NASA Contractor Report 189643

Evaluation of Outdoor-to-Indoor Response to Minimized Sonic Booms

D. Brown and L.C. Sutherland

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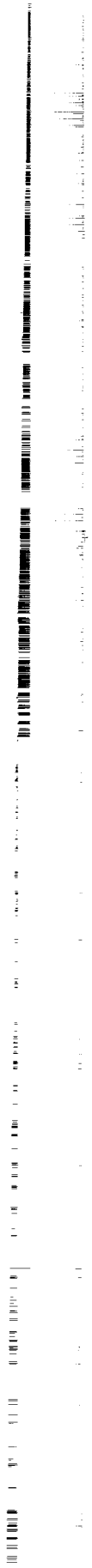

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FOREWORD

This report contains interim results of work performed by Wyle Research for NASA–Langley Research Center, under subcontract to McDonnell Douglas Corporation. These results were presented at the First Annual High-Speed Research Workshop at Williamsburg, Virginia, on May 14–16, 1991, and are contained in the proceedings of that Workshop.

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1.0 INTRODUCTION

Various studies have been conducted by NASA and others on the practical limitations of sonic boom signature shaping/minimization for the High-Speed Civil Transport (HSCT) and on the effects of these shaped boom signatures on perceived loudness. This current effort is a further part of this research with emphasis on examining shaped boom signatures which are representative of the most recent investigations of practical limitations on sonic boom minimization, and on examining and comparing the expected response to these signatures when experienced indoors and outdoors.

2.0 SONIC BOOM SIGNATURES

Figure 1 shows the wave forms of six different sonic boom signatures selected for use in this study. These signatures are intended to be representative of a range of sonic boom characteristics which have either been studied in previous research (and are therefore considered to be reference wave forms) or have wave form shapes which are of specific interest in HSCT studies. All of the wave forms shown in Figure 1 and evaluated in this report have a peak (positive and negative) pressure of 1 pound per square foot and a total duration of 350 milliseconds. Except for the zero rise time N-wave in Figure 1(a), all waves have a shock wave rise time of 8 msec. Because peak pressure and rise time are fixed, these waveforms do not exhibit the kind of tradeoffs inherent in boom minimization studies. Comparisons of loudness between these booms are therefore not of direct interest. They provide example cases for evaluating the difference between loudness indoors and loudness outdoors.

The reference wave form shown in Figure 1(a) is a symmetrical N-wave with zero rise time, and the wave form shown in Figure 1(b) has shock wave rise times of 8 milliseconds. These wave forms can be used for comparisons relative to other research studies and relative to analyses discussed herein for other shaped wave forms.

The shaped wave forms shown in Figures 1(c) through 1(f) exhibit two basic variations on characteristics which may be associated with HSCT signatures. These include the initial shock characteristics associated with low-boom aircraft shaping, denoted herein as the Front Shock Minimized wave forms (Figures 1(c) and 1(e)), and the Flat Top wave forms (Figures 1(d) and 1(f)), and the symmetry (Figures 1(c) and 1(d)) and non-symmetry (Figures 1(e) and 1(f)) of the wave form history. Recent studies of HSCT configurations indicate that the rear shock may not be as readily controllable as the front shock and may therefore play a significant role in determining human and structural response to HSCT sonic booms.

N-Wave Reference Signatures
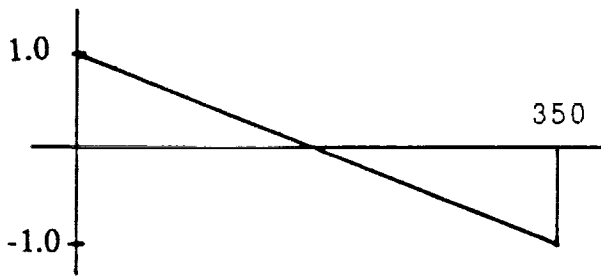
(a) Ideal N-wave with zero rise time
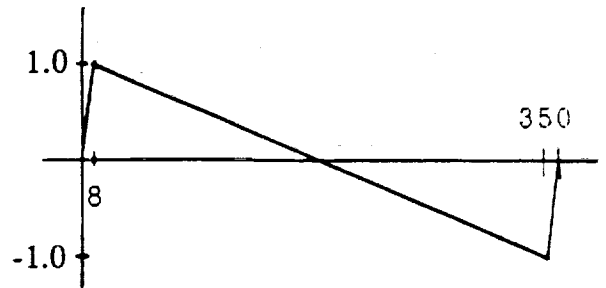
(b) Symmetric N-wave with a finite 8 ms rise time

Symmetric (Minimized) Wave Forms
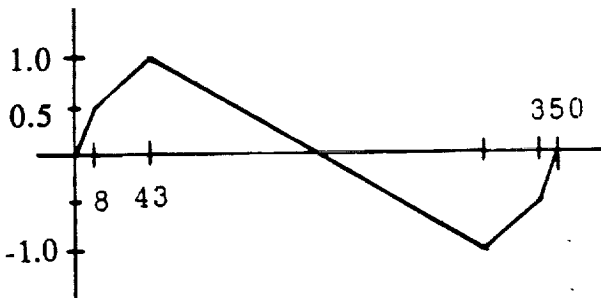
(c) Front Shock Minimized, 8 ms rise time to 0.5 psf followed by 35 ms rise to 1 psf – mirror image of this pattern at end
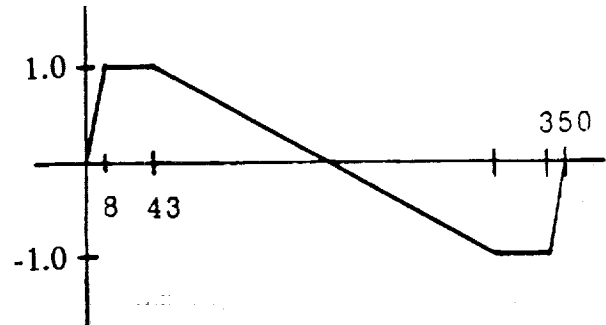
(d) Flat Top, 8 ms rise time, 35 ms duration for flat top - mirror image of this pattern at end

Non-Symmetric (Minimized) Wave Forms
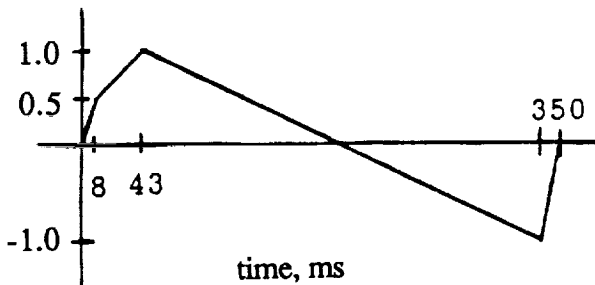
(e) Front Shock Minimized, 8 ms rise time to 0.5 psf followed by 35 ms rise to 1 psf, 8 ms decay time at end
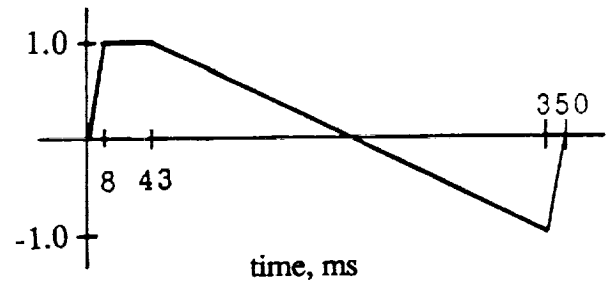
(f) Flat Top, 8 ms rise time, 35 ms duration of flat top, 8 ms decay time at end

Pressure, psf

Figure 1. Sonic Boom Signatures

3.0 SONIC BOOM DESCRIPTORS

While research on the objective (acoustical) and subjective (psychoacoustic) character-istics of sonic booms has been extensive over the past three decades, it is evident that there is no clear consensus of preferred terminology and descriptors to be used in evaluations of response.

Table 1 of this report is one attempt to summarize the options for sonic boom descriptors, with recommendations for preferred and optional descriptors which are consistent with current, standardized acoustical terminology. Some of these are utilized in the report and 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.

4.0 SPECTRAL CONTENT OF SONIC BOOMS

4.1 Acoustical Descriptor for Spectral Content

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 descriptors 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

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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)	

---

(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.

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

and E_0 = 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

4.2 Spectra of Sonic Boom N-Wave Forms

Figures 2 and 3 show the Sound Exposure Spectrum Levels over the frequency range from 0.25 Hz to 1000 Hz for the N-waves illustrated and described in Figures 1(a) and 1(b), respectively. As illustrated in Figure 2, 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:

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

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

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

Figure 3 shows the Sound Exposure Spectrum Level for the N-wave with a finite rise time of 8 milliseconds. In this case, the envelope of the high-frequency portion of the spectrum falls off at -40 dB/decade above a frequency equal to $1/(\pi t)$ where t is the rise time.

