

Table 1. Peak Pressure Levels of Various Firearms

<u>Rifle #</u>	<u>Description</u>	<u>dB PPL (SLM)</u>	<u>Pascals peak (RTA)</u>
1.	7 mm Mouser	154.9	1160
2.	.270 cal with BOSS; 130 grain Power Point	164.6	3140
2.	.270 cal with BOSS; 150 grain	163.9	3110
2.	.270 cal with attachment—No BOSS; 130 grain	158.1	1660
2.	.270 cal with attachment—No BOSS; 150 grain	157.3	-
3.	(?) No BOSS, no attachment; 130 grain	157.9	1520
3.	(?) No BOSS, no attachment; 150 grain	157.1	1400
4.	Browning .22/250 with BOSS; 40 grain	163.1	2960
4.	Browning .22/250 with BOSS; 55 grain	162.9	2790
4.	Browning .22/250 with cover—No BOSS; 40 grain	155.3	-
4.	Browning .22/250 with cover—No BOSS; 55 grain	154.1	-
5.	.300 Win Mag bolt with cover—No BOSS; xxx ammo	157.5	1630
5.	.300 Win Mag bolt with cover—No BOSS; high velocity	161.5	2380
5.	.300 Win Mag bolt with BOSS; xxx ammo	164.8	3170
5.	.300 Win Mag bolt with BOSS; high velocity ammo	165.5+	3240
6.	7 mm “Plain Jane”; 140 grain	158.3	1660
6.	7 mm “Plain Jane”; 160 grain	157.5	1545
7.	7 mm with BOSS; 140 grain (same as #6 ammo)	163.6	3110
7.	7 mm with BOSS; 160 grain (same as #6 ammo)	163.5	3110
7.	7 mm with cover—No BOSS; 140 grain (same as #6)	159.5	1880
7.	7 mm with cover—No BOSS; 160 grain (same as #6)	157.8	1460
8.	.300 Win Mag plain barrel; 180 grain	158.3	1650
8.	.300 Win Mag plain barrel; 180 grain high velocity	158.8	1780
9.	.338 Win with cover—No BOSS; 210 grain	157.1	1470
9.	.338 Win with cover—No BOSS; 250 grain	156.8	1430
9.	.338 Win with cover—No BOSS; 250 grain high energy	161.5	1530
9.	.338 Win with BOSS; 210 grain	164.5	3230
9.	.338 Win with BOSS; 250 grain	163.8	3100
9.	.338 Win with BOSS; 250 grain high energy	164.5	3200

Table 2. Duration of Peak Pressure Levels for Various Firearms

<u>Rifle #</u>	<u>Description</u>	<u>dB PPL (SLM)</u>	<u>Duration (millisec)</u>
3.	7 mm Mouser	154.9	3.3
4.	.270 cal with BOSS; 130 grain Power Point	164.6	3.5
2.	.270 cal with BOSS; 150 grain	163.9	3.8
2.	.270 cal with attachment—No BOSS; 130 grain	158.1	3.5
2.	.270 cal with attachment—No BOSS; 150 grain	157.3	-
3.	(?) No BOSS, no attachment; 130 grain	157.9	3.4
3.	(?) No BOSS, no attachment; 150 grain	157.1	3.2
4.	Browning .22/250 with BOSS; 40 grain	163.1	2.9
4.	Browning .22/250 with BOSS; 55 grain	162.9	3.1
4.	Browning .22/250 with cover—No BOSS; 40 grain	155.3	-
4.	Browning .22/250 with cover—No BOSS; 55 grain	154.1	-
5.	.300 Win Mag bolt with cover—No BOSS; xxx ammo	157.5	3.5
5.	.300 Win Mag bolt with cover—No BOSS; high velocity	161.5	3.0
5.	.300 Win Mag bolt with BOSS; xxx ammo	164.8	4.1
5.	.300 Win Mag bolt with BOSS; high velocity ammo	165.5+	3.5
6.	7 mm “Plain Jane”; 140 grain	158.3	3.7
6.	7 mm “Plain Jane”; 160 grain	157.5	3.4
7.	7 mm with BOSS; 140 grain (same as #6 ammo)	163.6	3.7
7.	7 mm with BOSS; 160 grain (same as #6 ammo)	163.5	3.6
7.	7 mm with cover—No BOSS; 140 grain (same as #6)	159.5	2.8
7.	7 mm with cover—No BOSS; 160 grain (same as #6)	157.8	3.5
8.	.300 Win Mag plain barrel; 180 grain	158.3	3.5
8.	.300 Win Mag plain barrel; 180 grain high velocity	158.8	4.0
9.	.338 Win with cover—No BOSS; 210 grain	157.1	3.5
9.	.338 Win with cover—No BOSS; 250 grain	156.8	3.8
9.	.338 Win with cover—No BOSS; 250 grain high energy	161.5	3.7
9.	.338 Win with BOSS; 210 grain	164.5	3.4
9.	.338 Win with BOSS; 250 grain	163.8	3.8
9.	.338 Win with BOSS; 250 grain high energy	164.5	3.8

The Decibel (dB) & Sound Measurement (What do those dBs mean?)

The Decibel (dB)

Most individuals have heard the word "decibel" used to describe how loud something is. It's probably no surprise that a 100 decibel (dB) noise would be a lot louder than a 50 dB noise. What may be surprising, however, is that 100 dB isn't twice as loud as 50 dB (60 dB is approximately twice as loud as 50 dB!). And zero dB doesn't mean "no sound." This confuses a lot of people, but a brief explanation of sound and the decibel scale, plus a few analogies (for those who dread algebra), follow.

Any vibrating object creates local changes in atmospheric pressure. These pressure fluctuations travel as waves through the air to our ears, and we experience sound. How rapidly an object vibrates determines its frequency or "pitch." Musicians often use the term "pitch" as a synonym for frequency. Technically, frequency (measured in Hertz or Hz) is what we measure; pitch is what we perceive. The intensity, or what we call "loudness," depends on how great these pressure changes are. Sound pressure level (SPL) is the objective measure of sound intensity, loudness is the perceptual correlate. Sound pressure level is normally expressed in decibels sound pressure level (dB SPL). The reason for not expressing SPL as a unit of pressure (e.g. Pascals) follows.

The metric unit of pressure is the Pascal (Pa). Under optimal conditions, the lowest pressure that can be heard by a person with normal hearing is approximately 0.00002 Pa (= 20 μ Pa). The loudest sound pressure that most humans can tolerate is about 200 Pascals, which is 10 million times greater than the lowest sound pressure that can be heard. Dealing directly with so wide a range is cumbersome; consequently, the decibel scale was devised to make sound measurements manageable. The decibel scale quantifies sound level by taking the logarithm of the ratio between a sound pressure divided by a reference pressure and multiplying this result by 20, thus allowing us to compress a very wide pressure range into more easily managed numbers. By definition, the reference pressure (0 dB) for the sound pressure level scale is 20 microPascal (μ Pa). Here's an example to demonstrate how the decibel scale allows us to compress a wide pressure range to a more manageable range:

The average sound pressure of speech at a distance of 5 ft. is about 0.064 Pa. The SPL, in decibels, is

$$20\log \frac{0.064 \text{ Pa}}{0.00002 \text{ Pa}} = 20\log 3200 = 70.1 \text{ dB SPL.}$$

(Note that the pressure of speech at this distance is 3200 times greater than the faintest sound pressure we can detect.)

