NASA CR-132430

COMMUNITY ACCEPTANCE OF HELICOPTER NOISE: CRITERIA AND APPLICATION

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Prepared Under Contract No. NAS1-12495 By
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Stratford, Connecticut

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SYMBOLS

C	Total number of aircraft types
CNEL	Community Noise Exposure Level
CNR	Composite Noise Rating
EPNL	Effective Perceived Noise Level (tone and duration corrected PNL)
EPNdB	Units of Effective Perceived Noise Level
L	Overall Sound Pressure Level
L_A	A-weighted sound pressure level; A-weighted sound pressure level for 1 exposure of 10 second duration
L_B	B-weighted sound pressure level
L_C	C-weighted sound pressure level
L_D	Daytime noise level
L_{DN}	Day-Night noise level
L_N	N-weighted sound pressure level; nighttime noise level
L_{NN}	NN-weighted sound pressure level
LL_S	Stevens' loudness level
L_T	Total accumulated noise exposure during a day
LL_Z	Zwicker's loudness level
L_n	Noise level of the n-th period of the day
L_{50}	Level of ambient noise that is exceeded 50% of the time
L_{90}	Level of ambient noise that is exceeded 90% of the time
L_o	Steady blade airloading; Ambient noise level
L_λ	λ-th blade airloading harmonic
$L(t)$	A-weighted sound pressure level as a function of time
N	Number of operations per day or night; number of Δt increments contained in the internal t_o to $t_o + \Delta T$

SYMBOLS (continued)

NC	Noise Criterion level
NEF	Noise Exposure Forecast
NI	Noisiness Index
NNI	Noise and Number Index
N_t	Number of constant noise energy periods per day
P	Total number of flight paths over which "C" aircraft types fly
PNL	Perceived Noise Level
PNdB	Units of Perceived Noise Level
PNL_t	Tone corrected Perceived Noise Level
$\overline{Q}$	Mean Annoyance Level
SENEL	Single Event Noise Exposure Level (tone and duration corrected dBA)
SIL	Speech Interference Level
SPL(A)	A-weighted Sound Pressure Level
ΔT	Time interval during which the aircraft noise level is above the ambient level
dB	Decibel
dBA	Units of A-weighted sound pressure level
dBA_t	Tone corrected dBA
k	Airloading harmonic delay factor
Δt_n	Duration of the n-th period of the day
t_o	Time when aircraft noise level first exceeds the ambient
Δt	Time increment between successive values of L(t)
t	Time
λ	Airloading harmonic number

SYMBOLS (continued)

σ	Standard deviation
	Isopheric Index

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SUMMARY

A study was conducted to define those criteria necessary for civil helicopter operations to be acoustically acceptable to the communities from which they operate and over which they fly. The study involved surveying existing domestic and foreign Federal regulations and guidelines, state and local noise ordinances, results of community noise annoyance studies, and results of individual aircraft noise annoyance studies in order to establish the criteria.

The final criteria selected are based on the Day-Night Noise Level, L_{DN}, a measure of total noise exposure. The basic rating unit is the "A" weighted sound pressure level (dBA) which has accuracy comparable to other units currently used for aircraft. An L_{DN} of 60 is recommended as a criterion for areas where the ambient noise is below 58 dBA. An L_{DN} value 2 dBA above the local ambient is recommended for areas where the ambient is above 58 dBA. This assures that the energy contributed by any new noise source (such as aircraft operations) is less than the existing ambient noise energy. Characteristics found important for aircraft noise rating such as tone content, duration, and number of operations have been accounted for. In addition to the capability for rating individual and cumulative aircraft operations for community acceptability, these criteria include the effects of other non-aircraft noise sources and the ambient noise environment. This broad capability makes the criteria widely applicable.

As part of the study a current generation 50 passenger civil transport helicopter developed from a 18100 to 22700 kg (40,000 to 50,000 pound) single main rotor military transport was acoustically evaluated for typical commercial service using the recommended L_{DN} criteria. It was found that the unmodified aircraft meets the criterion levels in cruise flight. For typical takeoffs and landings, some modifications to the main and tail rotor were found to be necessary for the helicopter to meet the criteria, however these changes do not greatly alter the aircraft's performance.

The modifications found necessary include tip speed reductions and use of advanced design blades. Some turbine engine inlet and exhaust noise suppression was found to be necessary, however, the penalty in weight and power loss is quite small.

INTRODUCTION

The current study was undertaken in recognition of the fact that there is a growing need for significant improvements in civil short-haul air transportation systems. With major airports moving further and further from the city center (or business district) there is an obvious need for reliable, efficient city center to city center short haul air transport systems that can be good neighbors to the residents of the communities they serve. In this regard, the helicopter is an ideal candidate as a vehicle to use in such a transport system. It is capable of reasonably high speeds, it can carry 50 to 100 passengers or more, and it can operate from small terminals, a necessity in city centers where land is at a premium. Perhaps most importantly, the helicopter is generally quieter tha n other V/STOL systems (for a given size) because it has a much lower disk loading than the other systems.

In undertaking a study to evaluate helicopters in a civil transport system it is necessary to have available a noise acceptance criteria against which their acoustic performance can be measured. There are in existance today as many as 25 to 30 descriptors for scaling an individual's annoyance to noise and perhaps 8 to 12 methods for describing community annoyance and/or reaction to all types of noise. Therefore, one of the primary aims of the present study is to evaluate all of these measures along with existing or proposed federal, state, and local noise guidelines and regulations and from them evolve workable, accurate noise criteria to predict the acceptability of projected helicopter operations to a community.

The other main objective of this study is to compare the noise characteristics of a current generation 50 passenger helicopter with the criteria and then determine hardware changes that can be made to the aircraft to allow it to meet the criteria. For the purposes of the study, the civil helicopter is considered to be a derivative of a military transport helicopter in the 18100 to 22700 kilogram (40,000 to 50,000 pound) gross weight category. Hardware changes considered are those that are developed enough to be applied to the helicopter in the 1975-1976 time frame with little or no additional development time required. Preliminary estimates of changes in aircraft performance due to the hardware changes are to be made.

NOISE ACCEPTANCE CRITERIA

Selection of a community noise acceptance criteria involves several discrete steps starting with selection of the basic unit relating physical sound to human reaction. Once the rating scale is selected, the number on this scale that corresponds to a noise exposure acceptable to the average member of the community must be determined. Further, it must be determined whether the environment to which this average community member has become aclimated has an influence on his "acceptable" noise level and if so what the relationship is between this ambient noise envieonment and his tolerance to new noise exposure. Another factor to be considered is the effect of exposure duration on the acceptability of noise. The duration of each exposure as well as the number of exposures per day has been shown to influence noise acceptability and this too must be included in the final criteria. Finally, there is the question of the annoyance of periodic impulsive noise (known as "blade slap" on helicopters). The annoyance of this type of noise is not adequately accounted for in any existing rating scale and therefore requires a correction to properly define its annoyance.

Each of the considerations identified above will be dealt with in detail below. The resulting community noise acceptability criteria accounts for each of the factors in a conservative manner and will, if observed, result in community/helicopter compatibility. One topic requiring further resolution, however, is that of the blade slap annoyance penalty. There is not sufficient reliable data available at this time to finally resolve either the method of quantifying existence of blade slap in a noise signal or in measuring an observer's annoyance reaction to it.

Noise Criteria Development

Selection of a rating scale. - There are three basic considerations in choosing a scale for rating the annoyance of noise. First is the precision of the scale. This is perhaps the most important factor in the choice of a scale because it determines the degree to which a calculated rating matches the subjective rating of a typical member of the community. Scale inaccuracies could render an entire rating system worthless. The second consideration is that of commonality with other systems. The current trend of developing a new annoyance scale for each new noise source has led to some confusion, hence a scale that is easily recognized and is of use to non-acousticians must be selected. The third consideration is ease of use. A simple weighting scale that produces a direct readout on a simple meter is preferable to a method which requires a computer or long hand calculation to produce a result.

The "A" weighted sound pressure level (SPL(A) in dBA) has been selected as the basic unit of annoyance measurement for the community annoyance criteria because of the above considerations. Candidate units that were surveyed are listed in Table I. The "A" weighted sound pressure level was found in several studies to be as accurate as any of the other units. It is the most commonly used unit for rating a variety of noise types including aircraft, motor vehicles, and community ambients, and it is easily measured using a standard sound level meter.

The suitability of SPL(A) for rating the annoyance of aircraft noise is substantiated in several studies (eg. - References 1-7). SPL(A) was compared in these studies with several other measures of aircraft noise annoyance and found to be statistically as good or better than the rest. A study performed by Ollerhead (Reference 3) on general aviation aircraft noise resulted in correlation coefficients between measured and computed subjective ratings of 0.867 for SPL(A) and 0.88 for PNL. This and other data are listed in Table II. The other rating units had correlation coefficients in the range 0.714 to 0.879. The similarity in correlation between PNL, the commonly used unit for aircraft noise annoyance, and SPL(A) is typical and shows that the two measures differ insignificantly in their ability to rate aircraft noise for annoyance. Perhaps the large amount of study regarding the effectiveness of these similar rating units is summed best by D. M. Green in Reference 6: "The existing procedures, at least in my opinion, are so close that it is really rather pointless to argue about the superiority of one or another. What is needed is the result of an experiment using a carefully selected set of spectra where the differences in prediction are very great. Otherwise, I think we will continue to find that all of the methods are about equally good and while one, on the average, may be somewhat better, no one is clearly superior to all the others". An experiment such as that mentioned by Mr. Green was performed subsequent to his remarks by J. B. Ollerhead (Reference 1). Using spectra which varied from pure jet aircraft to rotorcraft he found that there was little difference among the rating units.

In summary, the SPL(A) unit, although not substantially better than any of the other units available, is of comparable accuracy to them and offers major advantages of commonality with non-aircraft rating schemes, ease of measurement, and availability of measurement equipment.

Tone corrections. - There is substantial evidence (References 1, 2, 8, 9) to support the need for a correction to account for the increase in annoyance of signals containing pure tones. This subjective increase in annoyance is over and above the calculated contribution made by the tone to the overall annoyance rating. The most recent and well documented studies (Reference 3 for one) indicate that such a correction enhances annoyance prediction only for tones above 500 Hertz in frequency.

The Federal Aviation Administration has adopted a tone correction in its noise standards for transport category aircraft (Reference 10).

Although applied in this case to the PNL rating unit, the correction is independent of the annoyance rating unit calculation procedure and hence is applicable to other units. There is a nearly constant difference between PNL and SPL(A) for most noise spectra so it will be assumed that because application of the tone correction enhances the annoyance prediction accuracy of PNL it will also enhance the annoyance prediction accuracy of SPL(A). The procedure to be used to determine this correction is that described in Reference 11, with the exception that only tones with frequencies above 500 Hz are included.

Duration effects. - Nearly all available evidence indicates that the time to which a subject is exposed to noise affects his judgement as to its annoyance. The consensus of this evidence further indicates that the time-annoyance relationship is a direct acoustic energy summation; i.e. annoyance increases 3 dB per doubling of exposure time. Other relationships have evolved from the many experimental investigations on the subject. These include doppler shift corrections, onset corrections, and higher and lower rates of accumulated annoyance with time. The more sophisticated of these other relationships have been developed for specialized classes of noise sources; in any case, they have not achieved general acceptance. The instances of other than direct energy summation for accumulating annoyance with time are in the minority and have been adopted for regulatory use only in a few foreign countries. The current federal regulation for transport aircraft includes the direct energy summation method of accumulating annoyance with time.

The near universal acceptance of the energy summation procedure as well as its simplicity of use has lead to its selection for use in the civil helicopter criteria. Not only may the duration of a single event (flyover, takeoff, or landing) be rated accurately for annoyance, but also effects of multiple sources and events are accurately and simple included.

Selection of a common comparison basis for rating schemes. - It is necessary to reduce to a common basis all of the rating schemes to be evaluated in order to develop the civil transport helicopter community noise acceptance criteria. The common unit selected is L_A, the "A" weighted sound pressure level (SPL(A)) of a single event with a constant noise level and a duration of 10 seconds. It was selected because SPL(A) is common to most non-aircraft annoyance rating schemes, SPL(A) is to be used in the developed criteria, the 10 second duration is common to most aircraft rating schemes, and use of a single event eliminates any confusion which might be caused by the various summation methods used in aircraft noise annoyance rating schemes. L_A is defined as:

$$L_A = 10 \log_{10} \left\{ \frac{\int_0^T \text{antilog} \left[\frac{\text{SPL(A)}}{10}\right] dt}{10 \text{ sec}} \right\}$$

$$L_A = 10 \log_{10} \left\{ \int_0^T \text{antilog} \ \frac{SPL(A)}{10} dt \right\} - 10 \qquad (1)$$

where $\int_0^T \text{antilog}\left\{\frac{SPL(A)}{10}\right\}dt$ represents the total energy in the signal over a full 24 hour period and 10 sec is the normalizing time. All criteria to be compared must now be converted to this unit. This is done rather simply by noting (References 3, 12, 13) that the difference between a spectrum's SPL(A) and its PNL is, on the average, 13 dB and that all criteria considered use one of these two basic units. So noting this relationship:

$$SPL(A) = PNL - 13 \qquad (2)$$

the various criteria may be compared. Composite Noise Rating (CNR) will be converted to L_A as an example. From Reference 12 for an exposure duration of 10 seconds:

$$CNR = 10 \ \text{Log}_{10} \ (10^{PNL/10}) + 10 \ \text{LOG}_{10}(n) - 12 \qquad (3)$$

Here the 10 second duration has already been accounted for hence L_A=PNL-13. The number of flights, n, is set equal to one resulting in the folowing relation for CNR:

$$CNR = 10 \log_{10} \left(10^{\left\{\frac{L_A+13}{10}\right\}}\right) - 12 = L_A + 13 - 12 = L_A + 1 \qquad (4)$$

or:

$$L_A = CNR - 1 \qquad (5)$$

Evaluation of current criteria. - The same conversion process given in the example above was applied to several domestic and foreign federal noise standards resulting in Table III. These conversions were applied to the various standards to define the range of acceptable levels for each standard in terms of L_A. To insure that the level derived is conservative in terms of being acceptable to the exposed community the various standards were treated as shown in Figure 1. For each standard listed a range of levels is blocked out. This range defines the investigators' best interpretation of the marginally acceptable range of levels that separate the clearly acceptable and clearly unacceptable levels in the particular standard. Some interpretation was necessary because of the variations in language used to define the degree of acceptability of noise in the standards. There is a large range of marginally acceptable levels with the average center falling in the L_A range of 100 to 110.

The lower end of the shaded regions in Figure 1, which is the upper boundary of the clearly acceptable region, was selected for further consideration. This level, rather than the center of the marginally acceptable range, was chosen in an effort to bias the ultimate criteria in favor of the community. This decision was made to provide resulting criteria levels acceptable to the community.

Figure 2 shows the "clearly acceptable" levels of Figure 1, again in terms of the common rating factor L_A. The mean of all the standards is 97.5 dB with a standard deviation of 6.5. When the obviously conservative HUD traffic noise (possibly out of the range of the others because of difficulty in interpreting it in L_A units) is removed from the average process the numbers become 100 and 4.7 dB respectively. It is felt that this 100 dB in L_A units represents a conservative estimate of noise exposure which would be considered clearly acceptable according to the criteria evaluated.

Community criteria: Twenty-two community noise regulations were evaluated on the same basis as the federal criteria. The L_A values computed from them are shown in Figure 3. The mean and standard deviation of the regulations described by the open circles are 93.5 and 3.0 respectively. Regulations corresponding to the darkened circles were considered out of line with the main body of data. The entire data set had a mean of 93 dB and a standard deviation of approximately 6 indicating that the main body, or two thirds of a standard set, of data was between 87 and 99 dB; data points outside of these bounds were not considered further and were dropped from the average.

The sixteen community noise regulations considered in the Figure 3 average include several large cities such as Chicago, Los Angeles, and Miami and some smaller cities and towns. New York City is not shown in Figure 3 because regulations for aircraft noise are just now being considered and tentative regulations are not yet available. The L_A numbers indicated in the figure are for residential zones except where a distinction was made in the regulation. Normally, commercial and industrial zones are allowed to be 5 to 10 dB higher than those levels shown.

The L_A values for community regulations were derived using the same ground rules and scale definition as for the federal criteria treated earlier. However, the nature of these community ordinances required a slightly different method of deriving the L_A value. The ordinances under consideration regulate the allowable noise over the total 24 hour period of a day. Therefore to develop the comparable 10 second allowable noise exposure (L_A) the total noise over this 24 hour period must be summed and converted back to an equivalent 10 second duration of constant level. The procedure is as follows:

The total noise exposure L_T accumulated during a day is:

$$L_T = 10 \, \mathrm{Log}_{10} \left\{ \sum_{n=1}^{N_t} \mathrm{antilog} \left(\frac{L_n}{10} \right) x \; \Delta t_n \right\} \qquad (6)$$

where L_n is the noise level for the nth period with duration Δt_n seconds. The N_t periods constitute a full day. The L_A term is then equal to L_T minus 10 dB (to account for the 10 second duration assumed). Hence:

$$L_A = 10 \text{ Log}_{10}\left\{\sum_{n=1}^{N} \text{antilog}\left(\frac{L_n}{10}\right) \text{x } \Delta tn\right\} -10 \qquad (7)$$

In cases where an allowable level is not given for night time periods the level is assumed to be five dB below that allowed for daytime periods. Night is assumed to have a duration of 9 hours and day is the remaining 15 hours.

As an example of the computation consider the case of Farmington, Connecticut. The allowable daytime noise level is 46 dBA with no correction given for nighttime. In calculating L_A the nighttime noise level will then be 51 dB, which is a penalty of 5 dB for this period. The calculation is as follows.

$$L_A = 10 \text{ Log}_{10} \left\{\text{antilog}\left(\frac{46}{10}\right) \text{x } 9 \text{ x } 3600 + \text{antilog}\left(\frac{46+5}{10}\right) \text{x } 15 \text{ x } 3800\right\} -10$$

$$L_A = 99 - 10 = 89 \text{ dBA}$$

State Criteria: State criteria for allowable noise exposure in residential areas are not common. However, those for the three states for which such information was available were treated in the same manner as the community ordinances. The resulting average is an L_A of 96.3 dBA.

"Impact" type criteria: Studies such as References 14, 15 and 16 indicate that the most equitable method of determining the amount of noise to which a community can be exposed is to relate it to the existing ambient noise conditions. This appears to be a reasonable approach to the problem because of the well known facility of individuals to become acclimated to their environment. Those living in high noise areas have become accustomed to it and are less disturbed by a noise of a given level than those living in a lower ambient noise area.

As a check on this theory and as an additional check on the tolerable noise levels in various communities, several categories of ambient noise level were evaluated in terms of the common unit L_A. Ambient noise levels were determined from Reference 15 (Ollerhead) and Reference 17 (Donley). These two references utilize large quantities of measured data to derive average quantities and they agree substantially on levels. Data from Reference 18 is for specific locations and also generally agree. For instance, in the case of suburban residential noise levels during the daytime hours Reference 15 cites L_{90} and L_{50} levels of 45.6 and 50.9 dBA respectively. The corresponding levels from Reference 17 are 43 and 50 dBA. The data of Reference 15 was used for the following computations because they were presented in a more easily used format. The specific data used is contained in Table IV. The L_{50} and L_{90} levels referred to in the table and above are the "A" weighted ambient sound pressure levels which are exceeded during the measurement period 50 and 90 percent of the time respectively. This method of presenting ambient noise is necessary due to its statistical nature.

The L_A values for these ambient noise conditions were determined with the same procedure used for community ordinances. L_A values for the city center and suburban residential areas are 110 and 85.3 respectively. They cover the full range of existing ordinances and provide at least a partial explanation for the wide spread in these regulations. The previous noise exposure environment of the various areas probably influence the levels which residents consider reasonable.

The impact to ambient type criteria take the existing ambient noise levels, sometimes bounded by a lower limit, and state that new noise in the area can increase this ambient only by "X" dB. In actual practice, this number "X" ranges from two to five dB for the regulations surveyed. Although not mentioned in previous sections a small percentage of the community noise regulations surveyed were in fact impact to ambient types and their allowable levels were determined by applying the allowable impact to the ambients typical of their location.

The impact of impulsive noise on acceptability of helicopters. - Very little information is available in the literature regarding the effect of repeated impulses (blade slap) on the acceptability of helicopter noise. Many studies on the annoyance of sonic booms have been performed, but the results are not directly applicable to blade slap conditions where the impulses are repetitive and where the overall amplitude increases and then decreases as the helicopter passes over. Based on the sketchy information available from the literature (References 19, 20, 21, 22, 23) it appears (as shown in Figure 4) that there should be a 4 to 6 PNdB penalty when impulsive noise is present in a signal. In terms of A-weighted sound level the penalty appears to be somewhat larger, on the order of 8 to 13 dBA.

One of the major difficulties in applying a penalty for impusive noise is in establishing an objective means to define its presence and severity. A study performed in 1963 (Reference 23) indicates that impulses repeated in excess of 18.80 per second are perceived as steady (continuous) noise. Most investigators, including the authors, have concluded that phase information is necessary to the determination of whether a spectrum has impulsive content. Others, in the minority, contend that phase information is irrelevant to the determination of the noisiness of impulsive noise. Leverton (Reference 20) defines no objective method of defining the presence of impulsivity in a signal but contends that if it is subjectively present a penalty of 12 dB should be imposed relative to the noisiness computed by conventional objective means.

Because of the lack of consistent information on the annoyance of impulsive noise and on objective means of determing its presence, a limited test was conducted. This test was meant to be no more than a crude beginning toward defining an accurate blade slap annoyance assessment method. Consequently, only preliminary recommendations can be made at this point.

The crest factor of a signal, which, in dB, is 20 times the common logarithm of the ratio of peak to root-mean-square (rms) sound pressure level, was selected for evaluation as an impulse noise indicator because it has known values for common noise types (3 dB for sinusoidal or pitched noise, 10 dB for Gaussian or broadband noise) and seems logical for the description of blade slap noise which is characterized by a highly peaked time history. It is also a parameter which is rather easily measured. Selection of a frequency spectrum based descriptor was avoided because of the need to include phase information necessary to distinguish the blade slap characteristic. The meter used to determine the peak signal level had a time constant τ of 0.005 seconds. The ear has a time constant of about 0.05 seconds. The effect of time constant is not known and should be the subject of further study. The instrumentation used for the investigation is described in Figure 5.

Unfortunately the peak meter used was a "capture-and-hold" type peak impulse meter which registers the highest peak level obtained. In retrospect, the peak level required in calculating the crest factor should have been the average peak level because a random peak or two in an otherwise repetitive signal would produce too high a peak reading for the signal in general, and hence, an abnormally high crest factor.

