Comparison of Methods of Predicting Community Response to Impulsive and Nonimpulsive Noise

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Abstract

Several scientific, regulatory and policy-coordinating bodies have developed methods for predicting community response to sonic booms. The best known of these is the dosage-response relationship of Working Group 84 of the National Academy of Science's Committee on Hearing, Bioacoustics and Biomechanics (Galloway, 1981). This dosage-response relationship between C-weighted Day-Night Average Sound Level and the prevalence of annoyance with high energy impulsive sounds was derived from limited amounts of information about community response to regular, prolonged, and expected exposure to artillery and sonic booms.

U.S. Army Regulation 201 adapts this approach to predictions of the acceptability of impulsive noise exposure in communities. This regulation infers equivalent degrees of effect with respect to a well known dosage-response relationship for general (nonimpulsive) transportation noise. Differences in prevalence of annoyance predicted by various relationships lead to different predictions of the compatibility of land uses with sonic boom exposure. An examination of these differences makes apparent several unresolved issues in current practice for predicting and interpreting the prevalence of annoyance due to sonic boom exposure.

BACKGROUND

Any systematic approach to predicting and interpreting community response to noise exposure requires solutions to four fundamental problems:

1) Definition of community response;

2) Characterization of noise exposure;

3) Derivation of a predictive relationship between "community response" and noise exposure; and

4) Inference of regulatory policy from one or more predictive relationships

Finding practical answers to these questions requires detailed attention to issues such as the ease and cost of measuring selected quantities, the desired accuracy and precision of predictions, and relationships among alternate metrics of noise exposure, community response, and land use compatibility.

Most of the debate about compromises and assumptions needed to predict and interpret community response to transportation and other non-impulsive noise was conducted in the 1970s. To make a long story short, a collection of federal agencies (FICUN) adopted a common approach - based in large part on the work of Schultz (1978) - built on the following assumptions:

1) that "community response" can be usefully treated for most purposes (and in particular, for the airport neighborhood case) as the proportion of a residential community annoyed to a consequential degree by noise exposure[1];

2) that a cumulative measure of outdoor A-weighted sound levels in residential neighborhoods incorporating a so-called nighttime penalty (the Day-Night Average Sound Level, or DNL, as developed in the Environmental Protection Agency's 1974 "Levels Document"), suffices for characterizing noise exposure;

3) that a dosage-response relationship between the prevalence of annoyance and DNL, derived from a curve fitting exercise, is adequate for predictive purposes; and

4) that regulatory policy can be based on interpretations of land use compatibility made in acoustic terms alone.

The basic notion in any dosage-response relationship is that whatever quantity is plotted on the abscissa as the predictor variable is uniquely responsible for whatever quantity is plotted on the ordinate. In this case, the proportion of a community highly annoyed by noise is assumed to be determined not by individually notable noise events, but solely by some integration of outdoor neighborhood noise levels over a prolonged period of time.

"Land use compatibility guidelines" were subsequently developed by interpreting predictions about the prevalence of annoyance derived from the dosage-response curve. "Compatibility" was treated as an issue of noise exposure rather than one of noise effects, as though land use compatibility were somehow a property of noise exposure per se.[2]

The compromises and assumptions of the 1970s are not the only ones that could have been made, nor are they necessarily the most appropriate for all purposes. However, they provide the basis for the most widely understood and applied approach to assessing impacts of non-impulsive noise exposure on communities.

DERIVATION OF DOSAGE-RESPONSE RELATIONSHIPS

The data set on which Schultz based his original (1978) synthesis of the community noise literature contained 161 data points. One recent update of the so-called "Schultz Curve" (Fidell, Barber and Schultz, 1991) is based on more than 400 data points, while FICON (1992) has developed another dosage-response relationship based on a subset of these points. Each data point represents a field observation of a pairing of an exposure value and a percentage of social survey respondents describing themselves as highly annoyed. The percentage of social survey respondents is treated as an index of the stable, steady state prevalence of a consequential degree of long term annoyance in the community at large.

