A POTENTIAL DESIGN WINDOW FOR SUPERSONIC
OVERFLIGHT BASED ON THE PERCEIVED LEVEL
(PLdB) AND GLASS DAMAGE PROBABILITY OF
SONIC BOOMS

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July 1973

Final Report

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
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16. Abstract

A potential design window for supersonic overflight based on the perceived level (PLdB) and glass damage probability of sonic booms is outlined.

The evaluation of a simple operational method of estimating the perceived level (PLdB) of sonic booms:

$$PLdB = 55 + 20 \log_{10} \frac{\Delta P \text{ (psf)}}{\tau \text{ (sec)}}$$

is discussed and compared with the Fourier transform computer program calculations of Pease based on the theory of Zepler and Harel. The resulting estimated perceived levels are in good agreement i.e., within 1 to 2 PLdB of each other in the important potential certification or design window that is in the 90 to 100 PLdB range. These perceived levels are shown to be acceptable to 95 to 100 percent of the people exposed to them.

The levels estimated using the method of May vary considerably with the levels determined by the other 2 methods, previously discussed.

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I. INTRODUCTION

Man's ability to fly aircraft faster than the speed of sound
generated one of the most controversial and most misunderstood
phenomena, namely, the sonic boom. The sonic boom is a major
environmental effect of supersonic flight that sets it apart
from other aircraft operations. As a result, the supersonic
era generated a great volume of research on the sonic boom and
its effects. Very significant accomplishments have occurred in
technical matters dealing with generation, prediction, propaga-
tion, simulation of the sonic boom and its effect on man and
his environment.

A notice of proposed rule making was issued in April of 1970
(Ref. 1) to afford the public protection from civil aircraft
sonic boom. On March 23, 1973, an amendment (Ref. 2) to the
Federal Aviation Act of 1958 was issued and, in brief, the rule
limits the speed of civil aircraft operated within the United
States territorial land or waters to a maximum which preclude
the generation of a sonic boom which will touch these areas.
Subject to authorization by the Administrator, exceptions to
the amendment are left open for research.

A design window for civil supersonic aircraft is required and
the following is presented as a start on its definition.

Design criteria for the U. S. Civil Supersonic Transport focused
on peak overpressure as it was readily predictable using Whitham's
(Ref. 13) equation. Due to the results of community reaction
studies such as Oklahoma City and simulator studies investigating
human reaction to sonic booms, it is now known that not only is
the maximum peak overpressure (ΔP) an important parameter, but
equally important is the rise time (τ) relationship with over-
pressure ($\Delta P/\tau$) or rate of on-set of the maximum peak overpressure.
The rise time is the time required to change from ambient pressure
to maximum peak overpressure. Designing towards the right com-
bination of overpressure and rise time would produce a sonic boom
in audible ranges acceptable to the public. If acceptable sonic
boom characteristics were established, then designers of future
civil supersonic aircraft could meet such standards. Therefore,
the need is to begin and continue psychophysical work in areas
that would determine acceptability limits for sonic booms as well
as aerodynamic work that would control both the rise time and
overpressure.

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II. BACKGROUND

Based on the 1965 work of Zepler and Harel (Ref. 3) a memorandum
(Ref. 4) was written February 21, 1968, and discussed with the
Operations and Engineering personnel of the U.S. Supersonic Trans-
port (SST) Development Office urging the adoption of a Sonic Boom
Index = k ΔP (PSF), /τ (SEC) (Ref. 4), to advance the state-of-
the-art in sonic boom research and to communicate with aircraft
designers the importance of another sonic boom signature parameter
in addition to overpressure, i.e., the interaction of rise-time
and overpressure.

It was believed at that time that rise-time τ in the above
equation was of equal importance as overpressure, i.e. ΔP in
affecting human reaction to sonic booms. This memorandum was
followed by papers (Ref. 5,6,7) outlining the relationship between
overpressure/rise-time and human reaction expressed in Figure 1
and subsequently adding the perceived noise levels based on the
Edwards Air Force Base (AFB) Sonic Boom test results. This was
possible as a jury of Edwards AFB subjects found sonic booms with
an average overpressure of 1.69 psf to be equivalent to the 105
PNdB flyover noise of a KC-135 aircraft (Ref. 8).

Convinced that average rise-time was equally important as average
overpressure regarding the judged noise level the next step was to
determine the rise-time associated with this judgement. A rise-
time of 0.005 seconds was found to be appropriate based on available
Edwards AFB test data. The noise level for other combinations of
ΔP/τ could then be calculated based on the conviction that a
doubling of overpressure or a halving of rise-time increased the
perceived level by 6 PNdB.

These ideas and References 5,6,7 were subsequently presented to
Mr. John Large of the Boeing Acoustics Staff with the objective of
entering considerations of sonic boom overpressure/rise-time into
U.S. SST design trades. Mr. Large now at the Institute of Sound and
Vibration through the work of May (Ref. 19) has supplied additional
evidence to support the validity of these ideas.

It only remained to quantify this relationship as shown subsequently
in Equation two (2) to arrive at a very quick and simple approach to
determining the perceived level of a sonic boom when overpressure
and rise-time are known. The most important idea is that the Boom
Index and Equation 2 hold the key to unlocking the required design
criteria for supersonic aircraft.

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The general formula for estimating the perceived levels of a
sonic boom was derived as follows:

> The Edwards AFB sonic boom test results (Ref. 8)
> indicated that a sonic boom doubled in perceived
> noise level (PNL) for each 6 PNdB increase as
> compared to aircraft noise which requires 10 PNdB.
> Therefore, the PNL of a sonic boom increases as a
> function of $20 \text{ Log}_{10} X$ as when X doubles or is 2
> then the PNL increases by 6 PNdB (20 times .3).

