FAA - SONIC BOOM NOISE AND OVERPRESSURE

(Excerpt from U.S. Air Force atmospheric interceptor technology (AIT) Environmental Assessment)

NOISE METHODS OF ANALYSIS

1.0 NOISE DESCRIPTORS AND EFFECTS

Noise is generally described as unwanted sound. Unwanted sound can be based on objective effects (hearing loss, damage to structures, etc.) or subjective judgments (community annoyance). Noise analysis thus requires a combination of physical measurement of sound with psycho- and socioacoustic effects.

Launch vehicles generate two types of sound. One is engine noise, which is continuous sound. The other is sonic booms, which are transient impulsive sounds. These are quantified in different ways.

1.1 DESCRIPTORS OF CONTINUOUS SOUNDS

Measurement and perception of sound involves two basic physical characteristics: amplitude and frequency. Amplitude is a measure of the strength of the sound and is directly measured in terms of the pressure of a sound wave. Because sound pressure varies in time, various types of pressure averages are usually used. Frequency, commonly perceived as pitch, is the number of times per second the sound causes air molecules to oscillate. Frequency is measured in units of cycles per second, or Hertz (Hz).

Amplitude.

The loudest sounds the human ear can comfortably hear have acoustic energy one trillion times the acoustic energy of sounds the ear can barely detect. Because of this vast range, attempts to represent sound amplitude by pressure are generally unwieldy. Sound is therefore usually represented on a logarithmic scale with a unit called the decibel (dB). Sound on the decibel scale is referred to as a sound level. The threshold of human hearing is approximately 0 dB, and the threshold of discomfort or pain is around 120 dB.

The difference in dB between two sounds represents the ratio of those two sounds. Because human senses tend to be proportional (i.e., detect whether one sound is twice as big as another) rather than absolute (i.e., detect whether one sound is a given number of pressure units bigger than another), the decibel scale tends to correlate linearly with human response.

Frequency.

The normal human ear can hear frequencies from about 20 Hz to about 15,000 or 20,000 Hz. It is most sensitive to sounds in the 1,000 to 4,000 Hz range. When measuring community response to noise, it is common to adjust the frequency content of the measured sound to correspond to the frequency sensitivity of the human ear. This adjustment is called A-weighting (American National Standards Institute, 1988). Sound levels that have been so adjusted are referred to as A-weighted sound levels. The amplitude of A-weighted sound levels is measured in dB. It is common for some noise analysts to denote the unit of A-weighted sounds by dBA or dB(A). As long as the use of A-weighting is understood, there is no difference between dB, dBA or dB(A). It is only important that the use of A-weighting be made clear. It is common to use the term A-weighted sound pressure level (AWSPL) to refer to A-weighted sounds.

For analysis of damage to structures by sound, it is common not to apply any frequency weighting. Such overall sound levels are measured in dB and are often referred to as overall sound pressure levels (OASPL or OSPL).

C-weighting (American National Standards Institute, 1988) is sometimes applied to sound. This is a frequency weighting that is flat over the range of human hearing (about 20 Hz to 20,000 Hz) and rolls off above and below that range. C-weighted sound levels are often used for analysis of high-amplitude impulsive noise, where adverse impact is influenced by rattle of buildings.

Time Averaging.

Sound pressure of a continuous sound varies greatly with time, so it is customary to deal with sound levels that represent averages over time. Levels presented as instantaneous (i.e., as might be read from the dial of a sound level meter), are based on averages of sound energy over either 1/8 second (fast) or one second (slow). The formal definitions of fast and slow levels are somewhat complex, with details that are important to the makers and users of instrumentation. They may, however, be thought of as levels corresponding to the root-mean-square sound pressure measured over the 1/8-second or 1-second periods.

The most common uses of the fast or slow sound level in environmental analysis is in the discussion of the maximum sound level that occurs from the action, and in discussions of typical sound levels. Figure A-1 is a chart of sound levels from typical sounds.

Assessment of cumulative noise impact requires average levels over periods longer than just the fast or slow times. The sound exposure level (SEL) sums the total sound energy over a noise event. Mathematically, the mean square sound pressure is computed over the duration of the event, then multiplied by the duration in seconds, and the resultant product is turned into a sound level. SEL is sometimes described as the level which, occurring for one second, would have the same sound energy as the actual event.

Note that SEL is a composite metric that combines both the amplitude of a sound and its duration. It is a better measure of noise impact than the maximum sound level alone, since it accounts for duration. Long sounds are more intrusive than short sounds of equal level, and it has been well established that SEL provides a good measure of this effect.

