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IMPULSE NOISE INDUCED HEARING LOSS
FROM SIMULATED WORK-WEEK EXPOSURES

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After preexposure thresholds had been determined, six adult monaural chinchillas were exposed to a repetitive, reverberant impulse for 8 hours per day, for 5 days. The noise impulses were produced by two automated, cam driven, brass hammers hitting a steel plate. Thresholds were measured at 0.25, 0.5, 1, 2, 4, and 8 kilohertz (kHz) 0.5 hour before and 0.5 hour after each of the five 8-hour exposures. After the last exposure the recovery of threshold was monitored for 5 successive days. Final hearing thresholds were obtained starting at 30 days postexposure and were either the average of 3 days of averaged evoked response (AER) testing or 10 days of behavioral testing. The AER thresholds were systematically higher than the behavioral thresholds by 5 to 18 decibels. All frequencies were shifted by approximately the same amount by the end of the 5-day exposure as they were at the end of the first day's exposure, and there was no cumulative effect. There was still some residual threshold shift with 2 days' recovery. The actual degree of oscillation of threshold presumably would be a function of the actual noise exposure as well as the acoustic environment during recovery.

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IMPULSE NOISE INDUCED HEARING LOSS FROM SIMULATED WORK-WEEK EXPOSURES

INTRODUCTION

Hearing loss from industrial noise exposure is often a slow process that grows over a period of many years. Ex post facto analysis of industrial noise and the resultant hearing loss is difficult. One complication is the uncertainty of reconstructing an individual's history of noise exposure. A second complication arises from the fact that symptoms that are similar to noise-induced, permanent, threshold shift (NIPTS) can also be caused by presbycusis, socioacusis and ototoxic drugs. Laboratory studies of the human response to noise provide a better control over noise exposure variables; however, they are usually restricted to short duration exposures (minutes to a few hours) and are ethically limited to exposures that produce relatively low-level, temporary, threshold shifts (TTS). Thus we are left with the problem of trying to understand the processes underlying a serious hearing problem, NIPTS, that developed over many years by using experiments that induce a minor hearing loss over a short period of time.

A possible solution to this problem is to study the dynamics of NIPTS using animal models in a long-term noise exposure lasting 2 to 10 days. One of the characteristics of such exposures is that thresholds stabilize at an asymptotic level. Asymptotic threshold shift (ATS) is an important phenomenon because for continuous noise the level of ATS for a given noise is quite predictable, the variability across subjects is small, and perhaps, most importantly, ATS for a given noise may also be the upper limit of threshold shift that a subject would develop from many years' exposure to that noise (Carder and Miller, 1972; Mills, 1973).

Previous studies by Blakeslee et al (1978) indicate that impulse noise produces a type of ATS. They exposed chinchillas to a 113 dB reverberant noise impulse 1/sec for ten days. By 2 hours, most of the animals had reached a stable level of threshold shift of approximately 40 dB at 8 kHz that was maintained for the duration of exposure. While impulse noise did produce ATS, the characteristics of the ATS pattern differ from those of continuous noise ATS. The animals exposed to impulse noise reached asymptote in 1 to 2 hours while exposure to continuous octave bands (80-96 dB range) produced an asymptote in 12 to 24 hours. Also, impulse noise produced a surprisingly large PTS (approximately 20 dB @ 2 kHz) and large hair cell lesions considering the relatively small ATS. Nevertheless, the important result from this study is that all the animals reached an ATS.

While the importance of ATS is not to be overlooked, most industrial exposures are eight hours a day for five days a week. A recent study by Saunders et al (1976) shares some of the temporal aspects of a "work week" exposure. They exposed chinchillas to a 4 kHz octave band of noise on an intermittent schedule for six hours a day for nine days. They found that after the first or second day the animals developed a consistent level of TTS and recovered to a consistent level during the 18 hour period before the next exposure. Consequently, the animals were considered to be in a state of ATS; however, the level of ATS was 8.5 dB lower than the ATS that would have been produced by an uninterrupted exposure for nine days.

Given that a form of ATS can be produced by daily 6 hour exposures and that impulse noise can also produce ATS, then it is reasonable to ask what is the pattern of ATS produced by a work-week exposure of impulse noise, 8 hours a day for five days.

METHOD

A. Subjects

Six adult chinchillas were used as subjects. All were made monaural by surgical destruction (Miller, 1970) of the left cochlea under sodium pentobarbital anesthesia (50 mg/kg, I.P.). While under anesthesia, chronic electrodes were placed in the skulls of those animals (4) which were to be audiometrically tested using the averaged-evoked response (AER) technique. For those four animals, an incision was made along a midline starting approximately 2 cm from the tip of the snout and proceeding posteriorly 3.5 cm. The periosteum was retracted, exposing the skull and left bulla. A hole was drilled into the skull over the tentorium and a plug with two stainless steel electrodes (Plastic Products MS303) with electrode lengths of 3 mm and 8 mm was placed over the opening allowing the electrodes to project into the brain. Figure 1 shows a schematic of the chinchilla skull and position of the bipolar electrode. A second hole (approximately 0.5 cm diameter) was made on the dorsal side of the left bulla. Dental cement was placed in the bulla and then extended from the bulla to the electrode plug and the area around the plug to firmly attach the plug to the skull. The skin was then sutured around the plug and the animals allowed to recover for several days. While under anesthesia, the right tympanic membrane of all animals was examined ososcopically to insure the absence of otitis media.

B. Apparatus and Procedure

1- Behavioral Testing

Behavioral testing was based upon traditional shock-avoidance conditioning principles. The animal was placed in a restraining device and was held in a standing position in the sound field. The chinchilla's reflexive tendency to jump when shocked on the tail was utilized as the avoidance response. Figure 2 shows the animal in the restrainer which positioned the animal's head 9 inches above the grid floor and 25 inches directly below the loudspeaker (Dynaco A-25). The responses of the animal were recorded by means of a microswitch which registered upward movement (approximately 0.5") of the restraining yoke. Shock was delivered to the animal's shaved tail by means of two disc electrodes taped to the tail with a separation of approximately 2 inches. Electrode paste was used under the electrodes to insure good conduction to the skin. Electric shock was produced by a constant-current, 60 Hz shocker at a level of 5 ma for all animals and conditions. A safety-signal, which indicated successful shock-avoidance to the animal, was a 40-watt light mounted on the wall of the sound booth facing the animal. The audiological test environment consisted of a single-walled sound booth (IAC 400) with 3-inch foam (Soundfoam) on the floor. The sound field was calibrated with a 1-inch condenser microphone positioned (at normal incidence) at a point approximating the center of the animal's head.