The subjects rating the sonic booms at Edwards judged the noise
level of a boom averaging 1.69 psf overpressure (ΔP) and rise-time
(τ) of 0.005 seconds as being equivalent to aircraft flyover noise
of 105 PNdB. Expressing this information mathematically as a
linear equation, we have:

$$\text{PNdB} = k + 20 \text{ Log}_{10} \Delta P/\tau \qquad (1)$$

$$105 = k + 20 \text{ Log}_{10} 1.69/.005$$

$$105 = k + 20 \text{ Log}_{10} 338$$

$$105 = k + 20 (2.5)$$

$$k = 105 - 50$$

$$k = 55$$

The general formula for estimating the perceived level of a sonic
boom is, therefore:

$$\text{Perceived Level (PLdB)} = 55 + 20 \text{ Log}_{10} \Delta P \text{ (PSF)}/\tau \text{ (SEC)} \qquad (2)$$

Equation 2 has been plotted in Figure 1 employing an overpressure
versus rise-time plot which yields the appropriate perceived level
in decibels, PLdB.

Examination of the psychophysical work completed during the last
30 years (Ref. 9) discloses that the annoyance and/or loudness
judgements of subjects are very similar in the frequency range
of sonic booms generated by high flying supersonic aircraft
which are for the most part below 1000 Hz. Therefore, the formula
is equally good in measuring and predicting human annoyance or
loudness reactions to sonic boom.

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For this reason it is proposed that the predictive equation for
sonic boom be labeled PLdB the perceived level in decibe. as
outlined in the work of S.S. Stevens (Ref. 9). The PLdB Level
may then be construed to be a measure of how people react to sonic
booms. The Perceived Level (PLdB) measure has another advantage
in that it solves a largely semantic problem. That is how can one
have an acceptable perceived noise level when by definition "noise"
is "unwanted sound". As a result, an operating agency has the
real problem plus a pseudo problem of trying to find an acceptable
level of something that is by definition "unwanted".

To eliminate this problem in communications, it is proposed that
the terminology perceived level (PLdB) be adopted by the scientific
community. This is borne out by the test findings that there are
indeed perceived levels, PLdB, of sonic booms which are acceptable
to 100 percent of the people exposed to them.

By studying the above equation, it becomes apparent that a
possible design window may be opened if the right overpressure
and rise time conditions for acceptable sonic boom perceived
levels are met.

Equation 2 can be easily rewritten to accomodate other units of
overpressure measurement. For example:

$$\text{Perceived Level (PLdB)} = 21 + 20 \, \text{Log}_{10} \, \triangle P \quad (N/M^2)/\tau \, (\text{SEC}) \qquad (3)$$

$$\text{Perceived Level (PLdB)} = 1 + 20 \, \text{Log}_{10} \, \triangle P \quad (\mu B)/\tau \, (\text{SEC}) \qquad (4)$$

Figure 2 presents a comparison of the results obtained by using
Equations (2), (3), or (4) which are identical but use different
units of measurement, i.e., psf, N/M^2 and uB respectively with the
Fourier transform computer program calculations of Pease (Ref. 20)
based on the theory of Zepler and Harel (Ref. 3).

The resulting estimated perceived levels are in good agreement, i.e.
within 1 or 2 PLdB of each other in the important potential certifi-
cation or design window that is in the 90 to 100 PLdB range. These
perceived levels are shown subsequently to be acceptable to 95 to
100 percent of the people exposed to them.

Figure 2 also shows that the levels estimated using the method of
May (Ref. 19) vary considerably with the levels determined by the
other two methods.

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III. CURRENT STATE-OF-THE-ART

To begin to outline the potential design ballpark, the rise-time and overpressure values presently attained by today's aircraft, SR-71 Data (Ref. 10), are presented in Figure 3. Operating at 70,000 feet and a Mach Number of 3.0, the average rise-time is 0.010 seconds and the average overpressure is approximately 1.0 pounds per square foot. Using the SR-71 data of Figure 3 and Equation 2, developed herein, it is found that the perceived levels range from a high of approximately 115 PLdB to a low of around 80 PLdB with an average of 95 PLdB. The question that remains is what is an acceptable sonic boom perceived level? Or, in other words, how does one define a sonic boom which is acceptable to humans?

Some past test data (Ref. 11), begins to answer this question. The study employed a simplified yes/no acceptability test for sonic booms of varying overpressures and rise-times. Using Equation 2 herein and the matrix of rise-times and overpressures used in this test, the noise levels of the sonic booms were established and are presented in Table 1B. The acceptability for each combination of $\Delta P/\tau$ with its resulting perceived level, PLdB established by Equation 2 are contained in Table 1A. The acceptability of the various perceived levels based on this computation is presented graphically in Figure 4.

From an average curve (Figure 5) established by the test data and Equation 2 to determine the perceived level, a sonic boom level of 108 PLdB was acceptable to 75 percent of the subjects tested and a sonic boom of 100 PLdB was acceptable to 95 percent of the subjects. A favorable comparison between the acceptability of various perceived levels of sonic boom and aircraft flyover noise together with several category scales of acceptability intrusiveness and noisiness is shown in Figure 6.

The validity of the predictive Equations (2), (3) and (4) for sonic booms having acceptable perceived levels is borne out by the objective test data presented in Table 1. The test data contained in Table 7 show that the acceptability of a sonic boom remained the same even if overpressure was doubled provided the rise time was also doubled. This shows the validity of the sonic boom index and Equation (2) or that the perceived level is indeed a function of $\Delta P/\tau$. This is also the rate of change of pressure in psf/sec; N/M^2/sec or uB/sec. For example: A sonic boom with an overpressure of 1.5 psf and rise time of .004 second, or a rate of on-set of 375 pounds per second, has a

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A) ACCEPTABILITY (%)

PSF \ Rise Time	.0016	.004	.008	.011
0.75	48	97	98	98
1.5	35	88	96	97
2.25	26	80	93	94
3.0	24	69	88	87

B) PERCEIVED LEVEL (PLdB)

PSF \ Rise Time	.0016	.004	.008	.011
0.75	108.4	100.5	94.5	91.7
1.5	114.4	106.5	100.5	97.7
2.25	117.9	110.0	104.	101.2
3.0	120.4	112.5	106.5	103.7

TABLE 1. Sonic Boom Acceptability and Perceived Level (PLdB) Variation With Overpressure And Rise Time.