While the spectral characteristics of these two N-wave forms clearly differ at frequencies greater than 39.8 Hz, which is the frequency at which the envelope of Figure 3 differs from that of Figure 2, the overall Sound Exposure Level of the two spectra (and their wave forms) remains the same. The Sound Exposure value for each wave form can be shown to be equal to $P_{pk}^2 T/3$. When referenced to $20\mu Pa$ for the two N-waves discussed herein, the Sound Exposure Level is 118.3 dB in each case. This value was also given by the spectral analysis integration in the Fast Fourier Transform (FFT) method which was used to develop Figures 2 and 3.
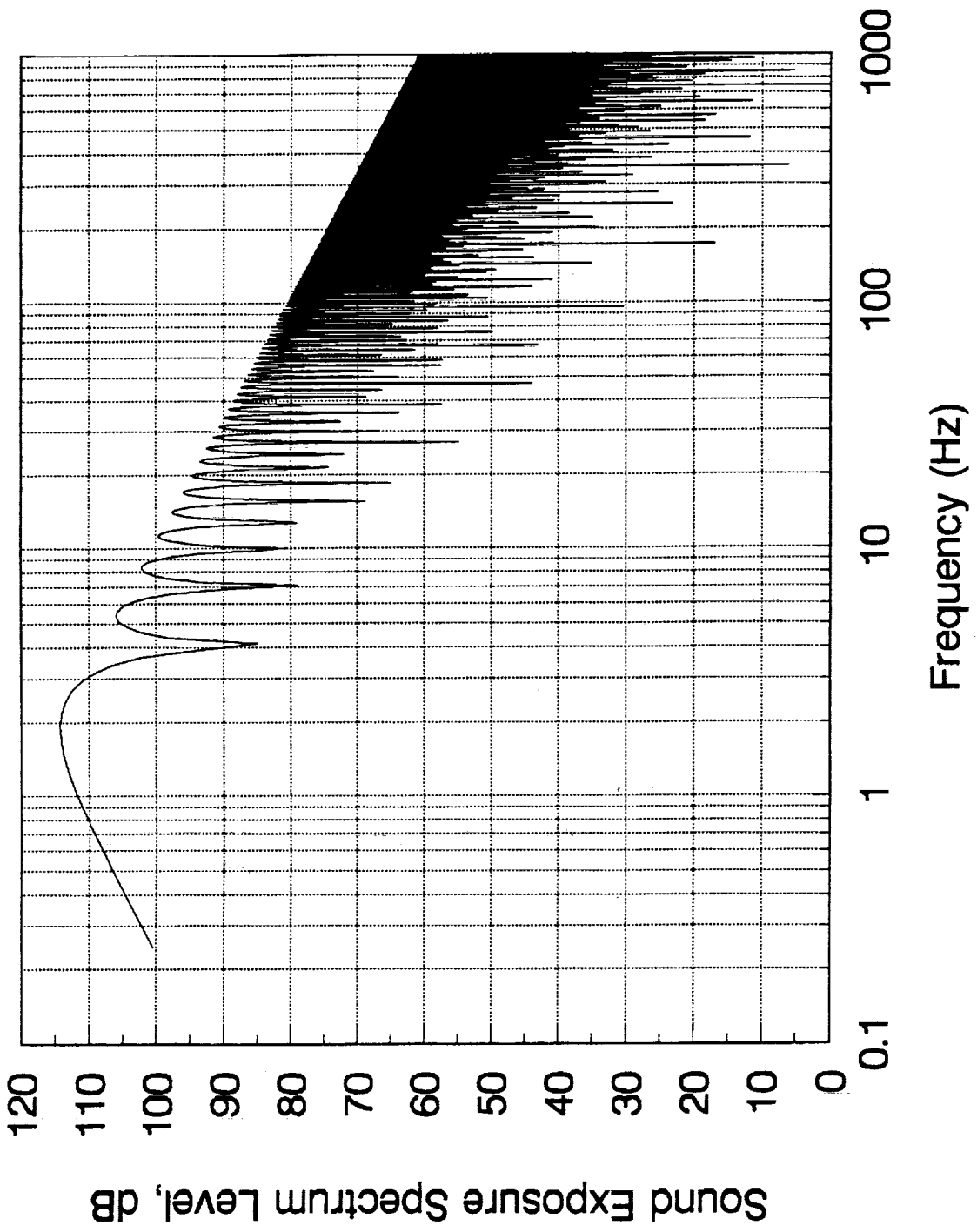
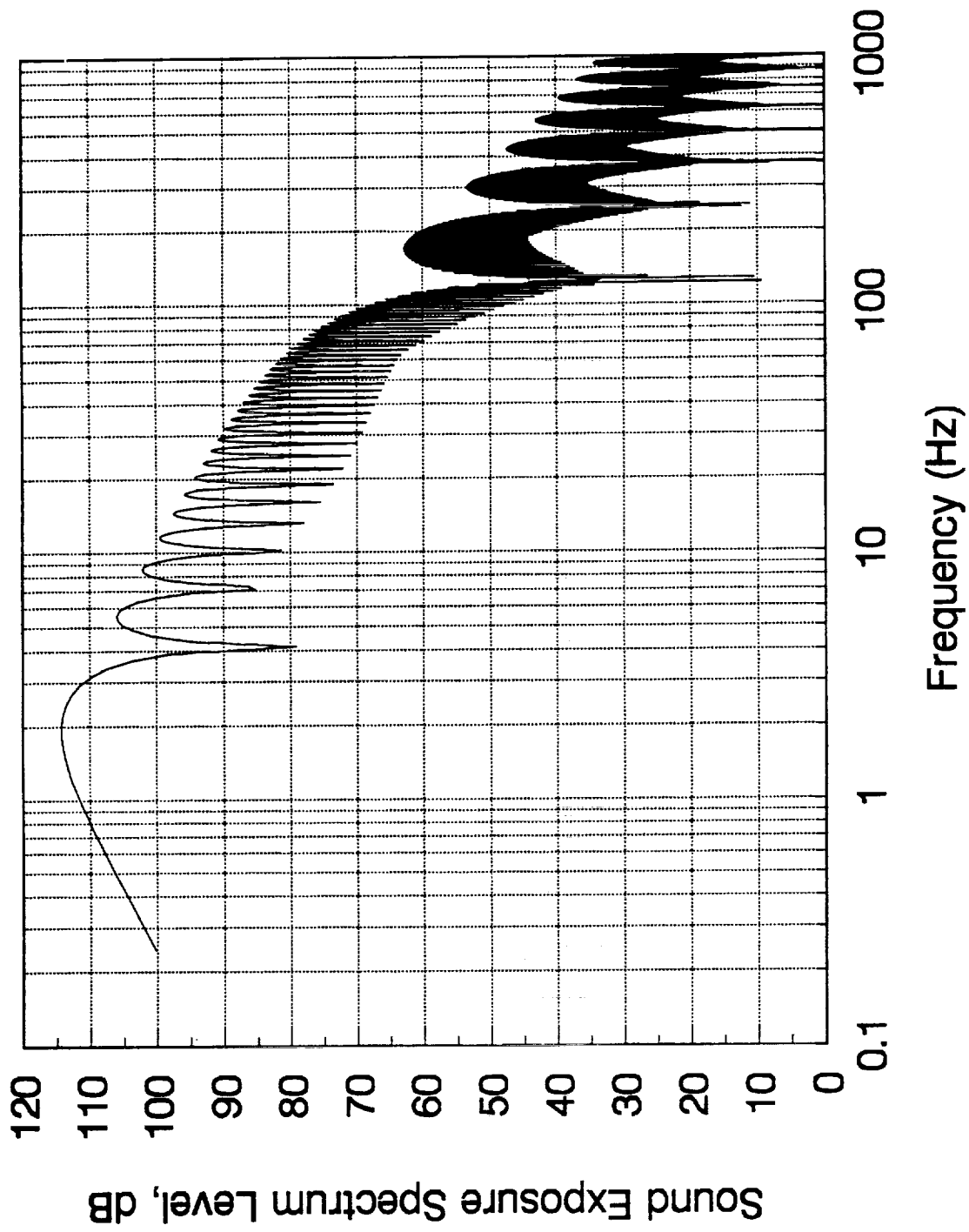Figure 2. Sound Exposure Spectrum Level, $L_E(f)$ for Ideal N-Wave with Peak Pressure of 1 psf

Figure 3.   L$_E$(f) for 1 psf N-Wave with 8 ms Rise Time (Fig. 1b)

4.3 Spectra of Generic Minimized Sonic Boom Wave Forms

Wave forms representing those shown in Figures 1(c) through 1(f) for generic minimized sonic boom signatures were frequency-analyzed by the same FFT method as that employed on the N-waves. The resulting Sound Exposure Spectrum Levels for these generic wave forms are shown in Figures 4 through 7, respectively.

In general, all of these spectra exhibit characteristics similar to those of Figure 3 for the finite rise time N-wave. Specific differences among the generic boom spectra are in the spectral detail at frequencies above that associated with the initial rise time.

4.4 Composite Envelope of Spectra

Figure 8 shows a composite version of the "envelope" of the spectra obtained for sonic booms with 8 millisecond initial rise time, peak pressure of 1 psf and duration of 350 ms. As previously discussed, the low-frequency portions of the spectra are nearly identical and the high-frequency portions exhibit similar envelope characteristics (to each other). The envelope amplitudes for the finite rise time reference N-wave and the generic wave forms (all with 8 milliseconds initial rise time) decrease in the following order:

- N-wave; Symmetric and Non-Symmetric Flat Top
- Non-Symmetric, Shock Minimized
- Symmetric, Shock Minimized

This result exhibits the dominance of the shock wave on the high-frequency spectrum. The "shock minimized" shock is half the amplitude of the N-wave or flat-top shock.

These spectra are further examined in terms of subjective measures later in this report. The spectra discussed so far are considered to be outdoor sonic boom conditions. A model which allows transformation of these outdoor spectra to indoor (room) conditions is developed in the appendix to this report and is summarized as follows.

4.5 Outdoor-to-Indoor Noise Reduction Model for Sonic Booms

One of the main purposes of the work reported in this and subsequent documents (resulting from the current research effort under this task) is to develop refined models for structural/acoustical transmission of sonic boom from outdoors to indoors. Two typical room

