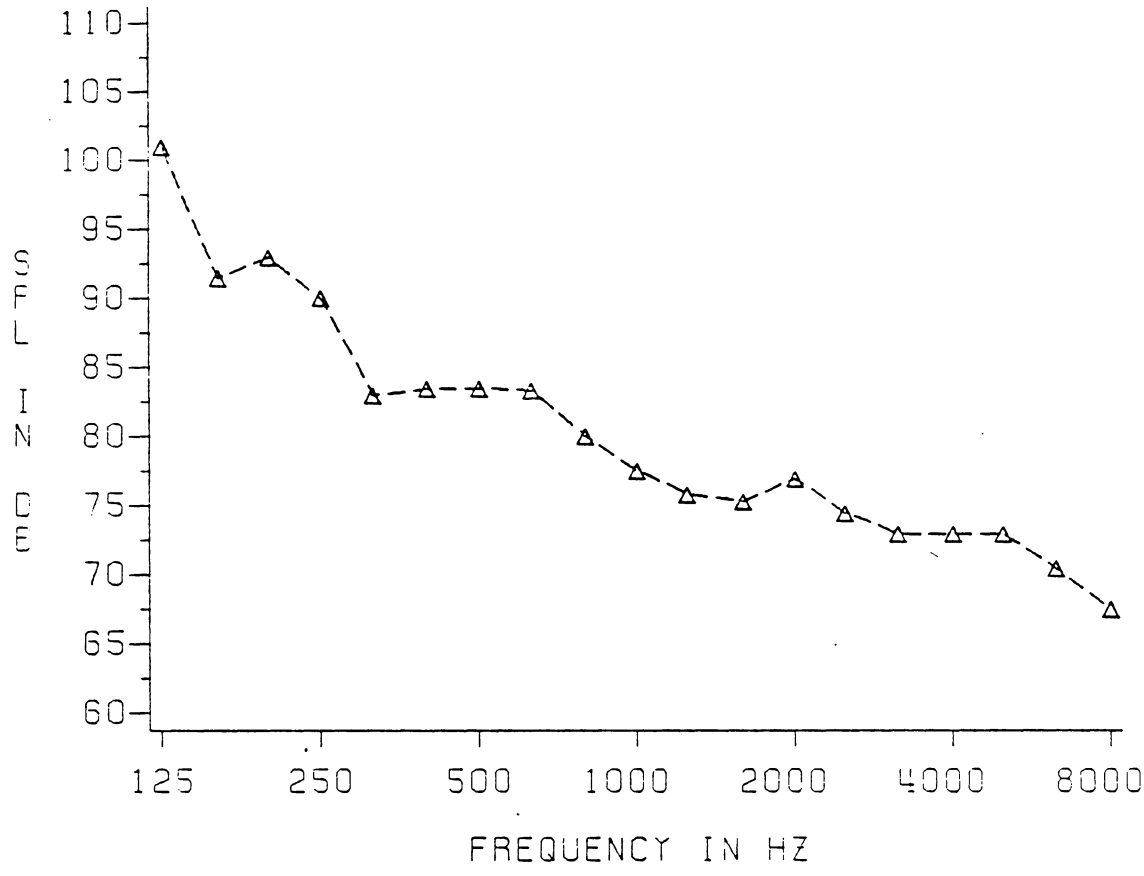
1/3 OB Noise spectrum for sand blaster and dust collector, single microphone position, linear SPL (to be used for HPD matching)



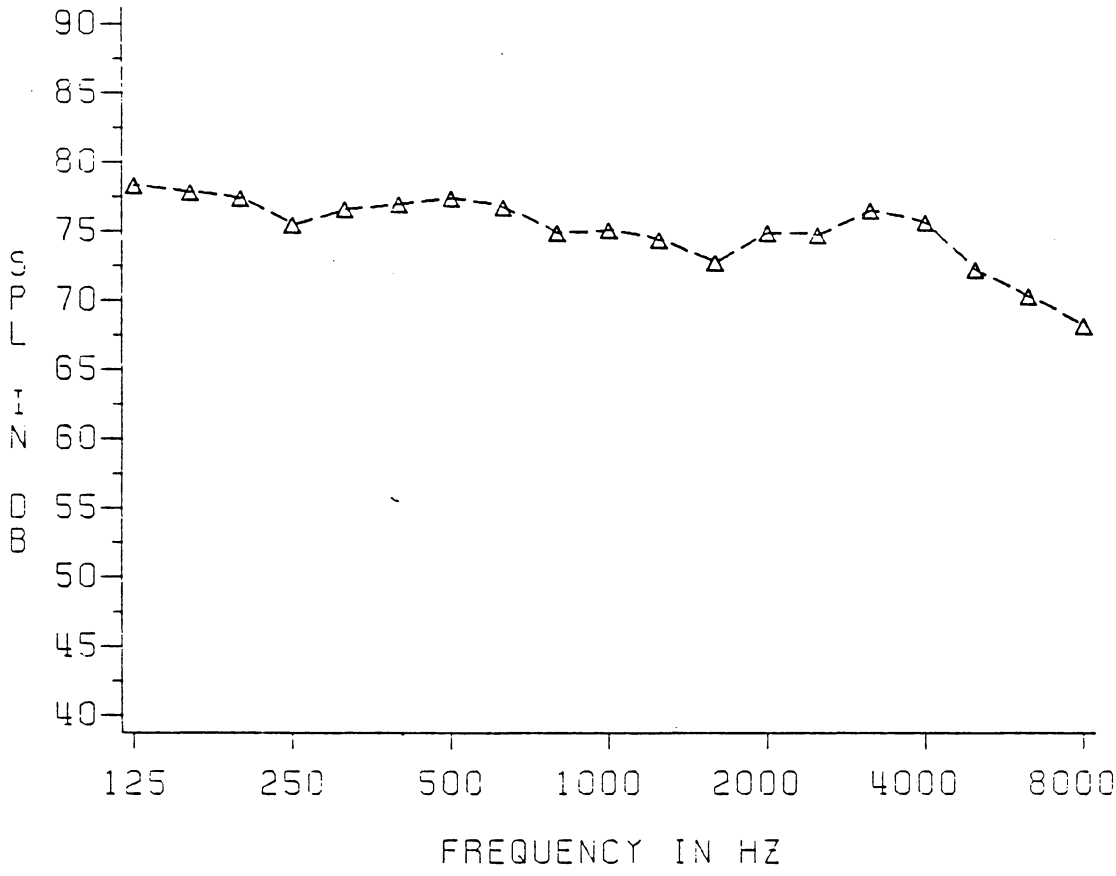
1/3 OB Noise spectrum for contour saw, average three microphone positions, linear SPL (to be used for HPD matching)



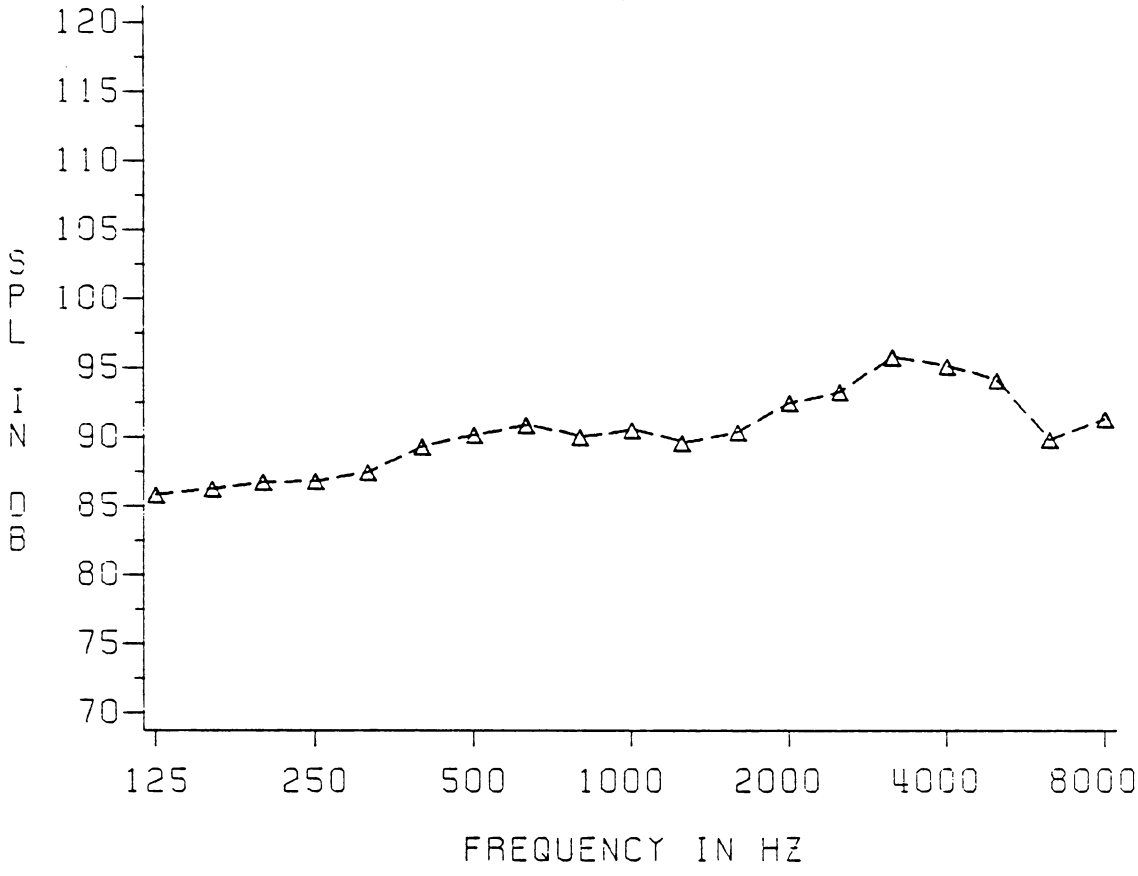
1/3 OB Noise spectrum for engine lathe, average four microphone positions, linear SPL (to be used for HPD matching)