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perceived level estimated by Equation (2) of 106.5 PLdB. This
sonic boom was found acceptable by 88 percent of the subjects
exposed to this type signature. When the overpressure was
doubled to 3.0 psf and the rise time increased to .008 seconds
or maintaining a rate of onset of 375 pounds per second, a
perceived level also estimated by Equation (2) of 106.5 PLdB,
this signature was also found acceptable to 88 percent of the
subjects. The same is true of the sonic booms having $\triangle P/\Upsilon$
of 0.75/.004 and 1.5/.008 or a rate of onset of 187.5 pounds
per second, both having a perceived level estimated by Equation
(2) as 100.5 PLdB. Sonic Booms having these characteristics
were found to be acceptable by 97 and 96 percent of the
subjects exposed to them.

Further verification of the validity of Equation (2) is presented
in Figure 2 which shows the close agreement within 1 or 2 PLdB
with the loudness prediction theory of Zepler and Harel (Ref. 3)
as modified by Pease (Ref. 20).

Table 1 also shows that subjective doubling of the perceived level
also occurs at least in the acceptable range every 6 PLdB. The
slope of Equation (2) is, therefore, verified as being 20 Log_{10}
as the log of a doubling is 0.3 and 20 x 0.3 is 6 PLdB. The
intercept of Equation (2) is still dependent on the Edwards
experimental comparison with aircraft flyover noise. It should
be revalidated in a similar test situation.

How simulated sonic booms in this test compared subjectively
with actual sonic booms is unknown. Presently a similar experiment
with different sonic boom simulation equipment but using similar
methods of rating the sonic boom perceived levels as developed
herein is being conducted by FAA.

However, taking these facts into consideration, it is shown that:

1. Rise time and overpressure are both important parameters
   in determining the perceived level of a sonic bocm.

2. Sonic booms do have predictable perceived levels which can be
   altered by varying either or both the rise time and overpressure.

3. The ability to vary rise time and overpressure by aero-
   dynamic design and by aircraft operations creates a potential
   design window for civilian supersonic aircraft. This design

window is based on the ability to determine the acceptable
boom level and then placing constraints on the corresponding
overpressure and rise time values (Figure 7).

Once acceptable perceived levels are determined and the ultimate
combinations of overpressure and rise time are determined, the
probability of glass breakage due to overpressure alone (Ref. 12)
completes the present definition of the potential design window
for supersonic overflight of populated areas. The rise time of
the sonic boom overpressure in relation to glass breakage predict-
ion is not significant as overpressure alone is the key prediction
variable (Ref. 12). For example; a sonic boom having a 2 psf over-
pressure striking a plate glass window in good condition head-on
having an area of 105 square feet (15' x 7') and ¼ inch thick has
a 99.98% chance of not being damaged. For 3 psf the odds are
99.85%. At 4 psf the odds are 99.6% and at 5 psf the odds are
99% that no damage will occur.

For smaller windows the odds are even better that they will not
break. In addition sonic booms do not always strike head-on
and the odds are better as a function of the cosine of the flight
path angle to the head-on or zero angle. For this reason the
potential design window for supersonic aircraft (Figure 6)
includes overpressures as high as 5 psf. The combinations of over-
pressure and rise time to the right of the 100 PLdB line are
those found acceptable to 95% or more of the test subjects.

Although there is still no way at present to completely silence
the sonic boom except by flying at speeds below Mach cut-off,
reduction of the sonic boom perceived level (PLdB) is possible
by reduction of the sonic boom index ($\Delta P/\tau$) or rate of onset of
overpressure. Research (Ref. 13) has already shown that the
overpressure of the sonic boom is controlled by parameters such
as: altitude, weight, speed (when operating in the lower Mach
number regimes), shape of the airplane, and the terrain over
which the aircraft passes. Currently, the length of the aircraft
has been shown (Ref. 18) to be a promising design parameter which
increases sonic boom rise time. Although the aircraft lengths
required to assure a significant rise time are apparently large,
the need for better understanding by the supersonic aircraft designer
of rise time's importance is warranted.

Operationally it is possible to increase the sonic boom rise time
by increasing the altitude above and the lateral distance to
populated areas thereby decreasing the perceived level (PLdB) of
the sonic boom. The calculated variation of perceived level with

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altitude and lateral distance is shown in FIGURES 8 and 9 based
on the variation of use time obtained from reference 10.

Using the (SR-71) overpressure/rise time data of Reference 10,
the sonic boom perceived levels (PLdB) versus altitude were
calculated for the winter and summer by employing Equation 2.
In addition, the acceptability of the sonic boom perceived
levels calculated herein and presented in Figures 3 and 4 are
included for easy reference in Figure 10. It can be readily
seen that almost all of the sonic booms are at perceived
levels that were acceptable to 50 percent of the subjects.

The variation of perceived level of sonic booms generated
by SR-71 aircraft operations at approximately 70,000 feet
and Mach 3.0 ranges from a high of 115 PLdB to a low of
80 PLdB with an average of 95 PLdB.

The average or mean perceived level of sonic booms generated by
SR-71 aircraft operations also varies with altitude being around
115 PLdB at 20,000 feet, 100 PLdB at 50, 000, and 95 PLdB at
70,000 feet. The distribution of PLdB around these mean
perceived levels is similar to that determined at 70,000 feet.