Figure 4. $L_E(f)$ for Symmetric Shock Minimized, 8 ms Rise Time to 0.5 psf, 35 ms Rise to 1 psf (Fig. 1c)
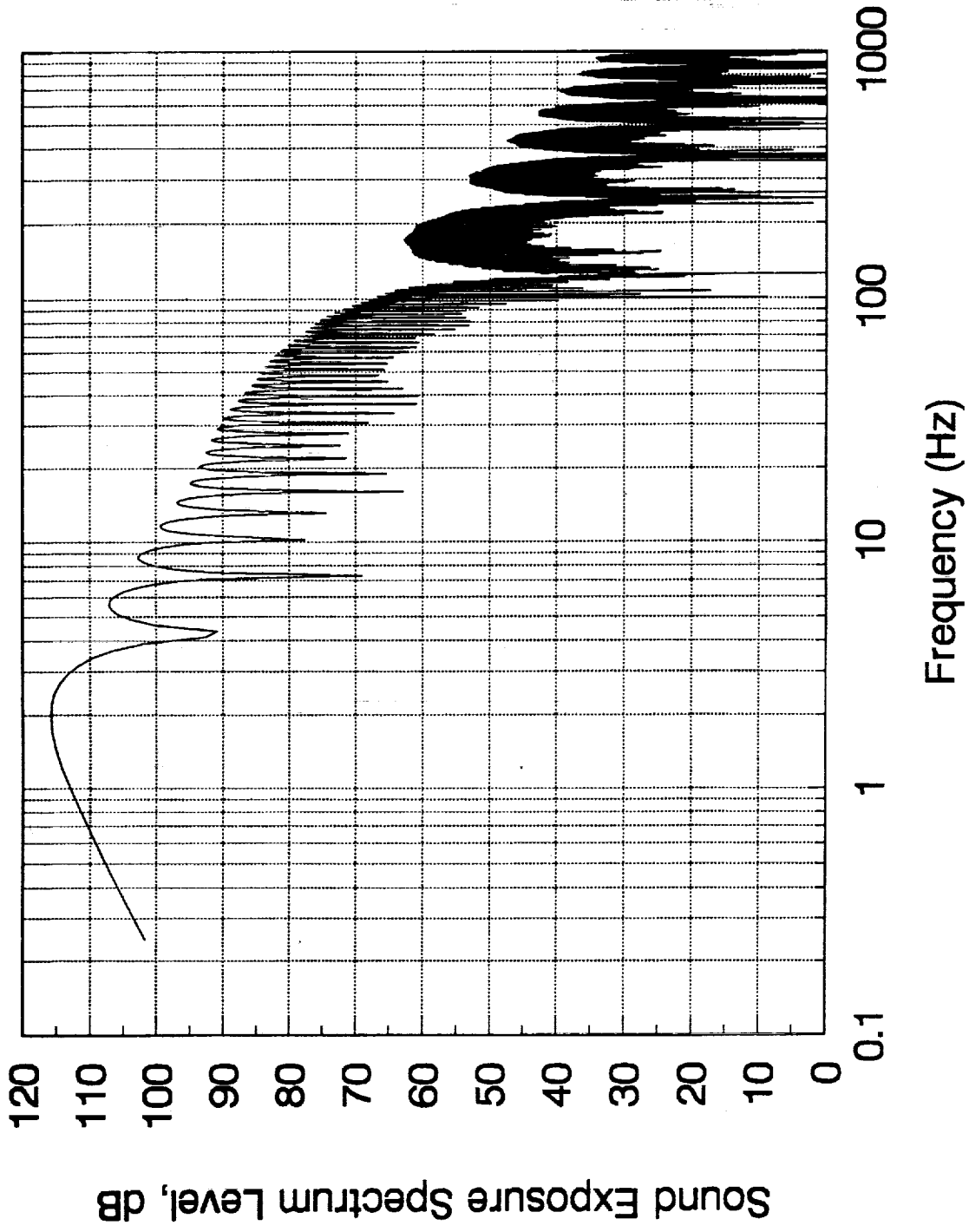
Figure 5. $L_E(f)$ for Symmetric Flat Top, 8 ms Rise Time, Flat Top for 35 ms (Fig. 1d)
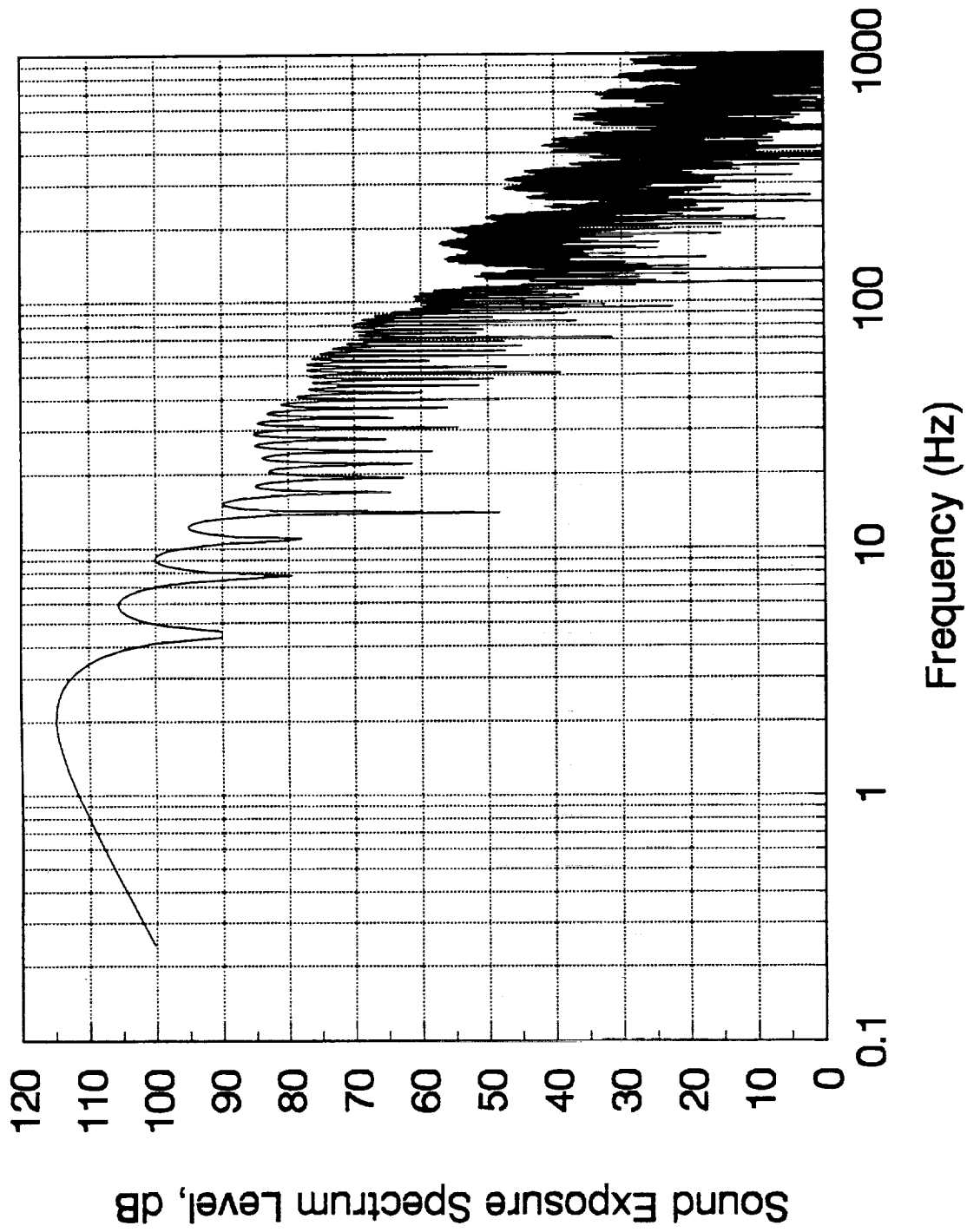
10

Figure 6. $L_E(f)$ for Non-Symmetric Front Shock Minimized, 8 ms Rise Time to 0.5 psf, 35 ms Rise to 1 psf (Fig. 1e)

