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SONIC BOOM (HUMAN RESPONSE AND ATMOSPHERIC EFFECTS) OUTDOOR-TO-INDOOR RESPONSE TO MINIMIZED SONIC BOOMS

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OUTLINE

1. Potential Waveforms and Spectra for HSCT Minimized Sonic Booms Signatures

2. Models for Exterior to Interior Sonic Boom Transmission into Dwellings

3. Resulting Interior (and Exterior) Subjective Noise Levels

4. Review of Some Existing Data on Subjective/Community Response to Sonic Booms
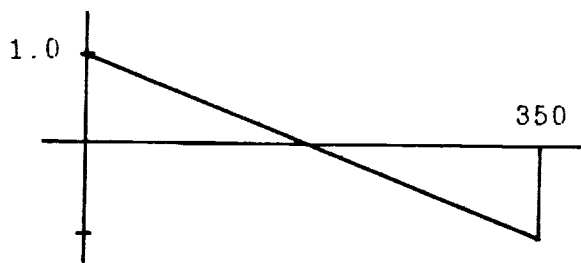
5. Summary

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The following types of sonic boom signatures were selected to represent the range of potential HSCT sonic boom signatures that may be realized or to provide reference signatures for comparison. In all cases, the signatures had a peak pressure of 1 psf and a total duration of 350 ms.
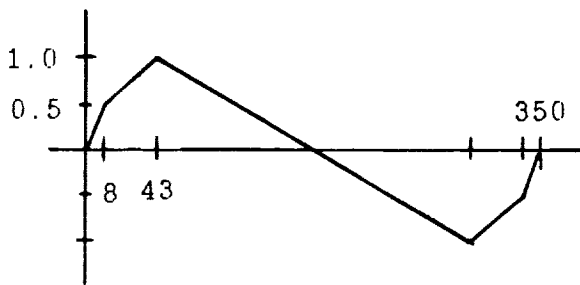
A.   N-Wave Reference Signatures

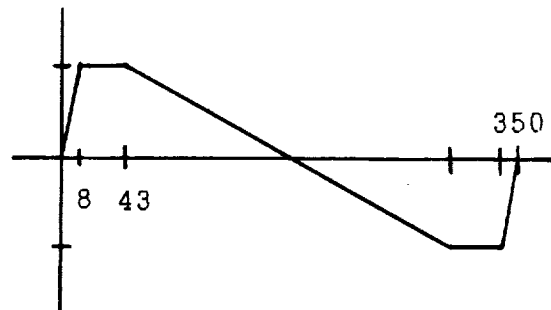(1)   Ideal N-wave with zero rise time
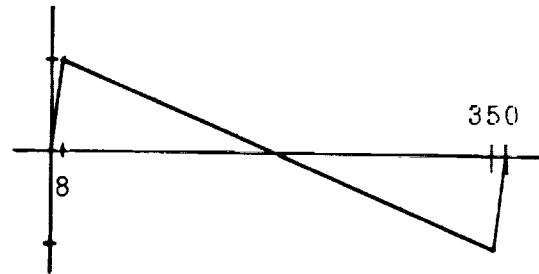
(2)   Symmetric N-wave with a finite 8 ms rise/decay time

B.   Symmetric (Minimized) Wave Forms

(3)   Delayed Ramp, 8 ms rise time to 0.5 psf followed by 35 ms rise to 1 psf - mirror image of this pattern at end

(4)   Flat Top, 8 ms rise time, 35 ms duration for flat top - mirror image of this pattern at end

C.   Non-Symmetric (Minimized) Wave Forms
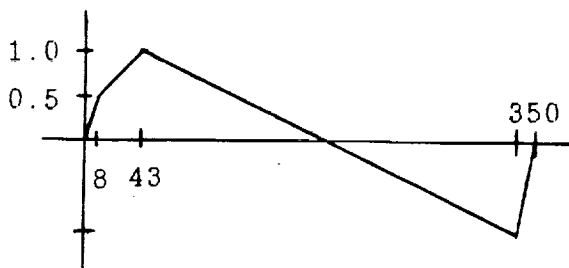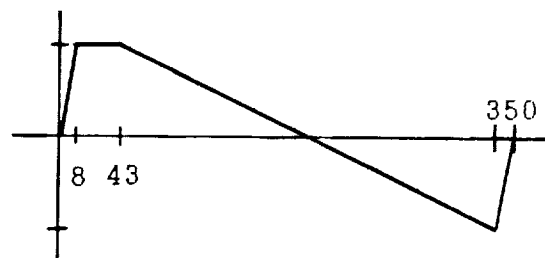
(5)   Delayed Ramp, 8 ms rise time to 0.5 psf followed by 35 ms rise to 1 psf, 8 ms decay time at end

(6)   Flat Top, 8 ms rise time, 35 ms duration of flat top, 8 ms decay time at end

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SONIC BOOM NOISE DESCRIPTORS

Table 1 summarizes the various descriptors commended to define the objective (acoustical) and subjective (psychoacoustic) characteristics of sonic booms that are used for evaluating human response to sonic booms. Some of these are utilized in the remaining figures shown in this presentation. The descriptors are identified by the name of the quantity, its abbreviation (used in text), its letter symbol and units (used in equations), and, where appropriate, its reference level when the quantity is expressed on a decibel scale.

Table 1

Acoustic Descriptors for the Evaluation of Human Response to Sonic Booms

For Physical Description of Sonic Booms

Quantity	Abbreviation	Letter Symbol	Units	Reference Level
Preferred				
1 Peak sound pressure (Flat weighting)	–	P_{pkT}	$Pa^{(1)}$	–
2 Peak sound pressure level (Flat weighting)	PKT	L_{pkT}	dB	$20\mu Pa$
3 Sound exposure spectrum level	SESL	$L_E(f)$	dB	$(20\mu Pa)^2 \cdot sec/Hz$
4 Sound Exposure	SE	E	$(Pa)^2 sec$	–
5 C-weighted sound exposure level	CSEL	L_{CE}	dB	$(20\mu Pa)^2 \cdot sec$
6 Day-night average C-weighted sound level	DNCL	L_{Cdn}	dB	–
Optional				
7 Sound exposure spectral density	SESD	$E(f)$	$(Pa)^2 sec/Hz$	
8 A-weighted sound exposure level	ASEL	L_{AE}	dB	$(20\mu Pa)^2 \cdot sec$
9 Day-night average A-weighted sound level	DNL	L_{dn}	dB	–
NOT RECOMMENDED				
10 Energy spectral density or energy spectrum	$S(\omega)$ or $S(f)$		$(Pa)^2 \cdot sec/Hz$	

For Subjective Description of Sonic Boom Loudness:

Quantity	Abbreviation	Letter Symbol	Units	Reference Level
Preferred				
11 Perceived Level (Mark VII)[2]	–	PL_{VII}	PLdb	
12 1/3rd Octave Band Sound Exposure Level	1/3SEL	$L_{1/3E}(f)$	dB	$(20\mu Pa)^2 \cdot sec$
13 Equivalent 1/3rd Octave Band SPL[3]	1/3ESPL	$L_{1/3eq}(f)$	dB	$(20\mu Pa)$
Optional				
14 Loudness Level (Mark VI or ISO-226 (1961)		LL_{VI}	Phons (on dB scale)	

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(1) 47.88 Pascals (Pa) = 1 psf.