Studies at White Sands, New Mexico have shown that for 1,494
sonic booms with scheduled overpressures from 1.9 to 19 psf,
the natural environment had more of a damaging effect on glass
and structures than the sonic boom (Ref. 14).

For the overpressure, associated with civil supersonic flight,
sonic boom research has also shown that there is no damaging
effects on wildlife and farm animals such as cows, chickens,
mink, and fish (Ref. 15, 16, 17).

IV. SUMMARY AND CONCLUSIONS

A potential design window for supersonic overflight based on the perceived level (PLdB) and glass damage probability of sonic booms is outlined.

The evaluation of a simple operational method of estimating the perceived level (PLdB) of sonic booms:

$$PLdB = 55 + 20 \ \log_{10} \frac{\Delta P \ (psf)}{T \ (sec)}$$

is discussed and compared with the Fourier transform computer program calculations of Pease based on the theory of Zepler and Harel. The resulting estimated perceived levels are in good agreement i.e., within 1 to 2 PLdB of each other in the important potential certification or design window that is in the 90 to 100 PLdB range. These perceived levels are shown to be acceptable to 95 to 100 percent of the people exposed to them.

The levels estimated using the method of May vary considerably with the levels determined by the other 2 methods, previously discussed.

There are two areas that need additional work:

1. Psychophysical studies regarding human acceptability of the sonic boom perceived level especially during actual supersonic flight conditions.

2. Aerodynamic studies aimed at reducing overpressure/rise time or rate of onset of sonic boom maximum peak overpressure with a view to reducing the perceived level PLdB of sonic booms to acceptable levels.

The ultimate goal is to maximize compatability between the aviation system and the environment in which it operates. If acceptability standards for sonic booms based on perceived levels, PLdB, are set, then Transonic, Supersonic, and Hypersonic Aerospace vehicle research and development will be accelerated and the road block to progress in commercial supersonic aviation presented by the sonic boom will eventually be overcome.

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LIST OF SYMBOLS

k	Constant
PLdB	Perceived Level (decibel)
PNdB	Perceived Noise (decibel)
$\triangle P$	Change in pressure, overpressure (pounds/foot^2)
τ	Onset time of peak overpressure, rise time (sec, msec)

LIST OF FIGURES

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FIGURE 1. Relationship of Overpressure and rise-time to the Sonic Boom Perceived Level, PLdB.

Chart employs the equation : $PLdB = 55 + 20 \log_{10} \dfrac{\Delta P(psf)}{\tau(SEC)}$

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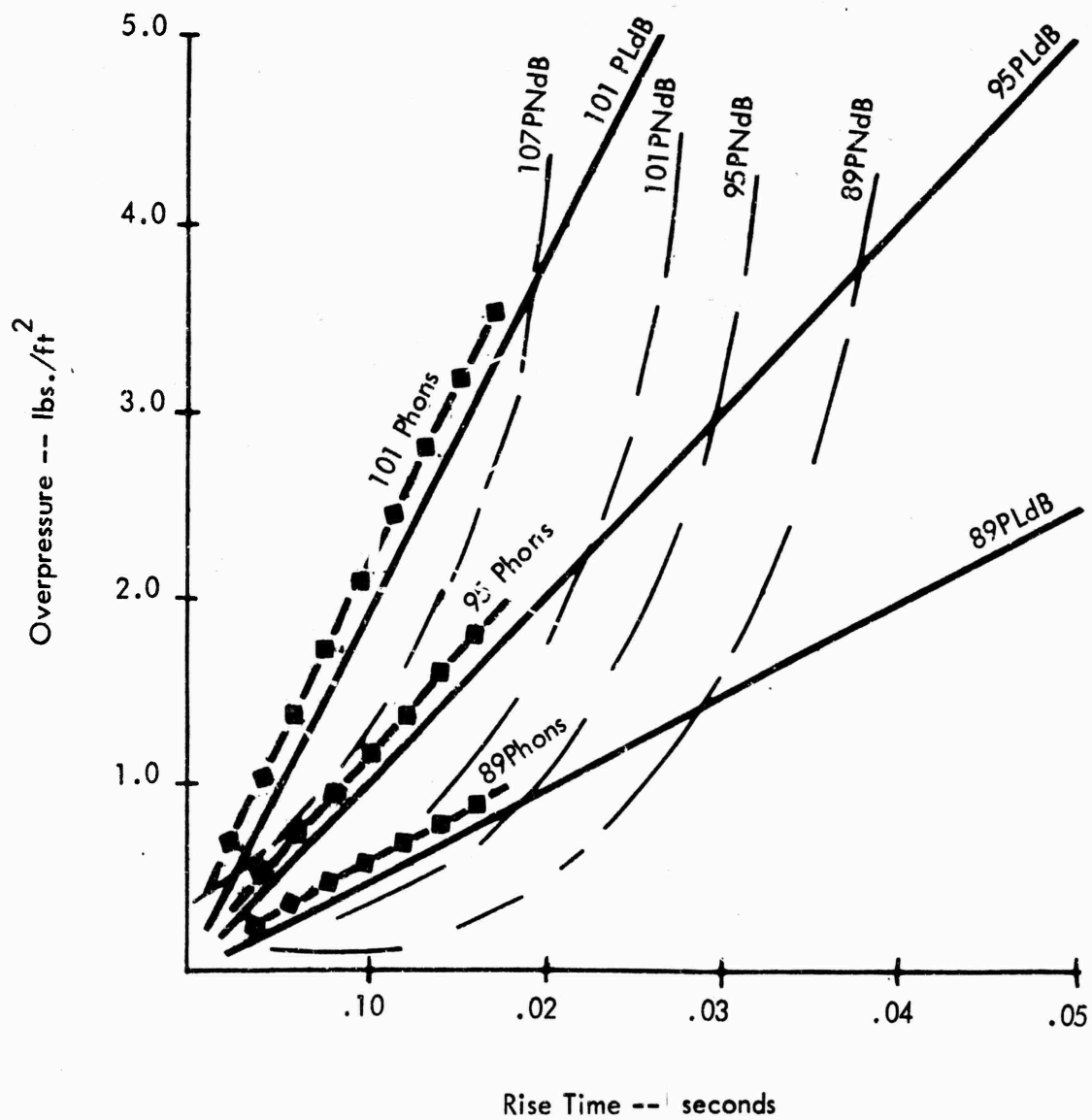
FIGURE 2   Comparison of Perceived Levels Calculated by
Pease and by Equation 2.