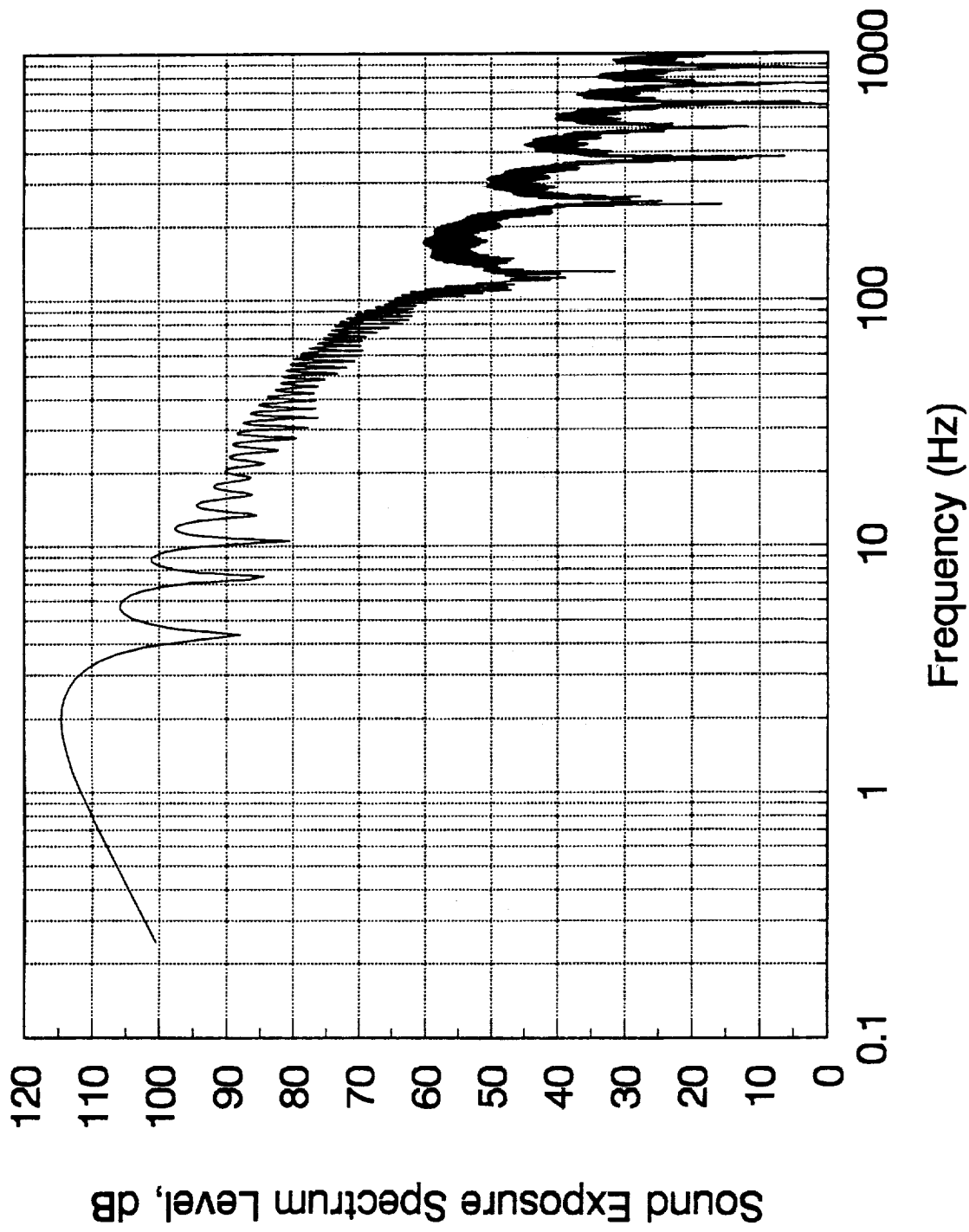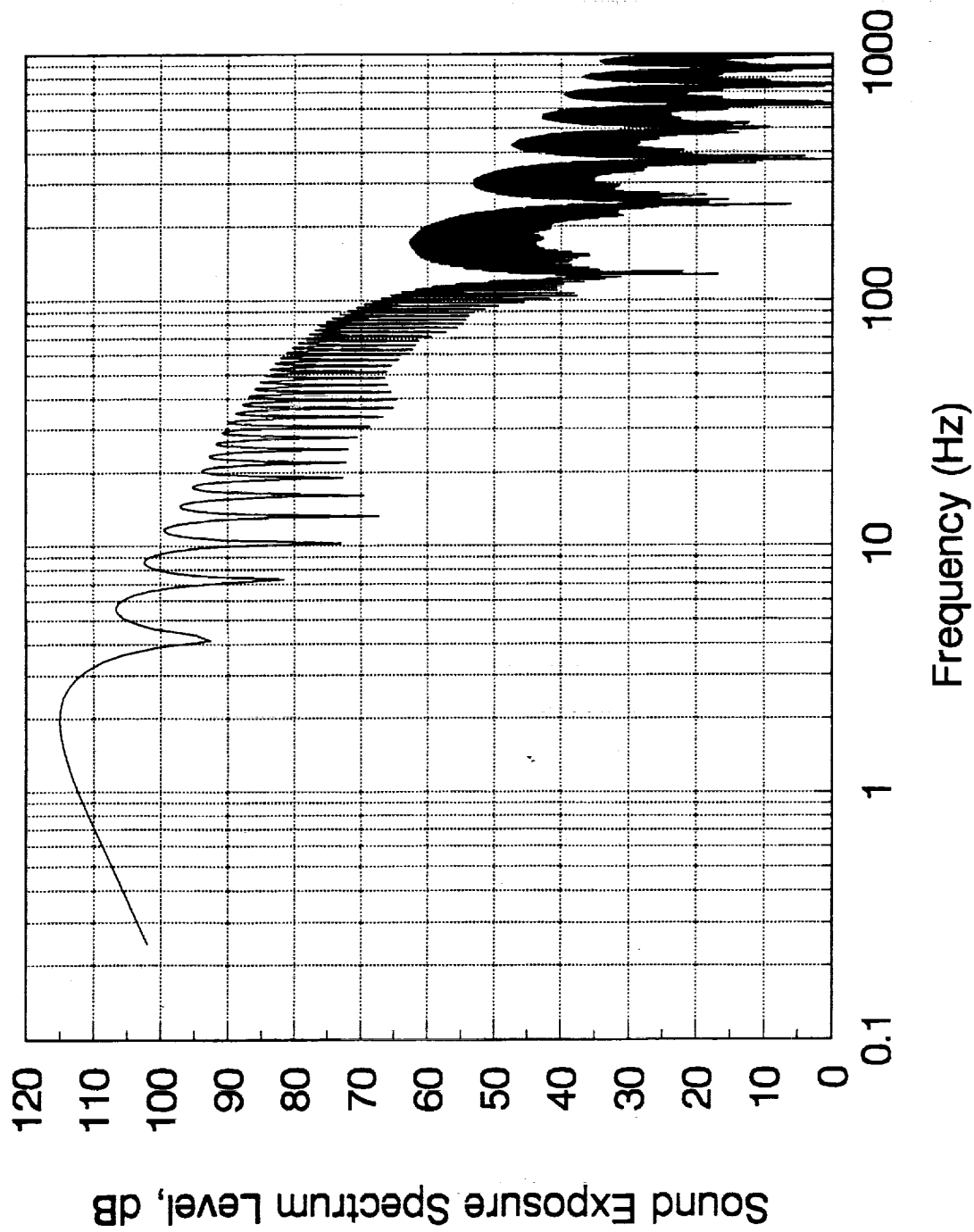Figure 7. $L_E(f)$ for Non-Symmetric Flat Top, 8 ms Rise Time, Flat Top for 35 ms (Fig. 1f)
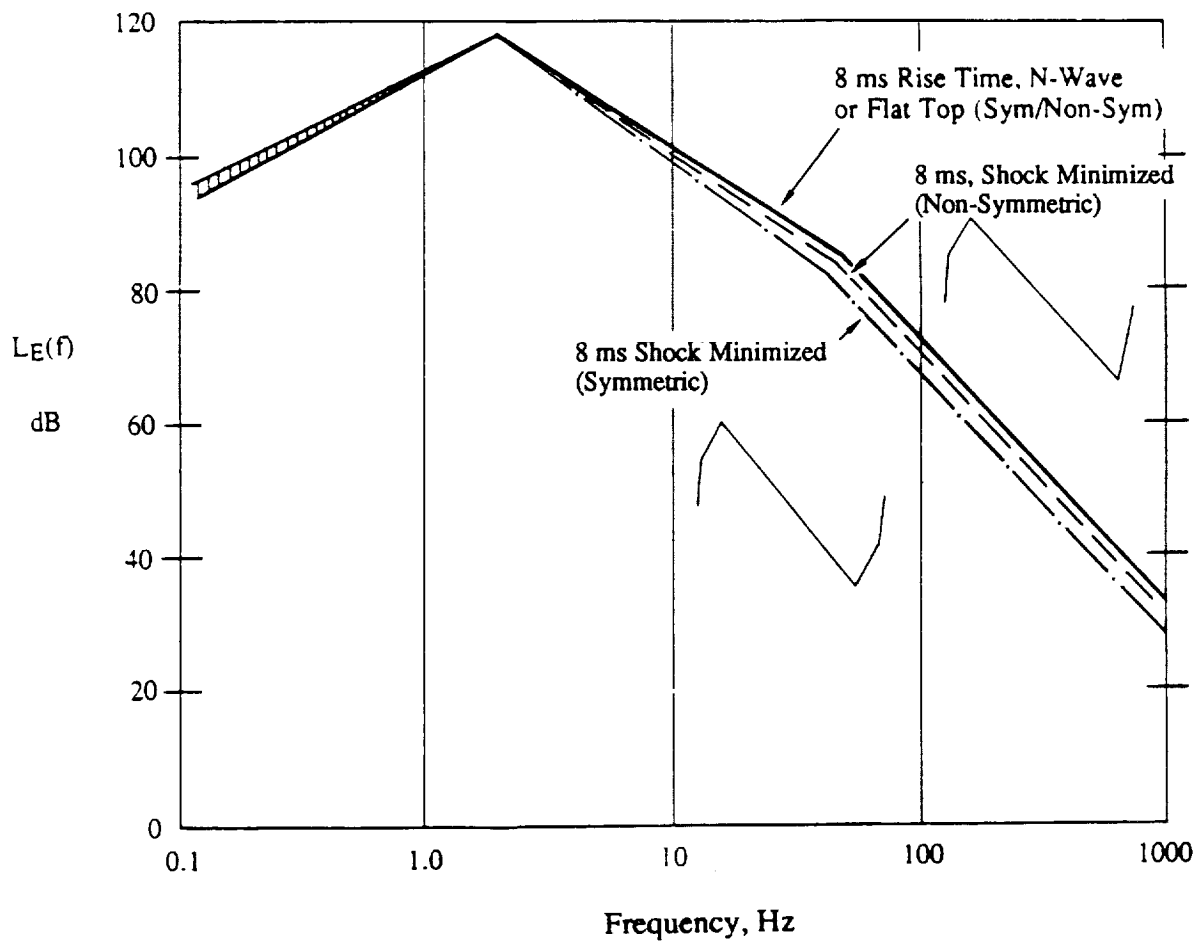
12

Figure 8. Comparison of Envelope of Sound Exposure Spectrum Levels for Various Wave
Shapes with Peak Pressure of 1 psf and Duration of 350 ms

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conditions are usually examined in this type of modelling, one with windows open and one with windows closed. The differences between the two conditions are due to:

a. the obvious reduction of facade transmission loss caused by open windows, and

b. the effect of the room/window combination acting as a Helmholtz resonator.

The model shown in Figure 9 has been developed using available information in terms of data (References 1 through 4) and a previous model for low-frequency noise (ref. 5). This is more extensively described in the appendix. Some generic characteristics of the model shown in Figure 9 are described as follows.

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.

5.0 LOUDNESS EVALUATIONS

5.1 Noise Descriptors

The noise descriptor used in this analysis of sonic boom signatures is the Stevens Mark VII Perceived Level (ref. 6). This descriptor has been used by other research studies of sonic boom signatures and has proved to be of enhanced usefulness (relative to other metrics) because of its capability to assess sounds with frequencies as low as 1 Hz.

Application of the Mark VII Perceived Level to sonic boom spectra requires a number of analytical procedures which are not explicitly defined in available literature. The method used in this analysis converts the Sound Exposure Spectrum Level data, for each sonic boom, to Equivalent One-Third Octave Band Sound Pressure Levels by integration of the spectrum levels within each one-third octave bandwidth and by changing the averaging time of the levels from 1 second to the boom duration (350 milliseconds). The resulting one-third octave band data are then processed in accordance with the Stevens Mark VII procedure (ref. 6).

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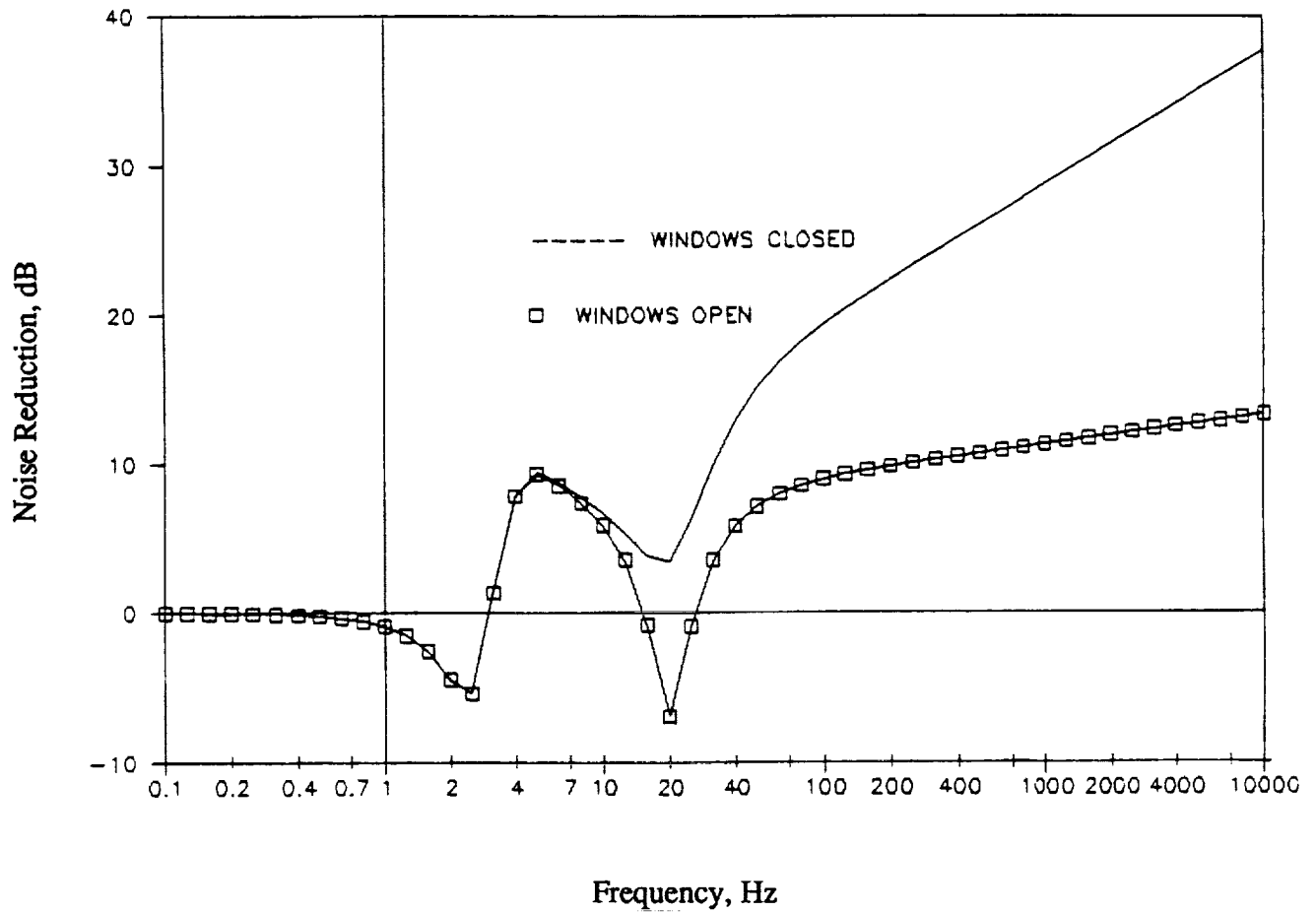
Figure 9.   Idealized Model for Outdoor to Indoor Noise Reduction for Typical Residential Buildings for Application to Predictions of Sonic Boom Loudness Indoors.