Nine recorded helicopter noise samples were evaluated during the study. They were subjectively classified as to the existence and extent of blade slap by the investigators (admittedly not an unbiased or naive evaluation) during a listening test. The true rms and peak sound pressure levels were then determined with the use of the Figure 5 instrumentation. Results are tabulated in Table V. The data is plotted as crest factor versus subjective blade slap rating in Figure 6. The tentative boundary for blade slap existence at a crest factor of 13 dB is shown in the figure. The boundary is not based on a least squares fit line crossing the blade slap/no blade slap ordinate division. Instead, it was merely selected as the point below which all data were subjectively rated as having no definitely discernible blade slap content and above which all data was rated as having blade slap to some degree. It should be noted that at the boundary crest factor value there are two data points with differing judgements as to blade slap content. This occurrence was not unexpected in a preliminary test such as the one conducted and serves to indicate that more data of higher quality is needed and the dividing line between the slap and non-slap condition is not clear cut.

Oscillograms of the overall sound pressure of the acoustic signals evaluated are shown in Figure 7. In general those signals which were subjectively rated as having blade slap appear impulsive in nature in the traces. The two cases which were shown in Figure 7 to have the same crest factor, the Vertol 107 and the Sikorsky S-61F, have entirely different pressure signatures. The reason for this apparent anomaly may lie in the method of determining peak sound pressure level as discussed above. It points out, in any case, that there is considerably more to be learned about the problem.

As noted in Figure 4, when blade slap is present there is an associated annoyance penalty. While the data used is very limited, it appears that penalties of 8 to 13 dBA are typical. It is possible that a preliminary impulsive noise annoyance penalty could be that shown in Figure 8. The penalty in dBA is added directly to the calculated (or measured) aircraft SENEL value to arrive at the corrected SENEL value for the aircraft. The corrected value is used in determining if the aircraft meets the L_{DN} criterion. It is recognized that this penalty is, at best, crude. The purpose of this limited study was not to define a specific criterion to measure the existance and extent of blade slap, but rather was to determine the potential of a simple measure (the crest factor) to objectively indicate the presence of blade slap. Much work remains to be done in this area to clearly define the presence of blade slap and the associated penalty to SENEL.

Selection of Criteria for Civil Helicopter Operations

Computation of L_{DN}. - A combination of the foregoing discussions indicates that the following characteristics should be incorporated in a civil helicopter noise criteria:

- The basic rating unit should be dBA
- Duration should be considered over a full day of exposure.
- Exposure accumulation should be by the energy summation method.
- The annoyance effect of tones above 500 Hertz should be considered.
- Ambient noise levels must be included.

These characteristics are included in the L_{DN} measure (Day-Night Noise Level). This unit has recently been recommended by the Environmental Protection Agency for aircraft annoyance rating in its recent deliberations in the Aircraft/Airport Noise Study. The draft report which describes this recommendation in great detail and with full technical substantiation is listed as Reference 24. The basic L_{DN} unit has been transformed somewhat in format to fit the requirements of this study as shown below:

$$\text{SENEL} = 10 \text{ Log}_{10} \int_{t_o}^{t_o + \Delta T} \text{antilog} \left[\frac{L(t)}{10}\right] dt \qquad (8)$$

OR

$$\text{SENEL} = 10 \text{ log}_{10} \sum_{k=o}^{N} \text{antilog}_{10} \left[\frac{L(t)_k}{10}\right] \Delta t \qquad (9)$$

$$L_D = 10 \text{ Log}_{10} \left\{ \sum_{i=1}^{C} \sum_{j=1}^{P} \text{antilog} \left[\frac{\text{SENEL}_{ij}}{10}\right] + \left(54{,}000 - \sum_{i=1}^{C} \sum_{j=1}^{P} \Delta T_{ij}\right) \text{antilog} \left[\frac{Lo}{10}\right] \right\} - 47.3 \qquad (10)$$

$$L_N = 10 \text{ Log}_{10} \left\{ \sum_{i=1}^{C} \sum_{j=1}^{P} 10 \text{ antilog} \left(\frac{\text{SENEL}}{10} ij \right) + \left(32{,}000 - \sum_{i=j}^{C} \sum_{j=1}^{P} \Delta T_{ij} \right) \cdot \text{antilog} \left(\frac{Lo}{10} \right) \right\} -45.1 \qquad (11)$$

$$L_{DN} = 10 \text{ Log}_{10} \left\{ .625 \text{ antilog} \frac{L_d}{10} + .375 \text{ antilog} \frac{L_n}{10} \right\} \qquad (12)$$

Equations (8) and (9) define the Single Event Noise Exposure Level (SENEL). The SENEL is the total noise dose for a single takeoff, landing, or flyby. It is the parameter which corresponds to Effective Perceived Noise Level (EPNL) in the current FAA certification procedure and it is the one which would be used for aircraft certification under the proposed procedure. It has been used in the State of California Noise Standards (Reference 25).

Equations (10) and (11) describe the average day and night noise levels respectively. They call for summation of the SENELs generated by the various aircraft on their various flight paths at the point of observation, the addition of ambient noise exposure over the time when it is not exceeded by the aircraft noise, and normalization to the time duration of the day or night periods to obtain an average rather than a total exposure level. The day and night periods are from 0700 to 2200 hours and from 2200 to 0700 hours respectively in accordance with the EPA recommendation (Reference 24) and the current NEF exposure criteria (Reference 12). Note that the night SENEL numbers are multiplied by a factor of 10 to attain the 10 dB penalty associated with this time period.

Equation (12) describes the method of combining the day and night average noise levels to obtain the day-night (L_{DN}) noise level which is to be the criterion for acceptability. The day and night periods are weighted according to the fraction of the full 24 hour day they occupy. Hence the 10 dB penalty imposed on the night period is partially balanced because of the smaller percentage of the total rating period it occupies.

Acceptability criteria in terms of L_{DN}. - L_{DN} has been defined as the unit which relates measured noise exposure to human annoyance to the same noise. It now remains to determine the actual L_{DN} number which correlates with community acceptance.

As a starting point in defining the acceptable L_{DN} it should be mentioned that the Environmental Protection Agency in its draft report (Reference 24) recommended a constant L_{DN} level of 60 as meeting requirements for human compatibility in the areas of annoyance, speech interference, and hearing damage risk. The excellent technical substantiation offered by EPA in their document makes this level worthy of strong consideration.

The average community acceptable noise levels specified by the three categories of standards were determined in terms of L_A in a previous section. These will now be converted into the L_{DN} scale to determine the criterion value to be used. The results are shown in Figure 10. The lowest mean value shown in the figure is that for community residential area standards, an L_{DN} level of 59.5 dBA. The other two categories fall at L_{DN} of 62 and 66 dBA.

The Figure 9 summary in combination with the EPA recommendation leads to the selection of $L_{DN} = 60$ as the basic criterion for community acceptance of civil helicopter noise. This is felt to be a conservative choice because it is designed to meet community noise standards as well as standards for other types of noise instead of being aimed principally at aircraft noise. Other aircraft oriented standards allow higher noise exposures than do the community regulations.

Selection of $L_{DN} = 60$ is not the final step in community noise criteria selection. This noise exposure is ultimately desireable, but cannot be attained under all circumstances at the present time. The reason for this is the existence of ambient noise levels* which already exceed the criterion (60 L_{DN}) and to which, presumably, no further noise may be added. This would preclude any aircraft operations at all in areas where high ambient noise levels exist. This situation can not be allowed to occur because it would eliminate aircraft operations in just those locations where aircraft noise would be the least noticeable.

To overcome this problem, the complete criterion is comprised of two segments based on ambient noise levels in the area under consideration. This criterion is illustrated in Figure 10. The allowable L_{DN} is 60 dBA for areas with ambient noise levels of 58 dBA and below. Where ambient noise exceeds 58 dBA the allowable L_{DN} equals the ambient level plus 2 dBA. The latter portion of the criterion may be termed an impact to ambient type. Because of this limit new noise sources in an area add less energy than the existing ambient noise.

The impact type standard does a number of things to make the proposed criterion workable as far as both the community and the aircraft industry are concerned. First, it allows operation of aircraft in areas where ambient noise is high and the public is acclimated to it. Second, it allows only a small impact to the ambient so that the increased noise exposure in these areas will not be so large as to draw significant notice. Third, automatic de-escalation of noise levels is built-in by way of the ambient noise level. As this ambient decreases over the years due to stricter controls on noise sources other than aircraft, the aircraft noise will have to be lowered accordingly. Perhaps application of such a criterion could call for periodic

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*Ambient noise is defined as the 24 hour L_{50} level plus 0.115 times the standard deviation about this level.

updating of the ambient noise statistics and corresponding adjustments of aircraft operations and equipment use at a specific site. If the updating is held to reasonable periods, the availability of new, quieter, aircraft and equipment would presumably keep pace with the ambient noise reductions. Air service would not then be severely impacted by ambient noise reductions.

Use of the Criteria

Use of the criterion is relatively simple and is similar to current aircraft noise annoyance evaluation procedures. First, the aircraft SENEL is calculated from the measured or predicted SPL(A) time history. The values of SPL(A) used may be tone corrected depending on the specific application. All of the SENELs from all aircraft for a day or night time period are summed and combined with the ambient noise and duration data to determine the day and night noise levels. L_{DN} is then computed as the final step.

Figure 11 shows an example of the SENEL and corresponding L_{DN} computations. Four simulated noise level - time histories are shown. For Event 1, the peak noise level is 25 dB above the ambient. In this case the SENEL is the summation of energy between the points 10 dBA down from the peak (an approximation made with little error to save computation time for predicted data) and has a duration of 10 seconds. The calculated L_{DN} value for a total of 100 flights with the identical time history is 3.5 dB above the ambient level. Event 2 has the same maximum SPL(A) as the previous (and the other) events except that the ambient level is now only 10 dB below the peak. The SENEL is unchanged, however the impact of 100 flights at this level on the L_{DN} is now only 0.2 dB due to the increased ambient level. For Event 3 the ambient is only 5 dB below the peak and the duration is consequently reduced to 5 seconds (the time the signal is above the ambient). The SENEL is reduced slightly compared to the two previous cases and the L_{DN} is approximately equal to the ambient noise level. For the case of Event 4 the ambient is higher than the peak of the noise time history, the SENEL is zero, and the L_{DN} is equivalent to the ambient. A complete example showing use of the criteria is given in the Appendix.

Some comment is in order regarding the consequences of modifying the criterion to attain lower community noise exposure. It should be pointed out that there is no need seen for such modification because the criterion as constructed meets nearly all of the criteria and community annoyance studies surveyed and has an extremely high probability of community acceptance. However, if it were thought necessary to impose a restriction of L_{DN} = 60 for ambients above 60 dBA absolutely no new noise would be permitted. In fact, even the ambient would exceed the L_{DN} of 60. The establishment of aircraft (or any noise producing) facilities at high ambient locations is therefore precluded, a situation which should not be allowed to occur. A second alternate modification to the criterion is an extension of the impact to ambient type of ordinance to ambient levels below 58 dB.

Its consequence is that no reasonable aircraft (or perhaps even cars or trucks) could operate in ambient locations much below 60 dBA because the impact of a fixed SENEL would become so large that an extremely low number of events would consume the 2 dBA impact allowed. This also should not be allowed to happen, especially in view of the bulk of information (Reference 24) indicating 60 L_{DN} to be a practical lower limit.

Selection of Typical Locations and Operations for Evaluation of Baseline Helicopter Noise

Because L_{DN} is an integrated measure including effects such as ambient noise level, time of day, and number of operations, it is necessary to specify certain ground rules to be used in evaluating the acceptability of certain helicopter types and/or operations. A set of specific conditions were compiled for evaluation of helicopters in this study. These conditions were chosen with the assistance of operations analysis personnel to make them realistic in terms of required heliport (or clear zone) size and number of operations required for economic viability.

Heliport locations and pertinent information are summarized in Table VI. The first three are city type operating locations, all with ambient noise levels above 58 dBA. The number of operations are relatively high which would be expected for locations in high population areas. Night operations are limited severely as they would have to be in a real operation because of the 10 dBA penalty associated with them. The allowable footprint area of Table VI is an estimate of what could be set aside for a heliport or available for a clear (noise insensitive) area for that location and the allowable L_{DN} is from the recommended criterion level at the specified ambient. The areas are small for city center operation, but large for the case of the urban shopping center where large areas set aside for automobile parking are available. The ambient noise level for the urban residential heliport, which is less likely to be used in actual practice than the others, is well below 58 dB. The number of operations is small and is limited to daytime only. The last two locations are not takeoff/landing locations, but rather they are for flyovers of normally quiet areas at 1500 and 3000 feet altitude. The allowable footprint area is zero indicating that the L_{DN} criteria may not be exceeded at any point on the ground when the helicopter passes overhead.

CIVIL TRANSPORT HELICOPTER NOISE EVALUATION

As a first step in assessing the applicability of helicopters to the city-center short haul market, the noise characteristics of current helicopters that are likely candidates for civil transport must be determined and compared with the community noise acceptance criteria developed in the previous section. Potential candidate aircraft are those military transport helicopters of 18100 to 22700 Kg (40,000 to 50,000 pounds) gross weight capable of carrying approximately 50 people in a civil configuration. Nominal range for these aircraft is at least 371 Km (200 nautical miles). The particular aircraft in this category selected for evlauation in this study is the Marine Corps CH-53D helicopter. This aircraft, to be described in detail below, meets all of the basic size, weight, and range criteria.

Characteristics of the Basic Helicopter

Helicopter description. - The helicopter selected for evaluation as a civil transport, the CH-53D, is described in detail in Figure 12. Briefly, it is a single main rotor military transport helicopter of 16750 Kg (37,000 pounds) mission gross weight (18600 Kg (41,000 lb) maximum gross weight). It's commercial derivative, herein called the S-65-40, has a design gross weight of 18600 Kg (41,000 pounds), achieved by using uprated engines and improved rotor blades. Figure 13 shows the general arrangement of this aircraft. The S-65-40 is the baseline aircraft which will be evaluated against the developed noise acceptance criteria.

Noise prediction method. - The method used to predict the helicopter noise for typical operations is based on the procedures presented in Reference 26. The Reference 26 computer program is designed to calculate the noise from V/STOL propulsion components such as rotors, propellers, turboshaft engines,fan engines, and jets and combine them to produce a time history of the aircraft noise at an observation station on the ground for a prescribed flight profile. For the present study, a modified version of the program was used. The modified version is specialized to helicopters by including in the program only rotors and turboshaft engines as noise producing components. The purpose of this is to make the program more compact and to speed processing time.

The time history of PNLT and dBA needed to compute the EPNL and SENEL respectively is constructed at an observer location by calculating (for successive aircraft locations) the noise from each of the components, summing the components' to produce the vehicle spectrum, and then converting this spectrum to PNLT and dBA levels. The time history is then integrated over the appropriate time interval to produce the EPNL and SENEL values. Aircraft locations along the flight path are computed by a separate subroutine. The complete flight path is simplified to a series of straight line and helical segments along any one of which all operating parameters are calculated by a helicopter low speed dynamic performance program. This program has been shown to be accurate for speeds up to 77 m/sec (150 knots) by correlation with flight test data. Figure 14 shows a comparison of predicted and measured flight parameters for the CH-53D indicating the accuracy of the program.

Main rotor and tail rotor noise is calculated using the simplified approach suggested by Lowson and Ollerhead (Reference 27). In this method the loading is considered to be concentrated at an "effective" radius and the harmonics of airloading are assumed to follow a uniform exponential fall-off in amplitude based on the steady loading. This is represented as $L_\lambda \propto L_o \lambda^{-k}$ where λ is the harmonic number, L_λ is the amplitude of the λ-th harmonic, L_o is the steady load, the k determines the rate at which the loading amplitude falls off with increasing λ. The broadband portion of the spectrum is calculated using a version of the method presented by Schlegel, King and Mull in Reference 28. Figure 15 demonstrates the accuracy of the rotor noise prediction method.

The procedure for calculating turboshaft engine noise is entirely empirical. It is based on noise data for several different engines. Both sound power and directivity are accounted for in the method. A modification to the program now allows use of measured engine data when it is available in sifficient detail. For the present study the generalized procedure was found to be acceptable as shown by the Figure 17 comparison of the measured and predicted time histories of noise for the CH-53D helicopter.

Detailed descriptions of procedures used in this study can be found in Reference 26.

Basic helicopter noise characteristics. - The basic civil helicopter, the S-65-40, was acoustically evaluated for several different takeoff and landing flight profiles to establish its acoustic characteristics. Four of the takeoff profiles are shown in Figure 17 Two of them are vertical climb-outs to a pre-determined altitude and the other two are more "normal" type takeoffs. These flight profiles were approximated by a series of straight line segments in the acoustic prediction program, as discussed above. Comparisons of the actual and approximate flight profiles are shown in Figure 18.

Figures 19, 20, 21 and 22 show the calculated constant SENEL ground contours for each of the four flights. It is readily apparent that the shapes of the contours are different for each flight. This is more easily seen in the Figure 23 comparisons of the four 95 SENEL contours. The noise contours for the flights with an initial vertical climb do not extend as far down range as the more normal type takeoffs, however they do extend further to the side and rear of the takeoff point . This is to be expected because of the time integration characteristic of the SENEL. For the vertical takeoffs the helicopter spends more time in the vicinity of the origin hence the duration correction at a point near the origin will be larger than for the oblique takeoffs.

Although contour shape is important, the unit of interest in regard to the noise criteria is the total area encompassed by a specified SENEL contour. Figure 24 shows this characteristic for the four takeoffs of Figure 17. It is interesting to note that although the contours have quite different shapes, Figure 24 indicates that the total area encompassed by a given SENEL contour is about the same for all flights. Apparently, down range distance is given up for increased sideline and rearward distance in performing a vertical takeoff. Thus while total area does not change significantly with changing flight profile, it is possible to alter the shape of the noise contour on the ground to suit special conditions, such as particularly noise sensitive areas located near or under the flight path.

The same characteristic of equal contour area regardless of flight profile was found to exist for different landings. Figure 25 shows the noise contours for a typical landing. A fact to be noted is that a given SENEL contour on landing is much smaller than for takeoff, thus when takeoff and landing operations are conducted from the same direction the total ground area encompassed by a given SENEL contour is about the same as for the takeoff alone.

Noise reduction requirements. - Because the total area enclosed by a given SENEL contour is independent of the takeoff profile all comparisons with criterion requirements and all hardware changes will be evaluated with only one takeoff type, the oblique takeoff (which is a standard helicopter maneuver). Figure 26 compares the SENEL footprint area characteristic with the criteria levels developed above. It is obvious that the noise level (the SENEL) must be reduced by at least 7 dBA to meet the criterion level at location 4 (urban residential area).

Figure 27 shows the contribution of each noise producing component (main rotor, tail rotor, engines) to total noise at several observer locations. To achieve a total reduction of 7 dBA the noise of all sources must be reduced although the main rotor noise must be reduced more than the other two sources.

Cruise noise is also a potential problem because flights may be routed over residential areas at relatively low altitudes (1500 ft and up). Figure 28 shows the cruise noise characteristic on the ground for level flight at 77 m/sec (150 knots). No modifications are necessary here because the baseline aircraft already is quieter than the recommended criterion level.

Effect of impulsive noise. - Figure 29 has been prepared to demonstrate the effect impulsive noise can have on the community annoyance of helicopter noise. If severe impulsive noise were present in the sound generated by the baseline helicopter performing the oblique takeoff maneuver the SENEL footprint area characteristic would be as shown in Figure 29 assuming the 10 dBA penalty discussed previously. The footprint area for a given SENEL level increases drastically. It is quite obvious that every effort should be expended to eliminate impulsive noise.

Noise Reduction to Meet the Community Acceptance Criteria

The baseline helicopter was found (above) to require a noise level reduction of up to 7 dBA in order that it meet the recommended community acceptance criteria. Several different techniques to reduce the noise were evaluated in an effort to find the best compromise between acoustic and aerodynamic performance. The techniques included reducing main and tail rotor tip speeds, reducing blade loading, increasing rotor solidity, using advanced blade designs, and silencing engine inlet and exhaust noise.

Table VII summarizes the design parameters for the baseline CH-53D and 6 modified aircraft evaluated for their noise reduction potential. Figure 30 compares the noise footprint shapes of the modified and baseline aircraft and Figure 31 compares the noise characteristics of the modified aircraft with the recommended noise criteria and Figure 32 shows the noise reduction by octave band for Modification F. Modifications A and B do not meet the criteria at Location 4 (urban residential), but Modifications C, D, E and F meet all of the criteria. It remains to select the best aircraft from among the C,D,E, or F Modifications.

The prime considerations in selecting one or more of the modified aircraft for further study are minimizing the performance losses and minimizing the hardware changes required. Performance must be maintained to retain as much of the design range/payload as possible. By keeping hardware changes to a minimum, expensive (both in dollars and in weight) design changes can be avoided. Modifications E and F, therefore, appear to be the most promising because the changes required are minimized, especially for the main rotor, and becuase as shown in Figure 33 flight performance is degraded the least.

Of the two modified aircraft, E and F, Modification F is the most attractive because very little in the way of design changes are required. The 10% tip speed reduction required for the main and tail rotors can be accomplished by lowering the engine speed rather than by designing a new transmission. This is especially attractive because rotor speed can be increased to 100% to improve performance once the helicopter is clear of noise sensitive areas. In fact, the only hardware changes required are the addition of engine silencers and use of advanced design rotor blades.

Modification F, however, is a somewhat higher risk design than is Modification E. Tip speed reduction, engine silencing, and increased rotor solidity have all been previously verified as effective noise reduction methods (Reference 29). The noise reduction potential of the advanced design main rotor blades has been demonstrated by whirl tower and flight testing. Unfortunately, the acoustic performance predicted for the advanced design blades on the tail rotor has not yet been completely experimentally verified. Recent preliminary unpublished full scale test data, however, show promising results in this area. On the other hand, Modification E which also meets the noise criteria, will suffer a loss of payload, will require new hardware (gearbox, wider blades, hub to accept 6 blades, etc.), and long, expensive design and test programs to substantiate the new hardware and receive FAA certification.

HARDWARE TESTS REQUIRED

The previous section described two modified aircraft that meet the requirements of the community noise acceptance criteria and potentially result in the least performance degradation. In order to develop the noise reduction concepts into flight worthy hardware a series of ground and flight tests must be performed for each item in addition to detailed structural and dynamic analyses. In particular, the Modification F tail rotor design must be both acoustically and aerodynamically substantiated.

The required engine noise reductions must be achieved through use of acoustically treated inlet and exhaust ducts. The technology necessary to design inlet noise suppression is available from NASA sponsored studies of acoustically treated nacelles for turbofan engines and there is some information available on design of exhaust noise treatments. However, work must be done to adapt this technology to turboshaft engines and methods of incorporating anti-icing into the design must be developed. A preliminary study by the authors indicates that the necessary noise reduction can be achieved within the current duct outer envelope.

Most of the work necessary to incorporate the advanced design main rotor blades on the aircraft has already been completed and the acoustic performance measured. Acoustic substantiation of the blades on the aircraft remains to be completed. Analyses must be performed, however, to determine dynamic stability at the reduced operating speed.

The tail rotor is the one piece of hardware requiring the most extensive analysis and testing. The Modification E design with more blades, wider chord, and substantially reduced tip speed must be analyzed and then tested (static and flight) to be sure of dynamic stability in all flight regimes. A new gearbox must be designed and tested. The Modification F design incorporating advanced design blades and blade tips must be acoustically as well as dynamically substantiated.