(2) Mark VII denotes the use of the S.S. Stevens Mark VII Loudness contours for frequency-weighting of a sound spectrum according to its loudness sensation (Stevens,1972).

(3) The effective steady sound pressure level used to compute the loudness for a transient sound.

ACOUSTICAL DESCRIPTOR FOR SPECTRAL CONTENT OF SONIC BOOMS

The preferred descriptor to define the spectral content of sonic booms is the Sound Exposure Spectrum Level, $L_E(f)$. This descriptor represents the spectral content of the basic noise decriptors used for describing any single event – the Sound Exposure Level, L_E. The latter is equal to ten times the logarithm, to the base ten, of the integral, over the duration of the event, of the square of the instantaneous acoustic pressure, divided by the square of the reference pressure, $20\mu Pa$. When applied to the evaluation of community response to sonic booms, it is customary to use the so-called C-Weighted Sound Exposure Level, L_{CE} for which the frequency content of the instantaneous acoustic pressure is modified by the C-weighting curve.

The Sound Exposure Spectrum Level, $L_E(f)$ is obtained from the Fourier spectra, $F(f)$ of the sonic boom signature in the following manner.

$$L_E(f) = 10 \cdot \lg [E(F)/E_o]$$

where $E(f)$ = Sound Exposure Spectral Density

                   = $2 \cdot |F(f)|^2$

                   =   2 times the square of the absolute value of the Fourier Spectrum $F(f)$ of the instantaneous acoustic pressure, $p(t)$, and

         $F(f)$ = $\displaystyle\int_{\infty}^{\infty} p(t) \exp(-2\pi ft) \, dt$

and E_o = Reference Sound Exposure Spectrum Level

                   = $p_o^2 \, t_o/\delta f$

         p_o = Reference acoustic pressure, $20\mu Pa$

         t_o = Reference time, 1 second

         δf = Reference frequency bandwidth, 1 Hz

SPECTRA OF SONIC BOOM N-WAVE FORMS

The following figures show the spectra of these wave forms in terms of their Sound Exposure Spectrum Level, $L_E(f)$. As illustrated in Figure 1, for the ideal N-wave, with a peak pressure P_{pk}, the envelope of $L_E(f)$ can be described by two asymptotic lines which meet at a pseudo-peak frequency, $f_{max} = \sqrt{3}/(\pi T)$ where T is the sonic boom duration. These lines are defined by:

$$L_E(f)|_{f \to 0} \rightarrow 10\lg [2(P_{pk}T)^2(\pi fT/3)^2/E_o(f)]$$

$$\overline{L_E(f)}|_{f \to \infty} \rightarrow 10\lg [2(P_{pk}/\pi f)^2/E_o(f)]$$

where $\overline{L_E(f)}$ signifies the envelope of $L_E(f)$.

Figure 2 shows the same spectra for the non-ideal N-wave with a finite rise (and fall) time of 8 ms. In this case, the envelope of the high frequency portion of the spectrum falls off at -40 dB/decade above a frequency equal to $1/(\pi \tau)$ where τ is the rise (and fall) time.
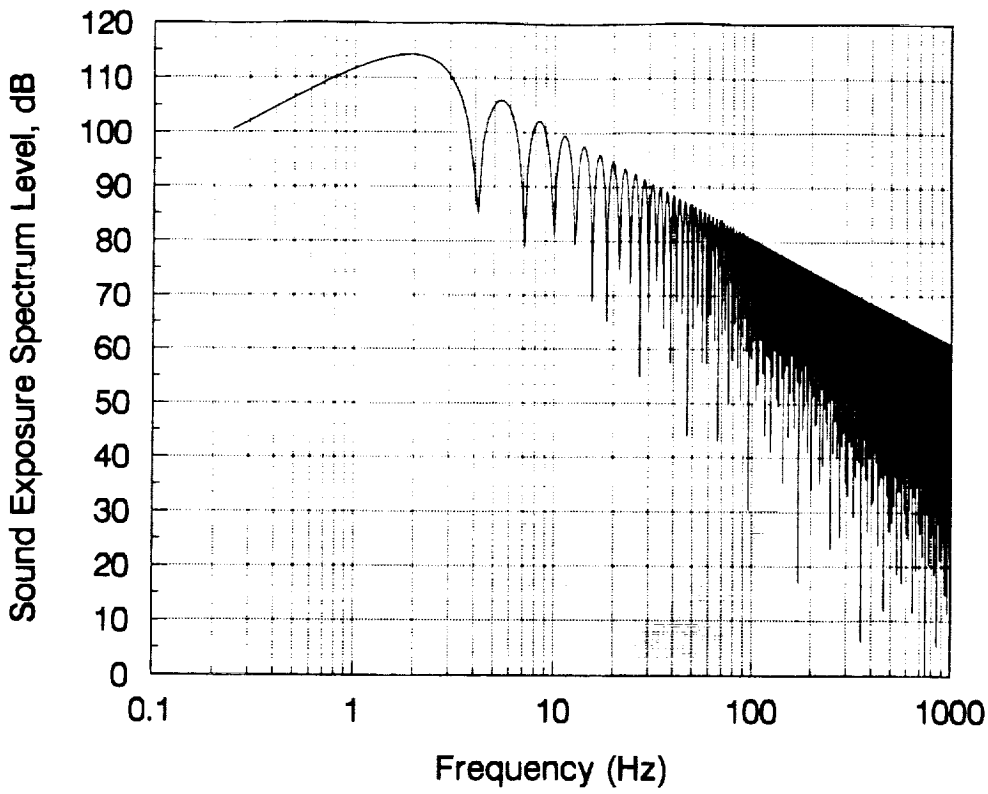
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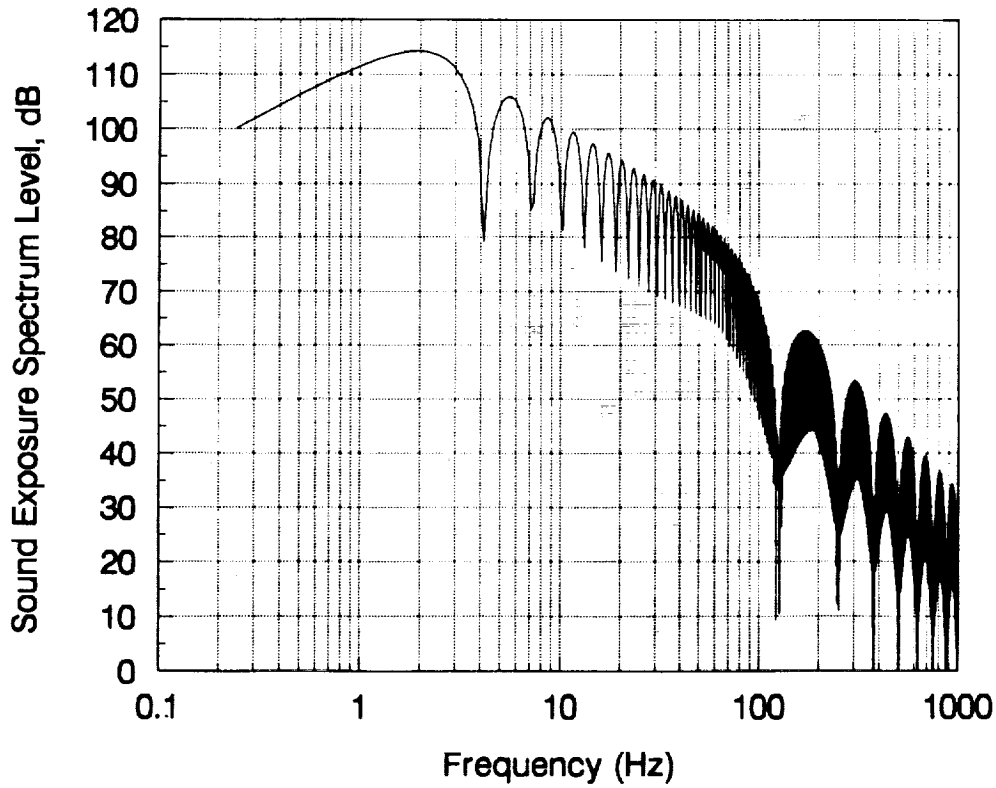Figure 1. $L_E(f)$ for Ideal N-Wave