The utility of Schultz's approach to assessing community response to non-impulsive noise exposure quickly led to efforts to apply similar methods to the case of high energy impulsive noises[3]. Working Group 84 of the Committee on Hearing, Bioacoustics and Biomechanics (Galloway, 1981) of the National Research Council of the National Academy of Science made the initial (and still best known) effort to adapt the methods developed by Schultz (1978) to the case of impulsive noise.

CHABA Working Group 84 preserved Schultz's definition of community response; modified reliance on DNL as a noise metric only to the extent of substituting C-weighted for A-weighted sound levels[4]; and developed a dosage-response relationship from an eyeball fit to a small number of social survey observations about the annoyance of impulse noise.[5]

The resulting dosage-response relationship for impulsive noise (Galloway, 1981), illustrated in Figure 1, is as follows:

$$\%\ \text{Highly Annoyed} = 100/(1 + \exp(11.17 - 0.153L_{Cdn})) \quad \text{Eq. 1}$$

where L_{Cdn} is the C-weighted Day-Night Average Sound Level created by sonic booms.

The form of this dosage-response relationship is a sigmoid given by a logistic fitting function. The sigmoidal shape is a reasonable one, given the need for asymptotes in the relationship in the vicinities of 0 and 100%. The prediction equation reflects a negotiated consensus of engineering judgments, and is intended as an approximate curve fit rather than the product of a formal statistical analysis.

INTERPRETATIONS OF DOSAGE-RESPONSE RELATIONSHIPS

The CHABA Working Group 84 relationship is derived from a considerably smaller data set than any of the relationships for non-impulsive noise. Of a total of fourteen data points, five represent observations of the annoyance associated with exposure to artillery fire, while the remaining nine are all derived from the only extensive study ever conducted of community response in an urban area subjected to sonic booms over a prolonged period.

For six months in 1964, residents of this city were exposed to a maximum of 8 booms a day at overpressures of 1 to 2 psf. Figures 2 and 3 are linear regressions between the prevalence of annoyance and A-weighted and C-weighted exposure values, respectively, for this data set, as described by Galloway (1981). The former (C-weighted) regression accounts for 94% of the variance in the annoyance data, while the latter (A-weighted) regression accounts of 87% of the variance.

The circumstances of impulsive noise exposure in the artillery and Oklahoma City studies which are summarized in the CHABA relationship are noteworthy: they were all familiar, expected, predictable and of long duration. In the case of artillery noise, respondents were residents of neighborhoods near fixed firing points. Daily artillery noise was a familiar part of the noise exposure environment in these respondents' neighborhoods. In the case of the sonic boom exposure in Oklahoma City, advance schedules for the numbers and times of occurrence of sonic booms were well advertised, and the aircraft producing the booms flew a single flight track for the entire half year study period.