The psychophysical method used in threshold testing was a modified method of limits, similar to that used by Miller (1970). A test trial consisted of a train of five tone bursts (500 msec on, 500 msec off, 5 msec rise-fall). At the onset of the third tone burst, pulsed shock was delivered to the tail (5 ma, 200 msec on, 200 msec off). At the end of the fifth tone burst, the shock was terminated. If the animal responded during the first two tone bursts, it successfully avoided shock, the signals were terminated and a safety signal was turned on for 20 sec. If the animal responded during the shock period, the signals were terminated and it escaped further shock. At each frequency, testing commenced at a high intensity (approximately 60-80 dB SPL) and after each successful avoidance, the intensity was lowered by 20 dB. When the animal failed to avoid, the intensity was raised by 10 dB. Threshold was defined as half-way between the lowest intensity at which the animal avoided and the highest intensity at which it failed to avoid. The inter-trial interval (ITI) was randomly varied between durations of 30-90 seconds. The shock was turned off approximately 20 dB above the expected threshold. No secondary reinforcer, such as a buzzer, was used and the animal was never intentionally shocked at or near threshold. The animal was allowed one false response during each inter-trial interval. If the animal responded twice during the ITI, the automated interval timer was shut off and the experimenter waited until a period of 30 seconds without responding passed before initiating another trial. This insured a false response level of less than 6.7%. False response level is defined as the ratio of the time interval for a possible avoidance (2 seconds) over the entire period in which false responses can be made (30 seconds, as a minimum).

Auditory thresholds were measured at five frequencies: 0.5, 1, 2, 4, and 8 kHz. The order in which these frequencies were run each day was randomized and the initial signal level at which testing commenced was varied. Ten measurements were made at each frequency, thus ten days of testing were required. By the use of a unit attenuator (0-9 dB in 10 dB steps), the attenuation values used each day were randomly incremented by 0-9 dB over the ten days of testing. This presumably moved the 10 dB threshold "window" about the "true" threshold and was intended to provide a better estimate of threshold. In the manner of Miller (1970), when the chinchilla failed to respond at a signal level more than 20 dB above the estimated threshold (in the range where shock would be given), that trial was run again. The results of the second run were always accepted. Thresholds from the first day of testing were not used. The results of the following ten days of testing were averaged regardless of any particular threshold's divergence from the expected value. Figure 3 compares the median pre-exposure thresholds of the two behaviorally-tested subjects with those published by Miller (1970).

2- AER Testing

Four monaural animals were tested using auditory-evoked response measures (AER). The testing was done in a single-walled acoustic chamber. The awake animal was placed in a restraining device which insured constant distance and orientation to the sound source.

Auditory signals consisted of 20 msec sinusoids (5 msec rise-fall, 10 msec plateaus) presented 2/sec. The evoked response was obtained from the average of 128 EEG samples, each of which was taken over a 100 msec period after the stimulus onset. The AER that was recorded from the chinchilla is seen in Figure 4. The actual complex that was used for threshold estimation was the negative and the positive wave at 15-30 msec. The threshold procedure involved the recording of a series of AER tracings starting significantly above the animal's threshold and descending in 5 or 10 dB steps. The actual threshold is defined as the midpoint between positive and negative response and was based on the consensus of three independent judges. Pre-exposure thresholds were obtained at 0.25, 0.5, 1, 2, 4 and 8 kHz test frequencies. The final pre-exposure threshold was an average of three separate threshold determinations on three consecutive days. Figure 3 compares the median AER thresholds with the behavioral thresholds of the other animals in this experiment, as well as the normative values from Miller (1970).

3- Exposure and TTS Measurements

After pre-exposure thresholds were obtained, the animals were exposed to a repetitive, reverberant impulse for 8 hours per day, for 5 days.

The noise impulses were produced by two automated, cam-driven, brass hammers hitting a steel plate. The impulses occurred at a rate of 1/sec and had a peak overpressure of 113 dB. The B-duration or the total time that the envelope of the pressure fluctuation is within 20 dB of the maximum peak pressure level was 160 msec. The calibration of sound level was performed before and after each 5 day exposure. The pressure waveform and spectral analysis are shown in Figure 5. During the exposure, the animals were confined to a 5 x 8 x 6-inch, wire-mesh cage and were provided free access to water and hay. Since the animals were free to move within the cage, the sound pressure at the ear was 113 dB ± 2 dB. This degree of acoustic variability was tolerated because fixing the animal in position for 5 days was unacceptable.

Thresholds were measured at 0.25, 0.5, 1, 2, 4, and 8 kHz one-half hour before and one-half hour after each of the 5 eight-hour exposures. After the last exposure the recovery of threshold was monitored for 5 successive days. Final hearing thresholds were obtained starting at 30 days postexposure and were either the average of 3 days of AER testing or 10 days of behavioral testing.

4- Histology

When final thresholds had been determined (50-70 days post-exposure), the animals were sacrificed and their cochleas analyzed using the flat preparation technique (Engström et al, 1966). The animals were decapitated and the right bulla was excised and opened to expose the cochlea. The cochlea was perfused through the round window with a 2.5% gluteraldehyde solution in 0.1 M PO_4 buffer (pH of 7.3). The stapes was removed and additional fixative was perfused through the oval window for 5 minutes. The cochleas were left in the fixative, refrigerated for at least 12 hours, then washed in PO_4 buffer and post-fixed in 1% OsO_4 (in PO_4 buffer) for one-half hour. The cochleas were washed in buffer and dehydrated to 70% ETOH. The entire sensory epithelium was dissected from the cochlea, mounted in glycerine, and counts of hair cells present or absent were made using a light microscope. Cochleagrams were plotted using average hair cell populations over 0.4 mm segments. A hair cell was counted as present if the cell body cuticular plate complex was intact.

RESULTS

A. Pre-exposure Thresholds

The pre-exposure thresholds are shown in Figure 3. Miller's (1970) normative threshold data are represented for the chinchilla when measured by avoidance procedures in a shuttle box. Except for the lower thresholds at 4 kHz, there is quite good agreement between the shuttle box and jump-stand conditioning procedure. The AER (median of 4) thresholds are systematically higher than the behavioral thresholds by 5 to 18 dB. However, the AER response is primarily an "on" response and proportional to the amplitude of the signal. If the behavioral thresholds were obtained with short duration signals (i.e., 20 msec), they would be elevated approximately 10-12 dB and the thresholds from the AER and behavioral measures would overlap (Henderson et al, 1973).

B. TTS During Exposure Week

Figure 6 shows the 1000 Hz thresholds for each chinchilla, measured over the five days of exposure. All animals show a regular oscillation of thresholds with a maximum threshold shift immediately following removal from the noise and a minimum threshold shift before being reintroduced into the noise the next day. The two behavioral animals fall within the range of the four AER animals; therefore, the two groups of animals have been collapsed for a better perspective on the pattern of threshold shift.

The median threshold shifts for test frequencies between 0.25 and 8 kHz are presented in Figure 7. An interesting frequency effect can be seen in the pattern of median threshold shifts across the five days. The high frequencies (4, 8 kHz) are shifted approximately 45 dB and recover to approximately 13 dB above pre-exposure threshold by 16 hours after the exposure; the low frequencies (0.58, 1) are shifted 38 dB but only recover to 22 dB above pre-exposure thresholds. Thus while the high frequencies are affected to a greater degree, they recover more quickly. The envelope of threshold shift during the five days represents a type of ATS. Furthermore, the daily recovery in threshold can be characterized by a plateau, i.e., the lower envelope of the curve of Figure 7. Two days after the last exposure (presumably, the beginning of the next work week) the median for all frequencies, except 2 kHz had returned to within 10 dB of pre-exposure values.