Figure 2. $L_E(f)$ for Non-Ideal N-Wave with 8 ms Rise Time

SPECTRA OF GENERIC MINIMIZED SONIC BOOM WAVE FORMS

Figures 3 through 6 show the Sound Exposure Spectrum Levels for the four generic types of minimized sonic boom wave forms identified earlier. They all have the same general pattern as indicated in Figure 2 above, but exhibit differences in fine detail at frequencies above the peak frequency, f_{pk}.
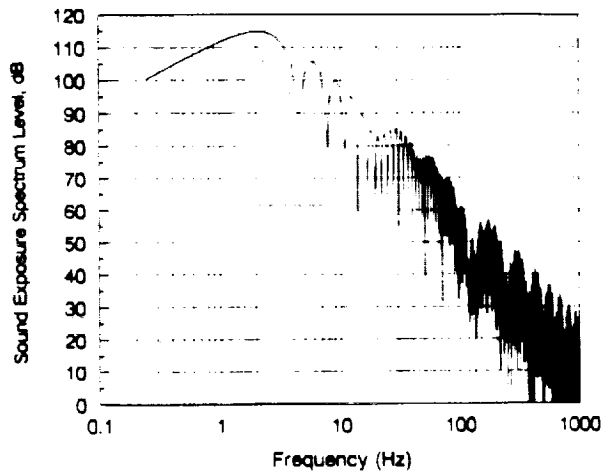

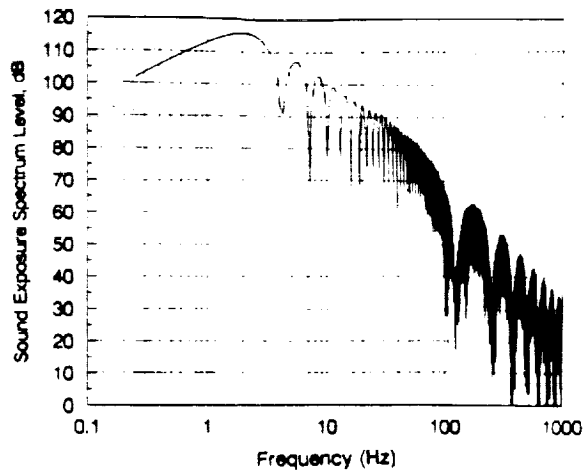Figure 3. Symmetric Delayed Ramp, 8 ms Rise Time to 0.5 psf, 35 ms Rise to 1 psf

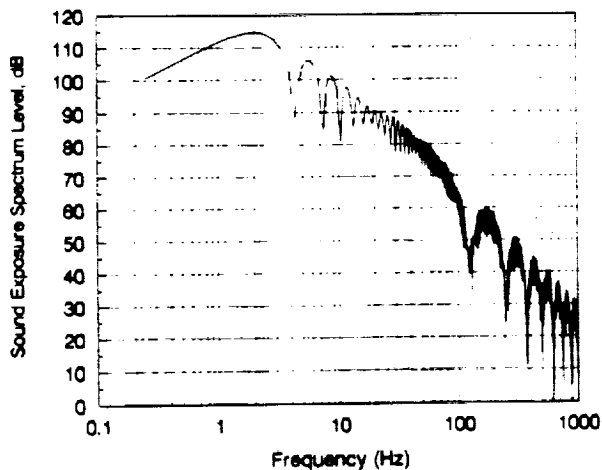Figure 4 Symmetric Flat Top, 8 ms Rise Time, Flat Top for 35 ms

Figure 5. Non-Symmetric Delayed Ramp, 8 ms Rise Time to 0.5 psf, 35 ms Rise to 1 psf
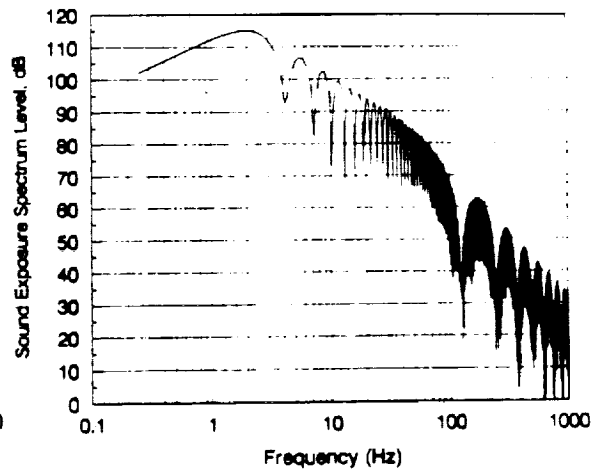
Figure 6 Non-Symmetric Flat Top, 8 ms Rise Time, Flat Top for 35 ms

Figure 7 shows a composite version of only the envelope of these spectra to show that the low frequency portions are nearly identical and the high frequency portions indicating essentially the same envelope, in decreasing order of levels for:

- Any of the N-waves with only a 8 ms rise or fall time to the same maximum peak pressure, regardless of whether they had a peak or flat top.