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FIGURE 3. Frequency Distribution of SR-71 Aircraft Perceived Levels PLdB As Function Of Overpressure Per Unit Rise Time.
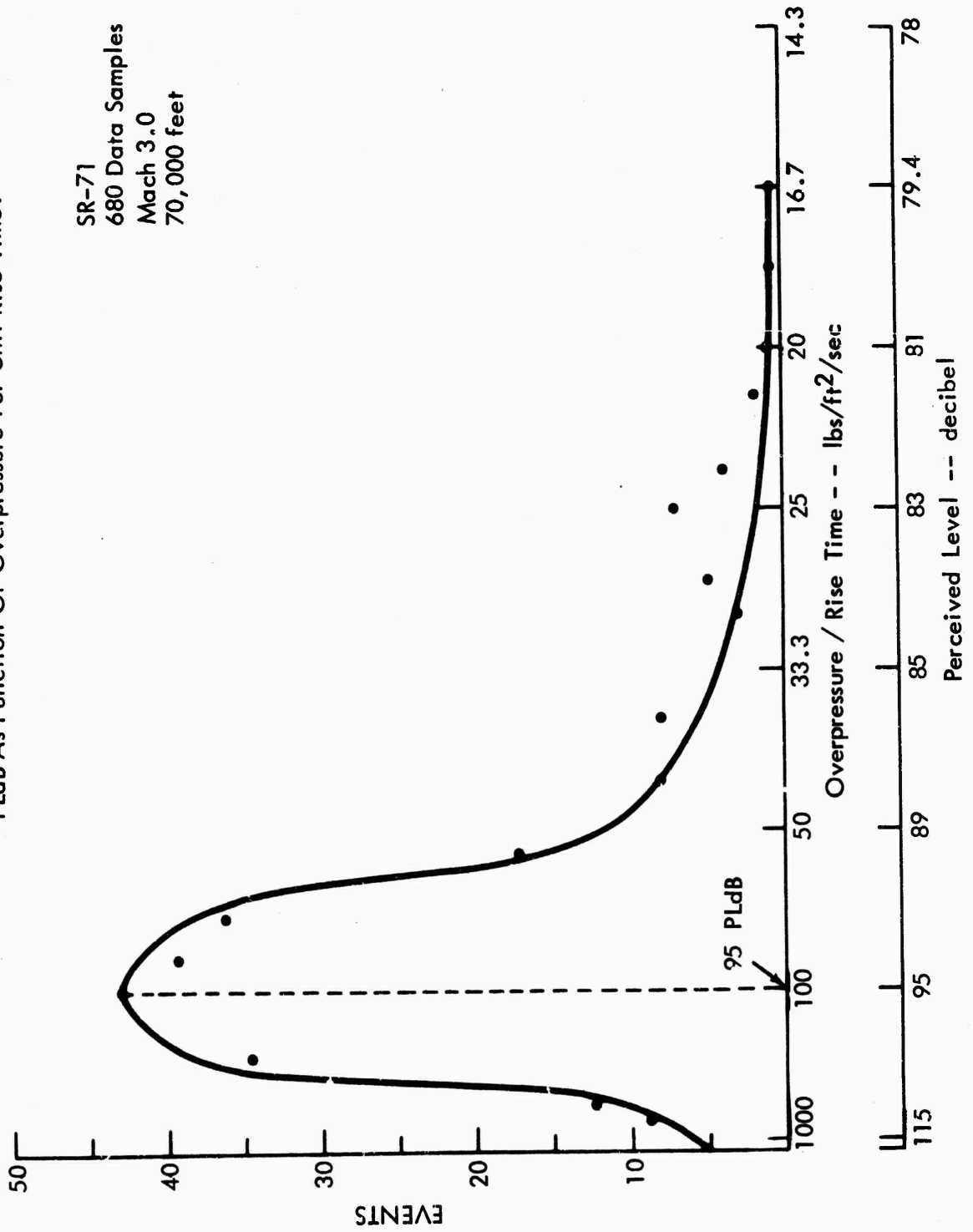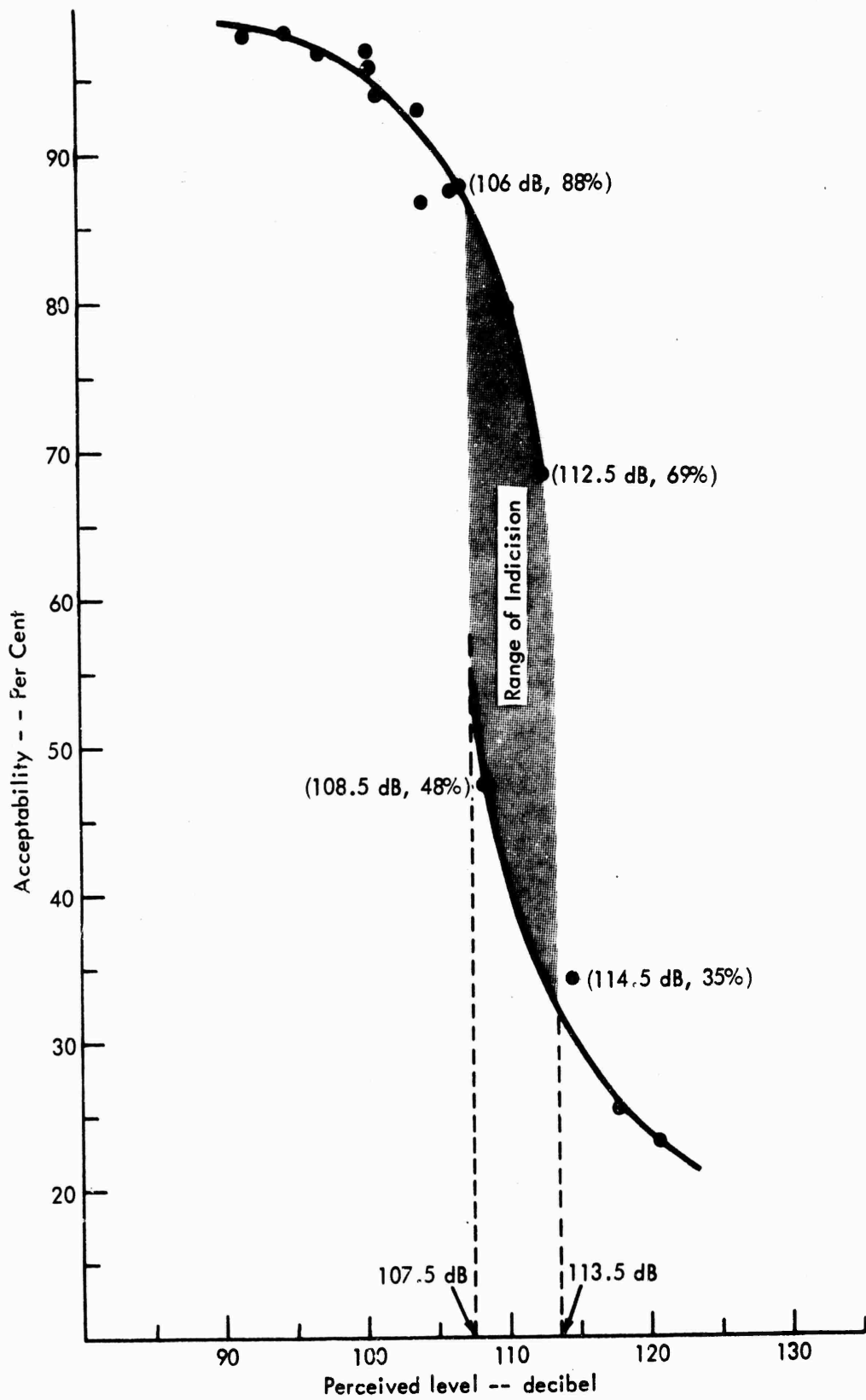
FIGURE 4. Acceptability Of Sonic Booms According To
Their Perceived Level, PLdB.