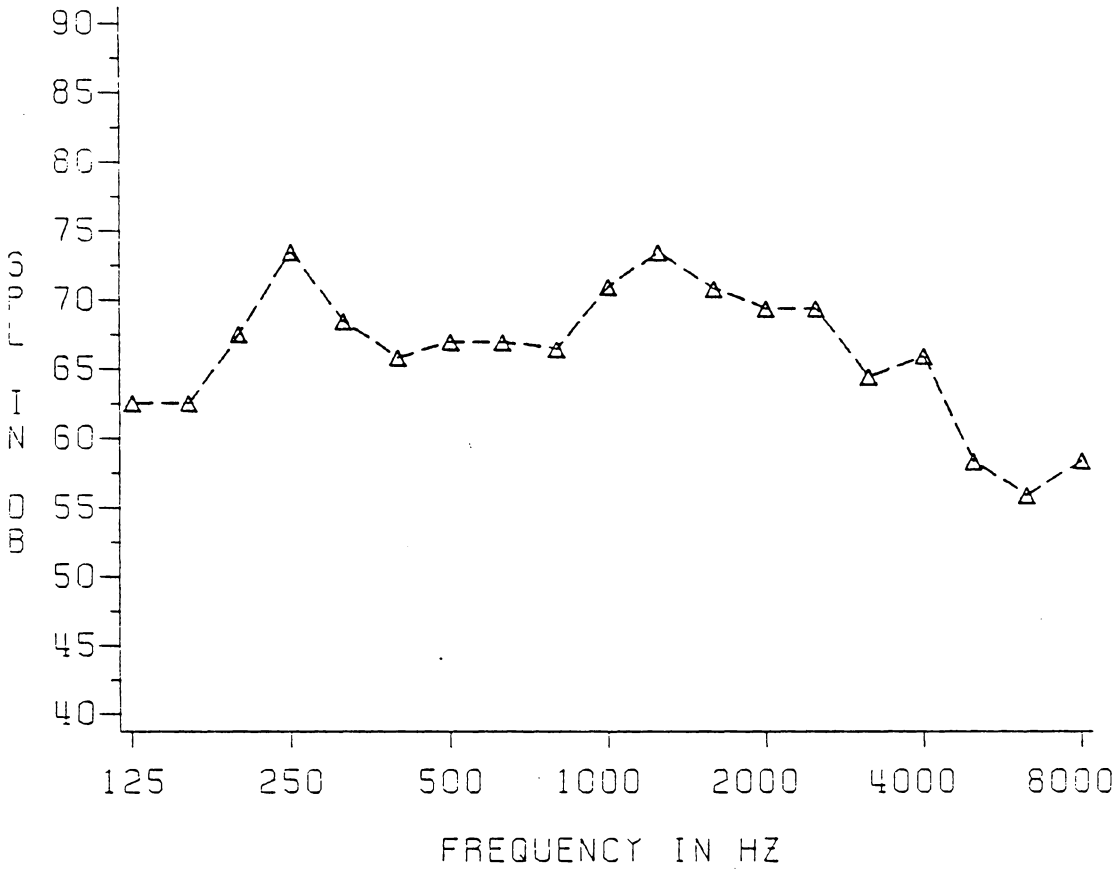
1/3 OB Noise spectrum for furnace and ventilation fan, average one microphone position, linear SPL (to be used for HPD matching)



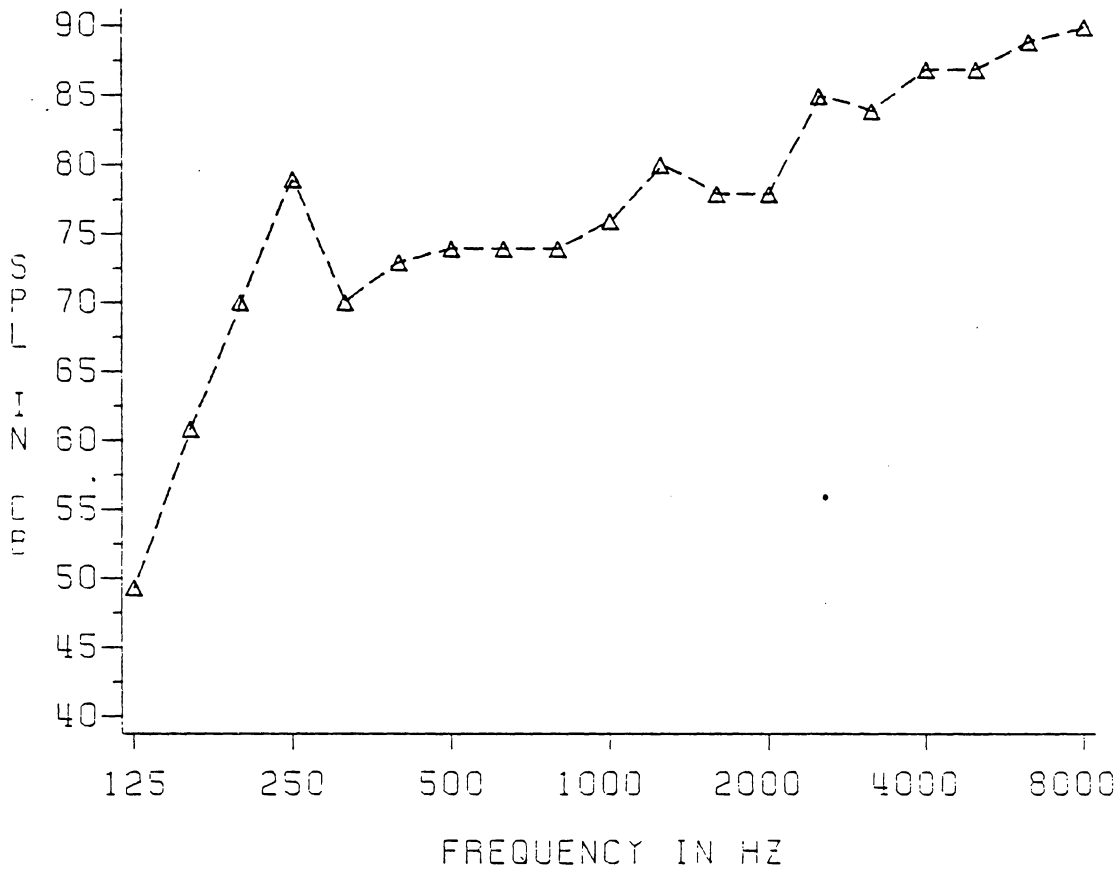
1/3 OB Noise spectrum for manual notcher, average three microphone positions, linear SPL (to be used for HPD matching)



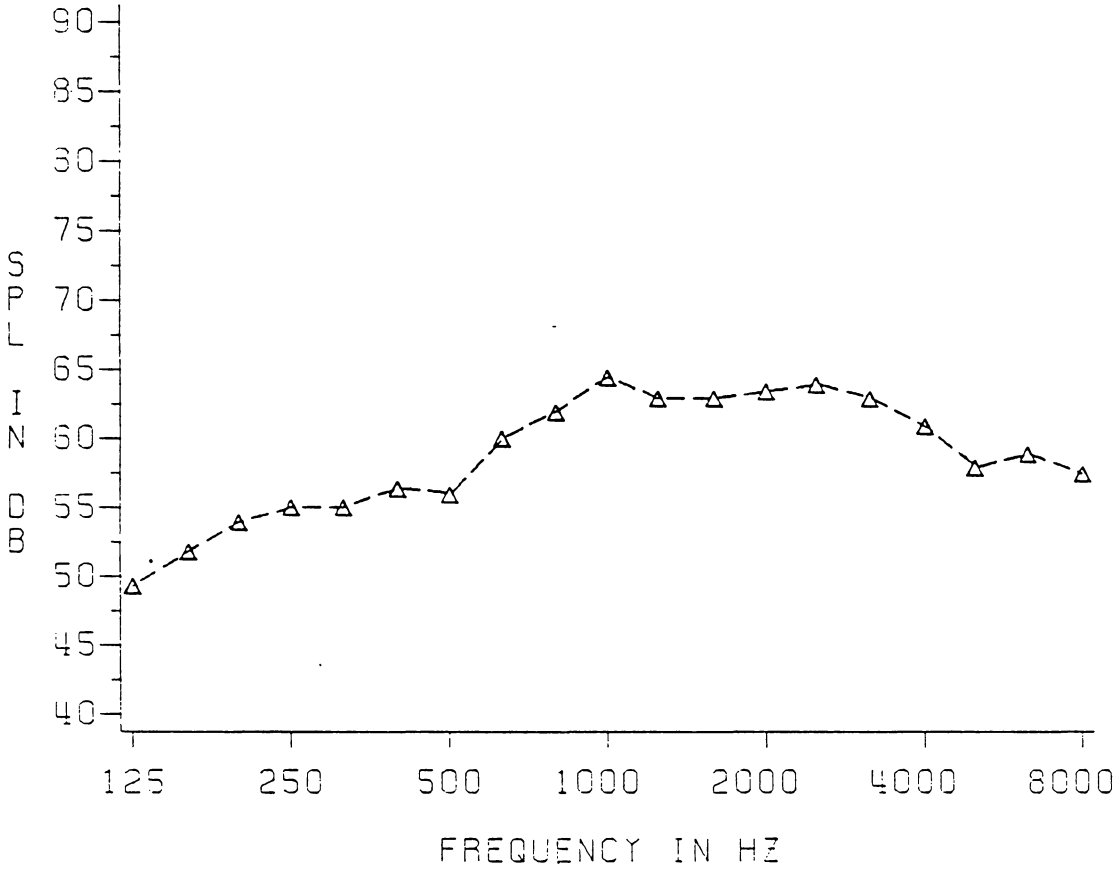
1/3 OB Noise spectrum for manual notcher, average three microphone positions, peak SPL (to be used for HPD matching)



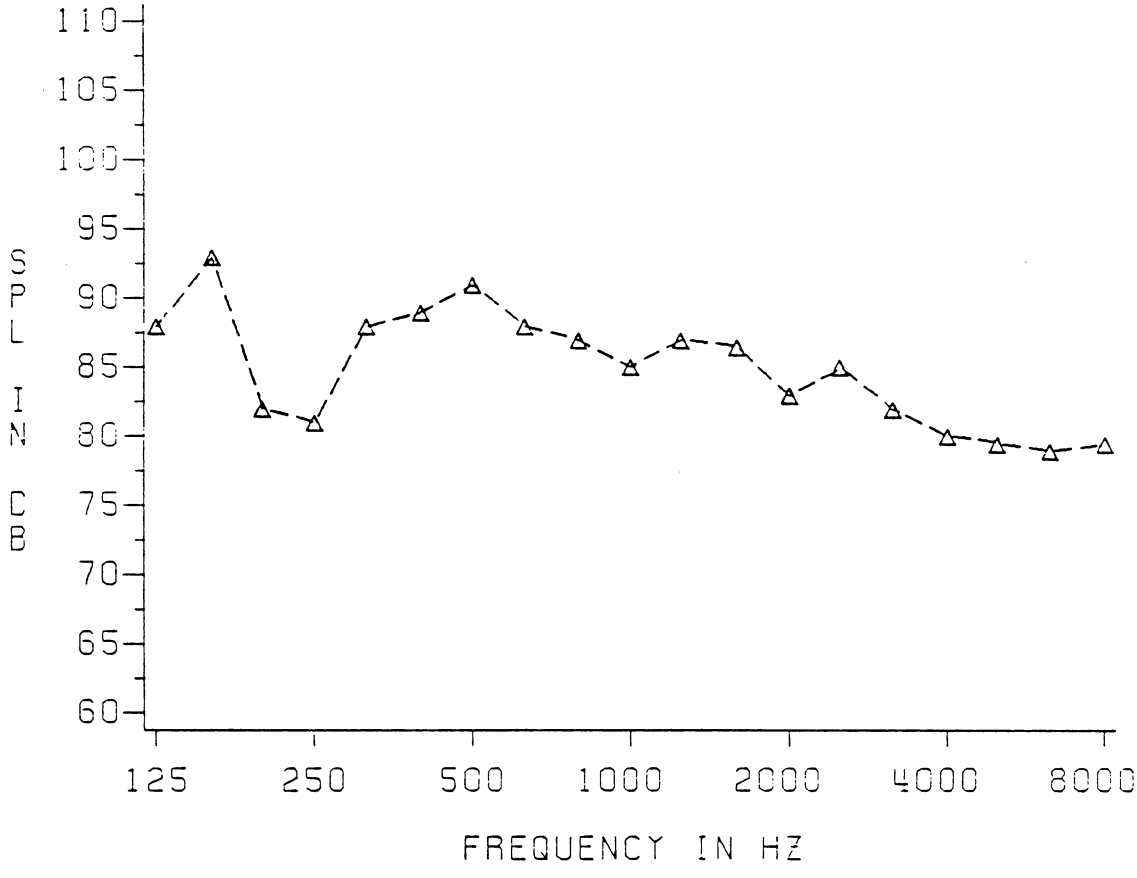
1/3 OB Noise spectrum for NC drilling machine and controller, single microphone position, linear SPL (to be used for HPD matching)