SEL can be computed for A- or C-weighted levels, and the results denoted ASEL or CSEL. It can also be computed for unweighted (overall) sound levels, with a corresponding designation.
For longer periods of time, total sound is represented by the equivalent continuous sound pressure level (Leq). Leq is the average sound level over some time period (often an hour or a day, but any explicit time span can be specified), with the averaging being done on the same energy basis as used for SEL. SEL and Leq are closely related, differing by (a) whether they are applied over a specific time period or over an event, and (b) whether the duration of the event is included or divided out.

Just as SEL has proven to be a good measure of the noise impact of a single event, Leq has been established to be a good measure of the impact of a series of events during a given time period. Also, while Leq is defined as an average, it is effectively a sum over that time period and is thus a measure of the cumulative impact of noise.

Noise tends to be more intrusive at night than during the day. This effect is accounted for by applying a 10-dB penalty to events that occur after 10 PM and before 7 AM. If Leq is computed over a 24-hour period with this nighttime penalty applied, the result is the day-night average sound level (Ldn or DNL). Ldn is the community noise metric recommended by the U.S. Environmental Protection Agency (U.S. Environmental Protection Agency, 1972) and has been adopted by most federal agencies (Federal Interagency Committee on Noise, 1992). It has been well established that Ldn correlates well with community response to noise (Schultz, 1978; Finegold et al., 1994).

The state of California quantifies noise by Community Noise Exposure Level (CNEL). This metric is similar to Ldn except that a penalty of 5 dB is applied to sounds in the evening, after 7:00 p.m. and before 10:00 p.m.

It was noted earlier that, for impulsive sounds, C-weighting is more appropriate than A-weighting. The day-night average sound level can be computed for C-weighted noise, and is denoted LCdn or CDNL. This procedure has been standardized, and impact interpretive criteria similar to those for Ldn have been developed (CHABA, 1981).

1.2 DESCRIPTORS OF SONIC BOOMS

Figure A-2 shows time histories (pressure versus time) for the two types of sonic boom signatures generated by launch vehicles: N-wave carpet booms and U-wave focus booms. Each consists of a pair of shock waves connected by a linear expansion (N-wave) or a U-shaped curve (U-wave). Each type of boom is well described by its peak overpressure in pounds per square foot (psf), and its duration in milliseconds (msec). Duration tends to have a minor effect on impact, so the peak pressure is all that is normally required.

For assessment of impact via LCdn as discussed in Section 1.0, the peak pressure is related in a simple way to CSEL, from which LCdn can be constructed. The peak pressure P (psf) is converted to the peak level (Lpk) dB by the relation

$$\text{Lpk} = 127.6 + 20 \log_{10} P \qquad \text{(A-1)}$$

CSEL is then given by Plotkin (1993):

$$\text{CSEL} = \text{Lpk} - 26 \quad \text{(N-wave)} \qquad \text{(A-2)}$$

$$\text{CSEL} = \text{Lpk} - 29 \quad \text{(U-wave)} \qquad \text{(A-3)}$$

2.0 NOISE EFFECTS

2.1 ANNOYANCE

Studies of community annoyance to numerous types of environmental noise show that Ldn is the best measure of impact. Schultz (1978) showed a consistent relationship between Ldn and annoyance. This relationship, referred to as the Schultz curve, has been reaffirmed and updated over the years (Fidell et al., 1991; Finegold et al., 1994). Figure A-3 shows the current version of the Schultz curve.

Some time ago Ldn of 55 dB or less had been identified as a threshold below which adverse impacts to noise are not expected (U.S. Environmental Protection Agency, 1972). It can be seen from Figure A-3 that this is a region where a small percentage of people are highly annoyed. Ldn of 65 dB is widely accepted as a level above which some adverse impact should be expected (Federal Interagency Committee on Noise, 1992), and it is seen from Figure A-3 that about 15 percent of people are highly annoyed at that level.

A limitation of the Schultz curve is that it is based on long-term exposure to noise. The proposed action is for a single launch. Therefore, analysis in the current study examines this on a single-event basis.

2.2 SPEECH INTERFERENCE

Conversational speech is in the 60 to 65 dB range, and interference with this can occur when noise enters or exceeds this range. Speech interference is one of the primary causes of annoyance. The Schultz curve incorporates the aggregate effect of speech interference on noise impact.