It is important to note that if we double the pressure we won't double the SPL. If we double the pressure from our previous example, we get

$0.064 \text{ Pa} \times 2 = 0.128 \text{ Pa}$. In units of dB, this is

$$20 \log \frac{0.128 \text{ Pa}}{0.00002 \text{ Pa}} = 20 \log 6400 = 76.1 \text{ dB SPL, a 6 dB increase.}$$

Similarly, we can show by calculation (or measurement) that if two rifles differ in SPL by 6 dB, the "louder" rifle is creating twice the sound pressure (in Pascal, not SPL) of the "quieter" rifle.

It is reasonable to assume that doubling the sound pressure would result in a sound that is twice as loud. Unfortunately, this isn't the case. Our perceptual response to intensity (and frequency) isn't linear, so what we perceive as being twice as loud isn't a simple function of sound pressure, or even sound power (see note 3). A very good approximation, however, is that a 10 dB increase in SPL will result in a doubling of "loudness." A rifle producing a SPL of 150 dB is approximately twice as loud as a rifle producing 140 dB. Here's a real-life analogy to help clarify the decibel (dB) and perceived loudness:

At a distance of 5 ft., the SPL of normal speech is approximately 70 dB SPL (we can easily measure this with a sound level meter—more on this below). If another person starts talking (also 5 ft. away), the SPL doesn't increase to 140 dB (this would be deafening!). What we would measure with the sound level meter is, in fact, more along the lines of a 3 dB increase. Perceptually, two people talking at once is louder than one person talking, but not twice as loud. If we had 10 people talking simultaneously in a room, we'd measure about 80 dB; this is approximately twice as loud as a single talker. We're assuming, of course, that no one is screaming or whispering.

For high-intensity sounds, a 3 dB change in SPL is quite noticeable. For example, compare the SPL of one rifle #7 (7mm) with its cover on (no BOSS) and with its muzzle brake (BOSS) on. The measured difference is $(163.6 - 159.5) \text{ dB SPL} = 4.1 \text{ dB}$. The difference in loudness is quite apparent. With regard to high-intensity sounds, a 1dB change in SPL is noticeable, even to the untrained ear. (Note: For low-intensity sounds, a 1 dB change is barely discernable—this has to do with the physiology of the human ear.) In summary, a rifle that produces a SPL of 141 dB is slightly "louder" than one producing 140 dB. A rifle producing 143 dB SPL is quite a bit louder, and a rifle producing 150 dB SPL is twice as loud (which is pretty loud considering 140 dB is loud enough). **Readers should be aware that a 10-dB increase in SPL is equivalent to a three-fold increase in pressure on the eardrum.**

The Measurement Process

Sound can be expressed in terms of power, pressure, or sound pressure level (SPL). Readers are referred to note 3 for an explanation of the relationship between sound power and sound pressure. Measuring sound power directly is difficult because it requires measuring the movement of the individual air molecules. Fortunately, it is relatively easy to measure the sound pressure level (SPL) directly using a sound level meter. Basically, the sound level meter consists of a pressure-sensitive microphone connected to an electronic voltmeter. The microphone converts sound pressure into an analogous electric voltage. Circuitry within the sound level meter (SLM) converts the signal from the microphone to an electrical equivalent of sound pressure level. The meter displays the voltage in units of dB SPL.

The "response time" (a meter-dynamic characteristic) of most sound level meters, even cheap ones, can be switched from "SLOW" to "FAST." In the FAST mode, the sound level meter must accurately respond to a signal of 200 millisecond (0.2 second) duration. Measuring steady-state noise (e.g. noise produced by machinery) is straightforward because the sound's duration is typically greater than 0.2 second. Unfortunately, sound level meters don't accurately measure the SPL of rifles because the duration of the sound (excluding echoes from surrounding hills or trees) is very short. For this reason, impulse precision sound level meters were initially used. But the response time in IMPULSE mode proved to be too slow for accurately measuring the SPL of rifle shots.

BIG NOTE: Sound level meters (SLM) used to perform noise surveys aren't designed to measure peak noise levels; they're designed to accurately measure steady-state noises such as noise produced by machinery. A SLM used for measuring steady-state noise (even in FAST response mode) will not accurately measure the SPL of a rifle shot. A SLM in SLOW response mode will barely detect a rifle shot! As I had discovered during previous firearms testing, a SLM designed to measure short-duration (e.g. 10 millisecond) impulse noises won't accurately measure the peak pressure produced by a muzzle blast.

Reader's familiar with sound measurement may question this, so let me explain a scenario I encountered when I first began analyzing muzzle blasts.

During one day of testing, about 15 different rifles were fired. I held the sound level meter close to the shooter's right ear and positioned myself so as not to interfere with the measurement. Two different sound level meters were used: A Larson-Davis model 800B and a Brüel & Kjær model 2209. The first of 15 rifles tested was a small-bore target rifle. With CCI Mini Group shorts, a reading of 105 dB SPL was obtained (IMPULSE mode). In the FAST mode, a reading of 102 dB was obtained. The lower reading in FAST mode was expected. In the

IMPULSE mode, a 117 dB reading was obtained using Super-X Expiditer ammo (same target rifle). So far, the measurements looked reasonable. The next rifle tested was an UltraLight 280 using Winchester Super-X ammo. I measured 136 dB SPL which seemed reasonable compared to the small-bore rifle's modest SPL. What became an obvious problem (obvious meaning 15 rifles later) was that all of the high-power rifles gave approximately the same reading of 133 dB SPL in IMPULSE mode, and a more compressed reading in FAST mode.

The problem at that time became apparent while testing a .22/250 with and without its muzzle brake (BOSS). Anyone who's fired a rifle (or has been in the vicinity of a rifle) with a muzzle brake knows that it's a lot louder than the same rifle/ammo without the muzzle brake. However, my first day of testing using supposedly "objective" measurements fell short of demonstrating this: I measured 133 dB SPL with and without the boss!

After a day of testing and suspect results, I made a few phone calls. I spoke with several other people who also perform noise surveys and know the OSHA guidelines for measuring noise in factories, etc. Unfortunately, nobody was able to provide any insight to the problem I was experiencing. One possibility that I had considered was that the sound level meters were "overloading" due to the intensity of the rifle shots. But both the Larson-Davis and Brüel & Kjær meters have built-in overload indicators. I briefed through the Instruction and Applications manual for the B&K sound level meter. A chart showed that the meter reading, even in IMPULSE mode, is (as was suspected) affected by the duration of the signal. The only available option was to measure the peak pressure level (versus sound pressure level) produced by each rifle, or record the rifle shots and observe the waveform on a storage oscilloscope. Both the L-D and B&K sound level meters are precision laboratory instruments and are capable of measuring peak pressures. A storage oscilloscope wasn't available at the original test site, but I was equipped with a portable Sony DAT (digital audio tape) recorder. The recorded rifle shots were recorded using a DAT recorder and subsequently analyzed using a spectrum analyzer and a digital storage oscilloscope (more on this below).

The reason for not using the sound level meters in PEAK (peak pressure) mode from the start was because this created another (but surmountable) problem. The maximum pressure that could be measured was 140 dB (peak pressure) before overload occurred. For small caliber rifles and pistols, this wasn't a problem. But the peak pressure level (PPL) at the shooter's ear exceeded 140 dB with the majority of the firearms tested. The problem, then, was how to determine the PPL at the shooter's ear without overloading the instruments. The only way to do this was to move the sound level meters a sufficient distance from the shooter so that even the loudest rifle wouldn't overload the meter. In order to determine the PPL at the shooter's ear, a "correction factor" would have to be added

to the results obtained with the meter some distance from the rifle. It was desirable to get the SLM as close as possible to the rifles in order to maximize the "signal-to-noise ratio." In short, if the meter is too far away, other noises (environmental, wind, etc.) would be nearly as loud as the noise being measured and possibly obscure the measurement. Fortunately, even the quietest rifle shots were loud enough at 50 ft. to be much louder than the ambient, or background, noise.