- Non-symmetric, Delayed Ramp

- Symmetric, Delayed Ramp

Figure 7. Comparison of Sound Exposure Spectrum Levels for Various Wave Shapes

OUTDOOR-TO-INDOOR NOISE REDUCTION MODEL FOR SONIC BOOMS

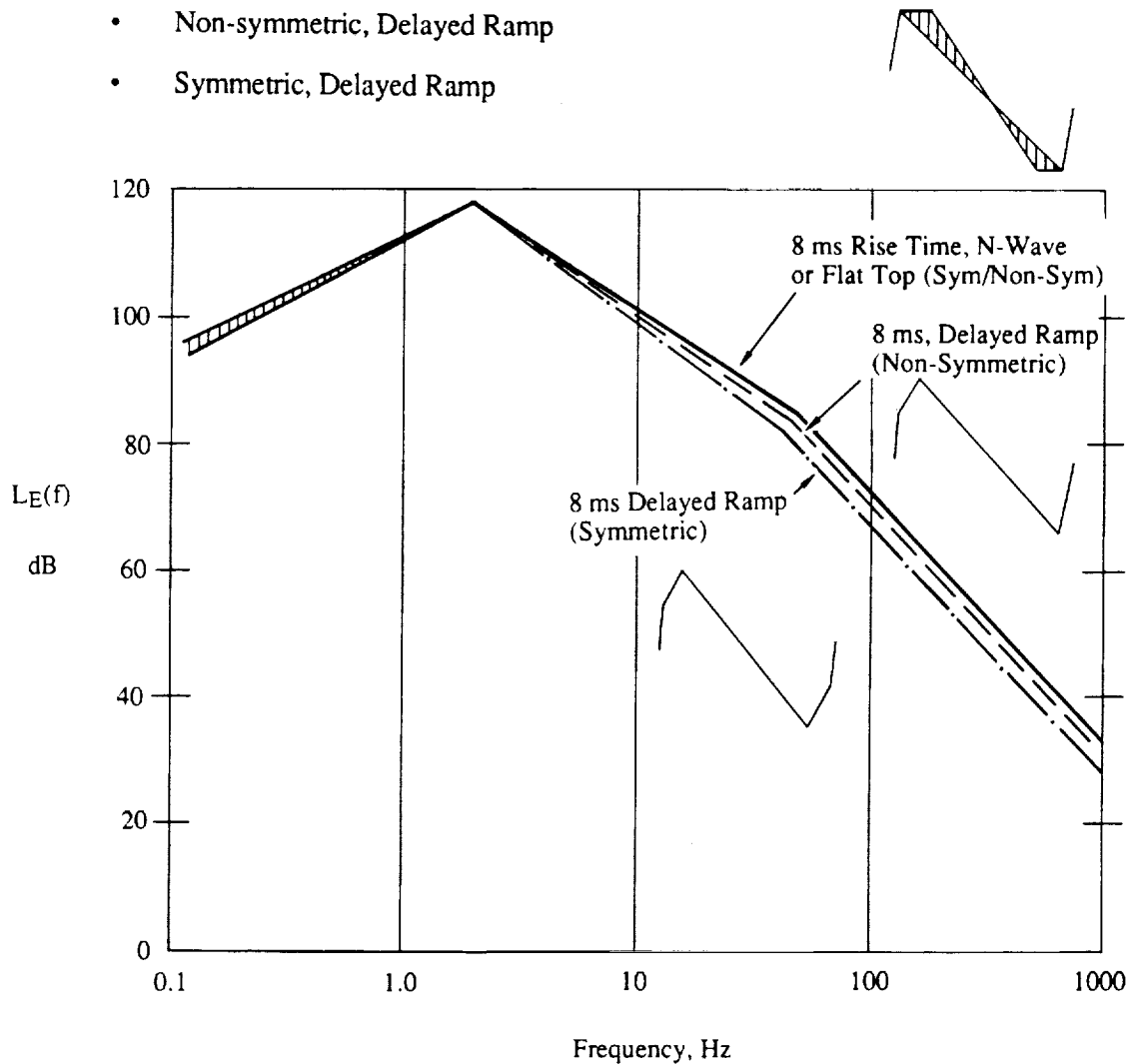In order to compute loudness levels from sonic boom as it would be heard indoors, an outdoor-to-indoor noise reduction model is needed. Available data from a number of sources (refs. 1-4) was utilized, along with a generic model for outdoor-to-indoor low frequency noise reduction (ref. 5) to construct the curve shown in Figure 8 for "windows closed" and "windows open" conditions. The dip in noise reduction at the lowest frequency for the windows closed condition is associated with a Helmholtz resonance effect that will vary widely depending on the area and length of air leakage paths into a room and the room volume. The second dip is generally more consistent from room to room and is normally associated with the lowest vibration mode of the largest outside wall. This resonance frequency may also interact with the lowest room acoustic modes to give a complex behavior to the noise reduction at these lowest frequencies. Although there are very limited noise reduction data at frequencies below 100 Hz, it is anticipated that loudness levels will be increasingly insensitive to variations in the noise reduction value at a specific frequency as this frequency decreases well below 100 Hz.
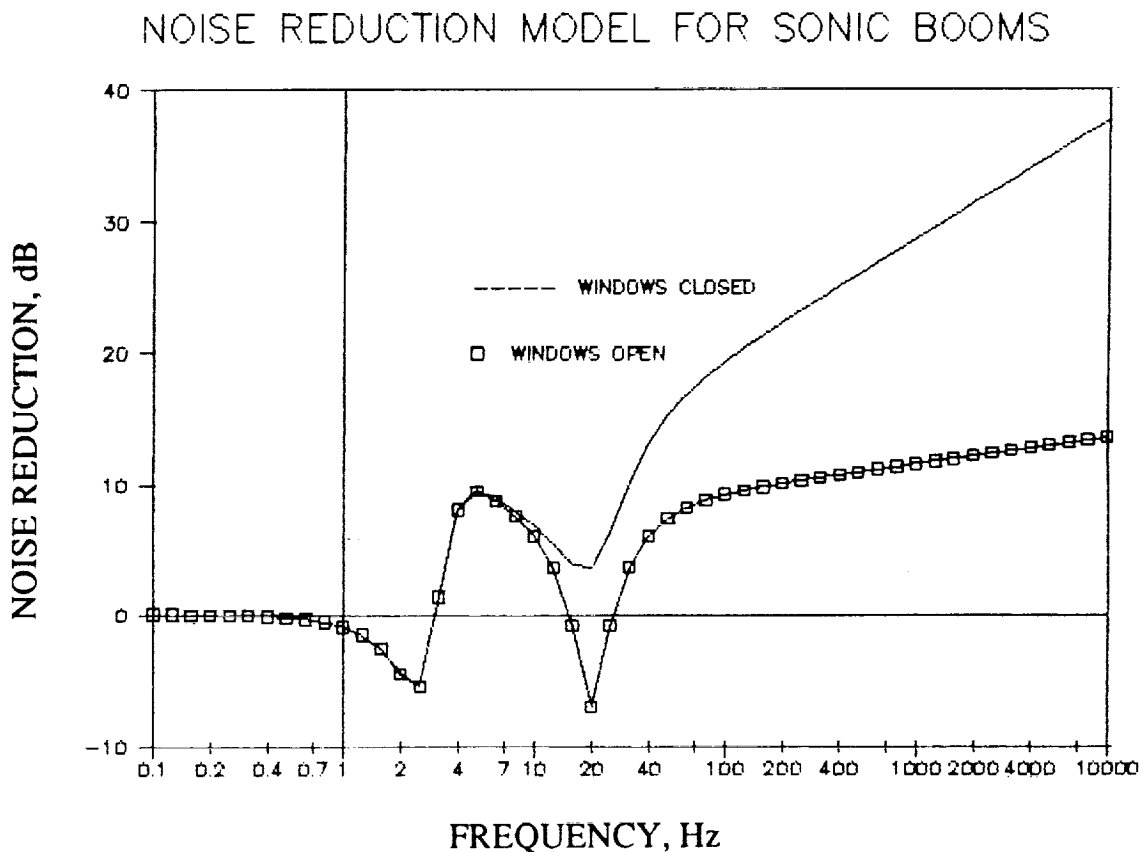
NOISE REDUCTION MODEL FOR SONIC BOOMS

Figure 8. Noise Reduction Model for Sonic Booms

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NOISE METRICS EVALUATED FOR SONIC BOOM LEVELS

The noise metrics being evaluated in this study include:

- Sound exposure levels

  (i)   A-weighted
  (ii) C-weighted

- Loudness levels

  (i)   Perceived Level (the Stevens Mark VII model) (ref. 6)

using loudness contours which extend down to 1 Hz.

