FINDINGS OF THE LOW-FREQUENCY NOISE EXPERT PANEL

of the Richfield-MAC Noise Mitigation Agreement
of 17 December, 1998

Annotated to Indicate Consensus or Absence of Consensus

VOLUMES I through III

30 September 2000

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VOLUME I OF III

EXECUTIVE SUMMARY

30 September 2000

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ACKNOWLEDGMENTS

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Note: This page is present only in the 30 September 2000 Annotated Document

INTRODUCTION TO ANNOTATED DOCUMENT

The City of Richfield (Richfield) and the Metropolitan Airports Commission (MAC) agreed in December of 1998 to undertake detailed studies of existing and potential impacts of low-frequency aircraft noise in communities around MSP. The agreement established a Low-Frequency Noise Expert Panel (the Expert Panel) and a Low-Frequency Noise Policy Committee (the Policy Committee).

Richfield appointed Sanford Fidell and MAC appointed Andrew S. Harris to the Expert Panel. The third member of the Expert Panel, Louis C. Sutherland, was selected by agreement of the appointed members. Richfield, MAC, Minneapolis and Bloomington are voting members of the Policy Committee. The Federal Aviation Administration (FAA), the Metropolitan Council, the Minnesota Pollution Control Administration (MPCA) and the Metropolitan Airport Sound Abatement Council (MASAC) are advisory members of the Policy Committee.

On 25 April 2000 a report was issued under the title “Findings of the Low-Frequency Noise Expert Panel” and described as reflecting “the views of the majority of the Expert Panel.” Prior to publication of the 25 April 2000 document, the Expert Panel had reach substantial agreement on most areas of its work. Nonetheless, there were significant aspects of the work where agreement was not reached by that date.

The principal points where the Expert Panel did not reach consensus were:

- Levels of low-frequency aircraft noise from departures and from the reverse thrust portion of arrivals;
- Whether to factor runway use percentages and fleet mix on runways into the contours for future levels of low-frequency aircraft noise; and
- the type of treatment required to achieve compatibility of residential land use with low-frequency aircraft noise.

The purpose of the present document is to identify clearly where consensus was reached, where it was not reached and what the disagreements were. The 25 April 2000 document forms the basis for this annotated report.[1] Highlighted notes (***red, bold, italicized***) in the text identify whether consensus had been reached on each element of the report. Footnotes and Appendix D present discussion of significant points of disagreement. There were points of disagreement in addition to those identified here. To avoid obscuring the significance of the points addressed in this document, the less important points are neither identified nor discussed.

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[1] BBN was custodian of master file for these documents during the study. The set of files received from BBN for the 25 April 2000 document bears the date 9 May 2000. The 9 May 2000 file was used here.

VOLUME I

1 INTRODUCTION AND SUMMARY

The City of Richfield (Richfield) and the Metropolitan Airports Commission (MAC) agreed in December of 1998 to undertake detailed studies of existing and potential impacts of low-frequency aircraft noise in communities around MSP. The agreement established a Low-Frequency Noise Expert Panel (the Expert Panel) and a Low-Frequency Noise Policy Committee (the Policy Committee).

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This three volume document reflects the views of the majority of the Expert Panel. Volume I contains an Executive Summary. Volumes II and III contain supporting technical detail and appendices, respectively.

1.1 PURPOSE AND CONTENT OF THE REPORT

The Expert Panel undertook the following Plan of Work, as approved by the Low-Frequency Noise Policy Committee:[2]

Task 1. Review the literature on audibility, noticeability and the effects of low-frequency noise on individuals and communities.
Task 2. Identify relevant noise effects and descriptors.
Task 3. Determine existing and predicted low-frequency noise levels in the vicinity of MSP runways.
Task 4. Identify criteria for acceptability of low-frequency noise in residences.
Task 5. Determine low-frequency noise reduction provided by typical residential construction in the vicinity of MSP.
Task 6. Determine low-frequency noise reduction provided by residences subsequent to treatment in the MSP Residential Sound Insulation Program.
Task 7. Evaluate the acceptability of low-frequency noise environments in residences without and with treatment from the MSP Residential Sound Insulation Program.
Task 8. Determine the types of treatment required to improve the noise reduction and achieve compatibility of the low-frequency noise environment.
Task 9. Prepare reports for the Policy Committee documenting the work of the Expert Panel.

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[2] The first nine tasks were approved on 26 April, 1999. The tenth task was added at the request of the FAA's Office of Environment and Energy and approved by the Policy Committee on 22 July, 1999. A final task (review of thrust reverser noise levels) was undertaken at the request of the Policy Committee on 10 January, 2000.

Task 10. Measure noise in the vicinity of MSP for comparison with calculated values from Integrated Noise Model 6.0 (INM 6.0).

1.2 SUMMARY OF RESULTS

This Volume of the Expert Panel's Report summarizes the Panel's principal findings, in the following order:

Literature Review: background information on acoustics and low-frequency noise (Task 1);
Effects of low-frequency aircraft noise on residential land use (Task 2);
Descriptors of low-frequency noise and noise dose (Task 2);
Potential criteria for residential land use compatibility with low-frequency aircraft noise (Task 4);
Existing (1999 without runway 17/35) and predicted (future with runway 17/35) levels of low-frequency aircraft noise (Tasks 3 and 10);
Noise reduction provided by existing residences without and with treatment in the MSP Residential Sound Insulation Program (Tasks 5 and 6);
Acceptability of low-frequency noise environments without and with treatment in the MSP Residential Sound Insulation Program (Task 7); and
Approaches to mitigate low-frequency noise impacts on residences (Task 8).

1.2.1 Literature Review

The Expert Panel reached consensus on these Conclusions.

The following conclusions may be drawn from the literature reviewed in this Appendix:

The primary effect of low-frequency aircraft noise on residential areas near runway sidelines is annoyance due to "secondary emissions": rattling noises and vibration of windows, doors, and household paraphernalia.

Loudness level contours (such as those of Stevens Mark VII) provide a reliable indication of the loudness, noise rating, and direct annoyance of sounds in the low-frequency range of current interest.

People may become aware of low-frequency sound pressure as a sensation of chest vibration in the octave band from about 40 to 80 Hz at sound levels on the order of 70 dB. The sensation itself has no adverse physiological consequences.

Source spectra of departing aircraft contain relatively greater amounts of low-frequency acoustic energy at points closer to the start of takeoff roll than at points successively greater in distance from the start of takeoff roll.

For purposes of predicting average sideline propagation of low-frequency aircraft noise from runway centerlines to points on the ground one or two

> miles distant, geometric (inverse square) spreading of acoustic energy is the propagation effect of major concern.
>
> Prediction of low-frequency noise levels produced by aircraft operating on or near the ground requires direct measurement to augment currently available computer models.

The full literature review may be found in Appendix B. Appendix A contains background information that may help readers who are unfamiliar with acoustic measurement to understand the contents of the Expert Panel Report.

1.2.2 Effects of Low-Frequency Aircraft Noise

The Expert Panel identified several effects of low-frequency aircraft noise on people.

1.2.2.1 Effects of low-frequency aircraft noise ***The Expert Panel reached consensus on this finding.***

The primary effect of current and anticipated low-frequency aircraft noise on the residents of neighborhoods near MSP is rattle-related annoyance. Low-frequency aircraft noise (apart from that of low altitude, high-speed military aircraft) poses no known risk of adverse public health consequences, nor a risk of structural damage. Under the expected circumstances of residential exposure, low-frequency aircraft noise will not interfere with indoor speech, nor is this low-frequency noise itself likely to awaken people.

Annoyance is not a trivial effect of aircraft noise exposure. The Federal Interagency Committee on Noise (FICON) recognizes annoyance as the best indication of adverse community reaction to aircraft noise. The prevalence of high annoyance provides much of the rationale for federal and state policies concerning mitigation of aircraft noise impacts in residential areas.

Additional information about the effects of low-frequency aircraft noise on individuals and communities may be found in Appendices A and B of Volume III.

1.2.2.2 Relative annoyance of low-frequency aircraft noise and aircraft overflight noise

A laboratory study in which test subjects judged the annoyance of recorded samples of low-frequency aircraft noise confirmed that

> Such noise was more annoying than aircraft overflight noise heard at the same A-weighted sound level. ***The Expert Panel reached consensus on this finding.***
>
> The addition of even minor amounts of rattle to such noise increased its judged annoyance by about 5 dB in this study. (Other studies have shown as much as a 10 dB increase in annoyance.)
> ***The Expert Panel did not reach consensus on this finding.*** [3]

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[3] ***While the Expert Panel reached consensus on the 5-dB effect, evidence of a 10-dB effect was not provided and consensus was not reached.***

Reductions in the low-frequency content of this noise proportionally decreased the annoyance of non-rattling test sounds.

The Expert Panel reached consensus on this finding

1.2.3 Descriptors of Low-Frequency Aircraft Noise and Low-Frequency Noise Dose

The Expert Panel reached consensus on these recommendations

The Expert Panel previously recommended that the Policy Committee adopt the sum of the maximum sound levels in the 25 - 80 Hz one-third octave bands ("low-frequency sound level," abbreviated LFSL) during individual aircraft noise events as the preferred descriptor of low-frequency aircraft noise in the vicinity of MSP. The Expert Panel further recommends that the Policy Committee adopt the arithmetic average of the greatest low-frequency sound levels of aircraft noise events in excess of LFSL = 60 dB as the measure of effective low-frequency aircraft noise dose.[4]

1.2.4 Criteria for Acceptability of Low-Frequency Noise in Residences

The Expert Panel reached consensus on this process.

The Expert Panel identified a range of criteria for acceptability of low-frequency noise in residences in three steps. First, A-weighted land use compatibility and other interpretations of noise impacts were reviewed. Second, the reactions of Minneapolis (and other) residents to rattle were determined. Third, equivalences were established between A-weighted and low-frequency sound levels through associated levels of prevalence of annoyance.

1.2.4.1 Criteria adopted by various bodies to describe acceptability of noise in human environments

While the Expert Panel reached consensus on the use of Figure 1 and the concept of Table 1, it did not reach consensus on portions of the text in Table 1.[5]

For guidance in setting policy, FICON and its constituent federal agencies have adopted the relationship shown in Figure 1 between Day-Night Average Sound Level and the percentage of the population that is annoyed by the noise exposure. Figure 1 shows the FICON relationship. Table 1 shows the levels of noise exposure and prevalence of high annoyance identified by various bodies for diverse purposes.

HUD, FAA, the Federal Railroad Administration (FRA) and the Urban Mass Transit Administration (UMTA) have adopted criteria for noise and vibration compatibility policies and regulations over a range of high annoyance from 12% to 37% (corresponding through the FICON relationship to DNL values between 65 and 75 dB). The Expert Panel recommends that the Policy Committee adopt similar reasoning to interpret low-frequency noise impacts in areas near MSP, taking into consideration local circumstances and policy purposes as well.

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[4] This value is intended to represent the maximum low-frequency sound level that occurs a few times a day in neighborhoods near runways, since "a few times a day" was the most common response to questioning about the frequency of annoyance produced by rattle and vibration.

[5] ***Under "Purpose" in Table 1, the 25 April 2000 document describes land uses as "compatible with airport operation." Both HUD and the FAA are indicating that the land uses are compatible with the environmental noise, described as values of the day-night sound level (DNL). "Compatible with airport operations" should be replaced with "compatible with noise exposure".***

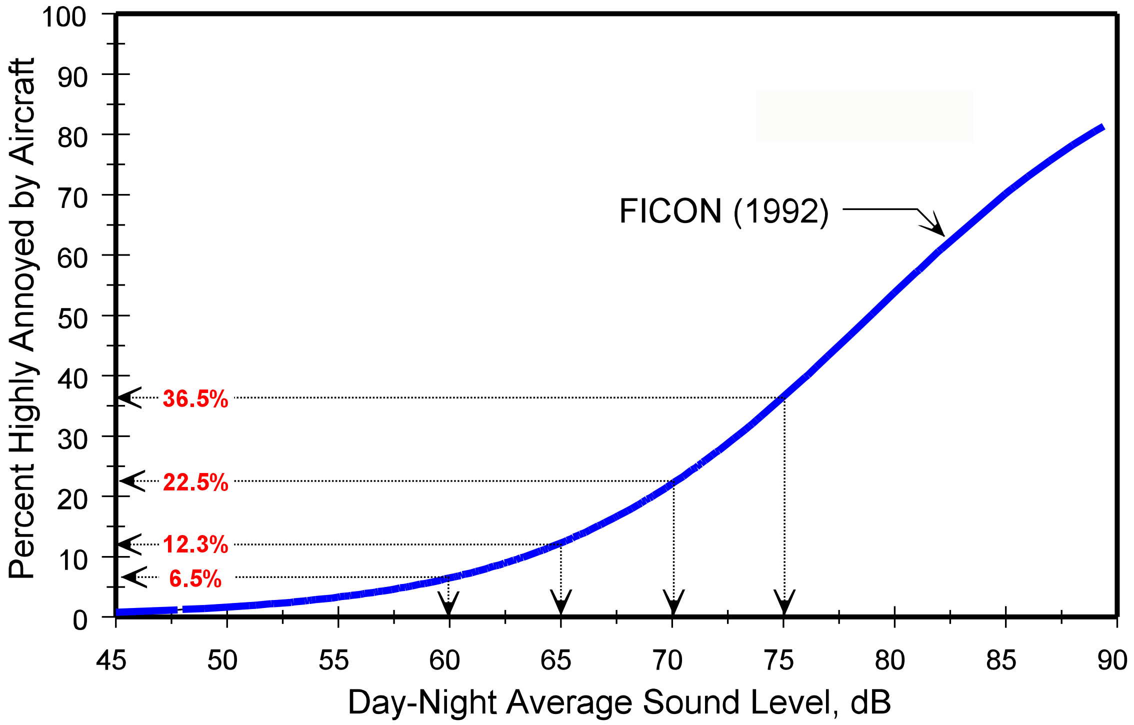

Figure 1 Relationship of noise exposure to the prevalence of high annoyance, per the dosage-response relationship adopted by Federal Interagency Committee on Noise (1992).

Table 1 Day-Night Average Sound Levels identified by various bodies and purposes, with associated percentages of highly annoyed population. ***(See comments in Section 1.2.4.1.)***

BODY	PURPOSE	IDENTIFIED DNL VALUE (dB)	PERCENT HIGHLY ANNOYED (%)
U.S. EPA	Level identified as requisite to protect health and welfare with margin of safety (non-regulatory)	55	3.3
Metropolitan Airports Commission	Lower limit of residential sound insulation at MSP	60	6.5
Minnesota Legislature	Identify area to study treatment	60	6.5
Minnesota Legislature	Identify area for sound insulation	65	12.3
HUD FAA	Regulatory level below which untreated residential land uses are compatible with airport operation	< 65	12.3
HUD FAA	Range of regulatory levels where improved noise reduction is required for compatibility with airport operation	65 - 75	12.3 - 36.5
HUD FAA	Regulatory level above which any residential land use is incompatible with airport operation	> 75	> 36.5

1.2.4.2 Findings about the prevalence of annoyance with low-frequency aircraft noise near MSP

The Expert Panel reached consensus on these findings except for the relationship in Figure 3.

A social survey of the annoyance of low-frequency aircraft noise and noise-induced rattle was conducted as part of Task 7 in a Minneapolis neighborhood north of the intersection of Runways 12L/30R and 4/22. The results of the survey closely resembled those observed within the comparable range of LFSL values in a prior survey conducted in a neighborhood near Runways 25 L/R at Los Angeles International Airport.

Annoyance due to low-frequency aircraft noise was strongly related to LFSL values. The most common frequency of notice of noise-induced rattle was "a few times a day." Windows were the most cited sources of rattling noises. Figure 2 summarizes the relationship between low-frequency aircraft noise levels in the MSP and LAX survey areas and annoyance. Figure 3 shows a dose-response relationship for the geographic association between rattle-induced high annoyance and runway sideline distance. This empirical relationship is based solely upon the proximity to runways of highly annoyed social survey respondents, and is thus completely independent of any acoustic measurement or prediction. ***(See note on Figure 3.)***

The relationships shown in Figures 1 and 2, along with the policy and regulatory decisions of federal agencies and the Minnesota Legislature, lead the Expert Panel to suggest that the Policy Committee interpret the acceptability of low-frequency noise impacts around MSP in terms of the prevalence of annoyance. Figure 2 shows that low-frequency sound doses between 70 dB and 87 dB cover most of the range of interest.

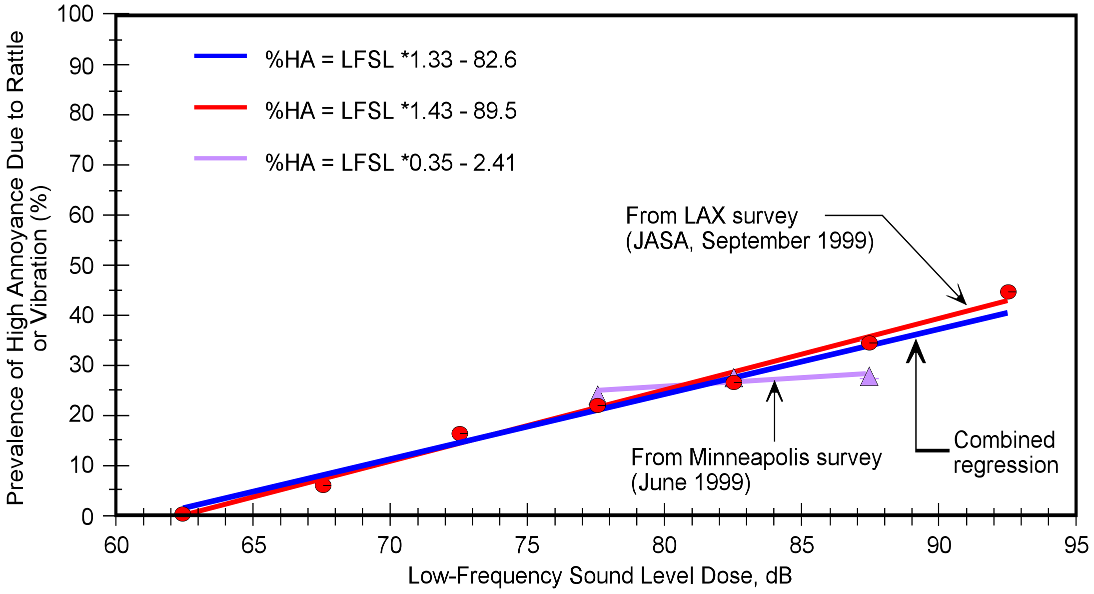

Figure 2 Noise levels and percentages highly annoyed in MSP and LAX surveys.

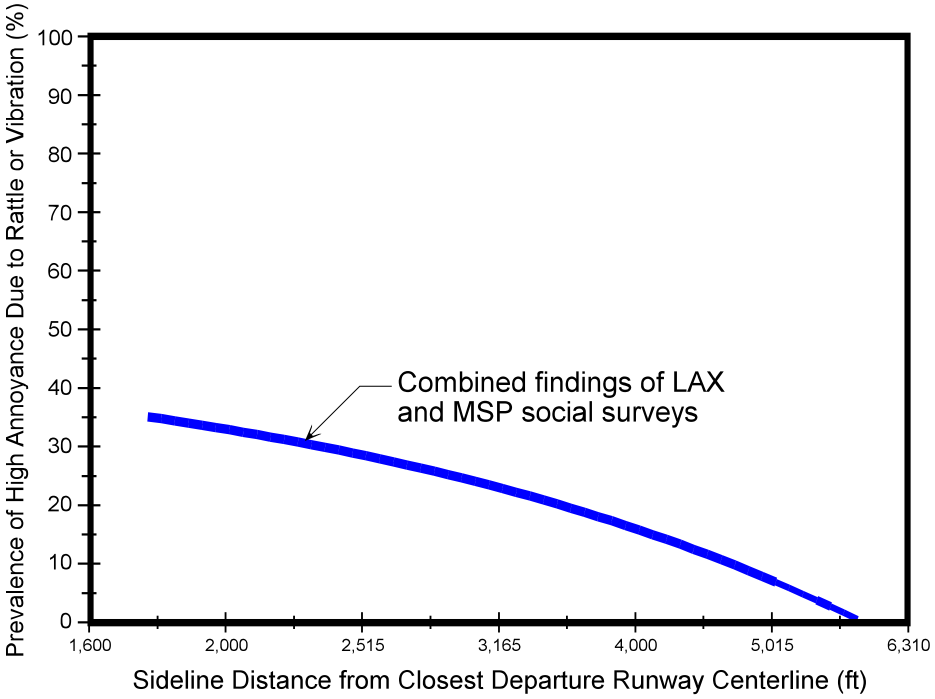

Figure 3 Relationship between sideline distance of households to runway and the prevalence of high annoyance in combined findings of LAX and MSP social surveys.

The relationship in Figure 3 gives the impression that the response to low-frequency aircraft noise is constant along the entire length of a runway and varies only as the distance from the runway. Such an impression is invalid. Mr. Sutherland, has stated that it does not reflect the effects of thrust reversal noise and that he had not considered whether it represented departure noise. Mr. Harris has stated that it does not reflect the effects from ether departure noise or thrust reversal noise. Figure 3 should not be in this report. (See also the discussion in Section 7.4.2.)

1.2.5 Existing and Predicted Low-Frequency Noise Levels in the Vicinity of MSP

1.2.5.1 Low-frequency ambient sound levels in neighborhoods near MSP

The Expert Panel reached consensus on these findings

Daytime ambient sound levels in low-frequency one-third octave bands in residential areas of Minneapolis, Richfield and Bloomington near MSP are currently on the order of 55 dB ± 5 dB. Nighttime ambient sound levels in Richfield are roughly 10 dB lower. These findings are consistent with previous surveys that identified approximately a 10 dB difference between daytime levels and nighttime levels in developed areas.

Details about these findings may be found in Section 6.2 of Volume II of this report.

1.2.5.2 Existing and predicted low-frequency aircraft noise levels in the vicinity of MSP runways

Figure 4 shows contours of low-frequency sound levels due to thrust reverser application. Like all other predictions of future conditions, these estimates cannot by definition be regarded as certain. They do,

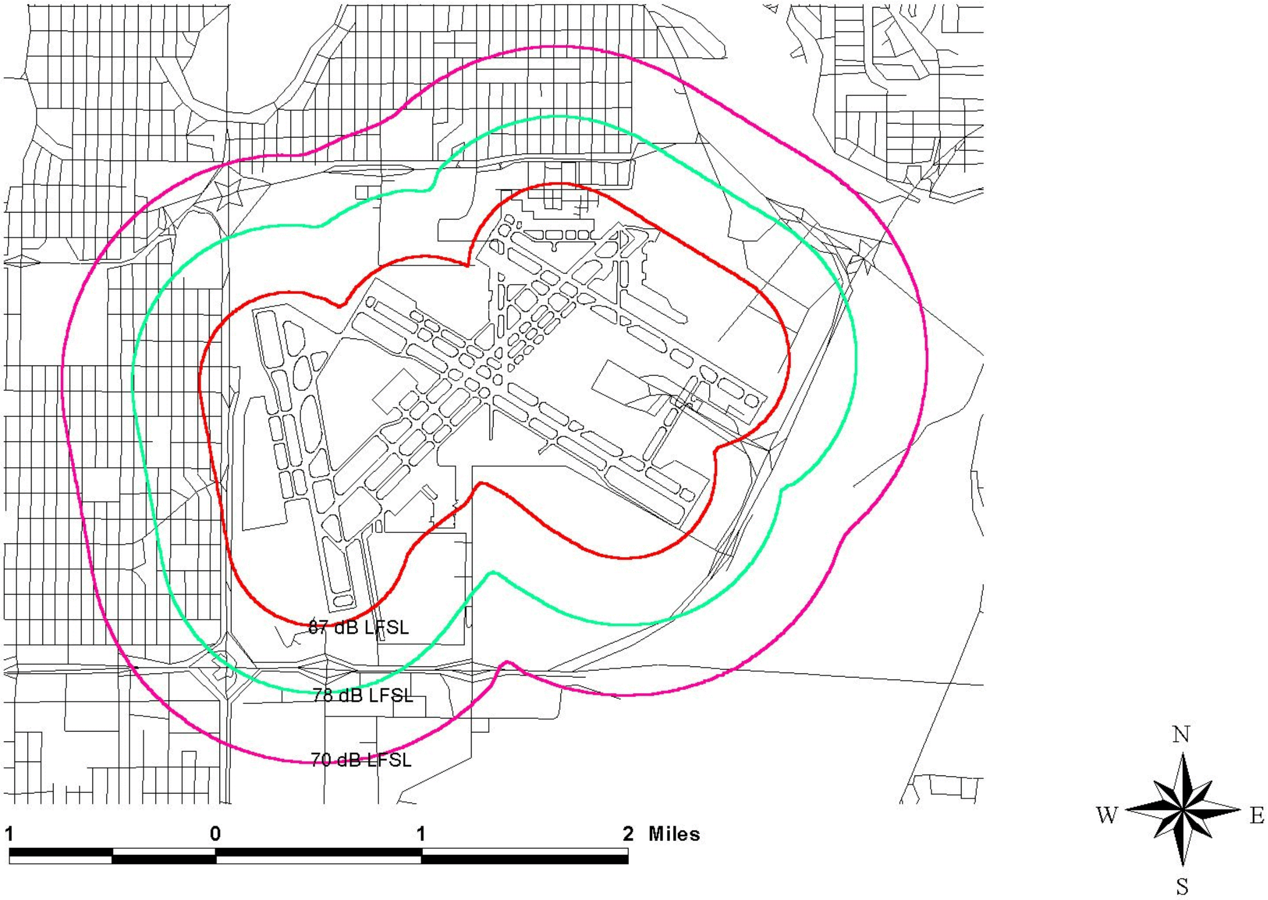

Figure 4 Contours of low-frequency sound levels due to thrust reverser application (per 3 February 2000 revision of Sutherland model).

The Expert Panel did not reach consensus on Figure 4.

however, represent a majority view of the Expert Panel, and are believed to be sufficiently accurate for land use planning purposes.

Although not stated in the 25 April 2000 report, the contours of Figure 4 are for the future, when Runway 17-35 is in use. The figure shows only the noise from reverse thrust operations, not departure noise. It presents contours that are not in agreement with the values measured at MSP. Rather, each contour is one standard deviation greater in extent than the average of the measured data. One standard deviation for these data is 4 dB. Thus the contour represented as 87 dB is actually from the average measured value of 83 dB. In addition, the contours of Figure 4 do not reflect the differences in runway use that have been forecast for future operations at MSP. See the detailed discussion of LFSL dose contours in Section 6.3 of Volume II.

Figure 5 shows the LFSL dose contours that are supported by the measurements at MSP and reflect forecast runway use. See Section 6.3 of Volume II for a discussion of the analysis that is the basis of Figure 5.

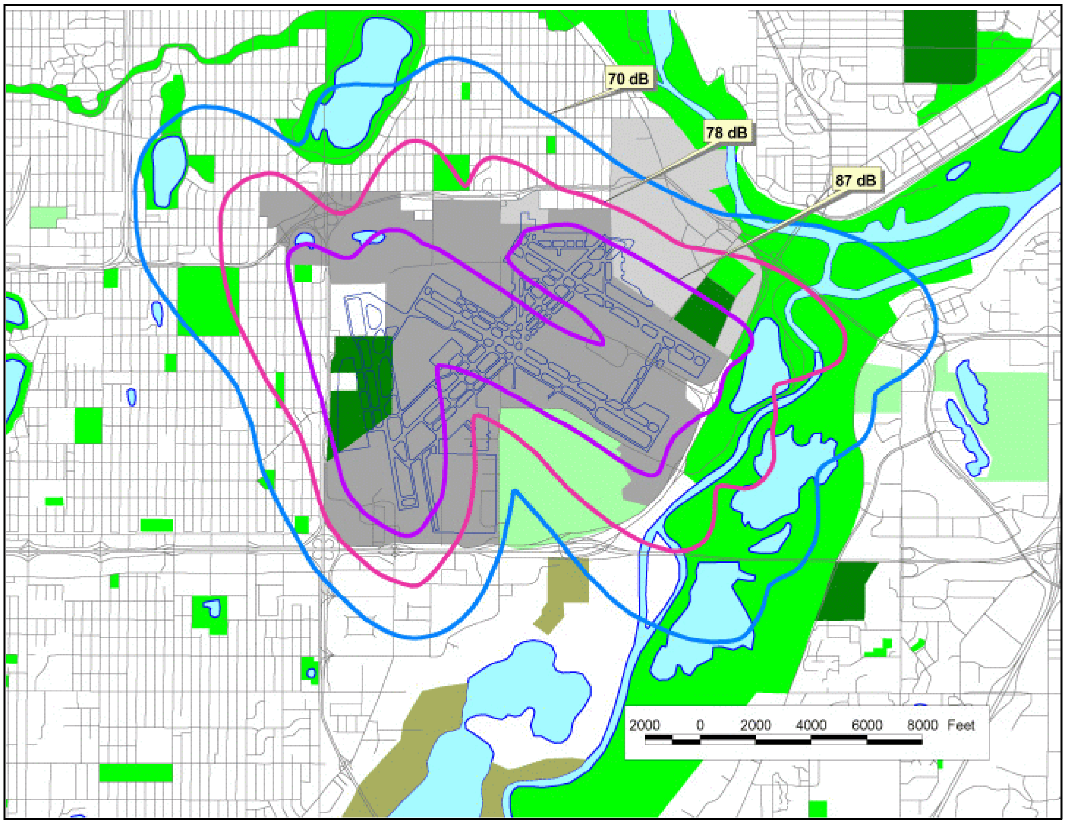

Figure 5 LFSL Dose Contours for Future Operations at MSP (including Departures and Arrivals)

1.2.6 Current and Potential Future Low-Frequency Noise Reduction Measures for Residences near MSP

The Expert Panel reached consensus on these findings

The Expert Panel measured the noise reduction of existing residences in Minneapolis and Richfield to determine the level of low-frequency noise reduction provided by typical residences. Low-frequency noise reduction potential was predicted from laboratory tests and from published findings. The Expert Panel also identified procedures to reduce interior levels of low-frequency noise-induced vibration in existing residences and in new residences.

1.2.6.1 Low-frequency noise reduction measures for current construction

The Expert Panel reached consensus on these findings

Single-family detached residences near MSP provide roughly 15 dB of noise reduction at frequencies between 25-100 Hz regardless of construction type. No meaningful differences were observed in the reduction of LFSL values of homes that had MSP's standard acoustic insulation treatments and homes that had not been so treated. However, the social survey indicates a decrease in percentages of people highly annoyed by rattle in homes that had received the standard treatment. The decrease was equivalent to a 5 dB decrease in sound dose or a 5 dB increase in noise reduction. The lower prevalence of annoyance may be associated with a reduction in window rattling in recently treated homes, or with lower noise levels at frequencies above 80 Hz.

1.2.6.2 Potential for low-frequency noise reduction of residences

The Expert Panel reached consensus on these findings

The low-frequency noise reduction provided by residences can be increased by modifications to the structure. An improvement of approximately 5 dB can be achieved by adding a heavy layer to the outside or inside (*e.g.*, the equivalent of a 1" heavy-weight plaster/stucco skin resiliently supported from the standard construction). The upper limit of improvement is approximately 10 dB. Such an improvement would require use of a complex structure (*e.g.*, a brick wall with minimal openings toward the noise source, and/or an insulated cavity wall with separately supported interior and exterior cladding and multi-pane windows of limited size).

1.2.7 Level of Noise Reduction Required to Achieve Compatibility with Low-Frequency Aircraft Noise Emissions

The Expert Panel did not reach consensus on certain of these recommendations.

Table 2 identifies the nature of treatments to existing residences that can yield increased low-frequency noise reduction. Table 3 identifies treatments required for new construction to be compatible with low-frequency aircraft noise.

Further information about rattle avoidance measures may be found in Section B.11.3 of Volume III.

Alternative proposals for treatment of residences were discussed by the Expert Panel. One set of proposals is presented in Tables 2 and 3. That set of proposals did not recognize the reduction in annoyance achieved by the MSP Residential Sound Insulation Program . A second set of proposals recognizing the reduction in annoyance achieved by the MSP Residential Sound Insulation Program is presented in Tables 2A and 3A.

Table 2 Treatment options for existing single family dwellings exposed to low-frequency noise.

LOW-FREQUENCY SOUND LEVEL (LFSL, in dB)	TREATMENT TO REDUCE RATTLE	TREATMENT TO REDUCE INTERIOR LFSL
< 70	None required	None required
70 - 78	Treat rattle directly, as described in sections B.11.3 *et seq.* of Volume III of this report	Increase low-frequency noise reduction by at least 5 dB
79 - 87	Treat rattle directly, as described in sections B.11.3 *et seq.* of Volume III of this report (may not be fully adequate)	Increase low-frequency noise reduction by more than 5 dB if practicable
> 87	Treat rattle directly, as described in sections B.11.3 *et seq.* of Volume III of this report (probably not fully adequate)	Increase low-frequency noise reduction by 10 dB (probably not economically or esthetically feasible in single family dwellings)

Table 2A Alternative Treatment options for existing single family dwellings exposed to low-frequency noise.

Average Exterior LFSL in dB	Treatment to Reduce Rattle	Interior LFSL Reduction
<70	*None Required*	*None Required*
70-77	*Treat Rattle Directly*	*Decrease interior LFSL by 5 dB**
78-87	*Treat Rattle Directly* *May not be fully adequate*	*Decrease Interior LFSL by 5 dB and Consider Reducing by more than 5 dB*
>87	*Treat Rattle Directly* *Probably not fully Adequate*	*Decrease Interior LFSL by at least 10 dB. Probably not Economically Feasible*

**Based on findings of the social survey, the existing Part 150 Residential Sound Insulation Program provides the equivalent of 5 dB reduction, therefore no further reduction is necessary.*

Table 3 Options for rattle prevention and low-frequency noise reduction for new residential construction in areas exposed to low-frequency noise.

LOW-FREQUENCY SOUND LEVEL (LFSL, IN dB)	RATTLE PREVENTION TREATMENT	MINIMAL LOW-FREQUENCY NOISE REDUCTION OF RESIDENCE
< 70	None required	No special requirement
70 - 78	Rattle prevention (assumes 15 dB low-frequency noise reduction)	15 dB
79 - 87	Rattle prevention (may not be fully adequate; assumes 20 dB low-frequency noise reduction)	20 dB (probably not economically or esthetically feasible in single family dwellings)
> 87	Do not develop for residential use	

Table 3A Alternative options for rattle prevention and low-frequency noise reduction for new residential construction in areas exposed to low-frequency noise.

Average Exterior LFSL in dB	***Rattle Prevention Treatment***	***Interior LFSL Reduction***
<70	*None Required*	*No Special Requirement*
70-77	*Rattle Prevention*	*15 dB*
78-87	*Rattle Prevention*	*20 dB*
> 87	*Do not develop for residential use*	

1.2.8 Plan for Mitigation of Existing and Predicted Impacts of Low-frequency Aircraft Noise

The 25 April 2000 did not present a plan for mitigation of existing and predicted impacts of low-frequency aircraft noise. The discussion of changes in noise reduction in Section 1.2.7 did not describe implementation of the changes. The Expert Panel did not reach consensus on the material in this section.

It is recommended that mitigation of existing and predicted impacts be implemented according to the following sequence:

> ***Evaluate potential barrier effects of existing or planned buildings and evaluate the potential benefits of other barriers. (Include consideration of potential loss of barrier effects due to any anticipated removal of existing buildings or other structures.)***
>
> ***Convert to compatible land use (e.g., commercial land use) any residential areas where the LFSL dose is determined to be 87 dB or higher.***

Evaluate methods for improving the low-frequency noise reduction of existing residences. The goal of the methods is a 5-dB improvement in low-frequency noise reduction for all noise sensitive spaces in a residence.

Evaluate techniques to reduce rattling in residences. Develop a program for rattle reduction to be incorporated into the MSP Residential Sound Insulation Program.

Modify the MSP Residential Sound Insulation Program to include methods to improve low-frequency noise reduction and rattle reduction when appropriate.

Identify blocks to be treated in terms of their LFSL dose in the categories shown by Tables 2A and 3A. (Treat blocks intersected by LFSL dose contours as if the whole block were included within the contour.)

Identify treatments to be undertaken in each residence in accordance with its noise environment and its degree of previous treatment, if any. (It is assumed that this treatment will be undertaken within the MSP FAR Part 150 process. Treatment is to be based on the LFSL dose that is identified in the FAR Part 150 process.)

Establish a schedule for treatment that is consistent with the approach used by the existing MSP Residential Sound Insulation Program.

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VOLUME II

2 LOW-FREQUENCY NOISE DESCRIPTOR RECOMMENDED FOR USE BY POLICY COMMITTEE

Section 2 does not fully describe the Expert Panel's actions. (See the comments below.)

This Chapter describes the Expert Panel's analyses of metrics of low-frequency aircraft noise, and recommends a preferred descriptor to the Policy Committee.

2.1 SUMMARY OF EXPERT PANEL RECOMMENDATION

The Expert Panel recommends that the Policy Committee adopt a descriptor of low-frequency sound level computed as the sum of the maximum levels during the course of individual aircraft noise events in the six one-third octave bands from 25 Hz through 80 Hz, inclusive. This descriptor is most directly related to the noise effect of interest (rattle-induced annoyance), and less susceptible than other descriptors to the influence of noise energy in extraneous frequency regions.

The Expert Panel reached consensus on two descriptors, a descriptor for single event low-frequency noise and a descriptor for low-frequency noise dose. See discussions in parts 1.2.3, 2.6.2 and 2.8.

2.2 PURPOSE AND INTERPRETATION OF A DESCRIPTOR OF LOW-FREQUENCY AIRCRAFT NOISE

Noise may be measured in as many ways as there are purposes for making measurements. Appendix B describes several low-frequency noise metrics intended for various purposes. The present need for a descriptor of low-frequency aircraft noise is to serve as a reliable predictor of the effects of such noise on residential populations. The preferred descriptor of low-frequency aircraft noise need not be optimal for any other purpose. In the present context, a noise descriptor that correlates usefully with the quantity that it is intended to predict suffices.

For present purposes, a noise descriptor is simply a physically measurable index of an acoustic quantity. A noise descriptor must therefore be distinguished from its interpretation. Without an interpretive criterion — a statement of the effect of noise on people, of the form "so much noise is associated with so much effect" — a noise descriptor is no more than an arbitrary numeric expression of a quantity of sound, devoid of any implications.

Thus, clear distinctions must be maintained

> between a *noise descriptor* and *criteria* relating the descriptor to a predicted effect;
>
> between such *criteria* and an environmental *policy* based on a particular value of a noise descriptor; and

between technical and other reasons for preferring certain noise descriptors.

An interpretive criterion relates a given quantity of sound, measured in a particular way, to some effect of interest. For example, FICON's (1992) well-known dosage-effect function relates values of DNL to the prevalence of consequential degrees of annoyance in residential populations. This interpretive criterion predicts that about 12% of residential populations will be highly annoyed by the quantity of transportation noise exposure characterized by a value of DNL of 65 dB. Note that FICON's relationship does not establish that DNL actually *causes* annoyance,[6] but only that it is an adequate predictor of the prevalence of annoyance for certain purposes.

It is important to distinguish further between an interpretive criterion for a noise descriptor and a policy statement based on the criterion. The fact that DNL is a useful predictor of the annoyance of aircraft overflight noise does not of itself compel selection of any particular value of DNL for policy purposes. Selection of DNL values to serve legislative or regulatory purposes is an expressly ***non-*** technical matter. In the present circumstances, it is the Policy Committee that must make value judgments about tolerable levels of low-frequency aircraft noise based on information provided by the Expert Panel.

Finally, it is important to bear in mind that entities other than the Expert Panel and the Policy Committee may view various noise metrics from non-technical (economic, legislative, regulatory, political, or other) perspectives. These alternate perspectives are independent of the information presented in this report about noise effects, descriptors, and interpretive criteria.

2.3 INADEQUACIES OF A-WEIGHTED MEASUREMENTS FOR PRESENT PURPOSES

As a matter of FAA policy, the Day-Night Average Sound Level (DNL) is the principal descriptor of aircraft noise for purposes of predicting community impacts of aircraft noise exposure. Since DNL is by definition an A-weighted noise metric, the A-weighting network underlies all common analyses of aircraft overflight noise undertaken for purposes of compliance with FAA's environmental impact assessment policies.

The A-weighting network is by design very insensitive to sound energy at low frequencies. For example, it reduces the unweighted sound level at 80 Hz by 22.5 dB, and it reduces the unweighted sound level at 25 Hz by 44.7 dB. This implies that two sounds of the same A-weighted level may differ by several orders of magnitude in low-frequency content. The A-weighting network is thus inappropriate for present purposes because A-weighted measurements cannot distinguish between sounds of vastly different low-frequency content, which also contain substantial energy at higher frequencies.

As noted elsewhere in this report, the aircraft noise of current interest is that which is likely to induce audible rattle in residences. The frequency range most likely to induce these secondary emissions

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[6] Indeed, no persuasive evidence has been produced that *any* time-weighted average sound level, calculated over any specific period with any particular weighting factors, truly *causes* annoyance. DNL was initially developed simply as a comprehensive and easily manipulated measure of environmental noise, well in advance of its subsequent use as a predictor of the prevalence of a consequential degree of noise-induced annoyance.

in homes is the region below 100 Hz. It follows that the most useful noise descriptor for present purposes is one sensitive only to the frequency region below 100 Hz.

An ideal descriptor of low-frequency aircraft noise would be simple to measure, insensitive to noise in extraneous frequency regions (whether produced by aircraft or other sources), and strongly predictive of noise-induced rattle in residences. Although low-frequency noise from aircraft operations has been studied to some extent at other airports, no single physical measure of such noise has yet gained acceptance as a *de facto* standard metric, nor has any single measure of low-frequency noise created by non-aviation sources gained widespread acceptance, nor has FAA adopted or rejected any descriptor of low-frequency aircraft noise for policy purposes.

The Expert Panel considered two types of potential descriptors: (1) those with which panel members had direct experience in prior airport-related studies, and (2) those identified through the literature review. The former group consisted of two descriptors: the sum of the maximum levels in the six one-third octave bands from 25 Hz through 80 Hz (Lind *et al.*, 1997), identified hereafter as Low-Frequency Sound Level (LFSL); and C-weighted sound level (HMMH, 1996, 1998). The latter group of low-frequency noise descriptors, including Low-Frequency Noise Rating (LFNR), Loudness Level (LL), Low-Frequency Sound Level Weighting (LSL), and the Energy Sum of Sound Levels in 16, 31.5 and 63 Hz octave bands (L_{LF}), is described in Section 2.5.

2.4 INADEQUACIES OF C-WEIGHTED SOUND EXPOSURE LEVEL FOR PRESENT PURPOSES

Figure 6, a comparison of the A- and C-weighting networks, shows that the C-weighting network does not discriminate as greatly against low-frequency sounds as the A-weighting network. C-weighting slightly de-emphasizes the very lowest frequencies, but has little effect on other low-frequency sound levels in the range of current interest.

However, the C-weighting network does not differ greatly from the A-weighting network at frequencies higher than 500 Hz. This implies that C-weighted measurements are strongly influenced by sound energy in mid- and high-frequency ranges that is unlikely to cause rattle in residences. Thus, the C-weighted levels of two sounds with identical low-frequency content can differ greatly if the high-frequency content of the two sounds differs.

In practice, aircraft noise heard at distances on the order of a mile or more from its source contains relatively little high-frequency energy. For purposes of predicting low-frequency aircraft noise levels in close proximity to runway sidelines, the sensitivity of C-weighted measurements to high-frequency sound energy clearly limits their utility. The Expert Panel did not dismiss C-weighted noise descriptors out of hand despite this important limitation, for several secondary reasons:

> The C-weighting network is a familiar one that is well understood by many environmental noise analysts (for example, C-weighted measurements have been made in earlier analyses of aircraft “ground,” *i.e.*, low-frequency, noise at MSP and elsewhere);

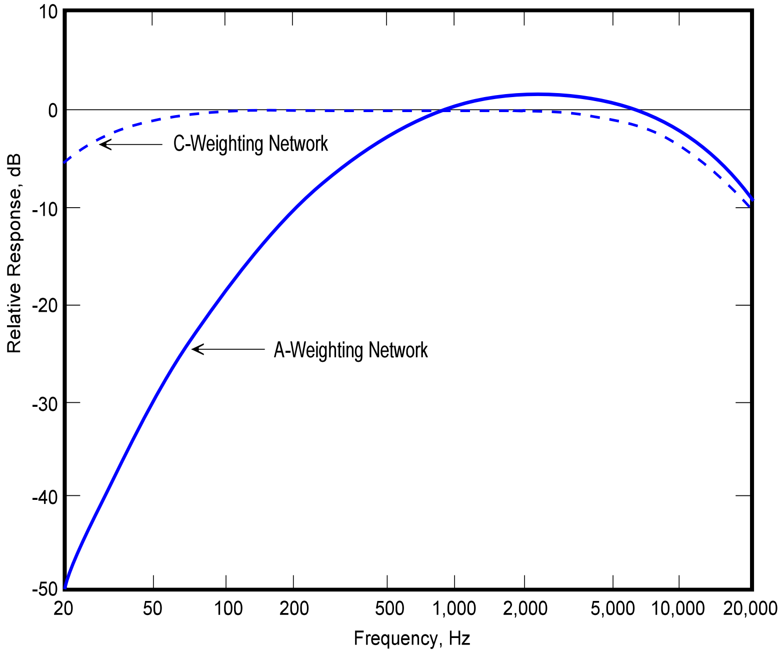

Figure 6 Comparison of A and C frequency-weighting networks.

Version 6.0 of FAA's Integrated Noise Model aircraft noise exposure prediction software computes C-weighted noise exposure and maximum sound level metrics; and

It is possible in certain circumstances to estimate low-frequency aircraft noise levels (*e.g.*, LFSL) from knowledge of C-weighted sound levels.

2.5 NON-PREFERRED DESCRIPTORS OF LOW-FREQUENCY SOUND

Many suggestions have been offered for means of describing low-frequency noise from various sources. The better documented descriptors of low-frequency noise that have emerged from this work are noted in this subsection. The Expert Panel considered and rejected each of these in recommending use of LFSL for current purposes.

2.5.1 Low-Frequency Noise Rating (LFNR)

LFNR is expressed in contours of one-third octave band levels *versus* frequency that closely resemble loudness contours over a frequency range from about 16 Hz to more than 1 kHz (Broner and Leventhall, 1983). The shape of the LFNR contour that passes through a one-third octave band level of 80 dB at 1,000 Hz is compared in Figure 82 (Volume III, Section B.3.1) with various loudness contours.

2.5.2 Equal Annoyance Contours for Low-Frequency Sound

Several researchers have identified one-third octave band sound levels for which the annoyance from low-frequency sound is constant (Andresen and Møller, 1984; Møller, 1987; Broner and Leventhall, 1984). As shown in Figure 88, contours of "equal annoyance" from Andresen and Møller (1984) and LFNR are quite similar to loudness contours in the low-frequency range. The differences between the "equal annoyance," "low-frequency noise rating" and the various loudness contours appear to be comparable to the differences between these loudness contours as measured by different investigators. Thus, the annoyance of very low-frequency sounds is probably adequately described by their loudness.