It should also be pointed out that other variations on this procedure for computing loudness of sonic booms have been proposed, including computing the loudness from only the first half of the boom signature and using a running average of the time history over a time period equal to the auditory time constant (ref. 7).

Although there are other loudness models, such as the Stevens Mark VI model embodied in an American National Standard (ref. 8) and the sophisticated loudness model by Zwicker (ref. 9), 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.

Comparisons are made of the relative relationships of the Mark VII Loudness Level with A-weighted and C-weighted Sound Exposure Levels. These are discussed later in this section as alternative noise metrics.

5.2 Loudness Level Evaluations

Results obtained from the calculation of loudness level 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 9.

Table 2

Stevens Mark VII Perceived Level, dB, for Sonic Boom Signatures

Boom Signature*	Outdoor Level	- - - - Indoor Level - - - - Window Open	Window Closed
Ideal N-Wave	97.2	87.9	76.2
N-Wave with 8 ms 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 Shock Minimized	81.8	74.7	63.2
Symmetric Delayed Ramp	76.4	68.5	56.1

* 1 psf overpressure – 350 ms duration

The 8 msec rise time N-wave and both flat-top waves have similar loudness, substantially less than that of the ideal N-wave, because loudness is dominated by the shock structure. Loudness of the symmetric shock minimized wave is lowest because it has half the shock amplitude of the N-wave and flat-top waves. The non-symmetric shock minimized wave has loudness closer to the flat-top because it is essentially half shock minimized and half flat top, and loudness is dominated by the louder half.

5.3 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. 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 wave forms would not be strongly sensitive to the listening environment. Note, also that, as expected from Figure 8, the relative loudness for the symmetric, shock minimized wave form is the lowest of all the wave forms considered. The key result of Table 3 is that benefits of shaped booms, as heard outdoors, appear to apply equally well indoors.

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. 10, 11) 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. 10), 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 versus outdoors.

Table 3

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

| Boom Signature* | Outdoor Level | ---- Indoor Level ---- | | Average ±S.D. (indoor level) |
		Window Open	Window Closed	
N-Wave	0	0	0	0
N-Wave with 8 ms Rise Time	-12.8	-10.2	-10.1	}-11.2 ± 1.5
Non-Symmetric Flat-Top	13.0	-10.4	-10.2	
Symmetric Flat-Top	-15.4	-13.2	-12.9	
Non-Symmetric Shock Minimized	-13.1	-10.7	-10.4	-13.8 ± 1.1
Symmetric Shock Minimized	-20.8	-19.4	-20.1	-20.1 ± 0.5

* 1 psf overpressure - 350 ms duration

5.4 Alternative Noise Descriptors

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 10, 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

Table 4

Relative Relationships of Alternative 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 Shock Minimized	12.4	-17.1	12.9	-24.0	10.4	-28.9
Symmetric Shock Minimized	11.7	-18.7	11.6	-2.6	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
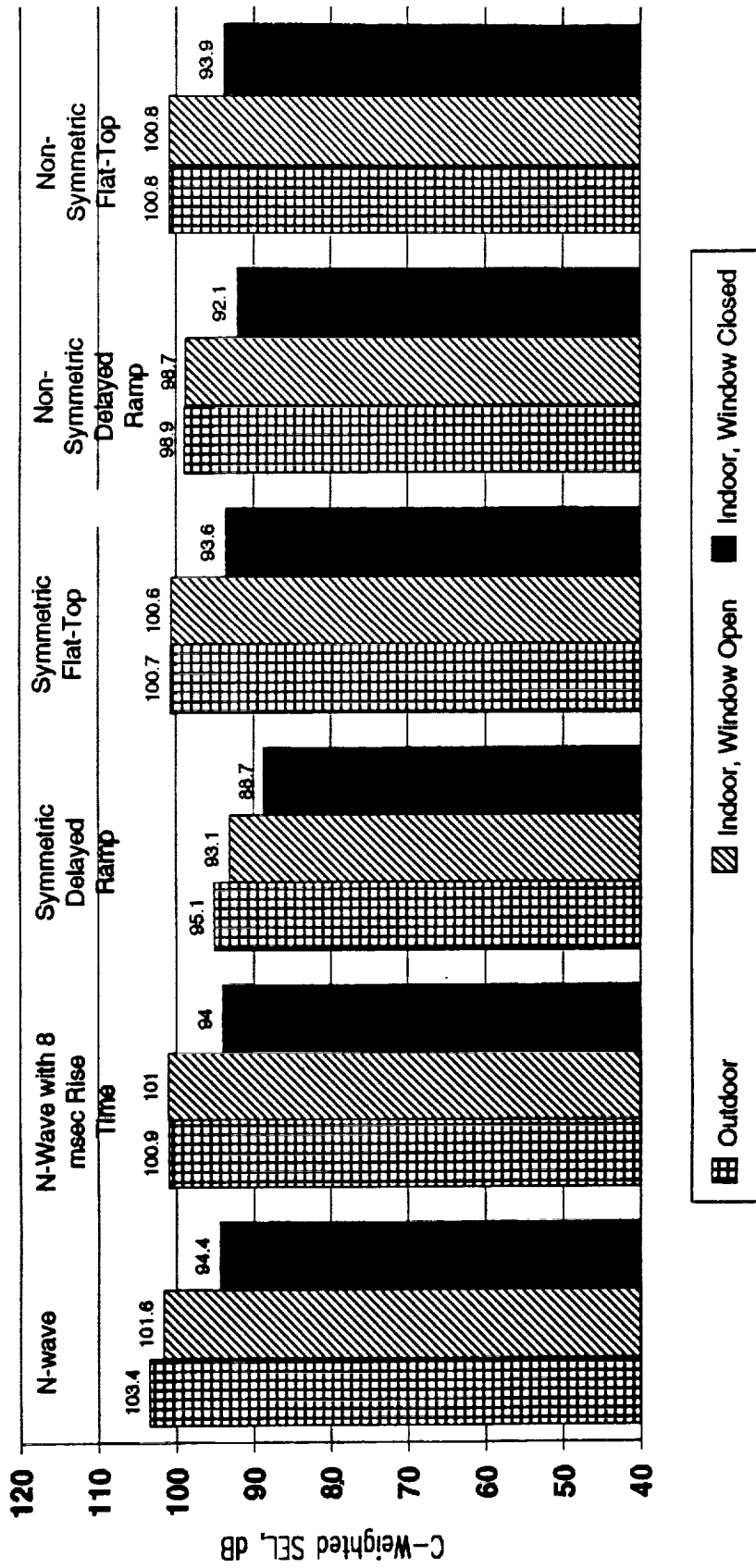
Figure 10. C-Weighted Sound Exposure Levels for Various Sonic Boom Signatures

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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.

5.5 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 11 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 1960s (refs. 12 and 13). 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. While the booms involved were N-waves, rather than the shaped signatures of current interest, rattle is clearly identified as a significant effect.

Additional evidence for a possible "rattle factor" may be provided by the results of controlled sonic boom tests conducted at Edwards AFB (ref. 14), again for N-wave booms. "Unacceptability ratings" to sonic booms were provided by subjects exposed to the booms outside and inside residential buildings. As indicated in Figure 12, which shows this subjective rating versus 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. 10, 11).