Gearbox noise has not been discussed in this report because it is of secondary importance compared with the engines and rotors. There is the possibility, however, that if gearbox noise is found to be a problem as other sources of noise are suppressed it can be dealt with in a straightforward manner.

CONCLUSIONS

The following conclusions result from the current study:

Noise Acceptance Criteria

1. The recommended noise acceptance criteria (based on the L_{DN} level of 60) are conservative from the community's point of view. They are well below the average of Federal (domestic and foreign) guidelines and slightly below the average of current state and local noise limits. They are also in line with EPA findings regarding community annoyance.

2. The recommended criteria are fair to the community as well as the helicopter operator. Criteria levels were selected to be within the "completely acceptable" range of community reaction to noise but at the same time this study showed that current generation aircraft, with some modifications, can be made acceptable for typical commercial transport operations.

3. The recommended criteria are not unduly restrictive to the commercial transport operator. Because of the nature of the criteria he has the ability to vary scheduling, aircraft type, flight profiles, takeoff and landing routes, and even the heliport location in order to design an operation that is acceptable both to the community and to himself.

4. The recommended criteria are preferable to other aircraft noise annoyance criteria because they consider the <u>total</u> noise load on a community. As such, all noises including ambient are accounted for in the calculated annoyance level, the L_{DN}. Other measures are designed for aircraft only, or for traffic only, etc.

5. Use of the criteria encourages de-escalation of aircraft noise in the future. Aircraft noise will automatically be de-escalated as other sources contributing to certain ambients are reduced. This occurs because the criterion level for a given area is a direct function of the local ambient down to a "floor" level of $L_{DN} = 60$.

6. Although very limited results are available, impulsive noise greatly increases perceived annoyance in a community. It appears that a penalty of 5 to 10 dBA should be added to the measured (or computed) Single Event Noise Exposure Level (SENEL) for an aircraft producing impulsive noise.

7. Tone corrections, as they are calculated for Tone Corrected Perceived Noise Level, should be applied to the A-weighted sound level (dBA), but only for tones above 500 Hz for helicopters and propeller driven aircraft.

Civil Helicopter Operations

A current generation 50 passenger helicopter, derived from a single main rotor military transport helicopter in the 18100 to 22700 Kg (40,000 to 50,000 pound) weight class was evaluated to determine those hardware changes necessary for it to meet the recommended community acceptance criteria:

1. The basic helicopter in the civil transport configuration meets the cruise noise criteria with no changes.

2. The basic civil helicopter meets all of the criteria with little modification. Main rotor changes involve use of advanced design blades and a 10% tip speed reduction, the tail rotor incorporates a 10% tip speed reduction and use of advanced design blades, and the engines require a small amount of inlet and exhaust noise silencing.

3. The modified aircraft suffers little degradation of performance. Additional weight added for engine silencing is less than 100 pounds, there is no loss of engine performance, and takeoff performance is virtually unchanged. Detailed studies are necessary to define actual performance and to determine any possible stability or other problems.

4. By paying careful attention to detail rotor and blade design and to engine selection and installation details it is possible to design a 100 passenger civil transport helicopter (or compound helicopter) for the 1980-85 time frame that will meet the noise acceptance criteria as well as reasonable performance objectives.

RECOMMENDATIONS

1. Subjective testing should be carried out to determine the annoyance penalty for the presence of impulsive noise. At the same time a method should be established to quantitatively define the existance of impulsive noise and to indicate its severity. The crest factor of the sound (Peak Level/RMS Level in dB) has shown some promise as the required impulsive noise measure. The subjective testing should include impulsive noise "severity" as well as peak amplitude as a parameter.

2. Further community subjective studies should be conducted to verify the absolute lower limit of 60 L_{DN} for areas with ambient levels below 58 dBA.

3. Additional psycho-acoustic testing should be carried out to verify the application of tone corrections to the A-weighted sound level (dBA) and to verify that only tones above 500 Hz should be included in the calculation of tone corrected dBA (dBA_t) for helicopters and propeller aircraft.

4. The indicated helicopter component tests should be conducted to verify the predicted noise reduction and to establish aerodynamic performance.

5. The basic helicopter should be modified to the recommended configuration and flight tested to verify the predicted noise levels and aerodynamic performance.

6. Using advanced design concepts for the main and tail rotors, auxiliary propulsion (if any), and engine installation a 1980-85 time frame 100 passenger civil transport helicopter should be designed to meet the recommended noise criteria as well as reasonable performance goals.

Sikorsky Aircraft,
United Aircraft Corporation
Stratford, Connecticut, February 27, 1974.

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TABLE I

FREQUENCY WEIGHTED TERMS USED TO DEFINE
JUDGED ANNOYANCE OR LOUDNESS

Symbol	Definition	Unit	
L	Overall Sound Pressure	dB	Unweighted
L_A	"A" Weighted SPL	dB	Standard Sound Level Meter
L_B	"B" Weighted SPL	dB	Standard Sound Level Meter
L_C	"C" Weighted SPL	dB	Standard Sound Level Meter
L_N	"N" Weighted SPL	dB	Inverse of 40 Noy Contour
L_{NN}	"NN" Weighted SPL	dB	Emphasis in 4000 Hz Range
LL_S	Stevens' Loudness Level	Phon	Some curves
LL_Z	Zwicker's Loudness Level	Phon	Some curves
PNL	Perceived Noise Level	PNdB	Noy curves
PNL_T	Tone Corrected PNL	PNdB	Noy curves
SIL	Speech Interference Level	dB	Average of 500, 1000, 2000 Hz Octaves
NC	Noise Criterion Level	dB	Matching of Spectrum to NC Curves

TABLE II

SIMILARITY OF SPL(A) AND PNL UNIT ACCURACY FOR ASSESSING NOISE SPECTRUM ANNOYANCE

Investigator	Reference	Standard Deviation		Correlation Coefficient	
		SPL(A)	PNL	SPL(A)	PNL
Adcock/Ollerhead	8	2.474	2.590	.957	.966
Ollerhead	1	3.9	3.9	.881	.905
Ollerhead	3	3.48	3.32	.967	.880
Kryter	9	4.87	3.99		
Pearsons	5	1.5	1.5		
Sternfeld et al	7			.934	.945

TABLE III

CONVERSION OF FEDERAL NOISE CRITERIA UNITS TO L_A

Symbol	Name	Unit	Origin - Used For	Relation to L_A
CNR	Composite Noise Rating	PNdB	U. S. - Aircraft	$L_A + 1$
NEF	Noise Exposure Forecast	PNdB	U. S. Aircraft	$L_A -69$
N	Isopheric Index	PNdB	France - Aircraft	$L_A -17$
$\overline{Q}$	Mean Annoyance Level	dBA	Germany - Aircraft	$L_A -39.3$
$\overline{NI}$	Noisiness Index	dBA	South Africa - Aircraft	$L_A -39.4$
NNI	Noise and Number Index	PNdB	England - Aircraft	$L_A -67$
L_{dn}	Day-Night Noise Level	dBA	U. S. - All	$L_A -34$
CNEL	Community Noise Exposure Level	dBA	California - Aircraft	$L_A -34$
	HUD Guidelines-Non Aircraft	PNdB	U. S. - All	$L_A -69$
	HUD Traffic Nose Criteria	dBA	U. S. Traffic	$L_A -42$

TABLE IV

MEASURED COMMUNITY NOISE LEVELS

	L_{50}		L_{90}	
City Center	73.0	65.5	69.1	60.8
Suburban Residential	50.9	44.2	45.6	39.8

TABLE V

DATA USED IN PREPARING BLADE SLAP CREST FACTOR INFORMATION

Aircraft	Flt. Condition	Subjective Blade Slap		Overall SPL		Crest Factor
		Yes	No	Peak	True RMS	
S-61N	Landing		X	118	110	10
V-107	Landing	X		128.5	115.5	13
CH-53D (Tail Rotor Downwind)	Hover		X	111	99	12
CH-53D (Tail Rotor Upwind)	Hover	X		131	114	17
Bell AH-1G	60 Knot Cruise		X	111	102	9
Bell AH-1G	140 Knot Cruise	X		125	106	19
S-67	80 Knot Cruise		X	107	97	10
S-67	200 Knot Dive	X		129	110	19
S-61F(aux jet propulsion)	165 Knot Cruise		X	117	104	13

TABLE VI

RECOMMENDED CIVIL HELICOPTER OPERATIONS FOR
DETERMINING AIRCRAFT COMPLIANCE WITH NOISE CRITERIA

Location	Local Ambient[1] dBA	Number of Operations[2]		Equivalent[3] Daytime Operations	Allowable L_{DN}/ Footprint Area dBA/Acres
		Daytime	Nighttime		
1. City center near highways, river, docks, etc.	80	64	2	84	82/2
2. City center near business district	75	64	2	84	77/2
3. Urban shopping center	65	36	0	36	67/15
4. Urban residential	50	18	0	18	60/5
5. Flyover of small town residential at 1500 ft.	45	32	1	42	60/0
6. Flyover of small town residential at 3000 ft.	45	32	1	42	60/0

Notes:

1. Local ambient is defined here as the L_{50} level; that is, the level exceeded 50% of the time.

2. Daytime = 0700 hrs to 2300 hrs
   Nighttime = 2300 hrs to 0700 hrs

   An operation consists of a takeoff and a landing. Thus the total L_{DN} at a point includes the noise from takeoff and from landings. (For example, if landings are from the West and takeoffs are toward the West, a point under the flight path is exposed to twice as many operations than if the takeoff were toward the East.)

3. A single nighttime event is equivalent to 10 daytime events.

TABLE VII

SUMMARY OF AIRCRAFT HARDWARE CHANGES EVALUATED

	CH-53D Baseline	A	B	C	D	E	F
Main Rotor							
Number of Blades	6	7	7	7	7	6	6
Radius (ft)	36	36	36	36	36	36	36
Chord (in.)	26	35	35	35	35	29	29
Tip Speed (%)	100	85	85	85	90	90	90
Twist	-6°	-6°	-6°	-14°	-14°	-14°	-14°
Airfoil	NACA-0011m	NACA-0011m	NACA-0011m	SC-1095	SC-1095	SC-1095	SC-1095
Tip	Square	Square	Square	Trap	Trap	Trap	Trap
Tail Rotor							
Number of Blades	4	6	6	6	6	6	4
Radius (ft)	8	8	8	8	8	8	8
Chord (in.)	15.4	20	20	20	20	20	15.4
Tip Speed (%)	100	70	70	70	70	70	90
Twist	-8	-8	-8	-8	-8	-8	-17
Airfoil	NACA-0011m	NACA-0011m	NACA-0011m	NACA-0011m	NACA-0011m	NACA-0011m	SC-1095
Tip	Square	Square	Square	Square	Square	Square	Trap
Engine							
Noise Suppression (db)	0	2.5	5.5	5.5	4.4	4.4	4.4

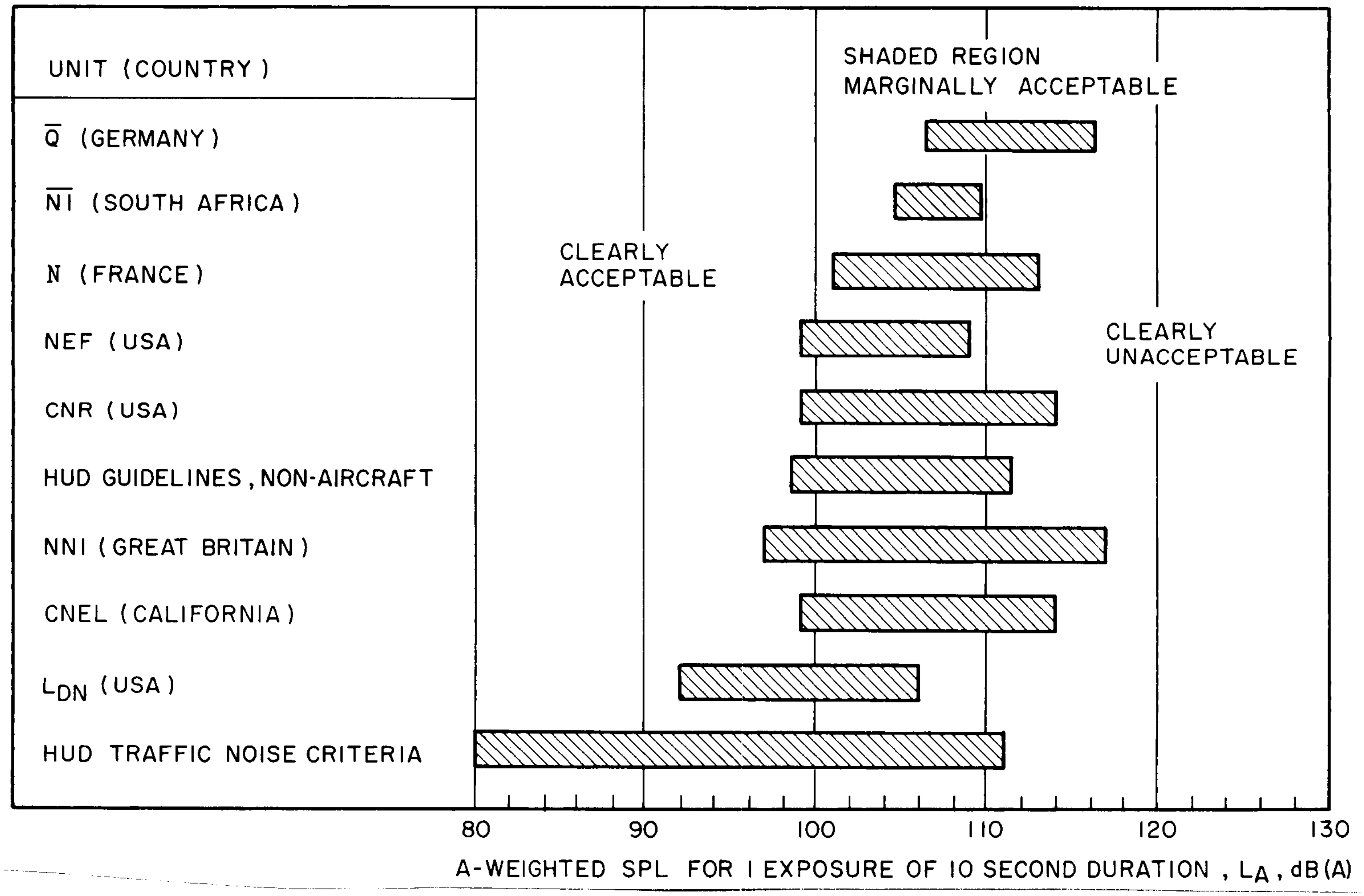


Figure 1. Comparison of Domestic and Foreign Federal Community Acceptance Noise Guidelines.

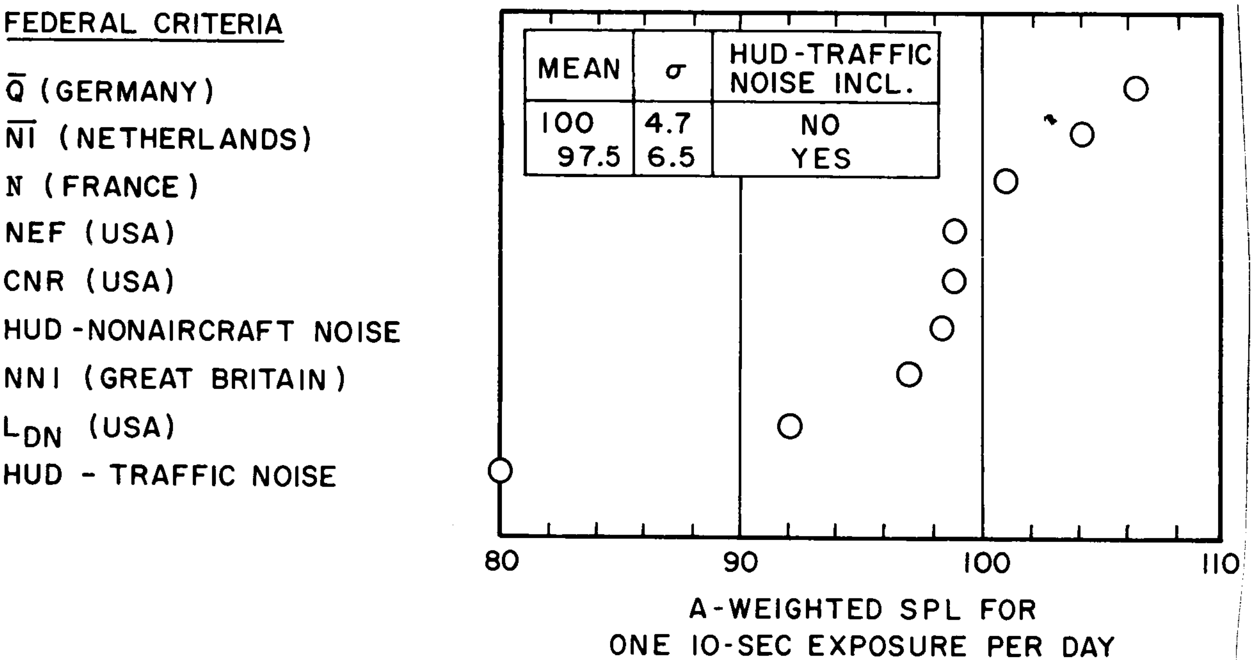


Figure 2. Comparison of Clearly Acceptable Limits of Federal Regulations.

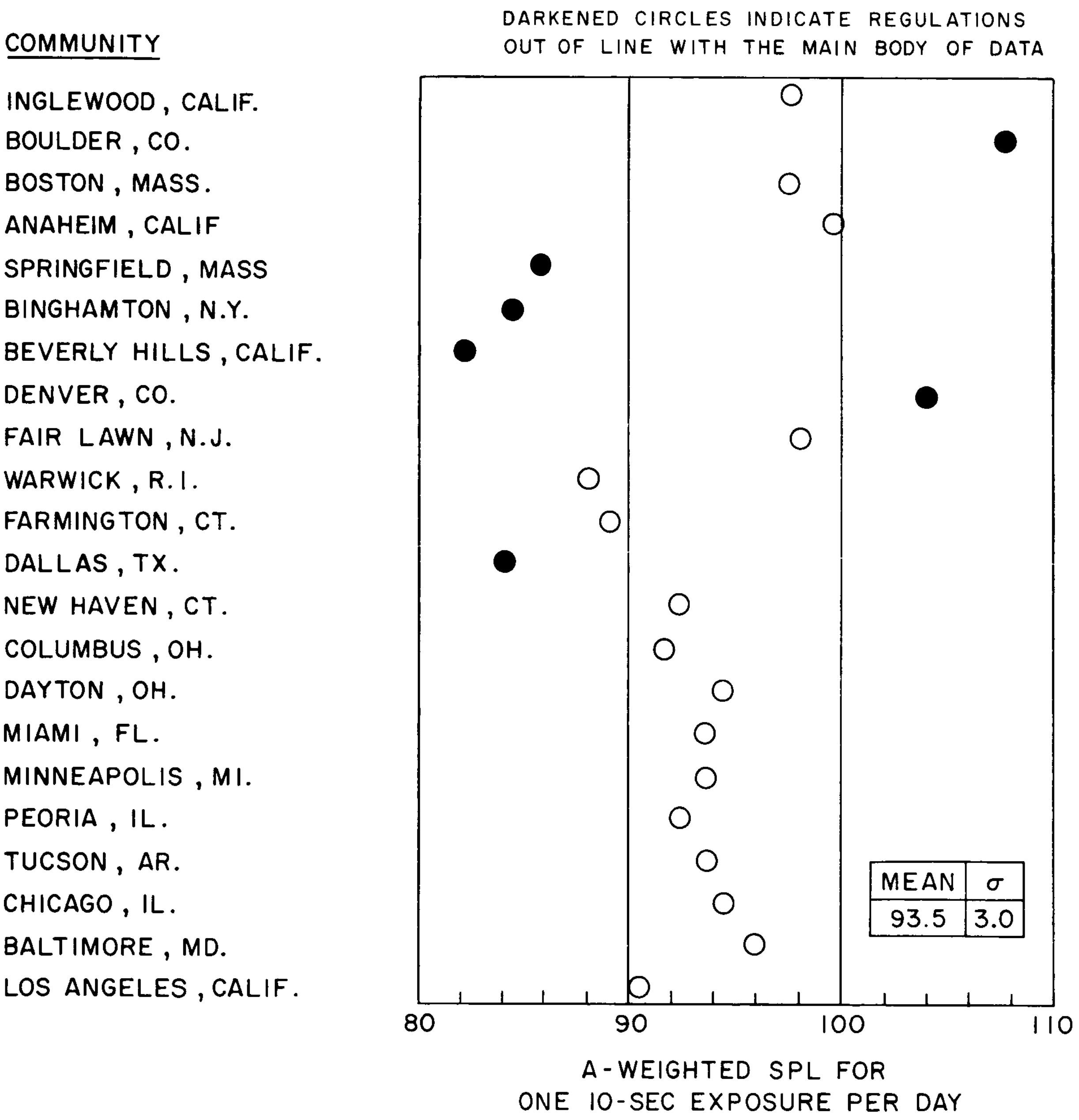
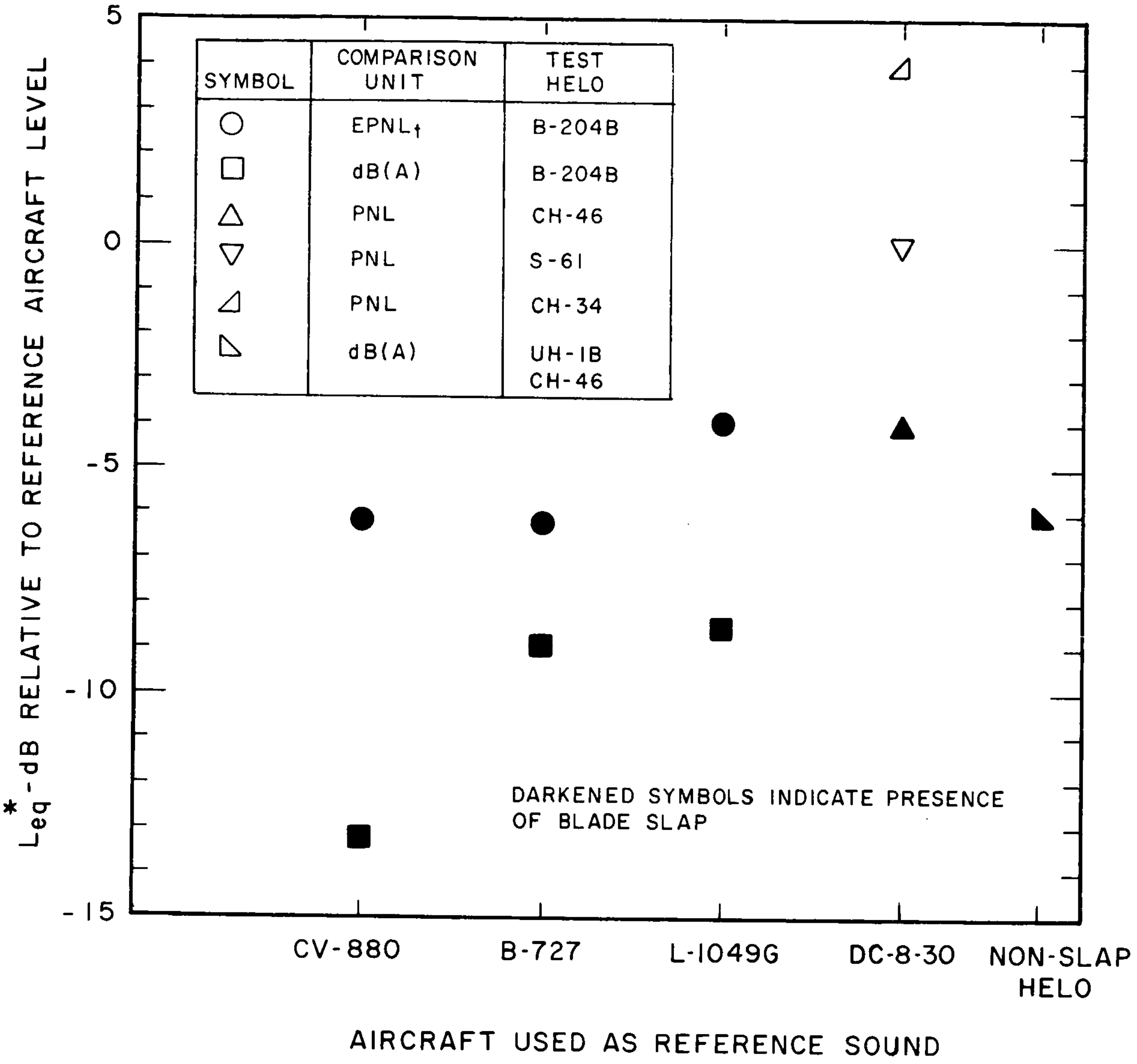


Figure 3. Comparison of Residential Community Noise Regulations.