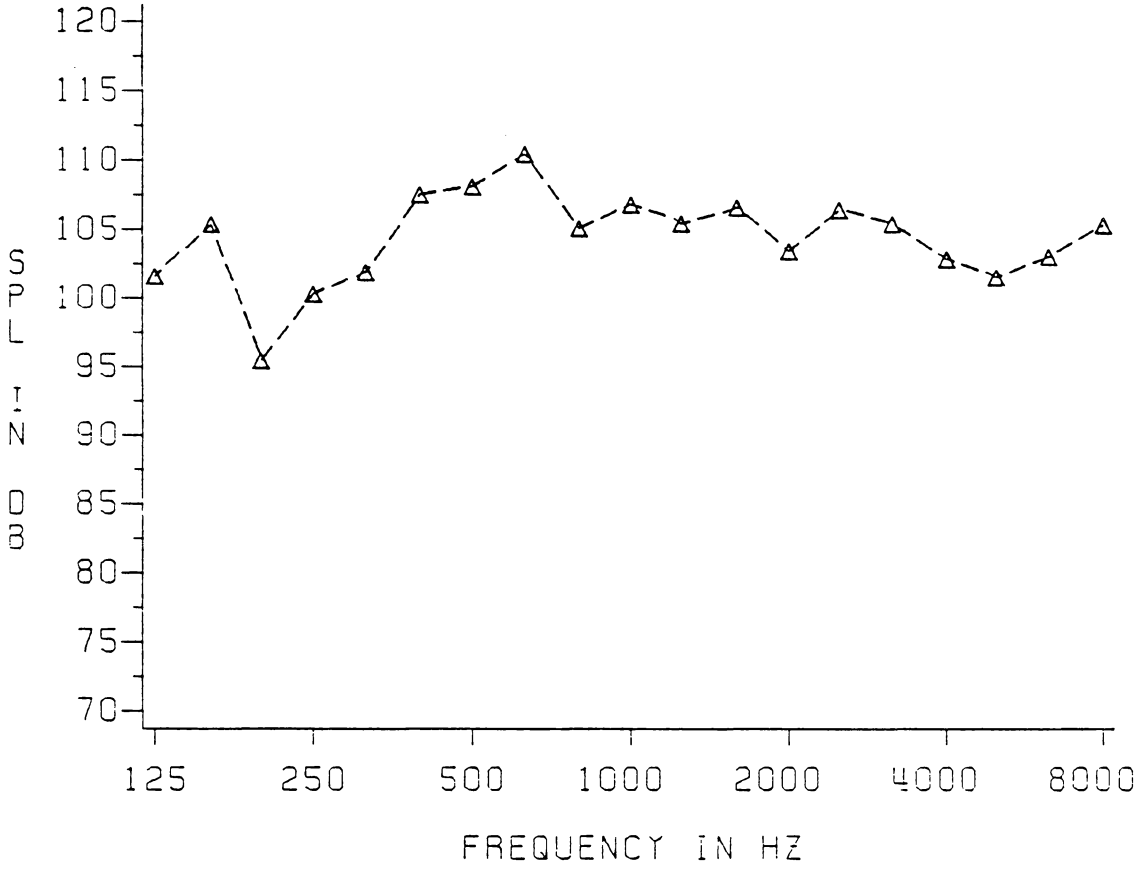
1/3 OB Noise spectrum for pedestal grinder, single microphone position, linear SPL (to be used for HPD matching)



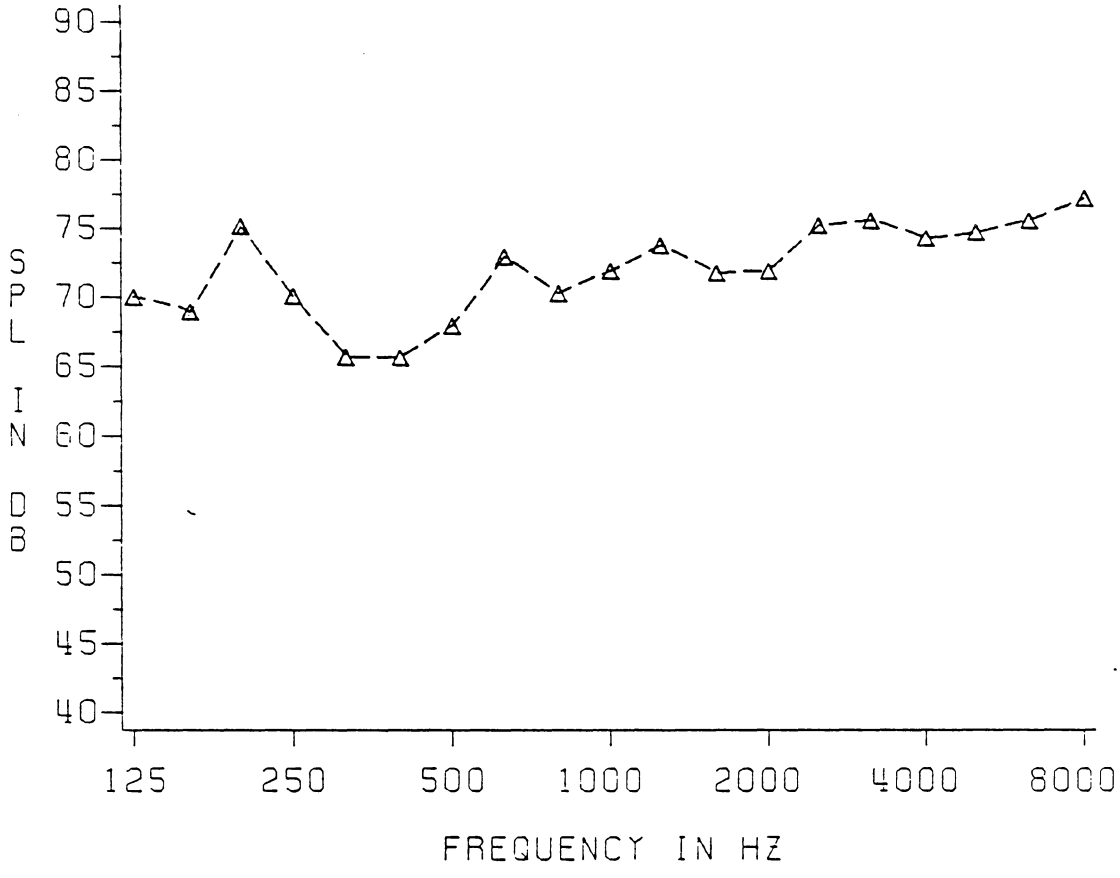
1/3 OB Noise spectrum for surface grinder, single microphone position, linear SPL (to be used for HPD matching)



1/3 OB Noise spectrum for 27 - ton press, single microphone position, linear SPL (to be used for HPD matching)

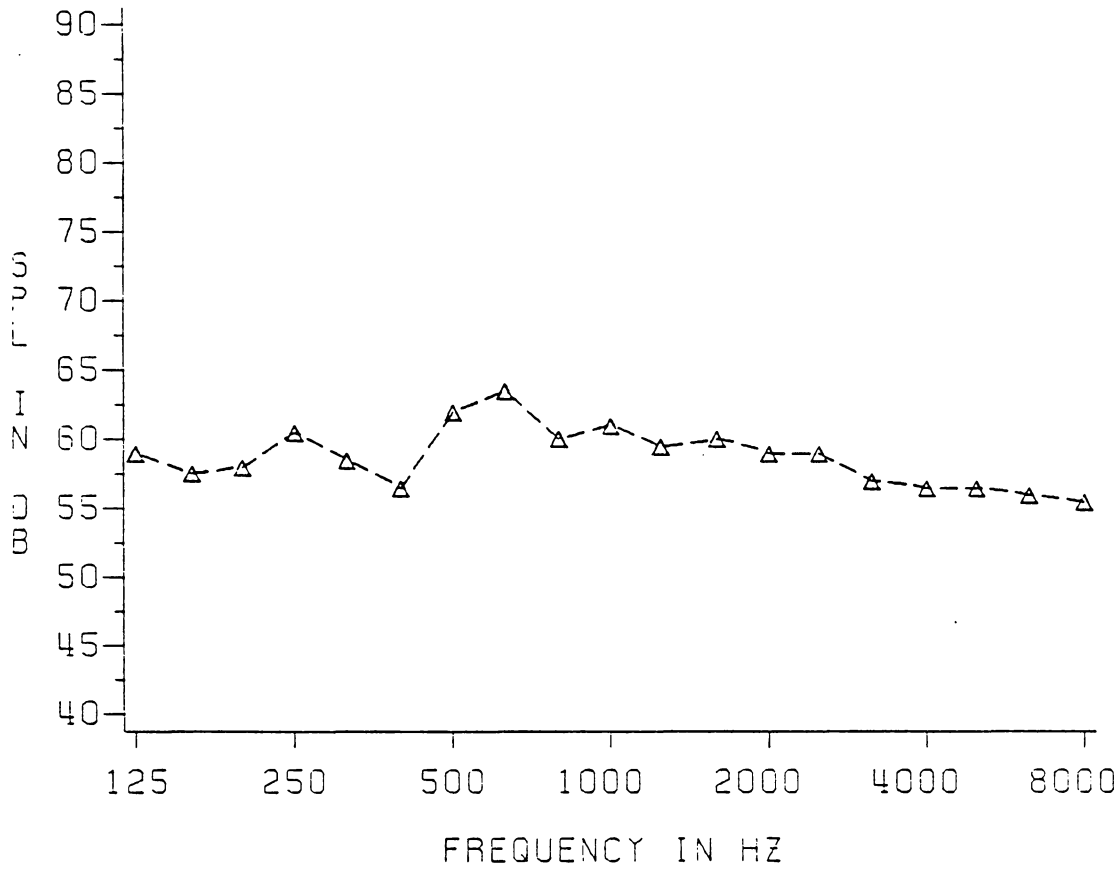


1/3 OB Noise spectrum for 27 - ton press, single microphone position, peak SPL (to be used for HPD matching)

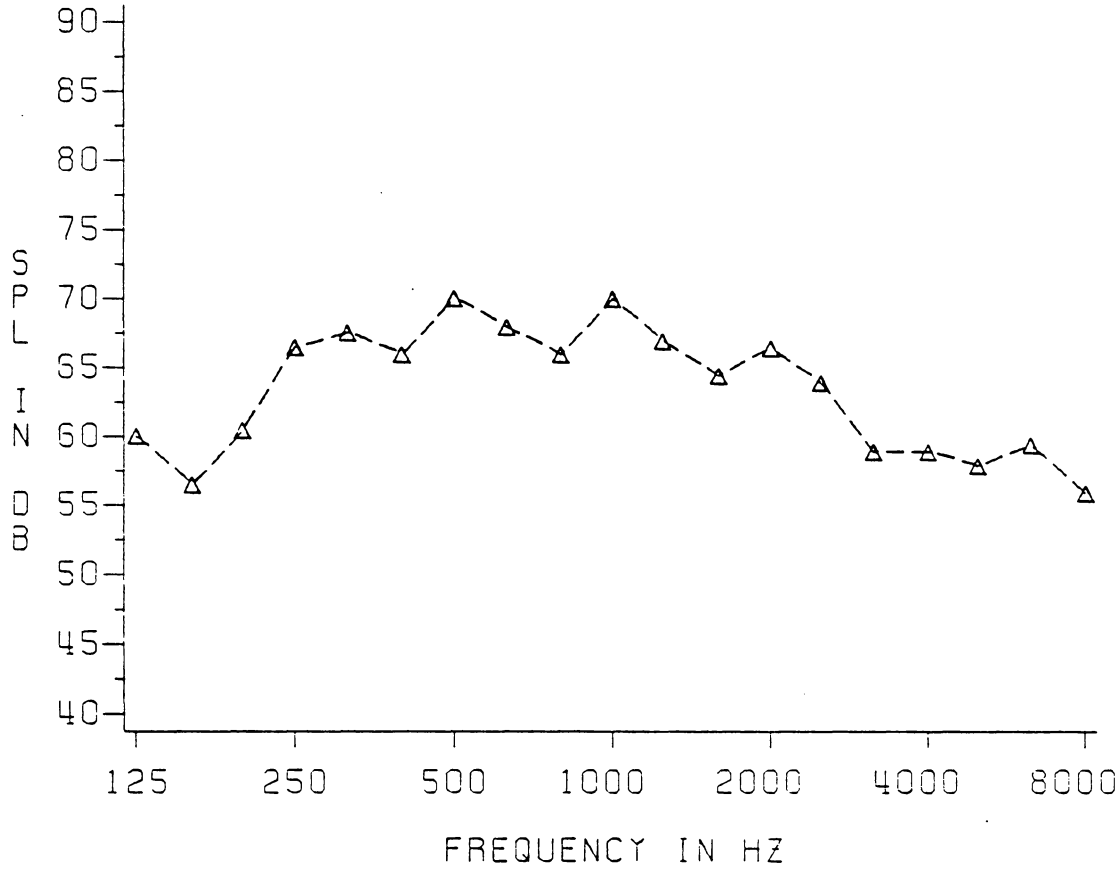


1/3 OB Noise spectrum for vibro - energy finishing mill, single microphone position, linear SPL (to be used for HPD matching)