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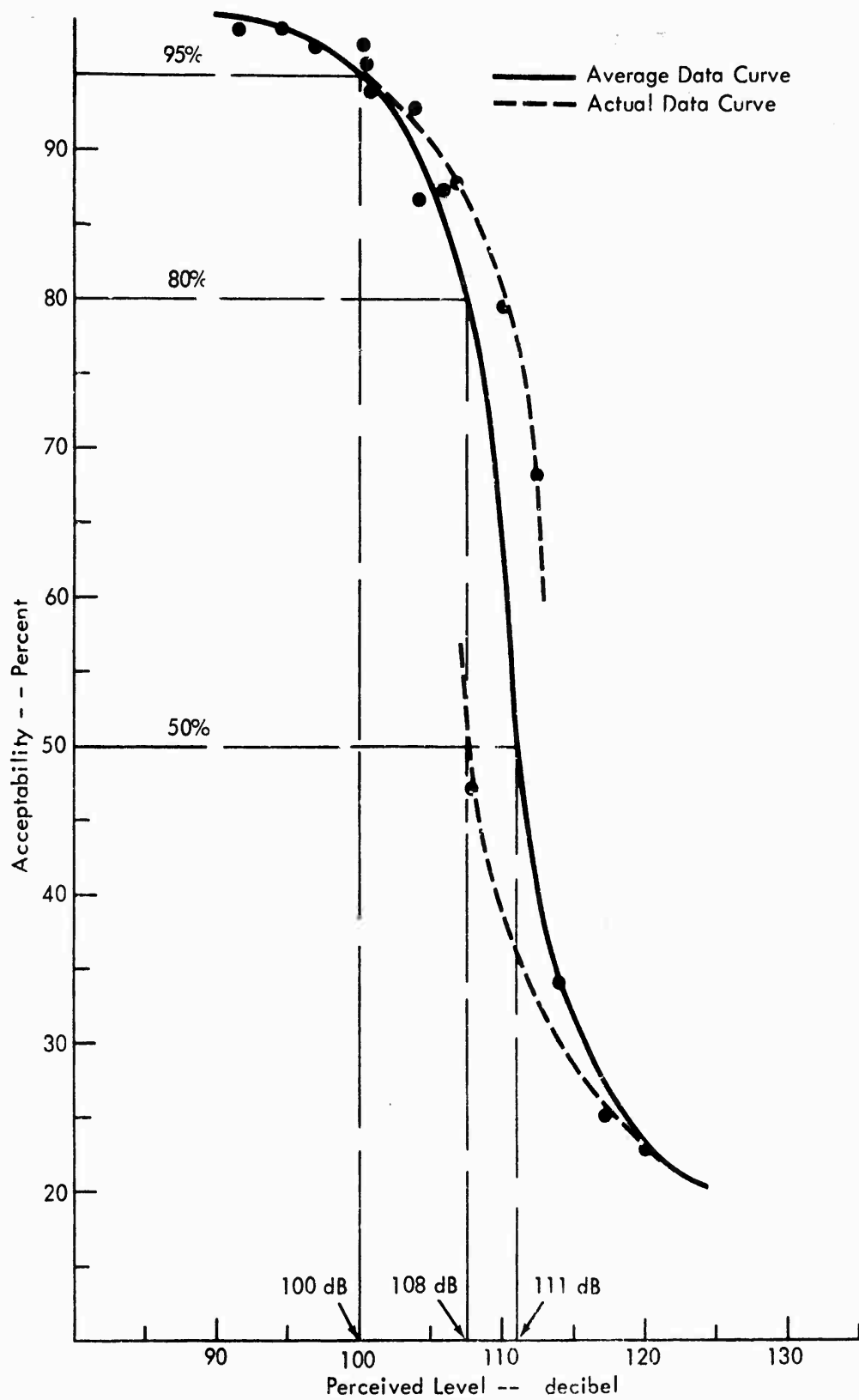
FIGURE 5. Sonic Boom Acceptability (Average Data) Curve