NASA has studied the threshold of building vibration levels which can induce rattle of wall-hung mirrors and plaques (ref. 15). That study indicated a "rattle threshold" at velocity response levels of about 0.008 to 0.04 in/sec. For wood-frame structures, these "rattle"
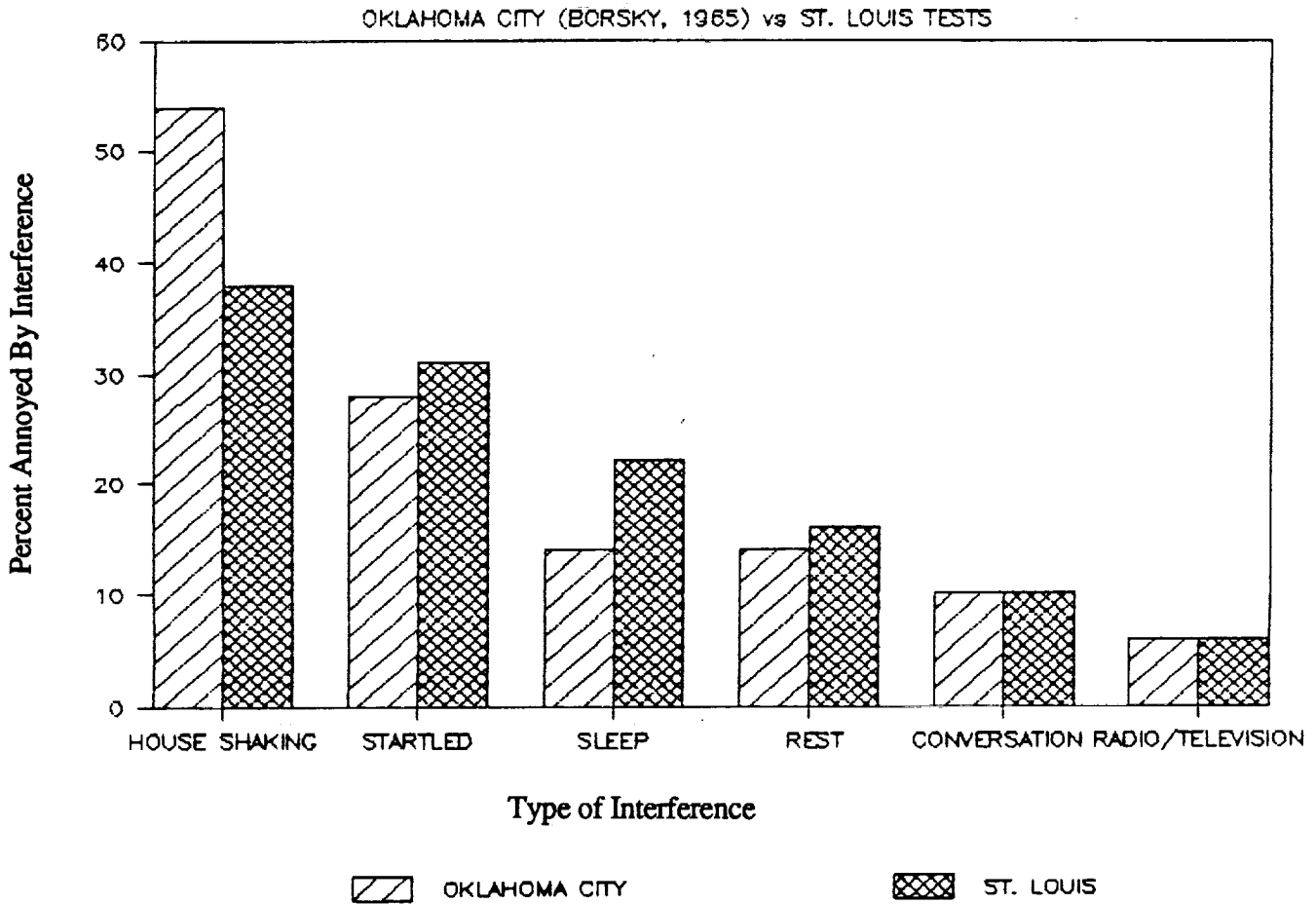
Figure 11. Types of Interference From Sonic Boom Community Response Tests.
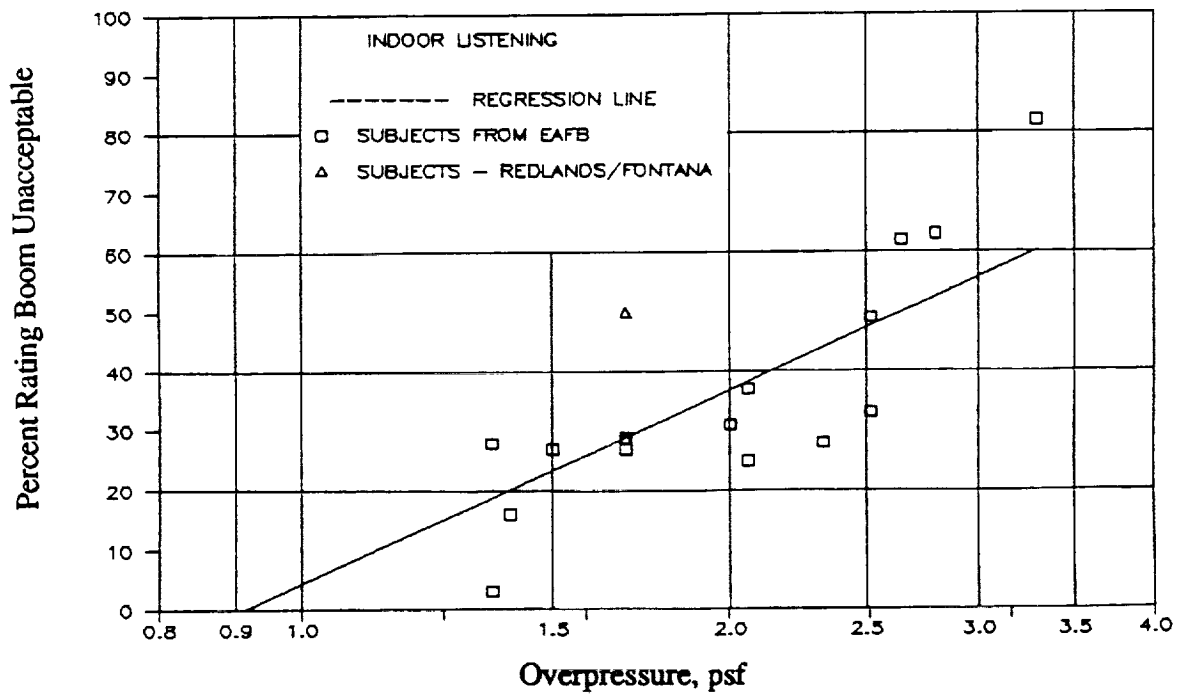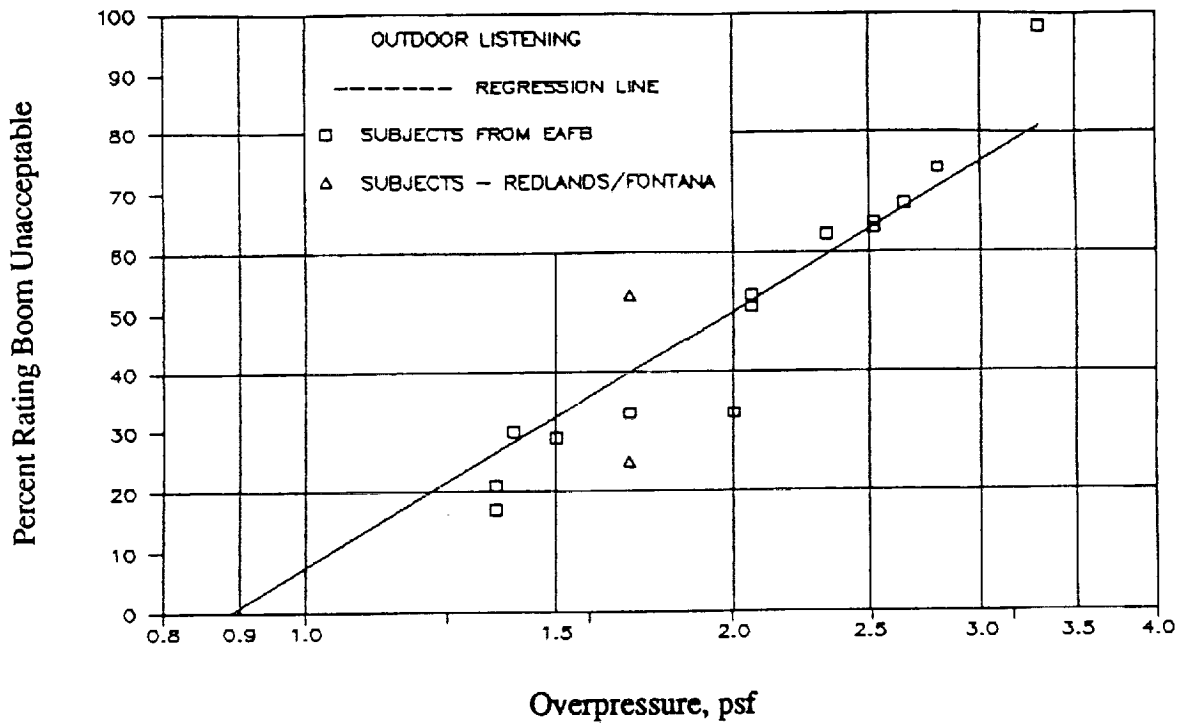(Data from Refs. 12 and 13.)

Figure 12. Acceptability Rating of Sonic Booms Heard (a) Outdoors, and (b) Indoors, During Edwards AFB Tests. (Data from ref. 14.)

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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. 16).

In summary, the assessment of sonic boom signatures may require an analysis beyond that of the loudness calculations discussed in this report. In such cases there may be a need to develop other means of assessment which account for building vibration response and rattle thresholds. This subject is addressed in a companion report (ref. 17) developed under the current contract.

6.0 SUMMARY AND CONCLUSIONS

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. Loudness of sonic booms is dominated by the shock waves. For a symmetrical N-wave or flat-top boom, loudness is determined by the peak pressure and the rise time. For a symmetric shock-minimized boom, loudness is largely determined by the pressure and rise time of the initial shock and is approximately independent of the peak pressure. The loudness of asymmetric booms is dominated by the loudest "half" of the signature.

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.

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APPENDIX

Outdoor-to-Indoor Noise Reduction Model
for Application to Sonic Booms

A realistic model for the outdoor-to-indoor noise reduction over the pertinent frequency range of sonic boom spectra is expected to include, in approximate ascending order of the pertinent frequency range, the following elements where windows are assumed closed.

REGION

1. A leakage path transmission loss (TL) which would tend to approach zero as frequency (f) approaches zero.

2. A Helmholtz resonance dip in TL, potentially resulting in a negative TL over the narrow frequency bandwidth of this resonance.

3. A frequency range of roughly constant TL above the Helmholtz resonance but below the first structural resonance frequency.

4. A minimum TL at the first mode of the largest wall facing the boom.

5. A region of complex variation in TL where wall and room resonances interact.

6. A gradual increase in average TL as mass law takes over well above the lowest resonances.

7. At higher frequencies, generally above 1000 Hz, a flattening out, or reduction in TL at or near the coincidence frequency for the exterior wall.

8. A further potential increase above the coincidence frequency but with a final leveling off as high-frequency leakage limits the maximum TL.

For purposes of this analysis, only the first six elements will be included in the model.

For an open-window condition, the first two elements will still appear but with a Helmholtz resonance at a higher frequency – perhaps in the order of 4 to 8 Hz.

For analysis purposes, it will be sufficient to treat these elements in groups – Regions 1 to 3 in one group (Group A) and Regions 4 to 6 in another group (Group B) – and simply add the separable and presumed non-interacting TL values for each group. (Note that we also neglect, for now, any correction to the TL values to obtain the actual noise reduction by accounting for interior absorption. This refinement, worth a few decibels of noise reduction, will be assumed to be included in an effective transmission loss.)

In fact, since the usual expression for outdoor-to-indoor noise reduction (i.e., the outdoor incident noise level (in the absence of the building facade) minus the indoor noise level) is:

$$NR = TL - 10 \cdot lg(S/A) - 6, \ dB \qquad (1)$$

where $10 \cdot lg(S/A)$ = the correction for interior absorption,

$\qquad$ S $\qquad$ = the area, in m^2, of the transmitting wall,

and $\qquad$ A $\qquad$ = total acoustic absorption, in m^2, of the room interior.

The quantity $10 \cdot lg(S/A)$ typically has values in the range of -2 to -4 dB for one wall exposed, so the terms $-10 \cdot lg(S/A)-6$ will be of the order of -4 to -2 for one wall exposed. Thus this small correction, which is not strongly frequency dependent in the audio frequency range[1] will be included, empirically, in the TL values for this model.

REGIONS 1–3 (GROUP A)

A simple lumped-parameter model will suffice for this region. This is shown in Figure A-1 in the form of an analog "circuit" with the following elements.:

1. The leakage path is represented by an acoustic mass with a value $M_L = \rho L/S_L$, kg/m^5

$\qquad$ where ρ_L $\quad$ = $\quad$ mass density of air, kg/m^3
$\qquad\qquad$ L $\quad$ = $\quad$ length of leakage path, m
$\qquad\qquad$ S_L $\quad$ = $\quad$ area of leakage path, m^2

2. The cavity stiffness, K_c, is given by:

$$K_c = \rho c^2/V, \ kg/m^4 \cdot sec^2 \qquad (2)$$

$\qquad$ where c $\quad$ = $\quad$ speed of sound
$\qquad\qquad$ V $\quad$ = $\quad$ volume of room

3. An effective wall stiffness K_p can be given in terms of the fundamental wall resonance by:

$$K_p = 4\pi^2 f_\rho^2 \, w/(g\,S), \quad N/m^5 \qquad (3)$$

where f_r = fundamental resonance frequency of wall, Hz

$\quad$ w = effective surface weight of wall, N/m^2

$\quad$ g = acceleration of gravity (9.81 m/sec^2)

$\quad$ S = area of transmitting wall, m^2

4. An acoustic resistance R_e in the leakage path which is more conveniently defined in terms of the resonance amplification factor Q relating this leakage resistance and the leakage mass by the expression:

$$Q = 2\pi f_L M_L / R_L \qquad (4)$$

where f_L = the acoustic resonance between the acoustic mass, M_L in the leakage path and the *panel* stiffness K_p. (Not the Helmholtz resonance.)

$$= \frac{1}{2\pi}\sqrt{K_p/M_L} \qquad (5)$$

Evaluation of low-frequency transmission loss data from NASA,[2] shown in Figure A-2, and data from other sources,[3,4,5] provide the bases for estimating the following typical values for these parameters:

$\quad M_L$ = 10 kg/m⁴

$\quad K_c \approx K_p/1.5 = 4210 \, N/m^5$

$\quad Q$ = 1.6

$\quad f_L$ = 4 Hz

These parameters can then be inserted in the equation for the transmission loss, TL_A for Group A between the outside pressure (P_o' in Figure A-1) and the inside pressure P_i which can be shown to be:[6]

$$TL_A = 10 \cdot \lg\left[\frac{P_o}{P_i}\right]^2 = -10 \cdot \lg\left[\frac{(1-\upsilon^2)^2 + (\upsilon/Q)^2}{[1-\upsilon^2(1+K_p/K_c)]^2 + (\upsilon/Q)^2}\right] \qquad (6)$$

where $\upsilon = f/f_L = 2\pi f\sqrt{M_L/K_p}$

and $\quad$ f = frequency in Hz.