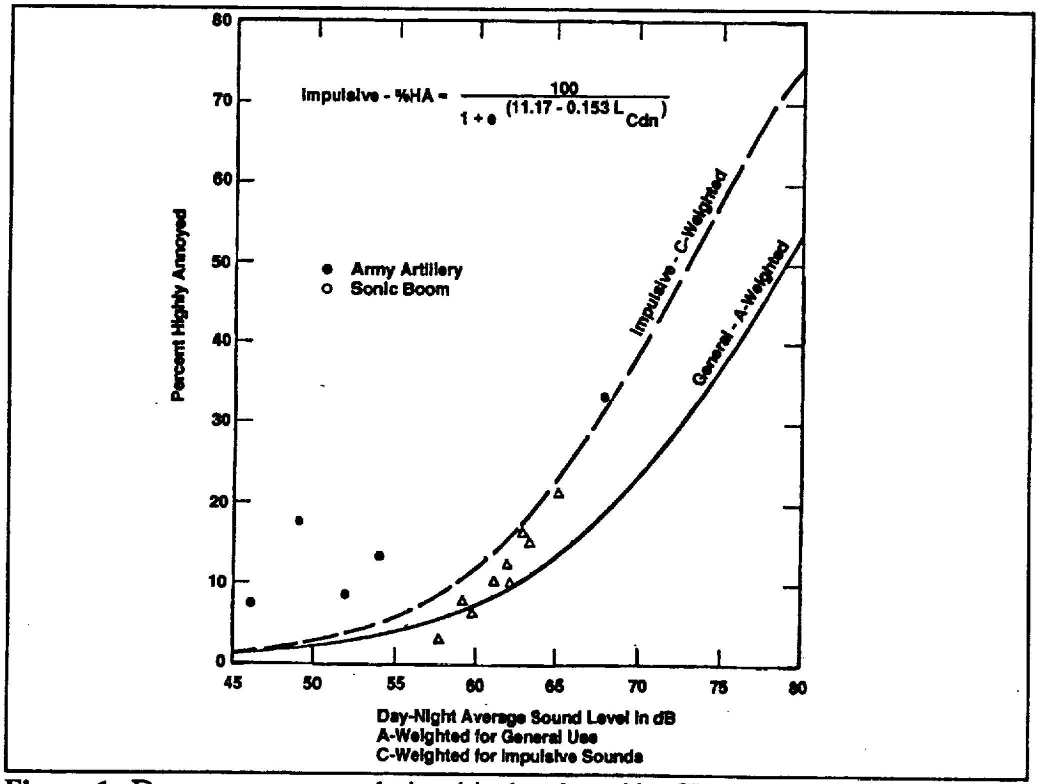

Figure 1: Dosage-response relationship developed by CHABA Working Group 84

The most common form of community exposure to sonic booms today is that produced in the vicinity of military supersonic operations areas. Caution is required in predicting community response and land use compatibility in such circumstances. Sonic booms are generally experienced at unpredictable and relatively infrequent times as short duration daytime noise intrusions of widely varying level. There is no agreement comparable to that for the case of urban noise about the most useful approach to predicting the annoyance of this type of noise exposure.

Use of DNL or CDNL to predict the prevalence of annoyance is based on the "equal energy hypothesis". The equal energy hypothesis expresses the notion that the number, level and duration of noise events are fully interchangeable determinants of annoyance as long as their product (energy summation) remains constant. In other words, quantification of noise exposure in DNL for purposes of predicting annoyance reflects a tacit theory: that people are indifferent between the annoyance of small numbers of very high level noise events of short duration and the annoyance of large numbers of compensatingly lower level noise and/or longer duration noise events.

This hypothesis is the underpinning of a convenient method for measuring noise exposure for purposes of predicting annoyance. When used as a predictor variable in a dosage-response relationship such as that synthesized by Schultz, DNL accounts for about half of the variance in a set of field observations about the annoyance of general transportation noise. This demonstrates that the equal