C. Permanent Effect

The final median audiograms are shown in Figure 8. The post-exposure thresholds had returned to essentially pre-exposure level. Two animals did, however, have approximately 20 dB of threshold shifts at 2 kHz. The greatest permanent audiological effect is at 2 kHz, a region approximately one-half octave above the peak of the amplitude spectrum (note Figure 5).

The cochleagrams for each animal varied from normal (2 animals) to 10-40% losses (4 animals). Figure 9 shows the audiogram and cochleagram from chinchilla #455 who had both the greatest hearing loss and largest number of missing hair cells. The cochleagrams depict inner and outer hair cell loss as a function of the location on the basilar membrane. The frequency scales for the graphs showing PTS at the 6 frequencies tested have been aligned with the location on the basilar membrane using the cochlear-frequency map of Eldredge, Mills and Bohne (1973). It should be pointed out that there are two independent ordinates, the left refers to cell loss and the right to threshold shift; however, there is no intention of drawing a quantitative relationship between these axes.

DISCUSSION

The envelope of threshold shifts can be thought of as a type of asymptotic threshold shift (ATS). All frequencies are shifted by approximately the same amount by the end of the five day exposure as they were at the end of the first day's exposure, and there is no cumulative effect. With two days' recovery there is still some residual threshold shift. The actual degree of oscillation of threshold presumably will be a function of the actual noise exposure as well as the acoustic environment during recovery.

In a previous study, Blakeslee et al (1978) exposed chinchillas to the same 113 dB impulse, but for ten successive days with brief interruptions only for threshold testing. Figure 10 shows the pattern of threshold shift at 8 kHz for the "work week" exposure compared to the uninterrupted 10 day exposure. The agreement between the two types of ATS is very close. In fact, the threshold shifts from the uninterrupted impulse noise exposure represents an upper bound for the work week exposures.

The previously mentioned experiment by Saunders et al reveals a potentially important difference between impulse and continuous noise. They exposed chinchillas to 72 dB of 2-4 kHz octave band continuous noise for six hour blocks over nine days. This exposure produced an asymptotic level of threshold shift by the second or third day. But the actual level of the threshold shift is 8.5 dB less than what would have been produced by exposure to the same band of noise continuously. As Saunders et al discussed, a 72 dB octave band of noise takes 12-24 hours to produce the classic ATS pattern. Consequently, the Saunders et al animals in the interrupted exposure paradigm never had an opportunity to reach the asymptotic level associated with a 2-4 kHz octave band of noise set at 72 dB. However, as Blakeslee et al pointed out, the time constant for impulse noise ATS was between 1 and 2 hours. Therefore, during each of the five days' exposure to impulse, the animal had time to reach an asymptotic level of threshold shift.

If, as Mills (1973) has suggested, ATS is a prediction of eventual PTS, then the thresholds at the end of a day's exposure to impulse noise are more likely indicative of the ultimate hearing damage. Conversely, the thresholds after a day's exposure to continuous noise are not at asymptote and are probably an underestimate of the ultimate hearing damage to be suffered over many years.

There is a temptation to equate traumatic effects of the "work week" exposure of this experiment with the results reported by Blakeslee et al of the ten day exposure to the same impulse. As Figure 10 shows, the level of ATS is remarkably close; however, when the cochleagrams are compared for the two exposures the 10 day exposure is much more traumatic. The "work week" exposure produced negligible PTS with only small hair cell loss in 2 out of 6 animals while the 10 day exposure produced severe basal lesions in 4 out of the 5 animals and the median PTS was 20 dB in the 2-4 kHz region. This is not a particularly surprising result. Bohne (1976) exposed chinchillas to one of 5 levels of octave band noise centered at either 0.5 kHz or 4.0 kHz for 2 or 9 days. She found that despite the fact that the threshold shifts in each group reached an asymptotic level by the second day, the nine day exposure produced significantly larger hair cell losses within each noise group. An obvious conclusion is that one cannot equate the severity of two noise exposures on the basis of the level of ATS alone.

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Saunders, J.C., Mills, J.H., and Miller, J.D., "Threshold Shift in the Chinchilla from Daily Exposure to Noise for Six Hours," J. Acoust. Soc. Am. 61: 558-570 (1977).

FIGURE LEGENDS

Figure 1:	Skull of the chinchilla with the bipolar electrode in place.
Figure 2:	View of a chinchilla being restrained by the jump-stand apparatus within the sound booth and showing: (a) microswitch for detecting responses; (b) electrodes attached to tail with tape; (c) support grid.
Figure 3:	Comparison of median pre-exposure thresholds for the two psychophysical techniques used in this study with those of Miller (1970).
Figure 4:	Samples of typical threshold determinations for 0.25, 2 and 8 kHz signals. Threshold is determined to be between a level that manifests a N_1-P_1 response and a level that does not.
Figure 5:	Acoustic characteristics of the clacker impulse noise generator.
Figure 6:	1000 Hz thresholds for each chinchilla measured over the 5 days of exposure.
Figure 7:	Median threshold shifts for test frequencies between 0.25 and 8 kHz measured over the 5 days of exposure. 0.25 kHz results based on AER data only.
Figure 8:	Comparison of pre-exposure thresholds with final median audiogram measured at 30 days post-exposure. 0.25 kHz results based on AER data only.

Figure 9: Inner hair cell (IHC) and outer hair cell (OHC) loss and permanent threshold shift (PTS) for the animal with the greatest hearing loss and largest amount of missing hair cells.

Figure 10: Comparison of the median threshold shifts at 8 kHz measured over the 5 days of exposure with the ATS level produced by uninterrupted exposure to the same impulse as reported by Blakeslee, et al., 1978.