Fifty feet was chosen because this was the minimum distance from the loudest rifle that wouldn't cause the meters to overload in PEAK mode. A correction factor of 25 dB was determined empirically as follows: A small-bore rifle was fired while the meter was held at the shooter's ear. (Unlike the larger rifles, this didn't overload the meter.) Several shots were fired from the same rifle to ensure measurement repeatability. Next, the sound level meter was placed 50 ft. behind the shooter (and free of obstructions). The same small-bore rifle was fired again. The measured PPL at 50 ft. was 25 dB less than at the shooter's ear; hence the 25 dB correction factor.

Readers who have been able to follow this discussion thus far may question the difference between dB SPL (which is the normal unit for sound measurement) and dB PPL. Peak pressure level measurements and SPL use the same reference pressure of 20 microPascal (= 0 dB). Conventional sound pressure level (SPL) measurements reference sound or noise that has a duration exceeding several cycles of vibration. Peak pressure levels measure the single greatest change in pressure, even though the duration may only be half of a cycle. This is justifiable when measuring the intensity of firearms because the peak pressure can occur within one vibratory cycle, plus the ear can perceive the loudness differences of such noise.

The results using PPL in lieu of SPL correlate well with our perception of loudness. (Note: This is true for rifle shots, but not necessarily all types of noise.) One noteworthy difference in the results obtained using PPL versus SPL comes to mind. During my first day of testing, I measured 132 dB SPL for an M30 Carbine using GI ammo. The .22/250 (with BOSS) gave a reading of 133 dB SPL. This would lead us to believe that the Browning is only 1 dB louder than the M30 and would suggest a discernible, but not big, difference in loudness. Results obtained using peak pressure measurements yielded a much greater difference. The M30 measured 123 dB PPL (at 50 ft.) and the Browning 22/250 measured 137 dB PPL (again, at 50 ft.). The difference here is 14 dB. Anyone in the vicinity of the test site would have told you that there was a huge difference in loudness between these two rifles. Measurements using PPL reveal this difference; conventional SPL measurements did not.

Two sound level meters, a Brüel & Kjær (B&K) model 2209 impulse precision sound level meter and a Larson-Davis 800B, were used to make recordings of the rifle shots. The output of the B&K meter was connected

to the right-channel input of a Sony DAT (digital audio tape) recorder. The Larson-Davis SLM was connected to the left-channel of the recorder. Recordings of the rifle shots were analyzed using a Tektronix model 7854 digital storage oscilloscope and SpectraPLUS (Pioneer Hill) spectrum analyzer software. The maximum pressure level using the analyzer was used primarily to confirm the results obtained using the SLM. Note: Both the L-D and B&K meters were calibrated before testing began. Calibration readings were obtained after we completed our testing to verify that the sound level meters did not incur damage during testing.

Table 1 shows the sound intensity of various firearms using peak pressure level (PPL) measurements. The second column, labeled "dB PPL (SLM)" is the reading obtained directly from the Larson-Davis model 800B SLM (mode = PEAK) plus the 25 dB correction. The right-most column, labeled "Pascals peak (RTA)" is the peak pressure (in Pascals) measured via the spectrum analyzer software.

Here are a few observations: The blast noise emanating from a rifle with a muzzle brake is measurably more intense than the same rifle without a muzzle brake. The .300 Win Mag bolt action (using xxx ammo—see Table 1) measured 7.3 dB more intense with the BOSS than without the BOSS. Note: A 7.3 dB increase in PPL is a 2.3-fold increase in sound pressure, as shown below:

$$20\log \frac{[2.32P]}{P} = 20\log \frac{2.32}{1} = 20 \times 0.365 = 7.3 \text{ dB}$$

Similarly, the Browning .22/250 (40 grain) measured 7.8 dB more intense with its BOSS than without it. Other comparisons can be made using Table 1.

Note: When comparing firearm peak pressure levels using Table 1, remember that a 1 dB difference can be heard, a 3 dB increase is “quite a bit” louder, and a 10 dB increase is “twice as loud.”

Noise and Hearing Loss

Noise surveys using sound level meters are performed in workplaces to determine if workers are at risk for hearing loss. Two primary variables dictate guidelines previously set forth by OSHA: The sound’s intensity ("loudness") and the time duration a worker is exposed to noise. According to OSHA guidelines, workers exposed to noise at or below 85 dB SPL(A) are not required to wear hearing protection. Workers exposed to noise levels at 90 dB SPL(A) for up to 8 hours must wear hearing protection. For 95 dB SPL(A), the maximum exposure time is 4 hours; for 100 dB SPL(A) the maximum time is 2 hours—this function of SPL versus time is known as the "5 dB exchange rate." When the noise level increases 5 dB, the maximum safe exposure time is halved. Workers are

required to wear hearing protection anytime a noise level exceeds 115 dB SPL(A). But even with these guidelines, approximately 50% of workers could experience some hearing loss at these levels without hearing protection.

The effects of hearing loss as a result of blasts (such as those produced by firearms) isn't as well documented as occupational hearing loss. There are individuals who have suffered permanent hearing loss as a result of shooting, but the effects of single, loud-noise events varies from person to person. One common complaint shooters have isn't hearing loss, but tinnitus (a "ringing in the ear"). It should be noted that tinnitus frequently accompanies hearing loss resulting from noise exposure.

The most well-known aftereffect of exposure to high-intensity sound is the change in auditory sensitivity. If an individual's auditory threshold (hearing sensitivity) is measured before and after an exposure, the difference in hearing threshold levels is, by definition, the threshold shift (TS). If the threshold shift later disappears, then it is called a temporary threshold shift (TTS). If the shift does not disappear, the final measured threshold shift is called a permanent threshold shift (PTS).