Because only one launch is planned, and noise would last for only a few minutes, speech interference is not expected to be a significant impact.

2.3 SLEEP INTERFERENCE

Sleep interference is commonly believed to be a significant noise impact. The 10-dB nighttime penalty in Ldn is based primarily on sleep interference. Recent studies, however, show that sleep interference is much less than had been previously believed (Pearsons et al., 1989; Ollerhead, 1992).

Traditional studies of sleep disturbance indicate that interference can occur at levels as low as 45 dB. Data indicates that at indoor SEL of 70 dB, about 20 percent of people will awaken (Federal Interagency Committee on Noise, 1992). Assuming a nominal outdoor-to-indoor noise reduction of 20 dB, these correspond to outdoor sound exposure levels of 65 dB and 90 dB, respectively. Note that the awakening threshold is comparable to the threshold of outdoor speech interference.

2.4 TASK INTERFERENCE

Due to startle effects, some task interference may occur to sonic booms. High levels of rocket noise may cause some task interference close to the launch sites. It is difficult to estimate degrees of task interference, since this is highly dependent on specific tasks. Startle from sonic booms is often stated as a concern, but there are no credible reported incidents of harm from sonic boom startle. Task interference from rocket noise is expected to occur at higher levels than speech interference.

2.5 HEARING LOSS

Federal OSHA guidelines (Title 29 CFR 1910.95) specify maximum noise levels to which workers may be exposed on a regular basis without hearing protection. Pertinent limits are a maximum of 115 dBA for up to 15 minutes per day, and unweighted impulsive noise of up to

140 dB. Exceeding these levels on a daily basis over a working career is likely to lead to hearing impairment. These levels are conservative for evaluating potential adverse effects from occasional noise events.

2.6 HEALTH

Nonauditory effects of long-term noise exposure, where noise may act as a risk factor, have never been found at levels below federal guidelines to protect against hearing loss. Most studies attempting to clarify such health effects found that noise exposure levels established for hearing protection will also protect against nonauditory health effects (von Gierke, 1990). There are some studies in the literature that claim adverse effects at lower levels, but these results have generally not been reproducible.

2.7 STRUCTURES

2.7.1 Launch Noise

Damage to buildings and structures from noise is generally caused by low-frequency sounds. The probability of structural damage claims has been found to be proportional to the intensity of the low-frequency sound. Damage claim experience (Guest and Sloane, 1972) suggests one claim in 10,000 households is expected at a level of 103 dB, one in 1,000 households at 111 dB, and one in 100 households at 119 dB.

Figure A-4 shows criteria for damage to residential structures (Sutherland, 1968), and compares them to launch noise spectra that could occur a few kilometers from the launch point of a medium (300,000 to 500,000 pound thrust) rocket. These data show that noise-induced damage to off-base property would typically be very minimal.

2.7.2 Sonic Boom

Sonic booms are commonly associated with structural damage. Most damage claims are for brittle objects, such as glass and plaster. Table A-1 summarizes the threshold of damage that might be expected at various overpressures. There is a large degree of variability in damage experience, and much damage depends on the pre-existing condition of a structure. Breakage data for glass, for example, spans a range of two to three orders of magnitude at a given overpressure. While glass can suffer damage at low overpressures, as shown in Table A-1, laboratory tests glass (White, 1972) have shown that-properly installed window glass will not break at overpressure below 10 psf, even when subjected to repeated booms.

The maximum sonic boom overpressures for the proposed launch will be 2.7 psf during launch (maximum focus boom) and 3.2 psf during entry, near the water impact point. These are well below the threshold where structural damage would be expected, were there structures in the vicinity.

3.0 NOISE MODELING

3.1 LAUNCH NOISE

On-pad and in-flight rocket noise was computed using the RNOISE model (Plotkin et al., 1997). Rocket noise prediction via this model consists of the following elements:

1. The total sound power output, spectral content and directivity is based on the in-flight noise model of Sutherland (1993). Noise emission is a function of thrust, nozzle exit gas velocity, nozzle exit diameter, and exhaust gas properties.

2. Propagation from the vehicle to the ground accounts for Doppler shift, absorption of sound by the atmosphere (American National Standards Institute, 1978), inverse square law spreading, and attenuation of sound by the ground (Chien and Soroka, 1980). A semi-hard ground surface (1,000 mks rayls) was assumed.

3. One-third spectral levels were computed at the ground, for every flight trajectory point, on a grid of 3721 points. ASEL and maximum A-weighted and overall sound levels were then derived from the results at each grid point.