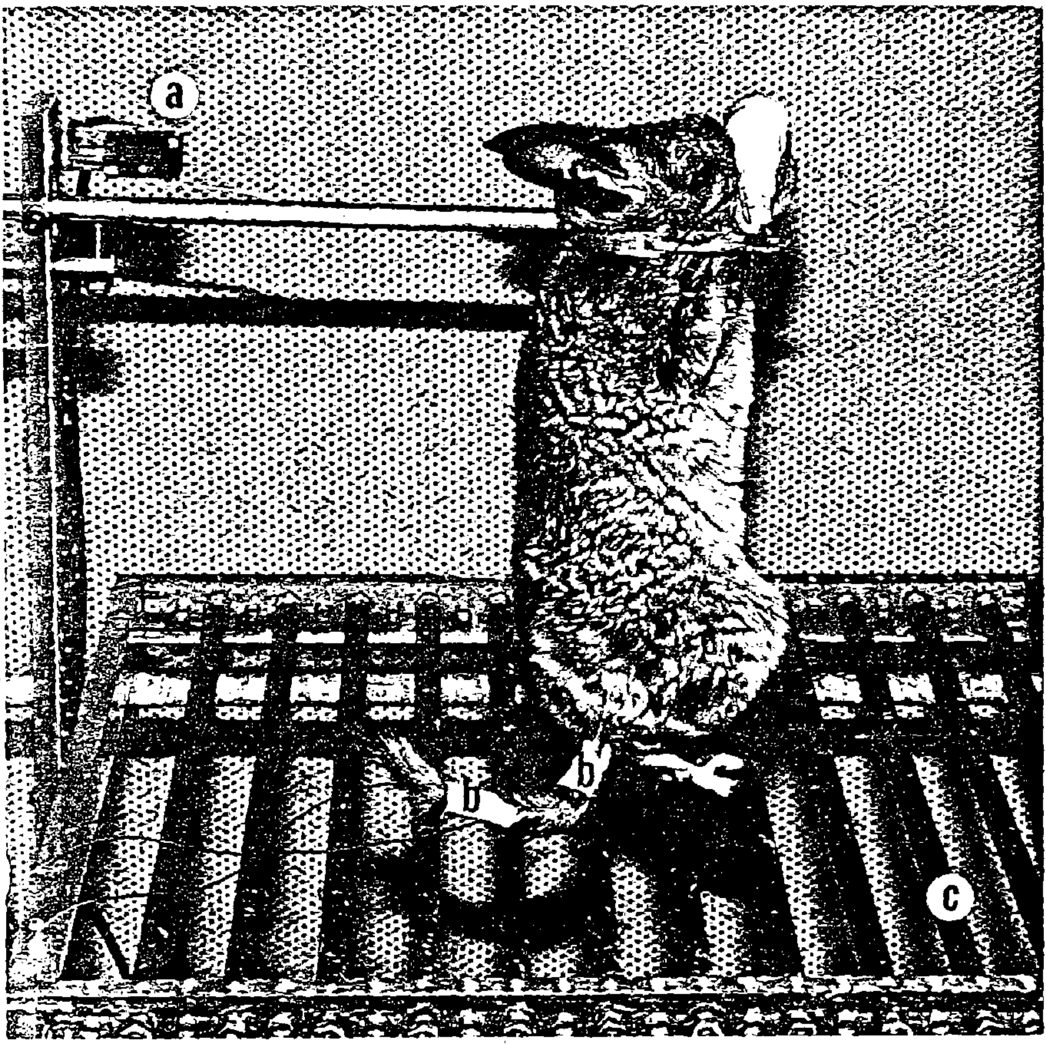


FIG.

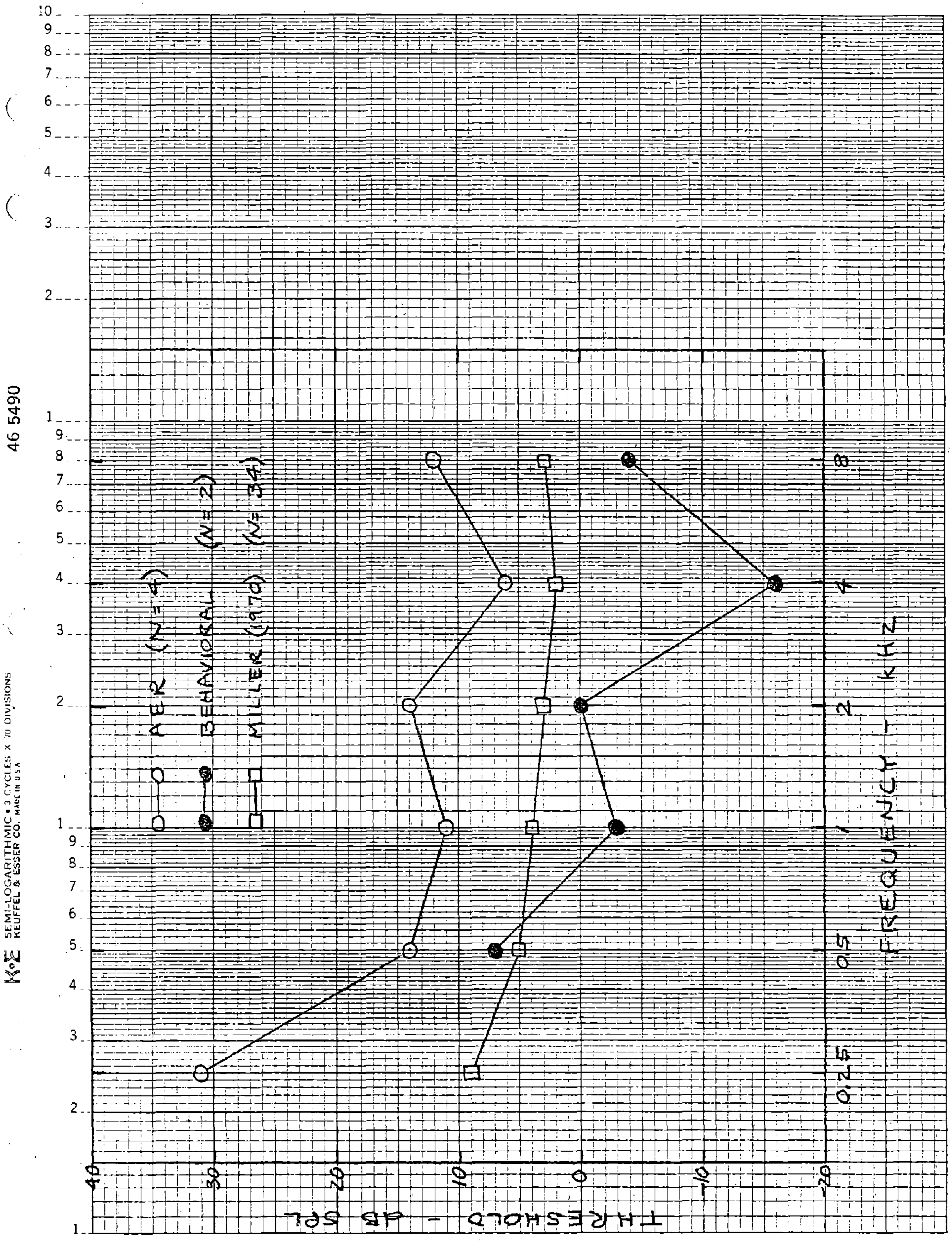

AER (N=4)
BEHAVIORAL (N=2)
MILLER (1970) (N=34)
THRESHOLD - dB SPL
40
30
20
10
0
-10
-20
FREQUENCY - KHZ
0.25
0.5
1
2
4
8
46 5490
K&E SEMI-LOGARITHMIC • 3 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