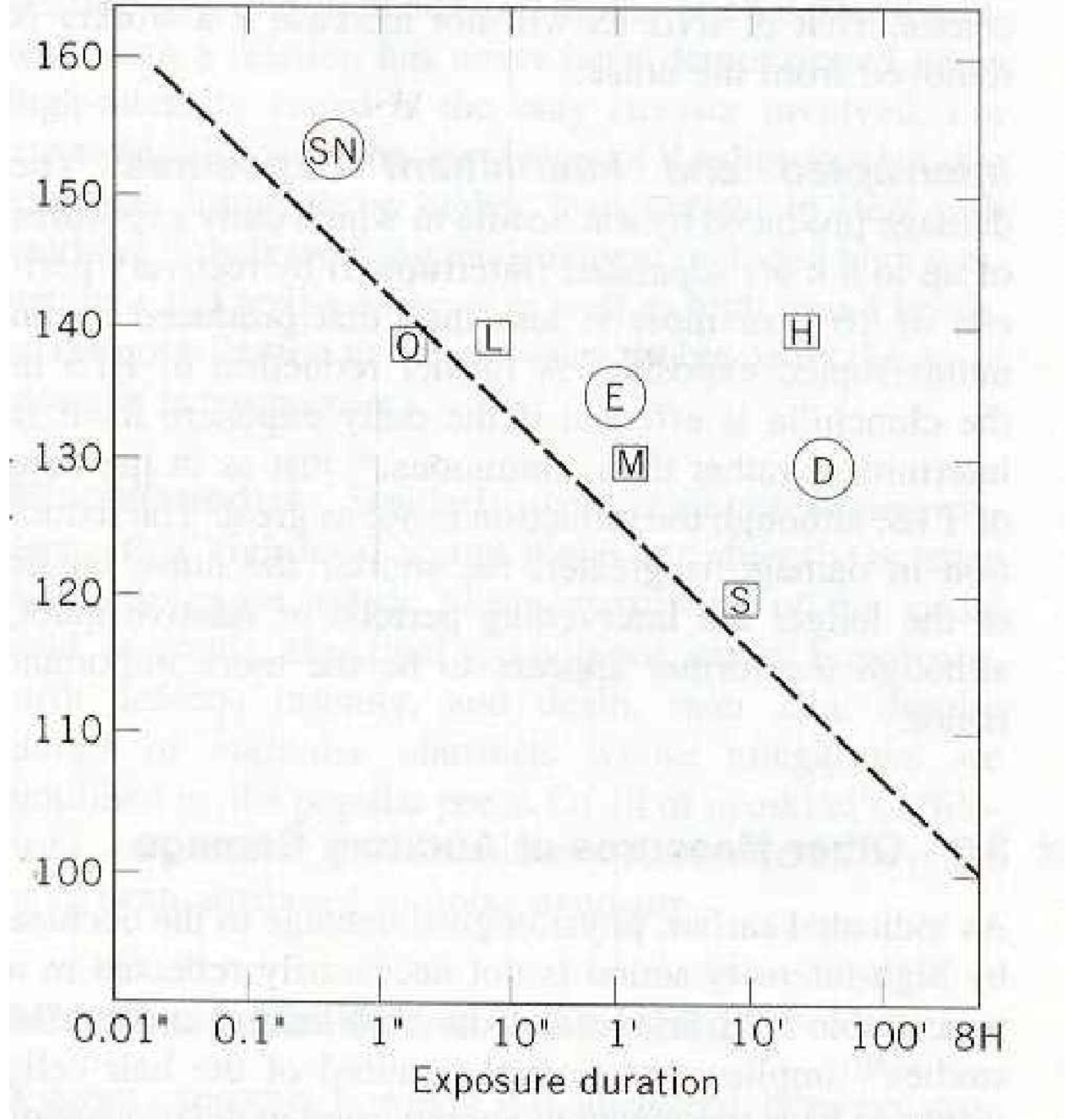
The most undesirable aftereffect of exposure to high-intensity sound is a PTS. Sound-induced PTS is commonly divided into two categories depending on whether the loss was produced by a single, short exposure at a very high intensity (acoustic trauma) or by repeated longer exposures to noise at more moderate sound pressure levels. It is clear from animal studies that in acoustic trauma the inner ear has been subjected to such stress that its mechanical (or elastic) limit has been exceeded. Various structures of the organ of Corti, including hair cells (the individual receptor cells within the inner ear), may become partly or wholly detached. Additionally, one or more of the several membranes in the cochlea may be ruptured, allowing an intermixture of fluids of different composition, thereby poisoning hairs cells that survived the mechanical stress. The end consequence is a pronounced loss of hearing sensitivity at the frequencies correlated with the locus of this destruction.

Less is known about acoustic trauma in humans, although it is not at all rare. Victims of acoustic trauma seldom have had a recent audiogram that would enable the amount of threshold shift to be determined with certainty. And unlike controlled studies utilizing animals, information regarding the exposure level and duration isn't always known. Finally, differences among people in susceptibility to damage are so great that single cases show that acoustic trauma is possible from a given exposure but not that it is inevitable to everyone exposed. In other words, a given exposure, however it is measured, does not produce the same hearing loss in every ear.

Figure 1 below shows a comparison of single noise exposures that have been shown to be "without hazard" to the [average young healthy ear](#) (circled symbols) and those that have apparently produced 15 dB or more of

permanent threshold shift in at least one person (symbols in squares). The dashed line, representing 8 hours of exposure at 100 dB SPL or its energy equivalent (more on this below), divides single exposures that are “probably safe” from those that are capable of causing permanent damage in individuals (ref. 1). Note: Physiological damage to the cochlea by high-intensity sound is not necessarily reflected in a measurable PTS. Evidence from both animal

Figure 1. Comparison of single noise exposures that have been shown to be "without hazard" to the average young healthy ear (circled symbols) and those that have apparently produced 15 dB or more of permanent threshold shift in at least one person (symbols in squares) (ref. 1).



and human studies implies that several hundred of the hair cells that have been presumed to be important in the process of hearing may be destroyed before a change in threshold is measurable (ref. 2).

Four of the exposures labeled in the figure are from the studies of Davis et al. (ref. 3) on the effect of noise: Point D—32 minutes at 130 dB SPL; Point M—1 minute exposure to a 2-kHz tone at 130 dB SPL; Point S—8 minute exposure to a 4-kHz tone at 120 dB SPL. Davis himself received a 30 dB increase in his preexisting high-frequency hearing loss after exposure for 20 minutes to a 500-Hz tone at 140 dB SPL (Point H). Other points in Figure 1 include Point SN (ref. 4)—0.4 second at 153 dB (an exposure designed to be equivalent to the sound produced by the opening of an air bag); Point E—1 minute at 135 dB (ref. 5); Point O—the effect of the ring of a cordless telephone in which the same transducer was used for the ringer as well as voice, and produced a measurable PTS in a small fraction of those individuals exposed (ref. 6); and Point L (ref. 7)—an exposure of “a few seconds” to a tone of about 138 dB SPL that was being used to elicit the acoustic reflex (and produced additional damage in two individuals who already had considerable hearing loss).

The “8 hours at 100 dB SPL energy equivalent” exposure duration for any intensity greater than 100 dB SPL can be calculated using the following equation:

$$\frac{2.88 \times 10^4 \text{ seconds}}{\text{Antilog}[(\text{SPL}(\text{dB})-100 \text{ dB})/10]} = \text{time (seconds)}.$$

Similarly, the exposure intensity for any duration less than 8 hours can be calculated using

$$10 \log \frac{2.88 \times 10^4 \text{ seconds}}{\text{time (seconds)}} + 100 \text{ dB} = \text{SPL (dB)}.$$

Table 1 shows the sound pressure level of each firearm (plus respective ammo and attachments) tested. The “Exposure duration” (the abscissa in Fig. 1) to single rifle shots was measured using a storage oscilloscope for each rifle tested; the results are shown in Table 2. The duration of multiple gun shots is simply the duration of a single shot times the number of shots fired. Superimposing the points whose X-Y coordinates are X=time & Y=SPL onto Fig. 1, we can determine the **likelihood of safety** or the **possibility of damage** for each firearm tested. If the point appears above the dashed line in Fig. 1, a permanent threshold shift is possible.