* L_{eq} IS TEST HELICOPTER LEVEL AT WHICH IT IS JUDGED TO BE AS ANNOYING AS THE REFERENCE SOUND

Figure 4. Effect of Blade Slap on Judged Annoyance of Helicopters.

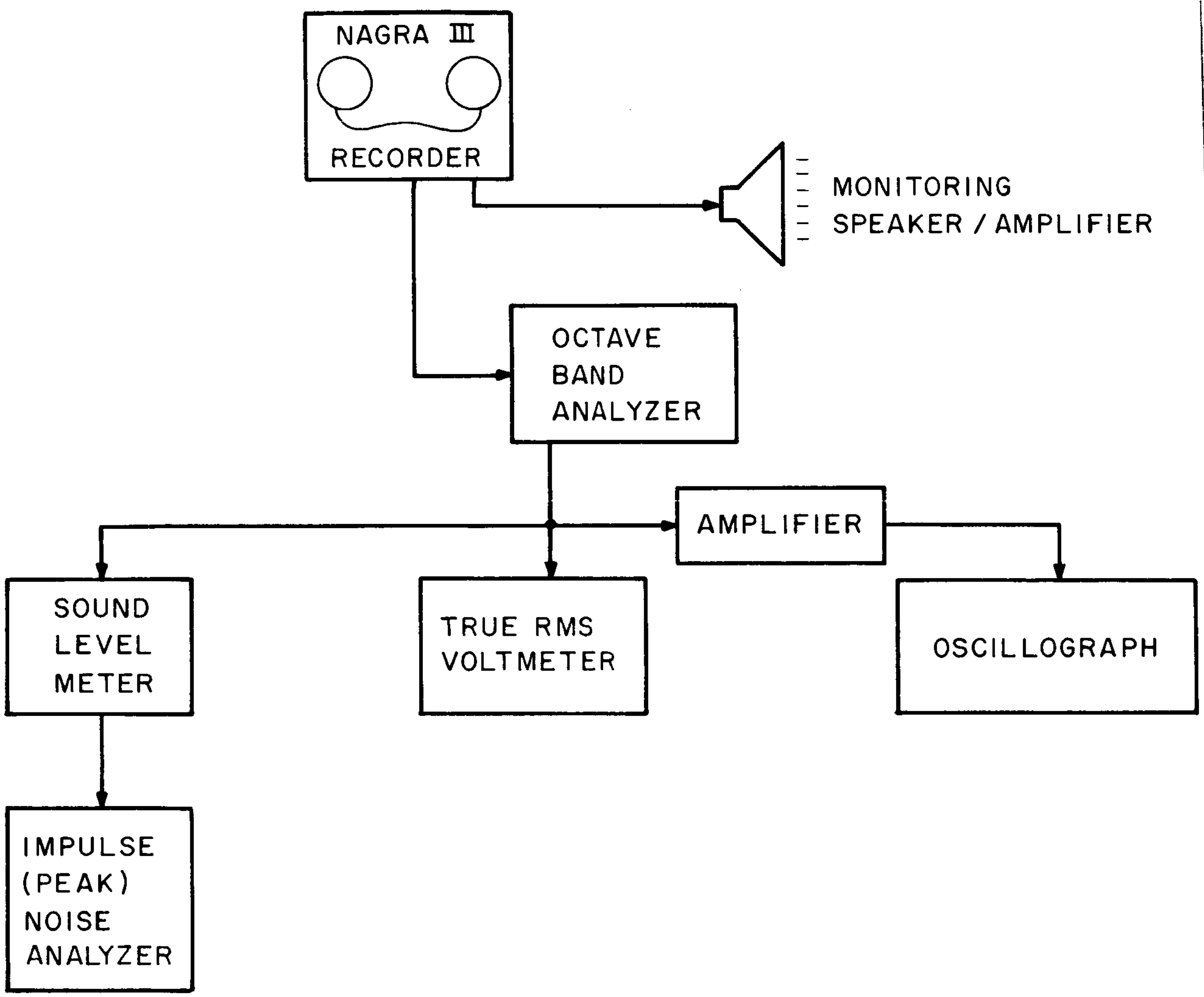


Figure 5. Instrumentation Used in the Investigation of Impulsive Noise Annoyance.

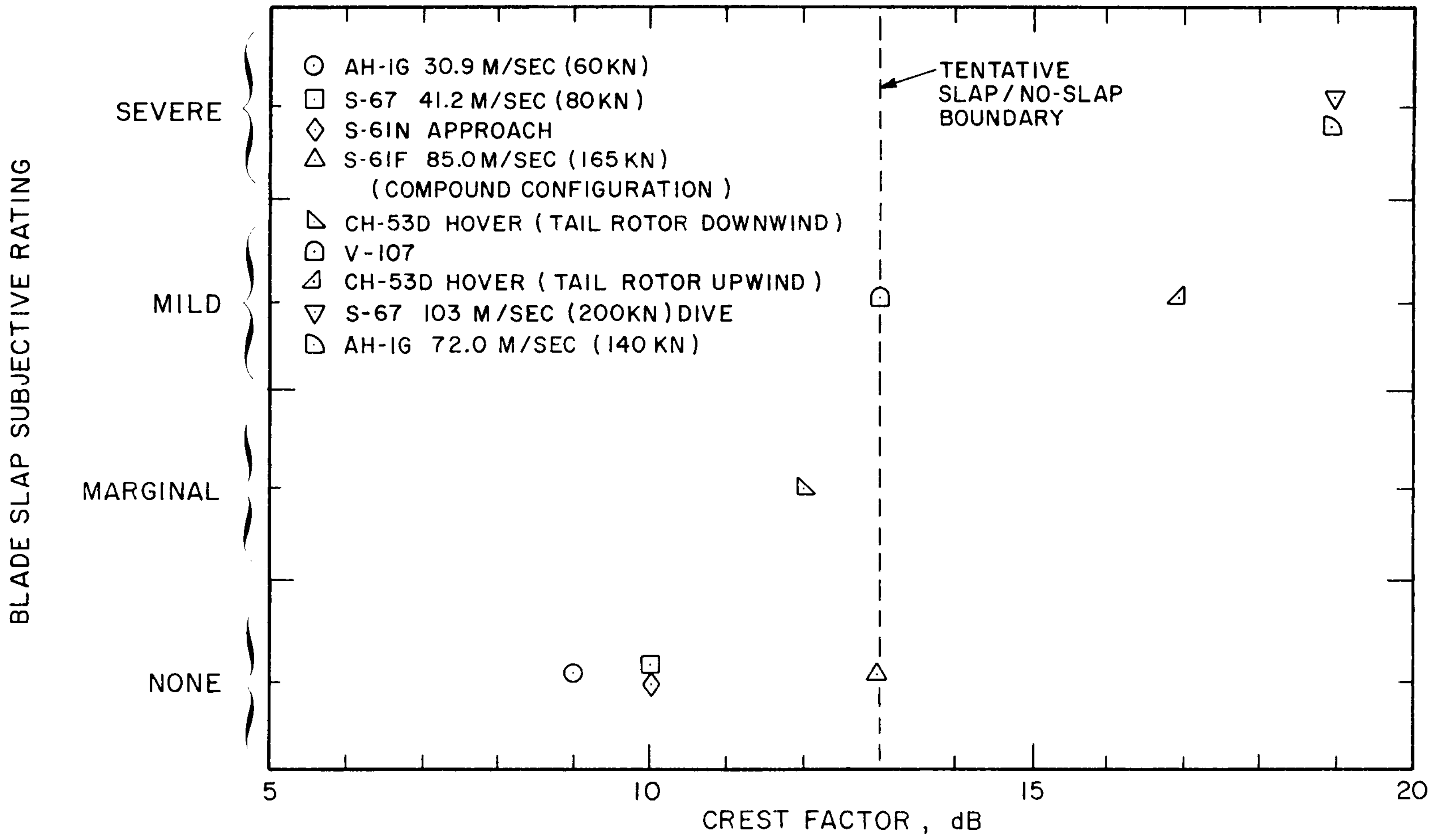


Figure 6. Blade Slap Annoyance as a Function of Signal Crest Factor.

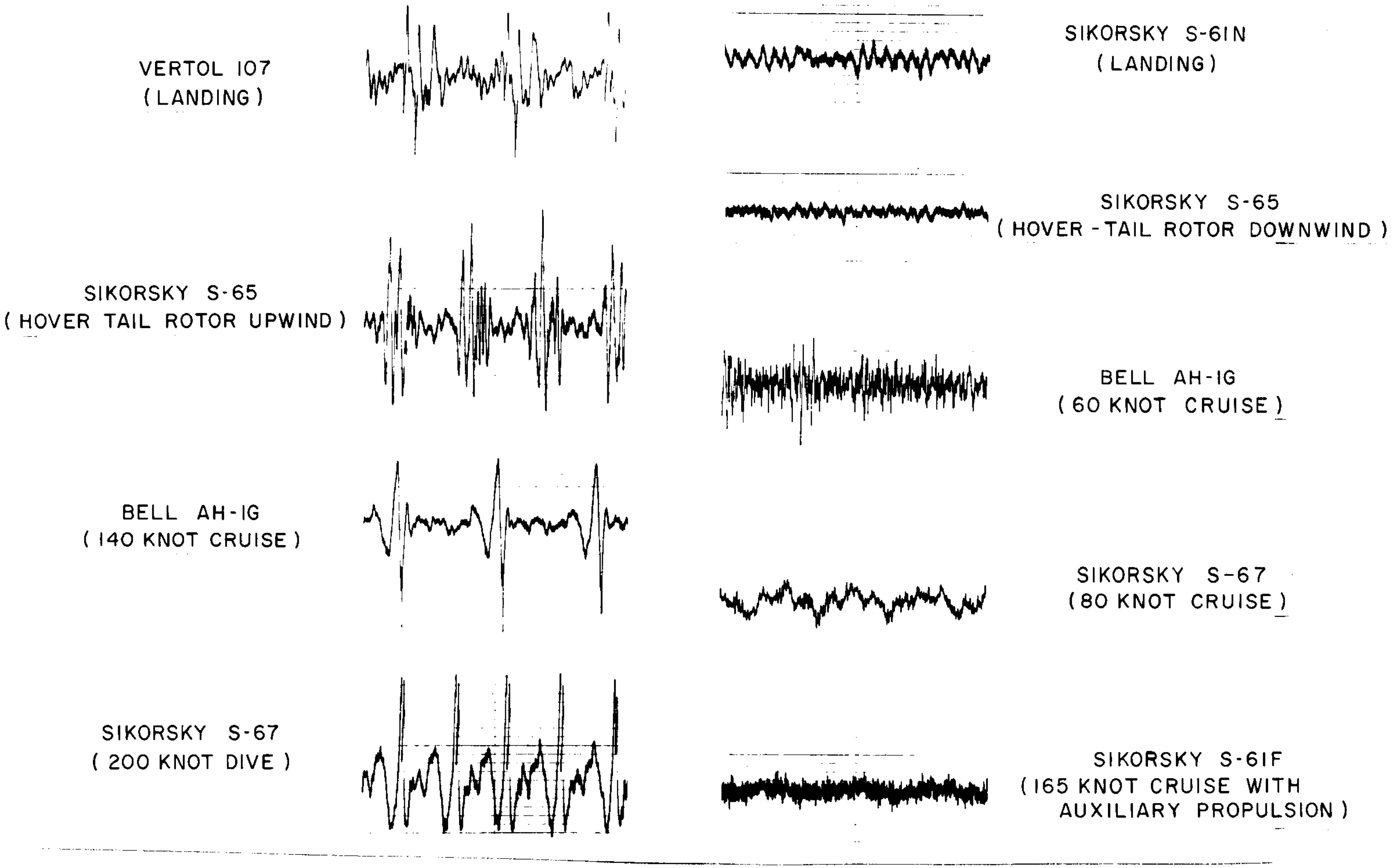


Figure 7. Oscillograph Traces of Helicopter Sounds Used in Impulsive Noise Test.

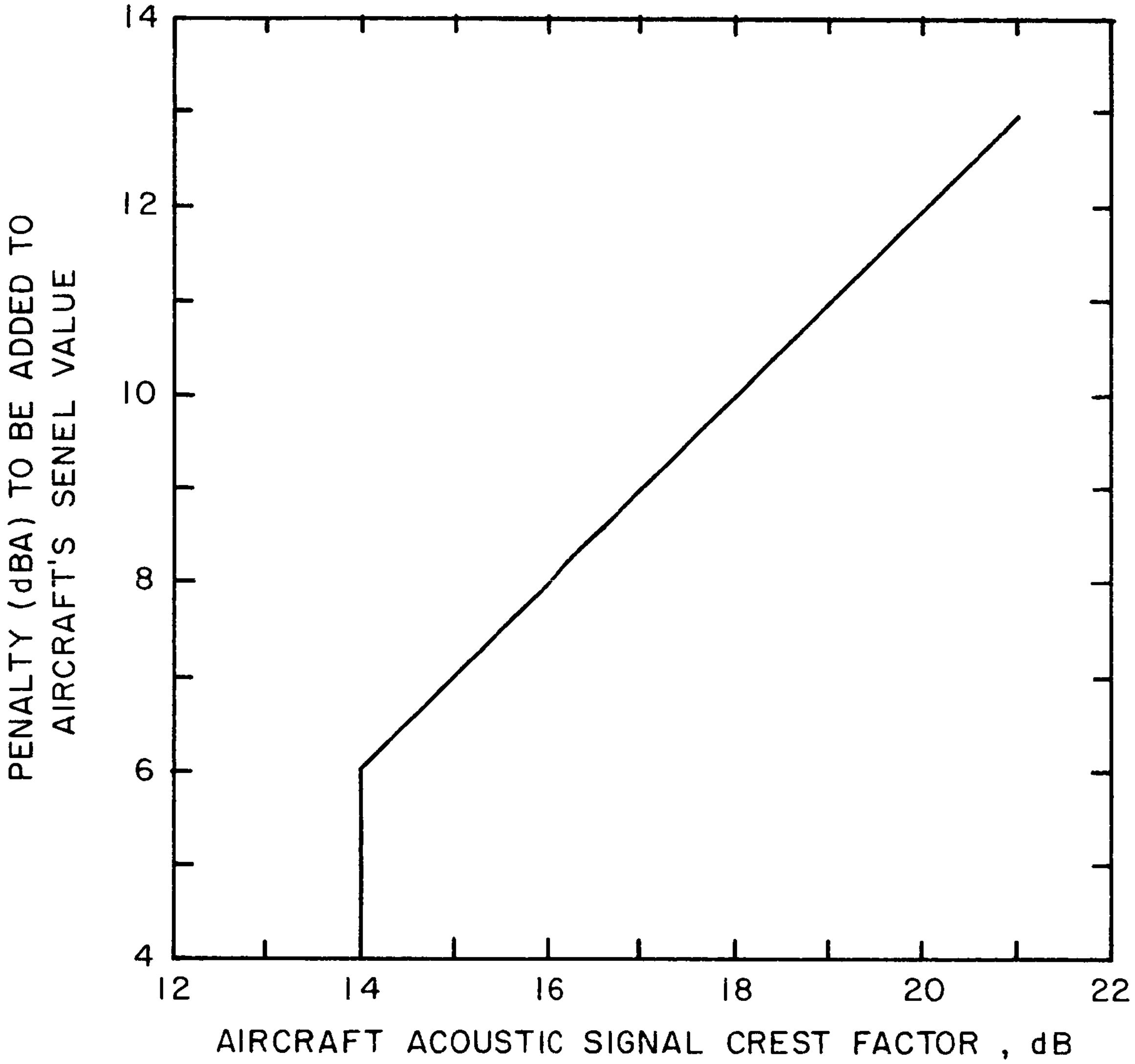


Figure 8. Possible Preliminary Impulse Noise Annoyance Penalty Criterion.

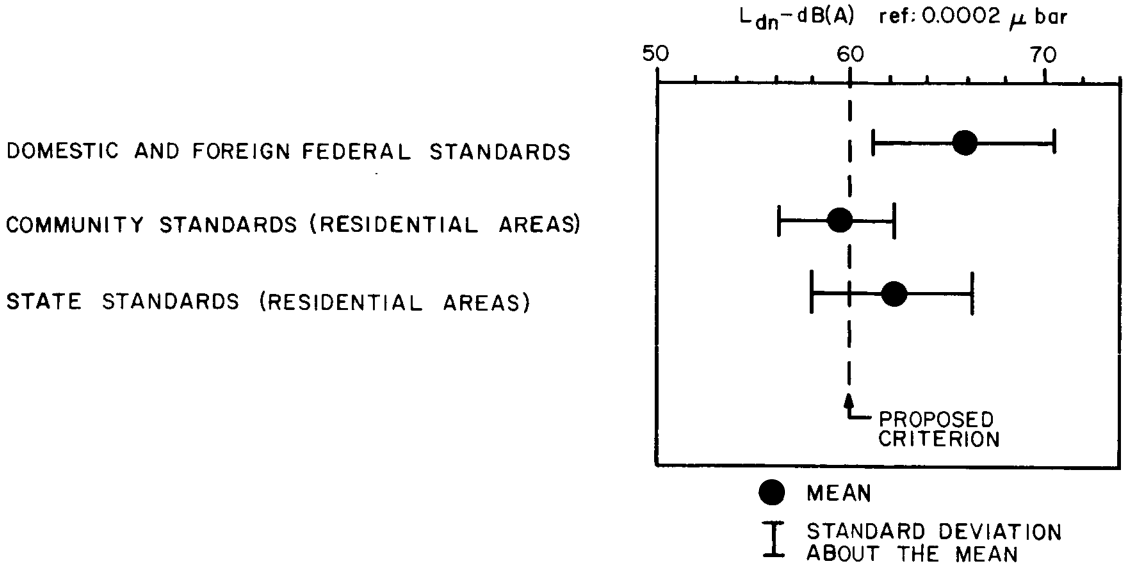


Figure 9. Comparison of Federal, Community, and State Noise Regulations and Guidelines with the Proposed Community Acceptance Criterion.

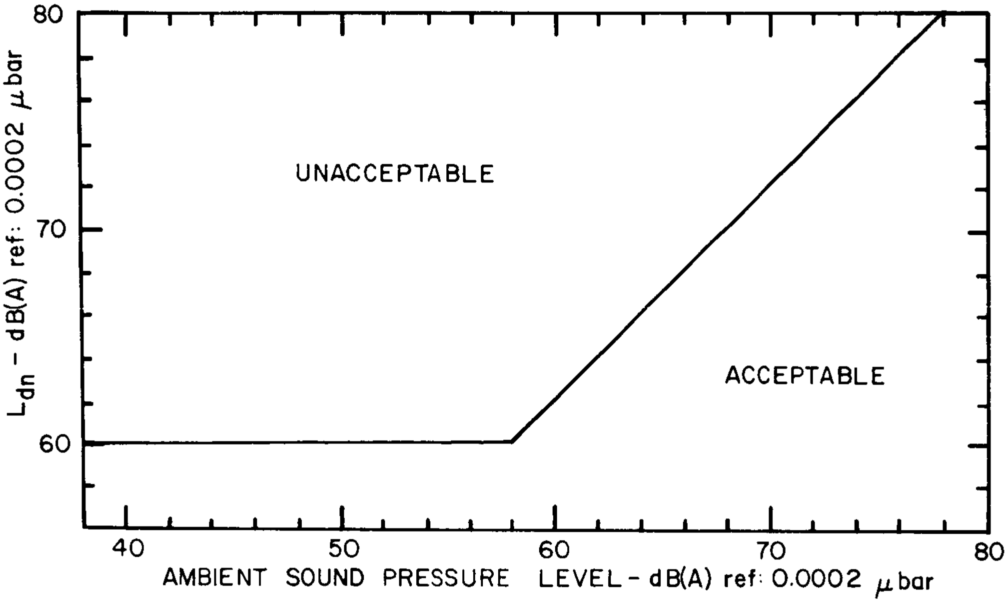
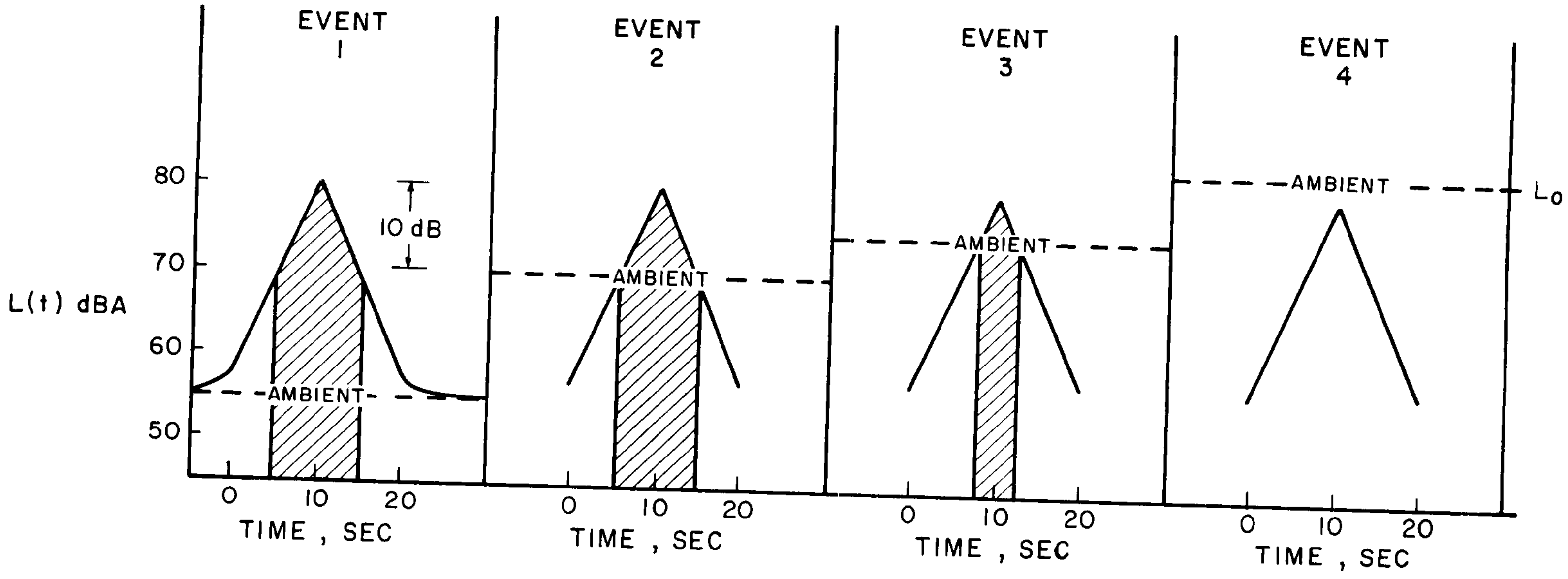


Figure 10. Recommended Community Noise Acceptance Criteria.