FIG. 3

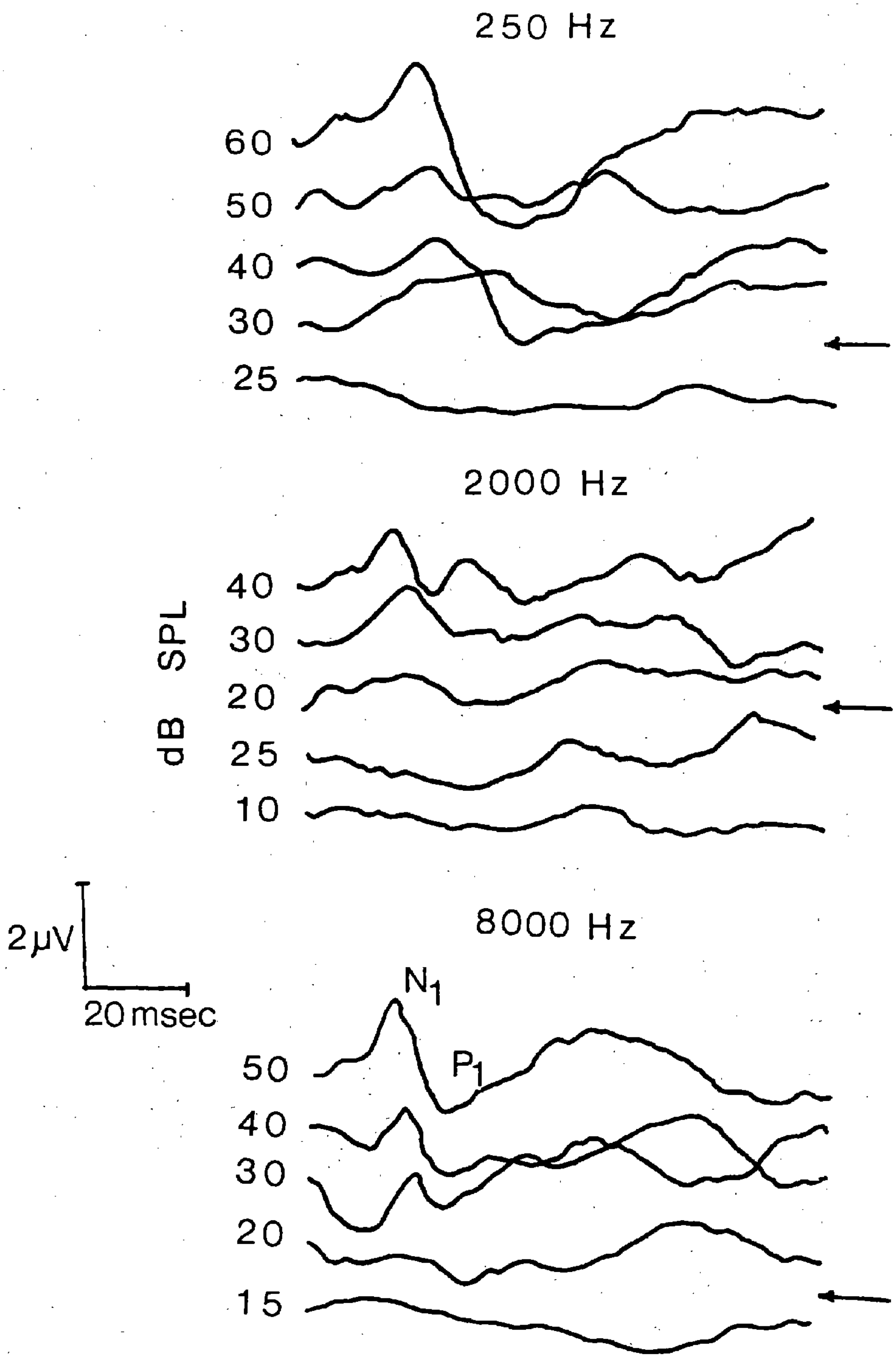
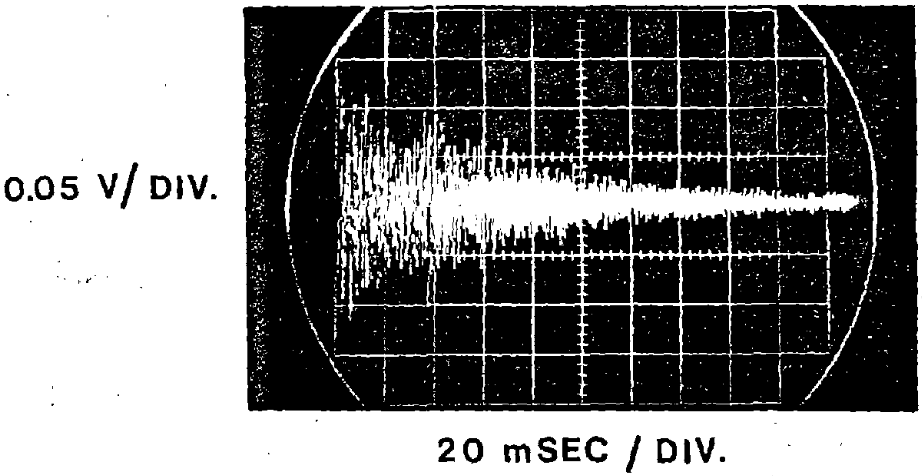