Figure 2 shows an extension of the plot shown in Fig. 1. The time scale has been modified to show points that are similar to the duration of the blast noise (e.g., 3.5 milliseconds). The line in Fig. 2 still represents the energy equivalent of 8 hours at 100 dB SPL. The duration of each blast was measured using a digital storage

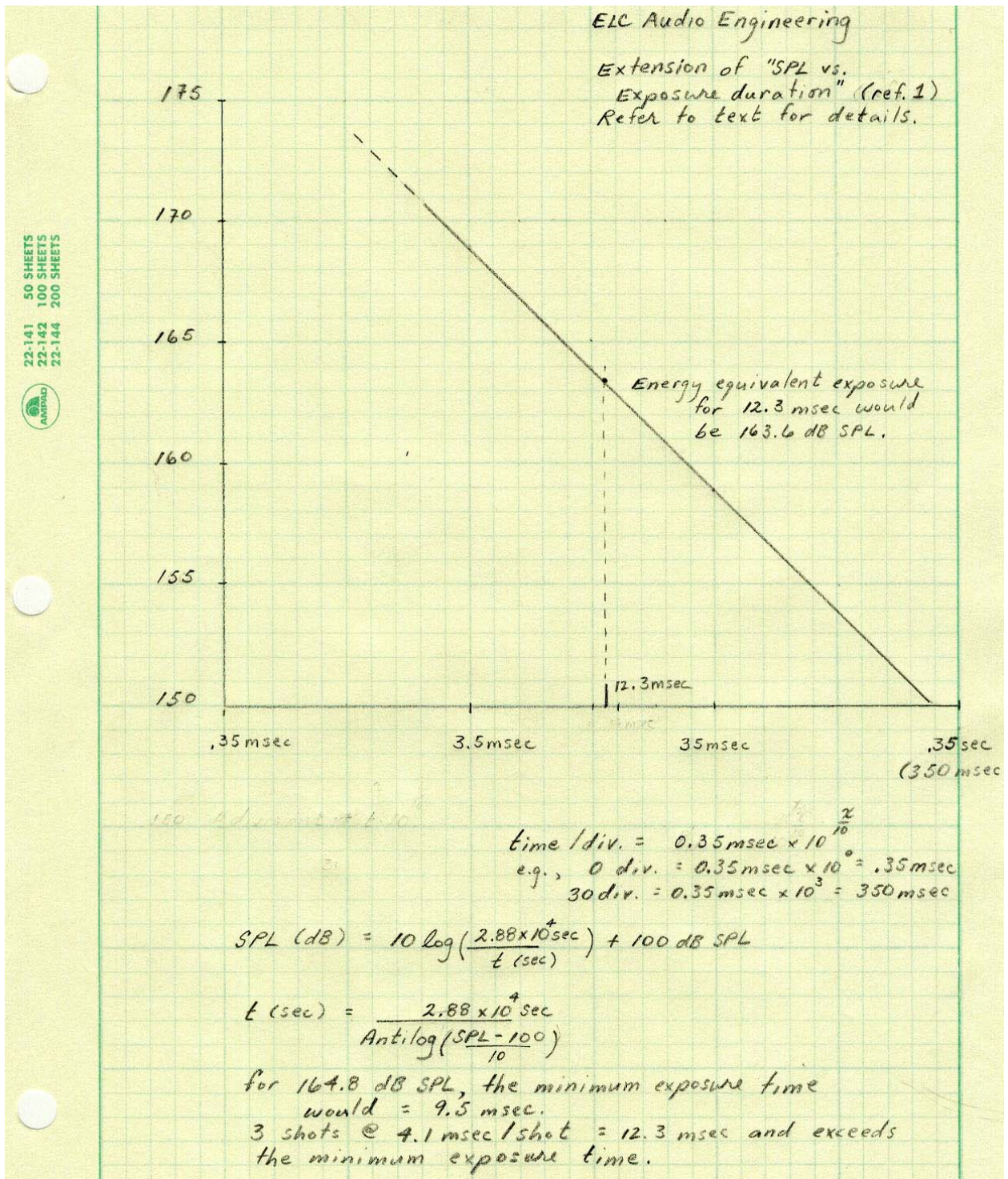


Figure 2.

oscilloscope—refer to Fig. 3 for an example. Because of the complexity of each waveform encountered, only the duration of the noise at its maximum compression and rarefaction is shown in Table 2. Residual peaks exceeding 140 dB SPL at times greater than 10 milliseconds can be seen on the oscilloscope printouts, but their contribution to

risk was not taken into account. It is interesting to note that the “louder” rifles also have measurably longer blast duration in addition to greater peak pressures; this is a significant observation because it is the combination of duration and intensity that determine the “equivalent energy” of the noise. Rifle #5 with its respective BOSS (see Fig. 3) produces both great enough SPL and blast duration that three successive rifle blasts would put the shooter at risk for permanent hearing damage resulting from acoustic trauma.

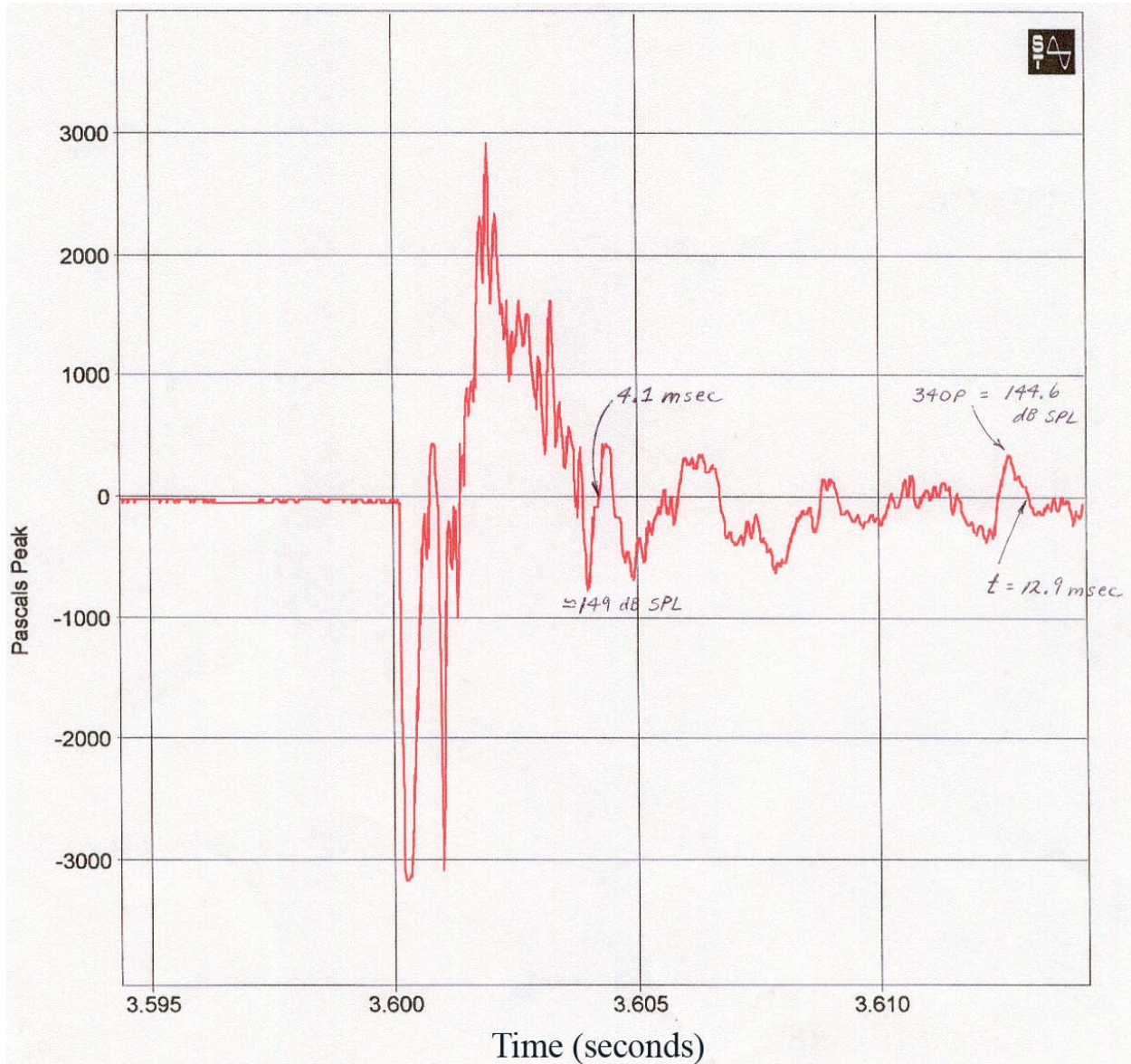


Figure 3. 300 WIN MAG Bolt Action with BOSS. Peak pressure = 3170 Pascals.