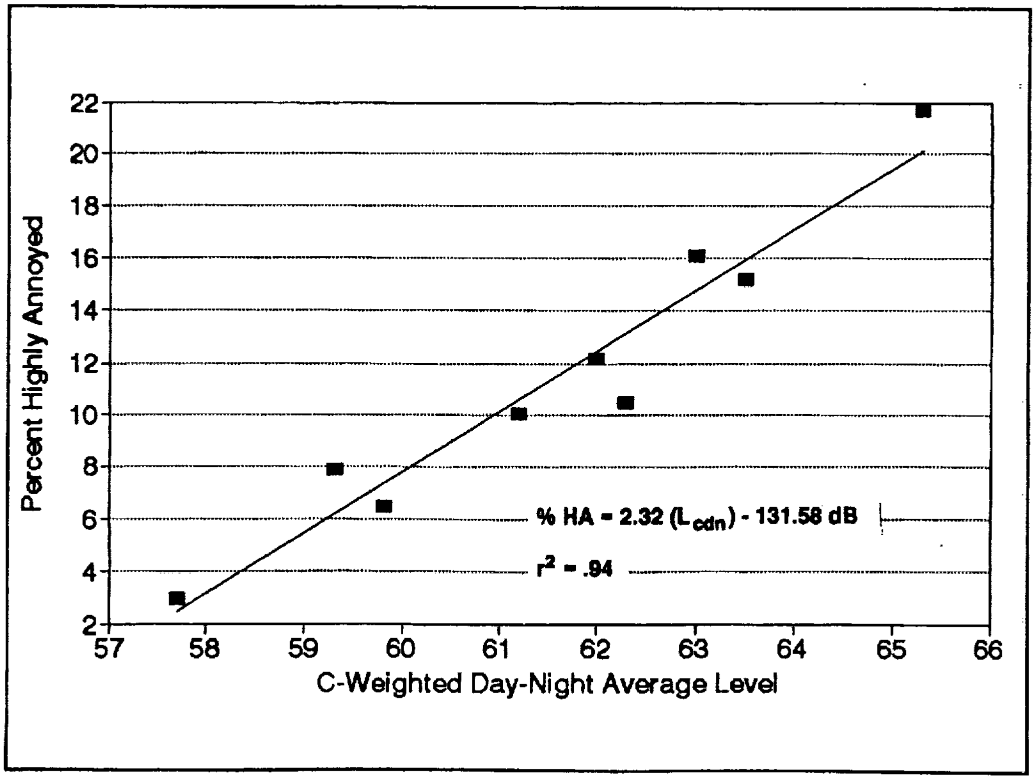

Figure 2: Linear regression between C-weighted sonic boom exposure and prevalence of annoyance in Oklahoma City (data from Galloway, 1981)

energy hypothesis can provide a useful account of the data over a range of at least 20 dB, from values of about 55 to 75 dB.

There is, however, little empirical evidence on which to base extrapolations of predictions of annoyance at the low values of CDNL associated with infrequent exposure to sonic booms. For example, all of the data summarized by Galloway (1981) at low values of CDNL represent reactions to artillery fire, not sonic booms.

ASSESSING LAND USE COMPATIBILITY WITH IMPULSIVE NOISE EXPOSURE

The notion that environmental noise impacts can be construed for global purposes in terms of land use compatibility may be traced through a chain of noise metrics and prediction methods four decades long to the pioneering work of Rosenblith and Stevens (1953). The latest embodiment of this approach may be found in the Appendix to ANSI Standard S12.40-1990.

The U.S. Army has adopted the clearest guidelines among federal agencies for land use compatibility with high energy impulsive noise exposure. Chapter 7 of U.S. Army Regulation 200-1, "Environmental Noise Abatement Program" (dated 23 April 1990) addresses land use compatibility issues with respect to impulse noise exposure. The recommendations in this regulation are based on an equivalence of