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FIGURE 6. Comparison Between The Acceptability Of
Various Perceived Levels Of Sonic Booms
And Aircraft Flyover Noise Together With
Several Category Scales Of Acceptability,
Intrusiveness And Noisiness.

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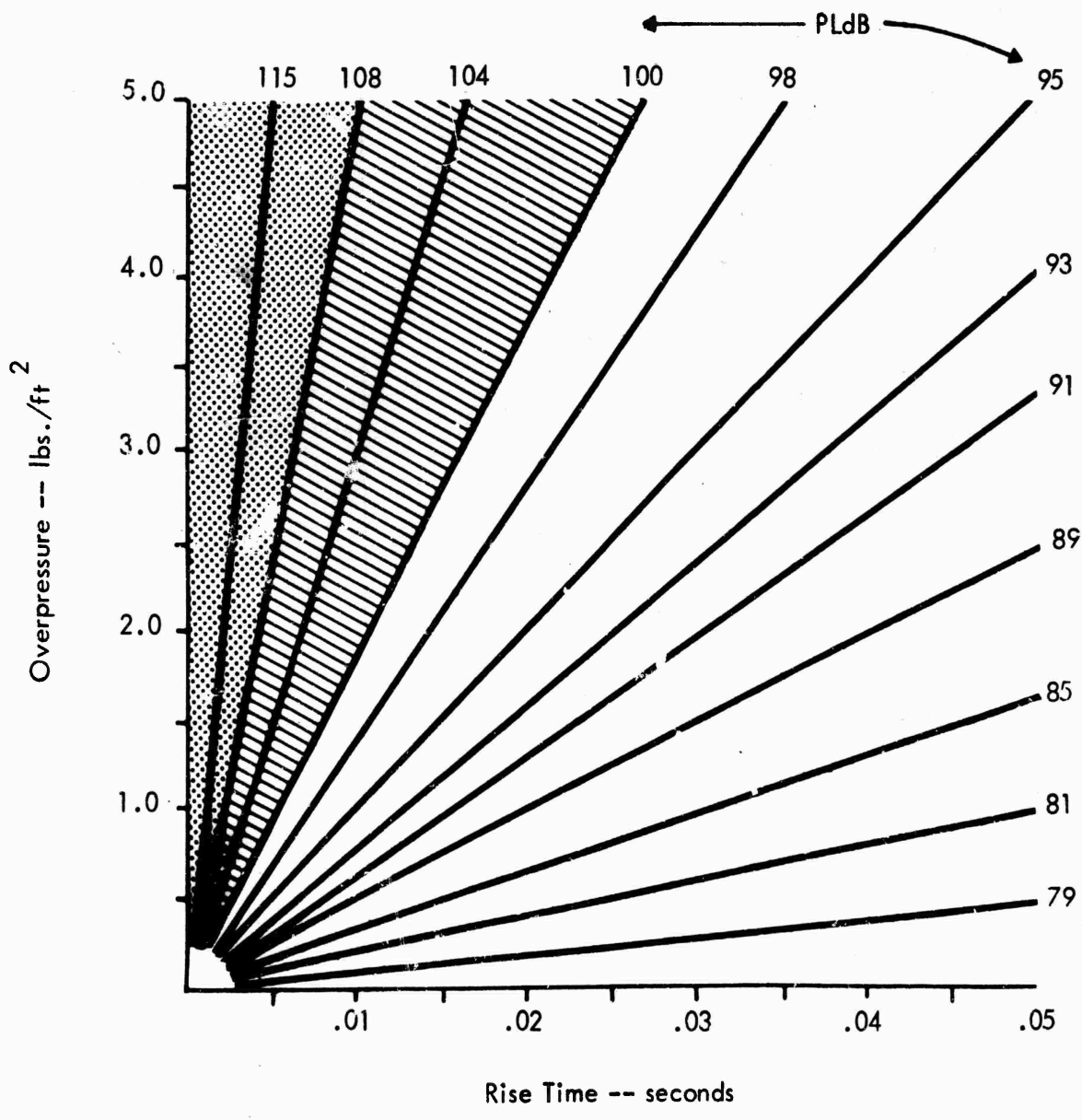
FIGURE 7. Potential Supersonic Aircraft Design Window
(The Acceptability Of Various Sonic Boom
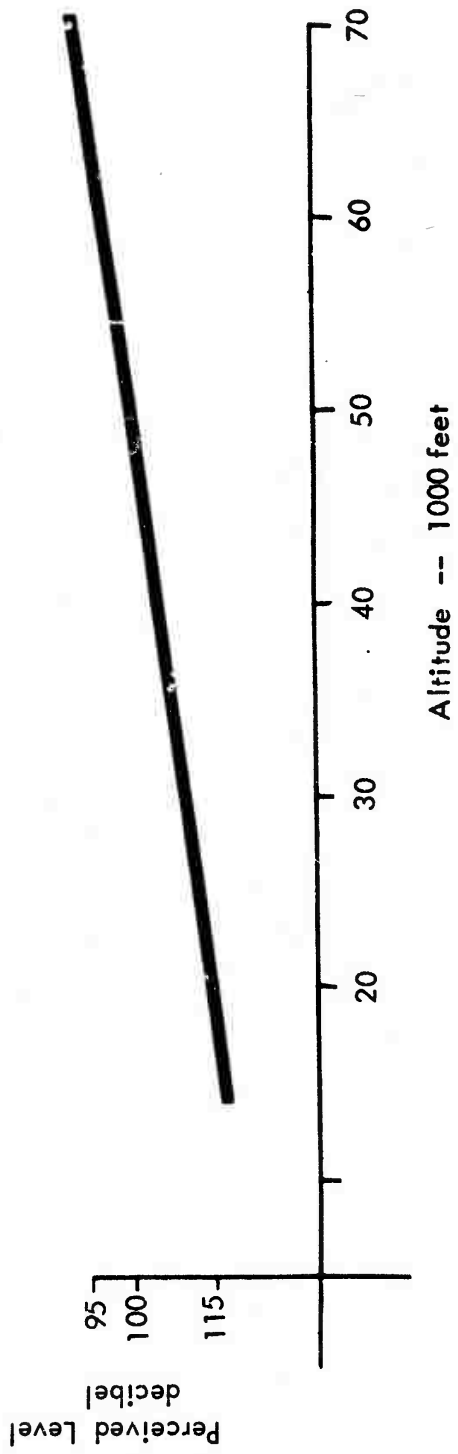Overpressure/Rise Time Combinations And Their
Perceived Level.)