250 Hz
60
50
40
30
25
2000 Hz
40
30
20
25
10
dB SPL
2μV
20 msec
8000 Hz
N1
P1
50
40
30
20
15

FIG. 4


WAVEFORM

PEAK PRESSURE : 113 dB SPL

B DURATION : 160 mSEC

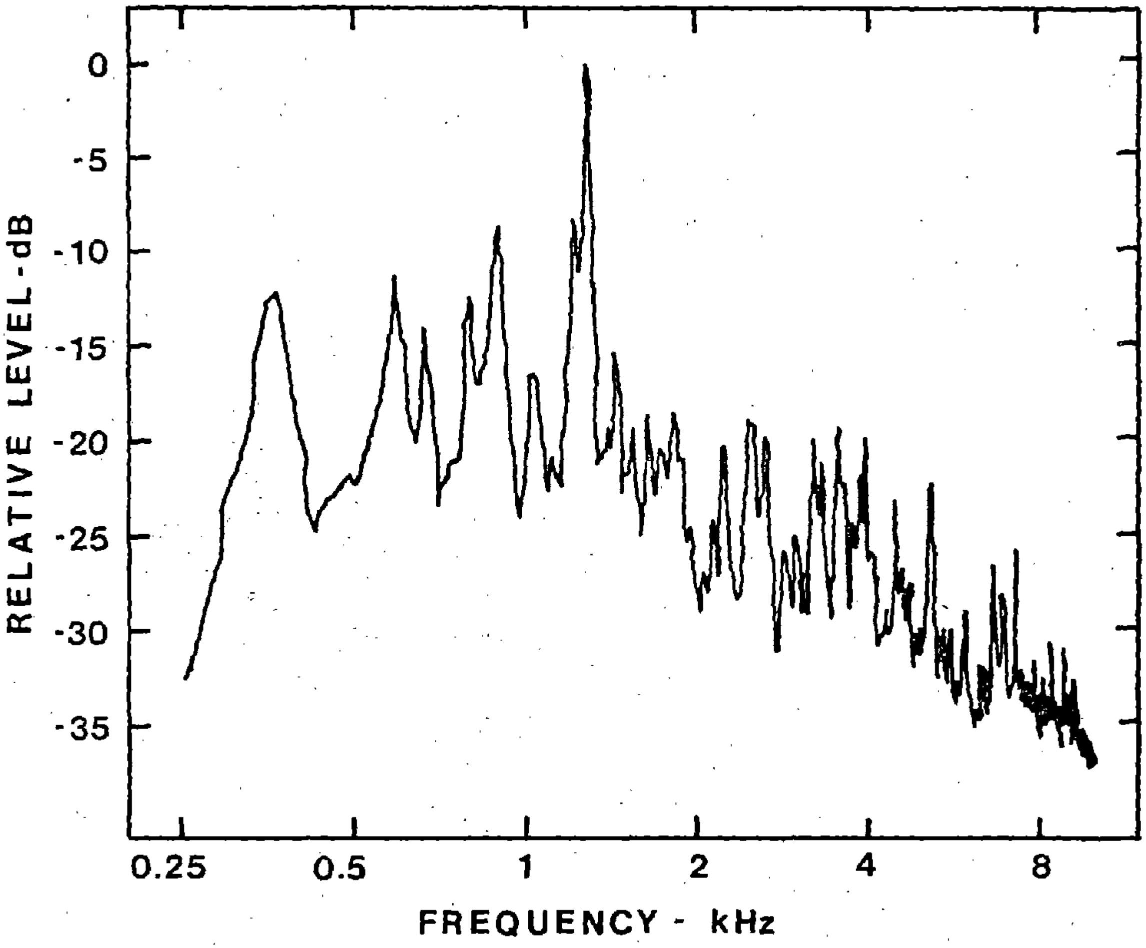

AMPLITUDE SPECTRUM

FIG. 5

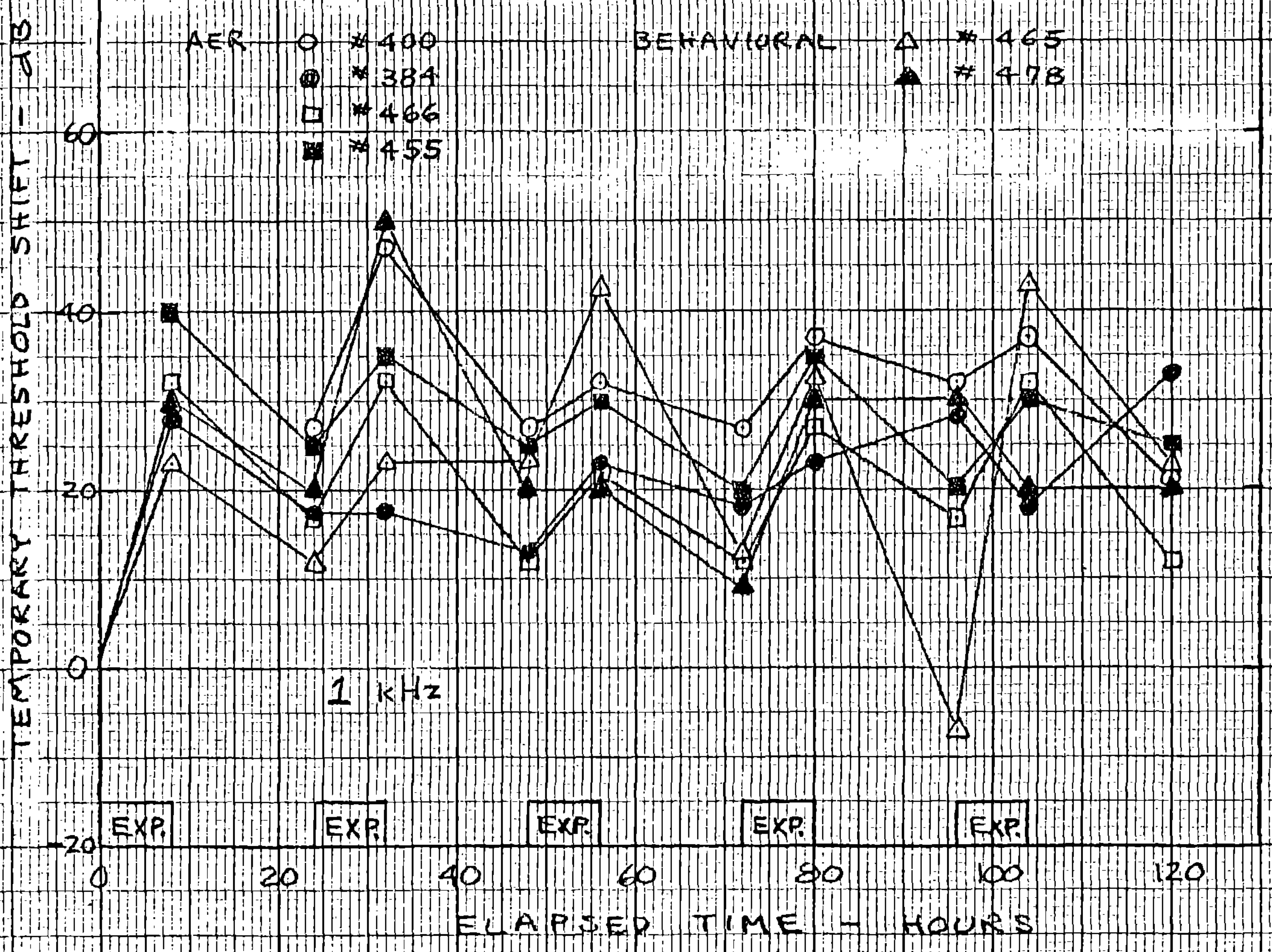
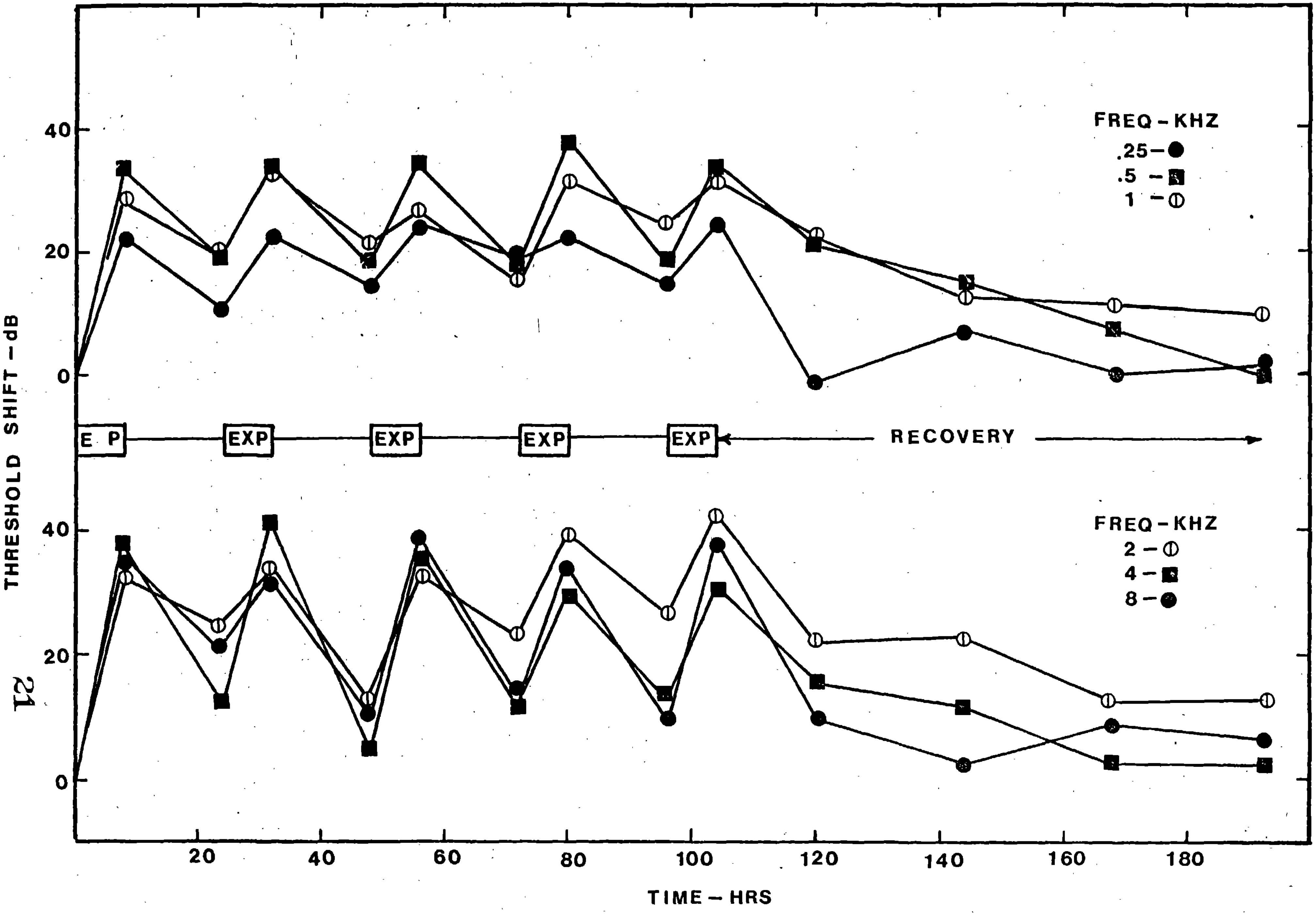