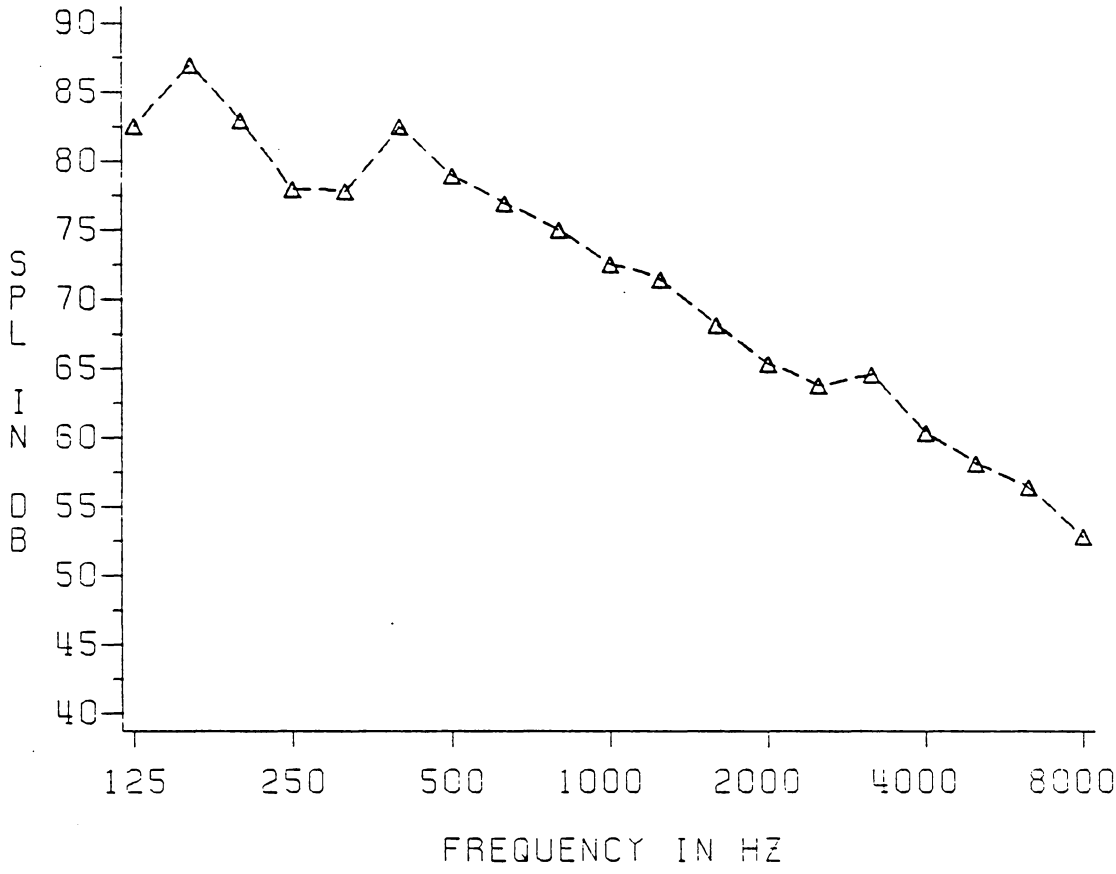
Sound Pressure Levels at Operator's Position



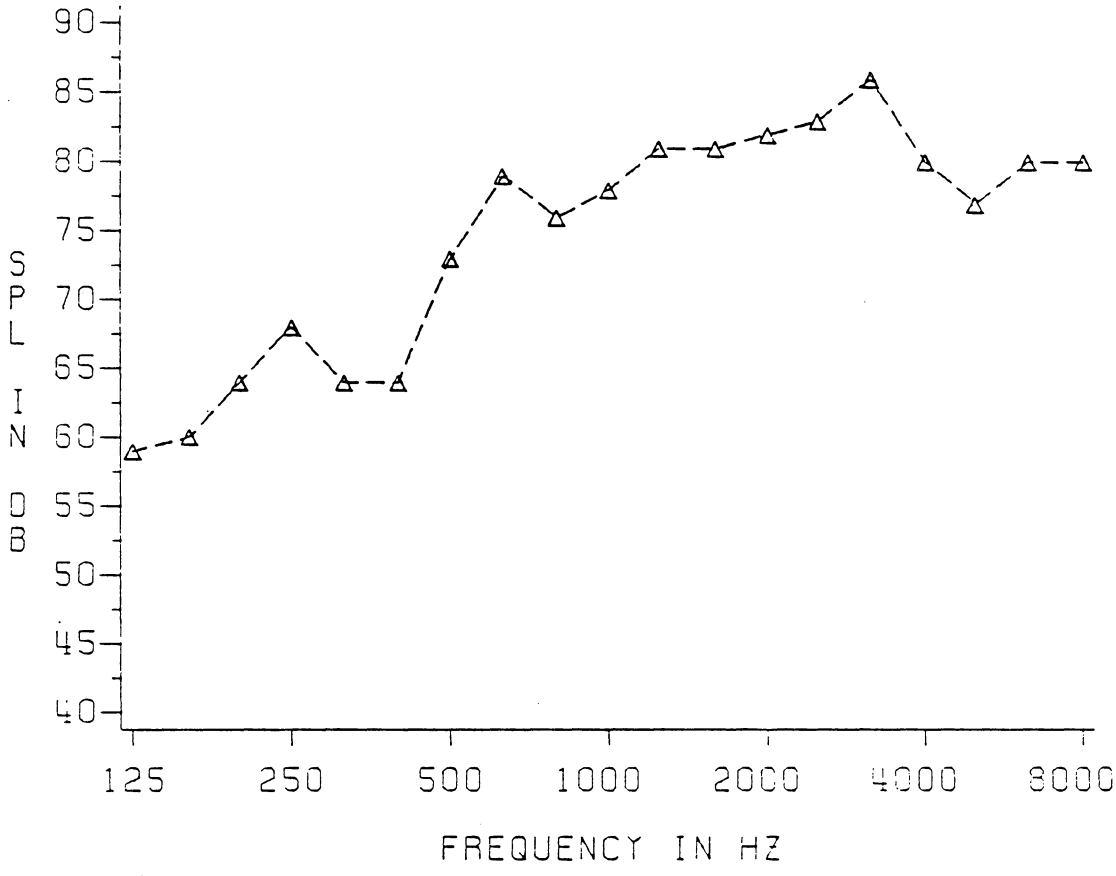
1/3 OB Noise spectrum for general background noise of a motor machine shop, single microphone position, linear SPL (to be used for HPD matching)



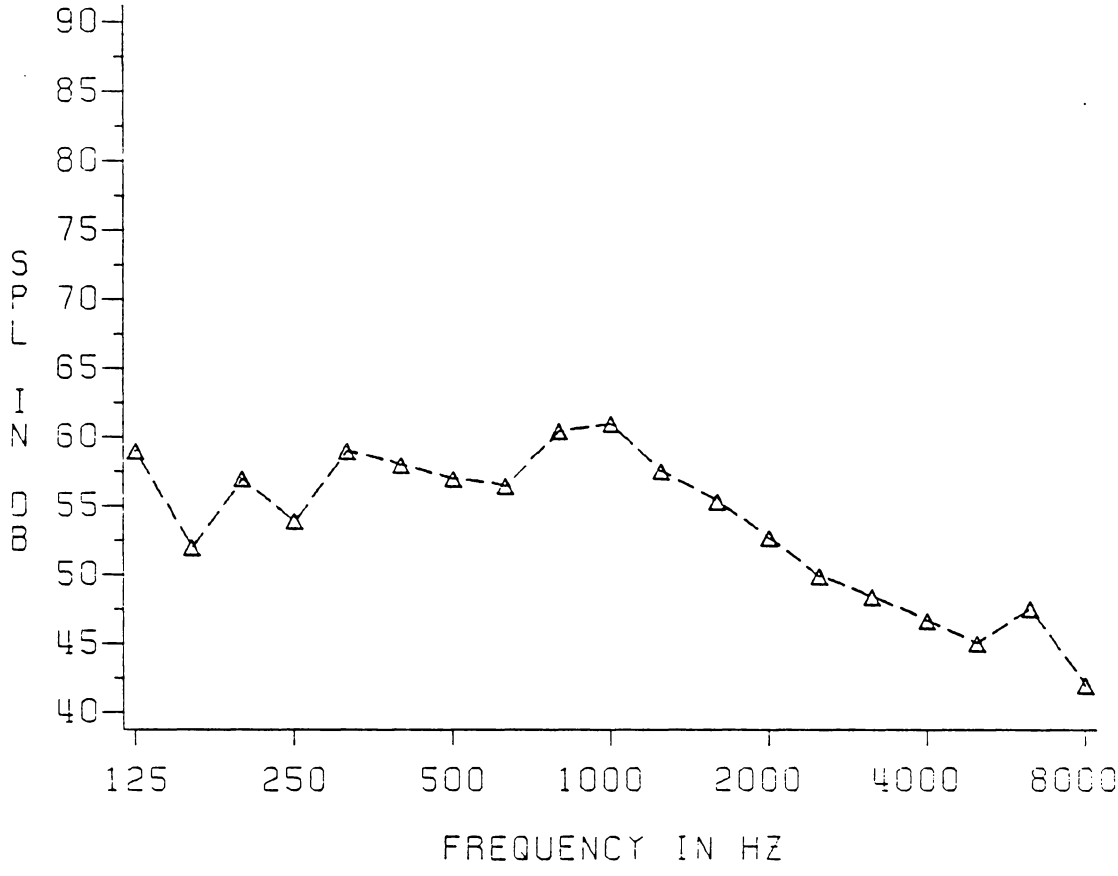
1/3 OB Noise spectrum for band saw, operator's position, linear SPL (to be used for HPD matching)