Although there are other loudness models, such as the Stevens Mark VI model embodied in an American National Standard (ref. 7) and the sophisticated loudness model by Zwicker (ref. 8), these other versions do not have loudness contours extended down to 1 Hz. Thus, these alternate methods may not be suitable for sonic boom loudness calculations where much of the energy is concentrated at frequencies below about 50 Hz.

Interim results obtained from the calculation of loudness outdoors and indoors for the family of sonic boom wave shapes and spectra shown earlier are listed in Table 2. Loudness, in terms of Stevens, Mark VII Perceived Level, are given for listening outdoors and indoors with windows closed or open, based on the noise reduction models in Figure 8.

Table 2

Interim Results

Relative Stevens Mark VII Perceived Level, dB

Boom Signature*	Outdoor Level	- - - - Indoor Level - - - -	
		Window Open	Window Closed
N-Wave	97.2	87.9	76.2
N-Wave with 8 msec Rise Time	84.3	77.8	66.1
Non-Symmetric Flat-Top	84.2	77.5	66.0
Symmetric Flat-Top	84.1	77.2	65.8
Non-Symmetric Delayed Ramp	81.8	74.7	63.2
Symmetric Delayed Ramp	76.4	68.5	56.1

* 1 psf overpressure - 350 msec duration

RELATIVE LOUDNESS FOR DIFFERENT WAVE FORMS AND DIFFERENT LISTENING SITUATIONS

It is helpful to view the preceding data from the standpoint of relative changes in loudness for the different wave forms and for the three different listing situations. Such a view is shown in Table 3 below. For each listening situation, the loudness for the ideal N-wave is assigned a reference loudness of 0 dB. Note that the relative loudness for each of the other wave forms, is approximately the same for all three listening conditions (i.e., outdoors; indoors, windows closed; or indoors, windows open) thus suggesting that the *relative* loudness of alternative waveforms would not be strongly sensitive to the listening environment. Note, also that, as expected from Figure 7, the relative loudness for the symmetric, delayed ramp wave form is the lowest of all the wave forms considered.

However, there is one important point not brought out by the calculated indoor loudness values. There is considerable evidence to show that people judge the loudness or annoyance of subsonic aircraft noise (refs. 9,10) and sonic booms heard indoors (as discussed later), by different criteria as compared to the same type of sound heard outdoors. The net effect is that subtracting the outdoor-to-indoor noise reduction from outdoor noise levels may underpredict indoor loudness levels. It is interesting to note that for one of the studies (ref. 9), loudness of subsonic aircraft noise calculated according to the Zwicker method was in much better agreement with the laboratory findings for the subjectively-perceived change in noise levels indoors vs outdoors.

Table 3

Relative Stevens Mark VII Perceived Level, dB re: Ideal N-Wave

Boom Signature*	Outdoor Level	---- Indoor Level ---- Window Open	Window Closed	Average ±S.D.
N-Wave	0	0	0	0
N-Wave with 8 msec Rise Time	-12.8	-10.2	-10.1	
Non-Symmetric Flat-Top	13.0	-10.4	-10.2	} -11.2 ± 1.3
Symmetric Flat-Top	-15.4	-13.2	-12.9	
Non-Symmetric Delayed Ramp	-13.1	-10.7	-10.4	-13.8 ± 1.1
Symmetric Delayed Ramp	-20.8	-19.4	-20.1	-20.1 ± 0.5

* 1 psf overpressure - 350 msec duration

ALTERNATIVE NOISE METRICS

For comparison to the preceding results for Perceived Level (Mark VII), in PLdB, Table 4 shows a comparison of the calculated difference between values of Perceived Level minus A-weighted Sound Exposure Level and C-weighted minus A-weighted Sound Exposure Level for both outdoor and indoor (windows closed) listening conditions. The differences between Perceived Level and A-weighted Sound Exposure Level are nearly the same for all of the non-ideal wave forms for both outdoors and indoors. However, this is not as true for the difference between Perceived Level in PLdB and C-weighted Sound Exposure Level. Furthermore, as shown in Figure 9, the absolute change in C-weighted Sound Exposure Levels among the different wave forms is much less than the change in Perceived (Loudness) Levels. Thus, a C-weighted sound level appears to rate alternative sonic boom wave forms very differently than would be indicated by Perceived (loudness) Level or A-weighted Sound Exposure Level. However, it is the C-weighted Sound Exposure Level which was chosen by a CHABA working group under the National Research Council, as the best and most reliable metric available at that time for use in the evaluation of community reaction to high energy impulsive sounds such as sonic booms. This choice was dictated by the greater emphasis in low frequencies inherent in the C-weighting which is considered a better indicator of the tendency for such high energy impulsive sounds to induce annoying rattle and vibration of buildings.