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FIGURE 8. SR-71 Aircraft Variation Of Sonic Boom
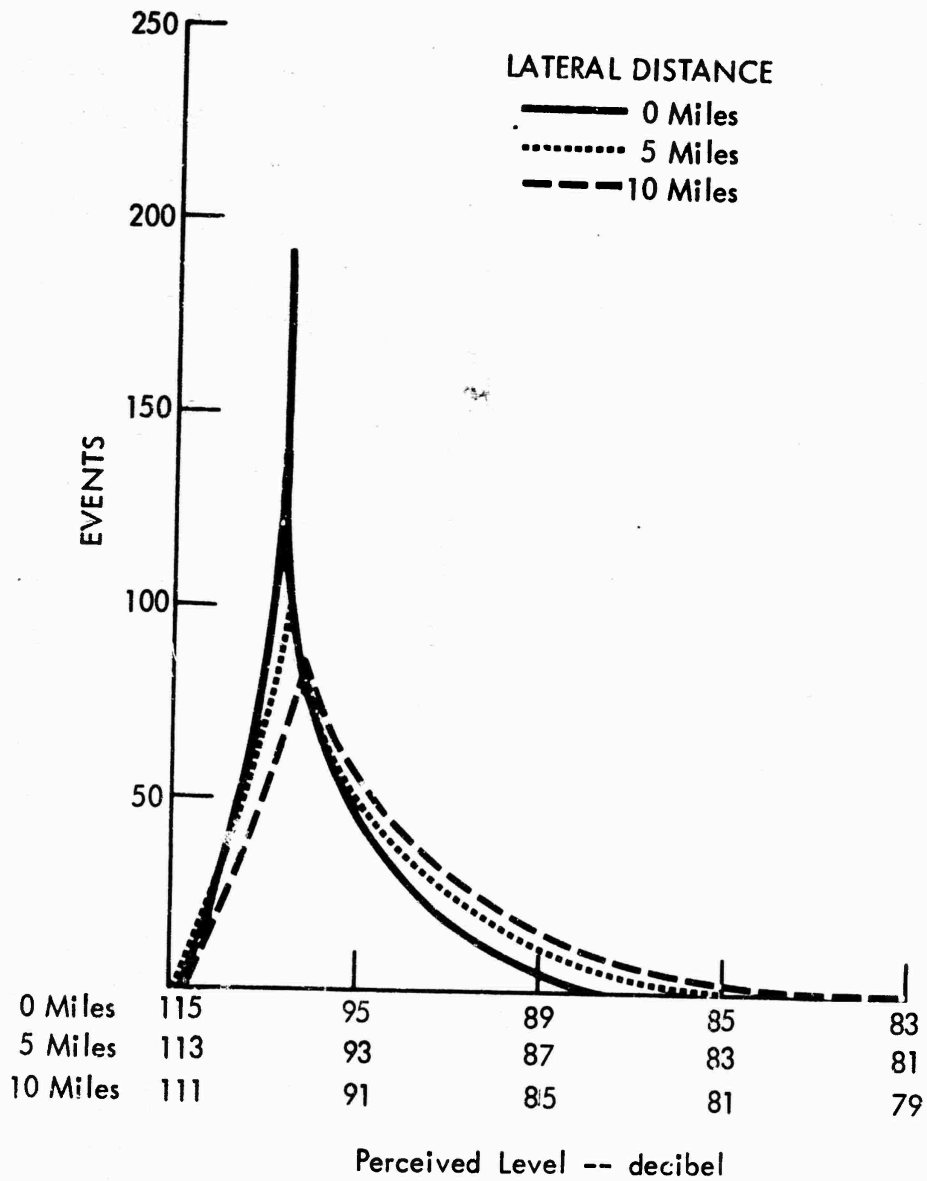Perceived Level With Altitude.

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FIGURE 9. SR-71 Aircraft Variation of Sonic Boom
Perceived Level With Lateral Distance.

FIGURE 10. Variation Of Sonic Boom Perceived Level, (PLdB) With Altitude During Winter And Summer.

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