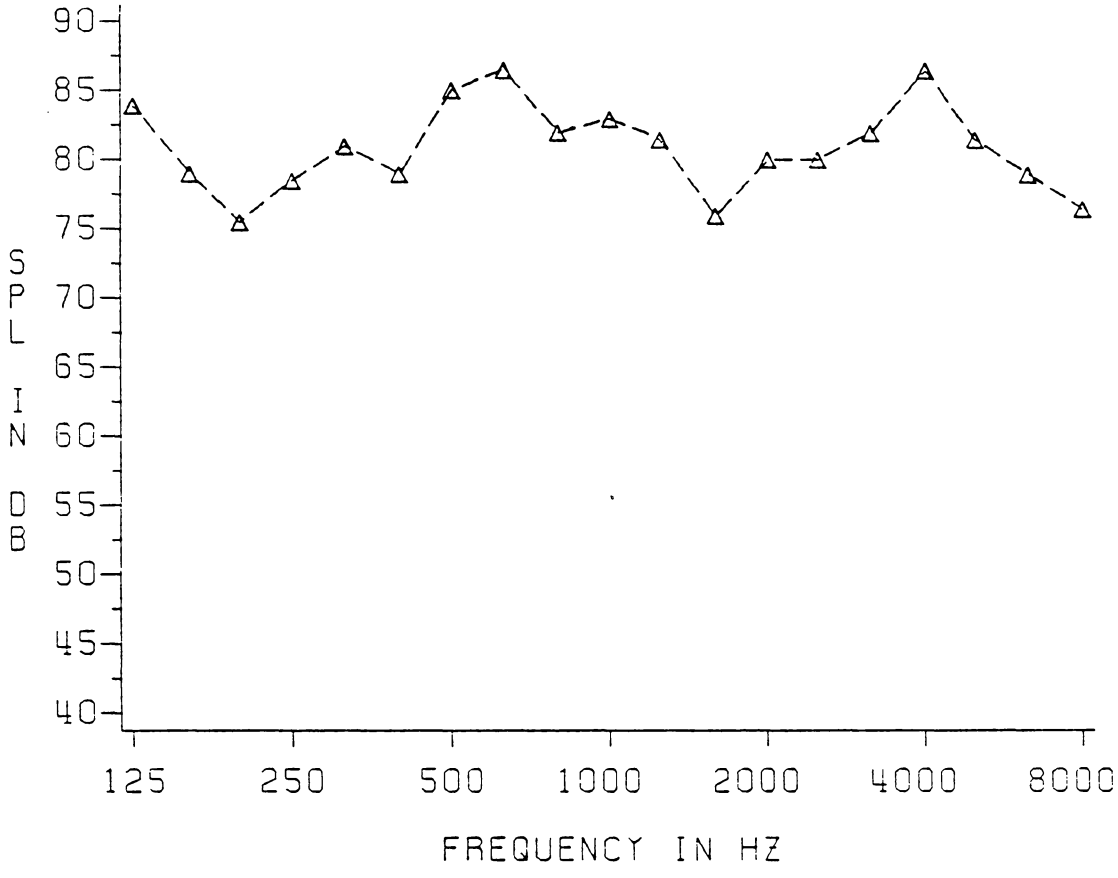
1/3 OB Noise spectrum for dust collector, operator's position, linear SPL (to be used for HPD matching)



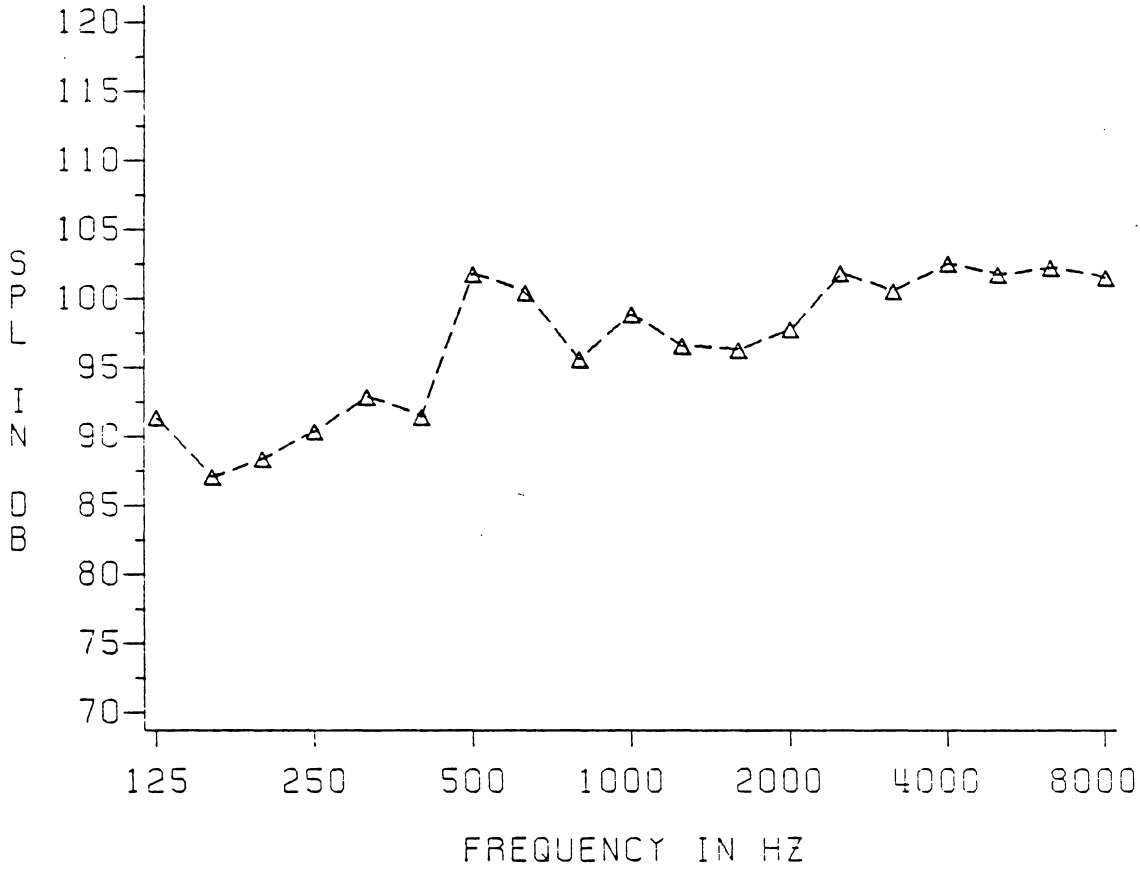
1/3 OB Noise spectrum for contour saw, operator's position, linear SPL (to be used for HPD matching)



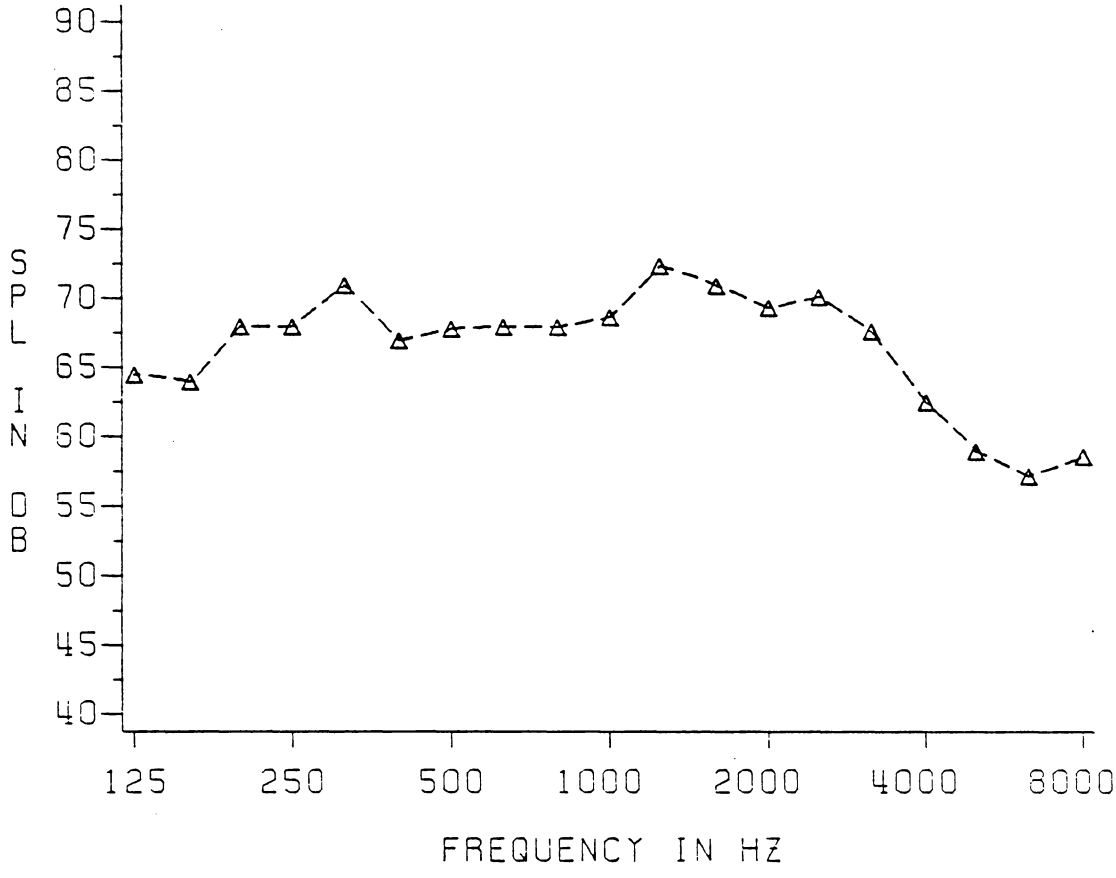
1/3 OB Noise spectrum for engine lathe, operator's position, linear SPL (to be used for HPD matching)



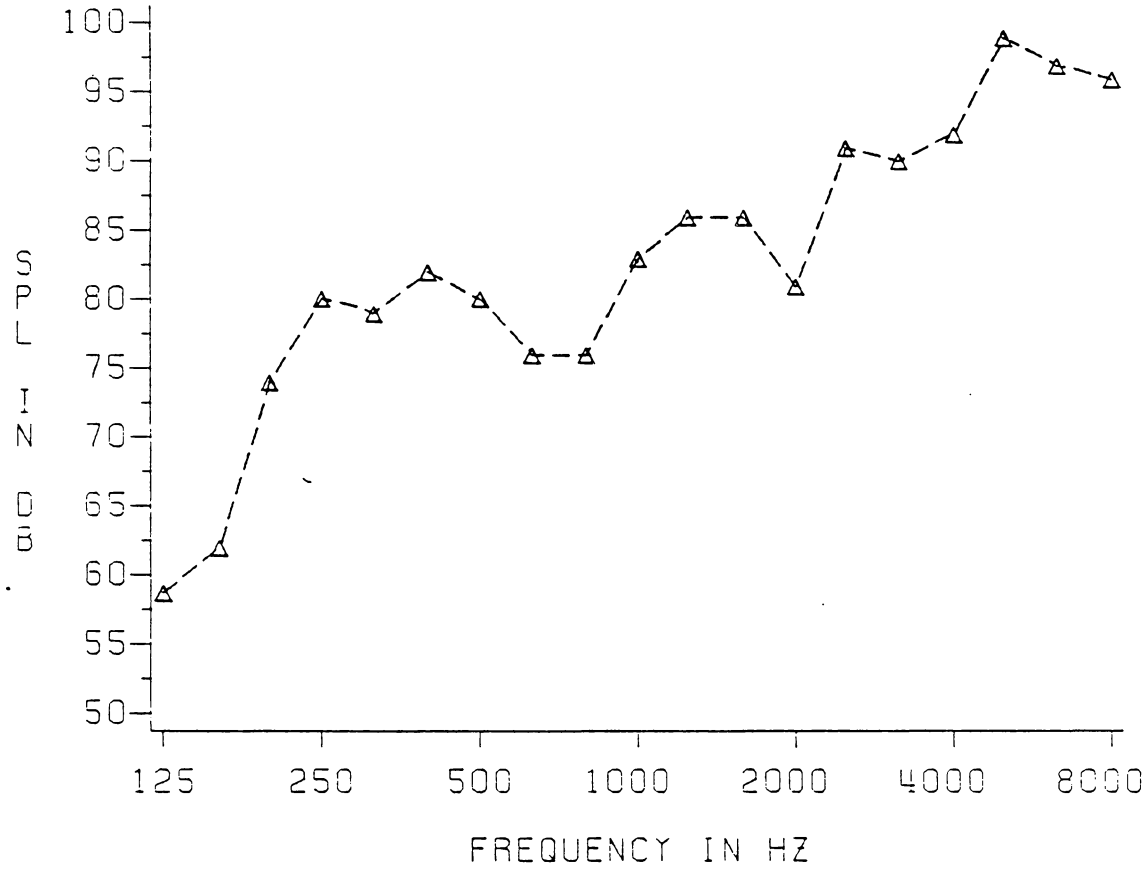
1/3 OB Noise spectrum for manual notcher, operator's position, linear SPL (to be used for HPD matching)