The spectra of the low-frequency sounds studied by Broner and Leventhall, (1983), Andresen and Møller (1984) and Møller (1987) tend to be dominated entirely by very low-frequency noise that lacks the higher frequency content that accompanies aircraft noise. One study of low-frequency sounds of varying spectral shape found that, all other things being equal, spectra closer to those of aircraft were more annoying than spectra with less energy above 250 Hz (Goldstein and Kjellberg, 1985).

2.5.3 Low-Frequency Level (L_{LF})

One recent descriptor of low-frequency sound is contained in American National Standards Institute standard, ANSI S12.9, Part 4 (American National Standards Institute, 1996). This low-frequency noise descriptor is defined as the energy sum of octave band sound levels in the 16, 31.5 and 63 Hz octave bands. This sum is translated into an equivalent A-weighted sound level to provide a measure, in terms of the more common A-weighted sound level, of community noise impact to relatively intense low-frequency sounds. This translation uses a non-linear conversion between C- and A-weighted sound levels to approximate the greater sensitivity of hearing to changes in low-frequency sound levels than for mid- or high-frequency sounds. The descriptor was intended primarily for evaluation of annoyance from high-energy sounds with substantial low-frequency energy, such as that produced by artillery, mining blasts, or sonic booms. Due to the lack of a database for aircraft noise measurements employing this descriptor, and the lack of experience with its use for evaluation of low-frequency aircraft noise, it was not considered for present purposes even though it is the only descriptor of low-frequency sounds codified in U.S. ANSI standards.

2.5.4 Balanced Noise Criterion Curves

These noise criterion curves evolved from earlier methods for rating the acceptability of noise in office spaces (Beranek, 1989; Blazier, 1991). The "NCB" curves are represented as contours of octave band sound levels from 16 to 8,000 Hz. The use of the curves is largely restricted to rating noise environments of non-residential occupied spaces such as theaters and offices, especially for purposes related to speech communication and musical entertainment. They are similar to loudness contours from about 63 to 1,000 Hz, but are generally lower than loudness contours for lower frequencies. The highest NCB contour lies generally below the maximum low-frequency octave band levels of present interest.

2.5.5 G-Weighting Curve for Infrasonic Measurements

An international standard has been developed for the evaluation of "infrasonic" noise environments with energy concentrated below 20 Hz (International Organization for Standardization, 1995). The standard provides a frequency weighting curve with a peak at a frequency of 20 Hz that falls off at about 12 dB/octave below 16 Hz, and at about 24 dB/octave at frequencies above 22 Hz. While such a weighted measure of low-frequency noise might be a sensitive measure of the levels likely to cause vibration of building walls, and hence rattle, it was not considered for several reasons:

1. the frequency range of the weighting is too restrictive for present purposes;

2. measurement of sounds at such low frequencies requires specialized equipment;

3. no database of G-weighted sound levels of aircraft noise emissions has been compiled;

4. noise sources other than aircraft, such as large industrial fans and helicopter main rotors, radiate strongly in this frequency range, thus complicating field measurements of low-frequency aircraft noise; and

5. no G-weighted criterion sound levels are known for assessing community response to "infrasonic" noise exposure.

2.5.6 Low-Frequency Level Weighting (LFL)

LFL was developed for assessment of community reaction to the unique low-frequency signature of wind turbines (Kelley, 1987). This large power generation machinery often produces high levels of narrow band (tonal) low-frequency energy that can be disturbing at considerable distances from the source. One form of the descriptor is obtained from a C-weighted sound level modified by passing the sound level signal through a 100 Hz low-pass filter (American Wind Energy Association, 1989). Levels obtained from such a descriptor would not differ markedly from LFSL values. The lack of an aircraft noise database measured with the LFL descriptor limits its utility for present purposes.

2.6 LOW-FREQUENCY SOUND LEVEL (LFSL)

This descriptor of low-frequency aircraft noise was developed from first principles as a predictor of aircraft noise-induced rattle. It was first used by Lind *et al.* (1997) to estimate future low-frequency aircraft noise levels in Richfield, and subsequently applied by Fidell, Silvati, Pearsons, Lind, and Howe (1999) to characterize low-frequency aircraft noise levels in social surveys of the annoyance of aircraft noise-induced rattle in the vicinity of Los Angeles International Airport and at MSP. LFSL is a single-event noise metric that sums the maximum one-third octave band sound levels from 25 to 80 Hz, inclusive, that occur during the course of an individual aircraft passby.

The rationale for constructing LFSL as a descriptor of low-frequency aircraft noise is described in the following subsections.

2.6.1 Range of Frequencies Considered

The bandwidth of the LFSL descriptor was selected to span the intersection of several frequency ranges:

> the low-frequency range in which aircraft engines produce relatively large amounts of noise during ground operations (including taxiing, queueing, takeoff run, and thrust reverser deployment);

the low-frequency range likely to excite secondary emissions in light architectural elements of residences (windows, doors), as well as the contents of residences (mirrors, pictures, bric-a-brac, *etc.*);

the frequency range for which common acoustic field instrumentation is designed;

the frequency range that preserves a sufficient degree of correlation with C-weighted aircraft noise levels that noise contouring software has some utility in predicting noise exposure gradients; and

the frequency range least adequately represented by A-weighted measurements.

It was further desired that LFSL be insensitive to the emissions of very low-frequency sound sources, such as large industrial fans and helicopter main rotors.

The noise emissions of the large engines of jet transport aircraft include a broad spectral peak in the one-third octave bands in the vicinity of 100 Hz. Although a jet noise spectrum contains energy at frequencies two or three octaves below its peak, the value of a noise metric sensitive to jet noise in the one-third octave band centered at 25 Hz will be highly correlated with a noise metric sensitive to jet noise at yet lower frequencies. For purposes of predicting rattle produced by the noise emissions of aircraft ground operations, a low-frequency noise metric need not encompass *all* of the low-frequency energy produced by jet engines. (When used as a predictor of rattle, the critical issue is not the scaling factor of the predictor, but the correlation of the descriptor with the prevalence of rattle-induced annoyance.)

The primary structural resonances in wood frame residential construction occur in the octave from about 10 to 20 Hz, a frequency range about an octave below that considered by LFSL. Although houses are most sensitive to structural vibration at these frequencies, Hubbard (1982) and others have shown that they are also excited by airborne sound at higher frequencies (*cf.* Section B.4.1 of literature review).

Measurement of sound levels at frequencies as low as 20 Hz are routinely made with common acoustic field instrumentation. Specialized acoustic instrumentation may be required to make meaningful measurements at frequencies an octave or two lower.

2.6.2 Non-Cumulative Nature of Descriptor

The Expert Panel did not reach consensus on this point.

LFSL was developed for basic physical and statistical reasons as a short-term, single-event noise measure, rather than as a long-term, cumulative, or time-weighted average metric. A cumulative noise metric is a useful predictor of the long-term annoyance of aircraft noise exposure because the degree of long-term annoyance is not determined exclusively by any single noise event. A window, on the other hand, rattles in real time, not at the end of some long-term averaging period. LFSL was intended primarily as a direct predictor of rattle, not of long-term annoyance *per se*. Although LFSL was constructed from first principles as a predictor of rattle, it has subsequently been shown empirically to function well as a predictor of the annoyance engendered by rattle.

The Expert Panel reached consensus on the use of LFSL as the descriptor of low-frequency noise of aircraft single events (i.e., a takeoff or a landing). As reported in Section 1.2.3 above, the Expert Panel also reached consensus on the use of "the arithmetic average of the greatest low-frequency sound levels of aircraft noise events in excess of LFSL = 60 dB as the measure of effective low-frequency aircraft noise dose." Since it accounts for multiple events during a day, the aircraft noise is inherently cumulative, not a single event descriptor. Nonetheless, the Expert Panel could not reach consensus on the point of cumulativity.

2.7 RELATIONSHIP BETWEEN LFSL AND C-WEIGHTED LEVEL

The Expert Panel compared C-weighted and LFSL descriptors of aircraft ground and near-ground noise measured at MSP and elsewhere. Figure 7 shows the locations of measurement sites for the data considered. The locations vary in distance perpendicular to the runway as well as in distance along the runway. The aircraft is on the ground and beginning its takeoff roll when measured at location "G." The aircraft is airborne when measured at location "f" or beyond that location.

Figure 8 shows the relationships between maximum LF level and maximum C-weighted level for eight sets of measurements at varying distances along runway sidelines at two airports. The data form three groups. The lines on the graph represent the best-fit straight line through each of the groups of data. The relationship between LFSL and maximum C-weighted level differs among the three groups of data. The data in Group 1, measured at location "G," show maximum LF level to be 0 to 2 dB greater than maximum C-weighted level. The data in Group 2, measured at locations where the aircraft are airborne but very close to the runway, show maximum LF level to be 5 to 7 dB less than maximum C-weighted level. The data in Group 3, measured at locations where the aircraft are airborne and at greater distances from the runway, show maximum LF level to be 10 to 12 dB less than maximum C-weighted level.

It is apparent from these data that the maximum C-weighted level is sufficiently influenced by the levels of noise at frequencies greater than 80 Hz that it does not have a constant relationship to LFSL. The Expert Panel concludes from this analysis that maximum C-weighted level alone is not an appropriate descriptor for low-frequency aircraft noise at MSP, but it may provide a useful means of estimating LFSL values.

2.8 RECOMMENDATION

The Expert Panel reached consensus on a more complete recommendation than is presented here. There was also an issue of application of the recommendations where the Expert Panel did not reach consensus.

The Expert Panel recommends that the Policy Committee describe low-frequency aircraft noise in residential areas near MSP in units of LFSL.

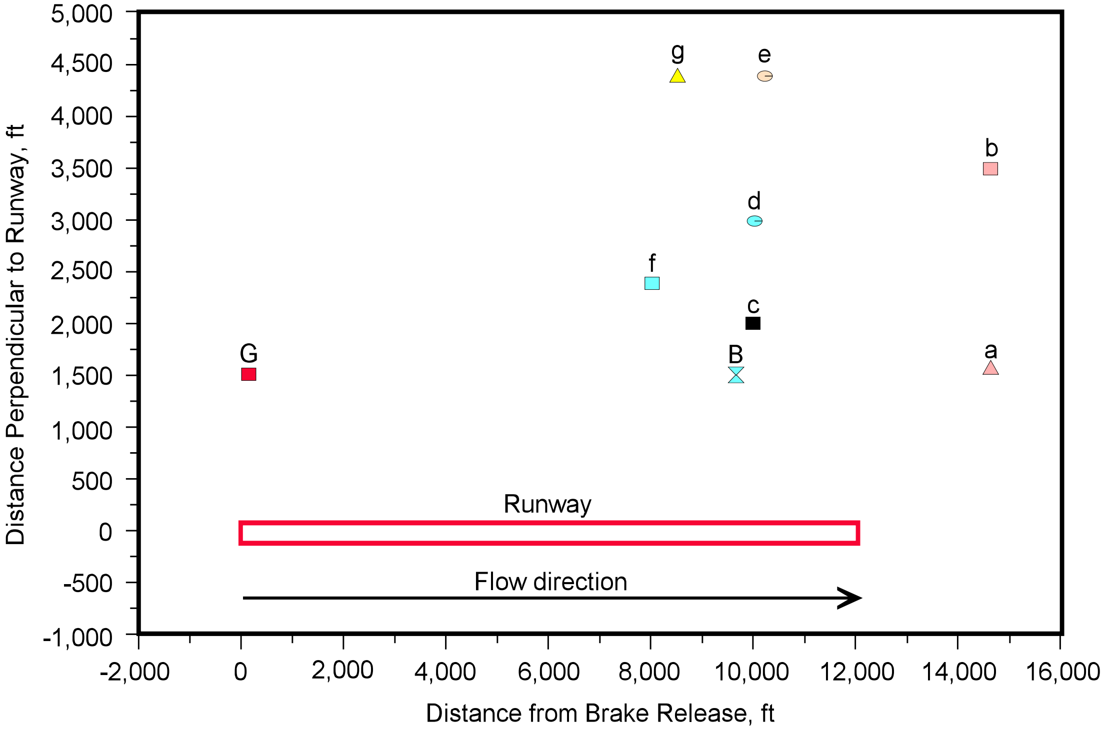

Figure 7 Locations of BBN and HMMH low-frequency aircraft noise measurements with respect to runways.

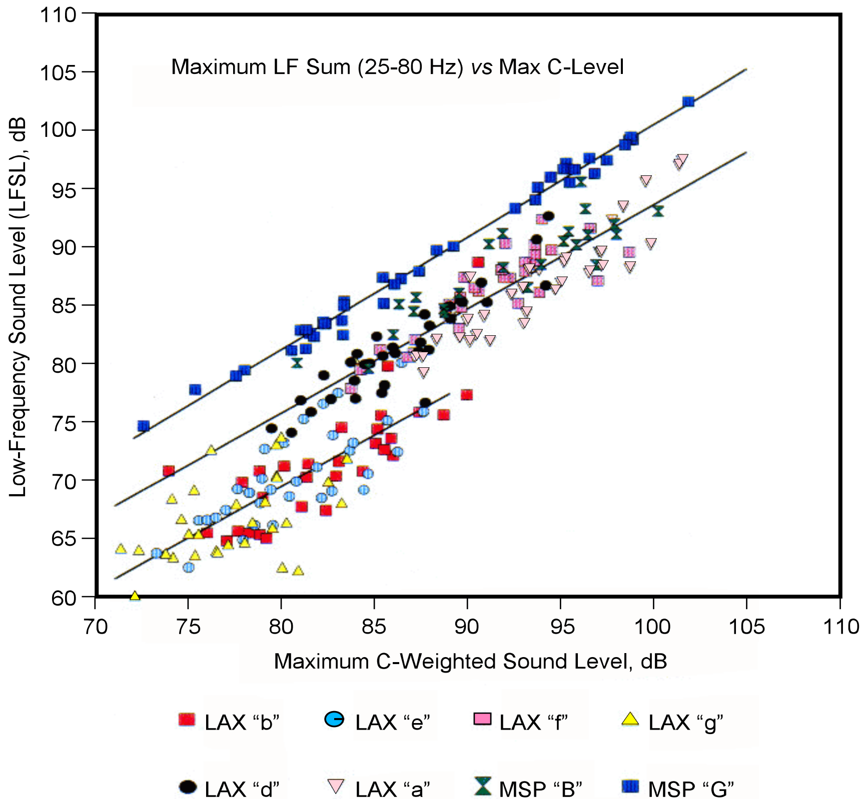

Figure 8 Linear regressions of measurements made at two airports of maximum C-weighted noise levels on LFSL values.

The Expert Panel reached consensus on single-event and multiple-event descriptors of low-frequency aircraft noise. They are repeated here from Section 1.2.3: vThe Expert Panel previously recommended that the Policy Committee adopt the sum of the maximum sound levels in the 25 - 80 Hz one-third octave bands ("low-frequency sound level," abbreviated LFSL) during individual aircraft noise events as the preferred descriptor of low-frequency aircraft noise in the vicinity of MSP. The Expert Panel further recommends that the Policy Committee adopt the arithmetic average of the greatest low-frequency sound levels of aircraft noise events in excess of LFSL = 60 dB as the measure of effective low-frequency aircraft noise dose."[7]

The Expert Panel did not reach consensus on the inclusion of runway use as a factor determining the LFSL dose on specific runways. Runway use is incorporated in the contours of Figure 5 as presented in Section 1.2.5.2. Relative runway use was used to adjust the contours of Figure 5. The adjustment factor was 10 x log (runway x / runway p) where runway x was the runway being adjusted and runway p was the primary runway for the type of operation. (See discussion in Section 6.5.3.)

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[7] ***See footnote at Section 1.2.3***

3 COMPARATIVE ANNOYANCE OF RUNWAY SIDELINE, DEPARTURE AND OVERFLIGHT NOISE

The Expert Panel reached consensus on the results reported in Section 3.

This chapter summarizes an experiment conducted under controlled laboratory conditions to quantify (1) the relative annoyance of runway sideline and aircraft overflight noise; (2) the annoyance of rattle associated with low-frequency runway sideline noise; and (3) the ability of low-frequency noise reduction treatments to homes to reduce the annoyance of low-frequency aircraft noise.

3.1 SUMMARY OF LABORATORY STUDY OF ANNOYANCE

It was found that the low-frequency content of runway sideline noise renders it more annoying than aircraft overflight noise at comparable A-weighted levels; that even minor amounts of rattling sounds increase the judged annoyance of runway sideline noise; and that reducing the low-frequency content of runway sideline noise proportionally reduces the annoyance of sideline noise.

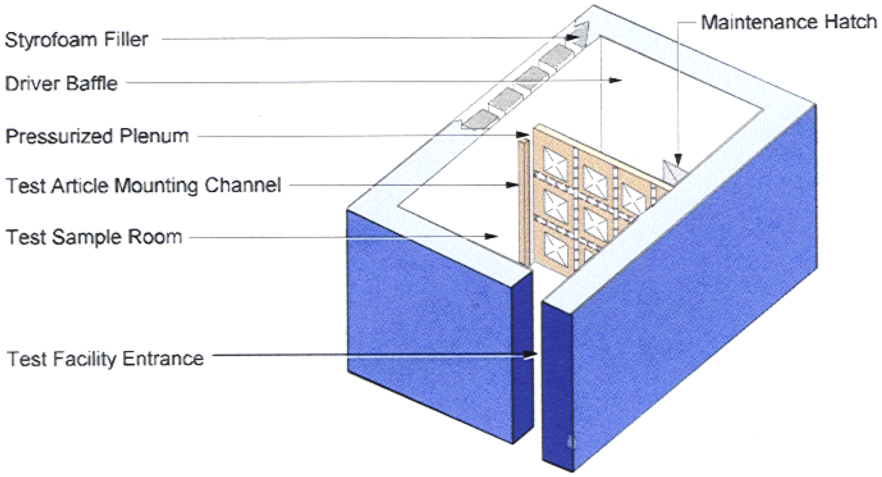
3.2 METHOD

An empirical study of the effects of low-frequency content of aircraft noise and of rattle on annoyance was conducted in a laboratory setting. Sounds heard by test participants were selected to test hypotheses about the relative annoyance of runway sideline and aircraft overflight noise; about the effect of rattle on annoyance judgments; and about the efficacy of potential reductions in the low-frequency content of runway sideline noise for mitigating the annoyance of such noise exposure.

3.2.1 Description of Test Environment and Procedures

All annoyance judgments were made in a large concrete chamber built for controlled generation of sounds at very low frequencies and very high sound levels. Figure 9 is a schematic representation of this facility. Figure 10 shows the drive modules that create noise at frequencies below 100 Hz.

Subjects entered the test facility with the experimenter prior to the start of testing to familiarize themselves with the environment and listen to typical signals. They were seated individually, facing a curtain (see Figure 11) hung in front of a full-scale plaster wall, behind which the low-frequency drive modules were mounted. Two high-quality loudspeakers installed just behind the curtain, but in front of the plaster wall, reproduced the high-frequency (above 100 Hz) portion of the signals. An intercom and a video camera permitted an experimenter located in a nearby control room to communicate with and view subjects at all times.



LOW-FREQUENCY TEST FACILITY

- Loudspeaker-based, sealed-enclosure-type test facility. Twelve clusters of servomotor-driven loudspeakers reproduce the signal of interest.
- Test facility is 4.6 by 6.7 m by 3.2 m tall, constructed from steel-reinforced concrete.
- Interior test volume can be repartitioned to suit a variety of testing requirements.

Figure 9 Schematic representation of low-frequency test facility.

Figure 10 Interior view of low-frequency test facility.

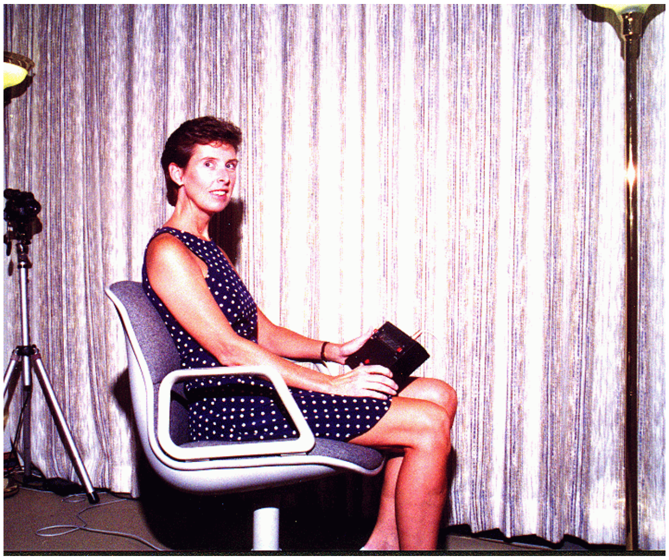


Figure 11 Interior view of low-frequency test facility test subject chamber, showing seated test participant holding response box used to record subjective judgments.

3.2.2 Solicitation of Annoyance Judgments

A paired comparison procedure was administered to solicit direct judgments of the relative annoyance of test signals. Subjects were instructed to judge whether the first or second signal presentation of each trial was the more annoying. Ten such trials were presented for each signal pair. The durations of the signal presentation intervals were determined by the durations of the signals themselves. The duration of the response interval was determined by a subject's response latency.

Signal generation and presentation, as well as all other aspects of data collection, were under real-time computer control. Figure 11 diagrams the signal generation and presentation hardware. The order of presentation of the fixed and variable signals was randomized on a trialwise basis. The order of presentation of signal pairs was independently randomized and fully interleaved, so that subjects were unable to predict which element of which signal pair would be heard next. Four test sessions lasting approximately 25 minutes each were conducted per day.[8] Subjects were required to leave the test facility between testing sessions.

A maximum likelihood estimation algorithm described by Green (1990, 1995) and by Zhou and Green (1995) adaptively controlled signal presentation levels in real time, on the basis of test participants' ongoing decisions. The underlying psychometric function was assumed to be a cumulative Gaussian with a standard deviation of 10 dB. The value of the estimated point on the psychometric function was 50%:

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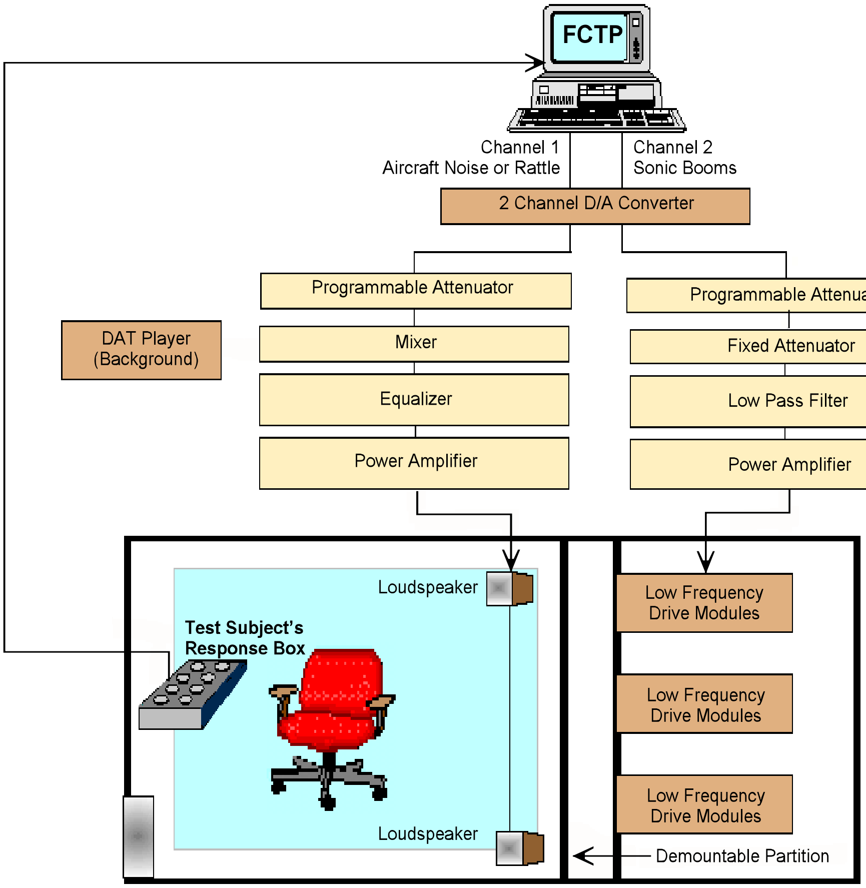
[8] Since subjects were not forced to respond within a fixed duration response interval, the pace of data collection varied slightly from session to session.

the point of subjective equality of annoyance. At this point, subjects rated the comparison (variable level signal) more annoying 50% of the time and the standard (fixed level) signal more annoying 50% of the time.

This point was approached by a binary search algorithm. Step sizes between trials ranged from a minimum of 2.5 dB to a maximum of 40 dB. The maximum signal presentation level was approximately 110 dB. Ten trials were administered for each determination of the relative annoyance of signal pairs, sufficient to yield a standard deviation of the point of subjective equality of annoyance of approximately 4 dB.

A long-duration digital recording of shaped Gaussian noise was reproduced at all times that subjects were present in the test facility. The A-level of the background noise at the subject's head position was approximately 41 dB.



Low-Frequency Test Facility

Figure 12 Illustration of instrumentation controlling administration of test conditions in the low-frequency test facility.

3.2.3 Description of Test Signals and Presentation Levels

Table 4 shows the five test signals presented at fixed levels and the three test signals presented at variable (subject-controlled) levels. Figure 13 shows the one-third octave band spectra of the signals at the listening position. All signals were presented for judgment as they would be heard indoors, at a fixed duration of 15 seconds each. The fixed level signal was an outdoor recording of runway sideline noise made at a distance of 1,500 feet from Runway 29L at MSP (Lind, Pearsons, and Fidell, 1997), filtered to modify its spectrum to represent indoor listening conditions in an acoustically untreated residence. Intermittent rattle was digitally added in two test conditions to the indoor sideline noise test signal near its peak, at a level that did not alter the A-weighted level of the test signal.

Table 4 Summary of signal pairs presented to subjects for relative annoyance judgments. Presentation levels refer to those occurring at the time of the maximum for each signal.

Fixed Level Signal	A-Weighted Presentation Level (dB)	Variable Level Signal	Paired Comparison ID Number
Sideline noise recorded at 1,500 feet	70	B-727	1
		B-757	2
		Departure ("backblast")	3
Sideline noise recorded at 1,500 feet with added rattle	70	B-727	4
		B-757	5
		Departure ("backblast")	6
Sideline noise with 5 dB of C-weighted noise reduction	65	B-727	7
		B-757	8
		Departure ("backblast")	9
Sideline noise with 5 dB of C-weighted noise reduction with added rattle	65	B-727	10
		B-757	11
Sideline noise with 10 dB of C-weighted noise reduction	60	B-727	12

The fixed level signal was further processed under other test conditions to attenuate it by 5 dB and 10 dB of C-weighted noise reduction. This noise reduction was assumed to increase at a rate of 6 dB per octave.

The test signals presented at subject-controlled level were a flyover by a Stage II aircraft (a Boeing 727), a flyover by a Stage III aircraft (a Boeing 757), and a recording of aircraft departure ("backblast") noise.

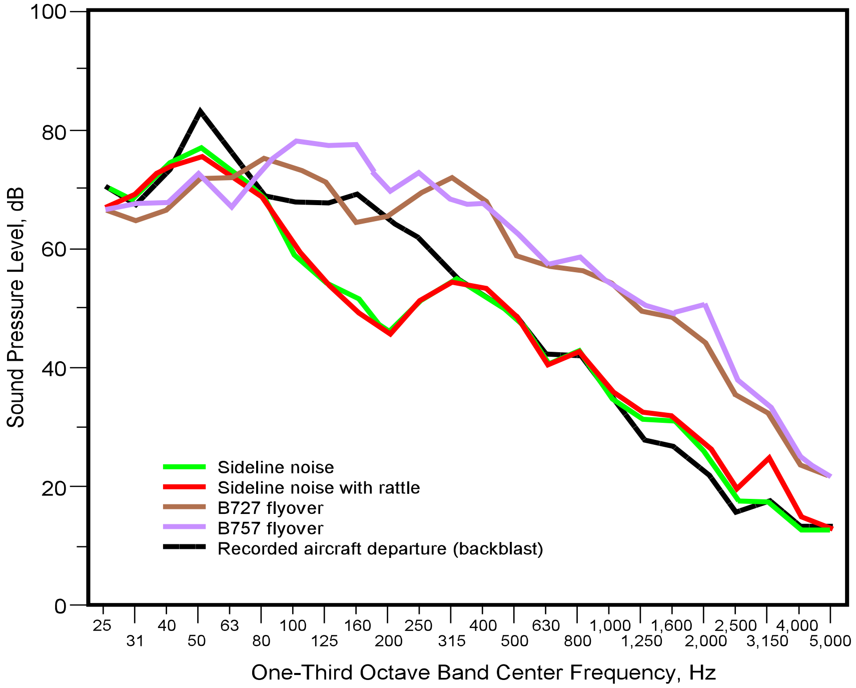


Figure 13 Spectra of test signals as measured at subject's head position.

3.2.4 Subjects

Informed consent for participation in the present study was obtained from 30 paid subjects. Test participants were audiometrically screened to within 20 dB of normal hearing (ISO, 1975, audiometric zero) over the frequency range of 100 to 6,000 Hz prior to testing. No meaningful changes in hearing were observed upon completion of the judgment tests. Twenty-eight test participants completed all testing. Twelve of the twenty-eight test participants were women ranging in age from 18 to 46, while sixteen were men ranging in age from 18 to 40. The average age of all participants was 24 years.

3.3 RESULTS

This section describes the results of data collection, reliability analyses, and analyses of paired comparison judgments. The basic unit of analysis is the sound level of a variable level signal when judged equal in annoyance to a fixed level signal on the final signal pair presentation.

3.3.1 Data Collection and Processing

The twelve signal pairs presented ten times to each of 28 subjects yielded a total of 3,360 paired comparison judgments. The twelve determinations of points of subjective equality of annoyance by each of the 28 subjects produced a total of 336 data points.

3.3.2 Reliability of Annoyance Judgments

3.3.2.1 Comparisons of signal versus itself

One paired comparison judgment was solicited for initial screening purposes, and to quantify the reliability of annoyance judgments. Subjects unable to adjust the level of the variable level signal to that of the same signal presented at a fixed level (within ±7 dB) were not permitted to participate in the study. Only two potential test subjects were unable to do so. Figure 14 shows the differences between the variable and fixed level signals at the point of subjective equality for 28 test subjects. The mean difference between the signal and itself at the point of subjective equality was -0.5 dB. Most subjects were able to adjust the variable level signal to within ± 4 dB of the same signal in this initial paired comparison.

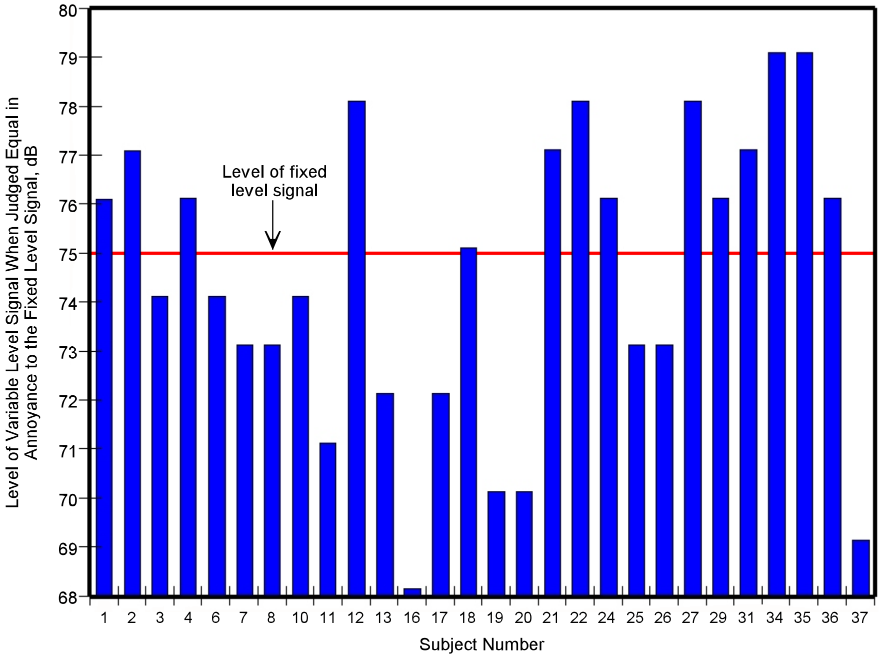


Figure 14 Level of the variable signal when judged by 28 test subjects to be equal in annoyance to the same signal fixed at 75 dB.

The standard deviations of the differences between the levels of the sideline noise and the variable level signals at points of equal annoyance for the 12 paired comparisons ranged from 3.2 to 9.2 dB. Widths of the 90% confidence intervals of the mean annoyance judgments were 1 to 2 dB.

3.3.3 Analysis of Relative Annoyance of Sideline and Overflight Noise

Figure 15 displays the differences in A-weighted sound level between the variable level signals and sideline noise when judged equal in annoyance by each subject for all 12 comparisons. (Many overlapping judgments are obscured by the plotting symbols.) Points above the heavy horizontal line at 0 dB indicate that the fixed level signal (sideline noise) was presented at a higher level than the variable level signal at the point of subjective equality.

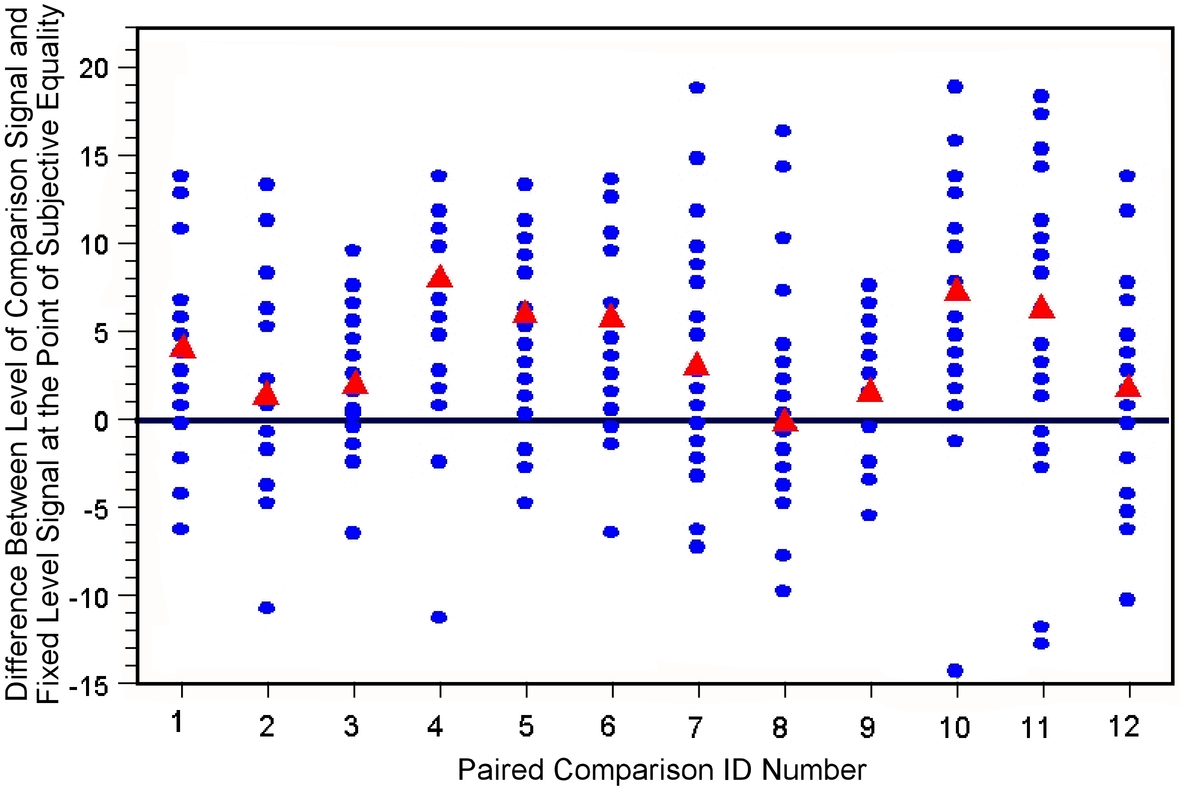


Figure 15 Differences between the levels of the comparison signals and the fixed level signals (sideline noise) at the point subjective equality for all test subjects. Mean values are plotted as solid triangles.

Most subjects judged the sideline noise to be more annoying than the overflight and departure noise variable level signals. In only one case was a variable level signal judged more annoying than runway sideline noise; in that case, the mean difference (represented by a solid red triangle) was a negative value.

3.3.4 Analysis of Relative Annoyance of Rattle

The six leftmost comparisons shown in Figure 14 were subjected to a repeated measures analysis of variance (ANOVA) to investigate the effects of rattle and type of comparison signal on subjects' judgments of annoyance. Table 5 shows the results of the ANOVA.

Table 5 Summary of analysis of variance results for effects of rattle and variable signal on annoyance.

Source	SS	df	MS	F	p
Rattle	634.9	1	634.9	18.25	.0005
Error (rattle)	939.1	27	34.8		
Variable level signal	168.1	2	84.1	3.19	.049
Error (variable level signal)	1,423.3	54	26.4		

The ANOVA confirmed that the effect of rattle on annoyance judgments was a statistically reliable effect. Figure 15 shows that the mean differences of the comparisons of the variable level signals and sideline noise are greater when rattle is present. The greatest difference in annoyance (4.6 dB) shown in Figure 15 is between the B-757 and sideline noise. The ANOVA also revealed a smaller but reliable effect of type of variable signal on judged annoyance.

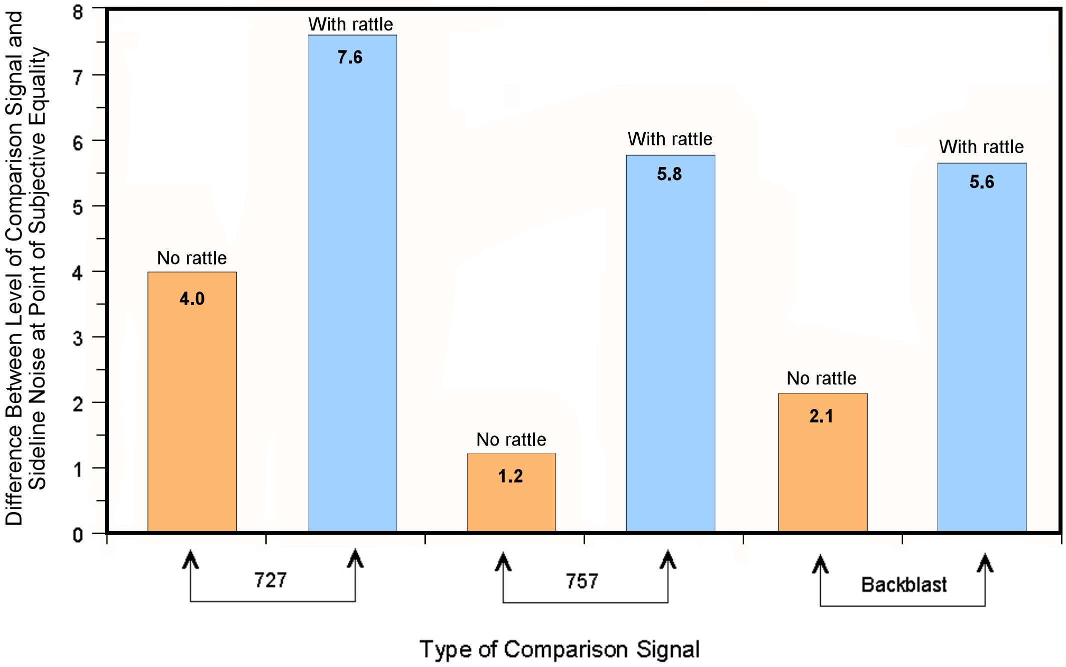


Figure 16 Difference between variable level signal and sideline noise presented with and without rattle at the point of subjective equality (mean judgments for 28 subjects).

3.3.5 Relative Annoyance of Sounds with Different Degrees of C-Weighted Noise Reduction

The annoyance of three levels of sideline noise was compared with that of an aircraft flyover to investigate the effect of mitigation of sideline noise through acoustic insulation of residences. The relative annoyance of sideline noise was judged as heard indoors with no added low-frequency attenuation; with 5 dB of simulated C-weighted noise reduction; and with 10 dB of simulated C-weighted noise reduction. A t-test between the judged annoyance of the outdoor and -10 dB presentation levels showed a significant difference in annoyance judgments ($t_{(df=27)} = 1.92$, $p = .03$).

Figure 16 shows the A-weighted levels of the B-727 when judged equally annoying to the sideline noise. When the level of the sideline noise was reduced by 5 dB, the subjects reduced the level of the B-727 by 5.8 dB at the point of equal annoyance. When the sideline noise was reduced by 10 dB, the level of the B-727 was lowered by 12.3 dB at the point of equal annoyance to the sideline noise.

3.4 DISCUSSION

3.4.1 Annoyance of Sideline Noise

Although individual subjects' annoyance ratings were characteristically variable, mean annoyance ratings for the group were orderly and readily interpretable:

> In all but one comparison, subjects were more annoyed by sideline noise than by the B-727, the B-757, and the backblast noise signals.
>
> Sideline noise accompanied by rattle was judged to be more annoying than sideline noise without rattle.
>
> Five and 10 dB reductions in sideline noise were associated with reductions of 5.8 dB and 12.3 dB in the mean annoyance ratings, respectively.

3.4.2 Loudness Level Interpretation of Findings

Another perspective on the current findings may be gained by expressing signal levels at points of subjective equality of annoyance in terms of Zwicker's loudness level (Zwicker, 1977), a more complex spectral weighting procedure than the A- or C-weighting networks. Two recent studies of the annoyance of subsonic aircraft noise (Pearsons *et al.*, 1996, 1997) have shown that loudness levels calculated by Zwicker's procedures reduce the variability in judgments of the annoyance of aircraft overflight and other transportation noise with appreciable low-frequency content.

Figure 17 compares the mean annoyance judgements in all 12 comparisons as measured by A-level and Zwicker loudness level. Annoyance judgments as measured by Zwicker loudness level are nearer to zero than A-weighted judgments. The mean A-weighted difference between the variable signals and sideline noise was 3.8 dB, whereas the mean difference with Zwicker's loudness level was only -1.1 dB. Zwicker's Loudness Level was clearly superior to A-level as a predictor of the relative annoyance of the present suite of aircraft noise signals.

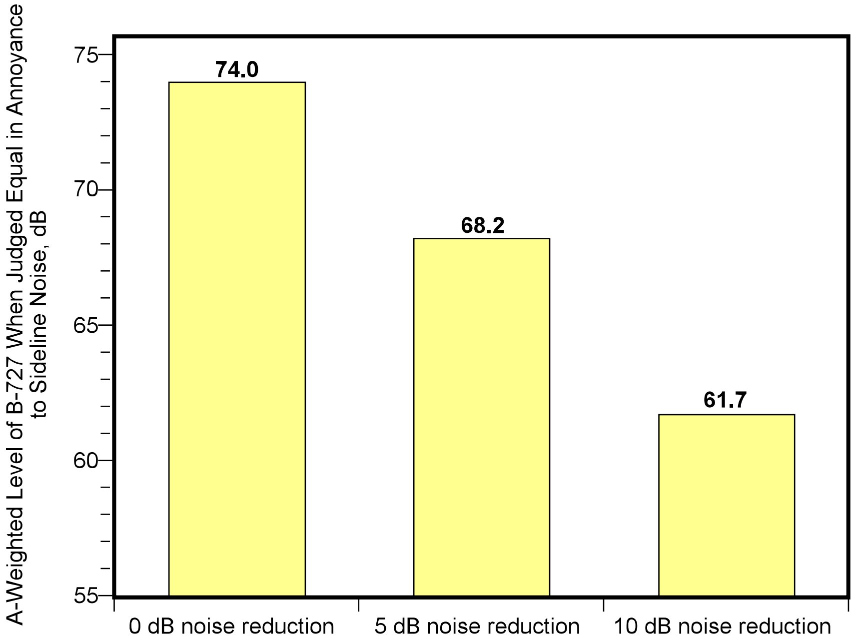


Figure 17 A-weighted level of the B-727 at the point of equal annoyance to sideline noise (mean judgments of 28 subjects).

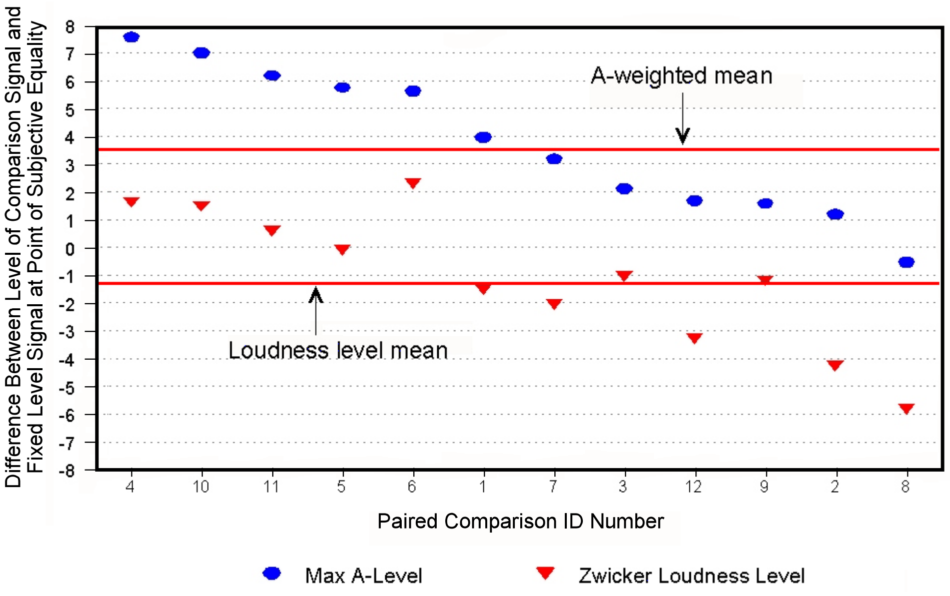


Figure 18 Comparison of A-level and Zwicker Loudness Level as measures of relative annoyance of signal pairs.

3.5 CONCLUSIONS AND IMPLICATIONS OF FINDINGS OF LABORATORY STUDY OF ANNOYANCE

Runway sideline noise is more annoying than that of aircraft overflights of similar A-weighted sound exposure level.

The annoyance of the low-frequency content of runway sideline noise from operations on Runway 17/35 will be annoying out of proportion to its contribution to A-weighted sound levels.

The addition of even minor amounts of rattling noise notably increases the annoyance of runway sideline noise.

The greater duration of runway sideline noise than that of overflights increases the annoyance of runway sideline noise by 10 log (duration).

Mitigation measures that reduce low-frequency content of runway sideline noise will provide a benefit in reduced indoor annoyance commensurate with the degree of low-frequency noise reduction.

4 SOCIAL SURVEY OF ANNOYANCE OF AIRCRAFT NOISE-INDUCED RATTLE

The Expert Panel reached consensus on the applicability of the social survey to the environment near MSP. [9]

This chapter describes a social survey of residents of a neighborhood near MSP with low-frequency noise exposure roughly similar to that expected to the west of Runway 17/35.