Table 4

Relative Relationships of Alternate Metrics

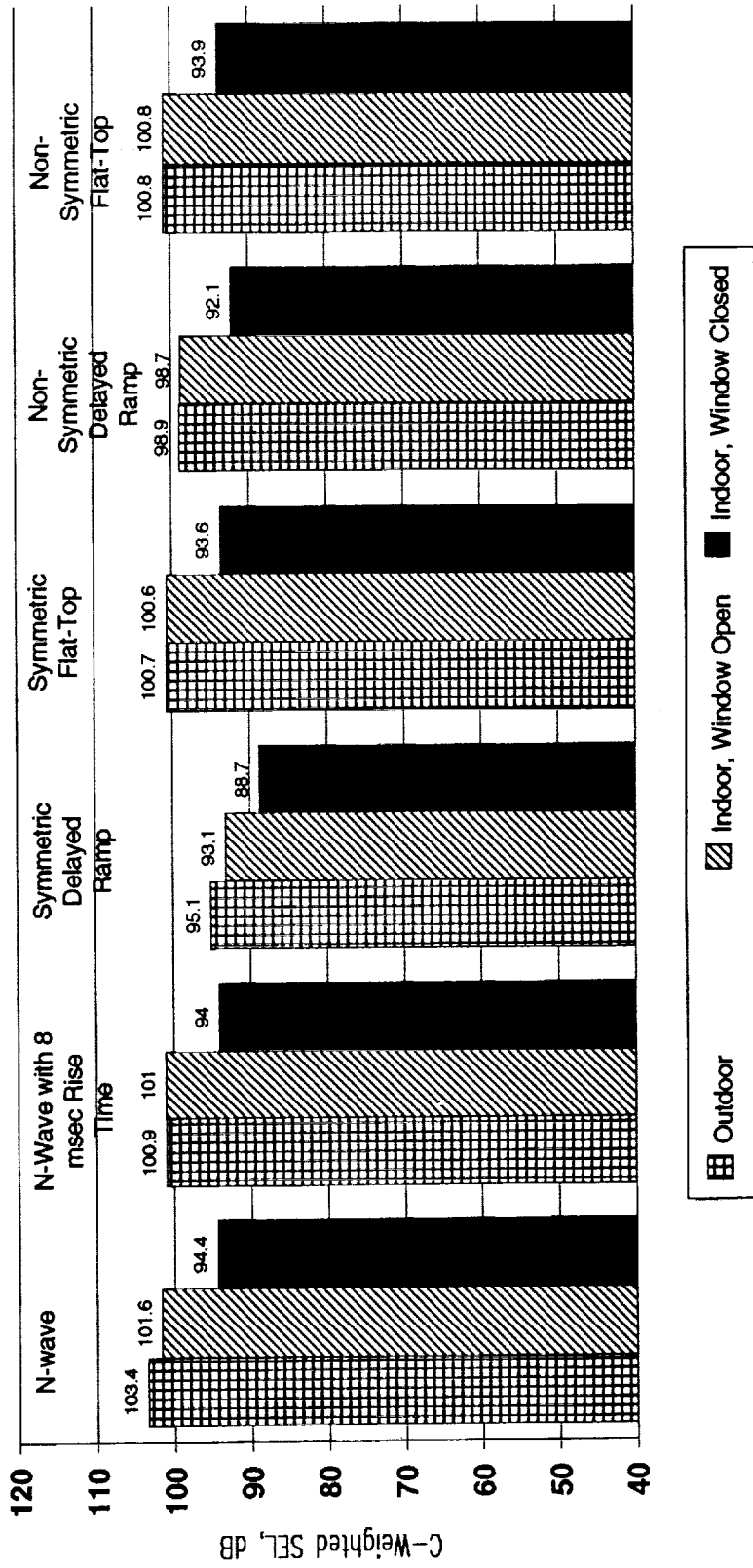| Sonic Boom Signature | – – – Outdoor – – – | | – – – – – – – – – Indoor – – – – – – – – – | | | |
| | | | Open Windows | | Closed Windows | |
	PL-ASEL dB	PL-CSEL dB	PL-ASEL dB	PL-CSEL dB	PL-ASEL dB	PL-CSEL dB
N-Wave	7.5	–6.3	8.7	–13.7	10.7	–18.2
N-Wave with 8 ms	12.7	–16.6	13.7	–23.3	11.0	–27.9
Non-Symmetric Flat Top	12.7	–16.6	13.6	–23.3	10.9	–28.0
Symmetric Flat Top	12.7	–16.6	13.4	–23.3	10.9	–28.1
Non-Sym Delayed Ramp	12.4	–17.1	12.9	–24.0	10.4	–28.9
Symmetric Delayed Ramp	11.7	–18.7	11.6	–24.6	8.0	–32.6
Average (without N-Wave)	12.4	–16.6	13.0	–23.7	10.2	–29.1
Standard Deviation	±0.4	±0.9	±0.9	±0.4	±1.3	±1.3

C-4.

Figure 9. C-Weighted Sound Exposure Levels for Various Sonic Boom Signatures

⊞ Outdoor   ▨ Indoor, Window Open   ■ Indoor, Window Closed

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THE RATTLE FACTOR

Loudness calculations for sonic booms do not indicate the potential significance in human response to such booms, *when heard indoors*, of rattle sounds caused by sonic boom-induced building vibration. Some aspects of this problem, identified here as the "rattle factor", are considered in the following figures. Figure 10 shows a summary of the type of interference noted by respondents queried during the tests of community reaction to sonic booms conducted during the SST program in the 1960's (refs. 11 and 12). As indicated, "house shaking" was the most frequently cited type of interference from these exposure tests. The peak sonic boom pressures involved were in the range of 1-2 psf for the Oklahoma City tests and less than 3.1 psf for the St. Louis tests.
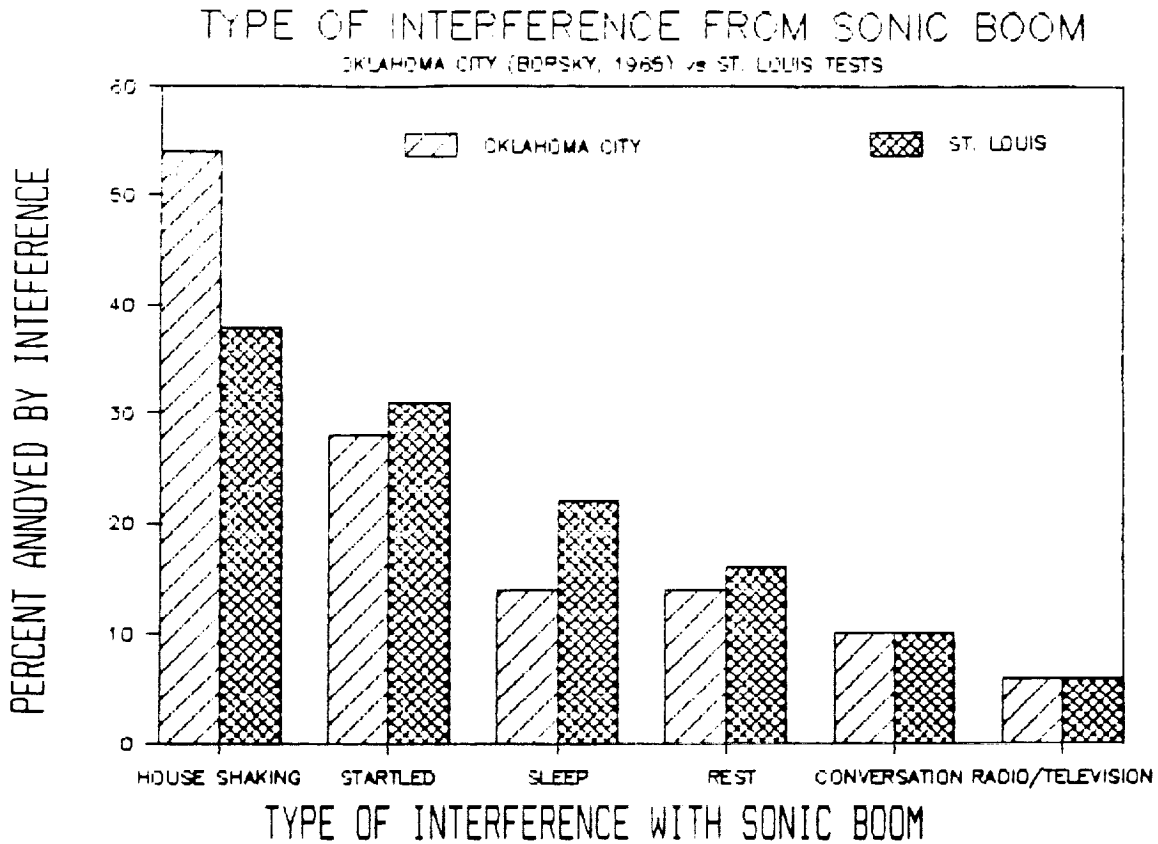

Figure 10.   Type of Interference from Sonic Boom Community Response Tests (Data from References 11 and 12).