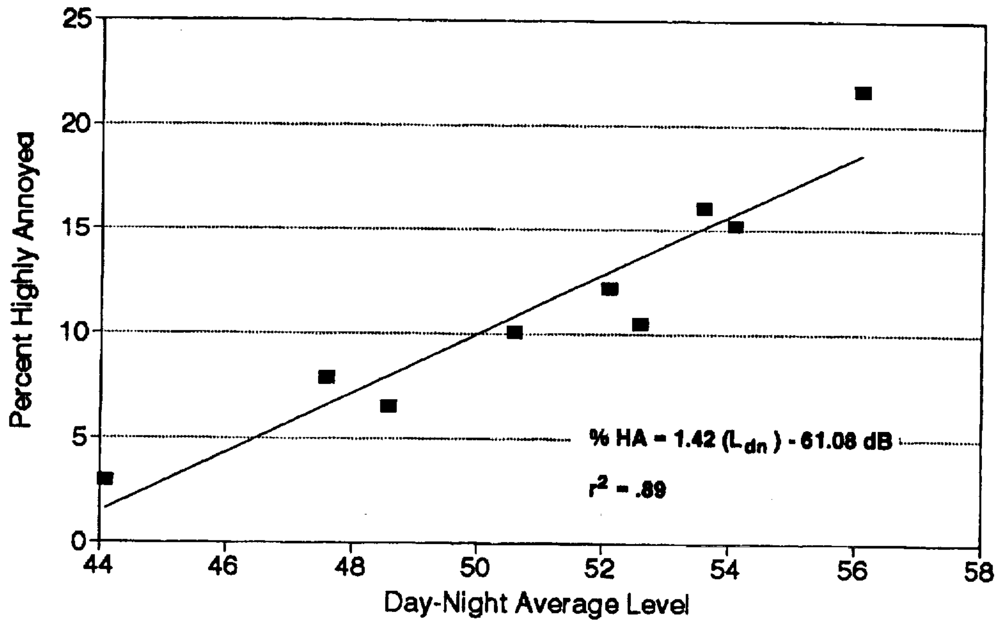

Figure 3: Linear regression between A-weighted sonic boom exposure and prevalence of annoyance in Oklahoma City (data from Galloway, 1981)

exposure of C-weighted to A-weighted cumulative exposure units. This equivalence is made not in terms of exposure levels, but rather in terms of the prevalence of annoyance implied by the FICUN (1980) and ANSI S12.40-1990 guidelines.

Equivalent exposure is inferred in the Army regulation through comparisons of annoyance predictions of Schultz's original (1978) dosage-response relationship for general transportation noise and CHABA's (Galloway, 1981) dosage-response relationship for high energy impulsive noise. Table 1 compares the prevalence of annoyance predicted by Schultz's and other relationships.

Table 2 examines the implications of drawing land use compatibility inferences on the basis of these equivalences. In the range of interest, differences in the slopes of the logistic fitting functions described by Galloway (1981) give rise to an approximate 5 dB difference in the criterion levels as expressed in A- and C-weighted cumulative exposure units. The net effect is to increase the difference between A- and C-weighted units associated with the same prevalence of annoyance. Thus, whereas Army Regulation 200-1 relies on the dosage-response relationship developed by Schultz (1978) to equate an A-weighted DNL of 65 dB with a C-weighted DNL of 62 dB, the equivalence developed from FICON's (1992) dosage-response relationship is to a C-weighted DNL of 60 dB. Even greater differences are apparent if the analysis is restricted to sonic boom data only.

Table I. Percentage of Community Highly Annoyed ("%HA") Predicted by Several Dosage-Response Relationships over a Range of DNL/CDNL Values.

FITTING FUNCTION	55 dB	60 dB	65 dB	70 dB	75 dB
$\%HA = 0.8553L_{dn} - 0.0401L_{dn}^2 + 0.00047L_{dn}^3$ [Schultz (1978)]	3.9%	8.5	15.3	24.6	36.9
$\% HA = 100/(1 + \exp(10.43 - .132L_{dn}))$ [USAF logistic fit to Schultz data]	4.0%	7.5	13.6	23.3	37.0
$\% HA = 0.0360L_{dn}^2 - 3.2645L_{dn} + 78.92$ [Fidell, Schultz, and Barber (1991)]	8.3%	12.7	18.8	26.8	36.6
$\% HA = 100/(1 + \exp(11.13 - .141L_{dn}))$ [USAF logistic fit to subset of Fidell, Schultz and Barber (1991)]	3.3%	6.5	12.3	22.1	36.5
$\%HA = 100/(1 + \exp(11.17 - .153L_{Cdn}))$ (CHABA WG 84 [Galloway, 1981])	2.9%	6.0	22.7	38.7	57.6
$\% HA = 2.324\ L_{Cdn} - 131.6$ (Linear regression through Oklahoma City data)	n/a	7.8	19.4	31.1	42.7

Table 3 shows some examples of predicted consequences of several sorts of sonic boom exposures. Note that even small numbers of relatively modest booms (for example, four booms at 1 psf per day) can lead to a prediction of noise exposure inconsistent with single family residential use.