4.1 SUMMARY OF SOCIAL SURVEY

The major goal of the social survey was to document the prevalence of annoyance due to aircraft noise-induced rattle among residents exposed to runway sideline noise at MSP. It was found that the prevalence of annoyance due to aircraft noise-induced rattle was consistent with that previously observed in a community exposed to runway sideline noise at Los Angeles International Airport (LAX); that similar objects were cited as sources of rattle; and that the frequencies of occurrence of rattle were comparable among respondents to the MSP and LAX surveys.

4.2 METHOD

4.2.1 Survey Design

A social survey was designed for administration by telephone to Minneapolis residents with varying degrees of aircraft noise exposure. For the sake of comparability of findings with those documented in communities near other airports, the detailed methods of the current study closely resemble those of similar social surveys conducted elsewhere (*cf*. Fidell, Barber and Schultz, 1991; Fields, 1998). These surveys include many of those relied upon by FICON (1992) in developing its dosage-response relationship for community response to aircraft noise exposure.

4.2.2 Questionnaire

A brief, structured questionnaire composed of two open response items and several closed response category items was administered. Respondents were asked from 11 to 20 questions, depending on their responses. The complete set of questionnaire items is shown in Table 6, while a flowchart illustrating the sequence of questioning is found in Figure 19.

The questionnaire was introduced as a study of neighborhood living conditions. The first explicit mention of noise occurred in Item 4 ("*Would you say that your neighborhood is quiet or noisy?*"), following preliminary questions about duration of residence, and about the most and least favored aspects of neighborhood living conditions. The next two items inquired about annoyance with street traffic noise and aircraft noise. Respondents were next asked if airplanes made vibrations or rattling sounds in their homes.

Respondents who had noticed rattling in their homes were asked five additional questions: how annoyed they were with the rattling sounds, how often they noticed the rattling sounds, what sorts of

---

[9] ***See the comments in Section 4.10.***

things rattled in their homes, whether they had tried to do anything to reduce the rattling in their homes, and whether they had ever complained to the airport about the rattling.

All respondents were asked if they had ever complained to the airport about aircraft noise in general, whether their home had been acoustically insulated, and (for those who homes had been insulated) whether they were pleased with the reduction in noise levels inside their homes since the insulation had been installed.

4.2.3 Selection of Interviewing Areas

Site selection criteria included eligibility for participation in MSP's home insulation program, estimated neighborhood aircraft noise exposure levels, and availability of sufficient numbers of listed telephone numbers. The contours used to estimate A-weighted aircraft noise exposure were based on information about 1996 aircraft operations that were provided by MAC. DNL contours at 1 dB intervals produced by INM Version 6.0 were overlaid on a base map of residences in Minneapolis to identify street address ranges with similar A-weighted aircraft noise exposure, as shown in Figure 20.

Table 6 Questionnaire administered to Minneapolis residents.

Item 1:	How long have you lived at ( )?
	Response Categories: less than 1 year, 1 yr but less than 2 years, 5 to 10 years, more than 10 years
Item 2:	What do you like best about living conditions in your neighborhood?
	Response Categories: verbatim
Item 3:	What do you like least about living conditions in your neighborhood?
	Response Categories: verbatim
Item 4:	Would you say that your neighborhood is quiet or noisy?
	Response Categories: quiet, quiet except for airplanes, noisy
If yes to Item 4, ask Item 4A:	
Item 4A:	Would you say that your neighborhood is slightly, moderately, very or extremely noisy?
	Response Categories: slightly, moderately, very, extremely
Item 5:	While you're at home are you bothered or annoyed by street traffic noise in your neighborhood?
	Response Categories: yes, no
If yes to Item 5, ask Item 5A:	
Item 5A:	Would you say that you are slightly, moderately, very or extremely annoyed by street traffic noise in your neighborhood?
	Response Categories: slightly, moderately, very, extremely
Item 6:	While you're at home are you bothered or annoyed by aircraft noise?
	Response Categories: yes, no
If yes to Item 6, ask Item 6A:	

Item 6A:	Would you say that you are slightly, moderately, very or extremely annoyed by aircraft noise?
	Response Categories: slightly, moderately, very, extremely
Item 7:	Do airplanes make vibrations or rattling sounds in your home?
	Response Categories: yes, no
If yes to Item 7, ask Items 8 through 12:	
Item 8:	Are you bothered or annoyed by these vibrations or rattling sounds in your home?
	Response Categories: yes, no
If yes to Item 8, ask Item 8A:	
Item 8A:	Would you say that you are slightly, moderately, very or extremely annoyed by vibrations or rattling sounds in your home?
	Response Categories: slightly, moderately, very, extremely
Item 9:	About how often do you notice vibrations or rattling sounds in your home made by airplanes?
	Response Categories: several times a day, once an hour, once a day , once a week, a few days a week, once a month, rarely, other
Item 10:	What sorts of things vibrate or rattle in your home?
	Response Categories: windows, doors, pictures, items on shelves, other
Item 11:	Have you tried to do anything in your home to reduce vibrations or rattling sounds made by airplanes?
	Response Categories: yes, no
If yes to Item 11, ask Item 11A:	
Item 11A:	Have the vibrations or rattling sounds made by airplanes been lessened by the things you have done?
	Response Categories: no, somewhat, yes
Item 12:	Have you ever complained to the airport about vibrations or rattling sounds in your home made by airplanes?
	Response Categories: yes, no
Item 13:	Have you ever complained to the airport about aircraft noise in general?
	Response Categories: yes, no
Item 14:	Do you know whether your home has been acoustically insulated by the airport in the last few years?
	Response Categories: yes, no
If yes to Item 14, ask Item 15:	
Item 15:	Are you pleased with the reduction in aircraft noise levels in your home since the insulation was installed?
	Response Categories: not at all, slightly, moderately, very, extremely

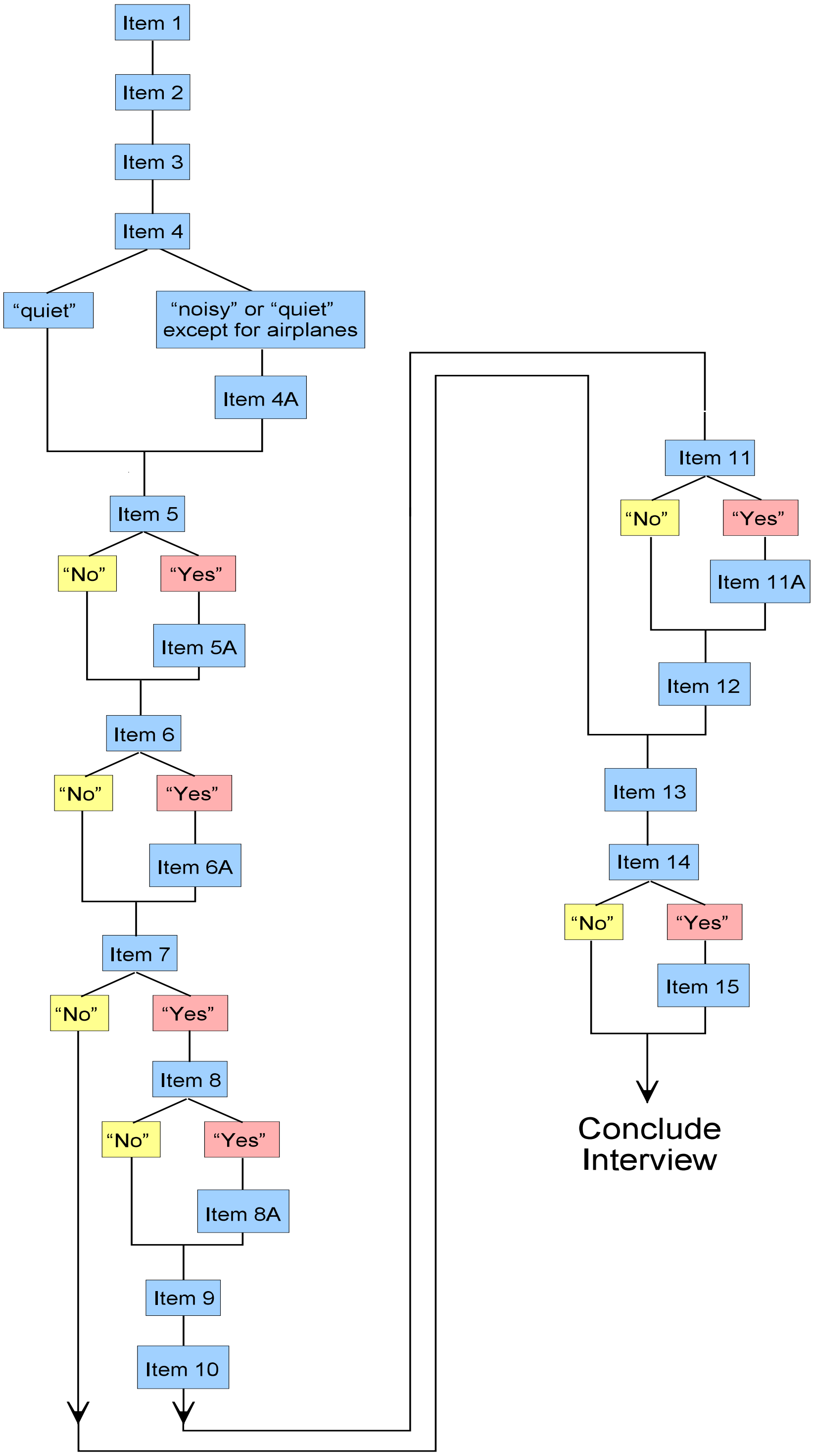


Figure 19 Sequence of questionnaire items.

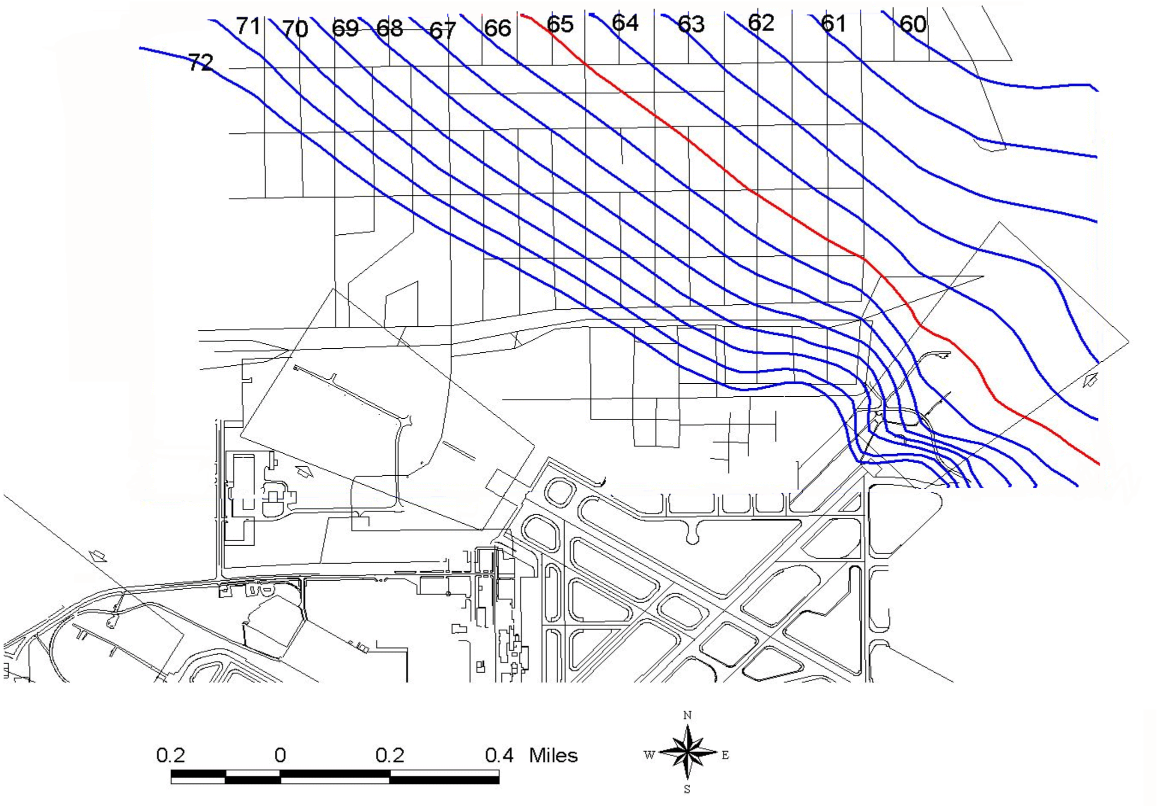


Figure 20 INM 6.0 prediction of DNL contours for 1996 operations at MSP.

4.2.4 Measurements of Low-Frequency Sound Levels in Interviewing Area

Figure 21 locates six sites (shown in yellow) throughout the interviewing area at which broadband digital recordings were made to characterize low-frequency sound levels due to aircraft operations. Unattended recordings were made for 12 daylight and evening hours per day, over the course of four days (from 24 - 28 August, 1999), yielding a total of 288 hours of recordings.

Figure 21 also locates six additional sites (shown in red) at which broadband digital recordings were made to characterize low-frequency sound levels produced by current aircraft operations on Runways 12/30 and 4/22. These locations were selected to correspond to locations in Richfield with respect to future Runway 17/35. Unattended recordings were made at these sites for 12 daylight and evening hours on 29 August, 1999.

4.2.5 Sampling and Interviewing

A sampling frame of 1,003 households with listed telephone numbers was assembled from several sources, including digital reverse directories and a MSP-provided database. Homes that had been acoustically treated through the sound insulation program at MSP comprised one interviewing group, while homes that had not been so treated comprised a second group. Potential respondents were randomly selected from the sampling frame at the time of conduct of the survey.

On 10 June, 1999, twelve centrally-supervised telephone interviewers began to make ten contact attempts: an initial attempt followed by nine callbacks at different times of day, over an eight day period ending 17 June. The opinions of one English-speaking, verified adult household member were sought from each selected household. All interviewers read a training manual and underwent half an hour of training, including practice interviews, prior to conducting interviews.

4.3 RESULTS

This section summarizes the results of interviewing and analyses of response patterns of respondents in acoustically treated and untreated homes. Table 9 (on page II-35) summarizes responses to individual questionnaire items.

Figure 21 Sites within the interviewing area (yellow) and near Runways 12/30 and 4/22 (red) at which low-frequency aircraft noise levels were recorded.

4.4 SUMMARY OF RESULTS OF INTERVIEWING

Table 7 summarizes the mechanics of data collection. The interview completion rate was 81%. Of the completed interviews, 177 were conducted in households that had been acoustically treated, and 318 were conducted in households that had not been so treated. Interview attempts yielded 25% non-contacts, 24% refusals, and 29% non-sample calls. The bulk (79%) of the non-sample telephone numbers included disconnected and changed telephone numbers. Failure to complete an interview was due in most cases to refusals and non-contacts after ten attempts. The average length of the interview was 6 minutes. Approximately 38% of the respondents were male, while 62% were female.

Table 7 Disposition of telephone interview contact attempts.

	Final Status
Total telephone numbers in sampling frame	1,003
Non-sample†	143
Non-contacts‡	248
Refusals	117
Completed Interviews	495
Completion Rate	.809

† Includes disconnects, non-residential telephones, fax machines, modem lines, wrong addresses, changed numbers and non-English speaking households.

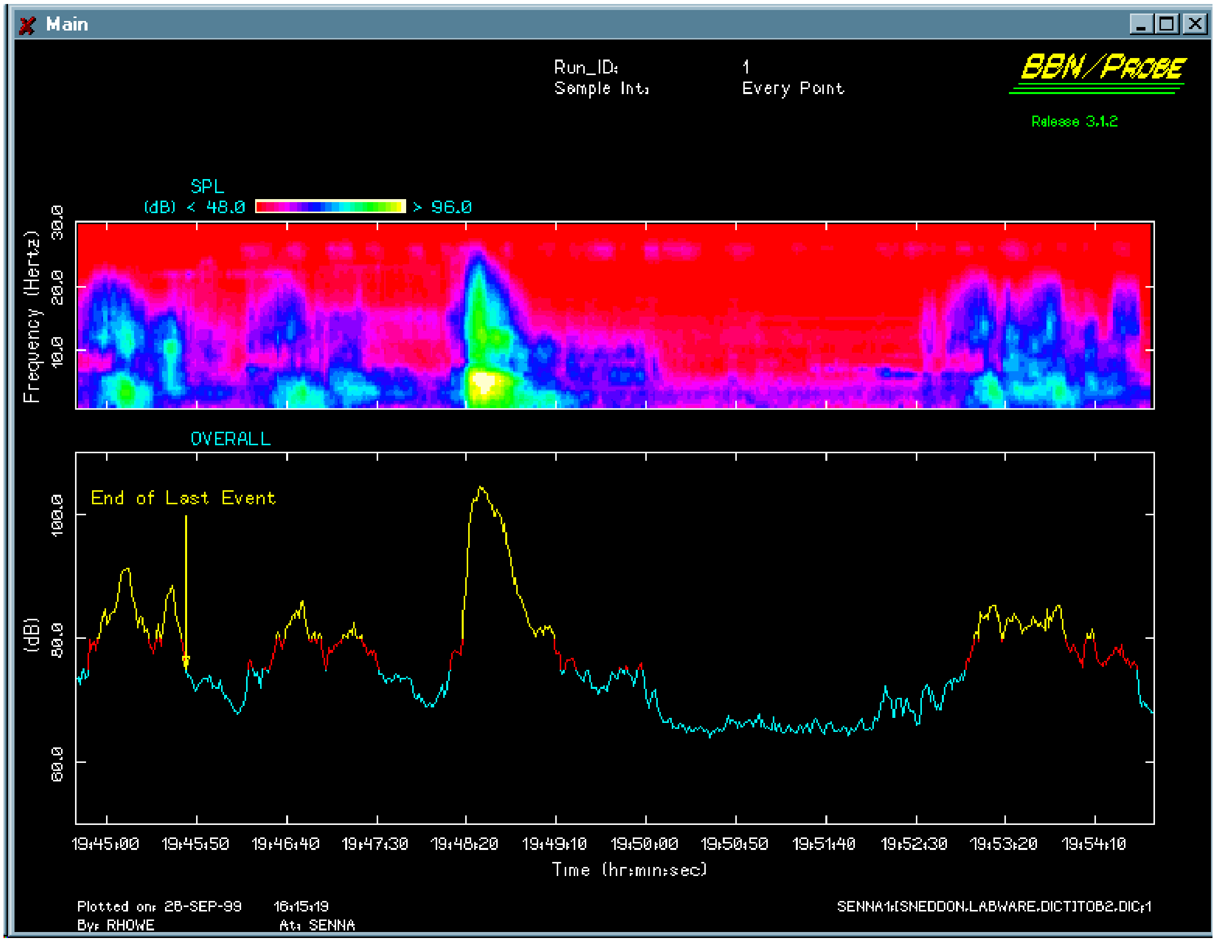
‡ Includes busy, no answer, not available, call blocked or answering machine after 10 contact attempts.

Completion rate calculated as: completed interviews ÷ [completed interviews + refusals]

4.5 MEASUREMENTS AND ESTIMATES OF LOW-FREQUENCY SOUND LEVELS DUE TO AIRCRAFT OPERATIONS

The lower panel of Figure 22 shows a short portion of a typical time history of aircraft noise events recorded at one of the six sites within the interviewing area. The color coding of the time history trace identifies portions of the C-weighted aircraft noise events between 75 and 80 dB, and in excess of 80 dB. The upper panel of Figure 22 is a spectrogram of the time history, color-coded to help identification of the low-frequency content of the aircraft operations.

Statistical distributions of low-frequency sound levels (computed by summing the energy in the one-third octave bands centered at 25 through 80 Hz) were derived from these recordings. Figure 23 compares the cumulative distributions of these low-frequency sound levels computed at the time of occurrence of the maximum C-weighted sound level of each noise event. Table 8 summarizes this distribution information in tabular form. The columns of the table contain information about the mean, median, number of observations, standard deviation, and several centile values of the distributions of low-frequency sound levels at the six sites.



Run_ID: 1
Sample Int: Every Point

Plotted on: 28-SEP-99 16:15:19
By: RHOWE At: SENNA

SENNA1:[SNEDDON.LABWARE.DICT]TOB2.DIC;1

Figure 22 Typical time history (lower panel) and spectrogram (upper panel) of aircraft noise events recorded at a site within the interviewing area.

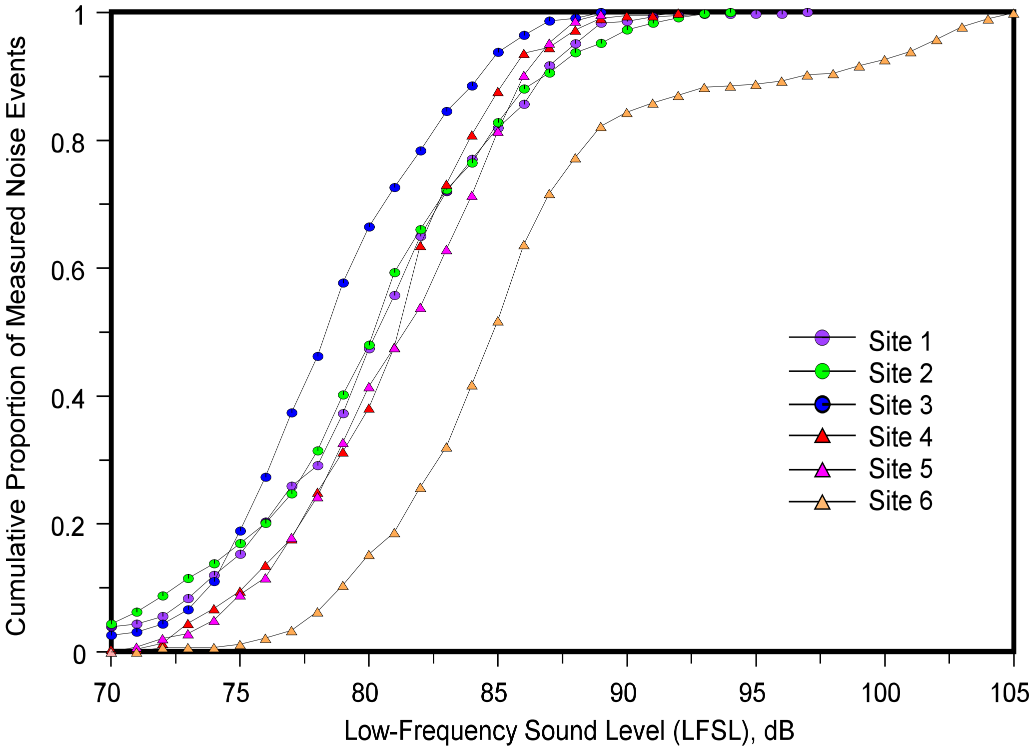


Figure 23 Cumulative distributions of low-frequency sound levels of aircraft noise events at six measurement sites within the interviewing area.

Table 8 Summary of distributions of Low-Frequency Sound Level values measured at the maxima of aircraft noise events at six sites within the interviewing area.

Site	Mean	Median	n		L_{10}	L_5	L_1
1	81.3 dB	83.2 dB	654	7.5 dB	89.2 dB	90.0 dB	91.5 dB
2	81.8	83.0	504	7.2	90.1	91.0	93.1
3	77.5	78.0	493	5.5	84.1	85.3	86.9
4	81.6	82.1	220	3.9	86.1	88.1	89.9
5	82.0	82.3	378	4.0	87.0	87.8	89.1
6	86.8	85.9	411	6.5	97.9	102.8	104.9

Version 6.0 of INM was exercised to produce C-weighted noise maximum aircraft noise contours from assumptions made in 1997 for MSP operations in the year 2005, as shown in Figure 24. The noise level gradients of this contour set (rather than the absolute values of contours) served as a basis for estimating low-frequency sound levels from aircraft noise events for respondents throughout the interviewing area. The estimation process involved the following steps:

> C-weighted maximum noise levels were determined for the street address of each respondent;
>
> The C-weighted maximum noise levels were converted to estimated low-frequency noise levels at each respondent's street address by means of the regression equations shown in Figure 25.

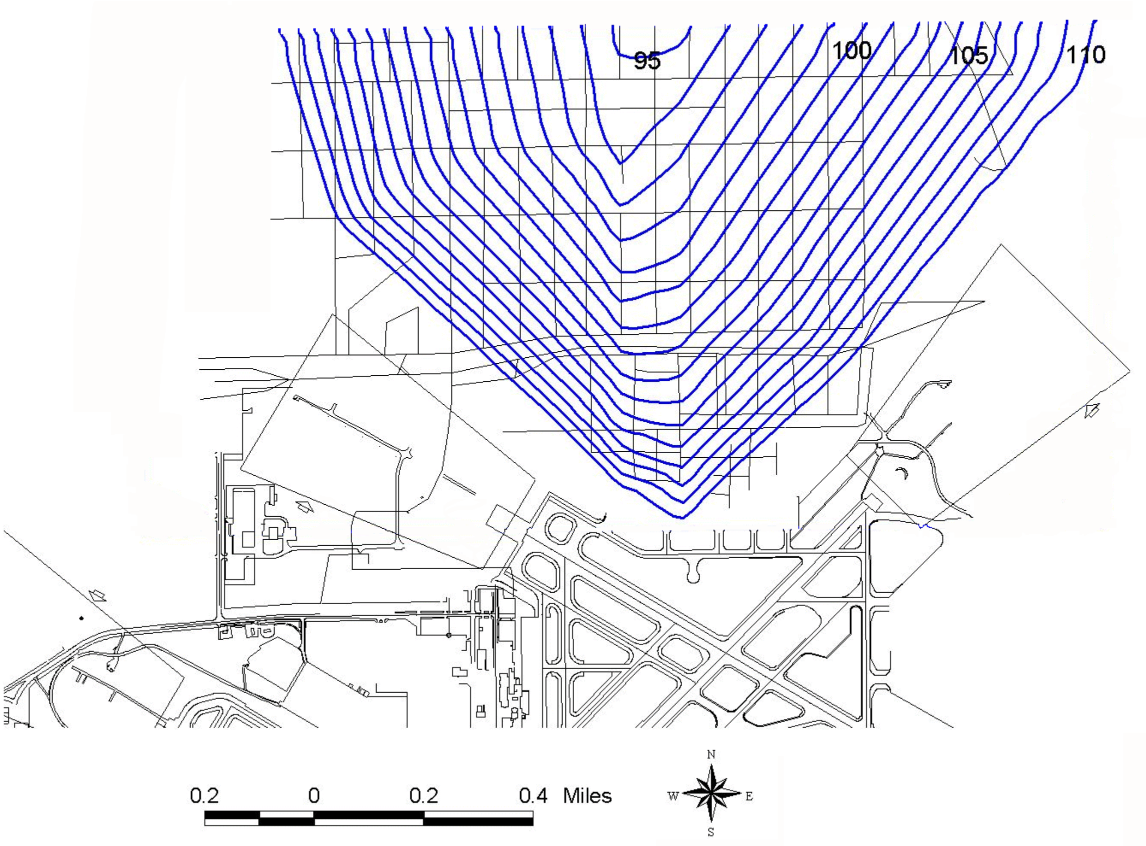


Figure 24 INM 6.0 prediction of maximum C-weighted aircraft noise levels in the interviewing area for 1997 operations at MSP.

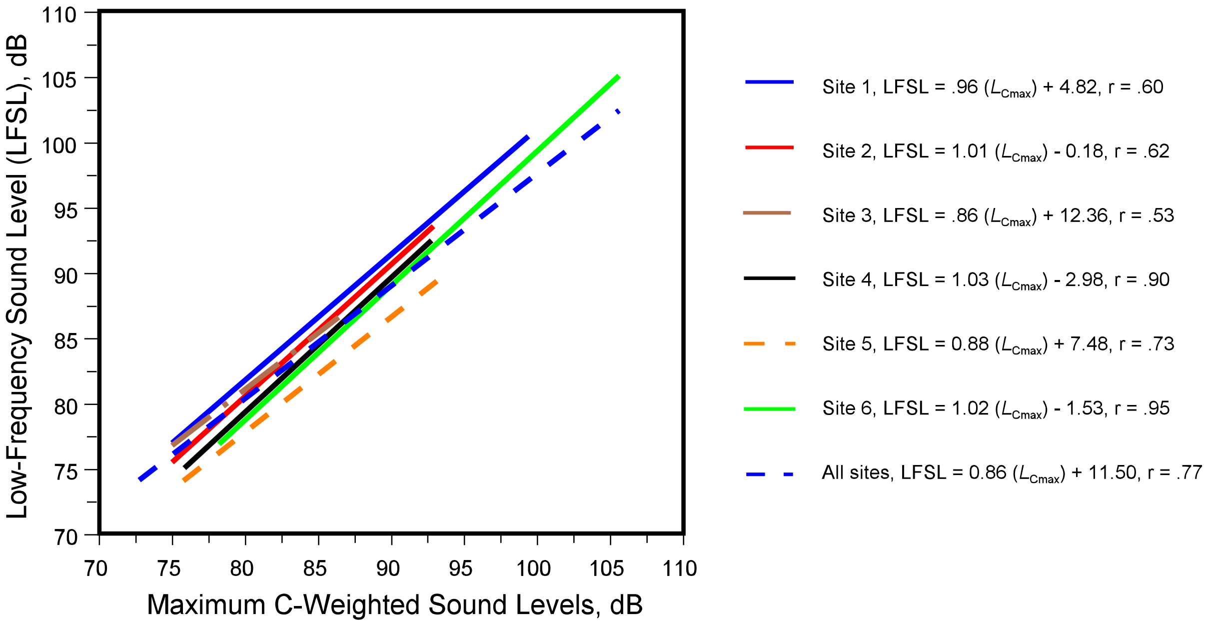


Figure 25 Comparison of regressions of LFSL values on C-weighted maxima of aircraft noise events at measurement sites within the MSP interviewing area.

The estimated low-frequency noise levels were adjusted to reflect the measurements made at six sites within the interviewing area.[10]

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[10] This final step took into account not only the absolute values of the measured LFSL values of aircraft noise events, but also their distribution function. The value sought was not the single maximum noise event level, but the arithmetic mean of the maxima of LFSL values of aircraft noise events in excess of 75 dB. Since the bulk of the aircraft noise event maxima exceeded 75 dB, the average LFSL value of the maxima in excess of 75 dB was little different from the average of aircraft noise events with LFSL values in excess of 60 dB. The average of the maxima of noise events in excess of 75 dB corresponds approximately to the 70th centile of the distribution of maximum LFSL values.

4.6 NARRATIVE ACCOUNT OF FINDINGS

Table 9 summarizes responses to each questionnaire item, cross-tabulated by residence in acoustically treated and untreated homes.

The distribution of duration of residence (Item 1) was similar for the two groups: at least half of the respondents had lived at their current residence for more than 10 years, while only 1-2% of the respondents in insulated and non-insulated homes had lived at their residence for less than 1 year.

Spontaneous mention of "quiet" as the best liked aspect of living conditions (Item 2) was reported by 18 % of the respondents in insulated homes, and by 22% of the respondents in non-insulated homes. Other verbatim responses included "nice neighbors," "convenience," "clean," *etc*.

Spontaneous mention of "noisy" or "airport" as the least liked aspect of living conditions (Item 3) was reported by 44% of the respondents in insulated homes, and by 48% of the respondents in non-insulated homes. Other verbatim responses included "crime," "low income housing," "nothing," *etc*.

Item 4 asked respondents whether their neighborhood was quiet or noisy. "Quiet" was reported by 40% of the respondents in insulated homes, and by 48% of the respondents in non-insulated homes. "Noisy" was reported by 38% of the respondents in insulated homes, and by 25% in non-insulated homes. "Quiet except for aircraft noise" was reported by 22% and 27% of the respondents in insulated and non-insulated homes, respectively.

Items 5 and 5A inquired about respondents' annoyance due to street traffic noise. A minority of respondents (16% in insulated homes and 14% in non-insulated homes) reported annoyance due to street traffic noise. Less than 6% of the respondents in both groups reported a consequential degree of annoyance due to street traffic noise (sum of "very" and "extremely" annoyed responses).

Table 9 Summary of responses to each questionnaire item for respondents in insulated and non-insulated homes.

Item 1: About how long have you lived at (street address)?	Insulated (%)	Non-Insulated (%)
less than 1 year	1.1	2.2
1 to less than 2 years	3.4	6.6
2 to less than 5 years	17.5	14.8
5 to less than 10 years	23.7	22.0
more than 10 years	54.2	53.5
Total N	177	317

Item 2: What do you like best about living conditions in your neighborhood?	Insulated (%)	Non-Insulated (%)
spontaneous mentions of "quiet"	17.5	22.3
other	82.5	77.7
Total N	177	318

Item 3: What do you like least about living conditions in your neighborhood?	Insulated (%)	Non-Insulated (%)
spontaneous mentions of "noisy"	44.1	48.4
other	55.9	51.6
Total N	177	318

Item 4: Would you say that your neighborhood is quiet or noisy?	Insulated (%)	Non-Insulated (%)
quiet	40.1	48.4
noisy	38.4	24.5
quiet, except for aircraft noise	21.5	27.0
Total N	177	318

Item 5: While you're at home are you bothered or annoyed by street traffic noise in your neighborhood?	Insulated (%)	Non-Insulated (%)
no	83.6	85.8
yes	16.4	14.2
Total N	177	318

Item 5A: Would you say that you are slightly, moderately, very or extremely annoyed by street traffic noise while at home?	Insulated (%)	Non-Insulated (%)
not at all	83.6	85.8
slightly	5.6	5.7
moderately	5.6	4.7
very	4.0	2.8
extremely	1.1	0.9
Total N	177	318

Item 6: While you're at home are you bothered or annoyed by aircraft noise in your neighborhood?	Insulated (%)	Non-Insulated (%)
no	26.6	14.8
yes	73.4	85.2
Total N	177	318

Item 6A: Would you say that you are slightly, moderately, very or extremely annoyed by aircraft noise while at home?	Insulated (%)	Non-Insulated (%)
not at all	26.6	14.8
slightly	14.7	17.9
moderately	26.6	26.4
very	14.7	22.3
extremely	17.5	18.6
Total N	177	318

Item 7: Do airplanes make vibrations or rattling sounds in your home?	Insulated (%)	Non-Insulated (%)
no	41.8	34.6
yes	58.2	65.4
Total N	177	318

Item 8: Are you bothered or annoyed by these vibrations or rattling sounds in your home?	Insulated (%)	Non-Insulated (%)
(of those who notice rattle)		
no	33.0	20.7
yes	67.0	79.3
Total N	103	208

Item 8A: Would you say that you are slightly moderately very or extremely annoyed by vibrations or rattling sounds in your home?	Insulated (%)	Non-Insulated (%)
(of those who notice rattle)		
not at all	33.0	20.7
slightly	12.6	11.1
moderately	19.4	23.6
very	15.5	25.0
extremely	19.4	19.7
Total N	103	208

Item 9: About how often do you notice vibrations or rattling sounds in your home made by airplanes?	Insulated (%)	Non-Insulated (%)
(of those who notice rattle)		
several times an hour	27.2	32.2
once an hour	16.5	12.5
once a day	19.4	19.7

once a week	3.9	7.2
a few times/week	21.4	15.4
once a month	1.0	2.4
rarely	2.9	1.4
other	7.8	9.1
Total N	103	208

Item 10: What sorts of things vibrate or rattle in your home?	**Insulated (%)**	**Non-Insulated (%)**
(of those who notice rattle)		
windows	43.7	68.7
doors	2.9	1.0
pictures	19.4	11.1
items on shelves	13.6	3.8
other	20.4	14.4
Total N	103	208

Item 11: Have you tried to do anything to reduce vibrations or rattling sounds made by airplanes?	**Insulated (%)**	**Non-Insulated (%)**
(of those who notice rattle)		
no	53.4	74.5
yes	46.6	25.5
Total N	103	208

Item 11A: Have the vibrations or rattling sounds made by airplanes been lessened by the things you have done?	**Insulated (%)**	**Non-Insulated (%)**
(of those who notice rattle)		
no	20.8	45.3
somewhat	25.0	30.2
yes	54.2	24.5
Total N	48	53

Item 12: Have you ever complained to the airport about vibrations or rattling sounds in your home made by airplanes?	**Insulated (%)**	**Non-Insulated (%)**
(of those who notice rattle)		
no	75.7	67.3
yes	24.3	32.7
Total N	103	208

Item 13: Have you ever complained to the airport about aircraft noise in general?	Insulated (%)	Non-Insulated (%)
no	81.4	75.5
yes	18.6	24.5
Total N	177	318

Item 14: Do you know whether your home has been acoustically insulated by the airport in the last few years?	Insulated (%)	Non-Insulated (%)
no	5.6	99.1
yes	94.4	0.9
Total N	177	318

Item 15: Are you pleased with the reduction in noise levels in your home since the insulation was installed?	Insulated (%)
(Of those who were aware that home had been insulated)	
not at all	9.6
slightly	10.2
moderately	31.1
very	34.1
extremely	15.0
Total N	167

Items 6 and 6A inquired about respondents' annoyance due to aircraft noise. The majority of respondents (73% in insulated homes and 85% in non-insulated homes) reported annoyance due to aircraft noise, while 32% in insulated homes and 41% in non-insulated homes reported a consequential degree of annoyance due to aircraft noise.

More than half of the respondents (58% in insulated homes and 65% in non-insulated homes) reported that airplanes made rattling sounds in their homes (Item 7). Of those respondents who noticed rattle, 67% in insulated homes and 79% in non-insulated homes reported annoyance due to vibrations or rattling sounds (Item 8), while 35-45% of these respondents reported a consequential degree of annoyance (Item 8A).

Figure 26 shows the locations of households in which respondents were highly annoyed by rattle and vibration.

About 30% of the respondents who noticed rattling sounds in their homes (in both insulated and non-insulated homes) reported that they notice vibrations or rattling sounds several times an hour (Item 9). Three percent or less of the respondents reported that they rarely noticed rattling sounds made in their homes by airplanes. The most common item that rattled in respondents' homes was windows (Item 10), as reported by 44% of the respondents in insulated homes and 70% of the respondents in non-insulated homes.

Of the respondents who had noticed rattling sounds in their homes, 47% of those in insulated homes and 26% in non-insulated homes reported that they had tried to reduce the rattling sounds made by airplanes (Item 11), while 54% and 25% of these respondents living in acoustically insulated and non-insulated homes, respectively, reported that the rattling sounds had been lessened by the things they had done (Item 11A).

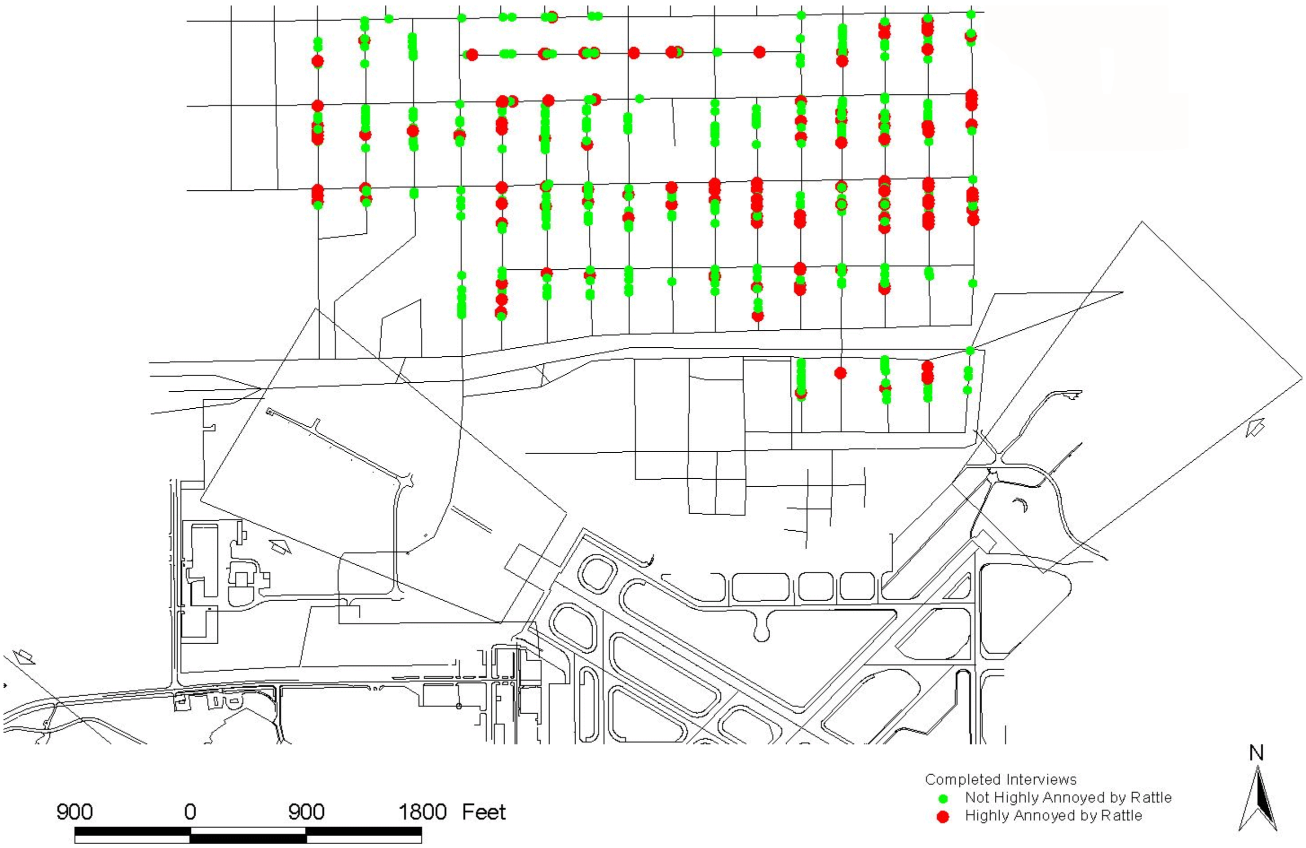

Figure 26 Locations of households in which respondents were highly annoyed by rattle and vibration.

Less than a third of the respondents who had noticed rattling sounds in their homes had complained to the airport about them (Item 12). Less than 25% of all respondents in insulated and non-insulated homes had complained to the airport about aircraft noise in general (Item 13).

Six percent of the respondents in insulated homes were unaware that their homes had been insulated by the airport (Item 14). Of the respondents who were aware that their homes had been insulated, 49% were very or extremely pleased with the reduction in noise levels inside their homes since the insulation had been installed (Item 15).

4.7 ANALYSES OF EFFECTS OF ACOUSTIC INSULATION

4.7.1 ESTIMATES OF C-WEIGHTED NOISE EXPOSURE LEVELS WITHIN THE INTERVIEWING AREA

Maximum C-level values estimated by INM Version 6.0 were assigned to the addresses of the completed interviews shown as red dots in Figure 27. Figure 28 shows the distribution of predicted DNL values in households that had received acoustic insulation and those that had not received acoustic insulation. The predicted mean DNL values of the acoustically treated and untreated homes were 71 dB and 65 dB, respectively.

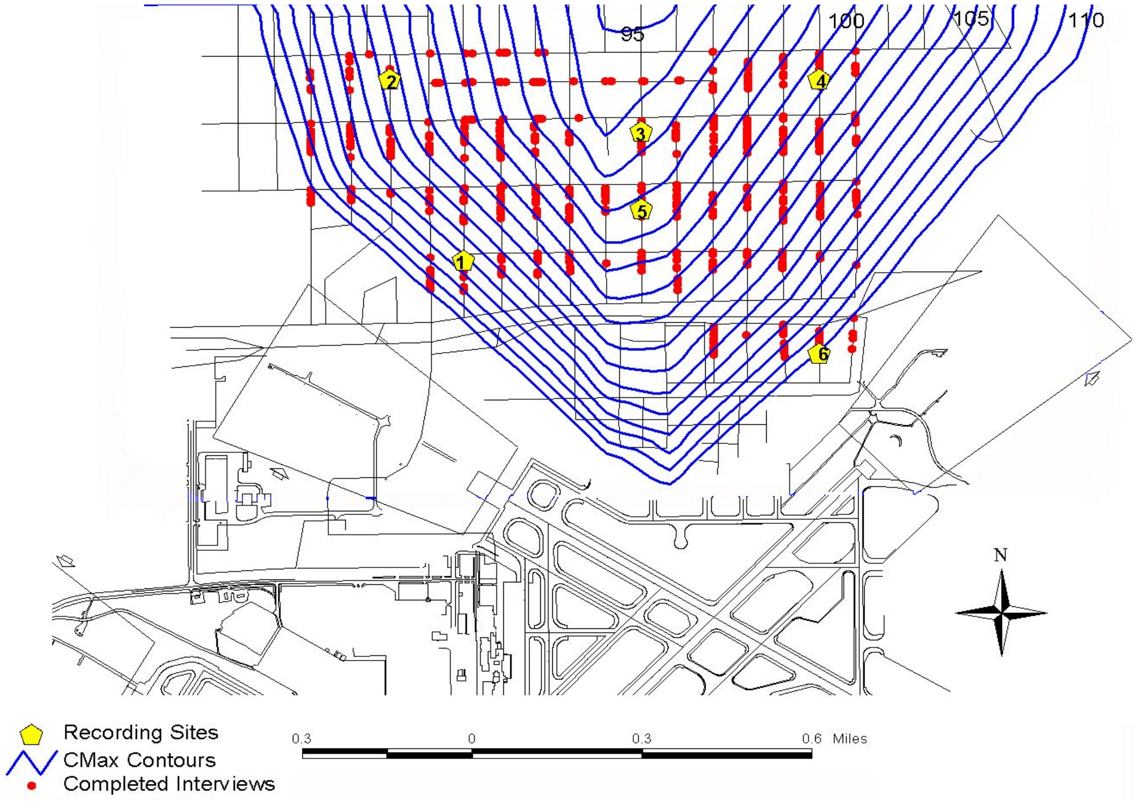

Figure 27 Maximum C-levels predicted by INM 6.0 in relation to low-frequency aircraft noise measurement sites and completed interviews.

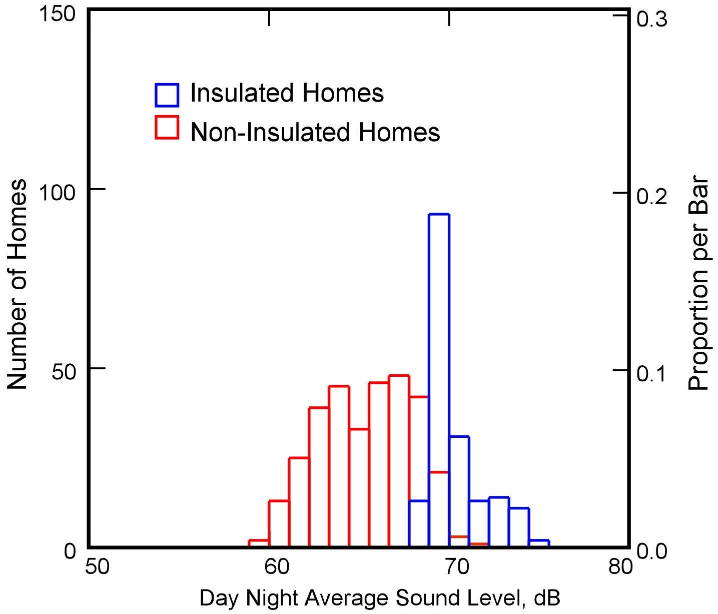

Figure 28 Distribution of predicted DNL values in households that had been acoustically treated and those that had not been so treated.