AER ○ #400
◎ #384
□ #466
▩ #455
BEHAVIORAL △ #465
▲ #478
TEMPORARY THRESHOLD SHIFT - dB
60
40
20
0
-20
1 kHz
EXP.
EXP.
EXP.
EXP.
EXP.
0
20
40
60
80
100
120
ELAPSED TIME - HOURS

FIG. 6


FREQ-KHZ
.25-●
.5 -■
1 -⦶
FREQ-KHZ
2 -⦶
4 -■
8 -●
E P
EXP
EXP
EXP
EXP
RECOVERY
THRESHOLD SHIFT - dB
40
20
0
40
20
0
20
40
60
80
100
120
140
160
180
TIME - HRS

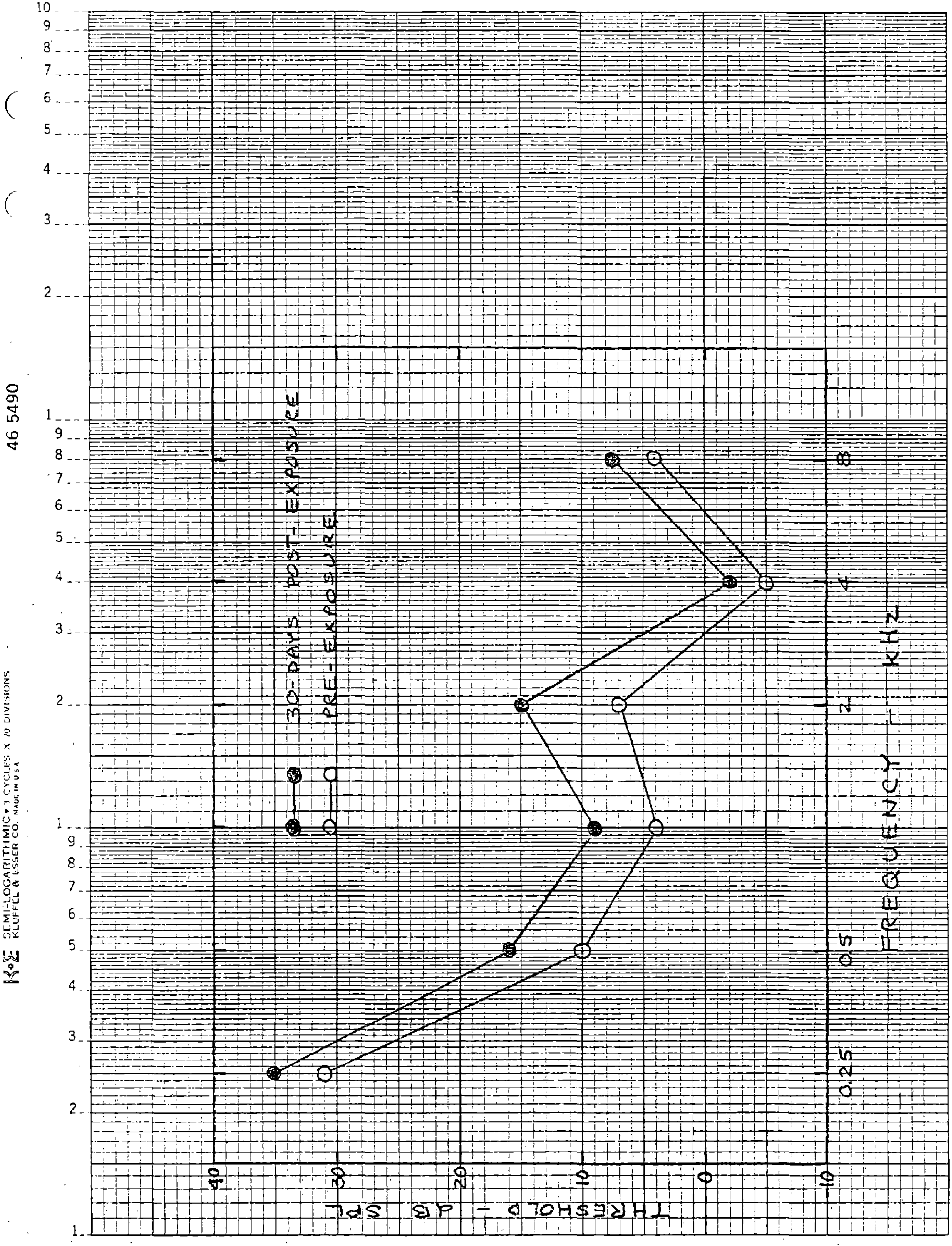
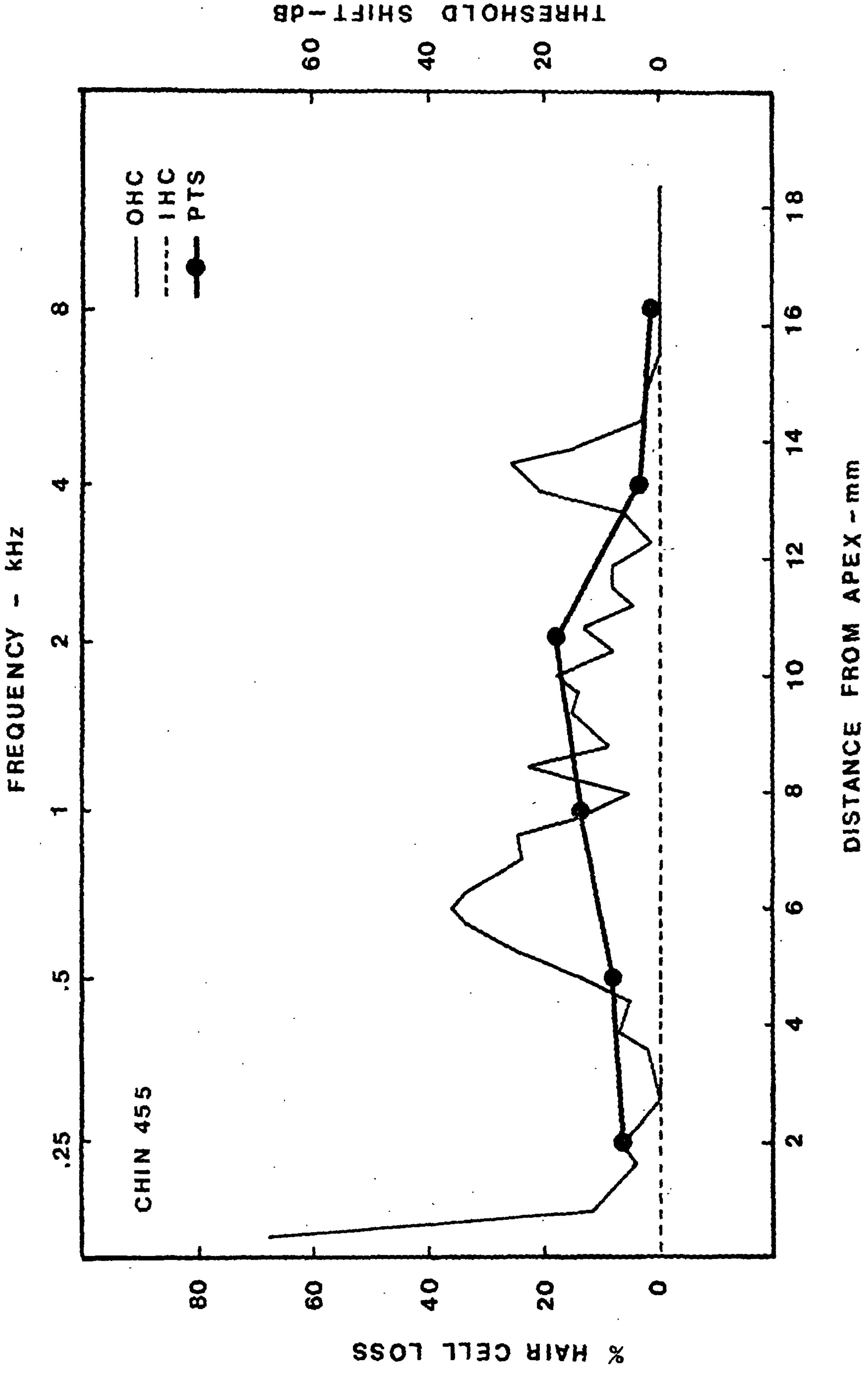
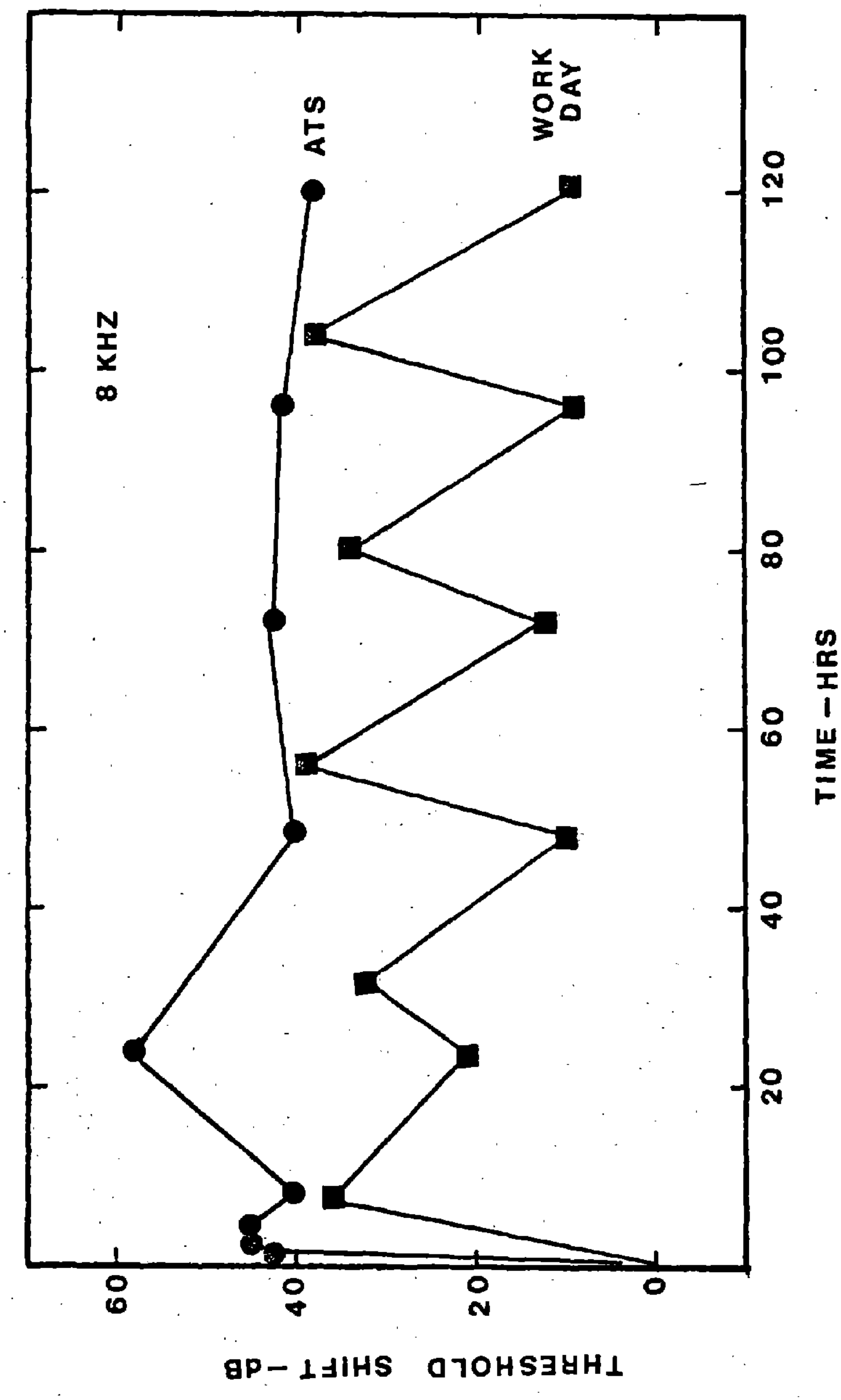

30-DAYS POST-EXPOSURE
PRE-EXPOSURE
FREQUENCY - KHz
0.25
0.5
2
4
8
THRESHOLD - dB SPL
40
30
20
10
0
10
46 5490
K&E SEMI-LOGARITHMIC • 3 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

FIG. 8


FREQUENCY - kHz
.25
.5
1
2
4
8
THRESHOLD SHIFT-dB
60
40
20
0
OHC
IHC
PTS
CHIN 455
% HAIR CELL LOSS
80
60
40
20
0
DISTANCE FROM APEX - mm
2
4
6
8
10
12
14
16
18


8 KHZ
ATS
WORK DAY
THRESHOLD SHIFT - dB
0
20
40
60
TIME - HRS
20
40
60
80
100
120