Note that, as shown in Figure A-1, the Helmholtz resonance is considered an anti-resonance – a minimum in transmission loss – and occurs at a frequency f_h given by:

$$f_h = \frac{1}{2\pi} \sqrt{\frac{K_p K_c}{K_p + K_c} / M_L} \tag{7}$$

Note, also, that if the panel stiffness $K_p \to \infty$, then the Helmholtz anti-resonance frequency simply becomes the expected value of the "spring" K_c and mass M_L.

$$f_h \to \frac{1}{2\pi} \sqrt{K_c / M_L} \tag{8}$$

Thus, to summarize, a reasonable model for Regions 1-3 involving frequencies below the lowest panel mode is given by Eq. (6) with the values for f_L, K_p/K_c, K_c, M_L and Q given on the preceding page.

For this model, as f(or $\upsilon) \to \infty$, TL_A approaches

$$TL_A|_{f \to \infty} = 10 \cdot \lg [1 + K_p/K_c]^2 \simeq +8 \text{ dB} \tag{9}$$

for the selected parameters.

REGIONS 4–6 (GROUP B)

The first region in Group B (Region 4) will be dominated by a dip in TL due to a panel resonance which can be modeled, for frequencies greater than f_L, as:

$$TL_4 = 10 \cdot \lg [(1 - (f/f_p)^2)^2 + (f/f_p \, Q_p)^2] + TL_A \tag{10}$$

where f_p = panel resonance frequency

Q_p = "Q" of this resonance

Typical values for these parameters are listed in Table 1.[7] For calculation purposes, use:

f_p = 15 Hz

Q_p = 1.5

K_p/K_c = 1.5 as before.

A lower value of Q_p is used than indicated by the data in Table 1 to reflect a room-average TL. Thus, at the panel resonance frequency f_p for $f_p \gg f_l$, the minimum TL is given by:

$$TL_4|_{min} \simeq 10 \cdot lg\left[\ (1+K_p/K_c)^2/Q_p\right] \simeq +6\ dB \tag{11}$$

for the values suggested.

Clearly, a tolerance or uncertainty in this quantity on the order of ± 5 dB is not unrealistic.

This dip in the TL will hold for only a narrow frequency range as other room and panel resonances and anti-resonances become important.

To approximate this effect in Region 5, an empirical TL model is suggested by multiplying the term inside the square brackets in Eq. (10) by an additional factor that is less than or equal to 1 so that TL_5 becomes:

$$TL_5 \simeq TL_4 - 10 \cdot lg\left[\ 1+ (f/f_r)^n\right] \tag{12}$$

where f_r is the "first room mode"

and n is an empirical constant between 2 and 4.

Trial and error indicates that the following values provide an approximate fit to experimental data.

For closed windows, f_r = 30 Hz
                        n = 3.1
                        Q_p = 1.5

For open windows, f_r = 20 Hz
                        n = 3.8
                        Q_p = 4.0

In summary, an overall TL model covering the full frequency range is given by Eq. (12) where TL_4 is, in turn, given by Eq. (10) and TL_A is, in turn, given by Eq. (6).

Figure A-3 is a plot of the result with the indicated parameters.

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Table A-1

Typical Fundamental Resonance Frequencies, f_0, Dynamic Magnification Factors, Q
and Surface Weights, w (lb/ft^2) for Some Building Walls
(from Reference 7, Sutherland, Brown and Goerner, 1990)

Type of Wall	Sample Size	f_0, Hz Mean	f_0, Hz Std.Dev.	Q Mean	Q Std.Dev.	w, Surface Wt lb/ft^2	kgf/m^2
Conventional Structures							
Wood Frame Wall (Wallboard)	40 (1)	16.7	5.6	23.0	6.1	5.0 (3)	2.27
Wood Frame Wall (Plaster)	10 (1)	15.7	4.6	10.4	1.0	9.75	4.42
Wood Frame Wall	4 (2)	15.2	3.5	NA		5.4 (3)	2.4
Brick Wall	1 (2)	12.3	5.7	NA		66.7 (3)	30.3
Concrete Block Wall		25.0		NA		38.0	17.2
Building Stone	5 (3)	NA	NA	NA	NA	110	50
Plaster Ceiling 3/4 in thick	2 (1,5)	14	+1.1	18.0	5.5	9.74 (7)	4.42
Metal Wall (Industrial Bldg)	4 (3)	14	±3.4	25		1.6-4.0	0.73-1.8
Unconventional Structures							
2.5 ft Limestone Block Wall (6 in thick)	1 (4)	26				63.5 (9)	46.3
3.5 ft Limestone Block Wall (9.6 in thick)	1 (4)	23				102 (9)	46.3
10 ft Adobe Wall (17 in thick)	4 (5)	11	2.8	21	±5.1	148-228 (6)	67-103
6.9-19 ft Masonry Walls	12 (8)	(See Note 8)		14.5	±3.2	180 (9)	35
10.5-12 ft Adobe Walls	12 (10)	16.6	1.4	16.7	±4.2	NA	NA
17-19 ft Adobe	5 (10)	11.4	2.9				

Following References cited in Reference 7 (Sutherland, Brown and Goerner, 1990)

(1) Data from Siskind, et al., 1980a,b
(2) Data from Siskind, et al., 1976
(3) Estimated from Sutherland, 1968a
(4) Data from Brumbaugh (estimated resonance frequencies consistent with measurements of vibration response). (Data obtained at prehistoric Anasazi site, Grand Canyon.)
(5) Data from Brown and Sutherland, 1989
(6) Surface weight based on range of densities for adobe of 98.5 lb/ft^3 (Smith, 1986) to 152.3 lb/ft^3 (Brumbaugh)
(7) Surface weight of roof structure (~6 psf) and plaster ceiling (3.85 psf) combined
(8) Data from King and Algermissen, 1987. Masonry walls (~1200 A.D.). Wall resonance frequency data described by: $f_0(Hz) \sim [194 \pm 32] / [h(ft)^2]^2$
(9) Surface weight based on density of Chaco Canyon masonry wall (approximately 1200 A.D.) of 127 lb/ft^3 (Lekson, 1984)
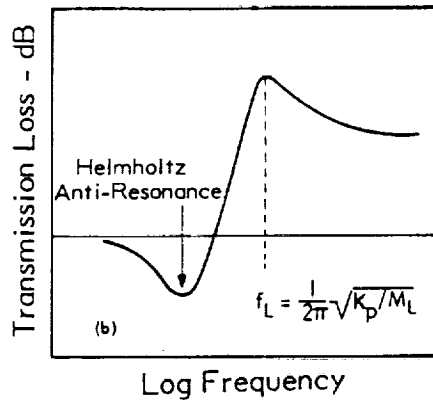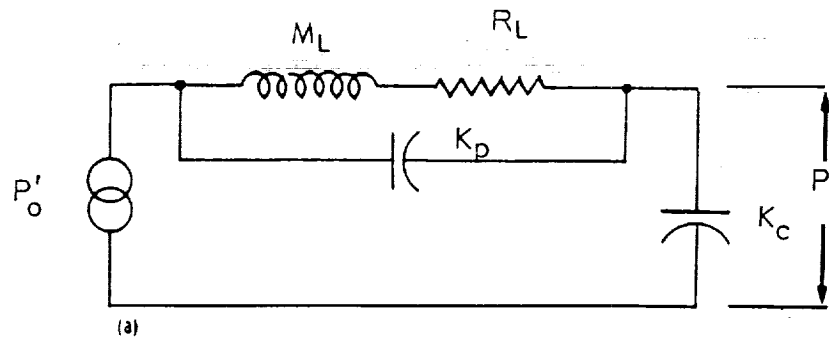(10) Data from King, et al., 1988