4.7.2 Differences in Prevalence of Aircraft Noise Induced High Annoyance (Questionnaire Item 6A)

The prevalence of high annoyance is the percentage of respondents within a defined geographic area or noise exposure interval who describe themselves as very or extremely annoyed by aircraft noise. The overall prevalence of high annoyance of respondents was 32.2% in acoustically treated homes and 40.9% in untreated homes, as shown in Table 9. The difference was unlikely to have occurred by chance alone ($^{2}_{(df=1)} = 3.6$, p = .056). This finding suggests that respondents who live in acoustically treated homes (and are thus exposed to higher aircraft noise levels than respondents in untreated homes) derive at least some benefit from additional A-weighted noise reduction of their homes. This benefit may be due to the routine installation of non-rattling windows as part of the standard acoustic treatment package.

4.7.3 Differences in Prevalence of Vibration-Induced High Annoyance (Questionnaire Item 8A)

The prevalence of high annoyance is the percentage of respondents within a geographic area or noise exposure interval who describe themselves as very or extremely annoyed by vibrations or rattling sounds in their homes from airplanes. The overall prevalence of high annoyance due to vibrations or rattling sounds in their homes was 20.3% in insulated homes and 29.2% in non-insulated homes. This difference ($^{2}_{(df=1)} = 4.7$, p = .03) was unlikely to have arisen by chance alone.

4.7.4 Differences in Prevalence of Complaints due to Vibrations (Questionnaire Item 12)

The percentages of respondents in insulated and non-insulated homes who had noticed aircraft induced rattling sounds in their homes were asked whether they had complained to the airport about the rattling sounds. Table 9 shows that 24.3% of the respondents in insulated homes (who had noticed rattle) had complained to the airport about the rattling sounds in their homes, whereas 32.7% of the respondents in non-insulated homes had complained to the airport. This difference was not statistically significant ($^{2}_{(df=1)} = 2.3$, p = .13).

4.7.5 Differences in Prevalence of Complaints due to Aircraft Noise in General (Questionnaire Item 13)

Table 9 shows that the percentages of respondents in insulated and non-insulated homes who had complained to the airport about aircraft noise in general were 19% and 24%, respectively. This difference was not statistically significant ($^{2}_{(df=1)} = 1.6$, p = .21).

4.8 SATISFACTION WITH NOISE INSULATION TREATMENTS

Respondents living in acoustically treated homes were asked if they were pleased with the reduction in noise levels inside their homes since the insulation treatment had been completed. All but 10% of these respondents were pleased to some degree with the reduction in noise levels inside their homes.

A chi-square test was conducted to assess the association between reports of satisfaction with home insulation and annoyance due to aircraft noise. Table 10 shows the numbers of respondents who were satisfied and dissatisfied with their home insulation tabulated by high annoyance. About a third of the respondents who were pleased with home insulation were highly annoyed by aircraft noise. Nearly half of the respondents who were not satisfied with home insulation reported high annoyance with aircraft noise. This association between satisfaction with acoustic treatments and reports of high annoyance was not statistically significant ($^{2}_{(df=1)} = 2.5$, p = .14).

Table 10 Numbers of respondents satisfied and dissatisfied with acoustic treatments who were and were not highly annoyed by aircraft noise.

	Not Highly Annoyed	**Highly Annoyed**	**Total**
Dissatisfied	9	8	17
Satisfied	108	45	153
Total	117	53	170

4.8.1 Relationship Between Annoyance and Satisfaction with Noise Insulation Treatments

Aircraft noise annoyance and satisfaction with home noise insulation treatments are separable issues. Homeowners may reasonably express satisfaction with measures taken to increase the noise reduction of their homes, while still reporting annoyance due to aircraft noise. As noted by Fidell and Silvati (1991),

> "Because there is no information about the relative influences of indoor and outdoor noise exposure on the prevalence of annoyance in airport communities, it remains unclear whether creation of an indoor acoustic sanctuary reduces the prevalence of annoyance in a community in direct proportion to the reduction of interior noise levels."

4.9 PRECISION OF RESPONSE MEASUREMENT

If the opinions of respondents in this survey are viewed as samples of populations of all residents of interviewing areas (including those not interviewed), then they should be interpreted in the context of confidence intervals. Confidence intervals for analyses of the present data, based on dichotomizing responses into respondents highly annoyed by noise exposure and respondents not highly annoyed, are shown in Table 11. The table shows the bounds of 90% confidence intervals for estimates of a consequential degree of annoyance. The margins of error in estimates of population percentages highly annoyed are 4-6%.

Table 11 Ninety percent confidence intervals for percentages of respondents highly annoyed by aircraft noise.

Interviewing Site	Number of Completed Interviews	Margin of Error	Prevalence of High Annoyance	90% Confidence Interval for the Prevalence of High Annoyance
Insulated homes	177	5.8%	32.2%	26.4% - 38.0%
Non-insulated homes	318	4.6%	40.9%	36.3% - 45.4%

4.10 DEVELOPMENT OF DOSAGE-RESPONSE RELATIONSHIPS

This section describes dosage-response relationships between aircraft noise exposure and the prevalence of high annoyance.

4.10.1 Low-Frequency Aircraft Noise-Induced Annoyance

The Expert Panel reached consensus on the applicability of the social survey to the environment near MSP. (See notes below).

Table 12 summarizes estimated aircraft noise exposure values and percentages of respondents reporting high annoyance due to aircraft noise and rattling sounds. Figures 29 and 30 plot proportions of respondents noticing aircraft-induced rattle in the LAX and MSP data sets, and in the combined data sets, respectively.

Figure 31 plots the percentage of respondents highly annoyed by vibrations or rattling sounds in their homes caused by aircraft against estimated low-frequency sound levels. The triangular points are from the current study. The circular points are from a similar study conducted near Los Angeles International Airport (Fidell, Silvati, Pearsons, Lind, and Howe, 1999b).

As stated in Section 1.2.4.2, the Expert Panel reached consensus on the applicability of Figure 31 to the range of exposure in the area of the survey at MSP. Outside of this range the data are all for LAX. The Expert Panel does not know whether a social survey at MSP in areas outside this range would yield results consistent with the LAX results.

Table 12 Prevalence of high annoyance due to aircraft noise and to vibrations or rattling sounds, and their associated noise levels.

Insulated Homes[a] (n = 177)	%HA Due to Aircraft	Insulated Homes (n = 177)	LFSL[b]	%HA Due to Rattle
65 - 70 dB	29.2%	85 - 90 dB	87.5 dB	14.6%
70 - 75 dB	36.6%	90 - 95 dB	92.5 dB	33.3%
Non-Insulated Homes[a] (n = 318)	**%HA Due to Aircraft**	**Non-Insulated Homes (n = 318)**	**LFSL[b]**	**%HA Due to Rattle**
60 - 65 dB	40.8%	80 - 85 dB	82.5 dB	17.1%
65 - 70 dB	41.4%	85 - 90 dB	87.5 dB	31.6%

[a] DNL values predicted by 1996 noise exposure contours at MSP.

[b] LFSL values predicted by conversion of INM maximum A-level contours at MSP.

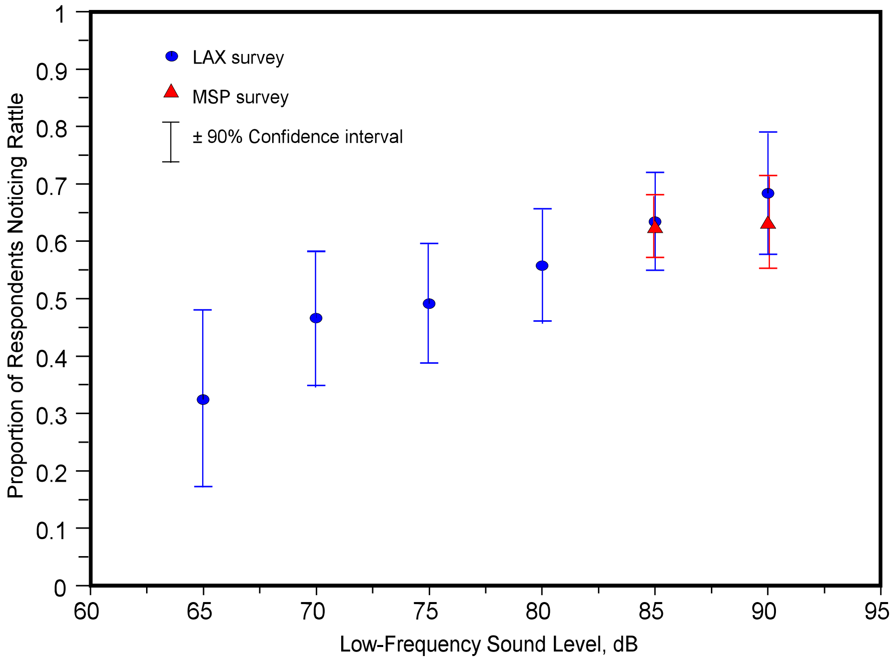

Figure 29 Proportions of respondents noticing aircraft-induced rattle in LAX and MSP surveys as a function of LFSL.

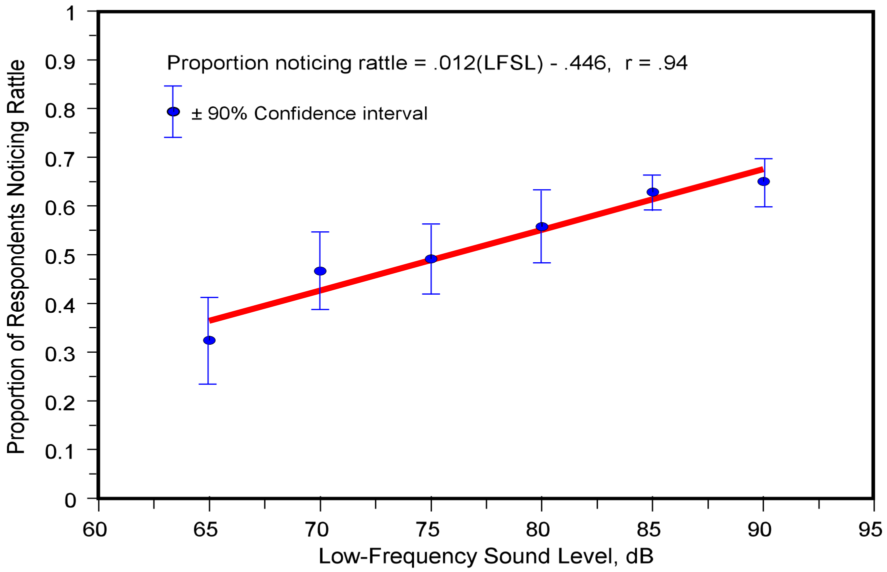

Figure 30 Relationship between proportion of respondents noticing aircraft-induced rattle and LFSL for combined LAX and MSP data sets.

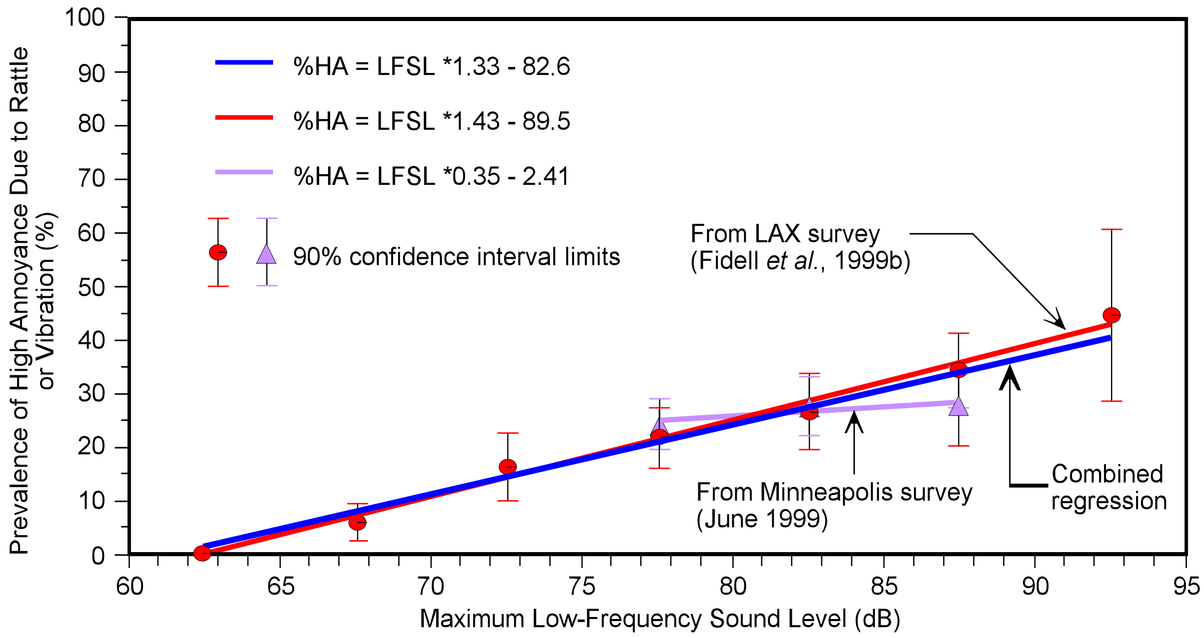

Figure 31 Relationship between percentage of respondents highly annoyed by vibrations or rattling sounds made by aircraft and low-frequency sound levels.

4.10.2 Comparison of Current Findings with FICON's Dosage-Response Relationship

The Expert Panel did not reach consensus on the full text of the following paragraph. [11]

Figure 32 shows the relationship between the prevalence of high annoyance in the present study and the FICON curve. Larger percentages of respondents in the present sample were highly annoyed by aircraft noise than predicted by the dosage-response relationship developed by FICON (1992). This finding is not unique to the present study. Kryter (1982), Finegold, Harris and von Gierke (1994) and Miedema and Vos (1998), among others, have noted that the FICON curve and other dosage response relationships intended to characterize community response to noise from both surface and air traffic systematically underestimate the prevalence of annoyance due to aircraft noise. The present observations of the prevalence of annoyance are consistent with the range of observations made in many communities elsewhere.

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[11] ***Consensus was not reached on the conclusions reached here. Since this is not a settled issue, the word "may" would be more appropriate than the word "systematically" in the next to the last sentence.***

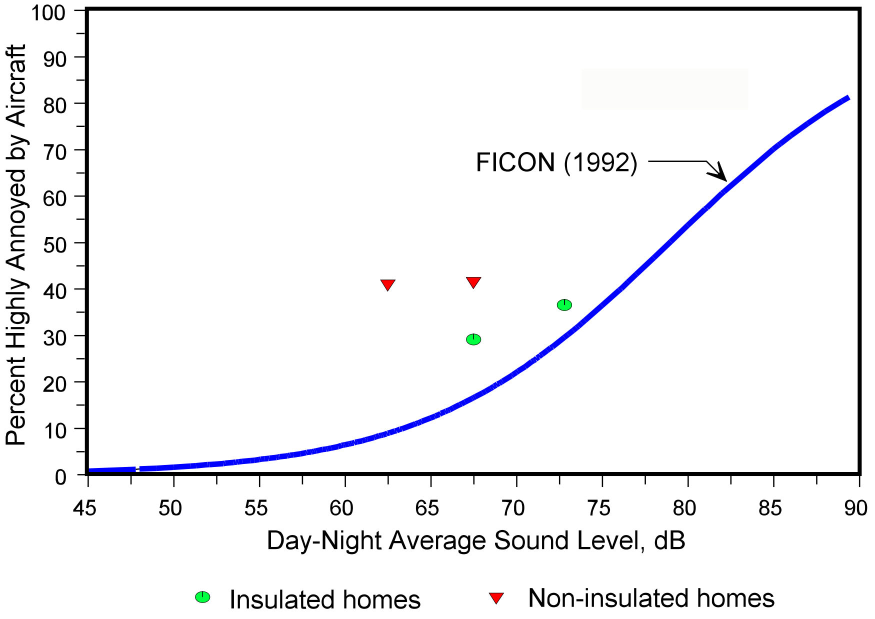

Figure 32 Comparison of prevalence of high annoyance due to aircraft noise in current study with the dosage-response relationship recommended by FICON.

Figure 33 plots the prevalence of annoyance due to aircraft noise in the current study against estimated DNL values, along with the mean high annoyance from 287 survey sites from prior studies. The short vertical lines illustrate the range of ±1 standard deviation around the mean values in 5 dB intervals of noise exposure. The figure shows that the prevalence of high annoyance due to aircraft noise in Minneapolis lies within one standard deviation of the mean high annoyance of prior aircraft noise annoyance studies.

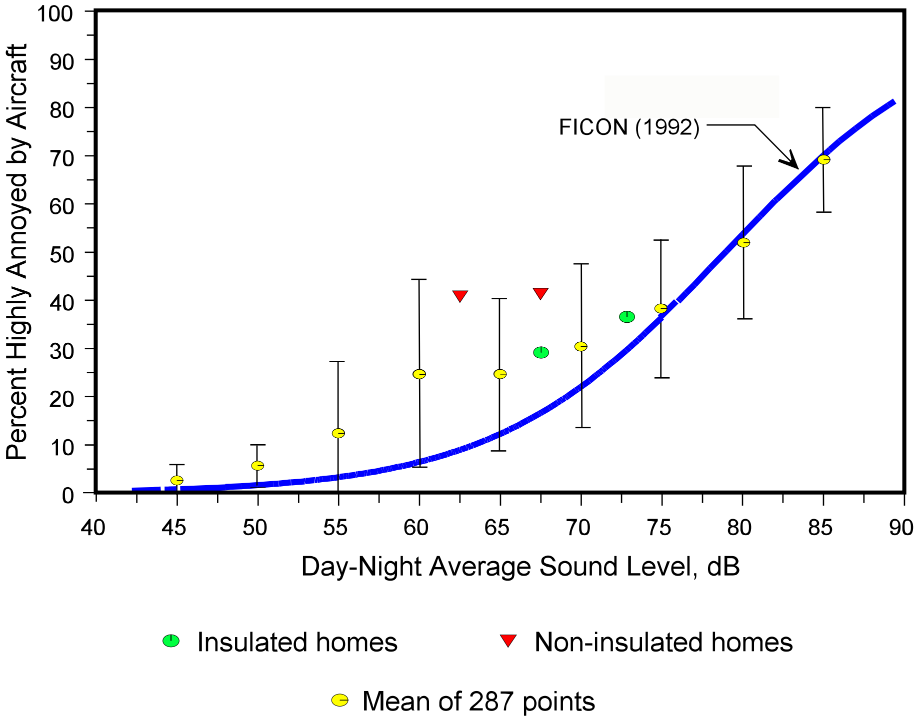

Figure 33 Comparison of prevalence of high annoyance due to aircraft noise in Minneapolis with mean high annoyance from 287 prior determinations of the annoyance of aircraft noise. Error bars show ± 1 about the means of the distributions of observed high annoyance due to aircraft noise in 5 dB intervals.

The generally greater prevalence of annoyance among residents of non-insulated homes than among residents of insulated homes (as shown in Table 11) exposed to higher levels of aircraft noise is also noteworthy.

4.10.3 Relative Sensitivities to Community Noise Exposure of Current Respondents and those Elsewhere

Cumulative noise exposure alone, as quantified by DNL, does not account for all of the observed variability in the prevalence of noise-induced annoyance in different communities. In fact, no dosage-response relationship based on a purely acoustic predictor variable is likely to account for more than about half of the variance in annoyance data, leaving the other half unexplained by noise measurements. Nonacoustic factors that might account for the remainder of the variance include the economic dependence of a community on the operation of a noise source, as well as a variety of attitudes (*e.g.*, malfeasance, misfeasance, fear of crashes, necessity of noise exposure, controllability of noise exposure, *etc.*) about noise source operation.

A theoretically-derived model developed by Green and Fidell (1991) characterizes the aggregate effect of all nonacoustic determinants of annoyance in terms of a single parameter, D^*. The slope of the dosage-response relationship between noise exposure and prevalence of annoyance is fixed in this model by the effective loudness of the noise exposure, while the position of the dosage-response relationship along the abscissa is determined by the value of D^*.[12] Figure 34 shows a dosage-response relationship constructed by the method of Green and Fidell for the annoyance of aircraft noise during the year prior to interviewing in the present study. The value of D^* in the present data set was 67.4. The average value observed by Green and Fidell (1991) for aircraft noise annoyance in many other communities was 70.2 dB. In other words, respondents in the current survey tolerated about 3 dB *less* aircraft noise exposure than residents of other communities before describing themselves as highly annoyed.

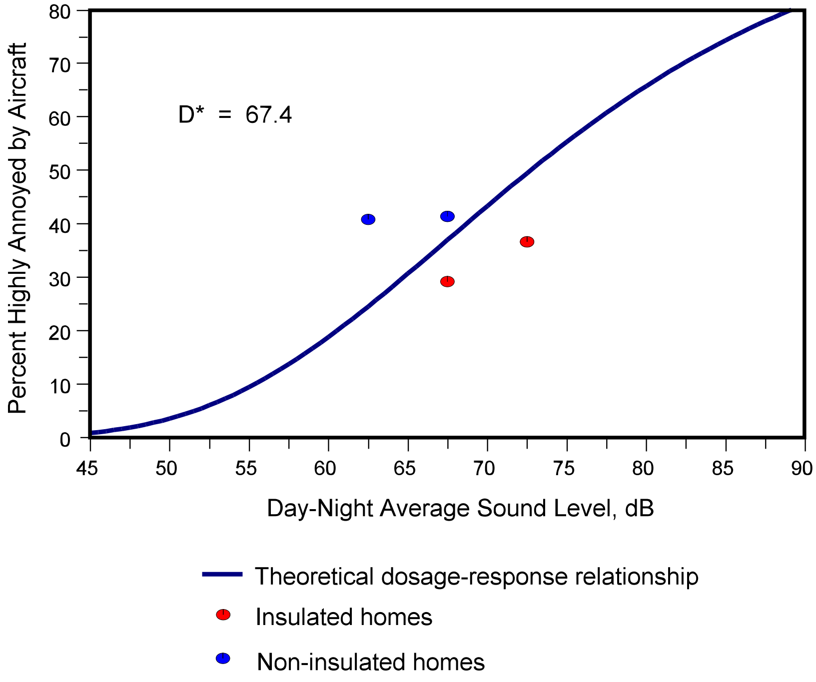

Figure 34 Prevalence of high annoyance in the current study in relation to a theoretically derived dosage-response relationship for residential noise exposure.

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[12] A D^* value may be interpreted as a value of DNL above which respondents describe themselves as highly annoyed by community noise exposure.

5 LOW-FREQUENCY NOISE REDUCTION MEASUREMENTS

The Expert Panel reached consensus on the results reported in Section 5.

This Section describes the results of Tasks 5, 6 and 8. Task 5 was undertaken to determine the low-frequency noise reduction of typical residential construction in the vicinity of MSP; Task 6 to determine the low-frequequency noise reduction afforded by treatments of the MSP Residential Sound Insulation Program; and Task 8 to determine the relative reduction of low-frequency noise of common forms of wall construction. The field measurements of Tasks 5 and 6 determined the noise reduction of entire homes (walls, roofs, windows, doors, other building envelope penetrations). The controlled laboratory measurements of Task 8 compared the low-frequency noise reduction of building walls, window and door openings separately.

5.1 SUMMARY OF NOISE REDUCTION MEASUREMENTS

The field measurements of Tasks 5 and 6 showed that (1) the low-frequency noise reduction of acoustically untreated and treated houses is nearly identical; (2) the low-frequency noise reduction provided by the untreated houses and treated houses is similar to that reported in published information about residential and commercial construction; (3) the mid- and high-frequency noise reduction of acoustically treated houses is greater than that of untreated houses; and (4) the mid- and high-frequency noise reduction provided by both the treated and untreated houses in the MSP study is somewhat greater than that generally expected for residential construction.

Table 13 Summary of laboratory measurements of low-frequency transmission loss of test articles.

Construction Element	Average Transmission Loss in 25-80 Hz One-Third Octave Bands
Brick wall	21.7 dB
Stucco	19.2
Wood siding	17.5
Window	16.9
Door	15.8

The results of the laboratory measurements of Task 8 are summarized in Table 13.

5.2 DESCRIPTION OF FIELD MEASUREMENTS

5.2.1 Approach to Determining Low-Frequency Noise Reduction of Residences

The American Society for Testing and Materials (ASTM) has adopted Standard E 966-92 for measurement of sound insulation of buildings that includes procedures for measurement of noise reduction (ASTM, 1992). Noise reduction of a building is the characteristic that describes the amount of noise kept out by a building's structure, expressed arithmetically as the difference between the outdoor noise level and the indoor noise level.[13] The Expert Panel developed a study plan in compliance with the Standard for the measurement of noise reduction, as required by Tasks 5 and 6.

The Standard describes two methods for measurement of noise insulation from outdoor sounds. The first method uses aircraft operations as the noise source. This method is most appropriate for situations in which large numbers of aircraft operations producing relatively high noise levels are anticipated. The noise source used for the second method is artificially-generated, amplified sound. This second method is appropriate for situations in which large numbers of aircraft operations producing relatively high noise levels are not anticipated. The Expert Panel preferred the latter method because it was anticipated that insufficient numbers of aircraft operations would occur at the measurement sites.

It was estimated from low-frequency measurements at other locations exposed to highway noise that exterior levels of low-frequency noise could be as high as 65 dB. The equipment selected to produce exterior noise produced sound levels of 85 dB or greater to assure that exterior and interior levels would be at least 10 dB greater than ambient levels of low-frequency noise. Figure 35 is a schematic diagram of the noise generation system. The electrical power available for the single-channel system was 3,000 watts. On-site measurements confirmed that exterior levels were between 85 and 95 dB in the one-half octave bands between 25 Hz and 80 Hz. The exterior levels were at least 15 dB above the measured ambient noise in all cases.

Standard E 966-92 specifies that the loudspeakers be directed at a facade at an angle of approximately 45° at a maximum ratio of 2:1 from the greatest and least distances to the facade. The loudspeakers were typically aimed at the center of the test facade, at a typical distance of between 38 and 43 feet. The ratio of distance from the loudspeaker to the most distant part of the facade and to the nearest part of the facade was always less than 2:1. Figure 36 schematically represents the location of the noise generation system's loudspeakers during the tests.

Figure 37 diagrams the noise measurement and analysis system. The outdoor microphone was located between 1.5 and 2 m from the facade at the aiming point. The microphone was moved in a circle approximately 1 m in diameter during measurements. The indoor microphone was located between 1.5 and 2 m from the facade and moved in a circle approximately 1 m in diameter.

The signals from the microphones were recorded by a Larson Davis 2900 signal analyzer and two digital tape recorders (DATs). The LD-2900 recorded one-third octave band levels of all events for subsequent analysis, while the DATs recorded the wide-band audio signals.

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[13] This formula for noise reduction assumed that the outdoor level is measured at a distance from all reflecting surfaces other than the ground. The text identifies the adjustment required for measurements near the building facade.

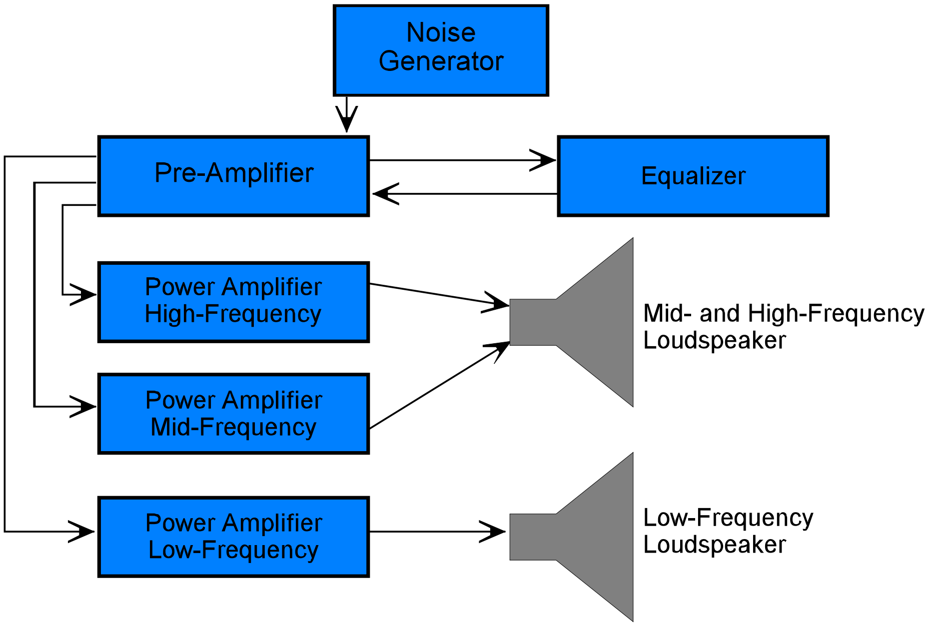

Figure 35 Equipment used to generate noise for noise reduction measurements.

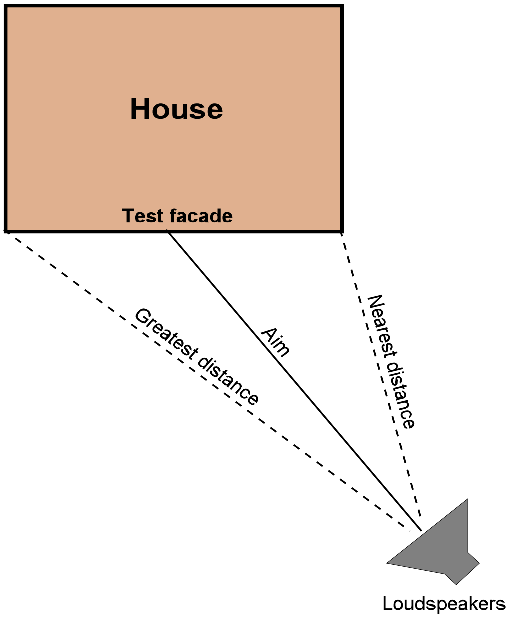

Figure 36 Relationship between loudspeakers and insonified facades of test sites.

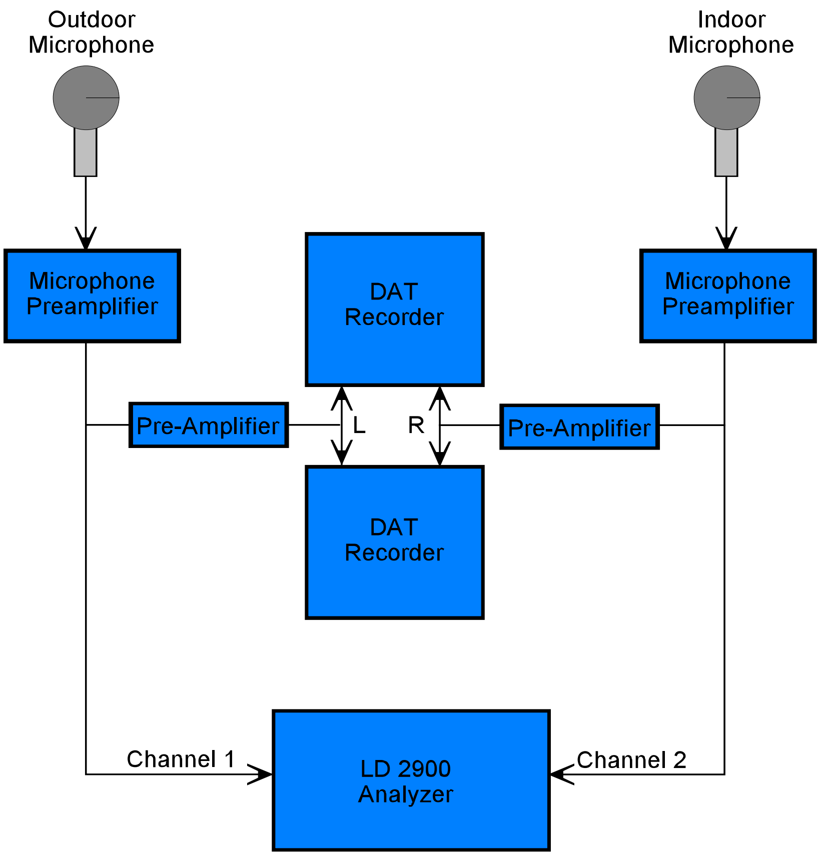

Figure 37 Schematic diagram of noise reduction measurement and analysis system.

The noise reduction of two or three rooms was measured at each house. In accordance with the Standard, noise reduction was calculated for one-third octave bands as the arithmetic difference between the outdoor level and the indoor level, minus a 3-dB adjustment to account for the measurement location closest to the facade. Low-frequency noise reduction was calculated from the one-third octave bands between 25 Hz and 80 Hz.

Noise reductions were measured at ten treated and nine untreated houses in Richfield and Minneapolis. The typical construction was wood frame with brick, stucco, wood, or aluminum siding. An attempt was made to include all siding types in the selection of both treated and untreated houses. Table 14 summarizes the addresses, siding treatments, and insulation status of the homes at which noise reduction measurements were made.

The tests were conducted from 17 May to 21 May, 1999. Personnel from the MAC Residential Sound Insulation Program arranged the test schedule with homeowners. HMMH personnel conducted the tests, which were observed by Dr. Fidell and Mr. Harris of the Expert Panel.

Table 14 Addresses and descriptions of test houses.

Site Number	Street Address	Sound Insulation Treatment	Siding Material
1	5713 39th Ave. S., Minneapolis	Treated	Stucco
2	5820 45th Ave. S., Minneapolis	Treated	Stucco
3	5841 45th Ave. S., Minneapolis	Treated	Wood
4	5605 39th Ave. S., Minneapolis	Untreated	Wood shakes
5	6414 12th Ave. S., Richfield	Treated	Wood shakes
6	5705 37th Ave. S., Minneapolis	Treated	Wood shakes
7	5841 44th Ave. S., Minneapolis	Untreated	Brick and wood shakes
8	6524 16th Ave. S., Richfield	Untreated	Stucco
9	5613 40th Ave. S., Minneapolis	Treated	Stucco
10	6434 12th Ave. S., Richfield	Treated	Brick
11	6411 Bloomington St. S., Richfield	Untreated	Aluminum siding
12	5733 42nd Ave. S., Minneapolis	Untreated	Stucco
13	6444 12th Ave. S., Richfield	Treated	Stucco
14	6517 Bloomington St. S., Richfield	Treated	Brick and wood shakes
15	6351 Bloomington St. S., Richfield	Untreated	Brick
16	6445 Bloomington St. S., Richfield	Treated	Brick
17	5729 42nd Ave. S., Minneapolis	Untreated	Wood shakes
18	6424 Bloomington St. S., Richfield	Untreated	Stucco
19	5617 40th Ave. S., Minneapolis	Untreated	Wood shakes

5.2.2 Noise Reduction of Untreated Houses

The measured values of the noise reduction at the untreated houses were calculated for the one-third octave bands from 25 Hz to 2,500 Hz. Figure 38 shows the measured noise reduction for the nine untreated houses. The data fall within a range of 10 to 20 dB in the different bands. Each house is represented by the average values for the rooms measured. The symbols used in this and related figures designate the four exterior sidings of the houses (*i.e.*, stucco, wood shakes or aluminum siding, brick, or a mixture of brick and wood shakes).

Figure 39 shows the measured noise reduction of the untreated houses averaged by type of siding. The data in the figure indicate no significant effect of weight of siding on noise reduction performance. No siding type yielded either the greatest or least noise reduction at all frequencies.

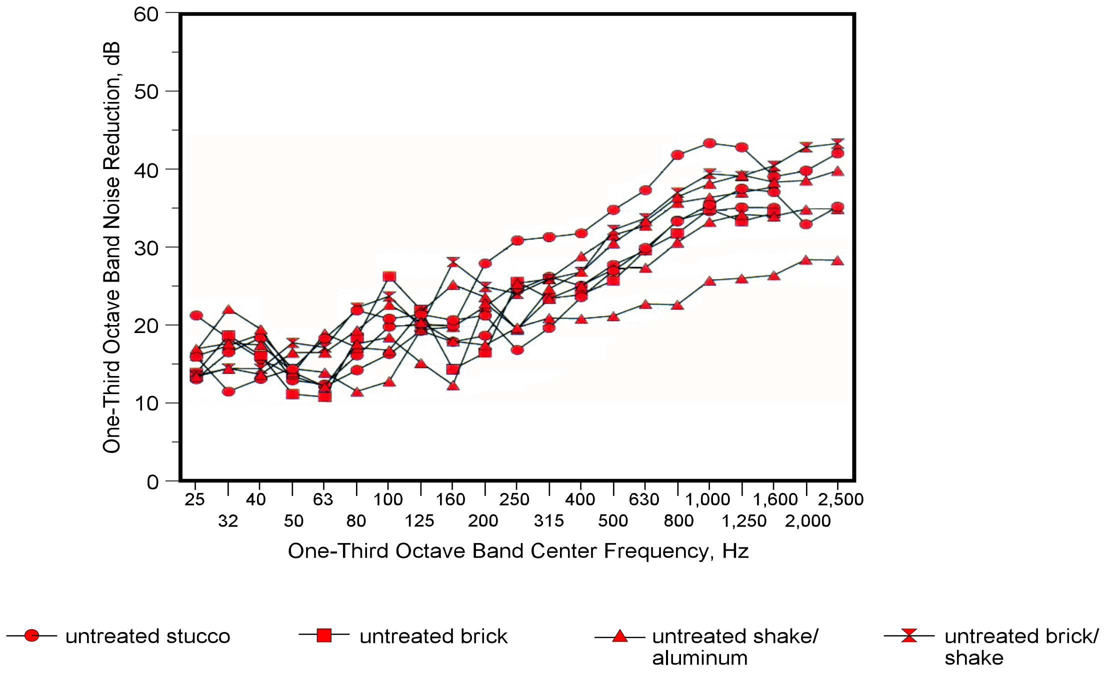

Figure 38 Measured noise reduction in untreated houses.

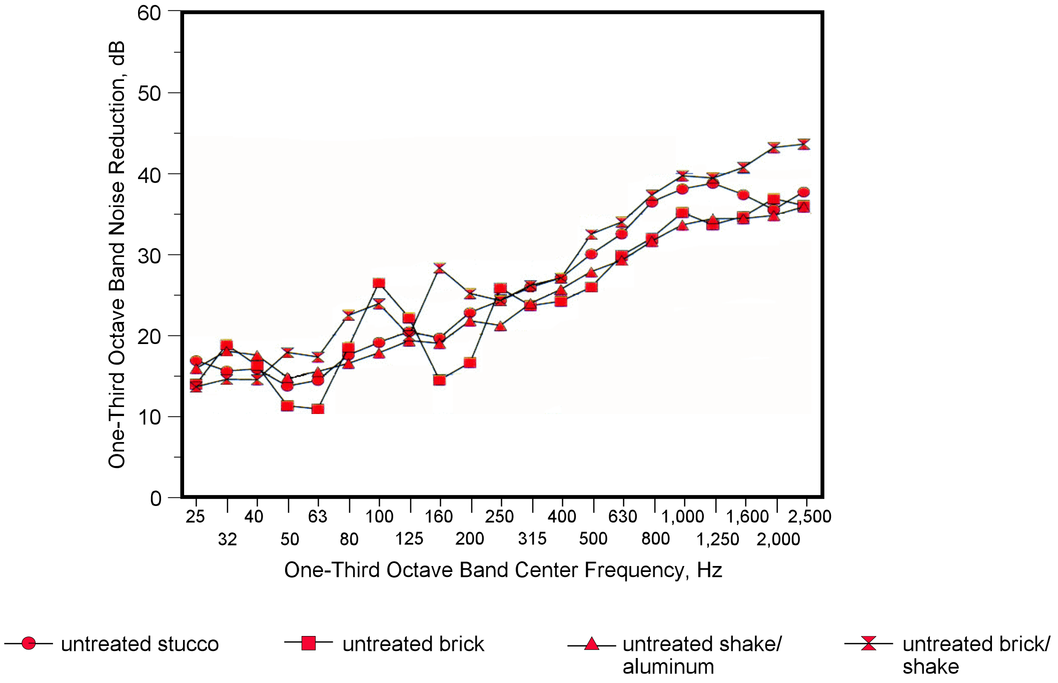

Figure 39 Measured noise reduction of untreated houses averaged by siding type.

Figure 40 summarizes the average noise reduction for the untreated houses, in terms of the average of the one-third octave bands from 25 Hz to 80 Hz. The range of values is narrow (from 13 dB to 17 dB, or ±2 dB), indicating that the low-frequency noise reduction is not related to type of siding.

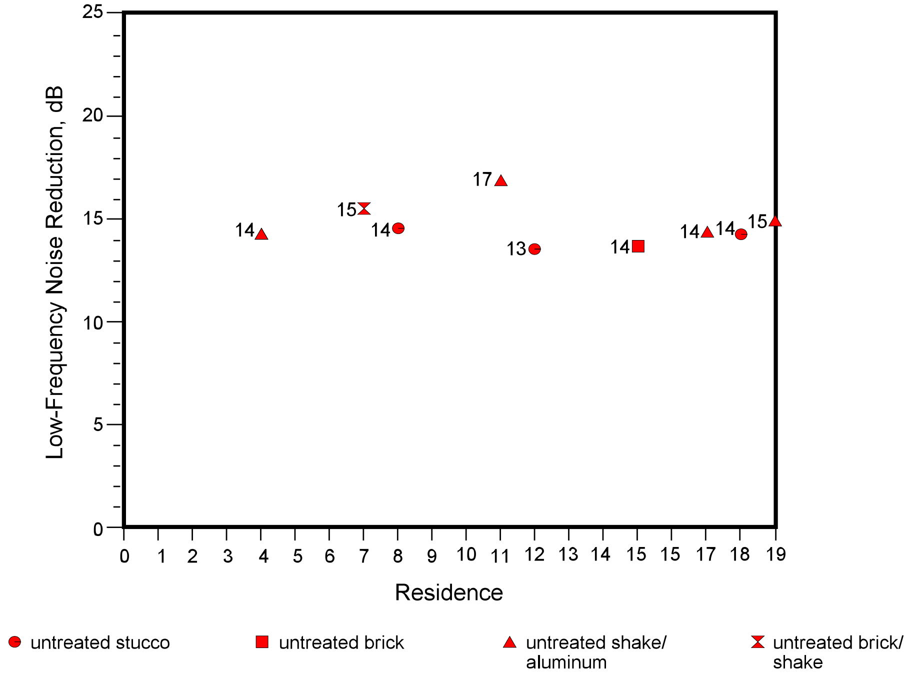

Figure 40 Average low-frequency noise reduction (from 25-80 Hz) for untreated houses.

5.2.3 Noise Reduction of Acoustically-Treated Houses

Analysis of the noise reduction of houses that MSP had acoustically treated paralleled that of the treated houses. Figure 41 shows the measured noise reduction of the treated houses. The data are typically in a tighter range than that observed in the untreated houses.

Figure 42 shows the measured noise reduction of the treated houses, grouped by type of exterior siding. As in the case for untreated houses, the data in the figure do not indicate that the heavier siding types have a higher noise reduction performance that the lighter siding types. The noise reduction performance of each of the siding types was mixed, with no siding type best or worst at all frequencies.

Figure 43 shows the average noise reduction for the treated houses, in terms of the low-frequency noise descriptor. The range of values is nearly identical to that for the untreated houses, from 13 dB to 18 dB. As in the case for untreated houses, the low-frequency noise reduction was not related to type of siding.

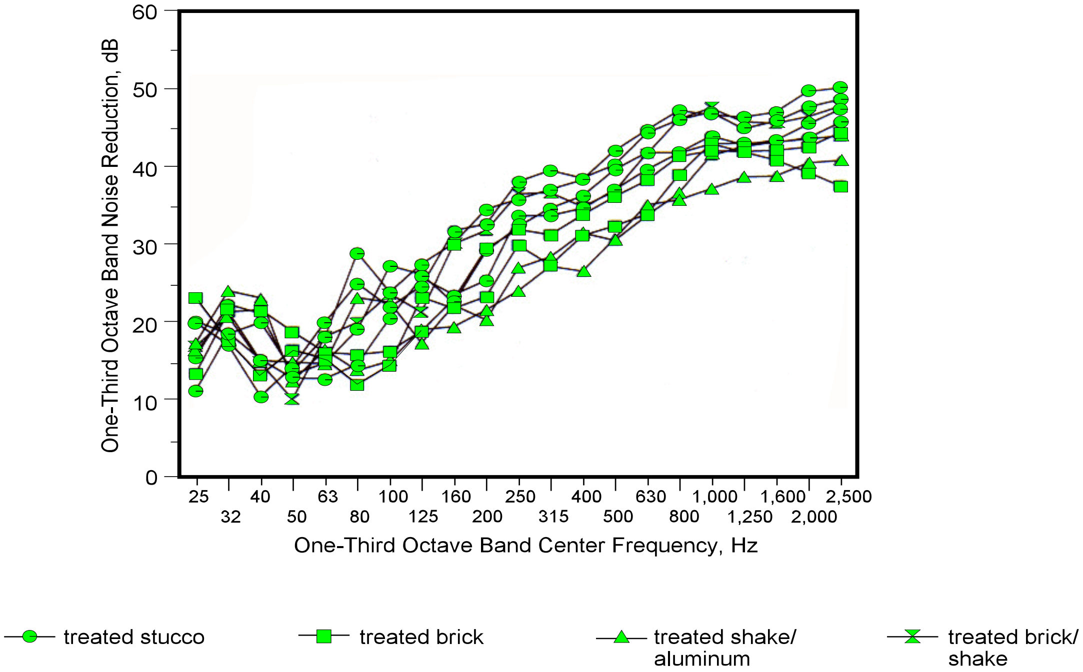

Figure 41 Measured noise reduction of treated houses.

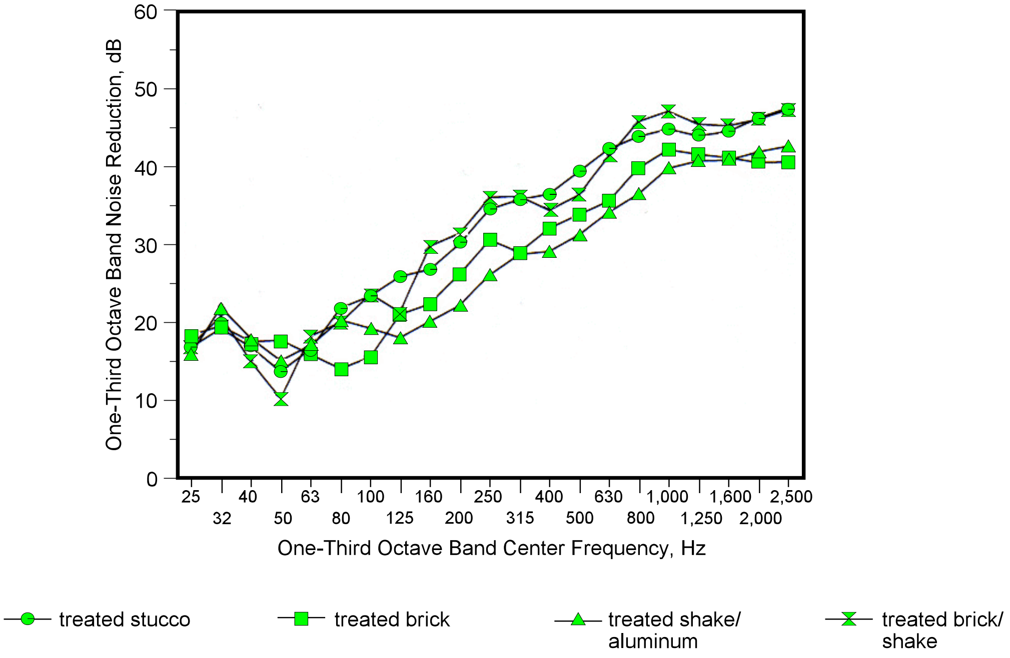

Figure 42 Measured noise reduction of treated houses averaged by siding type.