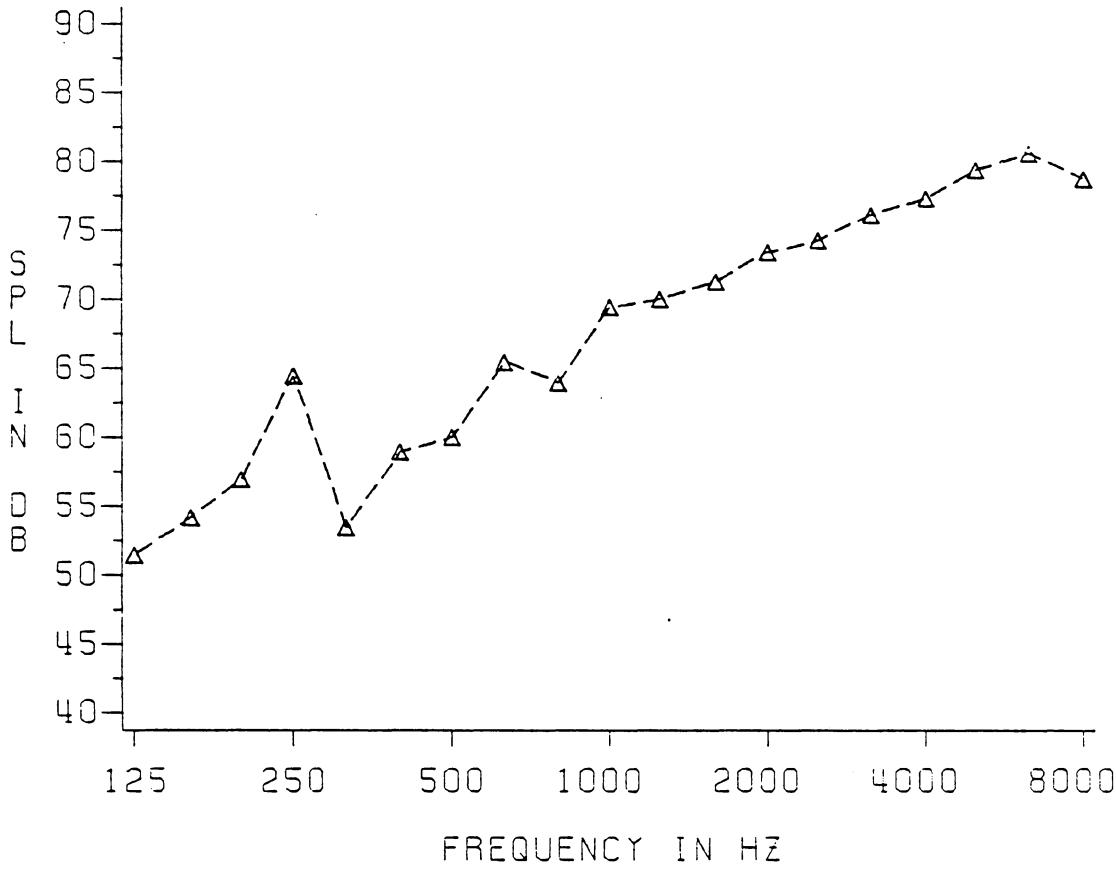
1/3 OB Noise spectrum for manual notcher, operator's position, peak SPL (to be used for HPD matching)



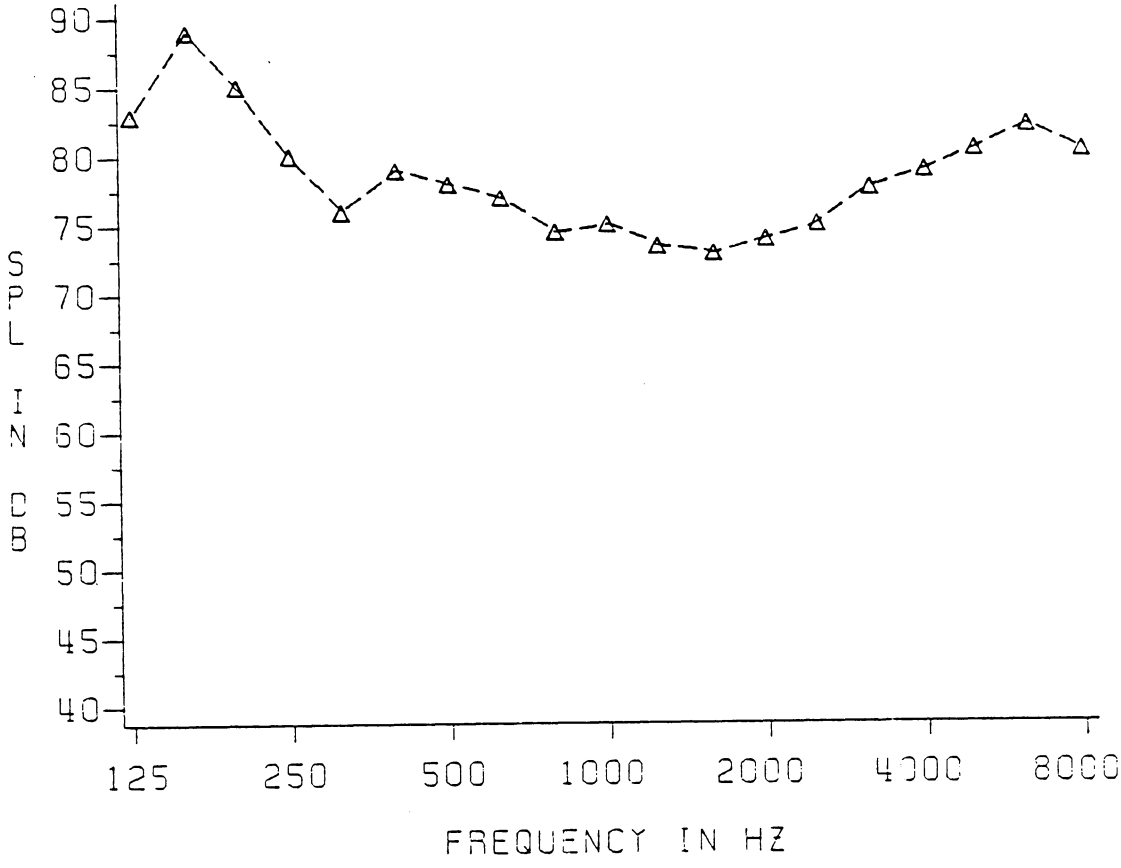
1/3 OB Noise spectrum for NC drilling machine and controller, operator's position, linear SPL (to be used for HPD matching)



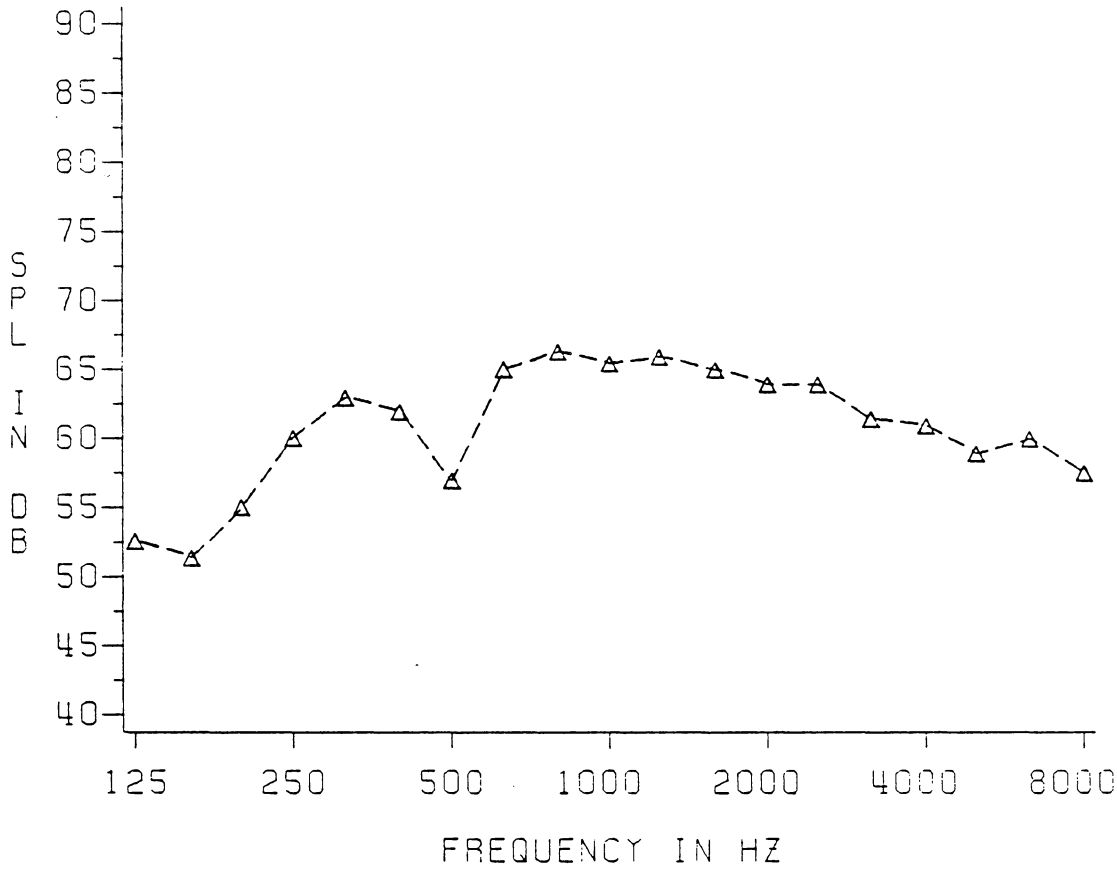
1/3 OB Noise spectrum for pedestal grinder, operator's position, linear SPL (to be used for HPD matching)



1/3 OB Noise spectrum for sand blaster, operator's position, linear SPL (to be used for HPD matching)



1/3 OB Noise spectrum for sand blaster and dust collector, operator's position, linear SPL (to be used for HPD matching)



1/3 OB Noise spectrum for surface grinder, operator's position, linear SPL (to be used for HPD matching)