Additional evidence for a possible "rattle factor" may be provided by the results of controlled sonic boom tests conducted at Edwards AFB(ref. 13). "Unacceptability ratings" to sonic booms were provided by subjects exposed to the booms outside and inside residential buildings. As indicated in Figure 11 below which shows this subjective rating vs outdoor peak overpressure, the results for the experienced subjects who lived near Edwards Air Force Base extrapolate to nearly the same peak overpressure (about 0.9 psf) for a 0 percent "unacceptability" rating for either outdoor or indoor listening. In other words, there is no apparent benefit for these subjects of outdoor-to-indoor noise reduction in lowering the "unacceptability rating" for booms heard indoors. While speculative, this result is consistent with the concept of the potential effect of added "rattle sounds or perceived building vibration" on subjective response to sonic booms indoors. However, another possible explanation for this trend, mentioned earlier, is the apparent higher "expectation" for lower levels of annoying sounds when heard indoors (refs. 9,10).
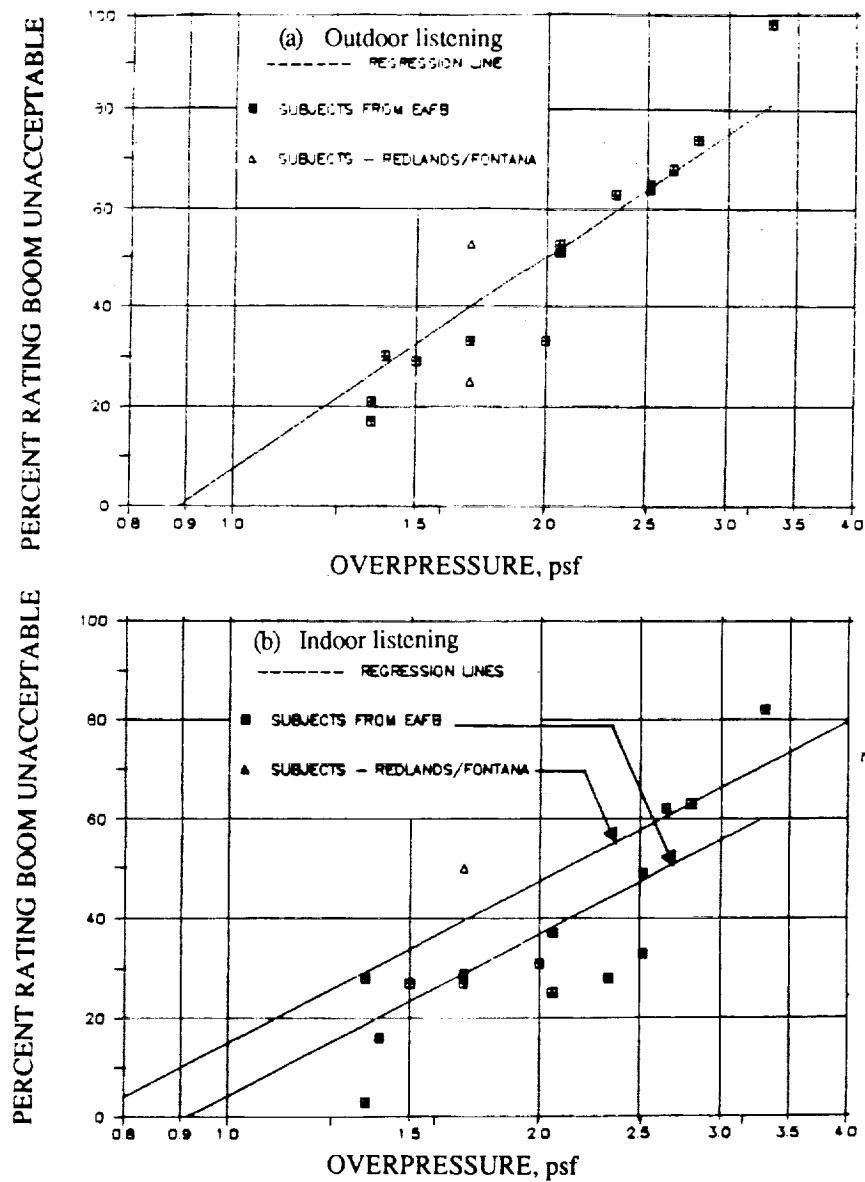

Figure 11. Acceptability Rating of Sonic Booms Heard (a) Outdoors and (b) Indoors During Edwards AFB Tests (data from ref. 13)

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RATTLE THRESHOLDS vs SONIC BOOMS EXCITATION

NASA has studied the threshold of building vibration levels which can induce rattle of wall-hung mirrors and plaques (ref. 14). These data, shown on Figure 12 below, indicate a "rattle threshold" at velocity response levels of about 0.008 to 0.04 in/sec. For wood frame structures, these "rattle" vibration thresholds are expected to be exceeded by a factor of at least 25 for sonic booms with nominal peak pressures of 1 psf (ref. 15).
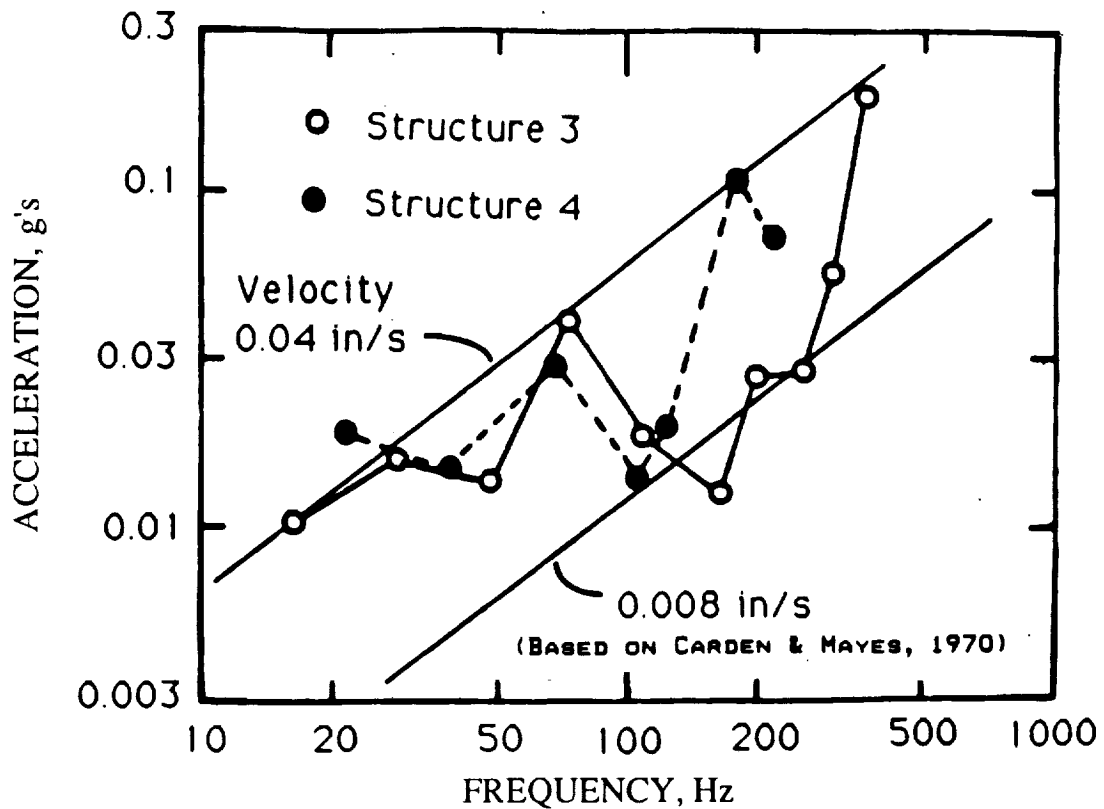