The computed noise levels were then depicted as contours of equal level.

3.2 SONIC BOOM

Sonic boom was computed using the U.S. Air Force's PCBoom3 software (Plotkin, 1996). This is a full ray tracing model. Details of sonic boom theory are presented by Plotkin (1989) and Maglieri and Plotkin (1991). The specific approach to sonic boom modeling included the following elements:

1. Trajectories provided by the vehicle manufacturers were converted into PCBoom3 TRJ format using PCBoom3's TRAJ2TRJ utility. This utility generated required higher derivatives, as well as converting file formats.

2. Vehicle F-functions were calculated using the method of Carlson (1978). Area distributions were obtained from vehicle drawings. The shape factors computed were used to obtain nominal N-wave F-functions.

3. The F-function associated with the plume was obtained by a combination of the Universal Plume Model (Jarvinen and Hill, 1970) and Tiegerman's (1975) hypersonic boom theory.

4. Ray tracing and signature evolution were computed by integration of the eiconal and Thomas's (1972) wave parameter method.

5. Focal zones were detected from the ray geometry, and focus signatures computed by applying Gill and Seebassís (1975) numerical solution.

The resultant sonic boom calculations were depicted as contours of constant overpressure (psf).

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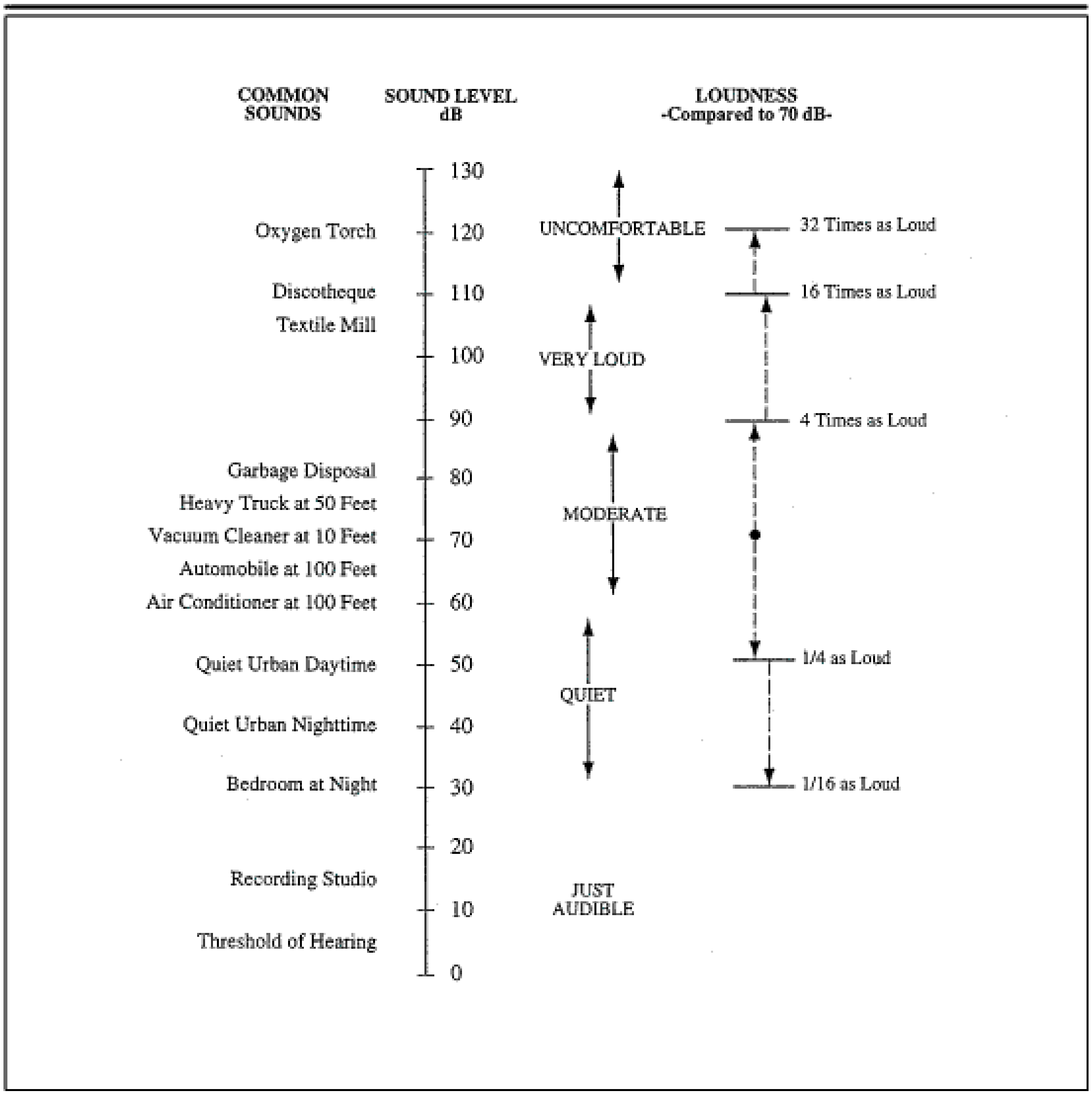
Table A-1. Possible Damage to Structures From Sonic Booms
Source: Haber and Nakaki, 1989