DURATION (SEC)	10	10	5	0
SENEL (dB)	85.2	85.2	84.2	0
L_o (AMBIENT dB)	55	70	75	83
L_{DN}^* (dB)	58.5	70.2	75	83

* FOR 100 SIMILAR EVENTS

Figure 11. Effect of Ambient Noise on the Calculated L_{DN} for a Given Aircraft Noise Signature.

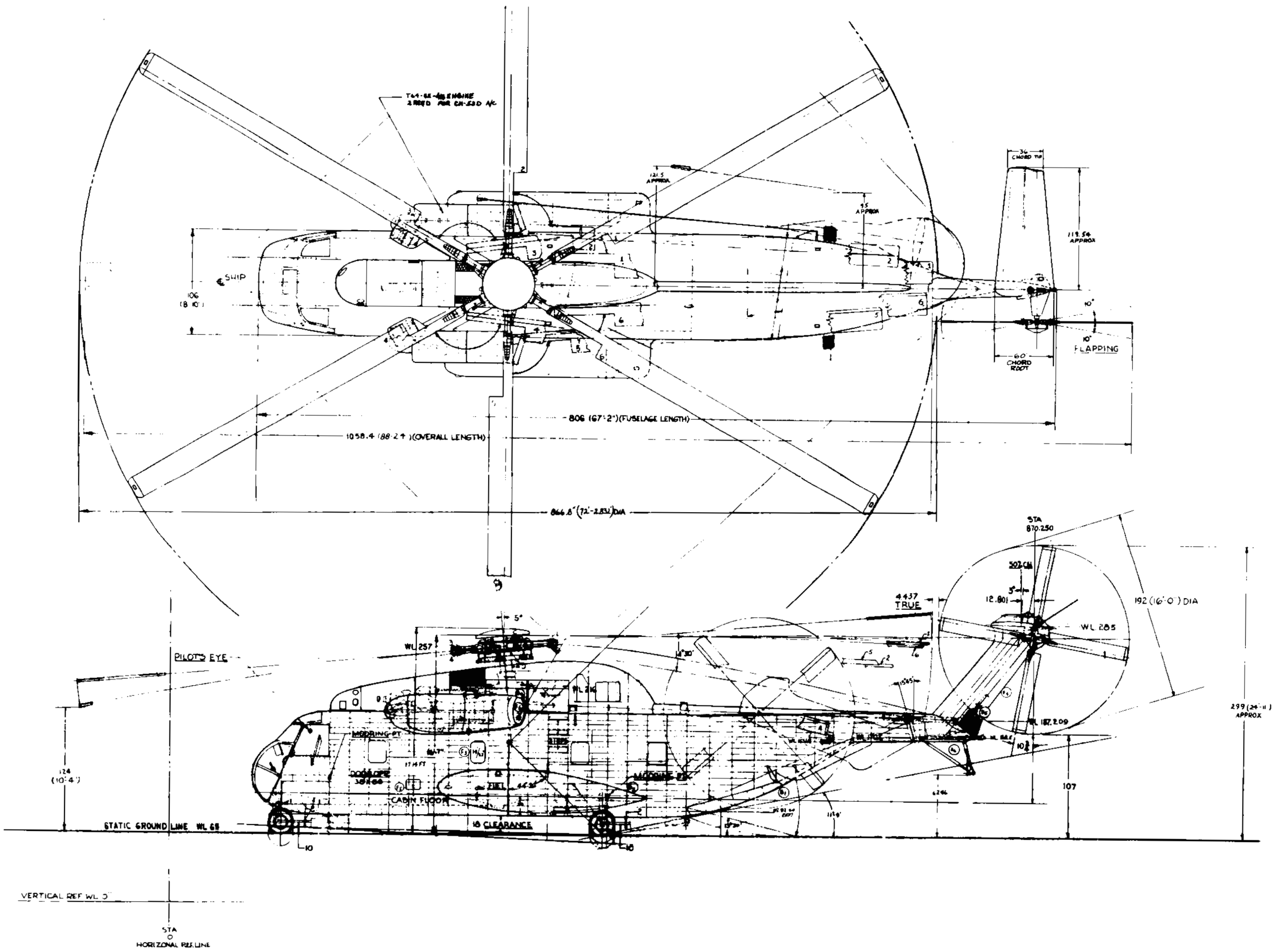


Figure 12. CH-53D Helicopter Description.

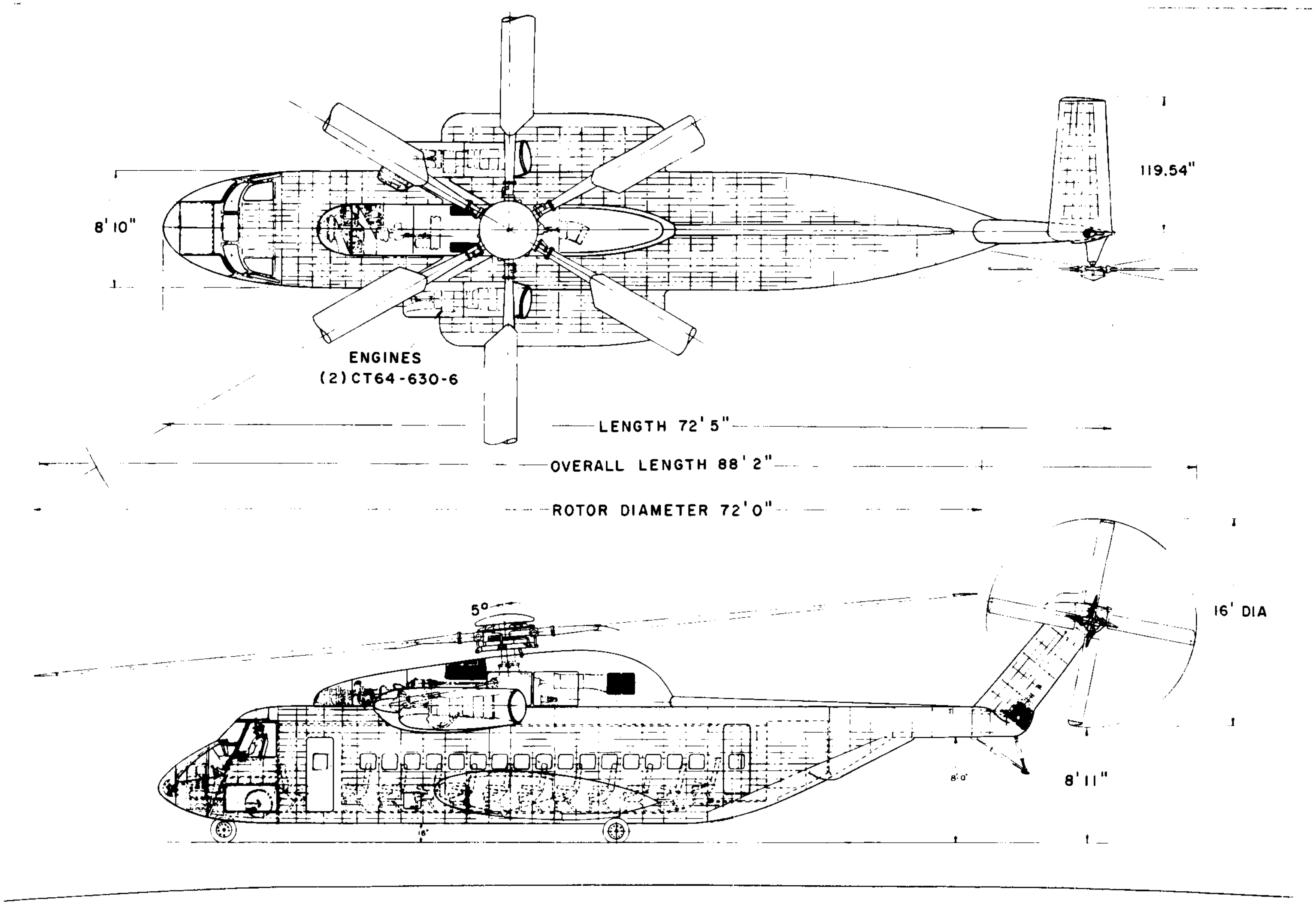


Figure 13. S-65-40 Commercial Transport Helicopter.

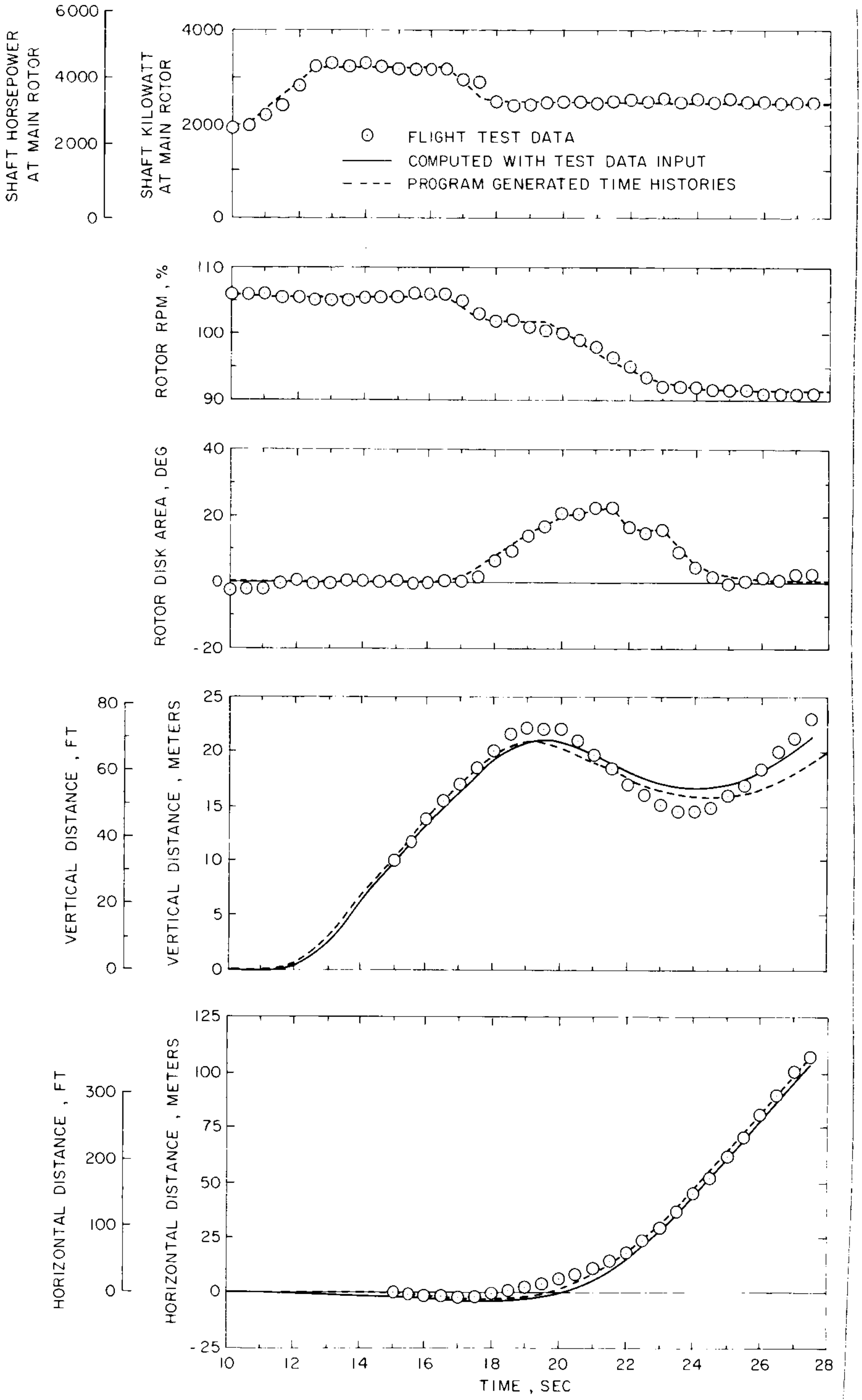
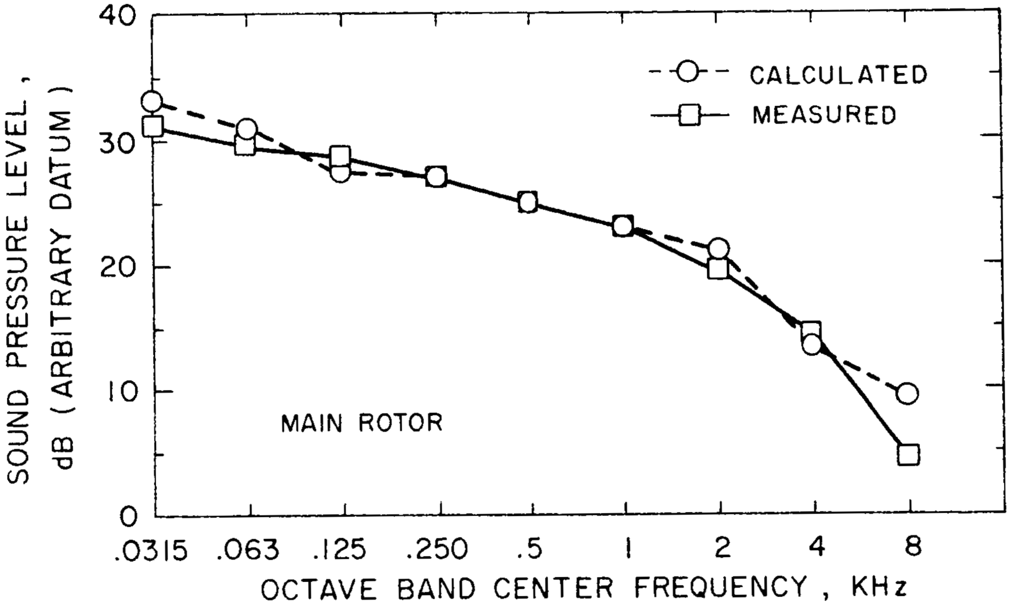


Figure 14. Typical Correlation of Predicted and Measured H-53 Helicopter Performance.



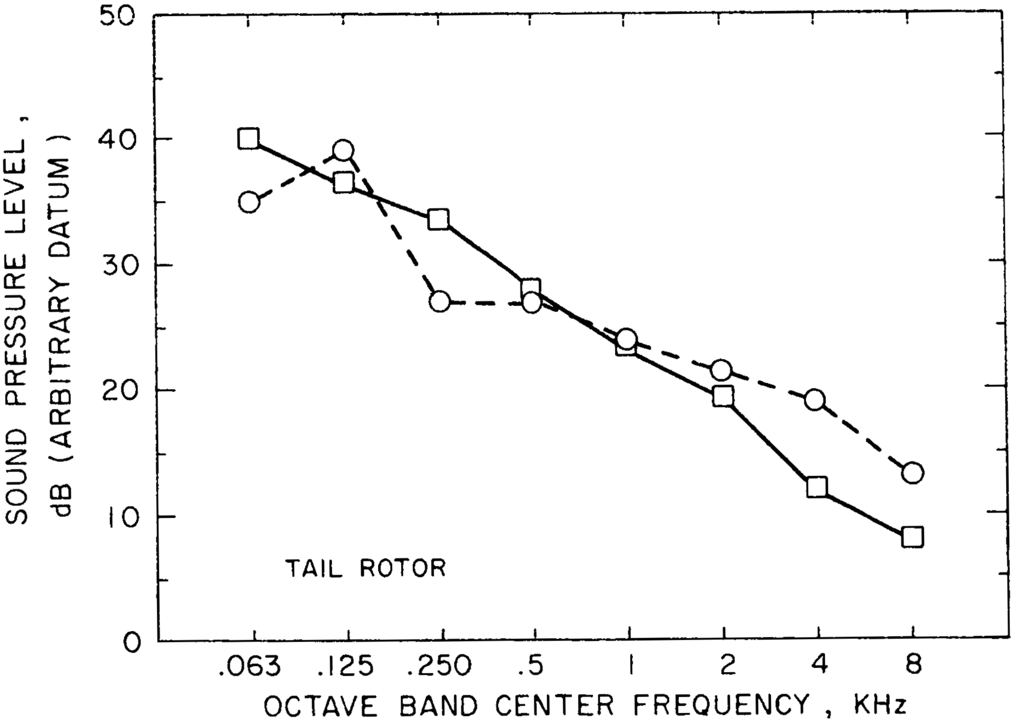


Figure 15. Comparison of Measured and Predicted Rotor Noise.

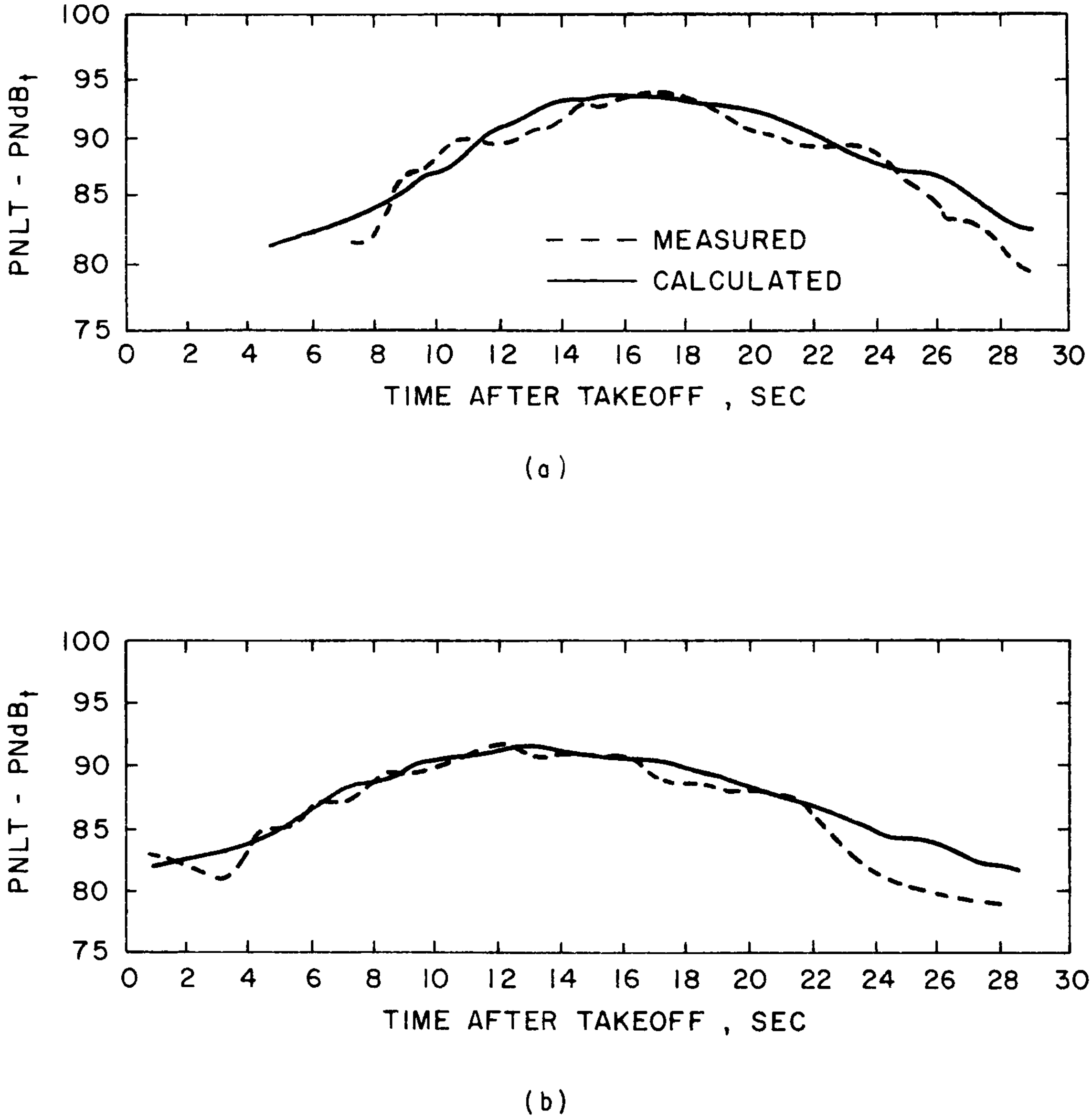


Figure 16. Comparison of Calculated and Measured PNLT Time History for the CH-53D Helicopter.