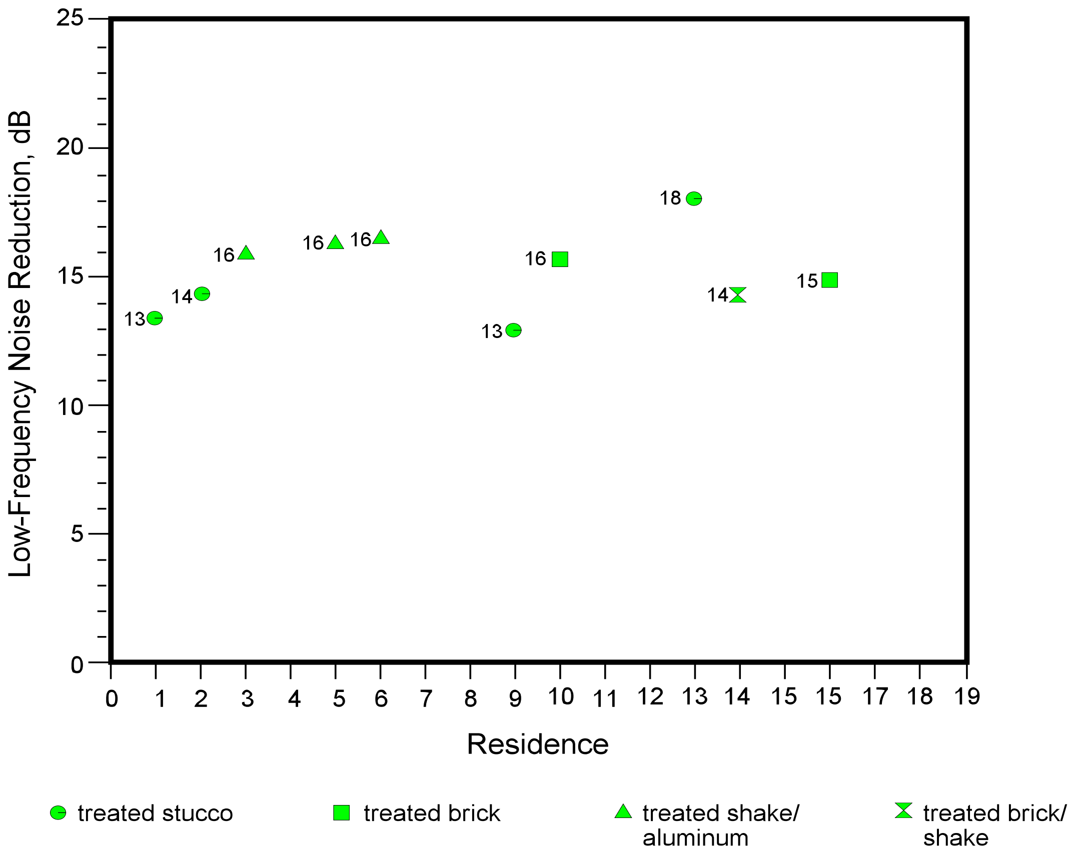

Figure 43 Low-frequency noise reduction in treated houses.

5.2.4 Comparisons of Untreated and Treated Houses

This subsection compares the noise reduction performance of untreated and treated houses over the range of frequencies from 25 Hz to 2,500 Hz, and the performance of measured houses with published information about measurements at other locations.

Figure 44 combines the data from Figures 39 and 42, allowing comparisons among the untreated and treated houses with data averaged by siding type. The treated houses clearly have better noise reduction than the untreated houses at about 125 Hz. The results are mixed at lower frequencies, as shown in Figure 45.

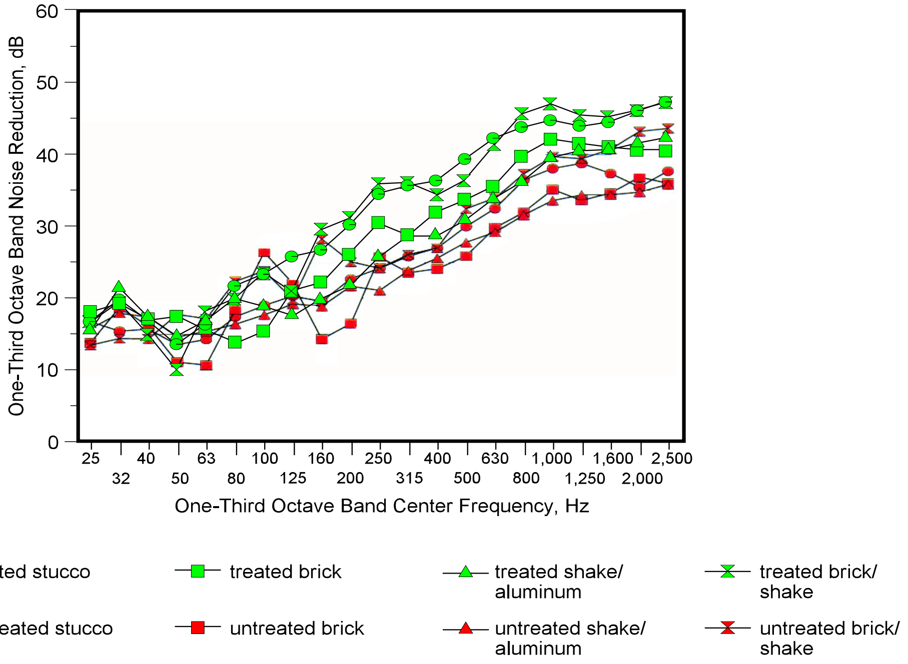

Figure 44 Measured noise reduction for both treated and untreated houses, averaged by siding type.

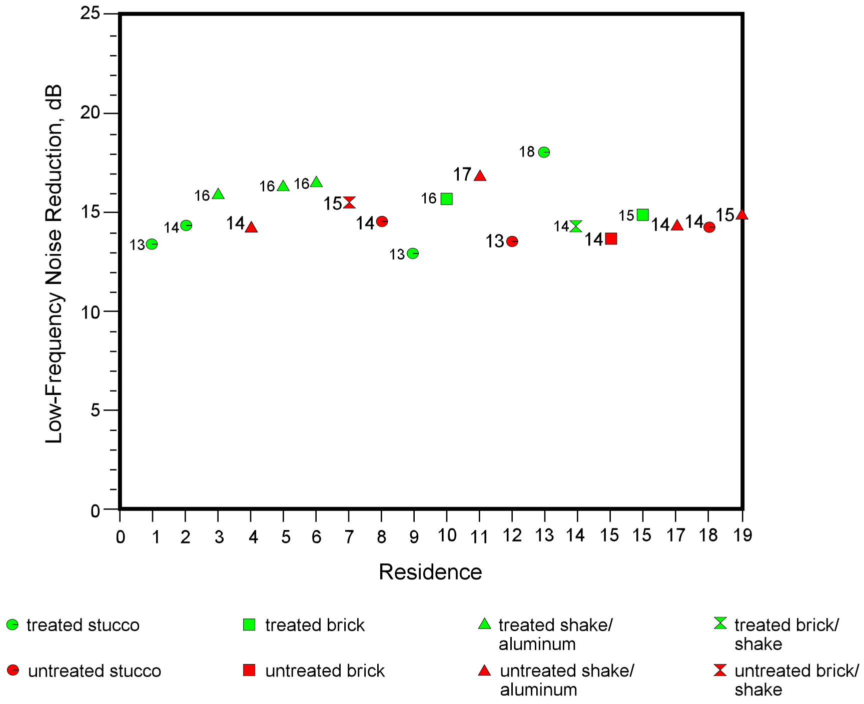

Figure 45 Low-frequency noise reduction of treated and untreated houses.

The average values of the low-frequency descriptor for untreated and treated houses from Figures 40 (untreated houses) and 43 (treated houses) are combined in Figure 45. While the highest value is for a treated house, it is only 1 dB better than the best untreated house. The average value for the treated houses is 1 dB higher than for the untreated houses. No meaningful difference was found between treated and untreated houses in low-frequency noise reduction.

MSP data were compared to data from other sources. Bishop (1966) described a "typical range in noise reduction for residential and commercial construction expected on [the] basis of previous studies." Figure 46 combines Bishop's range, data from Sutherland (1978), and MSP data. The MSP data fall within Bishop's range at lower frequencies, and are better at middle and higher frequencies. Even the untreated houses measured around MSP provided better noise reduction than the buildings in Bishop (1966) at frequencies above 600 Hz. While Bishop provides no information about the buildings from which the range of data came, his own measurements were of typical, light-weight, concrete block or brick buildings with single-pane glass windows. Since Bishop's measurements are similar to the range of data shown, it seems likely that the range of data come from buildings that were not as well closed and/or insulated as are typical in communities surrounding MSP.

Sutherland (1978) summarizes residential noise reduction measurements for aircraft noise in cold climates, measured under closed-window conditions. The MSP noise reduction measurements are similar to Sutherland's observations at low frequencies, but indicate greater noise reduction at mid and high frequencies, as shown in Figure 46. Sutherland's data are at the top of Bishop's range at frequencies as high as 1,000 Hz, and slightly above that range at yet higher frequencies.

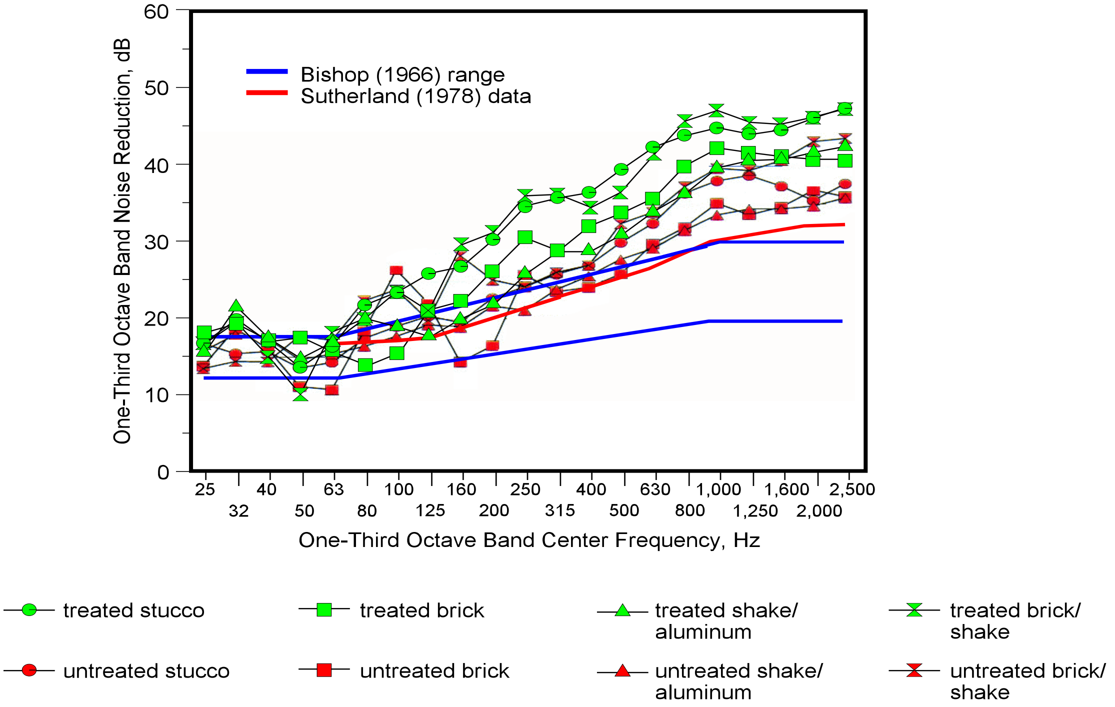

Figure 46 Residential noise reduction from MSP data *vs.* data from other studies.

5.3 DESCRIPTION OF LABORATORY MEASUREMENTS

Laboratory measurements of low-frequency transmission loss were undertaken to complement the field measurements of noise reduction described in Section 5.2. These field measurements established the low-frequency noise reduction of the entire building envelope. Since it is possible that penetrations of the building envelope (windows, doors, attic vents, plumbing stacks, *etc.*) influenced the low-frequency noise reduction of the measured homes, more controlled measurements were made in the Low-Frequency Test Facility illustrated in Figures 9 and 10 (on page II-12). The results of additional laboratory measurements help to establish whether treatments of walls, doors and window units afford any prospect of useful improvement in low-frequency noise reduction of homes near MSP.

5.3.1 Study Design

5.3.1.1 Test method

Several full-scale house wall sections were mounted in front of the wall of low-frequency drivers seen in Figure 10. Four additional loudspeakers were added to the corners of the low-frequency driver wall to reproduce sound at frequencies higher than 100 Hz. A cable and pulley system was rigged between the low-frequency driver wall and the interior surface of the test articles, so that a B&K Type 4155 microphone could be carried on an externally operated shuttle to measure sound pressures along a horizontal traverse of the insonified space. Figure 7 is a schematic representation of the measurement spaces on the two sides of the test articles.

A number of additional measures were taken to minimize various complications of low-frequency acoustic measurement. The surfaces of the plenum between the interior surface of the test articles and the wall of low-frequency drivers were covered with high-density acoustic insulation to minimize standing waves, and the corner speakers were driven with Gaussian noise from four independent generators. The rear wall of the Low-Frequency Test Facility was extensively treated with stepped density acoustic absorption, configured to minimize reflections and standing waves. Sound intensity rather than pressure measurements were made on the receiver side of test articles, so that sound power could be calculated inside the Low-Frequency Test Facility. The sound power measurements were made according to the method of ISO 9714-1.

5.3.1.2 Construction of basic stud wall

A 2” x 4" stud framed wall measuring 97" high by 122" wide was first constructed and mounted 18" in front of the low-frequency driver wall. Uprights were located on 16" centers. In accordance with standard practice at the time much of the housing near MSP was built, the frame contained no let-in diagonal bracing or fire blocking.

5.3.1.3 Boundary conditions

The attachment of the stud wall to the concrete walls, floor and ceiling of the low-frequency test facility was intended to resemble the typical attachment of walls to the foundation, roof, and other elements of residential structures. All attachment surfaces were caulked to provide an airtight seal between the source and receiver sides of the wall.

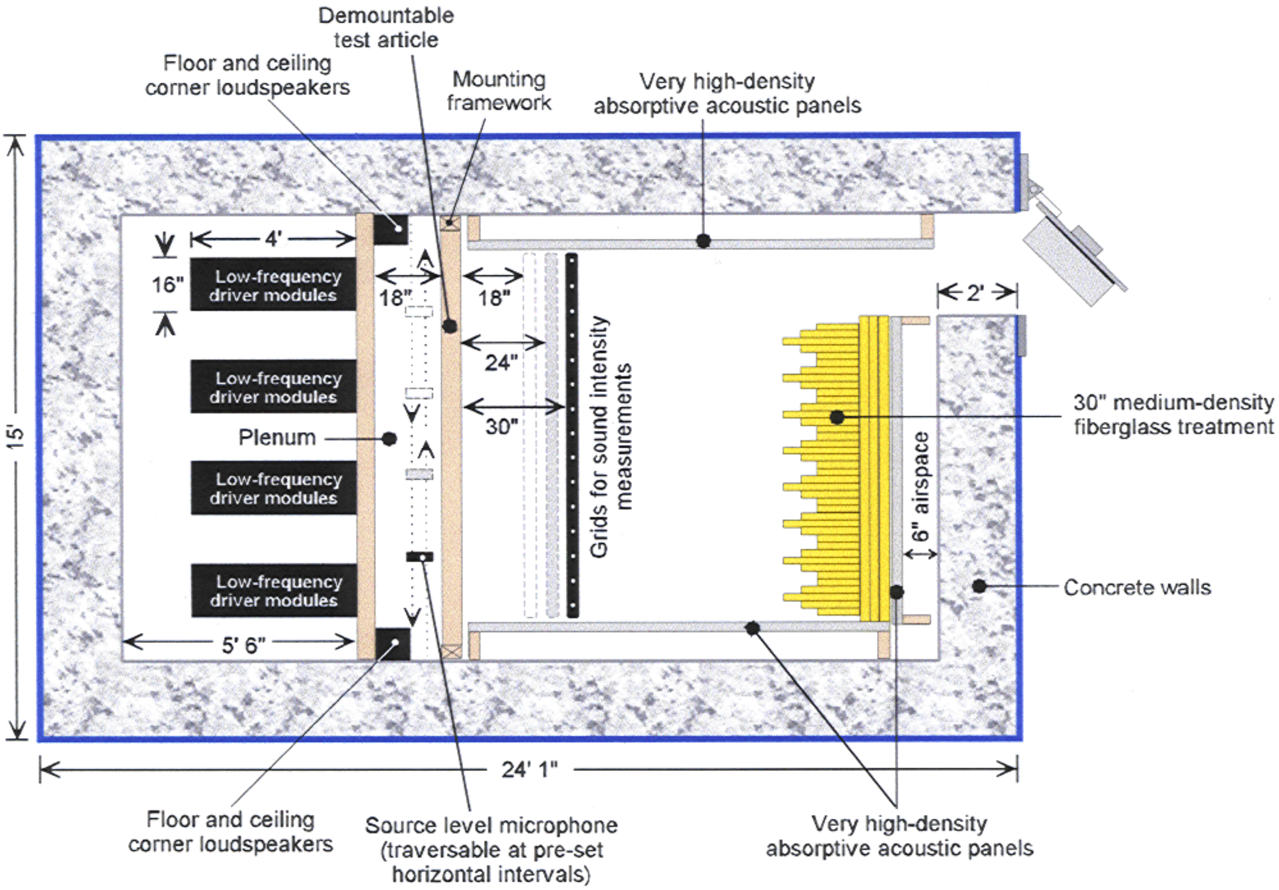

Figure 47 Low-frequency test facility as configured for transmission loss measurements.

The interior surface of the stud wall was composed of ½"-thick gypsum board panels. Seams between gypsum board panels were filled with joint compound and taped. The bays between upright studs were filled with fiberglass insulating batts and covered with construction paper. Horizontal 1" x 8" pine boards were then applied on top of the construction paper. Figures 48 through 56 show several stages in the construction of the wall sections. They also illustrate the placement of accelerometers on the test articles, and show the sound intensity probe at a grid point location.

Table 15 summarizes the nature and order of application of exterior treatments to the test article framework. Table 16 summarizes the densities of the three walls as built.

Figure 48 Sealing mounting framework for test articles.

Figure 49 Installation of stud wall frame in low-frequency test facility.

Figure 50 Installation of fiberglass insulation batts between stud wall uprights.

Figure 51 Application of 1" x 8" pine planks to stud wall.

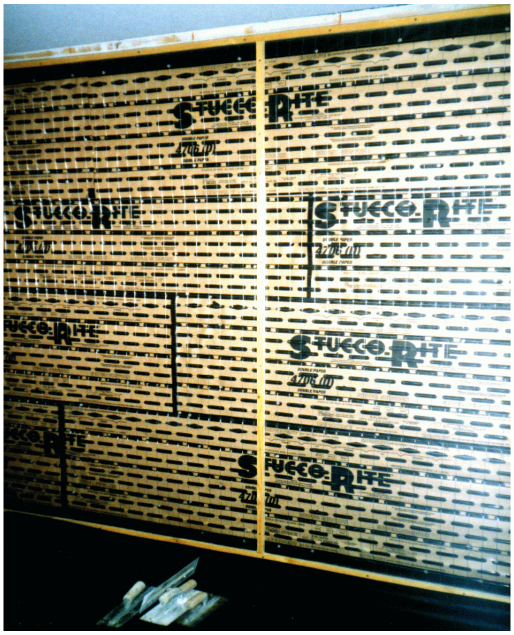

Figure 52 View of completed lath.

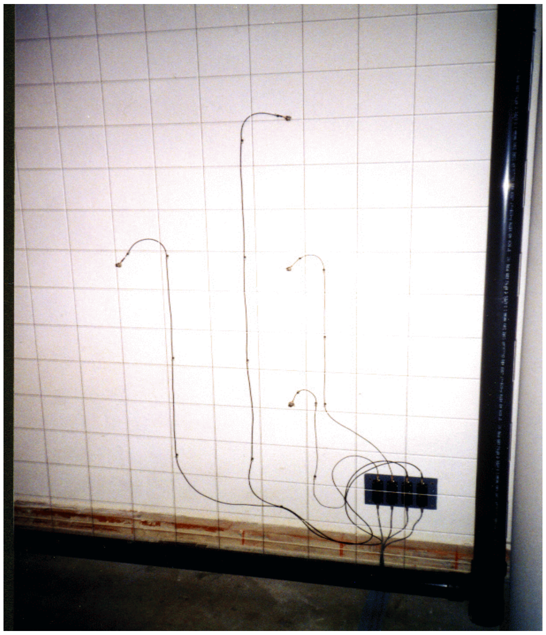

Figure 55 View of completed stucco wall and accelerometer attachments.

Figure 53 Measurement of sound intensity at one grid point location.

Figure 54 Appearance of brick facade with door installed.

Figure 56 Appearance of brick facade with window installed.

Table 15 Summary of construction and sequence of testing of test articles.

Test Article	Construction of Wall Section
1	2" x 4" stud framed wall with exterior wood siding (11/16" finished thickness)
2	Exterior (three-coat) stucco over stud wall
3	Full-height exterior brick facade over stud wall, with door
4	Full-height exterior brick facade over stud wall, with window
5	Full-height brick facade over stud wall, no penetrations

Table 16 Density of the three walls as built.

Wall Type	Density in Metric Units	Density in Common Units
Wood	37 kg/m^2	7.6 lb/ft^2
Stucco	63 kg/m^2	13 lb/ft^2
Brick	169 kg/m^2	34.6 lb/ft^2

5.3.2 Results of Measurements

Acoustic intensity measurements were made over a 6x7 point scanning grid established at two or three distances from the surface of each test article. Figure 57 shows the measured sound transmission loss of the wood siding, the stucco wall, the entry door, and the wood window relative to the brick wall.

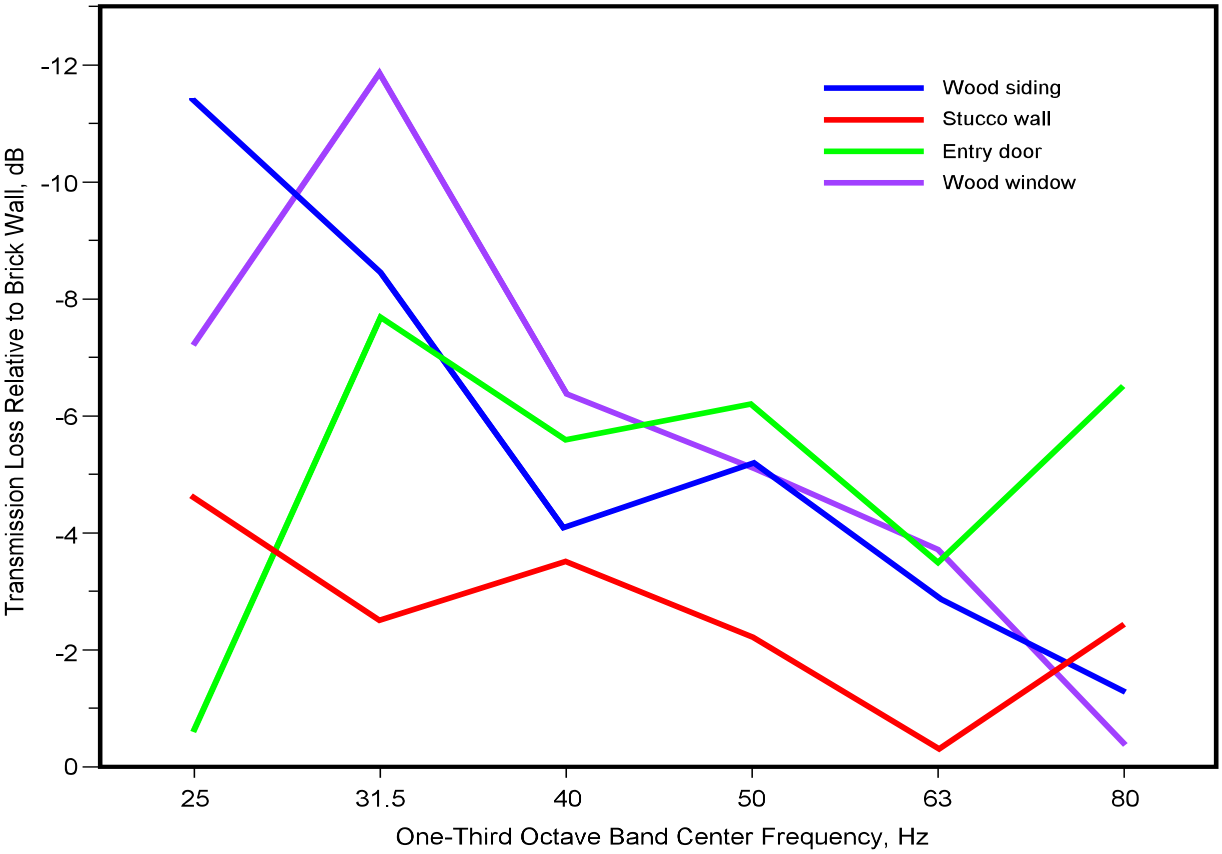

Figure 57 Sound transmission loss of four building elements relative to the transmission loss of the brick wall.

5.4 CONCLUSIONS ABOUT LOW-FREQUENCY RESIDENTIAL NOISE REDUCTION

The following conclusions were reached concerning the noise reduction of the houses at which field measurements were made:

> The low-frequency noise reduction of acoustically untreated and treated houses is nearly identical. In other words, the treatment provided by the MSP Residential Sound Insulation Program does not improve the low-frequency noise reduction of residences.
>
> The low-frequency noise reduction provided by the untreated houses and treated houses is similar to that reported in published information about residential and commercial construction.
>
> The mid- and high-frequency noise reduction of acoustically treated houses is greater than that of untreated houses. In other words, the treatment provided by the MSP Residential Sound Insulation Program increases the mid- and high-frequency noise reduction of houses.
>
> The mid- and high-frequency noise reduction provided by both the treated and untreated houses in the MSP study is somewhat greater than that generally expected for residential construction.

The following conclusions were reached concerning the laboratory measurements of low-frequency noise reduction:

> The transmission losses of brick, stucco, and wood walls in the range of 25 through 80 Hz were consistent with, but not wholly controlled by, the density of construction.
>
> The low-frequency transmission loss of an entry door was found to be comparable to that of wood siding construction, but inferior to that of stucco and brick walls.
>
> The average low-frequency transmission loss of a window was poorer than that of all forms of wall construction, and hence, likely to remain a limiting factor in practical efforts to improve the low-frequency transmission loss of homes.

6 EXISTING AND ANTICIPATED LOW-FREQUENCY NOISE LEVELS IN THE VICINITY OF MSP

The Expert Panel did not reach consensus on significant portions of Section 6. The consensus or absence of consensus is indicated at each subsection.

This section describes the methods developed to prepare maps displaying predicted low-frequency noise from future aircraft operations on Runway 17/35. This description is preceded by the findings of a number of measurements of current low-frequency ambient noise levels in the vicinity of MSP.

6.1 SUMMARY OF MEASUREMENTS OF CURRENT LOW-FREQUENCY NOISE LEVELS AND ESTIMATES OF FUTURE LEVELS

While the Expert Panel reached consensus on the text presented in this paragraph, the paragraph does not fully address the levels of low-frequency aircraft noise in the vicinity of MSP.

Ambient noise levels in neighborhoods near MSP are on the order of 55 dB ± 5dB in the frequency region lower than 100 Hz. These levels are similar to those measured in urban areas elsewhere, and appear to be linked to both population density and time of day. Low-frequency sound levels produced by future aircraft operations on Runway 17/35 are expected to considerably exceed current ambient levels in eastern Richfield.

Richfield's situation is not unique. The measurements reported in Section 6.4 show that current levels low-frequency aircraft noise in Minneapolis exceed ambient levels of low-frequency noise in Minneapolis. Low-frequency noise from non-aviation sources also exceed the ambient noise in all communities.

6.2 CURRENT LEVELS OF LOW-FREQUENCY NOISE IN RESIDENTIAL AREAS NEAR MSP

The Expert Panel reached consensus on the results presented in Section 6.2.

6.2.1 Introduction

Task 3 of the Expert Panel's Plan of Work required identification of current ambient and aircraft-related low-frequency noise levels near MSP, and resolution of any differences between BBN and HMMH estimates of future levels of low-frequency aircraft noise. The following subsections report the results of measurements of low-frequency ambient noise in Bloomington, Richfield and Minneapolis.

6.2.2 Measurements

HMMH measured daytime ambient noise levels at 19 locations in residential areas of Bloomington, Richfield and Minneapolis during the conduct of Tasks 5 and 6 (reported in Section 5). The measurement periods selected for analysis were without obvious noise from aircraft operations.[14]

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[14] Because part of the low-frequency range of interest is not directly audible, the absence of obvious aircraft noise does not imply that these measurements were not influenced by distant jet engines operating at low power settings.

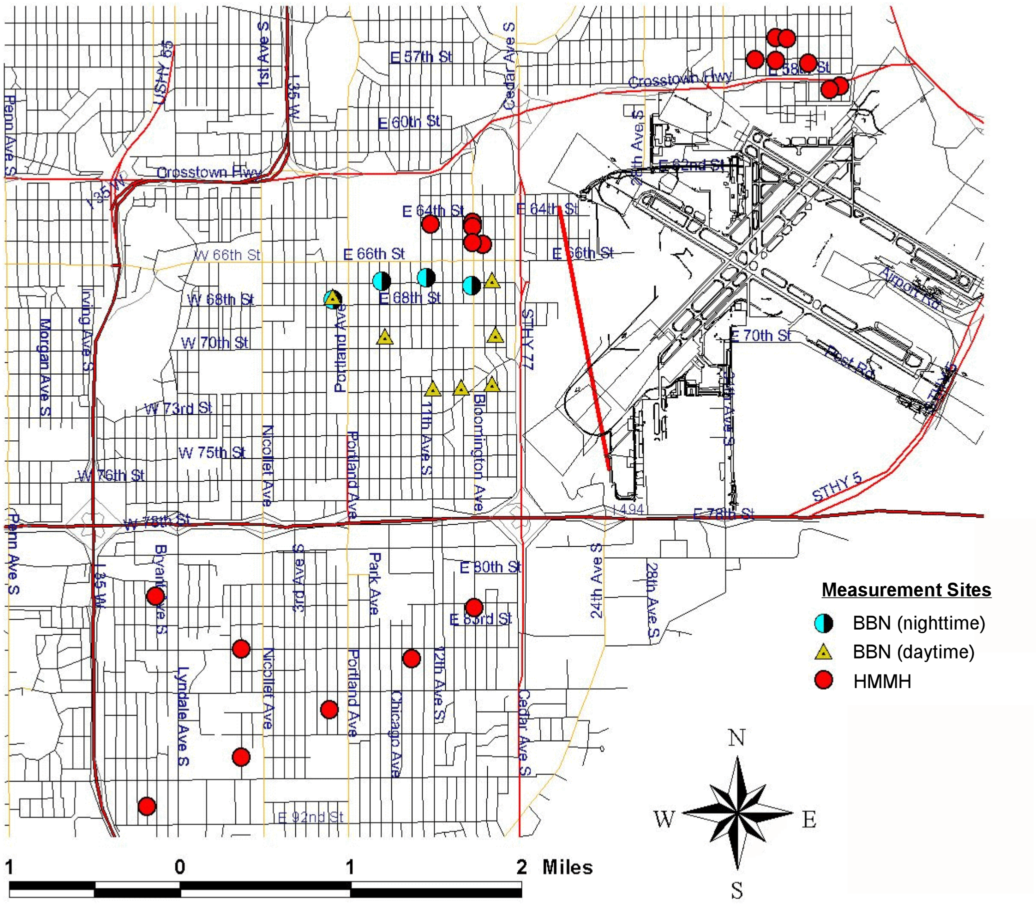

Figure 58 Locations of BBN and HMMH ambient noise measurement sites.

BBN measured daytime and nighttime ambient noise levels at an additional 11 locations in Richfield. Figure 58 shows the locations of all of these ambient noise measurement points.

Figure 60 shows the range of daytime short-term equivalent levels measured by HMMH in the three cities in one-third octave bands from 25 Hz to 2,500 Hz. While portions of the ranges of the ambient levels for the three cities overlap, ambient noise levels in Minneapolis tended to be the greatest, those in Bloomington tended to be the least, and those Richfield were intermediate in level. Since the housing density appeared to be greatest near the Minneapolis measurement sites, intermediate in Richfield, and lowest in Bloomington, this finding is consistent with the observation of Fidell, Horonjeff and Green (1981) that ambient noise levels vary directly with population density. Figure 59 compares mean levels of ambient noise measured by HMMH in Minneapolis, Richfield and Bloomington with those summarized by Sutherland (1978) from the work of Bonvallet (1951), Donley, (1969), and Veneklasen (1968).[15] The ambient levels observed in the vicinity of MSP are similar to those Sutherland summarized,

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[15] The data from Minneapolis, Richfield and Bloomington are short-term equivalent levels in one-third octave bands, while those reported by Sutherland data are median (L_{50}) octave band levels. These two similar measures are shown without adjustment.

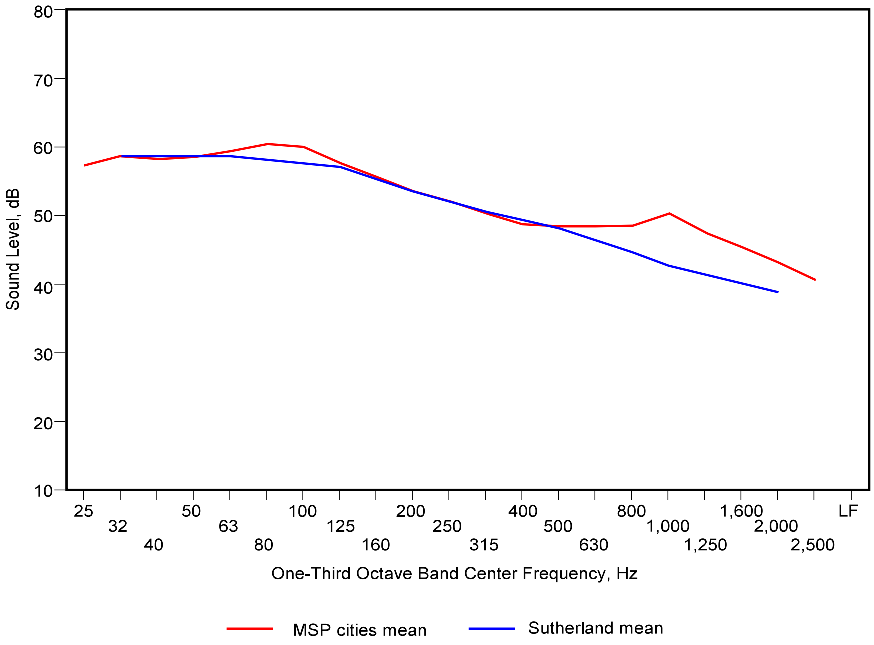

Figure 59 Comparison of ambient noise levels measured by HMMH near MSP with those reported by Sutherland (1978).

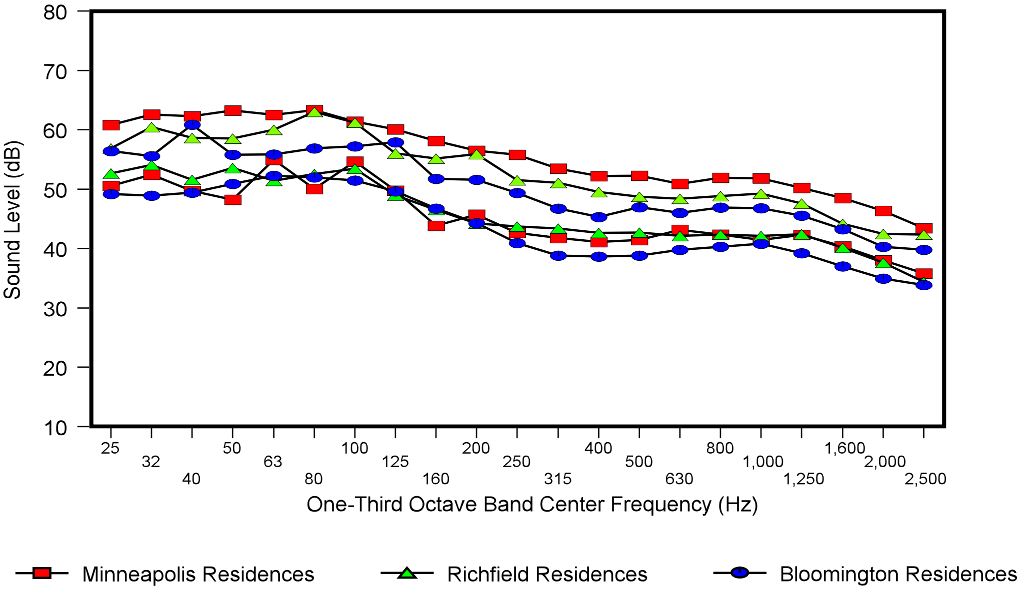

Figure 60 Ranges of daytime ambient noise levels measured by HMMH at sites in three cities near MSP.

although they are somewhat greater at frequencies between 500 Hz and 2,500 Hz.

Figure 61 shows daytime and nighttime ambient noise levels measured by BBN in Richfield and to the side of Runway 11/29. The nighttime one third octave band ambient noise levels observed in Richfield are quite similar to the nighttime levels reported by Fidell *et al.* (1981) in the one-third octave bands centered at 50 through 80 Hz for areas with population densities on the order of 5,000 people per square mile. Note, however, that the nighttime (0200 - 0300) noise levels in Richfield are about 10 dB lower in level than daytime noise levels. This finding is consistent with that reported by Fidell *et al.* (1981) that urban ambient noise levels decrease at night.

Table 17 shows means and standard deviations of LFSL values for all measurements made by HMMH and BBN, calculated separately by city and time of day.

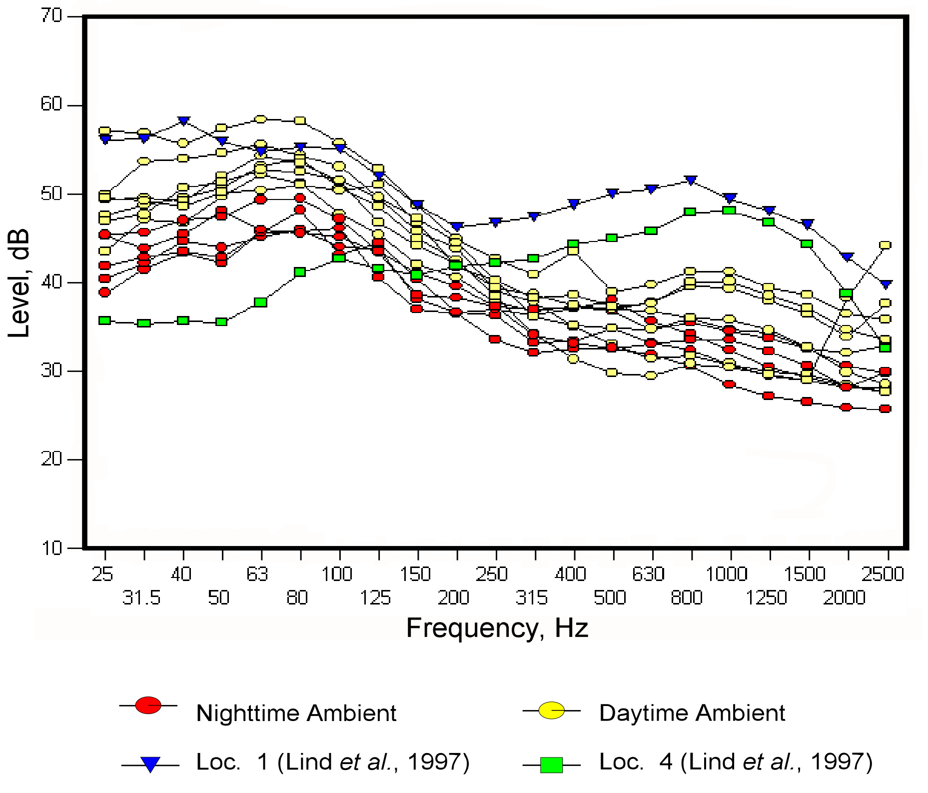

Figure 61 Ambient noise levels measured by BBN in Richfield and near Runway 11/29.

Table 17 Mean and standard deviation of LFSL values calculated separately by city, and for Richfield, by time of day.

CITY	NUMBER OF SITES	MEAN LFSL VALUE (dB)	STANDARD DEVIATION (dB)
Minneapolis	8	67.9	3.6
Richfield (day)	12	61.5	3.7
Richfield (night)	5	53.2	2.1
Bloomington	7	61.6	2.3

6.2.3 Conclusions Concerning Ambient Levels of Low-Frequency Noise

Ambient noise levels measured in areas around MSP are generally similar to those previously reported in other urban residential areas. They appear to increase with population density and to decrease at night.

6.3 EXPECTED LEVELS OF LOW-FREQUENCY NOISE DUE TO OPERATIONS ON RUNWAY 17/35

The Expert Panel did not reach consensus on the expected levels of low-frequency aircraft noise in the vicinity of MSP in the future.[16]

Estimation of predicted levels of low-frequency aircraft noise was one of the principal tasks of the Expert Panel (Task 3 of the Scope of Work). From the beginning of the Expert Panel's work, it was known that the INM would not be able to provide adequately accurate contours of the low-frequency noise. The FAA agreed with this conclusion and recommended that the study include measurements of low-frequency aircraft noise in the vicinity of MSP. A measurement program became Task 10 of the Scope of Work.

The primary source of low-frequency aircraft noise is departing aircraft from initial application of takeoff power until shortly after the aircraft has left the ground. During analysis of the measurements, the potential effects of low-frequency noise during the reverse thrust phase of landings became a point of debate among members of the Expert Panel. While the Expert Panel did not reach consensus on future levels of low-frequency noise from the initial phase of departures and from reverse thrust, there was agreement that low-frequency noise from other phase of aircraft operations was not of concern.

Past experience with community reactions to low-frequency aircraft noise has shown that noise from reverse thrust is only an issue in those instances where the reverse thrust operations are significantly closer to the community than departure operations. The Expert Panel's analyses were undertaken in the light of this knowledge.

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[16] ***Task 3 of the Scope of Work for the Expert Panel (presented in Appendix C) directed the Expert Panel to determine expected levels of low-frequency aircraft noise in all areas around MSP, not just those areas where low-frequency noise would be expected from operations on Runway 17/35.***

On an average annual day in 2005, the MAC expects Runway 17/35 to support 369 daytime and 53 nighttime operations. These operations will constitute 37% of all departures and 17% of all expected arrivals at MSP. Construction of prospective LFSL contours for these future aircraft operations was complicated by several factors:

The Expert Panel reached consensus on the following factor with the understanding it refers to the portion of a take off when the aircraft is on the ground or near to the ground and during the portion of an approach (more correctly "landing") when the aircraft is on the ground using thrust reversal.

> the relative low-frequency content of both take off and approach noise varies with distance from the start of takeoff roll and the landing threshold, respectively;

The Expert Panel reached consensus on the following factor.

> the current version of INM does not adequately model ground-to-ground propagation of runway sideline noise;

The Expert Panel did not reach consensus on the following factor. (See the discussion below.)

> absent direct measurements of low-frequency aircraft noise at sites in Richfield and elsewhere around the airport, conversion of INM-produced maximum C-level noise contours into LFSL contours by means of empirical relationships was unwarranted[17];

The Expert Panel did not reach consensus on the following factor. (See the discussion below.)

> attempts to construct empirical LFSL contours by transposing values of LFSL measured at various points relative to Runways 12/30 and 4/22 to equivalent positions with respect to Runway 17/35 yielded inconsistent and uninterpretable results; and

The Expert Panel did not reach consensus on the following factor. (See the discussion below.)

> uncertainty of several types (notably about source levels and propagation effects), as well as the non-cumulative nature of the LFSL noise metric, limited the precision with which any contours could be drawn.

Cumulatively, the final three statements above imply that the Expert Panel's field measurements of departing and arriving aircraft were useless, except as indicated in the footnote below. In fact, the field measurements provided the basis for LFSL contours for departing aircraft and aircraft using reverse thrust after landing. The contours were based on analyses by the entire Expert Panel with assistance from personnel from BBN and HMMH.

---

[17] INM-produced maximum C-weighted noise contours were interpretable for purposes of constructing a dosage-response relationship because they were used primarily for establishing exposure gradients, and because the absolute values of contour lines could be adjusted by empirically-established relationships derived from measurements made within the interviewing area.

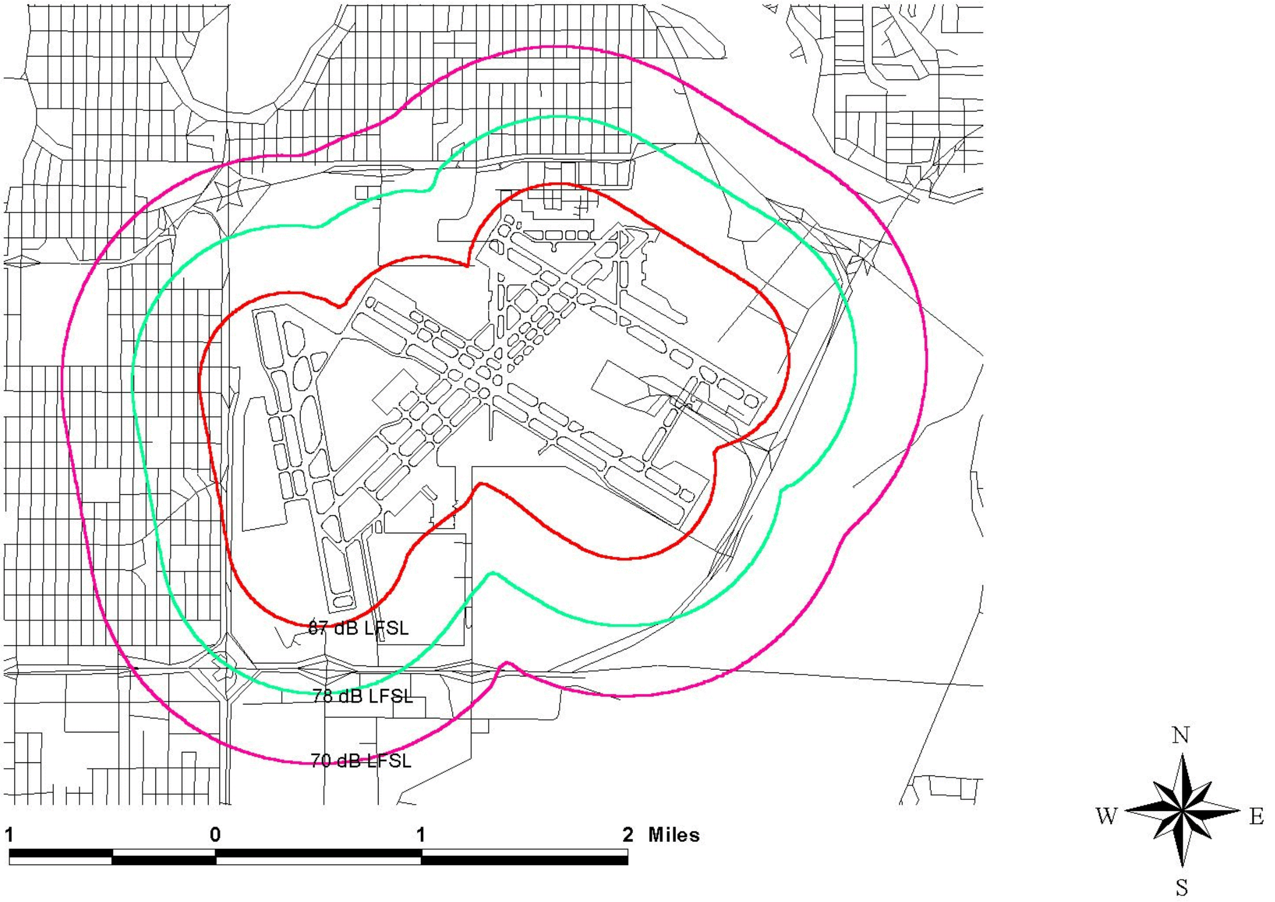


Figure 62 Contours of low-frequency sound levels due to thrust reverser application (per 3 February 2000 revision of Sutherland model).