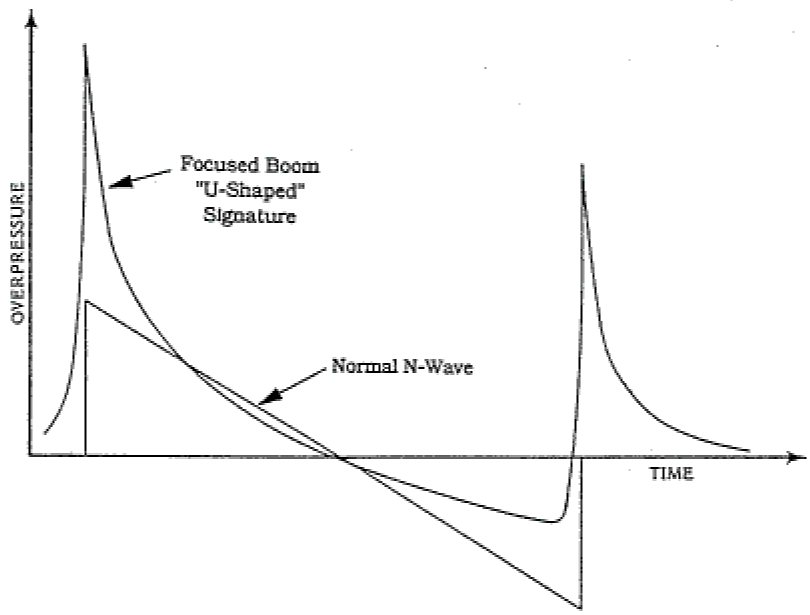
Sonic Boom Overpressure Nominal (psf)	Type of Damage	Item Affected
0.5 - 2	Cracks in plaster	Fine; extension of existing; more in ceilings; over door frames; between some plaster boards.
	Cracks in glass	Rarely shattered; either partial or extension of existing.
	Damage to roof	Slippage of existing loose tiles/slates; sometimes new cracking of old slates at nail hole.
	Damage to outside walls	Existing cracks in stucco extended.
	Bric-a-brac	Those carefully balanced or on edges can fall; fine glass, e.g., large goblets, can fall and break.
	Other	Dust falls in chimneys.
2 - 4	Glass, plaster, roofs, ceilings	Failures show that would have been difficult to forecast in terms of their existing localized condition. Nominally in good condition.
4-10	Glass	Regular failures within a population of well-installed glass; industrial as well as domestic greenhouses.
	Plaster	Partial ceiling collapse of good plaster; complete collapse of very new, incompletely cured, or very old plaster.
	Roofs	High probability rate of failure in nominally good state, slurry-wash; some chance of failures in tiles on modern roofs; light roofs (bungalow) or large area can move bodily.
	Walls (out)	Old, free standing, in fairly good condition can collapse.
	Walls (in)	Inside ("Party") walls known to move at 10 psf.
Greater Than 10	Glass	Some good glass will fail regularly to sonic booms from the same direction. Glass with existing faults could shatter and fly. Large window frames move.
	Plaster	Most plaster affected.
	Ceilings	Plaster boards displaced by nail popping.
	Roofs	Most slate/slurry roofs affected, some badly; large roofs having good tile can be affected; some roofs bodily displaced causing gale-end and will-plate cracks; domestic chimneys dislodged if not in good condition.
	Walls	Internal party walls can move even if carrying fittings such as hand basins or taps; secondary damage due to water leakage.
	Bric-a-brac	Some nominally secure items can fall; e.g., large pictures, especially if fixed to party walls.