Figure A-1. (a) Analog Circuit, and (b) General Frequency Response of a Closed Volume with Acoustic Stiffness K_c Bounded on One side with a Flexible Wall with Stiffness K_p and Short Circuited by a Leakage Path with Acoustic Mass M_L and Acoustic Resistance R_L. (From Reference 6, Sutherland, Sharp and Mantey, 1983.)
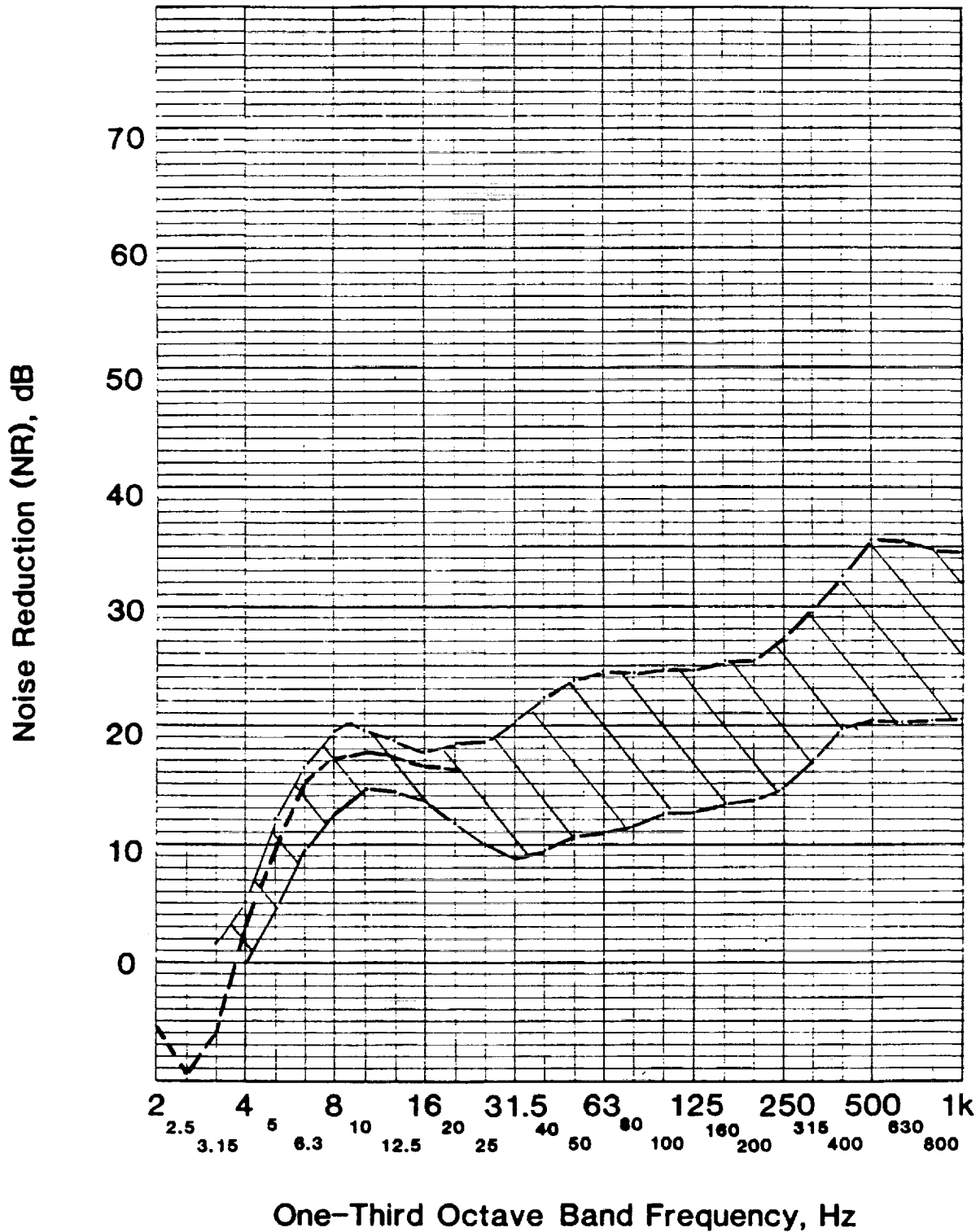
Figure A-2. Comparison of Experimental Data (▨) on Noise Reduction at Very Low Frequencies for Typical Residential Structures to Predicted Values (– – – –) Based on a Simplified Model for Low Frequency Leakage Anomalies (predictions not valid at frequencies above first panel mode). (From Reference 6, Sutherland, Sharp and Mantey, 1983.)

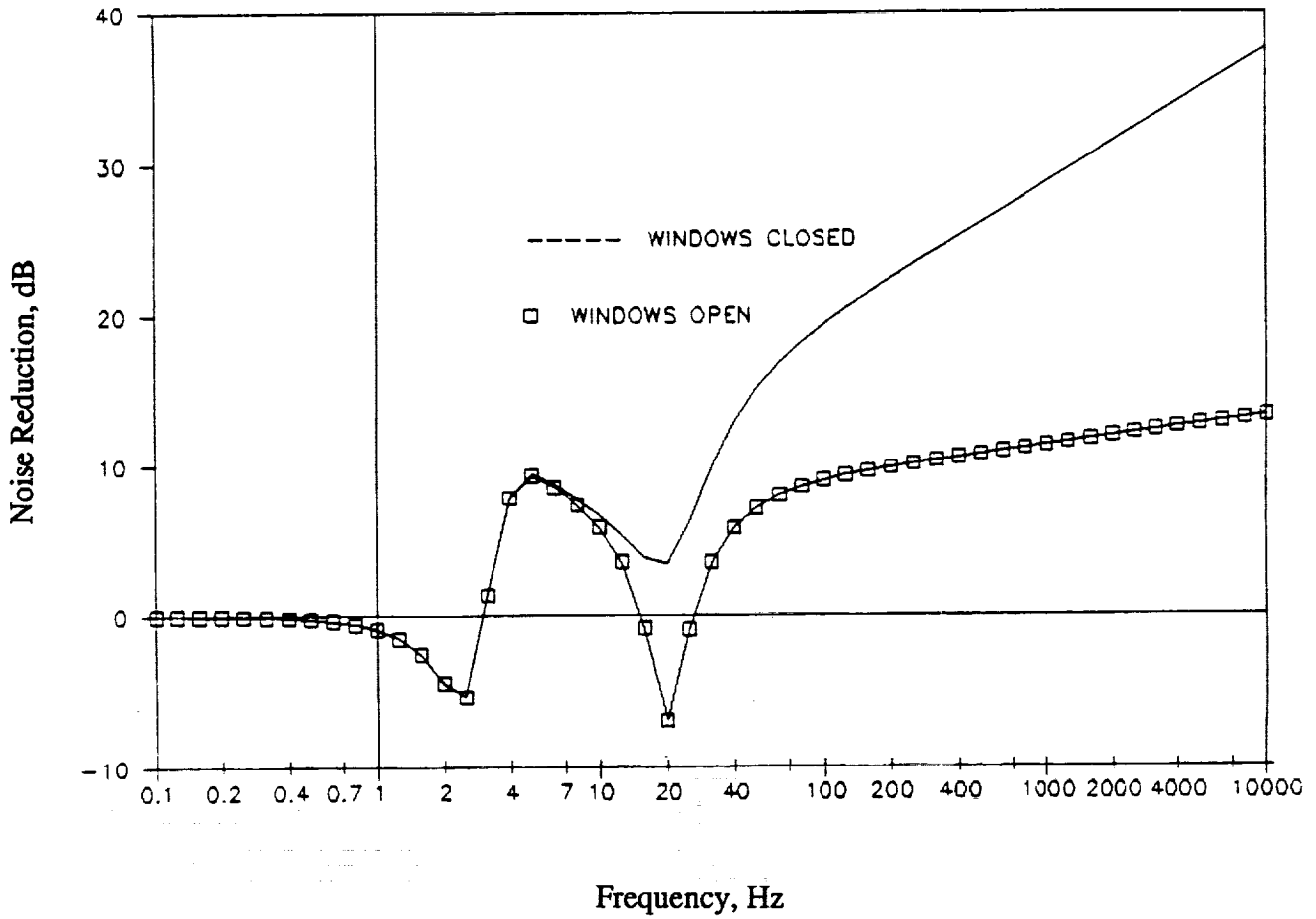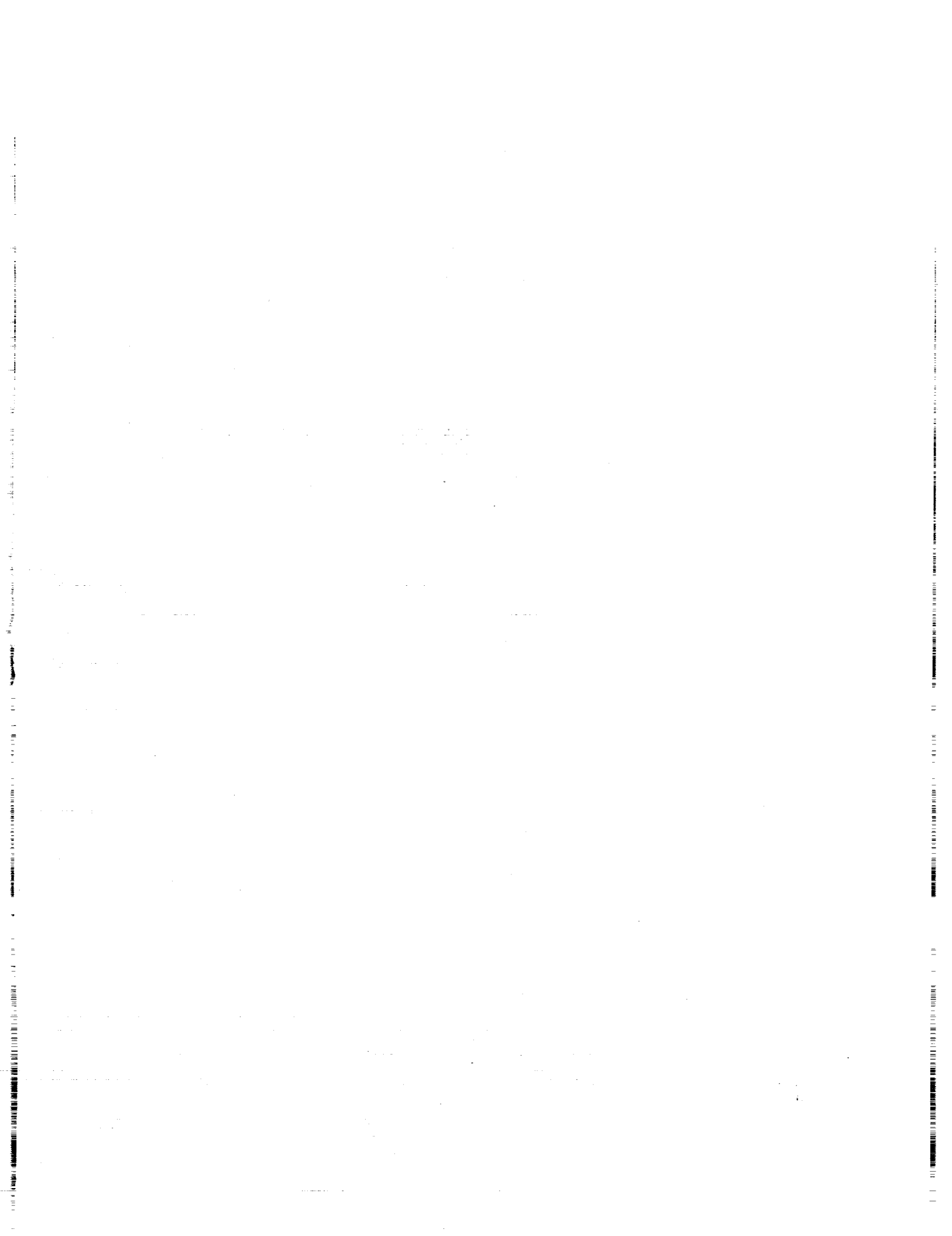# NOISE REDUCTION MODEL FOR SONIC BOOMS

Figure A-3. Idealized Model for Outdoor to Indoor Noise Reduction for Typical Residential Buildings for Application to Predictions of Sonic Boom Loudness Indoors.

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13. ABSTRACT (Maximum 200 words)

A study has been conducted to determine whether the loudness reduction computed for shaped minimized sonic booms when perceived outdoors is realized when perceived indoors. A model was developed for the transmission of sonic booms into residences, and applied to six nominal sonic booms, including N-waves and shaped minimized booms. The relative loudness between various types of booms heard indoors was found to be substantially the same as the relative loudness as heard outdoors. Thus the benefit of shaped minimized booms, when quantified by loudness, occurs equally indoors and outdoors. The potential for annoyance due to building rattle induced by shaped minimized sonic booms, which was not addressed here, remains to be investigated.

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