The Expert Panel did not reach consensus on the following paragraph.

A majority of the members of the Expert Panel determined that thrust reverser application shortly after landing would produce low-frequency aircraft noise of considerable relevance for purposes of predicting annoyance due to rattle from future operations on Runway 17/35. Figure 62 shows low-frequency sound level contours associated with such operations, developed as described in the following Section.

As described in greater detail at the end of Section 6.4.2, the field measurements from MSP provided the basis for LFSL dose contours for departures. Field measurements from MSP, supplemented by field measurements from LAX, provided the basis for LFSL dose contours for thrust reversal, including the contours in Figure 62. The assertions on the previous page to the contrary, the level of certainty about the values LFSL measured, especially at the higher exposure values, provided a fully adequate forecast of future levels of LFSL dose.

6.4 ESTIMATED REVERSE THRUST LOW-FREQUENCY NOISE DURING LANDING OPERATIONS AT MSP

Application of reverse thrust by landing aircraft is one source of low-frequency noise along runway sidelines. While not usually the dominant source of low-frequency noise around an airport, the contributions of reverse thrust noise to the low-frequency noise environment of runway sidelines was analyzed by the Expert Panel toward the end of its work. This section summarizes these analyses in some detail, since no prior prediction model or relevant evaluation of reverse thrust noise is known. The analyses, which started with limited information, were carried out over a period of a month and a half.

6.4.1 Characteristics of Reverse Thrust Noise

The Expert Panel did not reach consensus on several of the physical parameters of reverse thrust or on levels of low-frequency aircraft noise in the vicinity of MSP from the reverse thrust phase of aircraft operations.

Limited information available on this largely neglected source of low-frequency aircraft noise indicates that:

The Expert Panel reached consensus on this point.

> Large jet aircraft touch down on their main landing gear at airspeeds of about 140 knots. Different aircraft types apply reverse thrust either automatically or at pilot discretion after the nose wheels are firmly on the ground and the pilot is committed to the landing.

The Expert Panel did not reach consensus on this point.

> Reverse thrust is obtained in older engine designs by inserting "clam shell" scoops into the exhaust stream to redirect much of the exhaust flow to the forward direction. (Newer designs achieve the same effect with other mechanisms.) Engine power settings remain high while the aircraft decelerates. Intentional disruption of the flow of engine exhaust gas produces high noise levels, including high levels of low-frequency noise.
>
> ***It should be remembered that aircraft power levels during reverse thrust typically do not exceed 80 percent. The power level during departures are at or near 100 percent. The term "high" in the previous paragraph should be understood in this context.***

The Expert Panel reached consensus on this point.

> Reverse thrust is quickly reduced as aircraft ground speed drops below about 80 knots to prevent ingestion of dust and debris into engines.

The Expert Panel did not reach consensus on this point.

> The duration of reverse thrust operation can vary from about 5 to 20 seconds, depending on aircraft type, runway conditions, distance from the runway threshold to the touchdown point, locations of turn-off ramps, air traffic control directives, pilot technique, and airline protocol. Thus, noise

produced by reverse thrust is much more variable than the highly predictable engine operations during takeoff or approach.

Based on significant numbers of observations, the period of reverse thrust typically did not exceed 15 seconds. In addition, the variability in noise levels measured during reverse thrust operations and departure operations are comparable. (See the analysis that follows.)

The Expert Panel did not reach consensus on this point.

The position of the aircraft along the runway during reverse thrust operation varies from about 2,000 feet to as far as 6,000 feet from the runway threshold. Larger aircraft generally apply reverse thrust for longer periods.

The estimate of 6,000 feet was based on the assumption of a 20-second application time. A better estimate of the maximum extent is 4,000 feet. (See the analysis that follows.)

The Expert Panel did not reach consensus on this point.

The low-frequency content of reverse thrust noise is generally comparable to that of takeoff noise, and for comparable lateral positions near runways, of comparable level. An example of a spectrogram, time history and spectrum of reverse thrust noise observed at a location about 1,000 feet to the side of the runway and 3,565 feet from the landing threshold is shown in Figure 63.

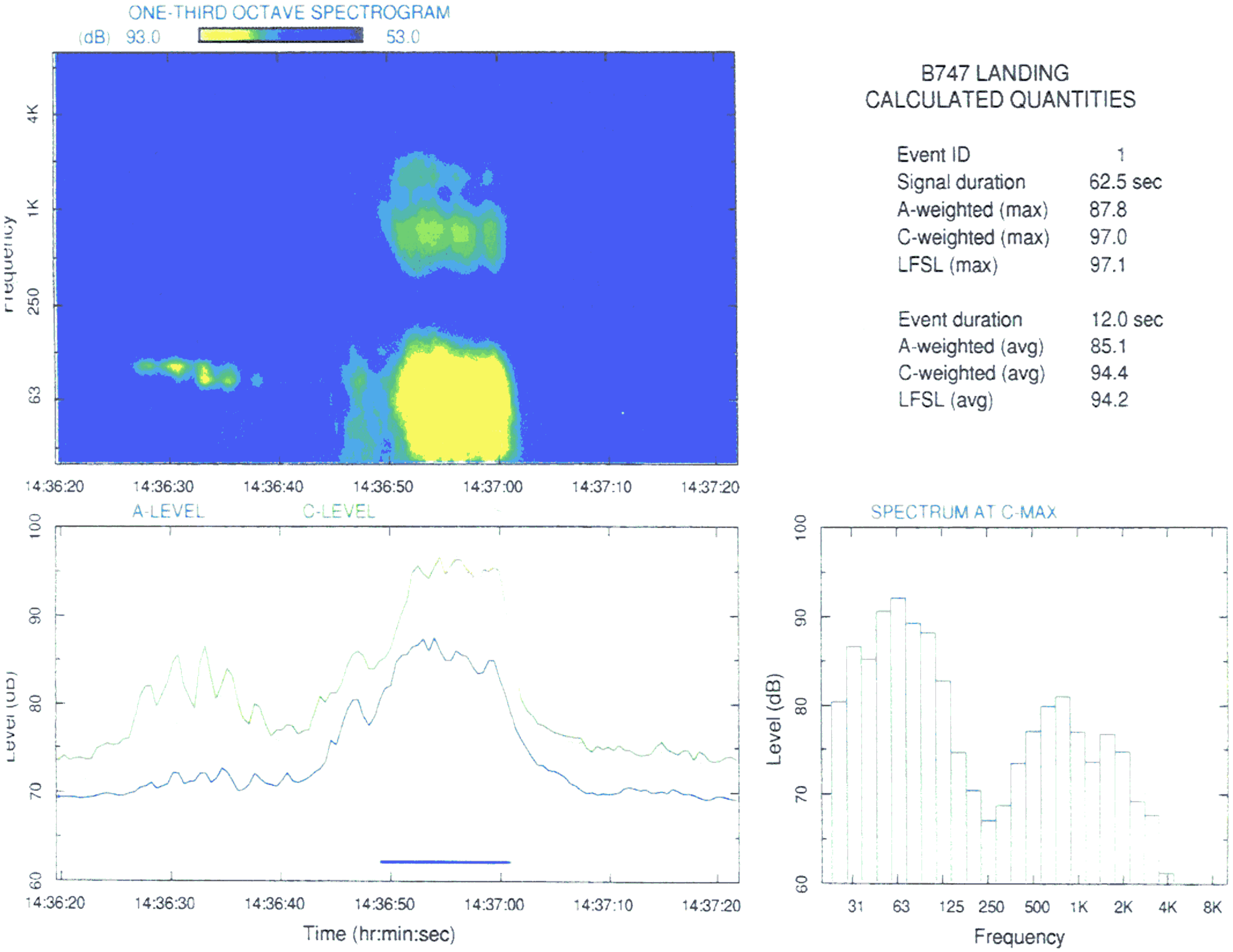
Figure 63 does not illustrate the comparability of departure noise and reverse thrust noise. In addition, as the discussion that follows makes clear, noise from reverse thrust noise is typically at significantly lower levels in sideline areas than the noise from departure operations.

6.4.2 Scope of Reverse Thrust Noise Evaluation

The Expert Panel did not reach consensus on the analysis presented in Section 6.4.2.

Reverse thrust noise measurements made at BOS, MSP, and LAX are summarized in Tables 18 and 19. Table 18 summarizes the dates and locations of measurements. It also contains a definition of the average “as-measured” reverse thrust LFSL value at each point, for all aircraft, as well as a normalized value at a convenient sideline reference distance of 4,000 feet. The latter value is simply the “as measured” value at the given sideline distance, Y, corrected by inverse square spreading loss to a distance of 4,000 feet.

Table 19 categorizes these measurements by average values for each aircraft type, for low- and high-bypass ratio engine types. Maximum differences for each aircraft type between the normalized values of LFSL at Y = 4,000 feet for different measurement points averaged about 4.5 dB. These differences may be attributed to variations in the source reverse thrust noise with runway position, X; variations in path attenuation other than spreading loss; and random variations between the data samples for each site.



B747 LANDING
CALCULATED QUANTITIES

Event ID	1
Signal duration	62.5 sec
A-weighted (max)	87.8
C-weighted (max)	97.0
LFSL (max)	97.1
Event duration	12.0 sec
A-weighted (avg)	85.1
C-weighted (avg)	94.4
LFSL (avg)	94.2

Figure 63 Spectrogram, time history, and one-third octave band spectrum produced during thrust reverser application of a B-747 landing.

Table 18 Summary of thrust reverser noise measured at MSP, LAX and BOS.

							LFSL		
Airport	Runway	Site No.	X, ft[a]	Y, ft[b]	Date	No. of Flights	As Measured		Converted to 4,000 ft
							Average[c]	Std Dev	Average[c,d]
MSP	12L	6	2,109	2,877	8/25/99	50	81.0	4.39	78.1
		6	2,109	2,877	8/26/99	35	81.1	3.59	78.2
		6	2,109	2,877	8/25-26/99	85	81.0	4.06	78.2
	30R	12	4,528	1,860	8/27/99	209	87.8	7.14	81.1
		13	2,496	1,164	8/27/99	192	80.8	5.20	75.8
LAX	22R	7	3,565	910	1/5/00	7	93.0	3.85	80.1
		7	3,565	910	1/18/00	84	85.8	4.52	72.9
		7	3,565	910	1/5 & 18/00	91	86.4	4.47	73.5
		8	2,795	1,095	1/18/00	59	82.5	3.52	71.2
		9	2,050	1,695	1/18/00	83	80.1	4.72	72.6
BOS[e]	22L	6	1,540	2,460	3/25-26/96	5	92.0	3.19	87.8
	27	6	0	3,540	3/25-26/96	23	93.2	3.52	92.1
	33	6	3,619	3,540	3/25-26/96	14	86.9	2.97	85.9

[a] The X coordinate is the distance along the runway.

[b] The Y coordinate is the distance orthogonal to the runway.

[c] Average weighted by number of flights.

[d] LFSL normalized to a sideline distance (Y) of 4,000 ft by assuming 6 dB/doubling of distance attenuation loss.

[e] LFSL data from Massport ENOMS believed invalid due to high winds.

Evaluation of these reverse thrust noise data was carried out in several stages, as described in the following subsections.

6.4.2.1 Initial evaluation of reverse thrust noise levels measured at BOS

Messrs Sutherland and Fidell were informed that the Boston measurements of reverse thrust were inadequately documented for use in this study prior to the analysis discussed here.

An initial evaluation was made of measurements made by the Logan Airport noise monitoring system, as reported by HMMH (1996a). The measurements, obtained at one site for reverse thrust landing operations for three nearby runways, are illustrated in Figure 109 in Volume III. They were subsequently considered to be contaminated by wind noise, and were eventually dropped from further consideration. (This conclusion would not have been reached without the more thorough evaluation of reverse thrust noise for this study.)

Table 19 Average reverse thrust noise data for MSP and LAX.

MSP							
By-Pass Ratio	Aircraft Type	Site 6, Runway 12L (X = 2,109 ft)		Site 12, Runway 30R (X = 4,528 ft)		Site 13, Runway 30R (X = 2,496 ft)	
		No. of Flights	LFSL at 4,000 ft (dB)	No. of Flights	LFSL at 4,000 ft (dB)	No. of Flights	LFSL at 4,000 ft (dB)
Low	B-727-200			10	78.8	7	74.5
	B-727-QN	19	76.3	27	81.2	23	74.5
	B-737-200			5	79.6	5	71.0
	DC-8-QN			4	81.9	3	80.1
	DC-9			6	78.7	6	73.8
	DC-9-QN	12	73.1	43	82.5	41	76.0
	E145			2	70.4	1	65.1
	MD-80	2	79.3	17	82.3	18	74.6
	Commuter jets	3	76.8				
	Average LBPR LFSL weighted by no. of flights	36	75.4	114	81.3	104	75.0
High	A-319			1	89.0	1	72.6
	A-320	5	81.1	21	81.2	19	76.3
	B-737-500	3	75.8	10	79.6	10	75.4
	B-747-100	2	79.5	2	74.9	1	75.7
	B-747-200	2	79.3	2	84.5		
	B-747-300			1	72.9	4	78.0
	B-757			2	82.0		
	B-757-200	24	79.8	30	81.4	29	77.8
	BA46			3	86.4	4	74.6
	C-130			2	80.5	2	81.4
	CARJ			3	83.9	3	75.9
	DC-10	13	81.8	12	78.0	10	77.3
	F-100			6	83.2	5	75.3
	Average HBPR LFSL weighted by no. of flights	49	79.5	95	81.0	88	76.8
	Average LBPR and HBPR LFSL weighted by no. of flights	**85**	**78.2**	**209**	**81.1**	**192**	**75.8**
LAX							
By-Pass Ratio	Aircraft Type	Site 7, Runway 22R (X = 3,565 ft)		Site 8, Runway 22R (X = 2,795 ft)		Site 9, Runway 22R (X = 2,050 ft)	
		No. of Flights	LFSL at 4,000 ft (dB)	No. of Flights	LFSL at 4,000 ft (dB)	No. of Flights	LFSL at 4,000 ft (dB)
Low	B-727	2	77.0	2	71.9	2	72.7
	B-737	45	71.5	35	70.7	44	71.7
	MD-80	9	71.4	7	68.2	9	69.5
	Average LBPR LFSL weighted by no. of flights	56	71.6	44	70.3	55	71.4
High	A-320	8	73.4	4	70.6	7	72.3
	B-747	7	83.5	2	80.0	4	83.2
	B-757	5	73.4	2	68.3	4	72.7
	B-767	8	74.7	5	72.2	8	74.8
	DC-10	3	79.5	1	76.1	2	81.5
	MD-11	2	76.6			2	74.3
	Average HBPR LFSL weighted by no. of flights	33	76.6	14	72.6	27	75.5
	Average LBPR and HBPR LFSL weighted by no. of flights	**89**	**78.2**	**58**	**81.1**	**82**	**75.8**

Notes: 1. BOS data are not included in this table due to probable contamination by wind.

2. Data taken from Site 13, Runway 30R at MSP may be unreliable due to local terrain and shielding effects.

After comparing the spectra obtained from BOS data with reverse thrust spectra measured at MSP and LAX, and after obtaining time-coincident wind velocity data for these data from the Logan Airport Noise Management Office, it appeared likely that the published reports of measured noise levels were corrupted by wind noise.

6.4.2.2 Initial measurements of reverse thrust noise levels at LAX

Following this initial evaluation, a limited series of measurements was made at one measurement site near LAX. The results of these two initial examinations of reverse thrust noise, made before the BOS data had been rejected, were presented to the Low Frequency Noise Policy Committee at MSP on 10 January, 2000. Due to the sparse and unexpected nature of these preliminary findings, the Policy Committee requested the Expert Panel to undertake a more thorough evaluation.

6.4.2.3 Evaluation undertaken after 10 January, 2000 Policy Committee meet

The Expert Panel did not reach consensus on several aspects of the analysis presented in Section 6.4.2.3. See the discussion at the end of this section and at the end of Section 6.4.4.

Ensuing evaluation included acquisition of more data at LAX from an expanded measurement program at three sites; a further analysis of landing noise measurements made at MSP in August of 1999 at three sites; and contacts with other aviation noise authorities in the US and in the UK. (The latter effort produced no useful information about reverse thrust noise.)

Extended analysis of the expanded data set was conducted by the three members of the Expert Panel and their delegates at a two-day meeting on 24-25 January, 2000. (By this time, the BOS data were beginning to be questioned.) Reverse thrust noise models and contours were developed from this body of information shortly before the final meeting with the Policy Committee on 7 February, 2000.

Two of the three members of the Expert Panel agreed that low-frequency noise contours based on thrust reverser measurements and analyses should be drawn at levels about one standard deviation above the mean of empirically measured levels. This decision was made because predicting annoyance from low-frequency noise and rattle from noise events occurring only "a few times a day" requires explicit consideration of the variability of anticipated thrust reverser noise levels.[18] ***(See footnote below.)***

The contours identified by the majority of the Expert Panel therefore took into consideration the wide range of low-frequency noise levels evident in measurements of thrust reverser noise and other uncertainties of measurement and modeling. This allowance was not a simple re-labeling of noise contour values, but a considered judgment that prudence requires that the variability of reverse thrust noise levels be reflected in the contours.

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[18] ***The proposal to use a one standard deviation margin of safety for the reverse thrust contours is not consistent with the entire basis of this study. The noise descriptors, the social survey and the compatibility criteria are all based on mean values. Now, based on the invalid assertion that there is unusually great variability in the measured values of low-frequency noise from reverse thrust operation, it is proposed to add a margin of safety rather than use the mean values. There is no reason to believe that there is any difference between the variability experienced by the respondents to the social survey and the variability observed during the measurements.***

The Policy Committee ultimately adopted the view that low-frequency contours based on thrust reverser noise need not make provision for the inherent variability of thrust reverser noise. The reverse thrust noise contours identified by a majority of the Expert Panel led to selection of the final reverse thrust noise prediction model illustrated in Figure 64. This figure shows LFSL values at a reference distance, Y, of 4,000 feet to the side of a runway as a function of the position, X, along the runway from the landing threshold.

During analysis of the noise from thrust reversers, the Expert Panel evaluated the data from field measurements at MSP and LAX. It also evaluated several models to develop LFSL dose contours. While the Expert Panel did reach consensus on a set of contours to represent the low-frequency noise from reverse thrust, it did not reach consensus on application of the contours to the future environment at MSP. The principal point of disagreement was whether a one standard deviation (approximately 4 dB LFSL) "factor of safety" should be applied when selecting the contour to represent LFSL dose. Although the Policy Committee determined that such a factor of safety was inappropriate, the contours of Figure 62 and the model value in Figure 64 incorporate a 4 dB LFSL factor of safety. As stated above and in the analysis presented in Section 6.5, addition of a 4 dB margin of safety is inconsistent with the method followed during this study and is inappropriate.

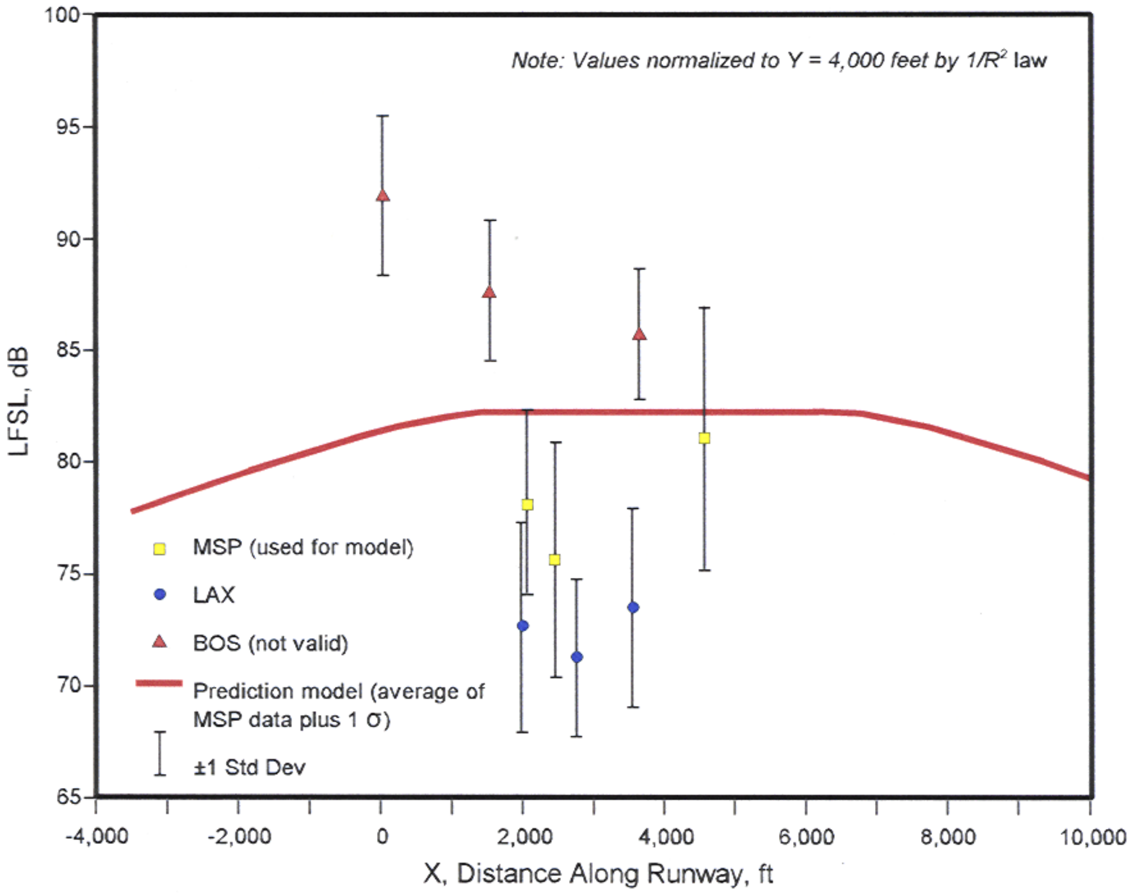

Figure 64 LFSL values of reverse thrust measurements at three airports.

6.4.3 Acoustic and Non-Acoustic Factors Considered in Evaluation of Reverse Thrust Noise

A number of factors that influence reverse thrust noise were considered in developing the model of reverse thrust noise. These are briefly enumerated here.

6.4.3.1 Effects of wind on sound propagation

The Expert Panel did not reach consensus on the second paragraph. (See the footnote.)

Since reverse thrust noise is generated only when an aircraft is on the ground, it is subject to considerable variation at moderate to large distances from the runway due to upward or downward refraction by the atmosphere, and especially by wind. This effect is apparent in the refraction- or wind-induced scatter in aircraft sideline noise data from takeoff noise measurements at DIA shown in Figure 115 in Volume III. For the BOS data, the effects of high winds (reported to be 16 to 32 knots on 25 March, 1996 and 9 to 25 knots on 26 March, 1996) are believed to be the primary sources of the artifactually high low-frequency noise levels. According to the Massport Noise Management staff, the sound propagation was roughly upwind during these measurements and thus could have caused high sound propagation loss or lower reverse thrust levels.

For the MSP data, the winds were moderate — from 1 to 11 knots, averaging about 5 knots in the (downwind) direction of sound propagation. An analysis of the reverse thrust levels *versus* wind speed or direction did not indicate any significant effect of wind.[19] For the LAX data, during the first test wind speeds were 0 to 5 knots and roughly in a cross-wind direction (90 to 130° with respect to the direction of sound propagation). These winds had no discernible effect. For the second LAX test, wind speeds were 0 to 4 knots and in a direction (0 to 340°) that could have favored reverse thrust levels only very slightly, if at all. In any event, the LAX data are lower in level than the MSP data.

6.4.3.2 Sound propagation effects of terrain and ground conditions

The Expert Panel did not reach consensus on this section of the report. See the notes in this section and the discussion in Section 6.5.2.

In addition to conventional inverse square spreading loss (6 dB/doubling of distance), two ground attenuation effects merit consideration:

attenuation by the propagation over bare ground and

attenuation by buildings in a built-up area.

Neither of these effects is significant for the usually dominant air-to-ground sound propagation conditions after aircraft takeoff or during landing approach before touch-down. The attenuation over bare ground is treated in Section B.8.2 of Volume III. For conditions other than deep snow at MSP, ground attenuation can be approximated by an attenuation rate of -0.2 dB/1,000 feet.

For attenuation of low-frequency reverse thrust noise over built-up areas, evaluation of unpublished data from Wyle Laboratories involving simultaneous measurements over a clear and an

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[19] ***The statement that there was no significant wind effect is incorrect. There was clearly an increase in noise levels as a result of the downwind propagation. See the discussion at the end of Section 6.4.4.***

adjacent built-up area provided the basis for the following attenuation model. This attenuation for built-up areas was assumed to reach a maximum of 10 dB in accordance with recommendations from an ISO Standard, ISO (1994). Table 20 shows the resulting algorithm for excess attenuation, A_e, for both ground effects. ***Table 20 is mislabeled. Mr. Sutherland confirmed that the distances in the table are perpendicular to the runway, not along it. (See also the discussion of propagation effects 6.5.2.)***

6.4.3.3 Influence of engine type and thrust

Some of the measured reverse thrust data from BOS suggest that, all other things being equal, reverse thrust noise for Stage 3 aircraft was greater than for Stage 2 aircraft by a negligible amount of about 1 dB. However, reverse thrust data at MSP did not show any measurable effect of Stage 2 *versus* Stage 3 aircraft, so this variable was ignored.

The LAX and BOS data showed a consistent, but small, effect of engine thrust on reverse thrust noise levels: the higher the thrust, the higher the reverse thrust level. The rate of increase was about +0.073 dB/1,000 pounds of net take-off thrust. However, no such effect could be discerned in analysis of the MSP reverse thrust data. Since this small effect was not consistent among airports and would be inherently included in any average measure of reverse thrust noise levels, no attempt was made to include aircraft type (that is, fleet mix) in evaluating reverse thrust noise for MSP.

6.4.3.4 Effect of position along the runway

The most difficult variable to assess accurately was the effect of the position, X, of the aircraft along the runway during reverse thrust operations. As indicated by the BOS data in Figure 63, these initial data suggest that reverse thrust noise peaked at the landing threshold and fell off approximately linearly with X. This misleading result, not discounted until the BOS data had been dropped from consideration, was not replicated in the MSP or LAX data. In fact, these latter data suggest a possible peak in reverse thrust levels at a position on the order of 4,000 feet from the landing threshold, but the evidence was not conclusive due to scatter in the measurements and the absence of any data for values of X greater than about 4,400 feet.

Thus, for prediction purposes, the source levels for reverse thrust were assumed to be represented by a constant-strength point source located at any position along a line parallel to the runway and extending from 2,000 feet from the landing threshold to 6,000 feet from this point. The starting point reflected what could be clearly seen on aerial photos of both LAX and MSP — the beginning of touchdown, where wheel tread marks were very apparent. The end point was based on a simple dynamic model for the aircraft trajectory along the runway, assuming reverse thrust lasted a maximum of 20 seconds (as observed for several of the landings at LAX). At this point, the aircraft speed was assumed to decrease from a touchdown value of 140 kts to a speed of 80 kts, where reverse thrust operation is normally terminated.

6.4.4 Prediction Model for Construction of Reverse Thrust Noise Contours

The Expert Panel did not reach consensus on several aspects of the analysis presented in Section 6.4.4. See the discussion in Section 6.5.

The contours for depiction of reverse thrust noise levels were computed in the following manner.

1. The reverse thrust noise level at MSP measurement Sites 6, 12 and 13 were averaged, arithmetically, over all jet aircraft at each site.[20]

   These average levels were then normalized to a convenient reference distance of 4,000 feet by applying a simple inverse-square spreading-loss attenuation correction to the "as measured" levels. (As indicated by the values in Tables 18 and 19, the LAX data, normalized to a sideline distance of 4,000 feet, displayed lower reverse thrust noise levels than the MSP data, thus the latter were used for construction of a conservative and more tenable estimate of reverse thrust levels for MSP.)

Table 20 Excess ground attenuation *vs.* distance ~~along~~ ***perpendicular to*** runway.

Distance ~~Along~~ *Perpendicular to* Runway (Y, in feet)	**Excess Attenuation (A_e, dB)**
<2,500	0 (ground attenuation is already included in estimates of close-in LFSL contours for thrust reverser noise)
2,500 - 6,500	-2.7(Y-2,500)/1,000
>6,500	-10.8 - 0.2(Y-6,500)/1,000

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[20] The measurements made at Site 13 appear to have been affected by terrain shielding.

2. The arithmetic average of these normalized, 4,000 foot levels (*i.e.*, LFSL = 78.3 dB) was then used to define the sideline distance, Y_{87}, at which a reverse thrust noise contour for LFSL = 87 dB would be located at positions between 2,000 and 6,000 feet along the runway. (The 87 dB level is the value identified in Sections 1 and 7 as coinciding with an A-weighted DNL of 75 dB which FAA considers incompatible with residential development.) This distance, 2,328 feet, was computed by re-applying an inverse-square propagation correction to the 4,000 foot level. Note that this process ignored the small excess ground attenuation described above in Section 6.4.3.2, since it would be approximately canceled out by first normalizing the "as measured" levels to 4,000 feet and then computing the distance to the innermost LFSL = 87 dB contour.

3. For lower LFSL contours for X = 2,000 - 6,000 feet, the lateral position of the contour line, parallel to the runway, was computed by trial and error, applying inverse-square law spreading loss and the excess ground attenuation algorithms in Section 6.4.3.2.

4. For positions of X less than 2,000 feet or greater than 6,000 feet, the reverse thrust level was assumed to fall off as it would for a point source at 6 dB per doubling of distance from each end point. Excess attenuation due to the ground and building effects defined above was also included.

5. This simple contour prediction model makes no attempt to account for the probable directivity of reverse thrust noise, *i.e.*, the deviation of the noise contours at different angles from the aircraft centerline, from the non-directional pattern assumed here.

Further evaluation of low-frequency reverse thrust noise by FAA and the aviation industry is encouraged.

6.5 Alternative Predictions of Low-frequency Noise Levels

This section contains descriptions of the process through which low-frequency noise contours were developed from on measurements at MSP. It includes LFSL contours from departures and reverse thrust operations and LFSL dose contours reflecting future operations and runway use.

6.5.1 Predictions of Reverse Thrust Noise Levels

The contours for depiction of reverse thrust noise levels were computed in the following manner. (For clarity, the model discussed previously, from the 25 April 2000 document, is called the Sutherland model. The one discussed here is the HMMH model.)

> ***The reverse thrust noise levels measured at MSP and LAX were plotted by average level and distance from the runway, as shown in Figure 65.***

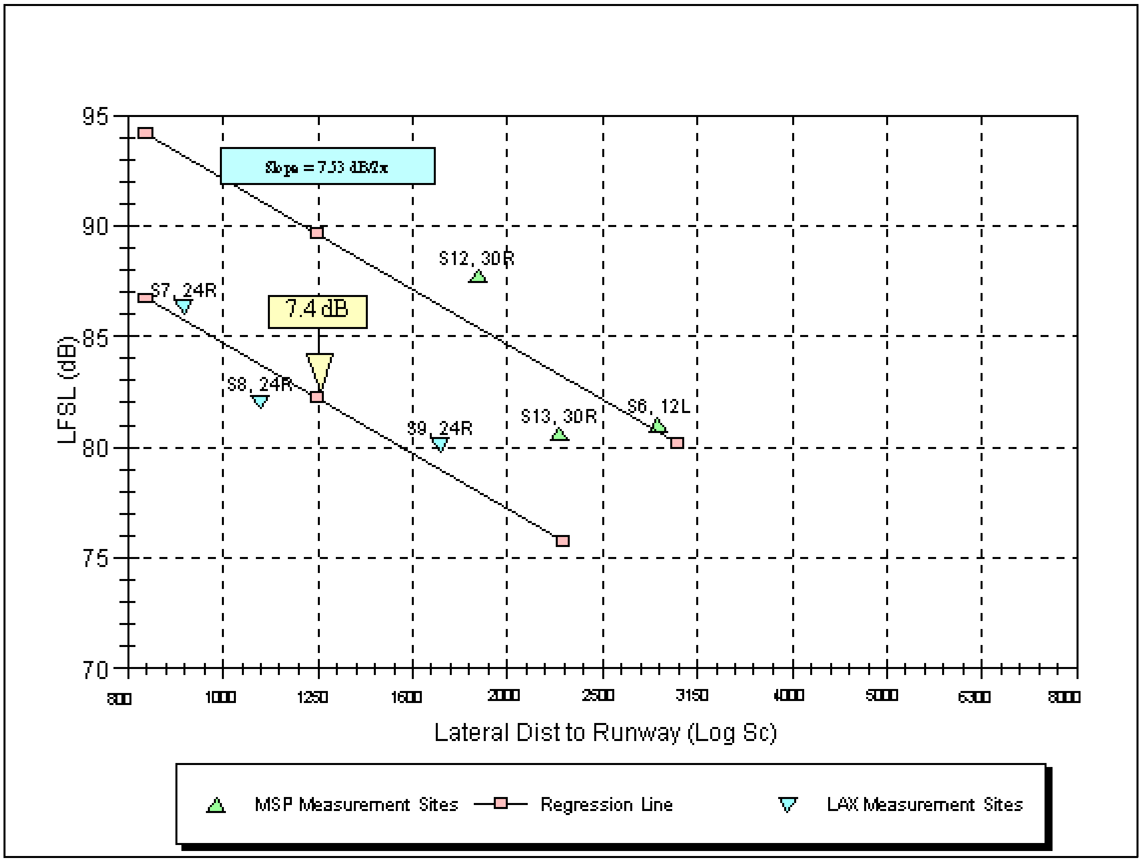

Figure 65 Reverse Thrust Sound Levels from MSP and LAX

Although the measurements at the two airports exhibited the same slopes, the noise levels drop off approximately 7.5 dB per doubling of distance, the LAX data averaged approximately 7.4 dB lower than the MSP data. The difference between the two sets of data reflects differences in wind environments and aircraft fleets during the measurements at MSP and LAX.

The wind during measurements at LAX was typically of low velocity and had essentially no effect on propagation. The wind during measurements at MSP was typically toward the measurement sites and ranged from 1 to 11 knots. While the 7.4 dB average difference between the measurements at the two airports is consistent with wind effects observed during other measurement programs, it is likely that the total difference is from a combination of factors. The 7.5-dB falloff in levels per doubling of distant observed during the measurements is similar to, but slightly greater than, the theoretical value of 6.0-dB falloff used by Mr. Sutherland in the analysis presented earlier.

> *The discussion in Section 6.4.2.3 asserts that there is greater variability in reverse thrust noise levels than in departure noise levels. Detailed analysis of the reverse thrust measurements showed a similar degree of variability in the data for the two types of operation. The measurements of reverse thrust operations exhibited an average range of 10 dB for each aircraft type when the aircraft are grouped by type and airline as did the measurements of departures.*
>
> *Based on observations of aircraft operations and discussions with pilots, the parameters for use of reverse thrust were determined. Reverse thrust modeled as follows: (1) power was applied approximately 2,000 feet along the runway from the threshold; (2) power application was rapid;(3) reverse thrust power had a duration of 10 to 15 seconds; and (4) power reduction was rapid at the end of the 15 seconds; and (5) the power reduction occurred approximately 4,000 feet along the runway from the threshold. Calculations based on the equations of motion showed that the deceleration assumed in this model was at a reasonable level.*
>
> *Contours based on this modeling approach were reviewed by the Expert Panel along with several sets of calculations by Mr. Sutherland and Mr. Horonjeff (of HMMH). (Mr. Sutherland's final calculations were the basis of the Sutherland model presented in Section 6.4.4.) The results of the two models were similar. However, Mr. Sutherland's analysis assumed that the period of reverse thrust application was 20 seconds. The Expert Panel reached consensus on contours from a compromise model based on the assumption that reverse thrust was 20 seconds, the HMMH model adjusted for a 20-second reverse thrust application.*
>
> *The Expert Panel did not reach consensus on a method to adjust the contours to reflect different percentages of runway use and aircraft mix. Figure 66 shows the contours adopted by the Expert Panel prior to any adjustment for runway use or other factors. The contours assume use of the fleet measured in 1999. The fleet is acoustically dominated by hushkitted aircraft. The number of operations underlying the contours for each runway is the number of operations that produced low-frequency noise levels during the measurements. (See the discussion of numbers of operations in "Development of Contours for Predicted LFSL Dose," in Section 6.5.4.)*

6.5.2. Propagation Effects

The effects of wind on measurements was addressed in Section 6.4.3.1. The discussion of excess ground attenuation in Section 6.4.3.2 proposes an algorithm for calculation of the excess ground attenuation based on lateral distance from the runway. (Note the corrections in Table 20.) This algorithm assumes that the first built up area is 2,500 feet from the runway. In those instances when the actual built up area is at a different distance than 2,500 feet, the excess attenuation due to the built up area, the second factor in Table 20, should begin at the actual distance rather than at 2,500 feet.

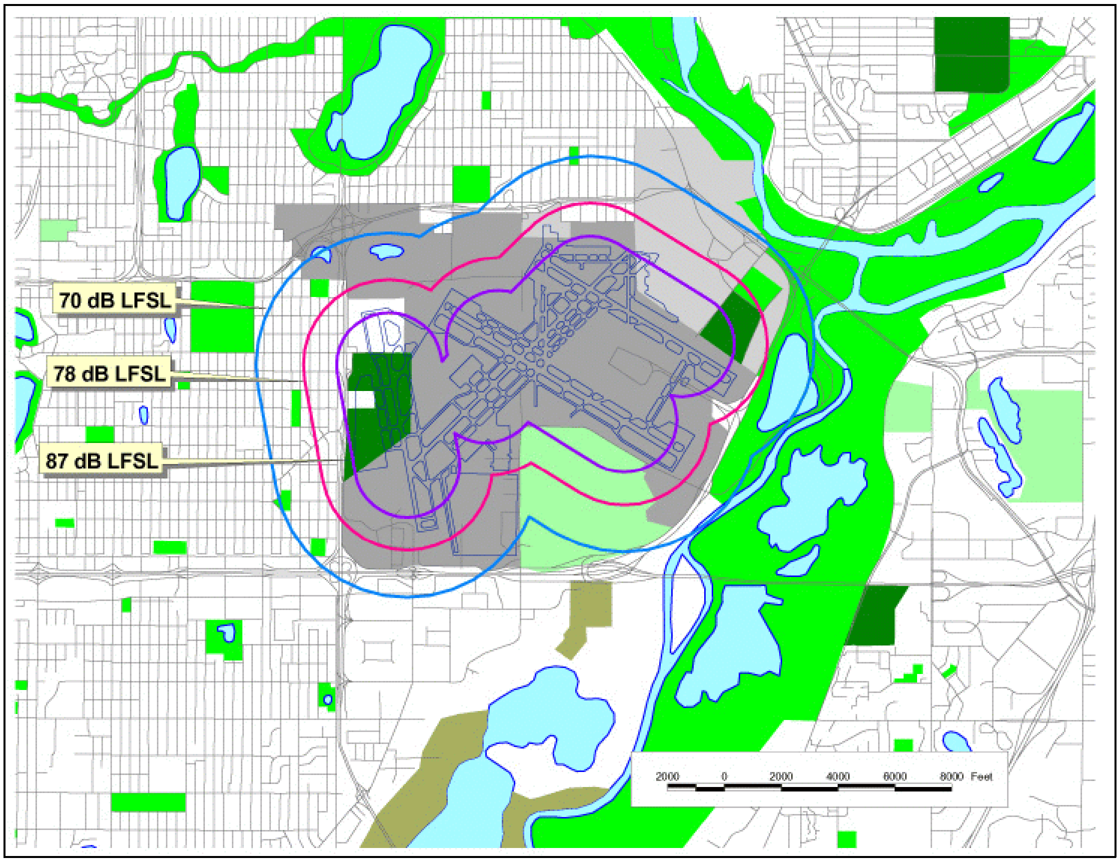

Figure 66 Predicted Reverse Thrust LFSL Dose Contours for MSP with Runway 17/35 in Use Not Adjusted for Runway Use

6.5.3 Prediction of Departure Noise Levels

Contours depicting the LFSL dose for values of 70 dB, 78 dB and 87 dB were derived from a combination of on-site measurements and computer predictions using the FAA's INM. Initially, BBN and HMMH measured noise from takeoffs and landings at 12 sites on MSP and in Minneapolis. Subsequently, contours of LFSL dose were developed and adjusted to depict conditions after the opening of Runway 17/35.

6.5.3.1 Development of Contours from Measurements and the FAA's INM

Theoretically, measurements alone might be sufficient for preparing a defensible set of noise contours. Practical constraints, however, preclude a pure-measurement approach, especially where large land areas are involved. In this study, the INM was used to assist in interpolating between the measured low-frequency levels at various sites to establish the shape and location of low-frequency sound level contours.

Figure 21 shows the locations where BBN and HMMH measured aircraft noise during August 1999. Figure 7 shows the positions of the measurement sites with respect to runways. Sites were selected to be in positions similar to the portions of eastern Richfield nearest to Runway 17/35 that will be exposed to noise from departures and the thrust reversal portion of arrivals. Wind data and radar data were obtained to facilitate analysis of the measurements. BBN and HMMH calculated LFSL and C-weighted maximum levels for noise from departures and thrust reversal. Data were aggregated by aircraft type, type of operation and measurement site. Table 20A presents the LFSL data obtained for hushkitted DC-9 departures at the measurement sites.

Table 20A Measured Low-Frequency Sound Levels for Stage 3 DC-9 Departures

	Runway 12L				Runway 30R				Runway 22			
Site	*Total*	*Meas*	*Avg*	*95%CI*	*Total*	*Meas*	*Avg*	*95%CI*	*Total*	*Meas*	*Avg*	*95%CI*
1	75	68	87. 10	0.53	48	48	84.62	0.82	22	11	77.25	2.46
2	76	69	86.74	1.03	39	39	83.85	0.77	25	6	80.40	1.54
3	57	43	77.10	0.85	32	24	77.57	0.99	31	25	78.91	2.78
4	---	---	---	---	5	3	75.23	0.53	20	16	81.50	1.74
5	26	11	81.05	1.98	34	33	77.27	0.67	30	25	84.91	0.62
6	57	45	86.62	0.44	23	18	79.81	0.54	17	2	85.55	0.29
11	---	---	---	---	33	23	81.97	1.55	47	16	88.40	3.72
12	---	---	---	---	30	15	90.57	1.98	26	19	89.57	2.05
13	---	---	---	---	---	---	---	---	---	---	---	---
14	---	---	---	---	---	---	---	---	27	25	86.26	0.60
15	---	---	---	---	12	12	87.71	1.13	9	3	83.13	1.76
16	---	---	---	---	30	30	85.84	0.85	12	4	79.78	2.12

Personnel from BBN and HMMH developed a technique to construct LFSL contours from measurements with the aid of the INM:

> ***The average sound level data from all site and runway combinations on a common base map.***
>
> ***LFSL values for locations without measurements were developed by interpolation and extrapolation from the measurements. Offsets from C-weighted contours developed with the INM were used to portray the observed dropoff over distance.***
>
> ***Contours for departures on a single runway were developed by connecting points of equal value.***
>
> ***The resulting contours were used to develop the contours of LFSL dose after Runway 17/35 is in use.***

When Runway 17/35 is completed and in use, virtually all departures (98 percent) will be on Runways 17, 12L, 12R, 30L and 30R. In the same way that Figure 66 shows noise from reverse thrust operation prior to adjustment for runway use, Figure 67 shows LFSL for departures on Runways 17, 12L, 12R, 30L and 30R prior to adjustment for runway use.

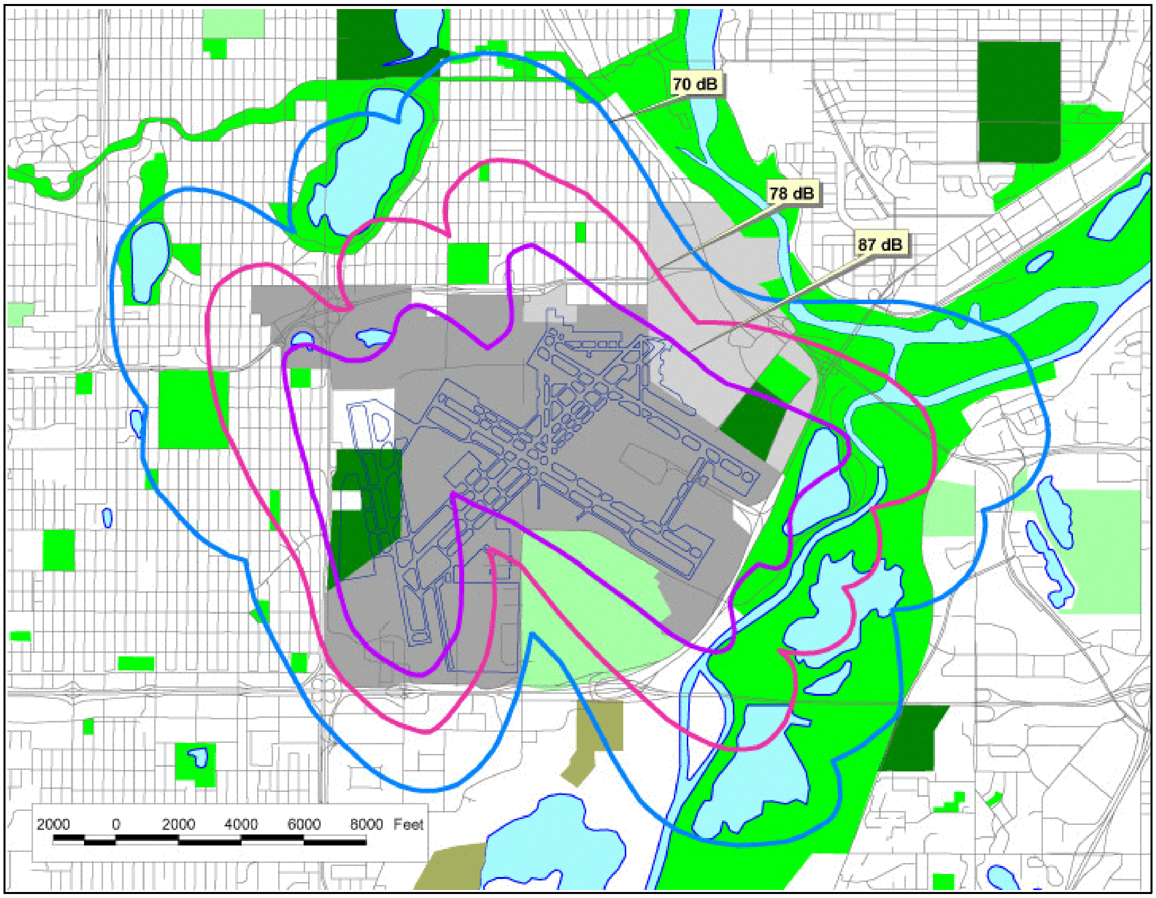

Figure 67 Predicted Departure LFSL Dose Contours for MSP with Runway 17/35 in Use Not Adjusted for Runway Use

6.5.3.2 Development of Contours for Expected LFSL Dose with Runway 17/35 in Use

The Expert Panel did not reach consensus on the method to develop contours for expected LFSL dose with Runway 17/35 in use. The 25 April 2000 document did not include contours with noise from departures. Further, as noted above, the Expert Panel did not reach consensus on a method to adjust contours to reflect different aircraft mixes or percentages of runway use. While all members of the Expert Panel agreed that there would be no reverse thrust contours on a runway that was not used for landings, Messrs Fidell and Sutherland insisted that contours on all runways with landings would be identical. Based on the belief that the impacts of low-frequency noise from runways with significantly different numbers of operations would be different, Mr. Harris asserted

that the contours for runways should be adjusted to reflect runway use. He proposed that the contours be adjusted by for relative runway use by a runway use adjustment factor:

Runway Use Adjustment Factor (dB) = 10 x log (usage x / usage p)

where usage x was the runway use percentage for the runway being adjusted and usage p was the runway use percentage for the primary runway for the type of operation (e.g., runway 17 is the primary runway for departures).