Very Important Notes: The measurements shown in Table 1 are for the actual sound pressure levels encountered at a distance of one foot away from the shooter's ear. The shooter would encounter additional noise (i.e., a greater SPL) in the ear resulting from closer proximity to the rifle's muzzle plus sound transmitted via bone conduction. Sound transmission via bone conduction is very real: Audiologist routinely use bone conduction to test patients' sensorineural (a.k.a. "nerve") hearing thresholds. A "bone conduction" transducer is placed on the mastoid process (bump behind the ear) to transmit sound to the inner ear via bone conduction. Similarly, a shooter's head placed on the rifle stock allows energy travelling through the rifle stock to be transmitted to the inner ear (this is in addition to the airborne blast noise). In short, the values presented in Table 1 would be the minimum sound pressure levels encountered by the shooter for each of the rifles tested.

Another important consideration regarding risk criteria is the "equivalent energy" theory: The idea that "equivalent energy" will result in the same amount of damage for a given person may be insufficient in determining risk for intensities greater than 150 dB SPL. One study (ref. 8) showed that 30 impulses (or "rounds") of simulated gunfire at 150 dB SPL peak level created a temporary threshold shift (TTS) in a particular ear, whereas 300 impulses of the same pulse shape at 140 dB SPL (to maintain the same total energy) usually produced no TTS in the same individual. This suggests that 3 impulses at 160 dB SPL would create an even greater TTS for the same individual than 30 impulses at 150 dB SPL, even though the "equivalent energy" is the same. In conclusion, greater sound pressure levels are at least, if not more, damaging than their lower-intensity, but longer duration, "energy equivalent" SPLs.

In addition to studies showing that high-intensity impulse noise affects the cochlea differently than does continuous noise, there are logical reasons why the equivalent energy theorem can't always predict risk for hearing damage. Logically, we know there are levels associated with impulses that are dangerous with just one exposure. But at lower levels, individuals can withstand almost an infinite number of the same "signature" impulses (same waveform, but at a lower intensity) without harm. Also, most of the data supporting the equivalent energy theorem have been large-scale demographic studies. Controlled laboratory studies using animals (e.g., ref. 9) have shown that hearing loss resulting from exposure to impulse noise of equal energy increases with peak level. **To iterate: The danger of hearing loss resulting from a single exposure to high-intensity impulse noise is at least as great as what we would predict using Figures 1 or 2.**

Another important question is “What is the risk using the same rifle and ammo (rifle #5 with xxx ammo) without its respective BOSS?” The peak pressure level without the BOSS is 157.5 dB PPL, and the duration of a single blast is 3.5 milliseconds (refer to Fig. 4).

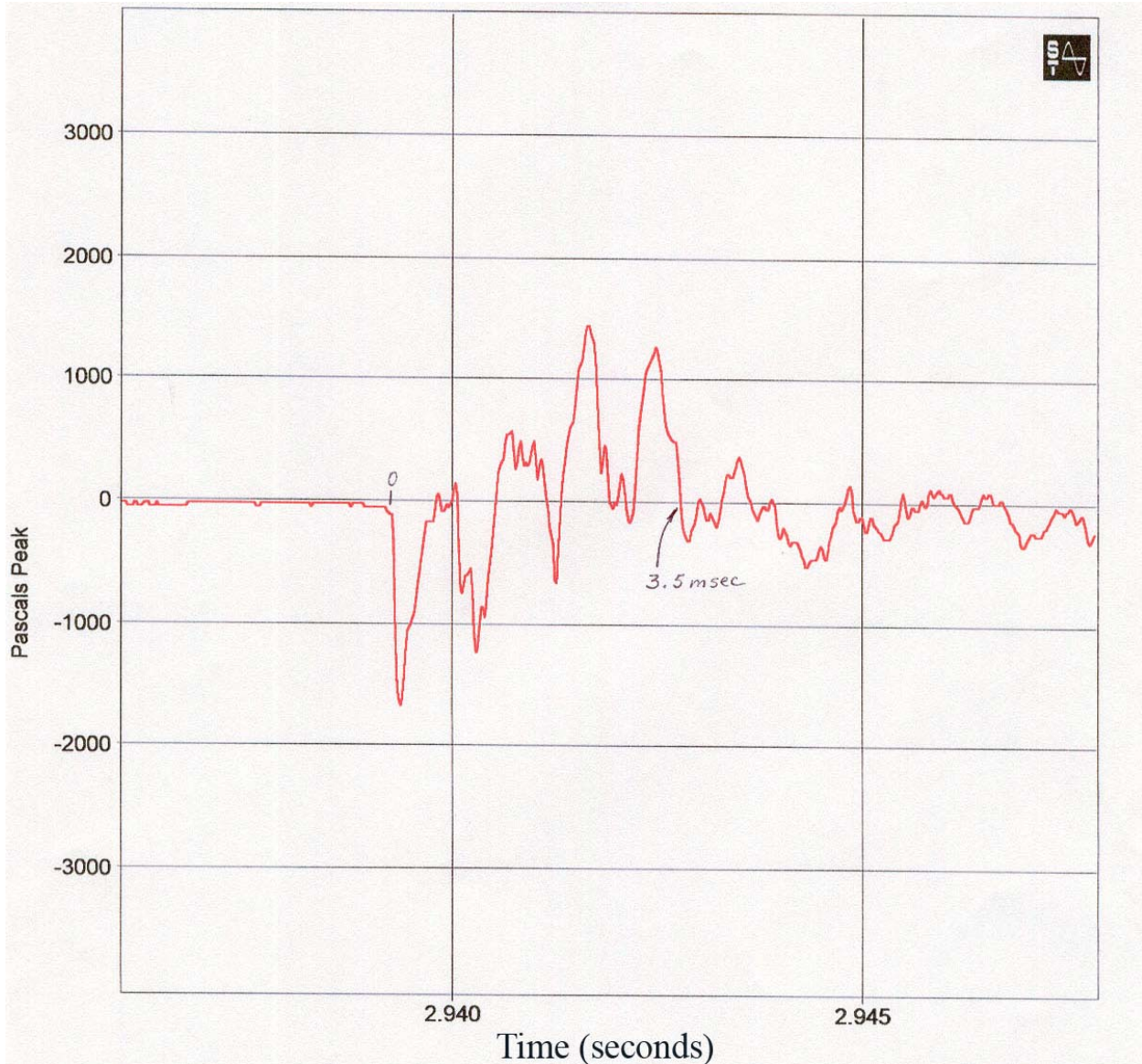


Figure 4. 300 WIN MAG Bolt Action with Cover—No BOSS. Peak Pressure = 1630 Pascals.