Although there is little alternative to relying on such predictions on an interim basis, a larger body of direct evidence about the annoyance of sonic boom exposure is clearly needed. It is possible, for example, that the time constants of arousal and decay of annoyance with impulsive noise exposure may differ from those for non-impulsive noise. People living near future overland supersonic flight corridors might react more quickly or more vigorously to the novel experience of sonic boom exposure than to more familiar forms of noise exposure.

CONCLUSIONS

Confidence in predictions and interpretations of the effects on communities of high energy impulses in general and sonic booms in particular is not as great as for the case of general transportation noise. Small differences in assumptions and procedures may lead to large differences in assessments of the effects of impulsive noises on exposed populations. Some of these assumptions and procedures that have not been revisited for a decade could benefit from further scrutiny.

The circumstances of noise exposure produced by sonic booms of en route aircraft

Table II. Land use compatibility guidance inferred from equivalent prevalence of annoyance for A-weighted and C-weighted Day-Night Sound Levels for alternate impulsive dosage-response relationships.

Compatibility with Single and Multiple Family Residential Land Uses (per ANSI S12.40-1990)	Percent Highly Annoyed	(A-Weighted) Day-Night Average Sound Level*	C-weighted Day-Night Average Sound Level**	C-weighted Day-Night Average Sound Level***
Normally compatible	1.7 %	50 dB	46 dB	57.4
Marginally compatible with single family, extensive outdoor use	3.3	55	51	58
Marginally compatible with multiple family, moderate outdoor use and with multi-story, limited outdoor use	6.5	60	55.6	59.4
Compatible with insulated multi-story use; incompatible with single and multiple family use	12.3	65	60.2	61.9
Incompatible with any residential land use	36.5	75	69.4	72.3

* % Highly Annoyed = 100 / [1 + exp(11.13 - 0.141L_{dn})] (FICON, 1992)

** % Highly Annoyed = 100 / [1 + exp(11.17- 0.153L_{Cdn})] (Galloway, 1981)

*** % Highly Annoyed = 2.324 LCdn - 131.6 (Oklahoma City data) are inherently more difficult to treat than those of airport neighborhoods. Sonic boom exposure produced by military operations is generally sporadic rather than regular, highly variable and difficult to predict accurately (due to the vagaries of long range acoustic propagation and uncertain flight tracks), and likely to be associated with nonlinear physical effects. Regular exposure to sonic booms near future overland flight corridors may be somewhat easier to predict.

Not only are there more complications and loose ends in dealing with impulsive exposure than with general transportation noise, but there are far fewer data about exposure effects. Although several DoD and NASA-sponsored laboratory and field studies on the annoyance of sonic booms have begun to contribute new information, the body of information available for analysis is still considerably smaller than for the case of general transportation noise.

Laboratory work, although useful for understanding how individuals' immediate annoyance is affected by various aspects of impulsive signals, does not directly produce the sorts of information needed to generate and interpret impacts at the community level. Controlled field studies of longer term individual reactions can serve as a bridge between laboratory and community studies, but are difficult to design and conduct in ways that can test basic assumptions about the applicability of the equal energy hypothesis to relatively infrequent sonic booms.

New technology, new assumptions, and new analyses are needed to identify and test improved means of predicting the effects of sonic booms on exposed individuals and communities.

Table III. Relationship between numbers of sonic booms and land use compatibility. (Calculations performed for N-waves with 0.5 ms rise time and a duration of 350 ms, as described by Shepherd and Sullivan, 1991.)