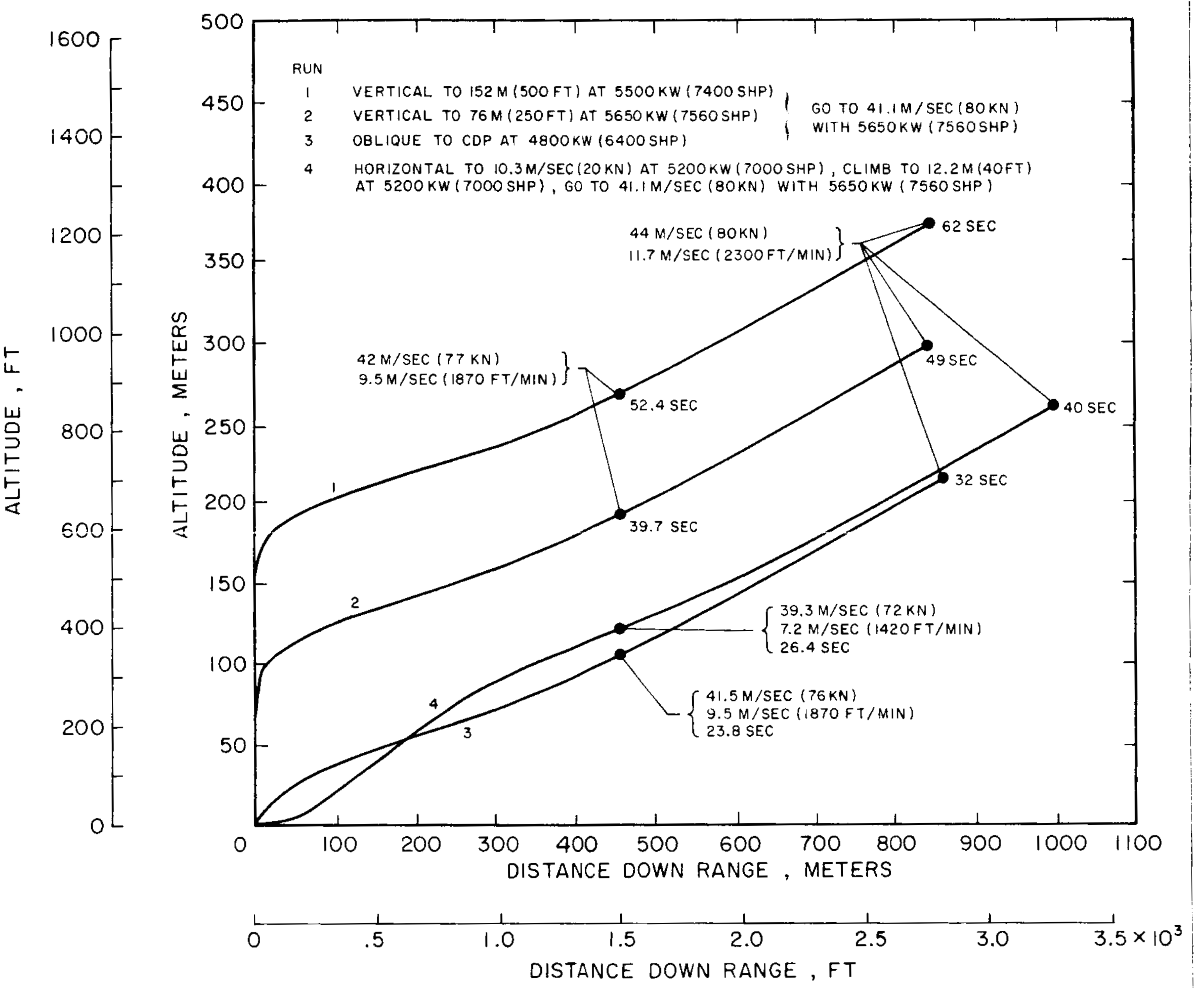


Figure 17. Four Takeoff Profiles for the S-65-40 Helicopter Used for Noise Evaluation.

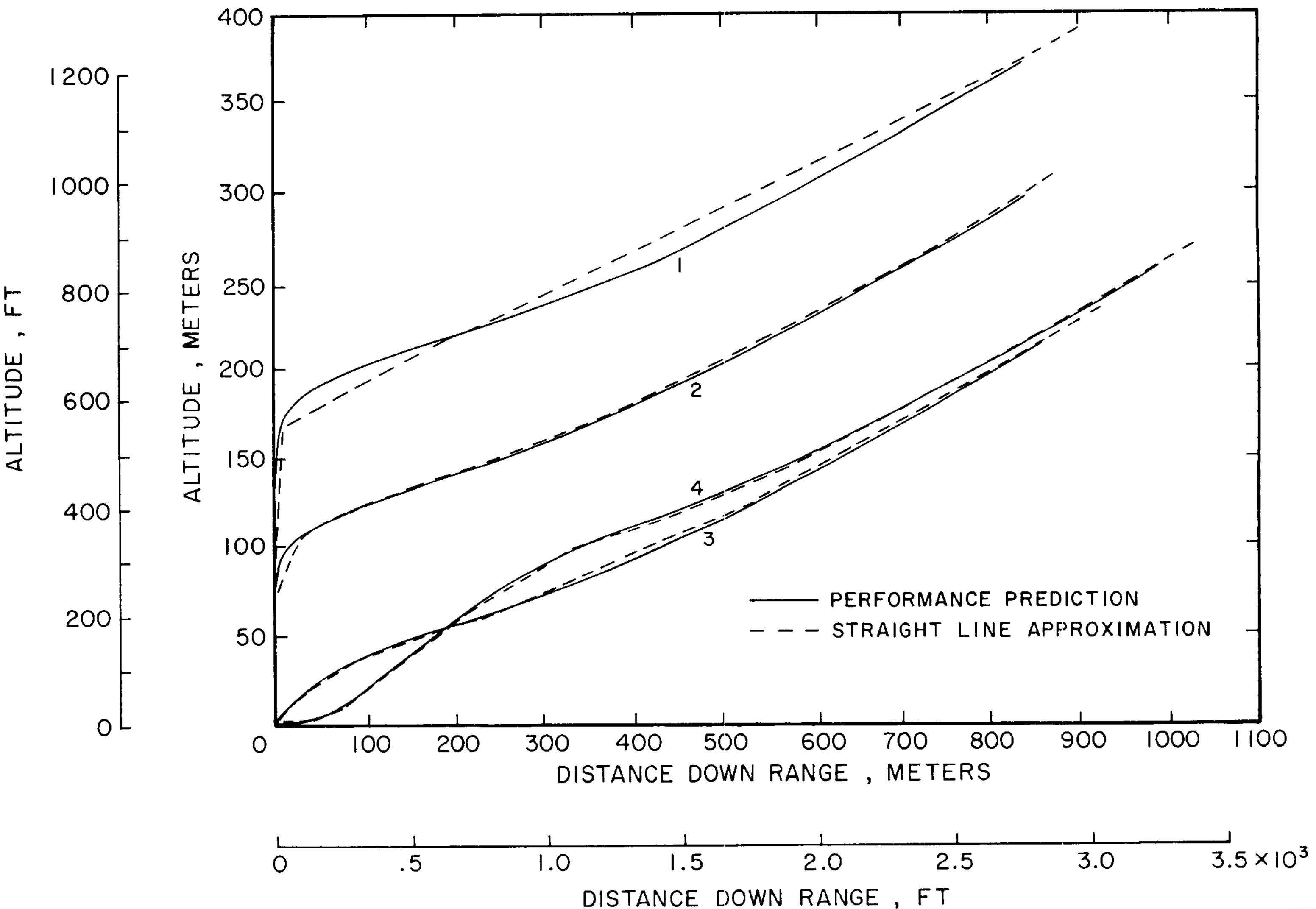


Figure 18. Comparison of Actual and Approximate Flight Profiles.

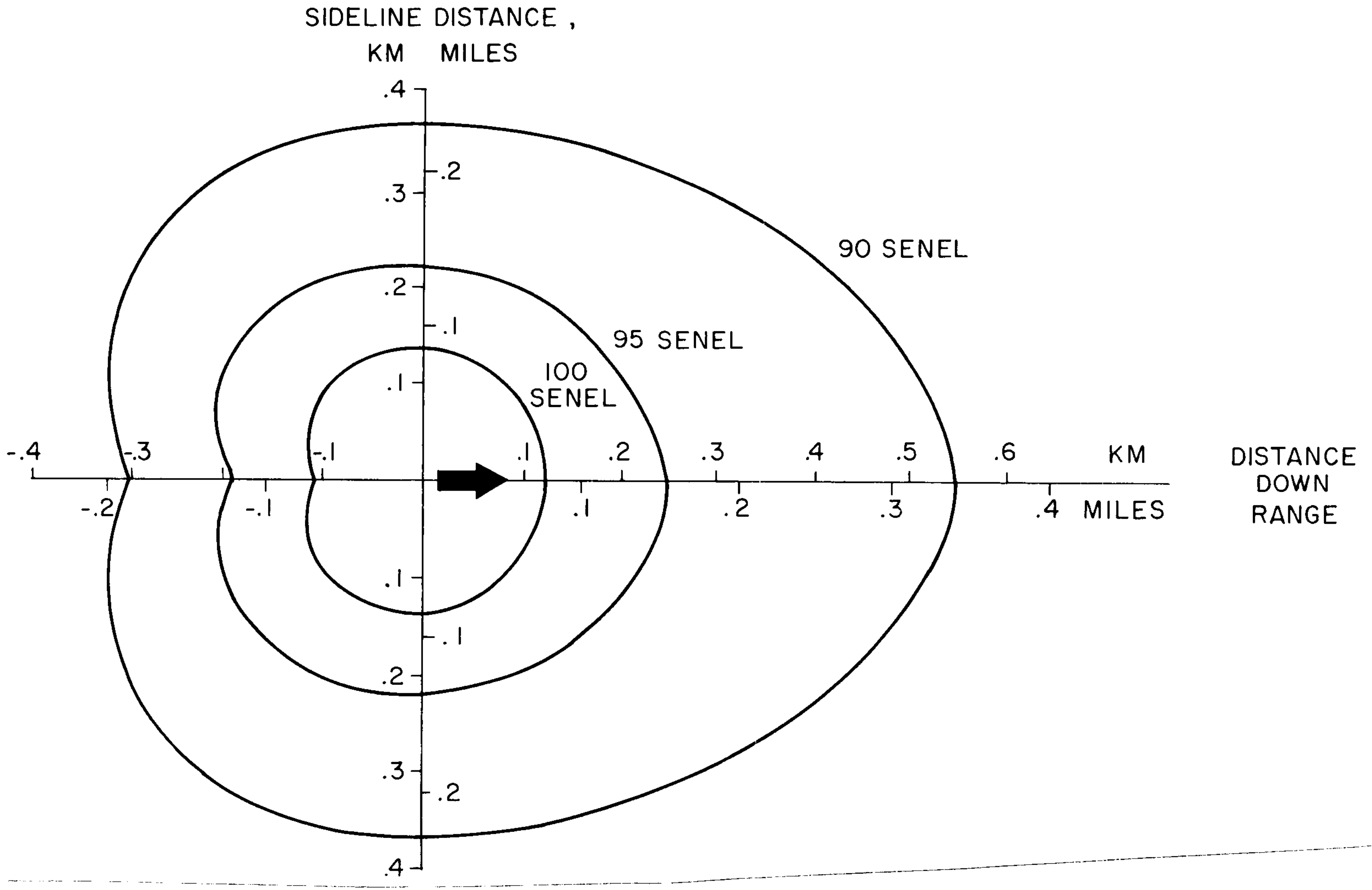


Figure 19. Equal Noise Ground Contours for Takeoff 1 - Vertical Climb to 500 Feet.

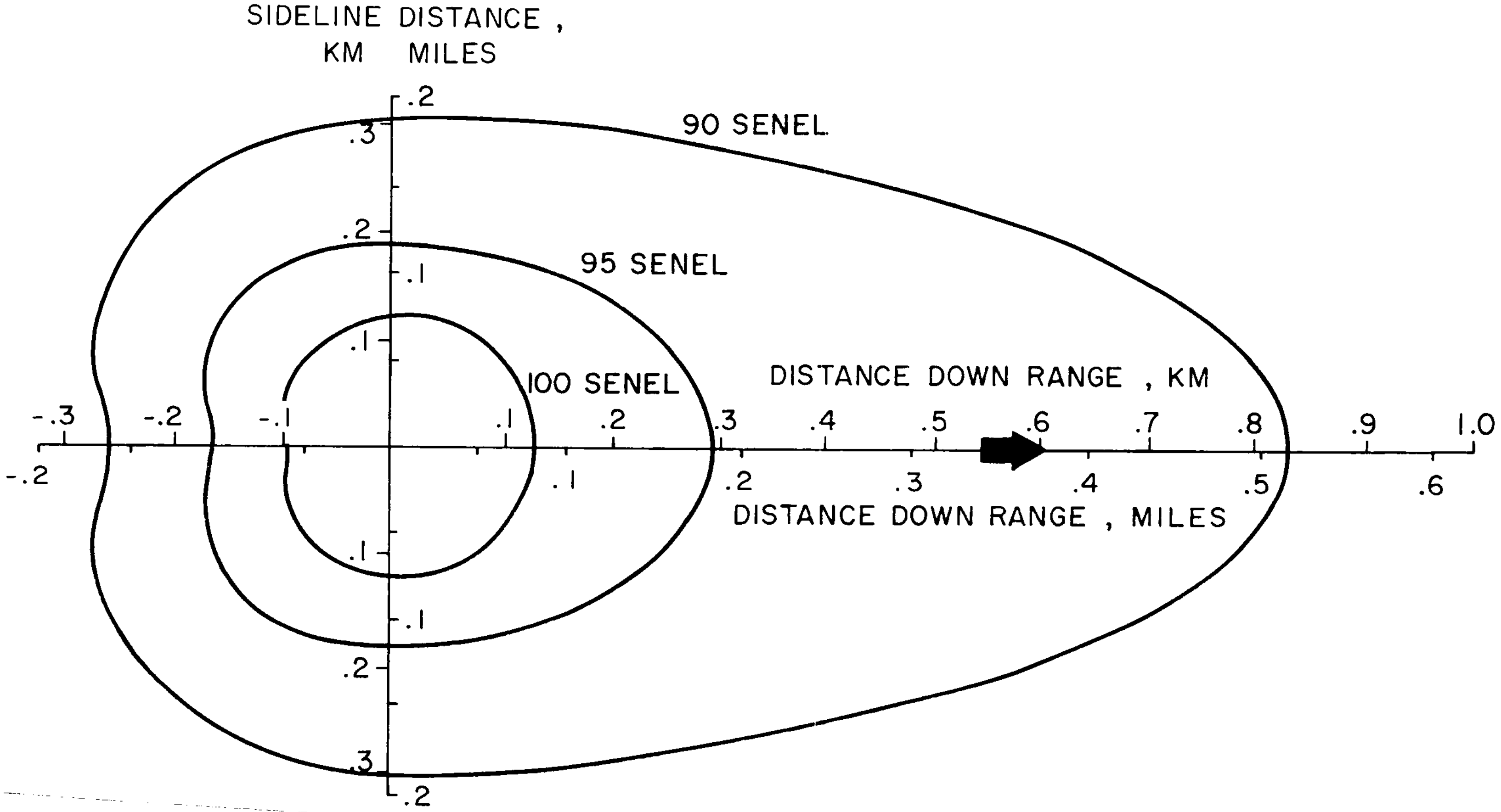


Figure 20. Equal Noise Ground Contours for Takeoff 2 - Vertical Climb to 250 Feet.

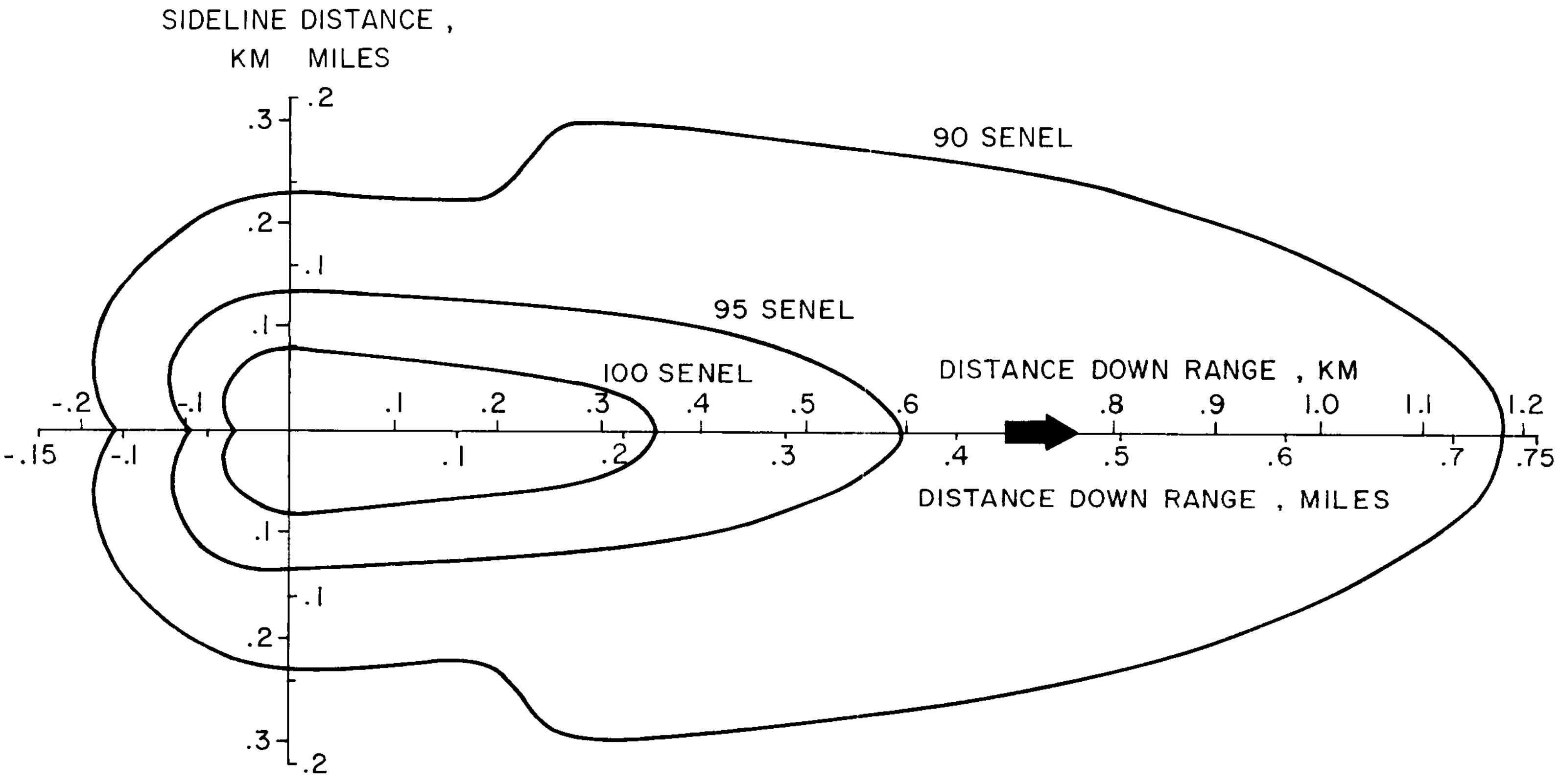


Figure 21. Equal Noise Ground Contours for Takeoff 3 - Oblique.

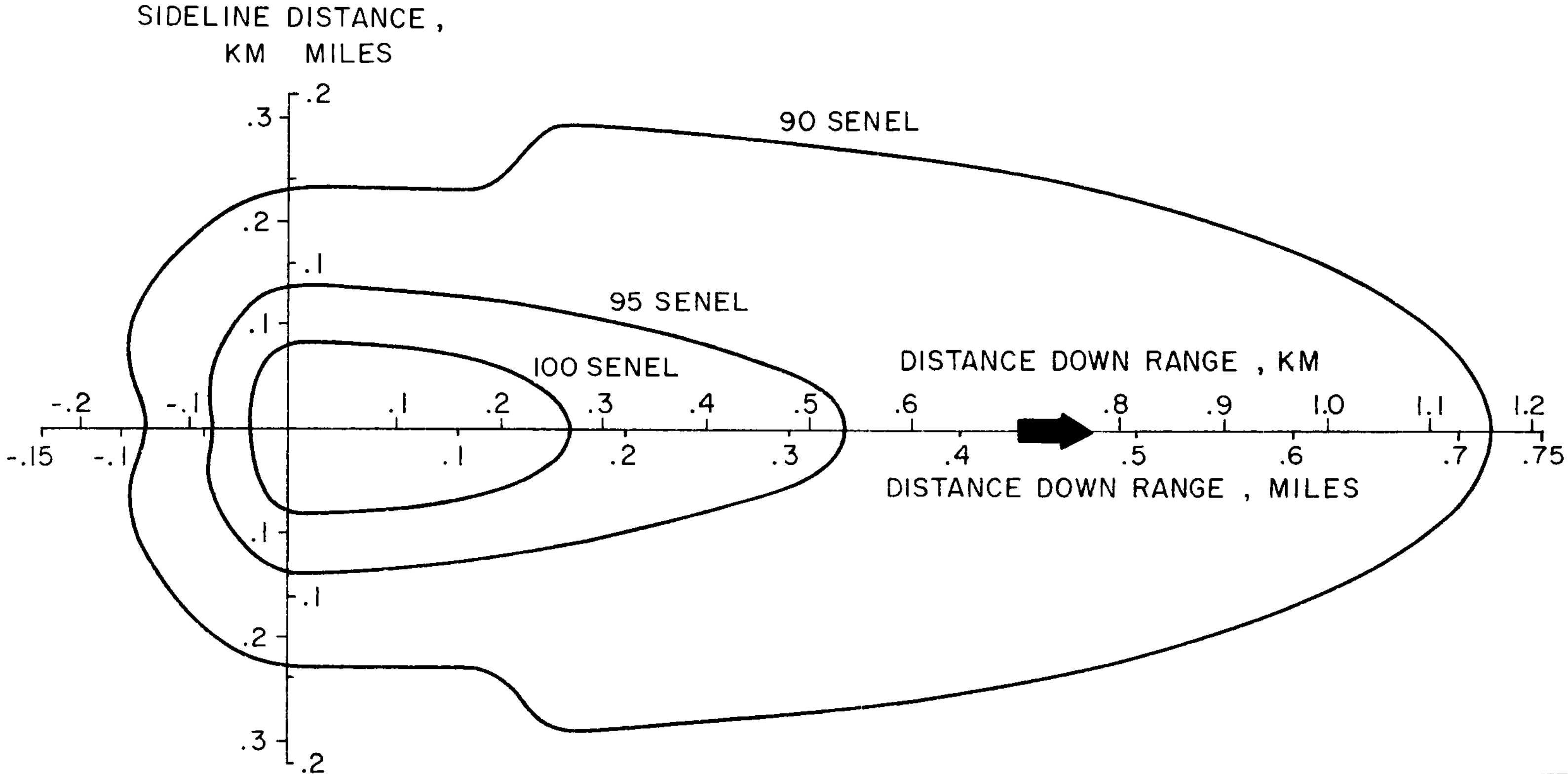
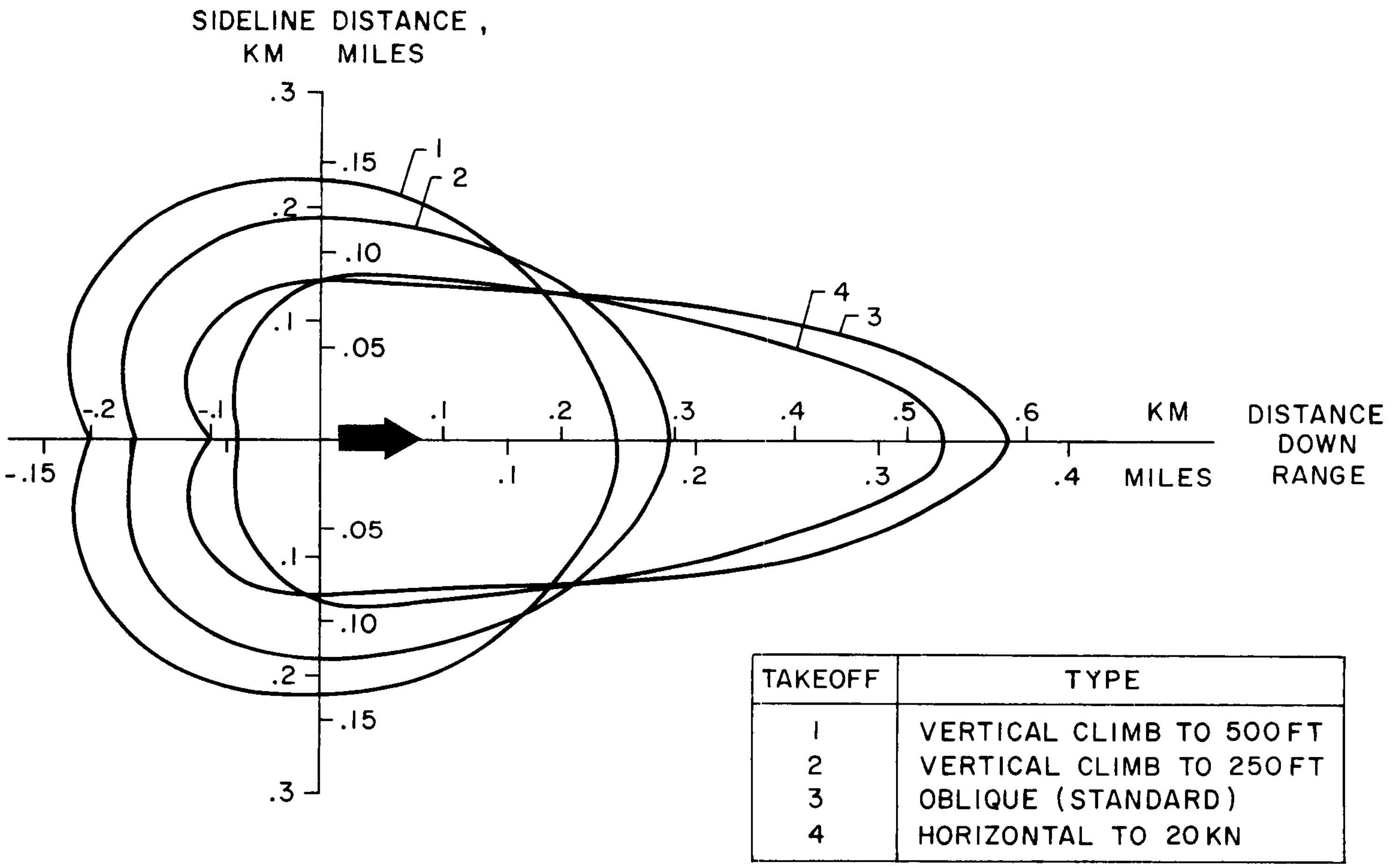


Figure 22. Equal Noise Ground Contours for Takeoff 4 - Horizontal.