A-Weighted Sound Levels of Common Sounds

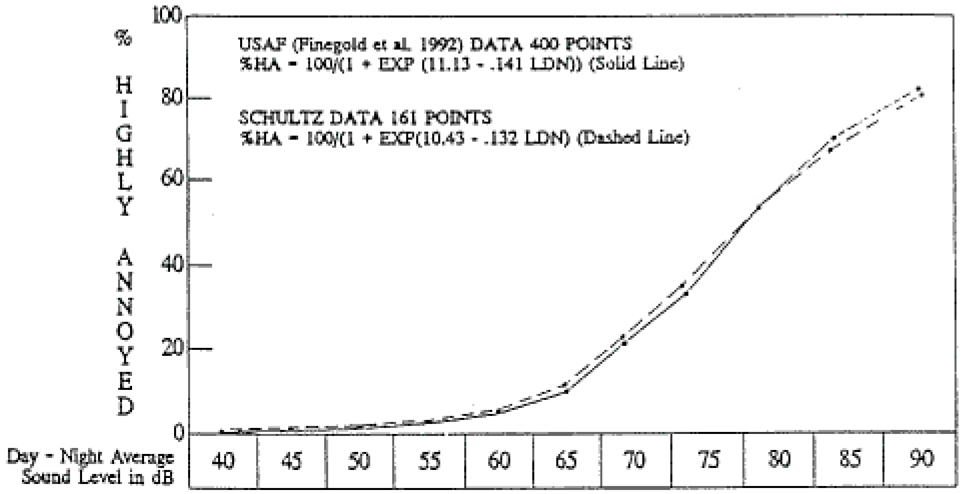
Figure A-1

Source: Handbook of Noise Control, C.M. Harris, Editor, McGraw-Hill Book Co., 1979.



Focused U-Wave and Unfocused N-Wave Boom Signatures

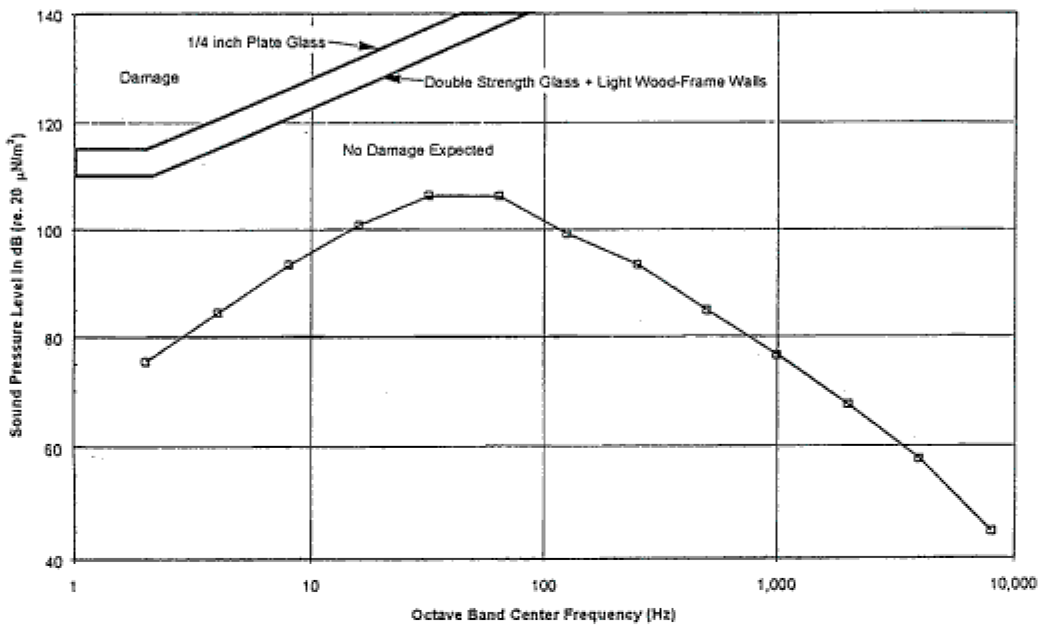
Figure A-2



Calculated %HA Points											
USAF	0.41	0.831	1.66	3.31	6.48	12.29	22.1	36.47	53.74	70.16	82.64
SCHULTZ	0.576	1.11	2.12	4.03	7.52	13.59	23.32	37.05	53.25	68.78	81

Community Response to Noise

Figure A-3



Criteria for Noise Damage to Residential Structures and Typical Off-Base Launch Noise Spectrum

Figure A-4