The maximum “safe” exposure time for 157.5 dB SPL is 51 milliseconds and is the time equivalent of 15 successive blasts. (Note that the blast duration is shorter for the same rifle/ammo combination without its BOSS.) Of the rifles tested, the rifle/ammo combinations that would put shooters at highest risk for hearing loss are rifles #5 and #9 with their respective BOSS plus high velocity or high-energy ammo. At 165.5 dB SPL (rifle #5), an exposure longer

than 8 milliseconds would put the shooter in the “danger zone.” This is slightly greater than the duration of two shots, but less than three rifle shots at the measured duration of 3.5 milliseconds per shot (see Fig. 5).

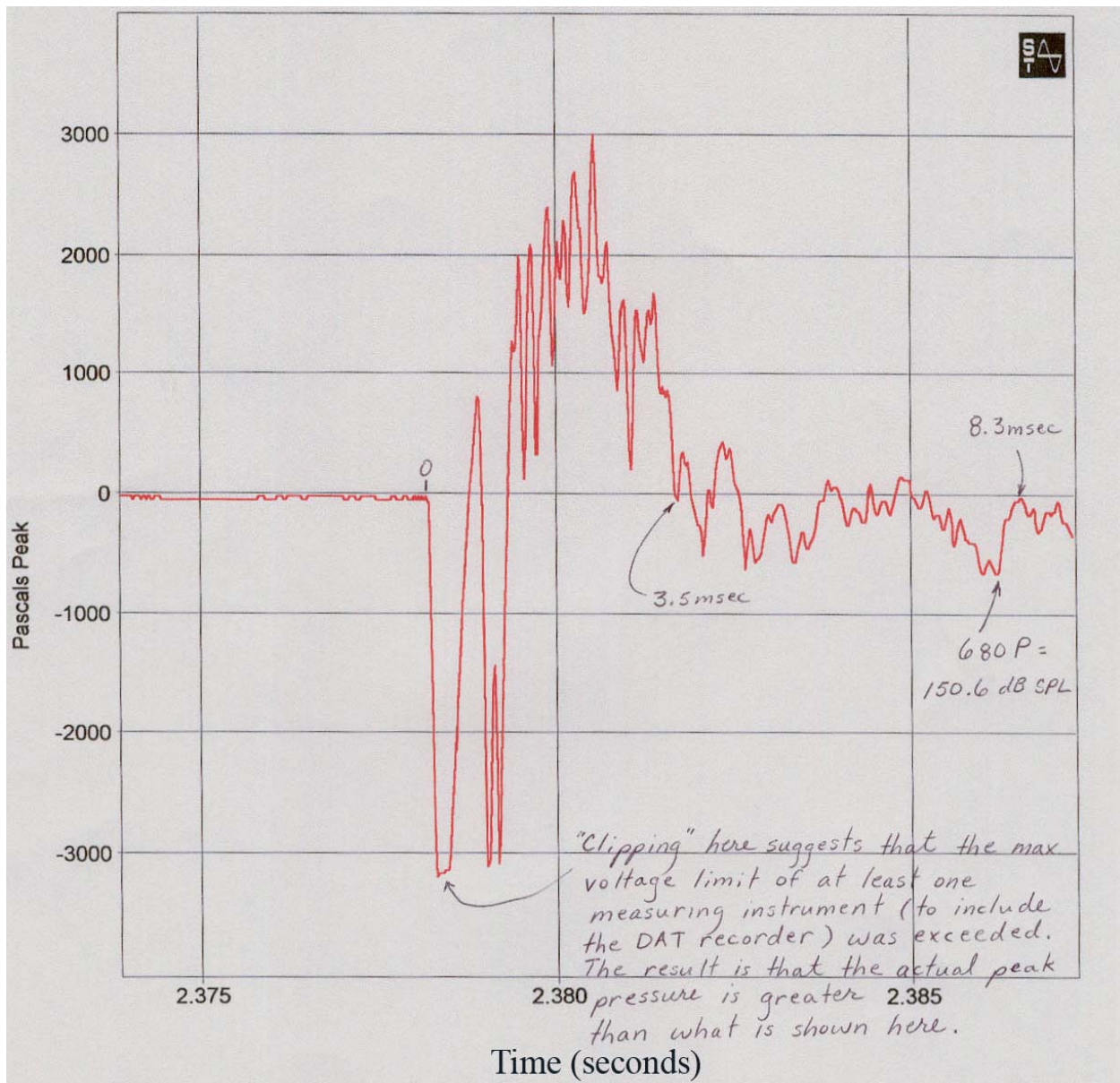


Figure 5. 300 WIN MAG Bolt Action with BOSS & High Velocity Ammo. Peak Pressure = 3240 Pascals.

As previously stated, the shooter would experience a minimum SPL of 165.5 (without hearing protection), and the duration of exposure to a single shot is at least 3.5 milliseconds. It is entirely possible that a single rifle shot at this intensity and duration could cause a temporary or permanent threshold shift! The calculations and measurements provide us with information that can be used in conjunction with prior studies to suggest what is “possible” or “likely” versus what is “unlikely” (but not impossible!!). Similarly, rifle #9 with its BOSS plus high-energy ammo

(Fig. 6) measured 164.5 dB SPL and 3.8 milliseconds duration. Again, the shooter would be in the “danger zone” between 2 and 3 shots. Referring to Figures 5 and 6, we see that there’s a lot of energy subsequent to the primary compression/rarefaction of these blasts; consequently, the actual duration of exposure is greater than the value used in the above calculations, and the chances of a PTS are increased.