Table 20B shows the runway use and adjustment factors derived from projected runway usage numbers and the relationship described above. Runway use was combined for the runways where reverse thrust operations overlapped (e.g., 12L/30R). The appropriate factors were applied to the reverse thrust contours of Figure 66 and the departure contours of Figure 67. The resulting adjusted contours were combined to produce the contours for combined operations. The contours for LFSL dose from takeoffs and landings are presented in Figures 5 (in Volume I) and 68. The contours from the start of takeoff dominate the overall contours in almost all areas around the airport. Only where the percentage of departures is low and the percentage of landings is high (e.g., the northern end of Runway 12L) does the noise from reverse thrust operations dominate the contours.

Table 20B Runway Use and Runway Use Adjustments

Runway	Type of Operation	Relative Use	% of Use	Adjustment (dB)
17	Takeoff	Primary	36.6	0.0
35	Takeoff	Secondary	Nil	No Contour
12L	Takeoff	Secondary	7.0	-7.2
30R	Takeoff	Secondary	23.3	-2.0
12R	Takeoff	Secondary	16.3	-3.5
30L	Takeoff	Secondary	15.0	3.9
4	Takeoff	Secondary	Nil	No Contour
22	Takeoff	Secondary	Nil	No Contour
12L/30R	Landing	Primary	46.3	0.0
12R/30L	Landing	Secondary	36.7	-1.0
17	Landing	Secondary	Nil	No Contour
35	Landing	Secondary	17.0	-4.4
4/22	Landing	Secondary	Nil	No Contour

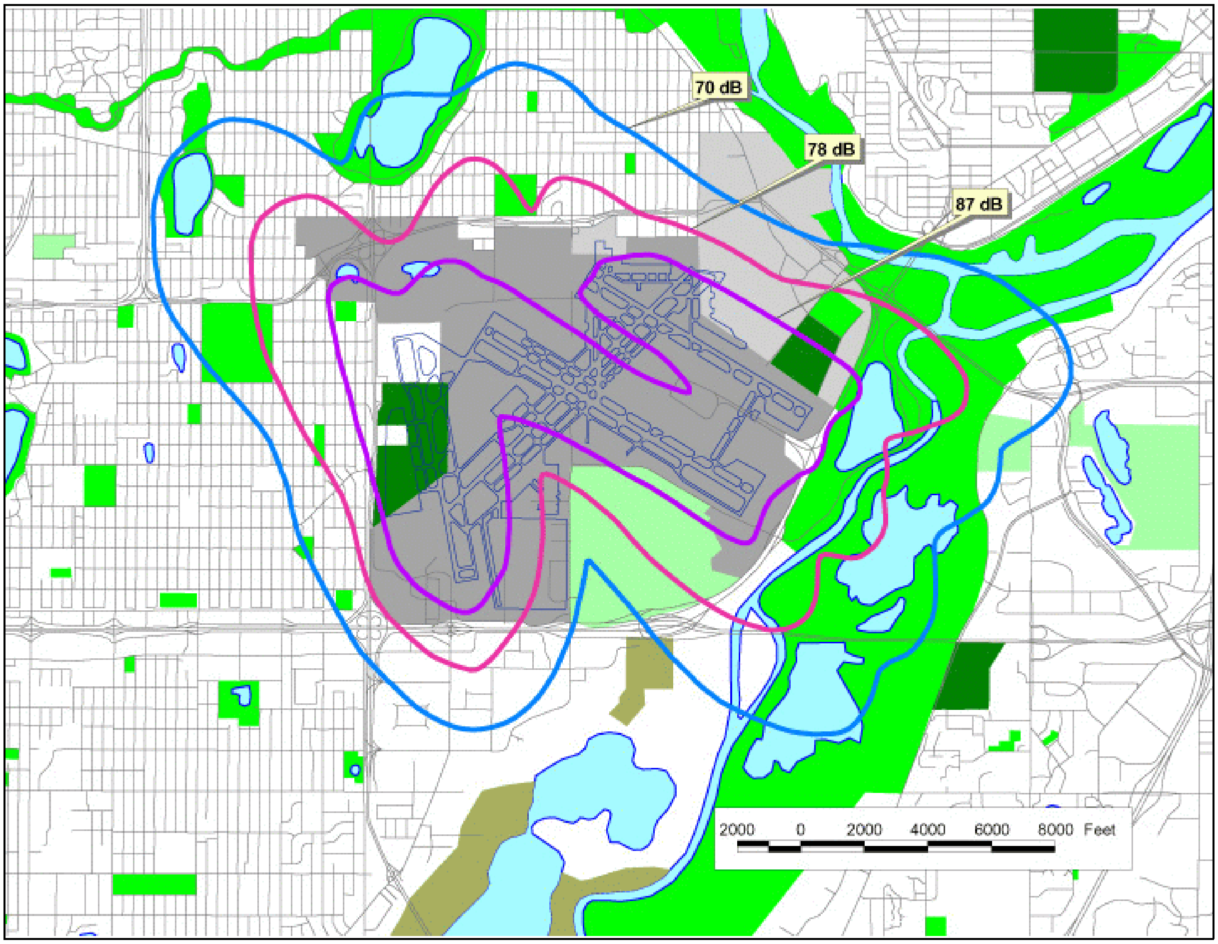

Figure 68 LFSL Dose Contours for Future Operations at MSP (including departures and arrivals) Adjusted for Runway Use

6.5.4 Effect of Adjustments to Reverse Thrust Contours Proposed by Fidell and Sutherland

Figure 62 shows the contours that Messrs. Fidell and Sutherland recommend to represent the LFSL dose for future operations at MSP (the Fidell/Sutherland contours). We have noted that they incorporated a 1 standard deviation (4-dB) adjustment to compensate for the "variability of anticipated thrust reverser noise levels "[21] Figure 69 allows us to see the extent that this approach increases the predicted impact of future reverse thrust operations.

Figure 69 shows LFSL dose contours for thrust reverser operations at MSP with Runway 17/35 in operation. The contours for LFSL doses of 70 dB, 78 dB and 87 dB are depicted. In addition, contours approximately 1 standard deviation (approximately 4 dB) higher and lower are

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[21] *Section 6.4.2.3.*

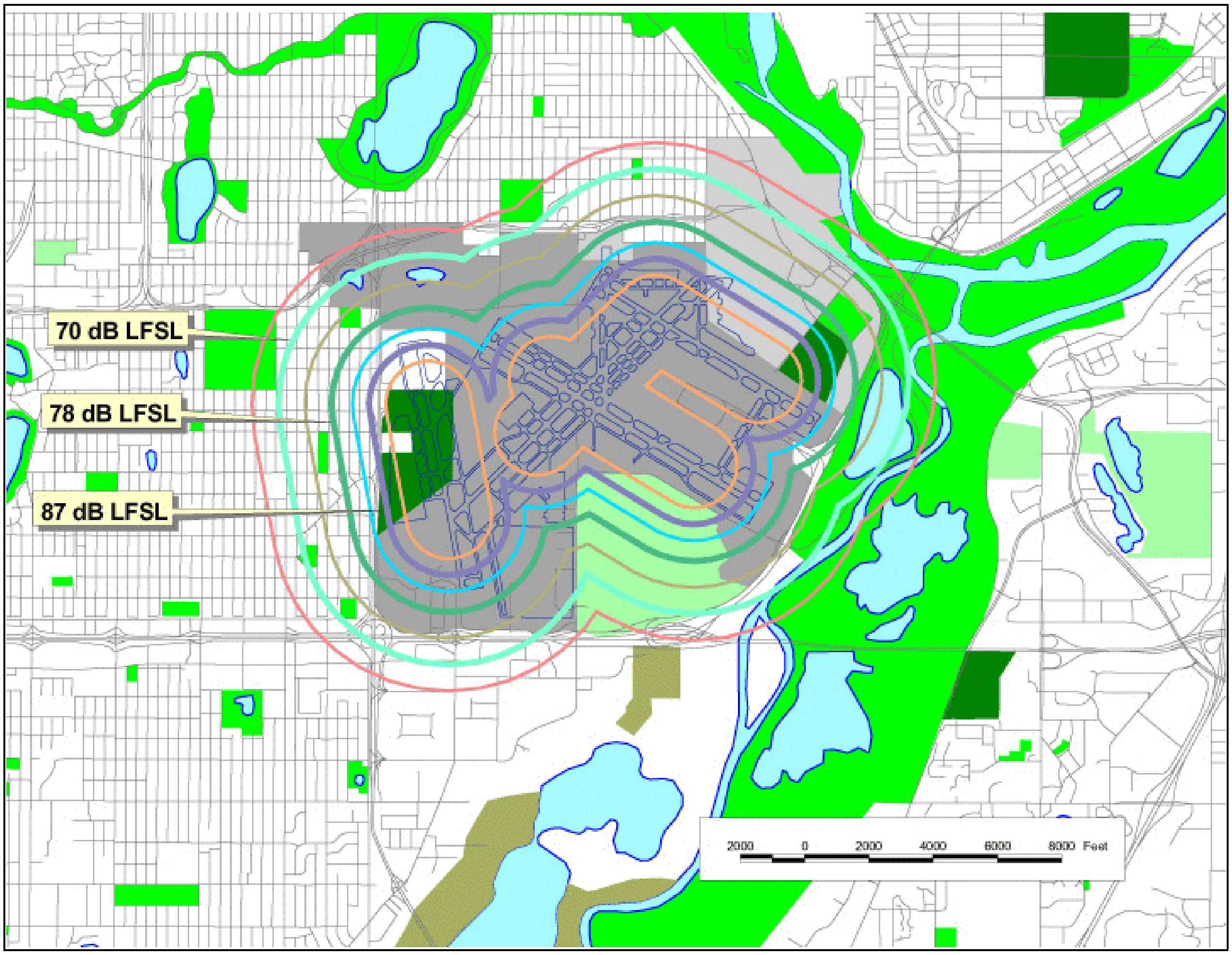

Figure 69 Predicted Reverse Thrust LFSL Dose Contours for MSP with Runway 17/35 in Use Showing Contours 4 dB lower and higher than the 70 dB, 78 dB and 87 dB Contours Not Adjusted for Runway Use[22]

depicted. The contours of Figure 62 are clearly the same as the contours in Figure 69 that are 1 standard deviation larger than the contours marked 70 dB, 78 dB and 87 dB. Figure 68 allows us to see the degree that the unwarranted "margin of safety" overstates the impact of thrust reverser noise even without any consideration of the percentage of landing operations that will occur on Runway 17/35.

From Table 20B we see that 17 percent of landings are forecast for Runway 35 and nil for Runway 17. Table 20B shows that the adjustment for 17 percent usage is -4.4 dB. Based on runway usage, the impact of landings on Runway 35 should be portrayed by a contour more than 1 standard deviation smaller than the labeled contours, not 1 standard deviation larger. Thus, the Fidell/Sutherland contours overstate the LFSL dose for thrust reversal by at least 8 dB.

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[22] ***Remember that without an adjustment for runway use, these contours reflect the LFSL dose that would be expected if each landing runway had the highest percentage of landings.***

7 CRITERION FOR ACCEPTABILITY OF LOW-FREQUENCY AIRCRAFT NOISE IN RESIDENTIAL AREAS NEAR MSP

The Expert Panel did not reach consensus on significant portions of this section.

This section identifies a range of alternatives to the Policy Committee for consideration in reaching decisions about pragmatic interpretations of the information contained in this report. It also describes the basis for the Expert Panel's identification of low-frequency sound level values as potential criteria for acceptability of low-frequency runway sideline noise in residential areas near MSP.

7.1 SUMMARY OF POTENTIAL CRITERIA FOR LOW-FREQUENCY NOISE ACCEPTABILITY

The Richfield-MAC Noise Mitigation Agreement of 17 December, 1998 assigns to the Policy Committee the responsibility for adopting a specific criterion for significance of low-frequency aircraft noise impacts in residential areas near MSP.[23] Table 21 summarizes a range of Low-Frequency Sound Level values corresponding to policy options that the Policy Committee may wish to consider for this purpose. The table also shows corresponding values of DNL at which the same proportion of the residential population is expected to be highly annoyed by aircraft overflight noise, and an approximate sideline distance to the runway centerline at which the prevalence of annoyance due to rattle and vibration has been empirically observed at communities near LAX and MSP.

The values for "approximate sideline distance" should not be in Table 21. (See next page.)

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[23] This approach is consistent with that of FICON (1992, p. 3-15), which states in part that "a value judgment must be assigned to reflect the quality of the environment as the result of noise exposure," and that issues such as the acceptability of noise "...impacts are not defined by scientific research, but rather are matters of policy decisions based at least partly on community standards."

Comments on Table 21

The values under "approximate sideline distance" come from Figure 3 in Volume I. This information gives the impression that the response to low-frequency aircraft noise is constant along the entire length of a runway and varies only as the distance from the runway. Mr. Sutherland, has stated that it does not reflect the effects of thrust reversal noise and that he had not considered whether it represented departure noise. Mr. Harris has stated that it does not reflect the effects from wither departure noise or thrust reversal noise. Neither Figure 3 nor the values in this column of Table 21 should be in this report.

Table 21 Summary of potential criteria for low-frequency noise acceptability.

RANGE OF POLICY GOALS	LOW-FREQUENCY SOUND LEVEL	DNL VALUE FOR COMPARABLE PREVALENCE OF HIGH ANNOYANCE WITH OVERFLIGHTS	APPROXIMATE SIDELINE DISTANCE TO DEPARTURE RUNWAY CENTERLINE
Consistency with various agencies' preferences for outdoor noise exposure in residential areas	65 dB	55 dB	5,800 feet
Compliance with Minnesota legislative direction	67	60	5,400
Consistency with FAA policy threshold for federal participation in funding of noise mitigation projects	70	65	4,700
Consistency with upper bound of HUD lending policy	79	70	3,500
Consistency with FICON's upper bound of residential land use compatibility	87	75	< 2,000

7.2 RATIONALE FOR ADOPTION OF A CRITERION OF SIGNIFICANT LOW-FREQUENCY NOISE IMPACT

The Expert Panel reached consensus on the overall procedure identified below. The Expert Panel did not reach consensus on Table 22 or Figure 64.

The Expert Panel believes that interpretation of low-frequency aircraft noise impacts in residential areas near MSP is best undertaken in the same manner that FICON adopted to gauge the impacts of A-weighted (overflight and other transportation) noise exposure. The three essential steps in FICON's approach are

> A decision that the prevalence of consequential noise-induced annoyance is the best overall indication of aircraft noise impacts in residential areas;
>
> Development of a quantitative ("dosage-response") relationship between an appropriate noise descriptor and the prevalence of noise-induced annoyance; and
>
> Adoption of an interpretive criterion for the dosage-response relationship that identifies an annoyance prevalence rate considered acceptable by the policy body.

Section 1.2.1 of this Volume indicates that rattle-related annoyance is the effect of low-frequency aircraft noise of primary concern for present purposes. The dosage-response relationship developed in Section 4 of this Volume is based on measurements of the prevalence of a consequential degree of annoyance with aircraft noise-induced rattle and vibration. This information comprises the most direct, appropriate and cogent basis for constructing a dosage-response relationship for present purposes.

No dosage-response relationship is self-interpreting, however. Table 22 summarizes a range of interpretive criteria adopted by various agencies for various policy purposes. For illustrative purposes, Figure 70 superimposes these interpretive criteria over the FICON curve.

Table 22 contains errors that are identified on the next page. Figure 70 also contains errors that are identified after the figure. These errors were discussed during meetings of the Expert Panel. Similar errors were in Table 1. Table 1 information was corrected. However, Table 22 was not corrected before publication of the 25 April 2000 document.

7.3 THE ROLE OF UNCERTAINTY IN POLICY DECISIONS

The Expert Panel did not reach consensus on Section 7.3. (See discussion on next page.)

It is important that the Policy Committee appreciate the role of uncertainty of measurement (see Section A.5 of Appendix A) in reaching decisions based on such information. Policy decisions inevitably waste information when they select action points to dichotomize an underlying continuum of costs and benefits into acceptable and unacceptable regions. They also waste information by expressing action points in "round" values, in tacit acknowledgment of a fundamentally arbitrary element of policy making. When setting traffic speed limits, for example, a 55 mile per hour limit may be adopted even when it is understood that a slightly higher or lower posted limit might yield a slightly more favorable ratio of costs to benefits.

Uncertainties of measurement and estimation are frequently overlooked for purposes of reaching policy decisions. In the interests of producing understandable and enforceable action points, for example, nominal values of critical variables are usually specified for policy purposes. Thus, speed limits are posted in nominal form (*e.g.*, "65 mph" rather than "65 ± 5 mph"), even though underlying safety information on which the limit is based may lack the precision necessary to distinguish between outcomes of driving at 60 and 70 miles per hour.

Table 22 Some policy perspectives on implications of FICON's dosage-response relationship for community response to environmental noise.

Agency	Policy Purpose	DNL	% HA	Comment
Office of Noise Abatement and Control, U.S. Environmental Protection Agency (1974)	Specification of level of noise requisite to protect public health and welfare with an adequate margin of safety	45 dB	< 1%	No consideration of economic or technological feasibility
World Bank, European Economic Community (Environmental Guidelines, September, 1988, p. 231) World Health Organization (Guidelines for Community Noise, June, 1999)	Identification of preferred outdoor sound levels in residential areas	55 dB	3.3%	1988 EEC guideline currently under review by European Commission Steering Group on Noise Policy
State legislature (Minnesota Statutes, 1994, section 473.661, subdivision 4, paragraph f, as amended)	Extent of mitigation of aircraft noise impacts on residential land uses near MSP due to construction of Runway 17/35	60 dB	6.5%	Specific legislative intent for consideration of mitigation of A-weighted noise impacts of Runway 17/35
Federal Interagency Committee on Noise (1992)	Recognition of noise exposure as causing a degree of impact warranting federal participation in mitigation efforts	65 dB	12.3%	Applicable only to federal agency decisions; non-binding for local land use planning authorities; threshold for access to Aviation Trust Fund
Federal Aviation Administration	Level of aircraft noise exposure beyond which no residential land uses are compatible with airport operations	75 dB	36.5%	No cost-effective or practical noise mitigation alternatives to purchases

The EPA identified a level of 55 dB as the outdoor level, not 45 dB. The 45-dB level was identified for indoor exposure. The Minnesota legislature identified 60 dB DNL as the level for investigation, not mitigation. See Table 1 for the correct information.

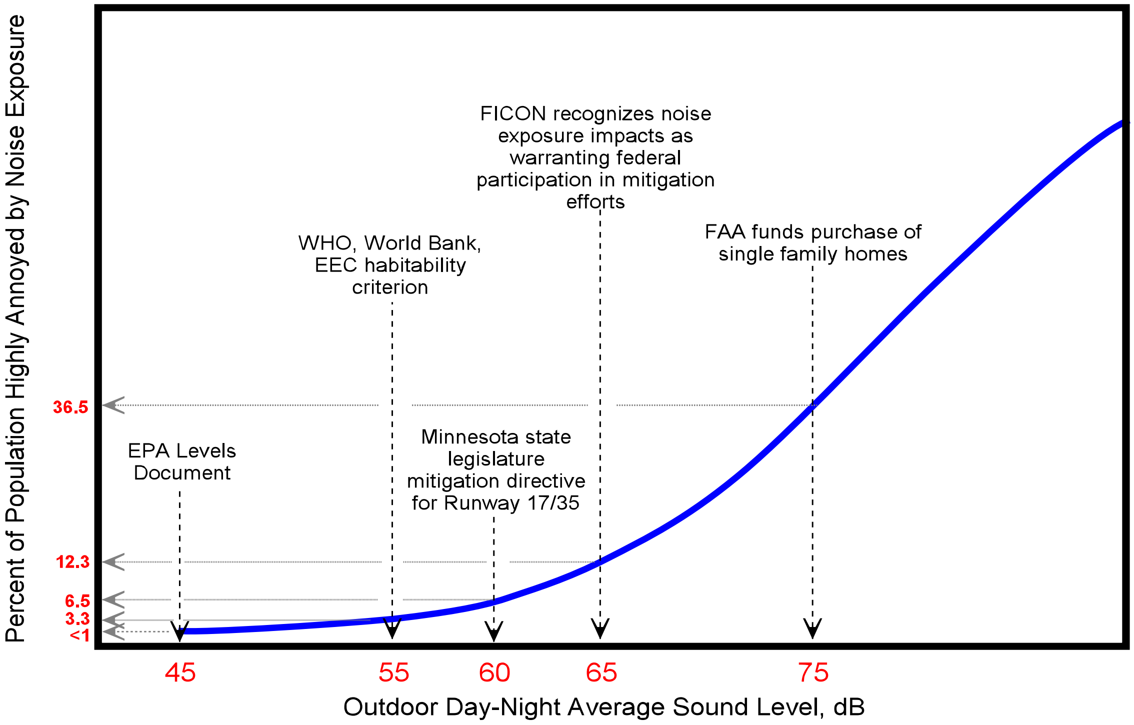

Figure 70 Various policy perspectives and interpretations of FICON relationship.

The EPA identified a level of 55 dB as the outdoor level, not 45 dB. The 45-dB level was identified for indoor exposure. The Minnesota legislature identified 60 dB DNL as the level for investigation, not mitigation. Table 1 presents the information correctly. These errors should be corrected before considering the information in the figure.

For the sake of consistency with common practice, information contained in Volume I of this report is presented in nominal form, as though it were of perfect accuracy and precision. To support greater understanding, certain information contained in this volume is accompanied by information about error bounds. Even when not accompanied by explicit information about error bounds, however, it should be understood that no measurements or modeling estimates can ever be error-free. Thus, when a measurement of the prevalence of annoyance is derived from a social survey, or when a computer program predicts that a particular noise contour will cross a particular street intersection, or when it is stated that a certain form of construction will yield a certain noise reduction, readers must understand that these values are necessarily inexact.

The Expert Panel discussed issues of uncertainty during this project. Consensus was not reached on Section 7.3. As published in the 25 April 2000 document, Section 7.3 gives the impression that there was an extraordinary degree of uncertainty in the work of the Expert Panel. That perspective was not shared by all members of the Expert Panel.

7.4 CORROBORATIVE ANALYSES

The Expert Panel reached consensus on only those portions of Section 7.4 so noted.

In developing the information summarized in Table 21, the Expert Panel did not rely solely upon a single computer program to estimate low-frequency sound levels from future operations on Runway 17/35, nor upon social survey findings alone, nor upon laboratory measurements of annoyance alone. This section describes supportive findings of alternate analyses.

7.4.1 Comparison of Sound Levels Likely to Cause Rattle with Dosage-Response Relationship for Rattle-Induced Annoyance

The Expert Panel reached consensus on Section 7.4.1.

A low-frequency sound level criterion for window rattle may be derived in the same manner that an NC rating for room noise is found, by shifting a background noise spectrum vertically to reach a point of tangency with an arbitrarily shaped criterion curve. The rattle threshold information for windows shown in Figures 103 and 123 in Appendix B of Volume III can serve as a criterion curve for this purpose.

Figures 71 and 72 summarize this process. The spectra in Figure 71 display the relative one-third octave band values (L(f) re: LFSL from measurements made at six airports as summarized in Table 27 on page 58 in Volume III. These relative spectra are average values for a range of distances from brake release (“X” values). The data exhibit a consistent trend toward lower values of low-frequency energy with increases in distances from . Values of [L(f) - LFSL] were averaged at all Y (sideline distance) values for a given range of X values, due to the expected small variation of low-frequency spectral shape with lateral distance.

Figure 72 superimposes aircraft source spectral shapes on a window rattle criterion curve (for typical 10-50 ft^2 windows) to identify the value of LFSL of each curve at the point of tangency to the rattle threshold curve. These “rattle criterion” values for LFSL vary from 86 dB for X in the range of -14,000 to -11,000 ft (SFO data), to 93 dB for X = >6,800 ft. These LFSL rattle criterion estimates are roughly 10 dB greater than implied by the social survey data discussed in Section 4 of this Volume.

However, the above “rattle threshold” curve applies only to one type of structural component — a window 10-50 square feet in area. Two methods were therefore devised to take into account the average of the predicted probability of occurrence of rattle for all three types of windows and the three types of walls of wood frame buildings, such as shown in Figure 112 in Appendix B of Volume III.

The probability of occurrence of rattle was estimated by the same scheme that Hershey and Higgins (1976) used to predict damage of windows from sonic booms. This method is based on computing the probability of a normally-distributed environmental stress (*i.e.*, the acoustic “load” from the low-frequency sound levels) of a component exceeding a threshold vibration level in units of standard deviations of vibro-acoustic response characteristics of the structure (Sutherland, 1989; Sutherland, Brown and Goerner, 1990).

Figure 73 compares the predicted probability of occurrence of rattle for typical wood frame buildings as a function of LFSL for each of the two methods, on the same ordinate as the prevalence of annoyance observed in the social survey data. Even though the predicted probability of rattle occurrence is imprecise (the standard deviation of the values over the three window and three wall types considered was about twice the mean value plotted in the figure for each method), the comparison demonstrates that an experimentally well-founded engineering model prediction for the probability of occurrence of rattle corresponds well with the subjective response survey data.

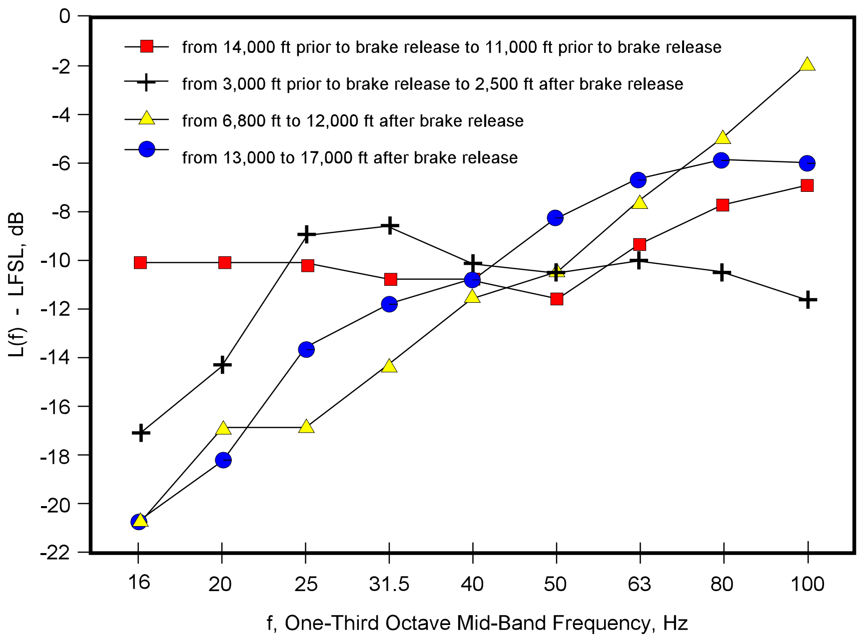

Figure 71 One-third octave band sound levels relative to low-frequency sound levels (LFSL) for four ranges of X values (distance from brake release). Data averaged for six airports (see Table 27, page 58 of Volume III).

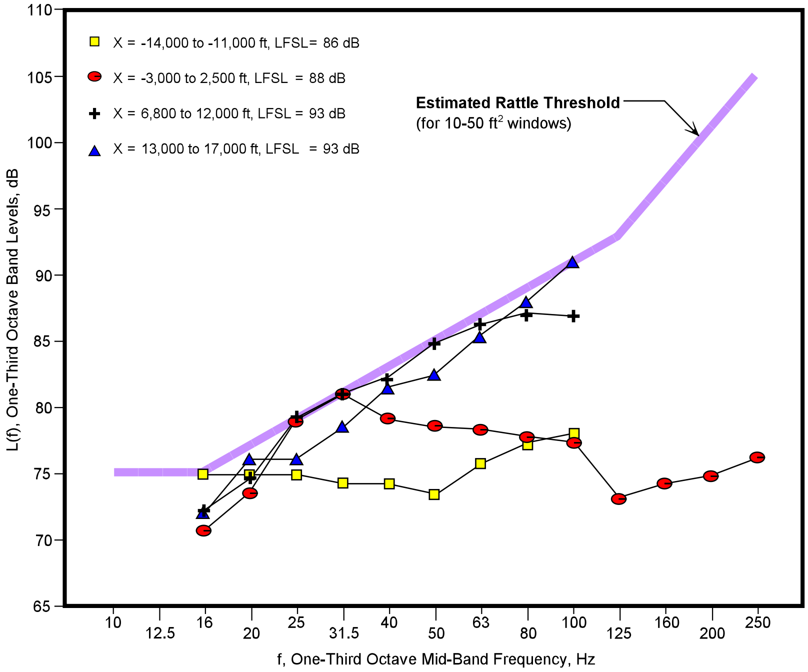

Figure 72 One-third octave band levels and corresponding LFSL values derived from Figure 65 adjusted to be tangent with a criterion line for expected rattle threshold for 10-50 ft^2 windows (see Figure 105, page 51 in Volume III).

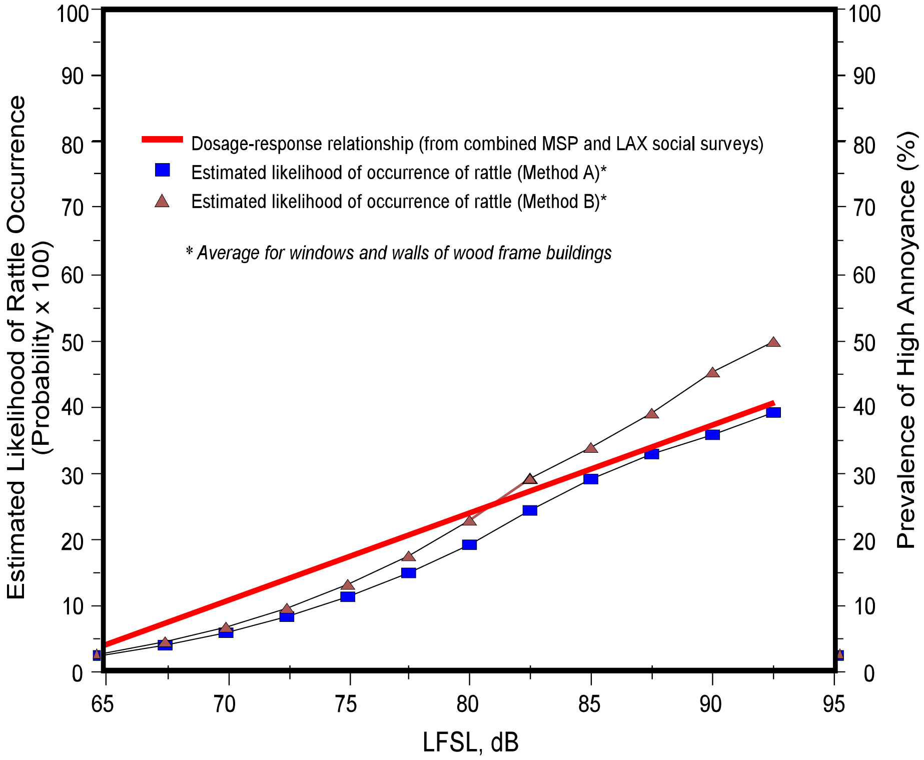

Figure 73 Comparison of growth rates of probability of rattle and prevalence of high annoyance.

7.4.2 Geographic Association

The Expert Panel did not reach consensus on Section 7.4.2. (See discussion at end of this section.)

It is also possible to estimate sideline distances at which low-frequency noise near departure runways renders residential land uses incompatible with airport operations by completely non-acoustic means. Figure 74 displays the prevalence of high annoyance with rattle or vibration with respect to sideline distance intervals.[24] The information in Figure 74 was developed in three steps:

> The distance to the centerline (or extended centerline, as necessary) of the nearest departure runway from each household at which an interview was completed in the LAX and MSP surveys was determined;

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[24] The abscissa of Figure 74 is scaled logarithmically to avoid the generic suggestion that the geometric spreading of acoustic intensity is linear. For the limited range of runway sideline distances of present concern, however, a linear regression equation (% Highly Annoyed by Rattle and Vibration = -0.008343(feet to centerline) +51.6) accounts for 90% of the variance in the data set.

The distances from households to runway centerlines were grouped in 500' intervals; and

The percentage of respondents describing themselves as very or extremely annoyed by aircraft-induced rattle and vibration was calculated for each distance interval.

Note that this approach does not rely upon estimation of any acoustic quantities, and is completely independent of the distance from homes to various points along the runway, and of fleet mix, propagation, and home construction variables. The independence of this line of reasoning is a useful complement to other analyses for two reasons. First, it provides an indication of the net effect of all of the interacting influences of low-frequency source levels and acoustic propagation into residences.

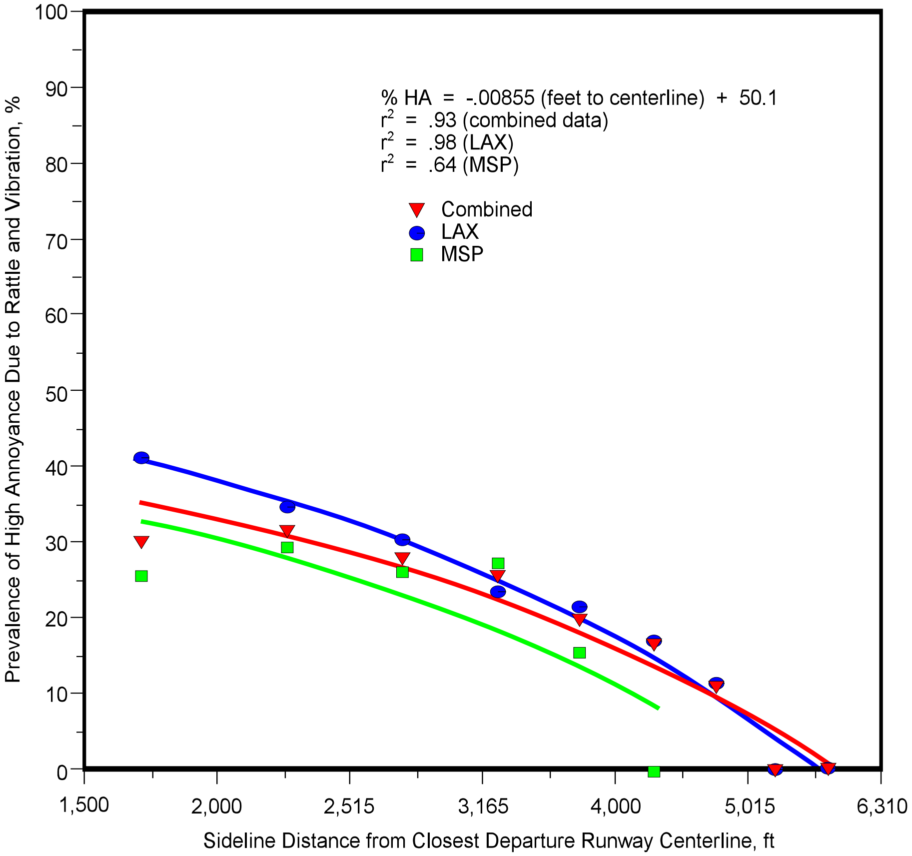

Figure 74 Empirical relationship between runway sideline distances and prevalence of annoyance due to rattle and vibration.

Second, because of the completely non-acoustic nature of the analysis, it is not susceptible to uncertainties of acoustic measurement or reasoning.

The relationship presented in Section 7.4.2 does not form an appropriate basis for determining compatibility of low-frequency aircraft noise in the vicinity of MSP. The Expert Panel did not reach consensus on the relationship. Section 7.4.2 gives the impression that the response to low-frequency aircraft noise is constant along the entire length of a runway and varies only as the distance from the runway. The noise measurements at MSP and the contours based on those measurements have shown that such an impression is invalid.

Although some early regulations about the noise from aircraft operations used the distance from the airport (e.g., within a certain radius of the airport) as the basis for planning, noise-related planning has long since adopted approaches related directly to the noise. For example, contours of DNL from actual operations are now the basis of planning for compatibility with overall aircraft noise. The current study has provided bases for low-frequency noise contours and a method to assess impacts from the noise. As presented in the discussion of Figure 3, Mr. Sutherland, has stated that the relationship does not reflect the effects of thrust reversal noise and that he had not considered whether it represented departure noise. Mr. Harris has stated that the relationship does not reflect the effects from either departure noise or thrust reversal noise. Therefore, neither Figure 3 nor the values in this column of Table 21 should be in this report.

7.5 RECOMMENDATIONS

The Expert Panel reached consensus on only a portion of the recommendations as presented here.

The Expert Panel reiterates that policy interpretations of the findings of this report require explicitly non-technical judgments. The Expert Panel recommends that the Policy Committee interpret the dosage-effect relationship shown in Figure 31 in the context of the information summarized in Table 22 and Figure 70, as complemented by the information presented in Figure 74.

The set of recommendations stated above does not represent consensus of the Expert Panel:

> ***The Expert Panel did not achieve consensus on the concept that the nature of the information about low-frequency aircraft noise "required" the Policy Committee to make nontechnical judgements.***
>
> ***As stated in Section 4.10.1, the Expert Panel reached consensus on the relationship shown in Figure 31 over the range for which there were data for MSP.***
>
> ***The Expert Panel reached consensus on the a process that would develop compatibility criteria in a manner consistent with the FICON relationship of Figure 1.***
>
> ***Table 22 contains the factual errors identified in Section 7.2. Table 1 does not contain these errors. The Expert Panel reached consensus on Table 1, but not on Table 22.***

Figure 670contains the factual errors identified in Section 7.3.

The Expert Panel did not achieve consensus on Figure 68 for the reasons identified in Section 7.4.

The Expert Panel did not develop a plan for implementation of mitigation measures. A plan is outlined in Section 1.2.8.

8 LOW-FREQUENCY NOISE MITIGATION OPTIONS

The Expert Panel did not reach consensus on significant portions of Section 8.

Single family detached residences require no treatments to increase their low-frequency noise reduction in areas with LFSL values less than 70 dB. No such treatments are likely to be economically or practically feasible in areas with LFSL values in excess of 87 dB. The appropriate degree of mitigation of low-frequency noise impacts in areas with intermediate LFSL values depends on policy interpretations of the tolerable prevalence of noise-induced rattle in a community. The information in this chapter is intended to serve as generic guidance for the Policy Committee to interpret in the context of non-technical considerations.

The Expert Panel investigated several proposals for control of noise-induced rattle in existing residences and for prevention of noise-induced rattle in new residences. Ultimately, two sets of proposals were discussed. One set of proposals was presented in the 25 April 2000 document and here in Tables 23 and 24. The second set recognizes the reduction in annoyance achieved by the MSP Residential Sound Insulation Program. The second set of proposals is presented below in Tables 23A and 24A.

Few projects have been undertaken to improve the low-frequency noise reduction of residences. Similarly, there have been no large-scale, systematic efforts to reduce noise-induced rattling in residences.[25] The discussion of building alterations to improve the low-frequency noise reduction of residences indicates the general nature of techniques that might be applied. Techniques should be investigated that apply to the wood frame residential construction that exists in the vicinity of MSP. They should be investigated in the context of the existing MSP Residential Sound Insulation Program. Similarly, plans to reduce noise-induced rattling should begin by developing a full understanding of the reasons that treatment in the MSP Residential Sound Insulation Program has reduced the level of vibration related annoyance experienced by residents.

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[25] ***Remember the conclusion in Section 1.2.6.1, "the social survey indicates a decrease in percentages of people highly annoyed by rattle in homes that had received the standard treatment. The decrease was equivalent to a 5 dB decrease in sound dose or a 5 dB increase in noise reduction. The lower prevalence of annoyance may be associated with a reduction in window rattling in recently treated homes, or with lower noise levels at frequencies above 80 Hz." .***

8.1 OPTIONS FOR EXISTING SINGLE FAMILY RESIDENTIAL CONSTRUCTION

The Expert Panel did not reach consensus on Section 8.1.

Treatments required to reduce rattle and increase low-frequency noise reduction are summarized in Table 23. Single family detached dwellings in the vicinity of MSP are typically constructed with 2" X 4" single stud wood frame walls. The exterior cladding of walls ranges from lightweight wood or aluminum siding and/or shingles, to stucco and partial or full brick veneer. Interior walls are typically gypsum wallboard or (in older construction) lath and plaster. Measures capable of increasing the low-frequency noise reduction of such construction are generally limited to

Increasing surface mass by adding dense material to the exterior and/or interior cladding; or
Adding one or more separated layers to wall to create complex wall structures; and/or
Incorporation of sound absorbing or vibration isolating provisions into walls.

Table 23 does not consider the benefits of sound insulation under the MSP Residential Sound Insulation Program. Table 23A assumes implementation of sound insulation treatment under the MSP Residential Sound Insulation Program.

Table 23 Treatment options for existing single family detached dwellings exposed to low-frequency noise.

LFSL IN dB	TREATMENT TO REDUCE RATTLE	TREATMENT TO REDUCE INTERIOR LFSL
< 70	None required	None required
70 - 78	Treat rattle directly, as described in sections B.11.3 *et seq.* of Volume III of this report	Increase low-frequency noise reduction by at least 5 dB
79 - 87	Treat rattle directly, as described in sections B.11.3 *et seq.* of Volume III of this report (may not be fully adequate)	Increase low-frequency noise reduction by more than 5 dB if possible
> 87	Treat rattle directly, as described in sections B.11.3 *et seq.* of Volume III of this report (probably not fully adequate)	Increase low-frequency noise reduction by 10 dB (unlikely to be economically or esthetically feasible in single family dwellings)

Table 23A Alternative Treatment options for existing single family dwellings exposed to low-frequency noise.

Average Exterior LFSL in dB	***Treatment to Reduce Rattle***	***Interior LFSL Reduction***
<70	*None Required*	*None Required*
70-77	*Treat Rattle Directly*	*Decrease interior LFSL by 5 dB**
78-87	*Treat Rattle Directly* *May not be fully adequate*	*Decrease Interior LFSL by 5 dB and Consider Reducing by more than 5 dB*
>87	*Treat Rattle Directly* *Probably not fully Adequate*	*Decrease Interior LFSL by at least 10 dB. Probably not Economically Feasible*

**Based on findings of the social survey, the existing Part 150 Residential Sound Insulation Program provides the equivalent of 5 dB reduction, therefore no further reduction is necessary.*

Note that these measures do not address roof or ceiling treatments, nor treatments of windows, doors, and other penetrations of the building envelope. Adding sufficient mass to roof and ceiling structures to gain 5 to 10 dB of additional low-frequency noise reduction can sometimes require structural modifications that may not be economically feasible for single family dwellings. Likewise, replacing windows with same-size windows of greater STC rating in homes with relatively high ratios of window to wall area may limit the effectiveness of wall treatments intended to increase low-frequency noise reduction. In such cases, the number and/or size of windows may have to be reduced, particularly on building facades facing the airport.

A range of such treatments has been applied to single family residences in an effort to increase both their A-weighted and low-frequency noise reduction. In Baltimore, for example, FAA has been willing to pay for treatments to homes in the Allwood subdivision to increase their low-frequency noise reduction. These treatments consisted primarily of adding mass to interior and exterior walls[26] and to ceiling and roof structures. The treatments appear to have increased the low-frequency noise reduction of homes by 5 dB at most.

Other treatments, including addition of varying numbers of layers of gypsum wall board and sound deadening board of varying thickness directly to interior walls, and mounting of layers of gypsum

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[26] Wall treatments in Allwood have varied from addition of a single ½" gypsum wall board layer, to addition of two 3/8" gypsum wall board and ½" fiberboard layers, on varying numbers of interior walls. Treatments for exterior walls have included addition of brick, 1" cement board, 1" fiberglass, and vinyl siding to varying numbers of walls. Roof and ceiling treatments have included addition of plywood subroofing and asphalt shingles, installation of attic insulation and 3/4" gypsum wall board, addition of insulation between ceiling joists, and installation of ½" cement board over ceiling joists.

wall board on resilient channels or on a separated metal stud framework have also been attempted. Depending on the numbers of layers of materials applied and the method of installation, the incremental costs of such interior wall treatments may range from roughly $1.00 to $3.00 per square foot. Costs for exterior wall treatments and for ceiling and roof modifications can be considerably greater.

8.2 OPTIONS FOR NEW SINGLE FAMILY RESIDENTIAL CONSTRUCTION

The Expert Panel did not reach consensus on Section 8.2.

Options for achieving greater than customary low-frequency noise reduction in new residential construction vary greatly. As summarized in Table 24, the total low-frequency noise reduction of new homes should be at least 15 dB in areas with LFSL values between 70 to 78 dB, and at least 20 dB in areas with LFSL values between 79 and 87 dB. Design measures for new construction, such as masonry or complex walls, careful placement and sizing of windows, and vibration isolation for roof and ceiling structures, can probably achieve the desired low-frequency noise reduction. Designs for such homes will require analysis by an architectural acoustician on a case-by-case basis, however, and may be prohibitively expensive to construct.

See alternative Table 24A on the next page. Table 24A reflects consideration of the MSP Residential Sound Insulation Program..

Table 24 Options for rattle prevention and low-frequency noise reduction for new residential construction in areas exposed to low-frequency noise.

AVERAGE LFSL IN dB	RATTLE PREVENTION TREATMENT	MINIMAL LOW-FREQUENCY NOISE REDUCTION OF RESIDENCE
< 70	None required	No special requirement
70 - 78	Rattle prevention (assumes 15 dB low-frequency noise reduction)	15 dB
79 - 87	Rattle prevention (may not be fully adequate; assumes 20 dB low-frequency noise reduction)	20 dB (probably not economically or esthetically feasible in single family dwellings)
> 87	Do not develop for residential use	

Table 24A Alternative options for rattle prevention and low-frequency noise reduction for new residential construction in areas exposed to low-frequency noise.