No. of 0.5 psf daytime booms/day	No. of 1 psf daytime booms/day	CDNL*	% HA (Galloway, 1981)	% HA (Oklahoma City)
1		48 dB	2.1%	n/a
2		51	3.3	n/a
4		54	5.2	n/a
8		57	8.0	0.9
	1	54	5.2	n/a
	2	57	8.0	0.9
	4	60	12.0	7.8
	8	63	17.8	14.8
1	1	55	6.0	n/a
2	2	58	9.1	3.2
4	4	61	13.7	10.2
8	8	64	20.1	17.1

*Constructed from computed CSEL values

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ENDNOTES

1. The term "exposure" is commonly used in two ways. One use of the term implies the time integral of intensity, while the other use implies the average sound intensity over a specific time period. Intensity is the rate of flow of sound energy per unit area per second. At distances from sound sources that are of interest in environmental analyses, sound intensity is directly proportional to the square of sound pressure. Thus, sound exposure is usually represented as the time integral of squared sound pressure. This process is often referred to informally as "energy summation". Magnitudes are reported in logarithmic terms. For example, sound exposure level is 10 times the logarithm to the base 10 of the ratio of sound exposure to a reference exposure of 400 μPa^2-seconds. In this logarithmic form, squared sound pressure is called sound level and expressed in units of decibels. Sound level in decibel notation is often expressed as an average (equivalent) sound level over a specified time interval (usually 1 hour or 24 hours). Single events are often described by their sound exposure level (SEL) with a reference time interval of one second.

2. This definition of "land use compatibility" does not deal directly with effects of noise exposure on people. Furthermore, certain of the remedies commonly used in airport neighborhoods to treat incompatible land uses (e.g., re-zoning land, insulating residences, purchasing avigation easements) are inappropriate in the case of en route exposure to sonic booms. Fidell (1992) contains additional discussion of the standard approach to dealing with the compatibility of aircraft noise and land use.

3. According to Galloway (1981), "High-energy impulsive sounds of concern for community response are ... those for which the C-weighted sound exposure level... in any 2-second period is greater than 85 decibels (or greater than 75 decibels at night) and is 10 decibels greater than the C-weighted sound exposure level due to other sources in any contiguous 2-second period. These levels correspond to peak overpressures greater than approximately 105 decibels (95 decibels at night), that is, greater than approximately 0.1 pounds per square foot.

4. The C-weighting network was selected in lieu of the A-weighting network in a noise metric intended to characterize high energy impulsive noise because two impulsive sounds with very different low frequency energy content may have the same A-weighted sound pressure level. This follows equally from the insensitivity of the A-weighting network to energy at frequencies below about 50 Hz, and from the fact that the spectral peaks of common impulsive noises are often two octaves yet lower in frequency.

Approximate equivalences between C-weighted measurements and A-weighted measurements of a class of sounds (such as sonic booms) may nonetheless be established in several ways. One such equivalence (between A-weighted and C-weighted SEL values for sonic booms) is as follows:

$$CSEL = 0.68(SEL) + 40.5 \text{ dB}$$

This relationship is derived from A- and C-weighted measurements of actual sonic booms made outdoors (Galloway, 1981) and of recordings of simulated sonic booms made indoors (Pearsons, Tabachnick, Howe, Ahuja, and Stevens, 1993). It is appropriate primarily for estimating A-weighted levels for characteristic sonic booms with well-formed N shapes, but may also work reasonably well for sonic booms which have propagated long distances through the atmosphere, or for sonic booms occurring near the lateral cutoff distance.

5. It was tacitly accepted in preserving Schultz's assumptions that for purposes of predicting community response due to impulsive noise exposure, startle was fully accounted for by annoyance. It was likewise tacitly assumed that annoyance associated with secondary emissions was fully accounted for by substitution of the C-weighting network for the A-weighting network. ("Secondary emissions" are indoor rattling sounds produced by nonlinear re-radiation of low frequency impulsive energy from household contents.)