TAKEOFF	TYPE
1	VERTICAL CLIMB TO 500 FT
2	VERTICAL CLIMB TO 250 FT
3	OBLIQUE (STANDARD)
4	HORIZONTAL TO 20 KN

Figure 23. Comparison of the 95 SENEL Ground Noise Contours for Four Different Takeoffs of the Baseline Helicopter.

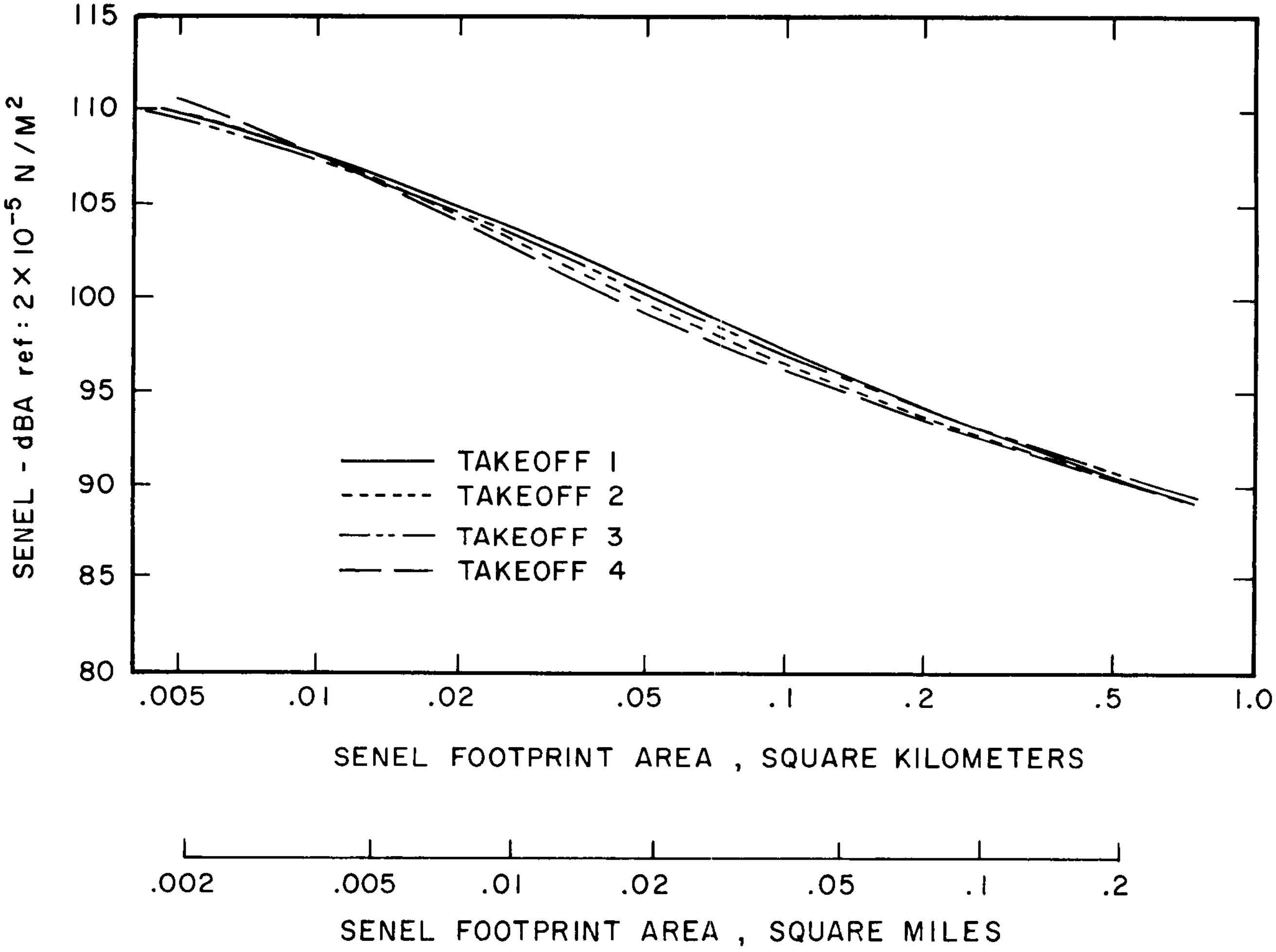


Figure 24. Noise Footprint Area Characteristic for Four Baseline Helicopter Takeoffs.

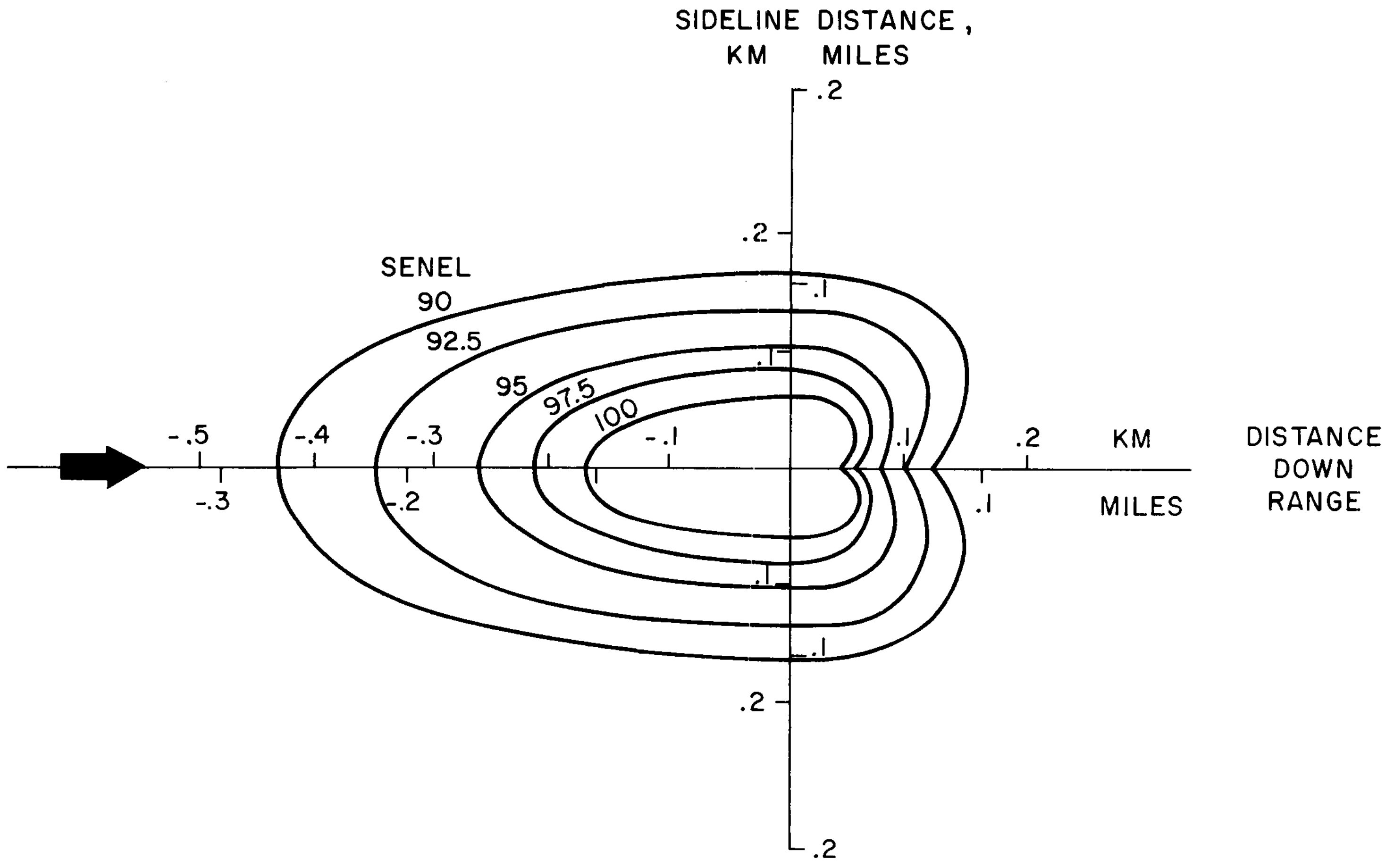


Figure 25. Equal Noise Ground Contours for Landing - 10° Glide Slope.

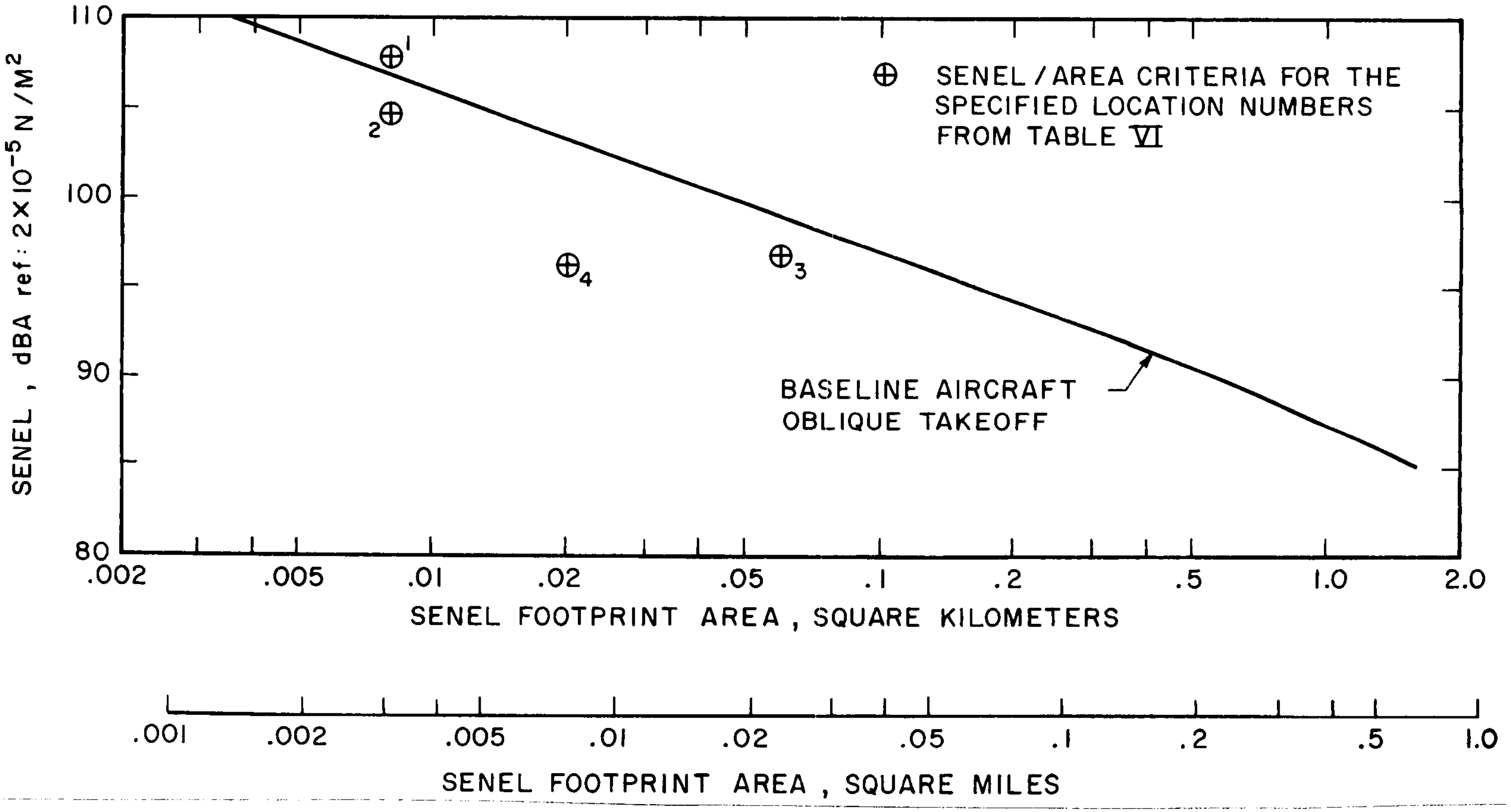


Figure 26. Comparison of Baseline Helicopter Noise Characteristics with Community Acceptance Criteria.

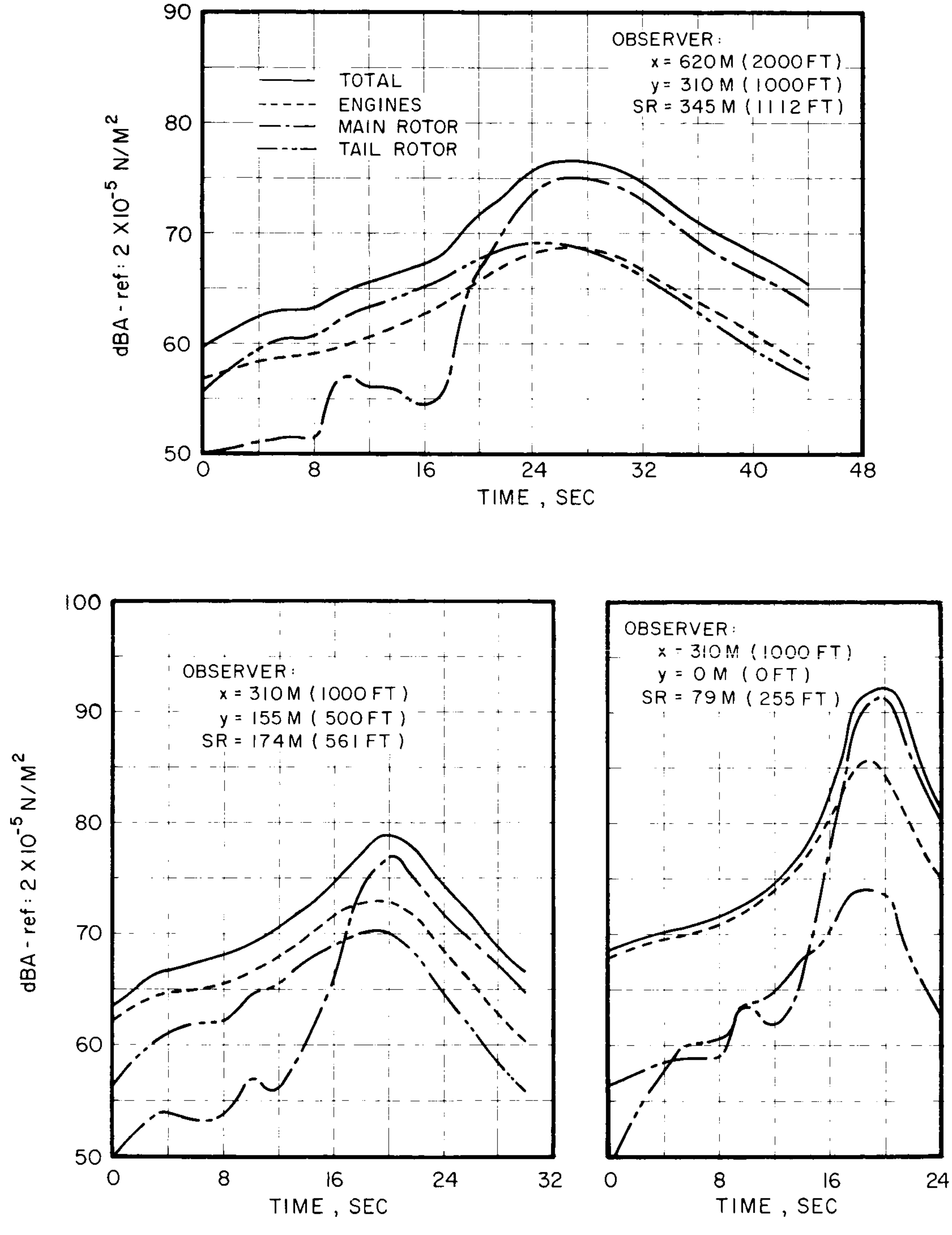


Figure 27. Contribution of Each Noise Source to the Baseline S-65-40 Helicopter Noise.

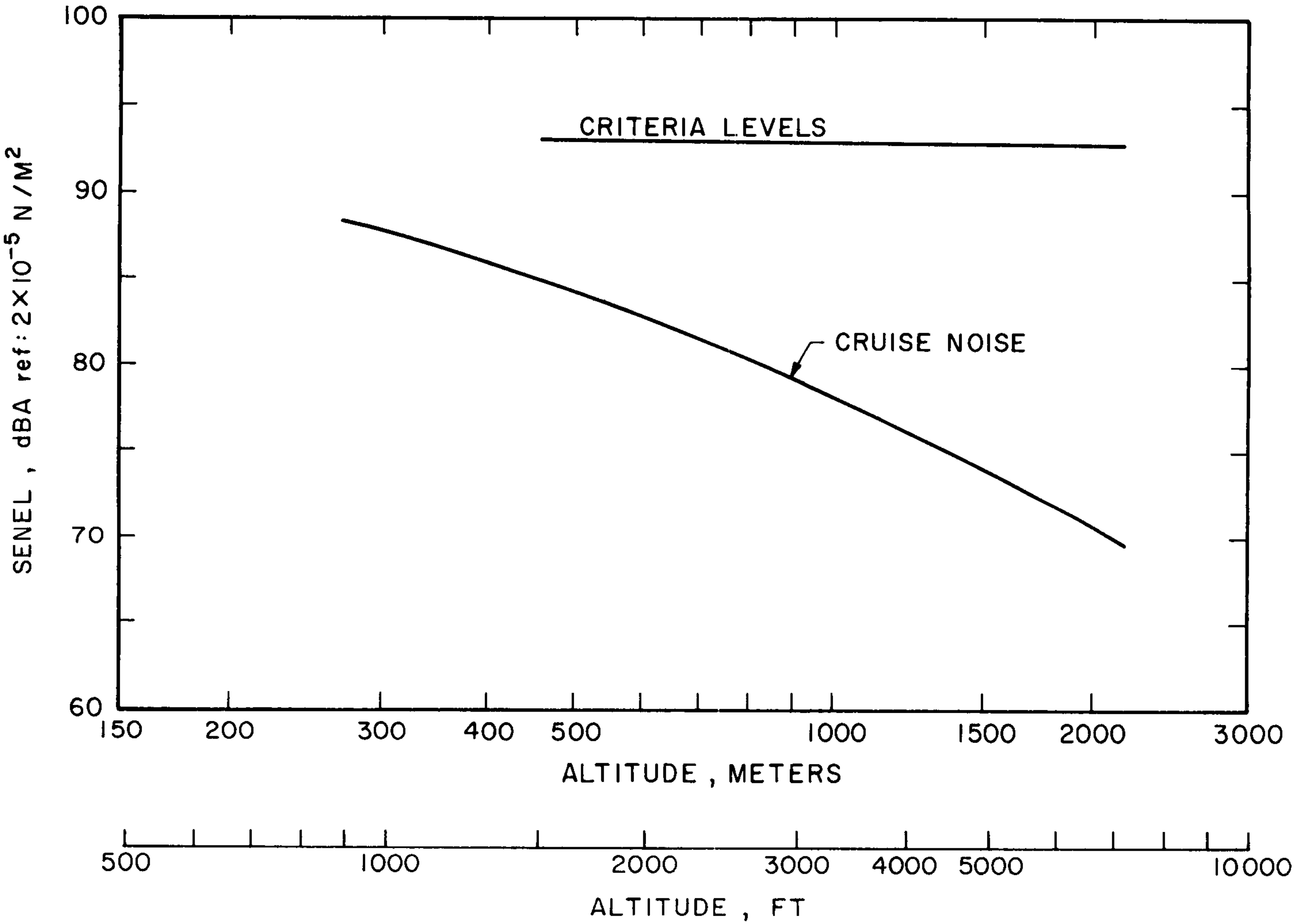


Figure 28. Baseline Helicopter Cruise Noise Compared with Noise Acceptance Criteria.