Figure 12. Vibration Levels at Rattle Thresholds for Wall-Hung Mirrors and Plaques

IS THERE AN ACCEPTABLE SONIC BOOM LEVEL?

The preceding material on subjective response to sonic booms relates to the determination of an acceptable sonic boom level. Another viewpoint on this question is provided by the data in the last figure (Fig.13). This compares one interpretation of the NASA Edwards AFB sonic boom test data and more recent community responses from Concorde-generated sonic booms (ref. 16) to a Wyle interpretation of the same Edwards data (ref. 13) augmented by results from both laboratory (refs. 17,18) and other field test data (ref. 11) used to extract additional data points on "acceptability" vs peak pressure. The unique form of analysis used in Leyman's interpretation of the Edwards AFB data (ref. 16) is preserved here in that the "% Acceptance" is plotted on a probability scale. Note that, fortuitously, there seems to be linear relationship with peak pressure plotted on a log scale. The implication is that "% Acceptability" has a log normal distribution as a function of peak sonic boom pressure. The (Wyle analysis) line is substantially different from the line labeled (Leyman, 1988) (ref. 16) and, with the corroboration by the other data, is believed to be a more reasonable estimate of the relative acceptability of the type of sonic booms evaluated. According to this line, such sonic booms with a peak pressure of the order of 0.8 psf would be expected to be "acceptable" about 95% of the time. For sonic booms shapes similar to those in the past, with a rise time of 8 ms, this peak pressure would correspond to a Perceived Loudness of about 89 PLdB and a C-weighted Sound Exposure Level of about 99 dB. It remains to be shown if "shaped" sonic booms would be expected to follow the same trend.

X   Lab Study   (Higgins and Sanlorenzo 1975)
●   Lab Study   (Mabry and Oncley, 1975)
◇   Field Study   Oklahoma City, (Borksy, 1965)
△   Field Study   Edwards AFB Tests (Wyle analysis from Kryter, et
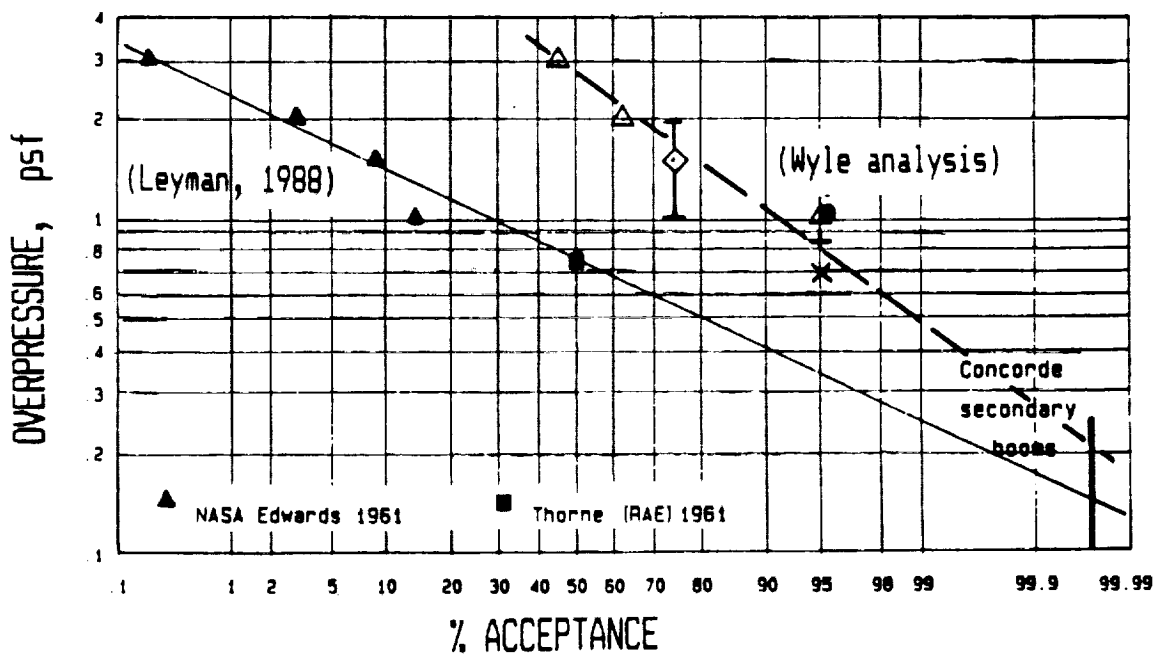   al., 1968)

Figure 13. Summary of Sonic Boom Acceptance Data

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SUMMARY

1. A preferred set of descriptors for assessing human response to sonic booms is based on the Sound Exposure Level - the measure of the integrated squared pressure in a sonic boom.

2. Consistent with this foundation, the spectral content of a sonic boom signature should be expressed in terms of the Sound Exposure Spectrum Level which can be derived from the Fourier Spectrum of the pressure signature.

3. The predicted effect of rise time on loudness appears to be more important than any shaping (e.g., flat top) of the peak pressure time history providing the peak pressure are the same in all cases.

4. The relative loudness ranking of alternative wave shapes is predicted to be roughly independent of the listening environment assuming no vibration or rattle effects are involved.

5. Noise reduction models applied for indoor loudness evaluation seem to show that the most important frequency range for indoor loudness levels lies at or above the lowest wall panel modes and is not likely to be very sensitive to Helmholtz resonance responses occurring at lower frequencies.

6. Rattle effects may be very important for indoor listening based on previous field experience.

7. For 95% acceptability of sonic booms of the type experienced in previous SST sonic booms tests, the peak pressure would have to be about 0.8 psf, the C-weighted Sound Exposure Levels would be about 99 dB and the Perceived Loudness (Mark VII) would be about 89 PLdB.

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