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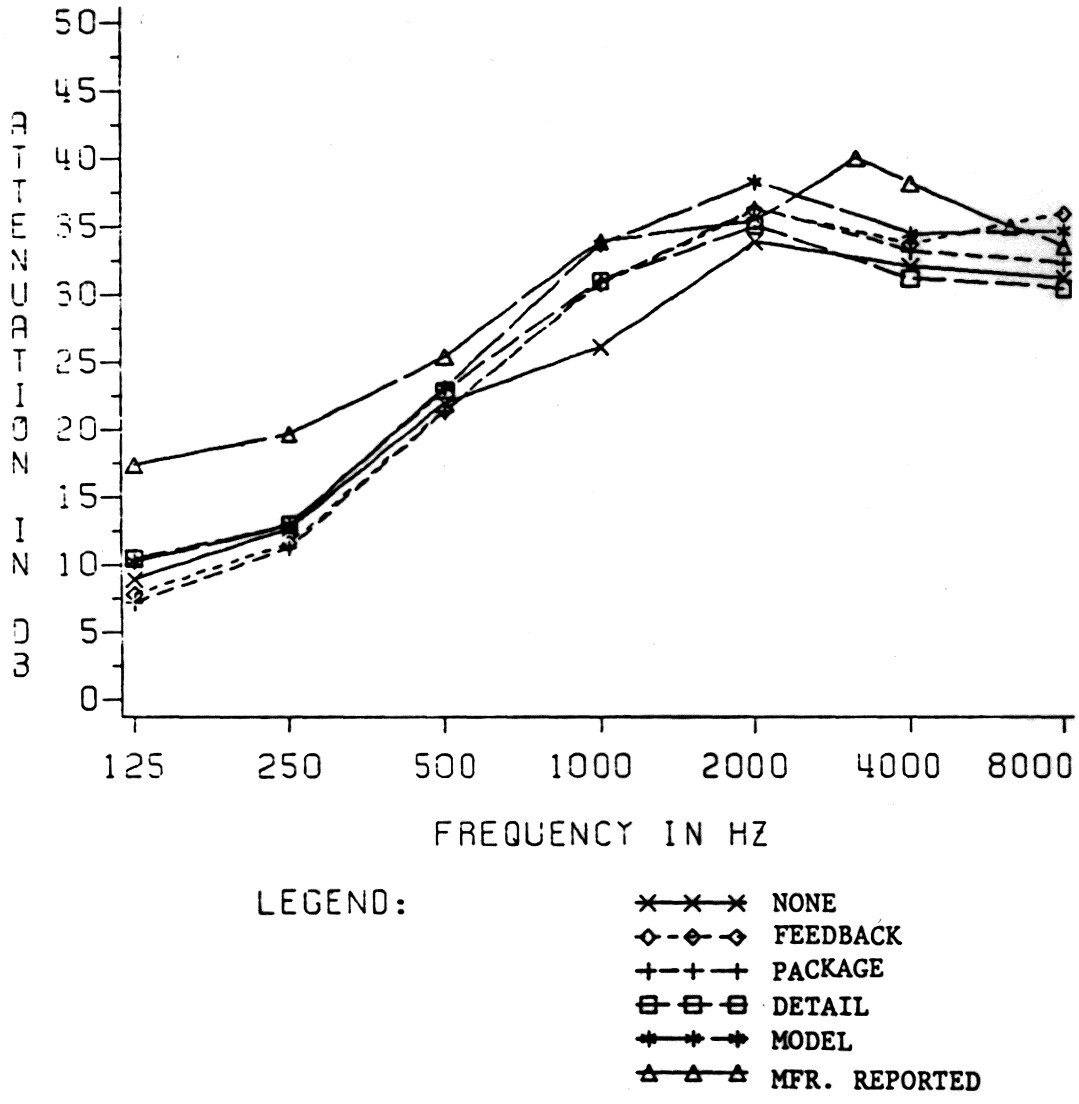
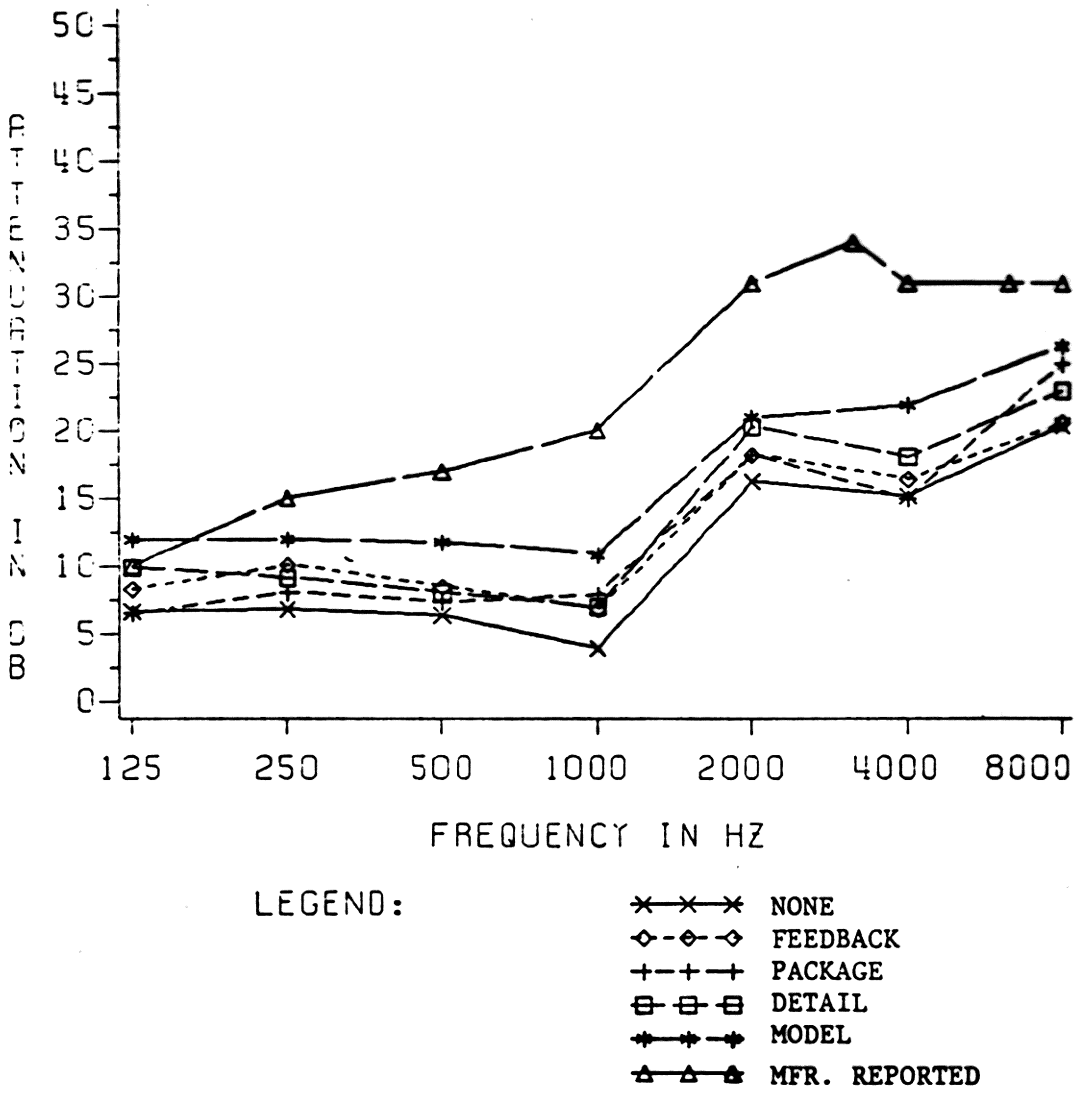
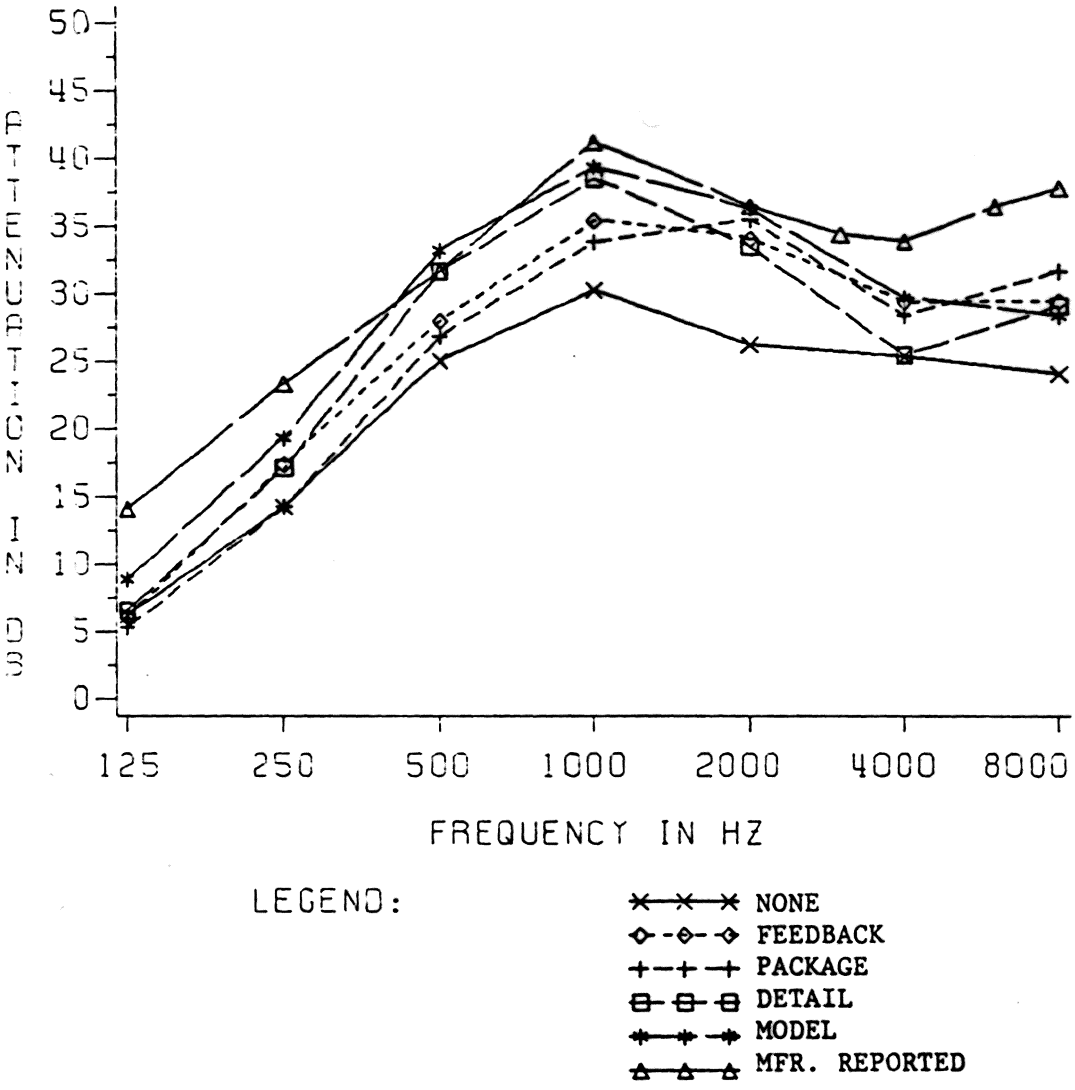