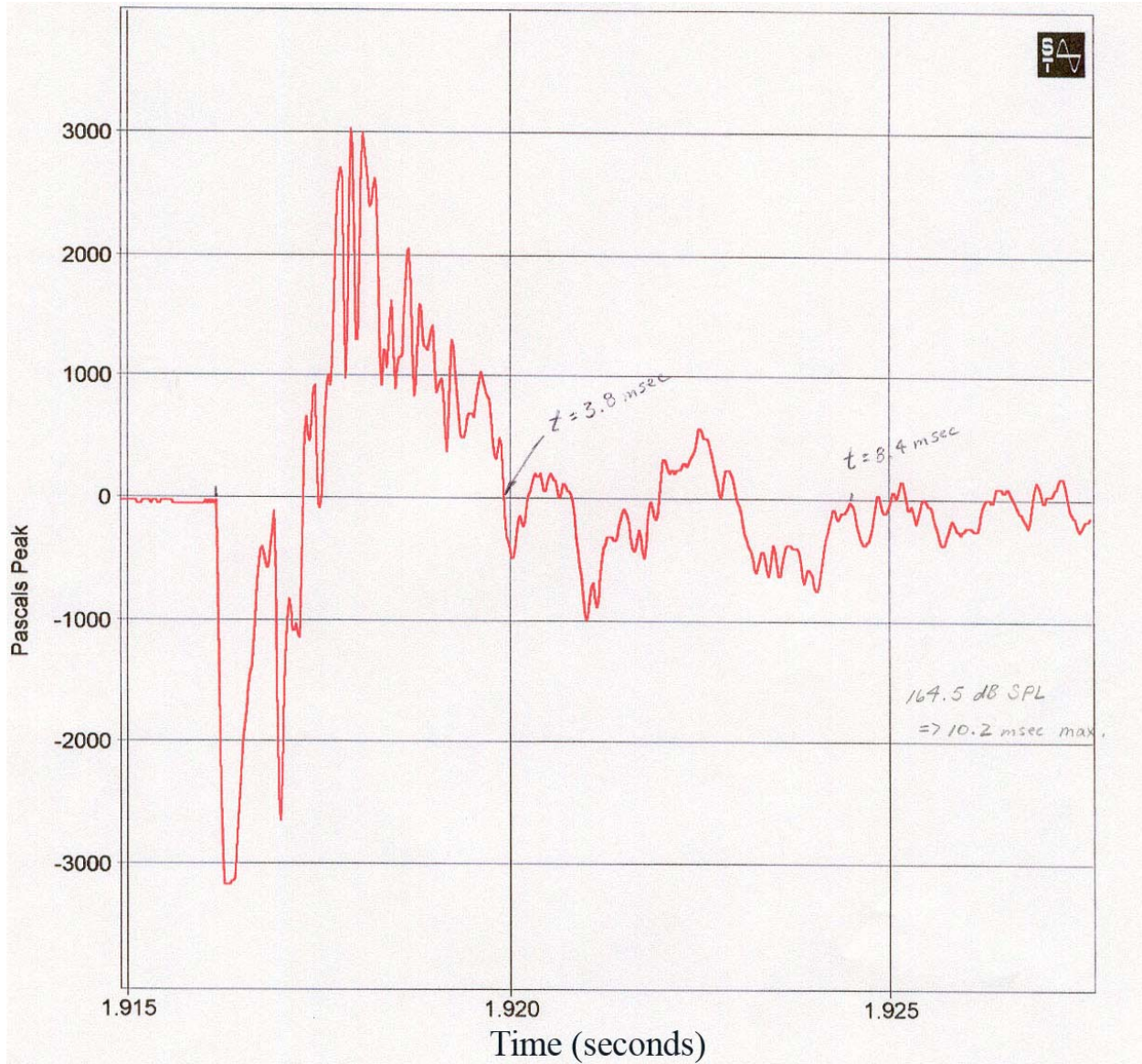


Figure 6. 338 WIN with BOSS. 250 Grain High Energy ammo. Peak Pressure = 3200 Pascals.

Additional Measurements and Notes

Sound level meters are but one type of instrument used to analyze sound: Other measuring devices are used to measure characteristics of sound other than intensity. One such device is known as a "spectrum analyzer." In general, spectrum analysis refers to a detailed observation of the individual parameters of a signal. In acoustics, the parameters of interest are time, frequency and amplitude. A simple example of spectrum analysis can be demonstrated using a prism. White light shown through a prism reveals that white light is actually composed of many colors. In essence, this is spectrum analysis because we see the color spectrum of white light.

Like light, most noise or sounds (other than pure tones) are made up of discrete tones or "colors." More accurately, any sound at a given time can be expressed as the sum of its individual frequency components. To give an example, a piano and violin sound different from one another, even when playing the same note. The reason for this is because each instrument produces harmonics, or overtones, in addition to a fundamental frequency or "pitch." A spectrum analyzer allows us to see the frequencies, or harmonics, that make up such sounds. A violin produces different harmonics than a piano or a flute; consequently, they sound different from each other. The same goes for the human voice: A man and woman talking at the same volume, or sound pressure level, are readily distinguishable. We can also use a spectrum analyzer to study the noise resulting from blasts.

Many of us claim we can identify a rifle shot from a pistol or a shotgun blast. Clearly, this isn't just a function of loudness because some rifles are louder than pistols, others aren't, etc. What allows us to distinguish a pistol from a rifle is the relative combination of frequencies that make up their individual, or characteristic, sound. The technique used to generate a plot of a sound's individual frequency components is called Fourier Transformation, named for the French mathematician who developed the technique. I used "Fast Fourier Transform" (FFT) spectrum analysis to obtain the results shown. Visual inspection of these plots gives evidence that not all firearms sound the same, but perhaps similar. Though not demonstrated here, other types of blasts, such as a balloon popping, don't sound like firearms.

Notes

Note 1. The Sony DAT recorder was "calibrated" as follows: An acoustic calibrator was attached to the microphones of the Larson-Davis and B&K SLMs. The calibrator provides a 1 kHz (1000 c.p.s.), 114 dB SPL acoustic signal. At this SPL, the DAT's record level was set at minus 34 dB. This allowed the Sony DAT to record signals as loud as 148 dB SPL without distorting. With a 114 dB input and the record level set to -34 dB, the electrical output was 163 millivolts. The recordings were later analyzed using a digital storage oscilloscope and spectrum analysis software. Here are two examples:

1. 7mm Mouser (no BOSS). Using a storage oscilloscope, a peak voltage of 1017 millivolts was measured. (A storage oscilloscope is needed because the duration of this signal is about 0.003 seconds.) Using 163 millivolts = 114 dB as the reference, we get

$$20 \log \frac{1017 \text{ mV}}{163 \text{ mV}} = 20 \log 6.24 = 15.9 \text{ dB. The 1017 mV signal is 15.9 dB greater}$$

than the 114 dB reference; the actual PPL (at 50 ft.) is then 114 dB + 15.9 dB = 129.9 dB and is exactly what we measured using the SLM in PEAK mode.

2. .270 cal with BOSS; 150 grain. The measured peak voltage was 2865 millivolts.

$$20 \log \frac{2865 \text{ mV}}{163 \text{ mV}} = 20 \log 17.6 = 24.9 \text{ dB. Adding this to 114 dB gives 138.9 dB,}$$

which is what we measured using the SLM.

Note 2. The 25 dB correction factor is explained in the text. Distance from the source and air itself account for the attenuation (very high frequencies are absorbed more readily by air because the acoustic energy is dissipated in the form of friction). Spectral analysis indicated that most of the energy produced by the blasts (rifles, shotguns, and pistols) was in the low- to mid-frequency range of audible frequencies. For this reason, the correction factor is accurate for all firearms tested, regardless of their PPL.

Note 3. Relationship between sound pressure and sound power. Sound pressure level (SPL) measurements use a reference pressure of 0.00002 Pascal (Pa). A reference power could be used, but this requires measuring the movement of the individual air molecules. The relationship between power (I) and pressure (P) is

$$I(\text{power}) = \frac{P^2}{Z_a} \text{ where } Z_a \text{ is the impedance (mechanical resistance) of air.}$$

What's important to note here is that if we double the pressure P , we get a four-fold increase in power (Z_a doesn't change). Consequently, if we use power (either acoustical or electrical) as our decibel (dB) reference, we no longer multiply the log of the ratio by 20. Instead, we multiply the log of the ratio by 10. An example demonstrates that our end result in dB is the same.

As previously shown, doubling the pressure gives us a 6 dB increase in SPL. Using the above equation ($I = P^2/Z$), we see that doubling the pressure gives four times the power. Our dB equation using power is

$$10 \log \frac{\text{Power}}{P_{\text{wr}}(\text{ref})}. \text{ If power increases 4X, we get } 10 \log (4) = 6 \text{ dB.}$$

This is why adding a second loudspeaker to your stereo only adds 3 dB SPL to the overall loudness. Imagine that your stereo is delivering 4 watts to the right loudspeaker. We connect the left channel's loudspeaker, so now we have a total of 8 watts. Using our ubiquitous dB formula, we get

$$10 \log \frac{8 \text{ watts}}{4 \text{ watts}} = 10 \log (2) = 3 \text{ dB increase in SPL.}$$

Remember, 3 dB is a noticeable increase in loudness, but a 10 dB increase is needed for the sound to be perceived as "twice as loud." Incidentally, a 10 dB increase is equivalent to a 10 fold increase in power (not to mention a 3.16 fold increase in pressure). This means 40 watts, not 8 watts, is twice as loud as 4 watts.

Eric L. Carmichel, M.S.
ELC Audio Engineering
www.elcaudio.com

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