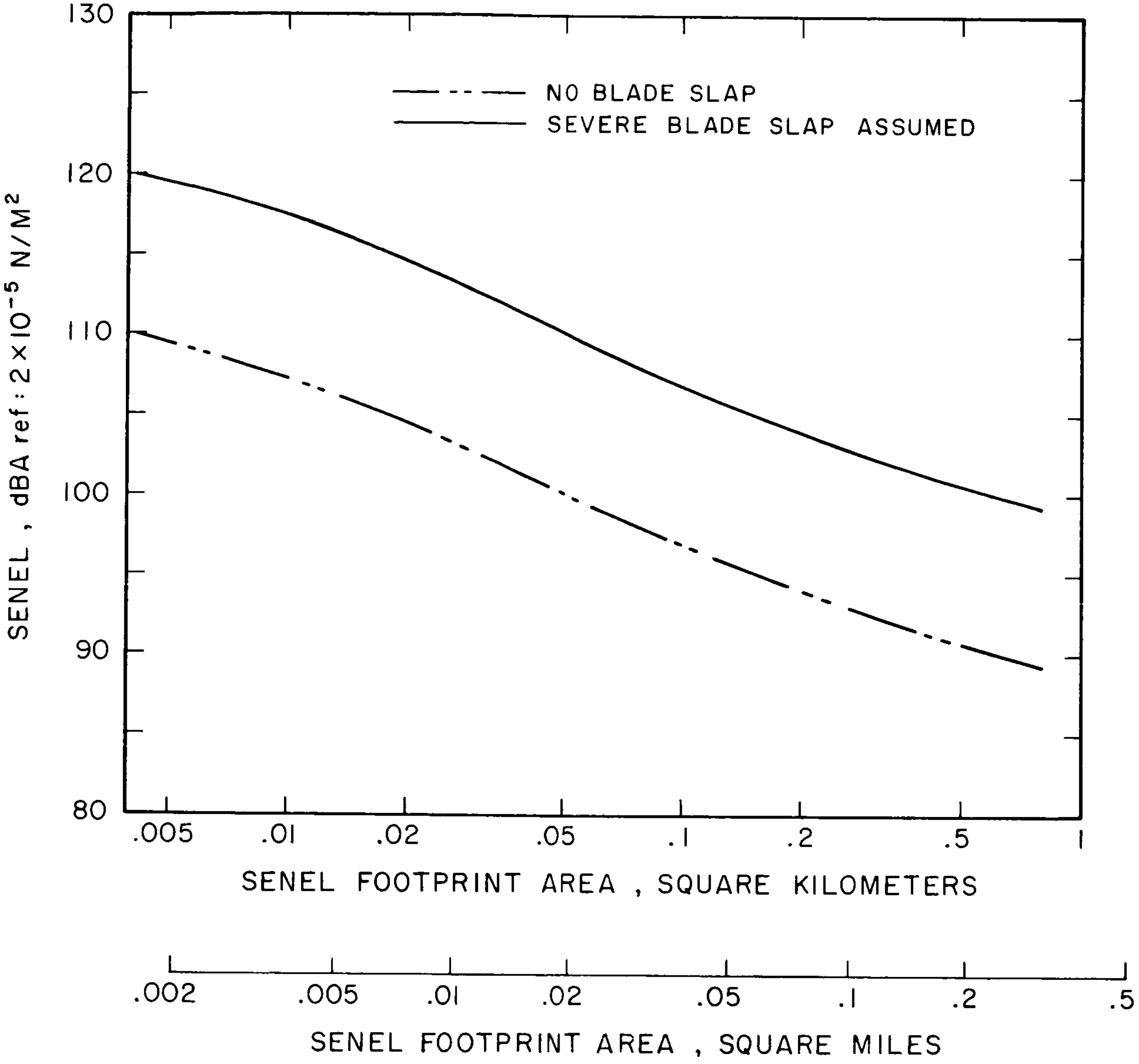


Figure 29. Effect of Impulsive Noise on a Helicopter's Noise Annoyance Characteristics.

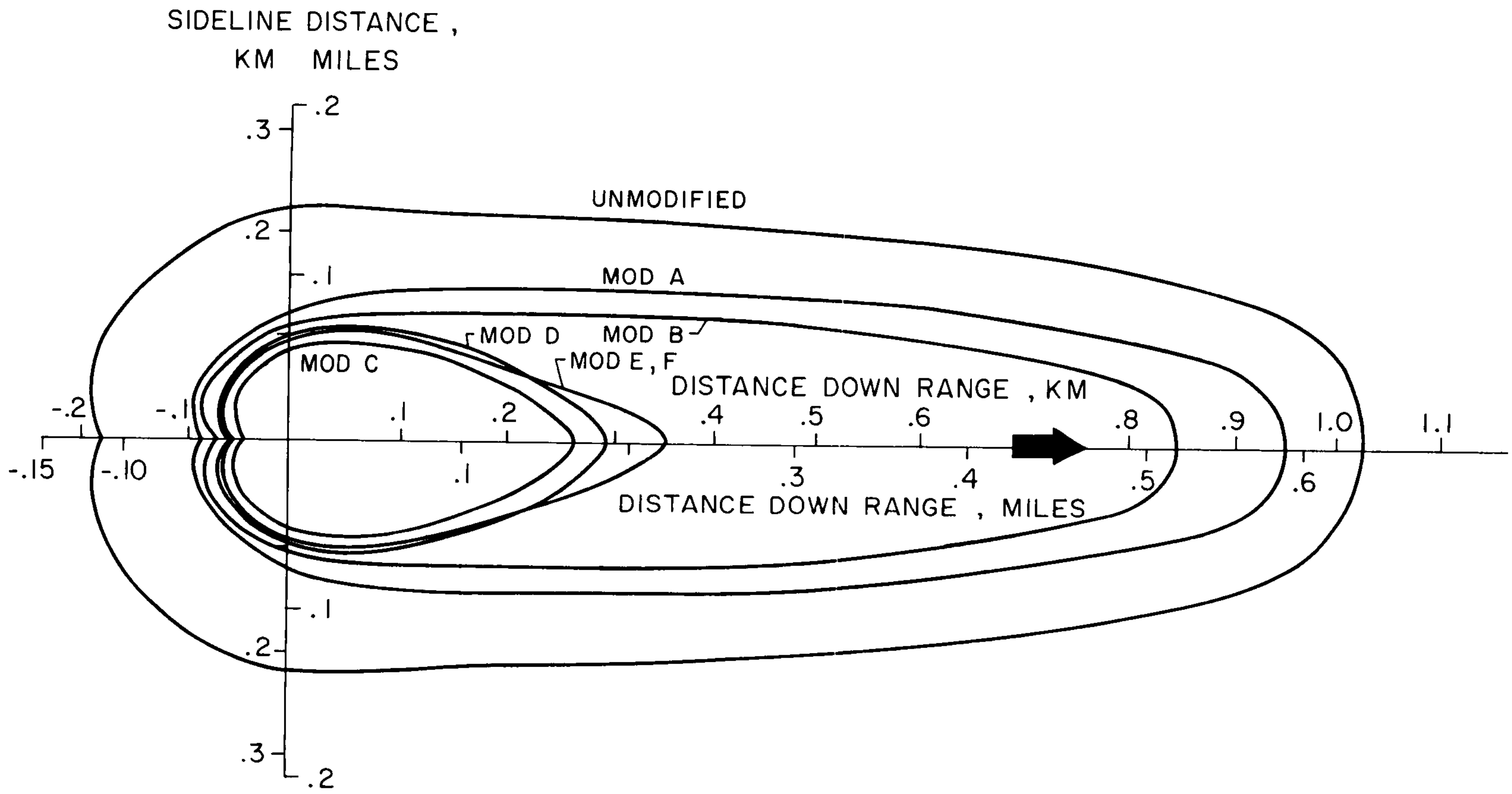


Figure 30. Comparison of the Noise Footprints of the Baseline S-65-40 Helicopter and Six Modified S-65-40 Helicopters (See Table III for Descriptions of the Modified Aircraft).

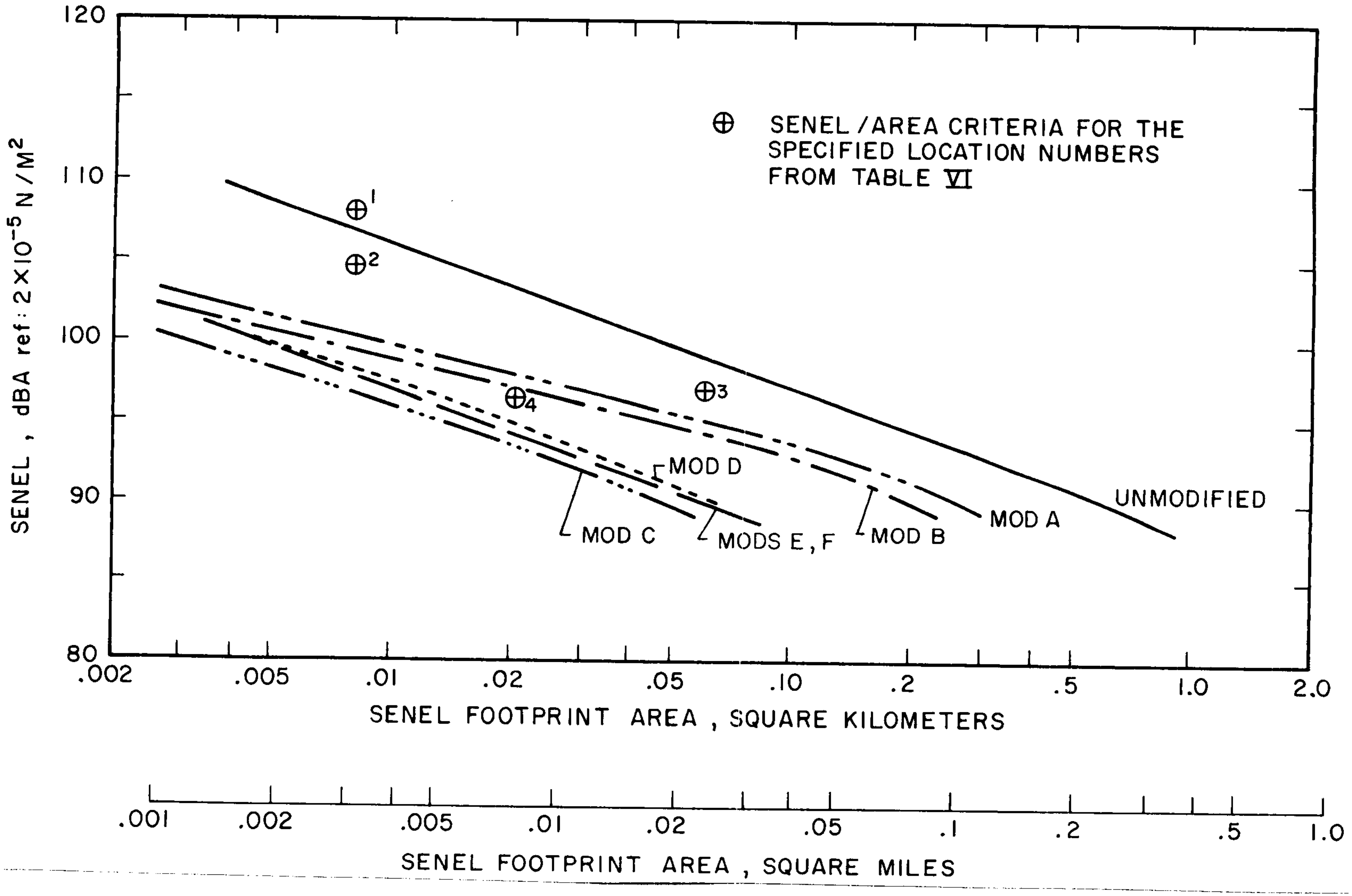


Figure 31. SENEL Footprint Area Characteristic for the Modified S-65-40 Helicopters.

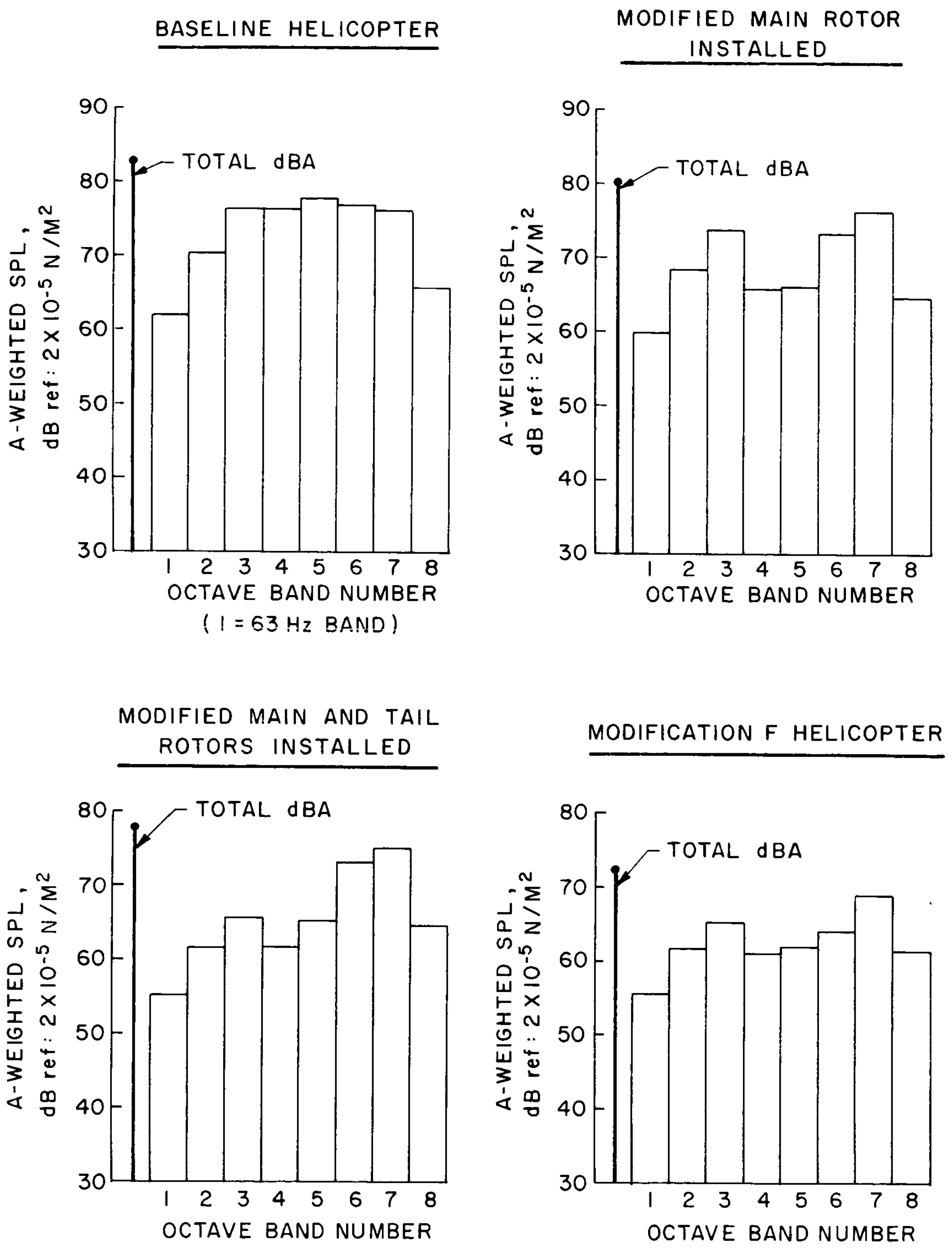


Figure 32. Octave Band Noise Reduction Resulting in Modification F Helicopter.

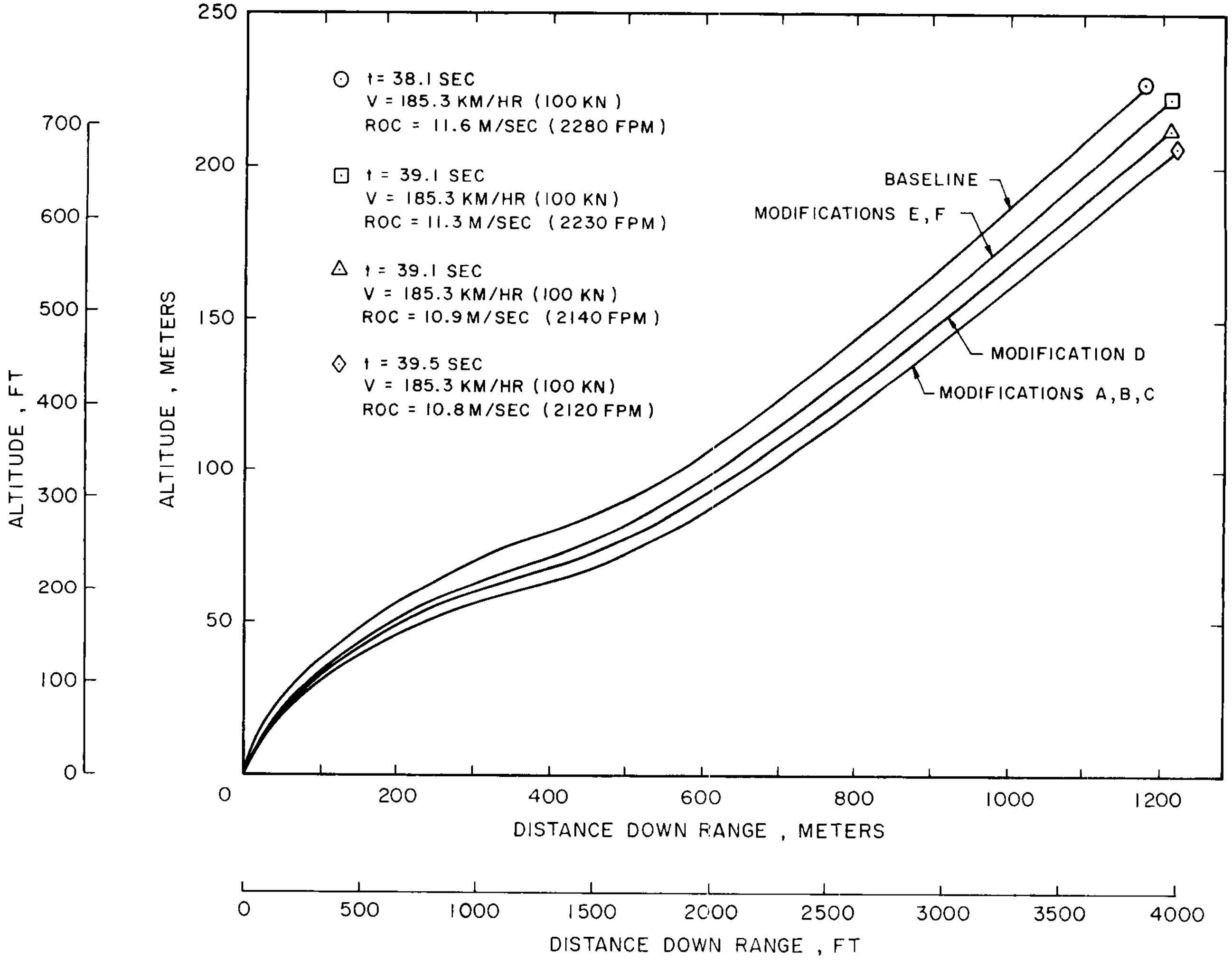


Figure 33. Flight Profiles of the Modified S-65-40 Helicopters.

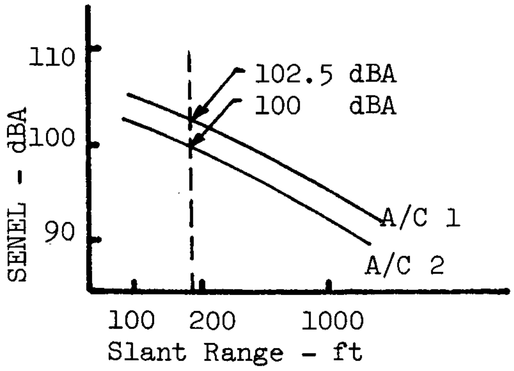
APPENDIX

SAMPLE CALCULATION OF L_{DN}

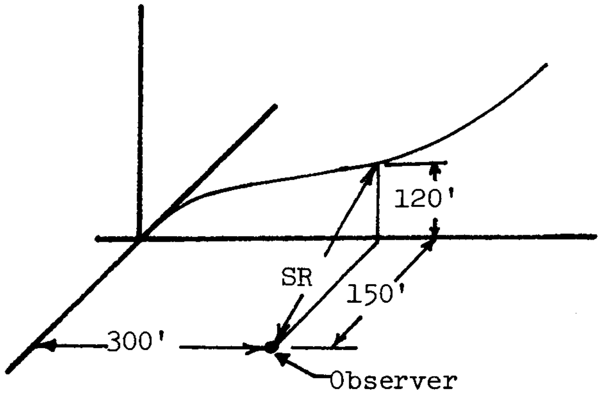
A sample calculation of the L_{DN} value at a single point on the ground will be computed using the equations of Figure 9 in the main body of the report. The necessary information is given below:

Number of different aircraft: 2
Number of flights: 50 day 1 night for aircraft 1
25 0 night for aircraft 2
Number of flight paths: 1
Time Aircraft Sound is above ambient: 15 sec for aircraft 1 and
10 sec for aircraft 2
Ambient Noise Level: 75 dBA

SENEL Characteristics



Flight Path:



SR = 193'

1. Calculate the Daytime Noise Level, L_D

$$L_D = 10\log_{10}\left\{\sum_{i=1}^{2}\sum_{j=1}^{1} N_{ij}\ \text{ant}\left(\frac{SENEL_{ij}}{10}\right)+ \left(54000-\sum_{i=1}^{2}\sum_{j=1}^{1}N_{ij}\Delta T_{ij}\right)\text{ant}\left(\frac{L_o}{10}\right)\right\}-47.3$$

$$L_D = 10\text{Log}_{10}\left\{50\text{ant}\,\frac{102.5}{10}+25\text{ant}\,\frac{100}{10}+(54000-50(15)-25(10))\ \text{ant}\left(\frac{75}{10}\right)\right\}-47.3$$

$$L_D = 10\log_{10}\left\{\left(8.90\text{x}10^{11} + 2.50\text{x}10^{11}\right) + (54{,}000-1000)\,\text{ant}(7.5)\right\}-47.3$$

$$L_D = 10\log_{10}\left\{1.14\text{x}10^{12}+1.68\text{x}10^{12}\right\}-47.3$$

$$L_D = 124.5-47.3 = 77.2 \text{ dBA}$$

2. Calculate the Nighttime Noise Level, L_N

$$L_N = 10\log_{10}\left\{\sum_{i=1}^{1}\sum_{j=1}^{1} N_{ij}\ \text{ant}\left[\frac{\text{SENEL}_{ij}}{10}\right]\right.$$

$$\left. + \left(32{,}000-\sum_{i=1}^{1}\sum_{j=1}^{1} N_{ij}\Delta T_{ij}\right)\text{ant}\ \frac{L_o}{10}\right\}-45.1$$

$$L_N = 10\log_{10}\left\{\text{ant}\ \frac{102.5}{10} + (32000-15)\ \text{ant}\ \frac{75}{10}\right\}-45.1$$

$$L_N = 10\log_{10}\left\{1.78\text{x}10^{11}+ 1.01\text{x}10^{12}\right\}-45.1$$

$$L_N = 75.6 \text{ dBA}$$

3. Calculate the Day-Night Noise Level, L_{DN}

$$L_{DN} = 10\log_{10}\left\{0.625\ \text{ant}\ (L_D/10) + 0.375\ \text{ant}\ (L_N/10)\right\}$$

$$L_{DN} = 10\log_{10}\left\{0.625\ \text{ant}\ (77.2/10) + 0.375\ \text{ant}\ (75.6/10)\right\}$$

$$L_{DN} = 10\log_{10}\left\{3.28\text{x}10^{7} + 1.36\text{x}10^{7}\right\}$$

$$\underline{L_{DN} = 76.7 \text{ dBA}}$$