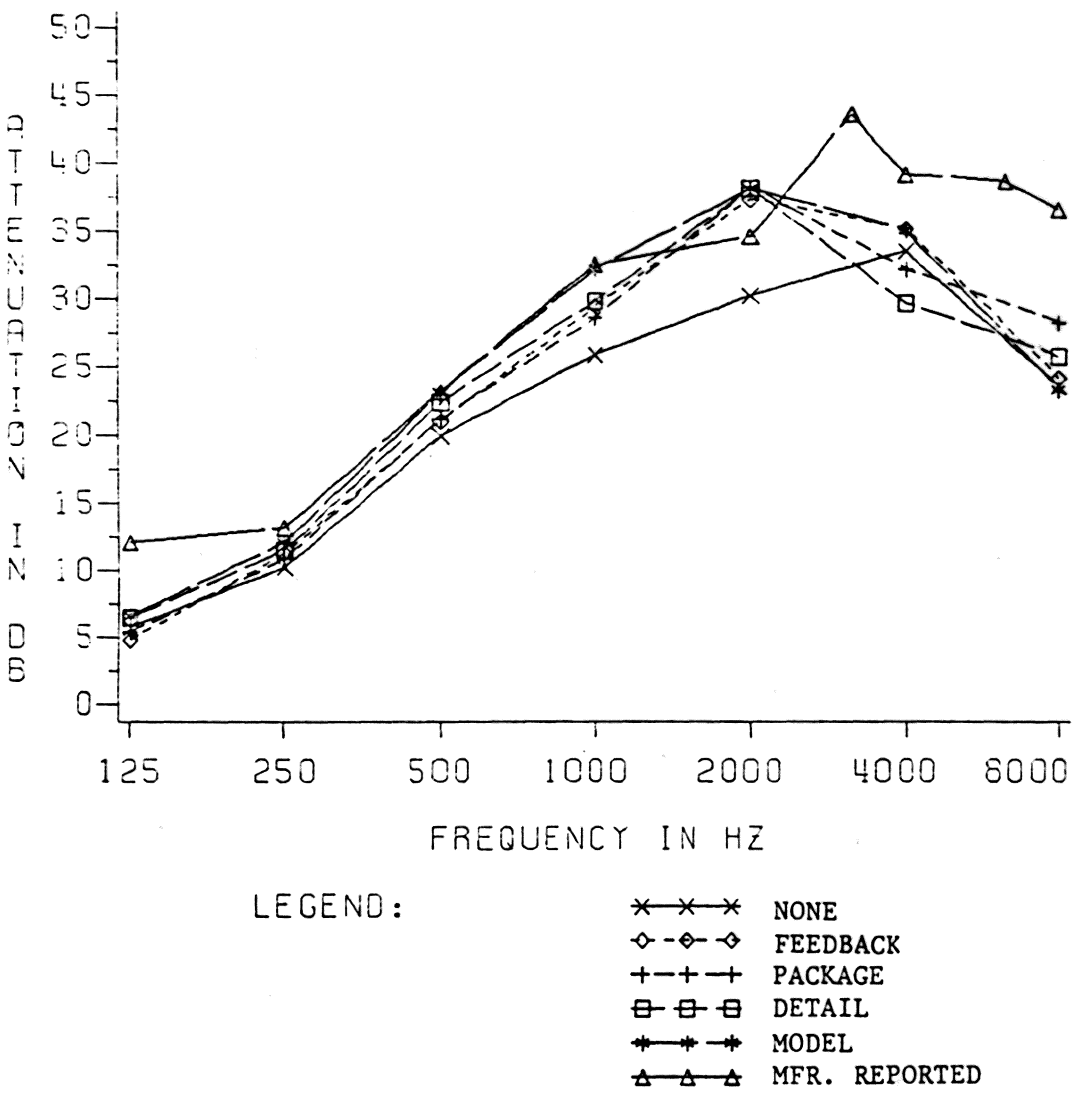
Attenuation characteristics of EAR muff model 1000 at each instruction technique



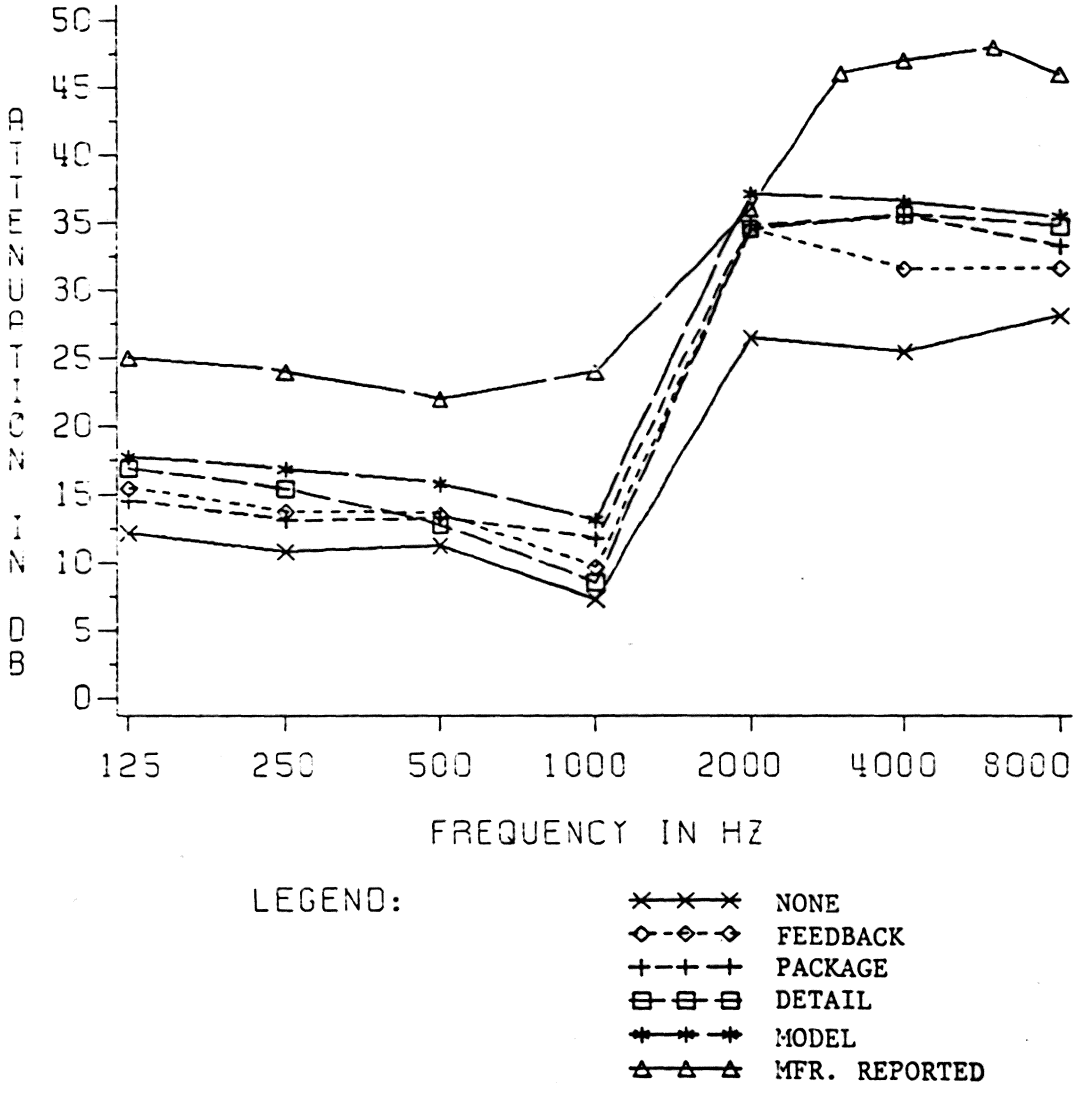
Attenuation characteristics of Flents earcap model #055 at each instruction technique



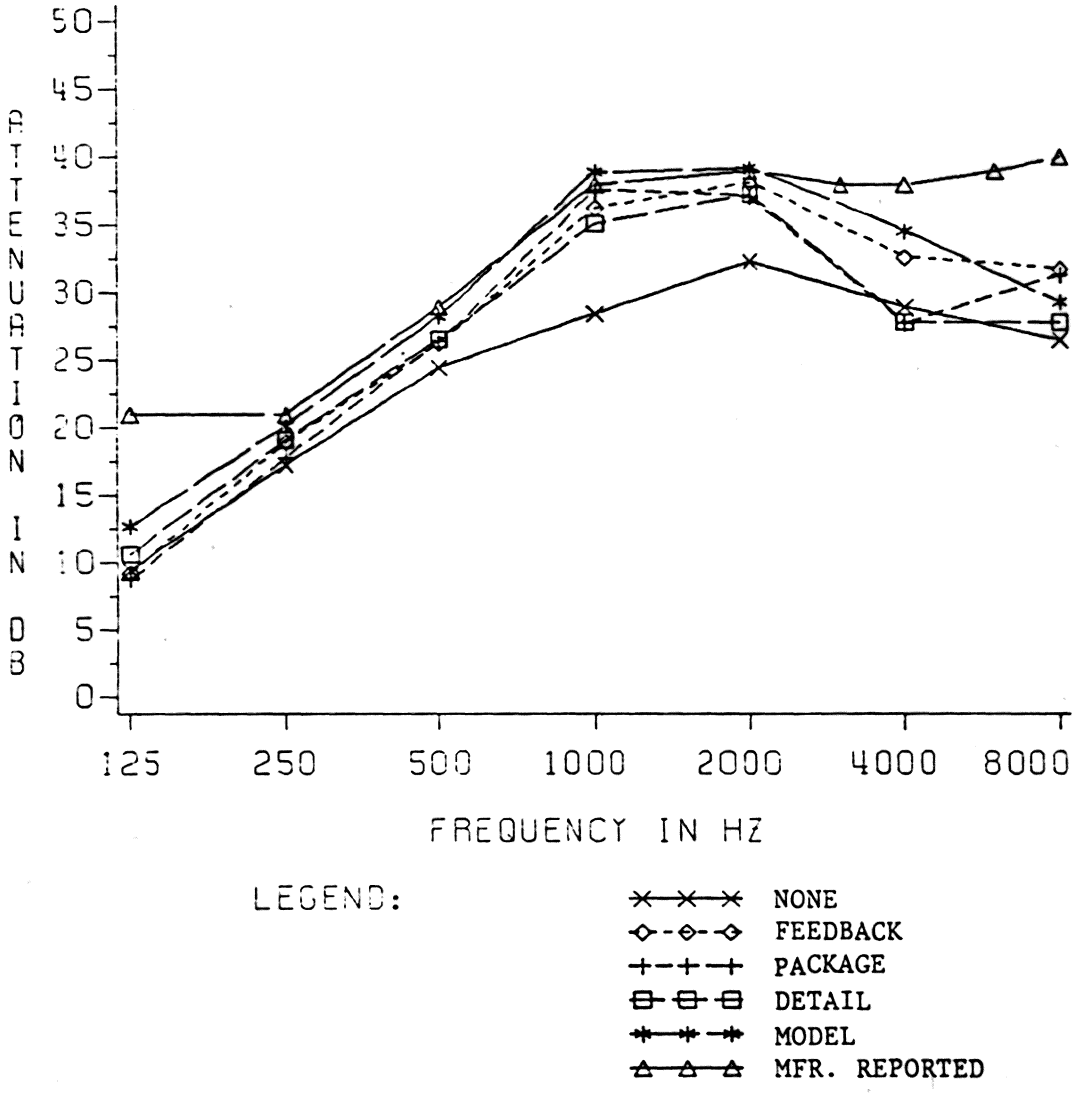
Attenuation characteristics of Norton muff model 4540 at each instruction technique



Attenuation characteristics of Peltor muff model H6A/v at each instruction technique



Attenuation characteristics of Willson earcap model #20 at each instruction technique



Attenuation characteristics of Willson muff model 365A at each instruction technique