Average Exterior LFSL in dB	***Rattle Prevention Treatment***	***Interior LFSL Reduction***
<70	*None Required*	*No Special Requirement*
70-77	*Rattle Prevention*	*15 dB*
78-87	*Rattle Prevention*	*20 dB*
> 87	*Do not develop for residential use*	

8.3 HIGHER DENSITY AND NON-RESIDENTIAL CONSTRUCTION

The Expert Panel did not reach consensus on Section 8.3.

Multi-story residential masonry buildings are often constructed of materials with greater density than single family residences. Unless specifically designed for high noise reduction at low frequencies, however, such buildings may not provide much better low-frequency noise reduction than single family residences. For example, rental units may include individual heat exchanger or air conditioning units and other relatively large penetrations of the building envelope. Applications for building permits for both low and high density residential construction in areas with LFSL values in excess of 78 dB should therefore be reviewed by an architectural acoustician.

Non-residential structures (including buildings used for retail, commercial, and industrial purposes) do not require any special treatments to increase their low-frequency noise reduction.

The discussion in Section 8.3 is a general overview of low-frequency noise issues in higher-density residential and non-residential buildings. Buildings that contain central air conditioning equipment or other kinds of machinery may well have higher levels of low-frequency noise and vibration than is typical in single family residences in the vicinity of MSP.

The environment of any building needs to be compatible with the activities in the building. The statement in the second paragraph may not apply if a building houses activities that are sensitive to vibration.

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10 GLOSSARY

Except as noted, this glossary was acceptable to all members of the Expert Panel.

Definitions of formal acoustic quantities correspond to those of *American National Standard S1.1-1994 Acoustical Terminology*. Other terms, abbreviations, and symbols are defined in the sense in which they are used in this report.

A-weighted sound level: A single number index of a broadband sound that has been subjected to the A-weighting network (*q.v.*).

A-weighting network: A frequency-equalizing function intended to approximate the sensitivity of the human hearing to sounds of moderate sound pressure level.

C-weighted sound exposure level: Sound exposure level, as defined below, where C-weighted sound pressure is used instead of A-weighted sound pressure. Unit, decibel; abbreviation, CSEL; symbol, L_{CE}.

day average sound level: Time-average sound level between 0700 and 2200 hours. Unit, decibel (dB); abbreviation, DL; symbol, L_{d}. Note: Day average sound level in decibels is related to the corresponding day sound exposure level, $L_{E\mathrm{d}}$, according to:

$$L_{\mathrm{d}} = L_{E\mathrm{d}} - 10 \log (54000/1)$$

where 54,000 is the number of seconds in a 15-hour day.

day-night average sound level: Twenty-four hour average sound level for a given day, after addition of 10 decibels to levels from 0000 to 0700 hours and from 2200 (10 p.m.) to 2400 hours. Unit, decibel (dB); abbreviation, DNL; symbol, L_{dn}. Note: Day-night average sound level in decibels is related to the corresponding day-night sound exposure level, $L_{E\mathrm{dn}}$, according to:

$$L_{\mathrm{dn}} = L_{E\mathrm{dn}} - 10 \log (86400/1)$$

where 86,400 is the number of seconds in a 24-hour day. A-frequency weighting is understood, unless another frequency weighting is specified explicitly.

departure noise: A general descriptive term for noise created by aircraft operations on a departure runway.

energy average. Colloquial term for time-mean-square average of a series of sound signals.

energy summation. Colloquial term loosely used to indicate addition of non-coherent sound signals by the sum of the squares of their sound pressures or sound exposures.

instantaneous sound pressure: Total instantaneous pressure at a point in a medium minus the static pressure at that point. Unit, pascal (Pa); symbol, p.

MAC: Minneapolis Airports Commission ***Metropolitan Airports Commission, not Minneapolis Airports Commission.***

maximum sound level; maximum frequency-weighted sound pressure level: Greatest fast (125 ms) A-weighted sound level within a stated time interval. Alternatively, slow (1000 ms) time-weighting and C-frequency-weighting may be specified. Unit, decibel (dB); abbreviation, MXFA; symbol, L_{AFmx} (or C and S).

night average sound level: Time-average sound level between 0000 and 0700 hours and 2200 and 2400 hours. Unit, decibel (dB); abbreviation, NL; symbol, L_{n}. Note: Night average sound level in decibels is related to the corresponding night sound exposure level, $L_{E\mathrm{n}}$, according to:

$$L_{\mathrm{n}} = L_{E\mathrm{n}} - 10 \log (32400/1)$$

where 32,400 is the number of seconds in a 9-hour night.

one-hour average sound level: Time-average sound level during a time period of one hour. Unit, decibel (dB); abbreviation, 1HL; symbol, L_{1h}. Note: One-hour average sound level in decibels is related to the corresponding one-hour sound exposure level, $L_{E\mathrm{1h}}$, according to:

$$L_{\mathrm{1h}} = L_{E\mathrm{1h}} - 10 \log (3600/1)$$

where 3600 is the number of seconds in one hour, 1 s is the reference duration for sound exposure, and sound exposure E is in pascal-squared seconds.

peak sound pressure: Greatest absolute instantaneous sound pressure within a specified time interval. Unit, pascal (Pa). Note: Peak sound pressure may be measured with a standard frequency weighting.

peak sound pressure level; peak frequency-weighted sound pressure level: Level of peak sound pressure with stated frequency weighting, within a stated time interval. Unit, decibel (dB); example abbreviation, PKA; symbol, L_{Apk}.

perceived noise level. Frequency-weighted sound pressure level obtained by a stated procedure that combines the sound pressure levels in the 24 one-third octave bands with midband frequencies from 50 Hz to 10 kHz. Unit, decibel (dB); abbreviation, PNL; symbol, L_{PN}.

> NOTE – Procedures for computing perceived noise level are stated in Federal Aviation Regulation Part 36, *Noise Standards: Aircraft Type and Airworthiness Certification*, Appendix B, and in International Civil Aviation Organization Annex 16, Volume 1, *Aircraft Noise*, Third Edition, July, 1993.

sound exposure: Time integral of squared, instantaneous frequency-weighted sound pressure over a stated time interval or event. Unit: pascal-squared second; symbol, E. Note: If frequency weighting is not specified, A-frequency weighting is understood. If other than A-frequency weighting is used, such as C-frequency weighting, an appropriate subscript should be added to the symbol; e.g., E_{C}.

Duration of integration is implicitly included in the time integral and need not be reported explicitly. For the sound exposure measured over a specified time interval such as one hour, a 15-hour day, or a 9-hour night, the duration should be indicated by the abbreviation or letter symbol, for example one-hour sound exposure (1HSE or E_{1h}) for a particular hour; day sound exposure (DSE or E_d) from 0700 to 2200 hours; and night sound exposure (NSE or E_n) from 0000 to 0700 hours plus from 2200 to 2400 hours.

Day-night sound exposure (DNSE or E_{dn}) for a 24-hour day is the sum of the day sound exposure and 10 times the night sound exposure. Unless otherwise stated, the normal unit for sound exposure is the pascal-squared second.

sound level; weighted sound pressure level: Ten times the logarithm to the base ten of the ratio of A-weighted squared sound pressure to the squared reference sound pressure of 20 µPa, the squared sound pressure being obtained with fast (F) (125 ms) exponentially weighted time-averaging. Alternatively, slow (S) (1000 ms) exponentially weighted time-averaging may be specified; also C-frequency weighting. Unit, decibel (dB); symbol L_A, L_C. Note: In symbols, A-weighted sound level $L_A\ (t)$ at running time t is:

$$L_{A\tau}(t) = 10 \log \left\{ \left[(1/\tau) \int_{-\infty}^{t} p_A^2(\xi)\, e^{-(t-\xi)/\tau}\, d\xi \right] / p_0^2 \right\}$$

where is the exponential time constant in seconds, is a dummy variable of integration, $p_A^2(\ )$ is the squared, instantaneous, time-varying, A-weighted sound pressure in pascals, and p_0 is the reference sound pressure of 20 µPa. Division by time constant yields the running time average of the exponential-time-weighted, squared sound-pressure signal. Initiation of the running time average from some time in the past is indicated by - for the beginning of the integral. ANSI S1.4-1983, *American National Standard Specification for Sound Level Meters*, gives standard frequency weightings A and C and standard exponential time weightings fast (F) and slow (S).

sound pressure; effective sound pressure: Root-mean-square instantaneous sound pressure at a point, during a given time interval. Unit, pascal (Pa). Note: In the case of periodic sound pressures, the interval is an integral number of periods or an interval that is long compared with a period. In the case of nonperiodic sound pressures, the interval should be long enough to make the measured sound pressure essentially independent of small changes in the duration of the interval.

sound pressure level: Ten times the logarithm to the base ten of the ratio of the time-mean-square pressure of a sound, in a stated frequency band, to the square of the reference sound pressure in gases of 20 µPa. Unit, decibel (dB); abbreviation, SPL; symbol, L_p.

time-average sound level; time-interval equivalent continuous sound level; time-interval equivalent continuous A-weighted sound pressure level; equivalent continuous sound level: Ten times the logarithm to the base ten of the ratio of time-mean-square instantaneous A-weighted sound pressure, during a stated time interval T, to the square of the standard reference sound pressure. Unit, decibel (dB); respective abbreviations, TAV and TEQ; respective symbols, L_{AT} and $L_{\text{aeq}T}$. Note: A frequency weighting other than the standard A-weighting may be employed if specified explicitly. The frequency weighting that is essentially constant between limits specified by a manufacturer is called flat.

In symbols, time-average (time-interval equivalent continuous) A-weighted sound level in decibels is:

$$\begin{aligned} L_{\mathrm{A}T} &= 10\ \log\left\{\left[\left(1/T\right)\int_{o}^{T} p_{\mathrm{A}}^{2}(t)\,\mathrm{d}t\right]/p_{0}^{2}\right\} \\ &= L_{\mathrm{Aeq}T} \end{aligned}$$

where p_{A}^2 is the squared instantaneous A-weighted sound pressure signal, a function of elapsed time t; in gases reference sound pressure $p_0 = 20\ \mu\mathrm{Pa}$; T is a stated time interval. In principle, the sound pressure signal is not exponentially time-weighted, either before or after squaring.

FINDINGS OF THE LOW-FREQUENCY NOISE EXPERT PANEL

**of the Richfield-MAC Noise Mitigation Agreement
of 17 December, 1998**

Annotated to Indicate Consensus or Absence of Consensus

VOLUME III of III

30 September 2000

VOLUME III

APPENDIX A GENERAL DISCUSSION OF AIRCRAFT NOISE AND ITS EFFECTS

Except as noted, this discussion was acceptable to all members of the Expert Panel.

A.1 SUMMARY OF DISCUSSION

This Appendix is intended to aid readers unfamiliar with aircraft noise effects by bringing to their attention basic information about environmental noise. It includes information about the effects of noise on people; about the nature and purpose of aircraft noise measurement and modeling; and about the characteristics of runway sideline, departure, and overflight noise. Appendix B contains more specific information about low-frequency aircraft noise and its effects.

A.2 TERMINOLOGY RELATED TO ASSESSMENT OF ENVIRONMENTAL NOISE EFFECTS

Any meaningful assessment of the effects of environmental noise involves an interaction of technical information and policy judgments, both of make use of specialized vocabulary. It is helpful to distinguish the terms "standard," "criterion," "policy," "impact," "guideline," and "regulation" as used in the context of environmental noise assessment.

A standard is an agreed-upon procedure for measuring or assessing some aspect of noise or its effects. For example, standards (such as *American National Standard S1.1-1994 Acoustical Terminology*) define common measures of environmental noise exposure for purposes of quantifying its effects on communities. Formal standards are developed by voluntary professional organizations, generally after prolonged consideration.

A criterion is a form of summary statement about an effect of noise exposure on people or their property, of the form "so much noise is associated with such a degree of effect." A dosage-response relationship is a common form of criterion. One of the more familiar of these (FICON, 1992) relates the prevalence of consequential degrees of annoyance to varying amounts of noise exposure. Criteria are merely descriptive, and do not of themselves either prescribe or proscribe any amount of noise exposure or noise effect.

Policy statements summarize internal decisions of issuing agencies about their interpretations of criteria. For example, as a matter of policy, FAA considers a value of L_{dn} = 65 dB as a threshold of effect for permitting access to federal Airport Improvement Trust funds, and for certain other aircraft noise-related matters. Formal policy statements may change from time to time, and are binding only on the issuing agency.

An "impact" is a noise effect recognized by some agency's policy as of sufficient magnitude to warrant consideration of abatement or mitigation. Note that the definition of an impact is an expressly ***non***-technical judgment, and that the opinions of different agencies (such as regional councils, state legislatures, and federal regulatory agencies) about what constitutes a noise impact may differ.

A guideline is an advisory statement that identifies and recommends to others the policy preferences of the issuing body. A guideline, which reflects the perspective of the agency issuing it, is often expressed as an interpretation of a criterion. For example, a group of federal agencies with aviation-related interests (the Federal Interagency Committee on Noise, or FICON) has widely publicized its views of noise-related “land use compatibility.” FICON has taken care to note, however, that these recommendations do not have the force of law, and do not supersede the views of local zoning authorities.

Government executive agencies issue regulations to implement laws passed by legislative bodies. Unlike guidelines and policy statements, regulations have the force of law, and generally evolve more slowly than either guidelines or policies.

A.3 WHY AIRCRAFT NOISE IS QUANTIFIED

Measurements of the noise of civil aircraft are commonly made for purposes related to compliance with federal aviation regulations and requirements of environmental disclosure regulations for prediction and assessment of noise levels and impacts. Measurement procedures devised for such purposes are closely tailored to regulatory requirements, but ultimately are meaningful only to the degree that they can reliably predict noise effects on human activities.

Since aircraft noise is measured for reasons of prediction and assessment of its effects on individuals and communities rather than for the sake of measurement alone, it is important to understand the nature of these effects. This is particularly so in the present case, in which means are sought for quantifying, predicting, and assessing the effects of a particular sort of aircraft noise for which standard measurement techniques have not yet been adopted.

A.3.1 Principal Effects of Noise on Individuals and Communities

The best documented effects of residential exposure to aircraft noise on individuals and communities are annoyance, speech interference, and sleep disturbance. For reasons described in Appendix B, only the first effect is of major concern in the present circumstance.[27] The following background information about annoyance paraphrases Fidell and Pearsons (Crocker, 1997).

As commonly used in aircraft noise impact analyses, the term “annoyance” refers to a long-term adverse attitude toward noise exposure, not to an immediate sensation. Annoyance differs from loudness in that loudness is an immediate sensation that does not increase in magnitude as the duration of a sound increases beyond a quarter of a second. U.S. federal agencies involved in evaluation of environmental noise effects recognize the attitude of annoyance as the primary basis for assessing an environmental noise “impact”: that is, an effect acknowledged by agency policy that may warrant abatement of source levels or some degree of mitigation.

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[27] Hearing damage risk and other potential adverse health consequences of occupational noise exposure are very unlikely in the present circumstances. Those interested in further information about noise-induced sleep disturbance may find a recent summary in Pearsons, Barber, Tabachnick and Fidell (1995).

The prevalence of noise-induced annoyance in communities (that is, the proportion of a residential population sharing a similar, consequential adverse attitude toward an environmental noise source) has both acoustic and nonacoustic determinants. Each set of determinants exerts a roughly equal influence on the prevalence of annoyance. Although the acoustic determinants of annoyance are amenable in principle to direct physical measurement, no well-developed body of theory dictates what quantities should be measured or in what manner. The lack of systematic theory greatly complicates prediction of the prevalence of annoyance from aircraft noise measurements alone, and has encouraged development of expedient methods for predicting annoyance.

A.3.2 Measurement of the Relative Annoyance of Sounds

Simple measuring instruments, such as rulers or thermometers, suffice to measure simple physical quantities such as length or temperature. Since annoyance is a more complex, non-physical quantity, the absolute annoyance of a given sound is not as readily measured. Under controlled listening conditions in laboratory settings, however, reliable and accurate estimates can be made of the *relative* annoyance of sets of sounds under acute (that is, immediate and isolated) conditions.

Information about the acute annoyance of individual sounds is routinely interpreted in the context of chronic environmental noise exposure. For example, if the annoyance of the noise created by a particular class of truck is found in the laboratory to exceed the annoyance of the noise made by another class of truck, then all other thing being equal, it is routinely assumed that cumulative, long-term exposure to the sounds created by the more annoying class of truck will be more annoying than exposure to the sounds of the less annoying class of truck.

A.3.3 Measurement and Prediction of the Absolute Prevalence of Annoyance in Communities

Information about the relative annoyance of sounds heard in controlled laboratory settings does not by itself provide sufficient information to permit rational regulation of environmental noise exposure in residential settings. The most direct empirical means for determining the proportion of a residential population highly annoyed by some form of noise exposure is to establish this proportion empirically by means of a social survey. Hundreds of such surveys have been undertaken world-wide in the last few decades.

To avoid trivializing the concept of noise-induced annoyance, people who describe themselves as only slightly or moderately annoyed by noise exposure are not considered to be consequentially annoyed. Thus, for example, if 100 of 1,000 people interviewed within a site with uniform noise exposure describe themselves as “very” or “extremely” annoyed by aircraft noise, the prevalence of a consequential degree of annoyance in this sample is considered to be 10%, even though many of the other 900 respondents may be annoyed to lesser degrees by aircraft noise.

The standard method for assessing noise-induced annoyance is with respect to a “dosage-response relationship” — a curve that predicts the percentage of the residential population highly annoyed from values of a long-term, time-weighted average measure of noise exposure. FICON has associated percentages of populations highly annoyed by transportation noise with noise exposure through analyses of social surveys conducted in communities worldwide. The basic datum of FICON’s analysis is the prevalence of a consequential degree of self-reported annoyance for a given noise exposure level.

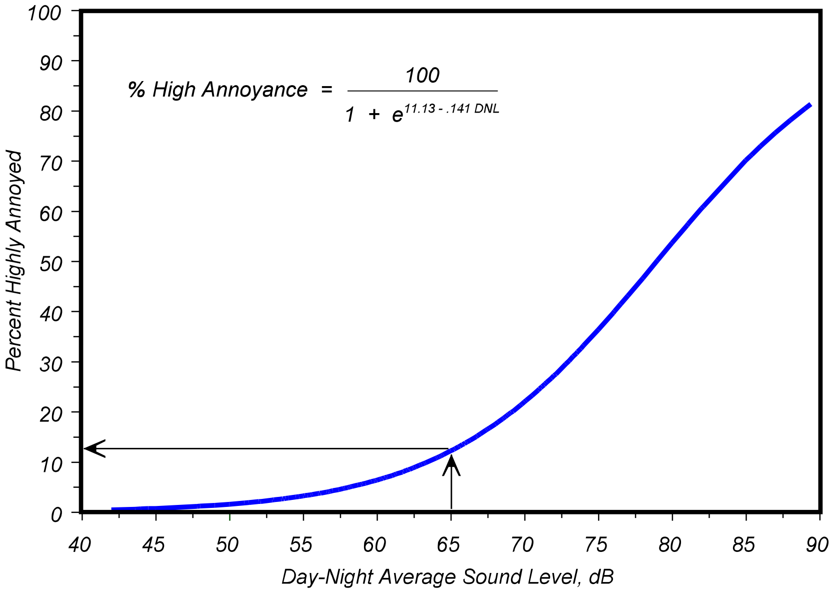

Figure 75 Dosage-response relationship adopted by the Federal Interagency Committee on Noise (FICON, 1992). Arrows indicate the prevalence of annoyance (12.3%) associated with a DNL value of 65 dB.

FICON's preferred measure of noise exposure gives equal consideration to the number, duration and level of noise events. Figure 75 shows the dosage-response relationship that FICON has developed for predicting the prevalence of annoyance due to transportation noise.

A.4 HOW AIRCRAFT NOISE IS MEASURED AND MODELED

Standardized procedures have evolved for both measuring and modeling aircraft noise for common purposes. These are outlined in the following subsections.

A.4.1 Frequency-Related Measurement Conventions

The human ear is capable in principle of detecting sounds within a ten octave range extending from about 20 Hz to 20 kHz. It has been well understood since the early 1920s, however, that sensitivity to sounds varies greatly over frequencies within this range. The greatest sensitivity is concentrated within a two octave range extending from roughly 1000 to 4000 Hz that includes many important speech sounds. At extremely low and extremely high frequencies, the ear is thousands of times less sensitive than in the speech range.

When systematic measurements of urban noise were first made in the late 1920s, it was quickly realized that an adjustment of some sort was needed to represent measurements of sounds of differing frequency content in terms meaningful for assessing effects of such noise on people. The simplest solution available at the time was to apply a "frequency weighting network" to measurements of environmental sounds. Three such networks were standardized initially during the 1930s: the A-weighting network for sounds of relatively low absolute sound pressure level, the B-weighting network for sounds of intermediate level, and the C-weighting network for relatively high level sounds. These weighting networks were intended as approximations to the inverse of human hearing sensitivity at increasing sound levels.

The A-weighting network eventually gained acceptance as the default weighting network for general environmental noise measurement purposes. When FAA was charged with regulating aircraft noise emissions, however, it adopted a different measurement procedure for the 1969 Part 36 of the Federal Aviation Regulations — Perceived Noise Level, or PNL. PNL is a more complex frequency weighting network than the A-weighting network, that is slightly more sensitive than the A-weighting network to low-frequency sounds, and also to sounds in the vicinity of 1 to 3 kHz.

Most references to FAR Part 36 cite the standard in terms of the Effective Perceived Noise Level (EPNL). While an instantaneous level is given in terms of PNL, the level from an event (i.e., a takeoff or a landing) is given in terms of the EPNL. This is analogous to the instantaneous level being cited as an A-weighted level and the sound from an event as the Sound Exposure Level (SEL).

When the Office of Noise Abatement and Control of the Environmental Protection Agency recommended adoption of the Day-Night Average Sound Level for general assessments of environmental noise levels in 1974, readily available instrumentation could not conveniently measure PNL values. The A-weighting network was therefore retained as the basis for routine environmental noise measurements, such as monitoring of aircraft noise levels near airports.

A.4.2 Duration-Related Conventions

A.4.2.1The "Equal Energy Hypothesis"

As a matter of regulatory policy, it is commonly assumed that people are indifferent between the annoyance of small numbers of very high-level noise events of short duration and the annoyance of large numbers of compensatingly lower level and/or longer duration noise events. In other words, it is conventionally assumed that the number, level, and duration of noise events are fully interchangeable determinants of annoyance, as long as their product (energy sum) remains constant. Thus, a small number of noisy aircraft operations is considered to create the same impact as that of a compensatingly greater number of operations by less noisy aircraft.

It is misleading to attribute the equal energy hypothesis to "regulatory policy." As part of its responsibilities under the mandates of the Noise Control Act of 1972, the EPA recommended adoption of DNL., based on A-weighted levels. As is clear from the report containing that recommendation, the "Levels Document," the EPA base its decision on previous research and experience in other countries, mainly in Europe, and in California, not regulatory policy. [28]

The assumption of linearity of acoustic effects underlies reliance on the equal energy hypothesis for purposes such as predicting the prevalence of annoyance from long-term, time-weighted average sound levels (such as Day-Night Average Sound Level). This assumption is untenable for present

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[28] ***Anon."Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety," EPA 550/9-74-004, March 1974.***

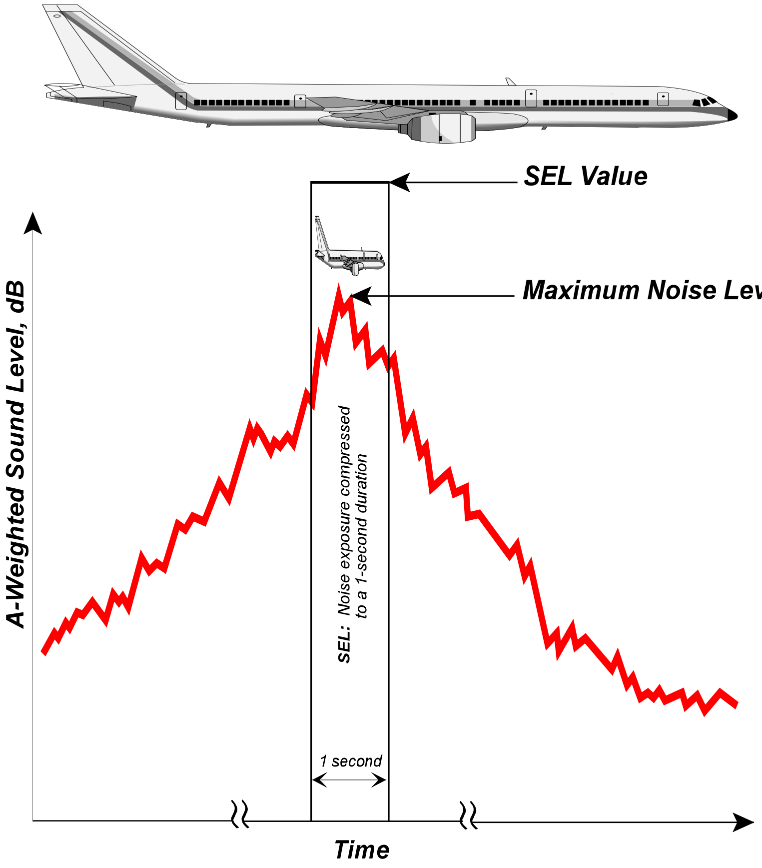

Figure 76 Relationship of sound exposure level (SEL) to time history of an aircraft overflight.

purposes, since the occurrence of noise-induced rattle is a threshold-like phenomenon. In residential settings, people hear rattle when outdoor noise levels exceed some structure-specific and frequency-specific sound level. Furthermore, sound levels of rattling objects do not necessarily increase in direct proportion to the amount by which sound levels exceed a rattle threshold (*cf.* Schomer *et al.*, 1987a).

Under these circumstances, time-integrated noise exposure cannot be expected to predict the annoyance of rattle as well as quantities such as the number or temporal density of noise events in excess of a threshold of rattle.

A.4.2.2Family of "equivalent level" noise metrics

Figure 76 shows the characteristic form of a time history of sound levels produced during an aircraft overflight of a fixed point on the ground. The sound pressure level at the measurement point initially rises to a maximum, after which it decreases. Since the sound pressure levels vary throughout the overflight, and since the durations of different overflights also vary, no single number can usefully characterize the moment-to-moment changes in sound levels. The usual method for representing the sound energy produced during the entire overflight is therefore to "normalize" the measurement to a standard time period (one second). This measure, "sound exposure level," simplifies the comparison of noise events of varying duration and maximum level by compressing the acoustic energy of the entire noise event into a standard time period.

The concept of a sound exposure level can be generalized to an "equivalent level" of time periods longer than one second. For example, a full day's worth of sound exposure can be expressed as a 24-hour equivalent level, symbolized as L_{eq24}. If a different weighting factor is assigned to the equivalent level of day time (0700 - 2200 hours) and night time (2200-0700 hours), the noise metric becomes a time-weighted 24-hour metric. When the nighttime weighting of the time average is ten times greater than the daytime weighting, the noise measure is known as Day-Night Average Sound Level, abbreviated DNL and symbolized as L_{dn}.

A.4.3 Field Measurement of Aircraft Noise

Part 36 of the Federal Aviation Regulations specifies levels of noise emissions of commercial aircraft offered for sale or otherwise operating in the United States. Regulatory language indicates in great detail the conditions of measurements and analysis of sound level measurements made for purposes of certifying that aircraft types are in compliance with Part 36. These include constraints on aircraft operating procedures, atmospheric conditions, multiple microphone positions, half-second sampling of one-third octave band levels from 50 to 10,000 Hz, calculation of variant forms of Perceived Noise Levels, and so forth.

Although Part 36 does not apply to aircraft noise measurements made for purposes other than certification, half-second sampling of one-third octave band sound levels in the 24 bands from 50 to 10,000 Hz are commonplace in field measurements made under less controlled circumstances as well. However, adventitious measurements of aircraft noise (those made under circumstances in which aircraft movements are unconstrained) are much more likely to be influenced by factors such as variability in aircraft operating conditions (thrust settings, flight profiles, *etc.*), weather conditions, and the presence of extraneous noise sources. These uncontrollable sources of error limit the precision of most field measurements of aircraft noise, and often contribute to the sort of scatter seen in Figures .

Another obvious limitation of field measurement of aircraft noise is that it is applicable only to existing circumstances of noise exposure. Noise that has not yet been made cannot be measured, but only modeled.

A.4.4 Standard Approach to Modeling Aircraft Noise Exposure Near Airports

Aircraft noise can be modeled in as many ways as there are purposes for modeling. The standard approach to aircraft noise modeling in the immediate vicinity of civil airfields answers the question "How much noise does an airplane flying *here* make *there*?" To answer this question, mathematical models of atmospheric propagation of sound are applied to standard sets of aircraft noise levels, to propagate noise emissions away from aircraft (whether in flight or on the ground) in all directions. These calculations are summarized graphically as sets of source-based emission contours, or sometimes as point values. The goal of this form of aircraft noise modeling is protection of public investment in an airport.

The results of contouring exercises are usually summarized in terms of a time-weighted daily average exposure index devised by the Environmental Protection Agency (EPA, 1974), known as Day-Night Average Sound Level (DNL). DNL provides a convenient means for combining all of the noise energy created in the course of daily flight operations into a single number, for which interpretive criteria and regulatory policy have evolved. Airports routinely produce aircraft noise exposure contours in units of DNL for NEPA disclosure purposes; for purposes related to federal aviation regulations; for land use planning purposes; and for various other purposes.

FAA's preferred aircraft noise prediction software, INM, can produce not only noise exposure (*i.e.*, DNL or CNEL) contours, but with equal facility, contours of maximum noise levels and contours of duration of aircraft noise in excess of a user-specified threshold level ("time-above" contours). INM can also produce spot estimates (rather than entire contour sets) for various noise metrics.

For reasons discussed in Section 2.3 of Volume II, DNL contours are of no direct value as predictors of low-frequency sound level.

A.4.5 Overview of Airfield-Vicinity Noise Exposure Modeling

Computer-based aircraft noise exposure modeling began in the 1970s with the creation of early versions of the U.S. Air Force's NOISEMAP software. FAA began construction of an "Integrated Noise Model" (Olmstead *et al.*, 1997) several years later. Both noise modeling programs have been released in versions for different computing platforms and operating systems. Variants on both programs have also been produced by various government and commercial organizations worldwide.[29]

Although the Air Force and FAA noise models were initially developed separately, recent versions share some algorithms and software modules. NOISEMAP and INM may both be used for retrospective and prospective purposes: to produce noise contours for an historical set of operating conditions, or to predict the noise exposure resulting from alternate hypothetical operating conditions. FAA accepts contours produced by either INM or NOISEMAP as equivalent for regulatory purposes.

INM remains under active development, with Version 6.0 recently released. Differences in DNL contours from release to release for the same input specifications can be sizable. It is expected, for example, that sideline noise contours will be notably wider in Version 6.0 than in current versions of INM. Version 6.0 can also produce C-weighted noise exposure estimates in addition to the A-weighted metrics to which earlier versions of INM were limited.

A.4.6 General Properties of Aircraft Noise Exposure Contours

As a generality, aircraft noise exposure contours about an individual runway are elliptical, with the major axis oriented along the runway centerline and the minor axis perpendicular to the runway heading. Contours produced by aircraft arriving at an airport are usually straighter and narrower than departure contours, which often show bulges or lobes corresponding to turns away from the runway heading shortly after takeoff. At an airport with intersecting or multiple runways and operating patterns, the number, complexity and variability in aircraft flight paths tend to obscure the basic shapes of noise contours for individual runways. In such cases, noise exposure contours for the airport as a whole tend toward broader shapes.

Noise exposure gradients (rates of change of noise exposure with distance from runway ends) on

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[29] For example, ARTSMAP is a commercial software package intended for retrospective use only. At airports with access to information produced by FAA's ARTS III surveillance radars, ARTSMAP replaces assumptions about aircraft operating conditions with information developed from position reports made by aircraft transponders during actual operations.

the order of a thousand feet per decibel are common at large airports. In such cases, uncertainties of fractions of decibels in predicted noise levels may lead to mis-classification of the noise exposure of many city blocks.

A.4.7 Sensitivity of Contour Size And Shape to Modeling Assumptions

A.4.7.1Major factors affecting noise contour shapes

The orientations of an airport's runways have a major but not necessarily dominant effect on the shape of aircraft noise exposure contours. At an airport with a complex runway layout, assumed departure and arrival tracks can also have pronounced effects on contour shapes, depending on how they are populated with different types of aircraft at different times of day.

A.4.7.2Major factors affecting contour size

The size of a set of aircraft noise exposure contours is sensitive to more factors than their shape. Two major operational factors affecting contour size are aircraft type and relative proportion of nighttime use. Numbers of operations, especially at large airports, may have a relatively minor effect on relative contour size as compared with flight profiles, stage length, and other factors. Under most conditions, aircraft ground operations do not greatly affect the size of A-weighted noise exposure contours more than a mile or two away from the airport.

A.4.7.2.1 Aircraft type

The proportion of airport operations flown by older (Stage II) aircraft has a major effect on the size of DNL contours. The increasing proportion of Stage III aircraft operations in recent years has been a main factor in shrinking departure contours at many airports. Approach contours are less sensitive to the proportion of Stage II aircraft operating at an airport, since airframe noise may contribute substantially to an aircraft's total A-weighted emissions during approach. Low-frequency noise produced by jet aircraft is more closely related to engine power than to the classification of an aircraft as Stage II or Stage III.

A.4.7.2.2 Fleet mix

All other things being equal, greater proportions of larger (three- and four-engine) jet transports in the fleet serving an airport will lead to larger noise contours. Greater numbers of operations of smaller commuter aircraft (both turboprop and jet) do not generally compensate for their lower noise levels on departures, so that increasing representation of smaller aircraft in an airport's fleet mix does not necessarily expand an airport's noise contours.

A.4.7.2.3 Time of day

The 10 dB nighttime "penalty" incorporated into DNL treats a single nighttime operation as the equivalent of ten daytime operations by the same aircraft. Thus, the 10% of operations that often occur at night at large airports have an effect on contour size equivalent to the 90% of daytime operations. Even small changes in the proportion of nighttime operations can thus have a substantial effect on the size of a set of noise exposure contours.

A.4.7.2.4 Indirect factors

Certain assumptions made in creating a noise model can also affect contour size substantially through their indirect influences on operational factors. These include assumptions about wind speed and direction and air temperature, which affect engine power settings, and hence, noise levels.

A.4.7.2.5 Propagation assumptions

FAA has not published figures on the fundamental precision of the acoustic propagation algorithms of INM. It is unlikely, however, that INM's air-to-ground acoustic propagation algorithms are much more precise than about ±1 dB directly beneath an airplane's flight path. Algorithms in past and current versions of INM that are intended to account for "lateral attenuation" — the absorption of noise in passage over the ground to the side of an aircraft flight track — are considerably less precise. Bias or random errors in these algorithms can lead to mis-prediction of contour size and shape under some conditions.

A.4.8 Manner of Use of INM

INM is a sufficiently complex program that operates on so many variables that it is possible to use the software in more than one way to accomplish the same end. In particular, a program parameter intended by INM developers to model a particular phenomenon may be used as a *de facto* means for modeling a different phenomenon, often for reasons of convenience. Rather than creating a custom flight profile for a particular aircraft type as flown from a particular runway, for example, a user might intentionally instruct the program that the destination of a particular flight was closer or farther than is actually the case. This might provide a conveniently simple method for taking into consideration air traffic constraints that prevent a departure stream from gaining altitude as rapidly as might otherwise be the case.

Likewise, rather than creating a unique noise-power-distance curve to describe the manner of operation of a certain class of aircraft at a particular airport, a user might instruct INM to achieve the same effect by treating the approach and departure noise of a particular aircraft type as though it were created by two different aircraft: one for approaches, and a different one for departures.

From the perspective of engineering expedience, use of INM parameters in ways unintended by its developers may be viewed as no more than a harmless tactic to save time, effort, and cost in creating an aircraft noise exposure model. Such expedients might also permit a complex noise model to execute on an available computing platform.

From other perspectives, however, such uses of INM carry certain disadvantages. Perhaps the most basic of these is directness of application. If there is reason to believe that INM does not operate appropriately on some particular information, is it preferable to correct the information or the algorithm that operates on it, or to manipulate the program into producing a modified prediction by other means? From the perspective of improving INM, it is clear that the only way to make progress in correcting potential deficiencies in the program is by addressing them directly rather than working around them. This is also the case from the longer term perspective of recurring uses of INM at the same airport.

Ultimately, the issue is whether INM is viewed as a means for inferring the size and shape of noise exposure contours from first principles — as intended by its developers — or whether it is simply an elaborate tool for drawing arbitrary shapes resembling aircraft noise contours. In practice, both the imperfections of modeling and measurement of aircraft noise, as well as differing short- and long-term perspectives on modeling purposes, create a gray area in which professional opinions may differ about the appropriateness of various uses of INM.

A.4.9 Limitations of Interpretations of Aircraft Noise Contours

Aircraft noise contours are often presented in the form of sets of detailed concentric closed form curves overlaid on street grids. This creates the impression that the contours are as fixed, precise, and real as the underlying mapping of streets. In reality, aircraft noise contours are mathematical constructs whose size, shape, and position depend wholly on computational algorithms and assumptions. A given set of assumptions will lead to one set of contours, while a slightly different set of assumptions (about numbers, and types and times of day of aircraft operations from particular runways, on varying flight paths, with different stage lengths and flight profiles, under various meteorological conditions) can lead to very different sets of noise contours. Since there are no facts about the future, any set of prospective noise contours is necessarily speculative and arbitrary to some extent.

All interpretations of aircraft noise contours made for purposes of prospective land use planning must take into consideration the uncertainties inherent in modeling aircraft noise that has not yet occurred.

A.5 UNCERTAINTY IN MEASUREMENT AND MODELING OF AIRCRAFT NOISE

All measurement and modeling is intrinsically imperfect, in that no real world measurement can be absolutely accurate, precise, and reliable, and no modeling is free of simplifying assumptions and approximations. Some of the factors that lead to imperfections of measurement and modeling are manageable, while others are not. Factors that introduce uncertainty into field measurements of aircraft noise include the vagaries of atmospheric propagation of sound (*e.g.*, atmospheric gradients of wind, temperature, humidity, and surface impedance in various propagation paths between the noise source and its measurement), calibration of instrumentation, operational variability in noise sources, and many other “nuisance” variables. Factors that can affect the credibility of aircraft noise modeling include the representativeness of a large number of unverifiable modeling assumptions (*e.g.*, numbers, types, flight paths, and stage lengths of future aircraft operations) and the adequacy of propagation calculations. Factors that can affect measurements of attitudes (such as annoyance) include representativeness and size of samples, as well as wording of questionnaire items.

In the best of circumstances, the inevitable uncertainties of measurement and modeling lead to random errors of specifiable size in estimates of quantities such as sound levels in one-third octave bands, noise reductions of structures, positions of aircraft noise contours, percentages of survey respondents highly annoyed, and so forth. Under less benign circumstances, these uncertainties can lead to systematic errors of unknown size. As a rule of thumb, it may be assumed that errors of estimation and measurement of acoustic quantities described in this report are generally on the order of ± 2.5 dB, and that errors of measurement of the prevalence of annoyance are generally on the order of ± 5%.

A.6 FREQUENTLY ASKED QUESTIONS ABOUT THE NATURE OF MEASUREMENT AND MODELING

The following subsections answer frequently asked questions about errors of aircraft noise measurement and modeling.

A.6.1 What is Measurement?

Measurement is a means of associating numbers with quantities such that the ordinary mathematical properties of numbers apply to the quantities of interest. The length of a hanging spring, for example, increases as the weight suspended from it increases. The deflection of a pointer attached to the spring measures *weight* by pointing to increasingly larger *numbers* as the weight attached to the spring increases.

A.6.2 What is Modeling?

In the present sense, "modeling" is the process of creating a computer simulation of real world phenomena for purposes of efficiently characterizing the effects of varying assumptions on model predictions. The basic rationale for modeling is cost-effectiveness: since the real world phenomena of interest are too expensive or otherwise inconvenient to characterize directly, a computer-based model of the phenomena is studied instead. The gross behavior of the model — its treatment of major influences on the phenomena of interest, its sensitivity to factors affecting the modeled real world phenomena, and so forth — is intended to resemble the phenomena of interest at a level of detail adequate to provide useful insights.

A.6.3 What is Error?

In the context of the present discussion, error is a technical term that describes a difference between one or more estimates of the numeric value of a quantity. The term does not carry any connotation of intentional or unintentional fault or mistake.

A.6.4 What is Error of Measurement?

Error of measurement is inescapable. No form of measurement, whether of length, weight, economic activity, political preferences, or aircraft noise, is ever error-free. Although more elaborate and costly measurement procedures may produce smaller errors, no amount of money can purchase perfectly error-free measurements. For most practical purposes, what matters is not whether a measurement system is perfect or imperfect, but whether the measurements it produces are adequate to support whatever decisions are made on their basis. It is therefore helpful to understand not only the nature of errors of measurement, but also the purposes for which the measurements are made in the first place.

A.6.5 What is Error of Estimation?

"Error of estimation" is a statistical term that refers to the probability that a given estimate lies within a certain interval about a true (but unknowable) exact value. Just as no measurement can ever be perfect, no prediction produced by a software model of long-term aircraft noise levels can be perfect. The statistical term "error of estimation" is sometimes borrowed to describe the inevitable discrepancies between modeled and actual quantities.

Each of the acoustic propagation effects modeled by INM has some associated error, ranging from fractions of a decibel to several decibels under differing conditions. For example, predictions of sound exposure levels at points on the ground directly beneath and relatively close to flight tracks can often be made to agree within a decibel of physical measurements, whereas prediction of sound exposure levels to the sides of flight tracks can be considerably greater.

A.6.6 What is a Confidence Interval?

A confidence interval is a range of values that has a high probability of encompassing a true ("population") value of some parameter. Different sets of measurements ("samples") of the same quantities virtually always differ from one another to some degree for various reasons. For example, average aircraft noise levels observed at the same point near a runway will almost certainly differ from one day to the next. A 90% confidence interval on the mean of a large set of such daily observations encompasses 90% of the daily values. To say that the 90% confidence interval about a mean noise level of 80 dB is 5 dB wide is thus to say that the means of 90% of all sets of measurements of this average noise level will lie between 75 and 85 dB.

The width of a confidence interval depends in large part on (the square root of) the number of observations on which it is based. All other things being equal, small numbers of observations will produce wide confidence intervals, while large numbers of observations will produce narrow confidence intervals. By itself, a wide confidence interval about a data point suggests only that relatively few measurements have been made of its value, not that the underlying variable is somehow incapable of supporting informed decision making.

A.6.7 What are Error Bars?

Error bars attached to data points in charts and graphs are visual indications of the extent of some measure of uncertainty. Plotting a data point with associated error bars serves as a reminder that the point is not the result of a measurement of infinite precision. Figure 77 illustrates error bars plotted for both the independent variable and the dependent variable for a hypothetical data point.[30] The ends of the error bars are often used to indicate the upper and lower bounds of confidence intervals. The interval between the upper and lower bounds of error bars need not necessarily be a well defined confidence interval. Charts and graphs are sometimes marked with upper and lower bounds of the envelope of all observations within a data set, or with even less formal ranges of values (such as a range of typical values).

A.6.8 Why Are Simplifying Assumptions Necessary for Modeling?

Computer models of real-world phenomena are necessarily simpler than the phenomena themselves. This simplification is necessary both for tractability of calculation, and also because a software model as complex as the modeled phenomena would be both unwieldy and uneconomical. A good software model seeks a balance between excessive and insufficient complexity in its algorithms; between the cost of its construction and use and the savings it yields in study of model rather than real-world behavior; and between accuracy and precision of prediction and the burden it imposes on users for detailed input information.

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[30] When it is desirable to emphasize errors of measurement on **both** the abscissa and ordinate, data points are sometimes plotted as ellipses of varying size. The area within an ellipse then serves as a graphic reminder of the uncertainties of measurement associated with each observation. The dashed lines outlining a rectangle in Figure 71 define a region of joint uncertainty of measurement of both the independent and dependent variables.

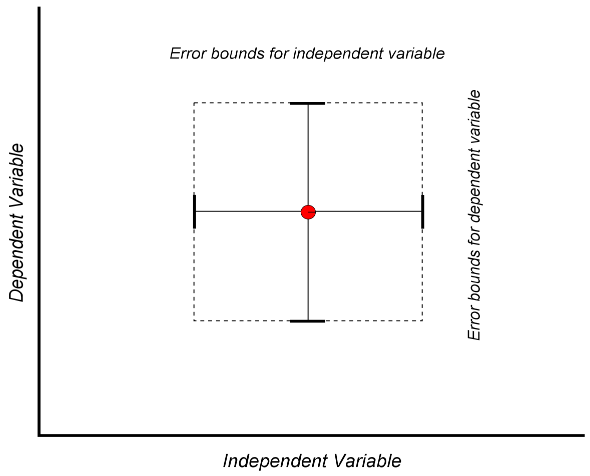

Figure 77 Illustration of the use of error bars to indicate measures of uncertainty for both independent and dependent variables.

A.6.9 What is the Difference between Accuracy and Precision?

Errors of estimation may occur either systematically or randomly. Systematic errors (bias errors) affect the accuracy of a measurement or model prediction, while random errors affect its precision. A pattern of target shots is a common metaphor useful for illustrating the two kinds of errors. The bull's eye represents the "true" value of a measurement. The pattern of shots illustrates the accuracy and precision of the measurement. The shot patterns in the four bull's eyes in Figure 78 represent (from top to bottom and left to right) measurements (or predictions) of low accuracy and low precision, low accuracy but high precision, high accuracy and low precision, and high accuracy and high precision.

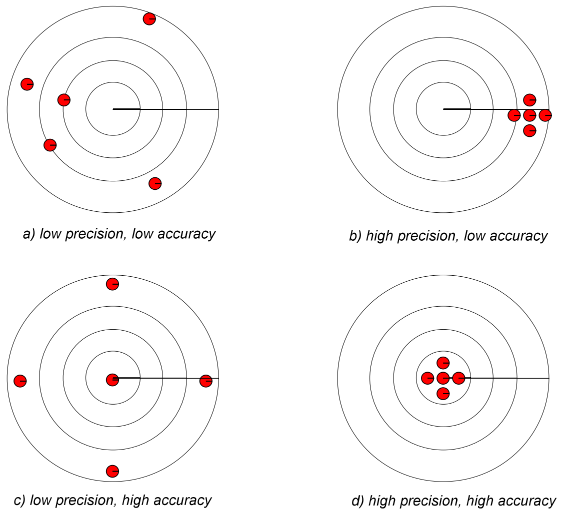

Figure 78 Shot patterns representing four combinations of low and high precision and accuracy in errors of measurement.

In statistical terms, accuracy reflects the difference between the mean of a sample of (say) aircraft noise measurements and the "true" (but unknowable) central tendency. Precision is a measure of the dispersal (variance) of a distribution of measurements. Both the accuracy and precision of measurement of a quantity can be improved by making repeated measurements, as long as the errors of successive measurement are not systematically related to one another. Accuracy and precision of modeling are generally improvable only through more sophisticated algorithms or more comprehensive input information.

A.7 GENERAL CHARACTERISTICS OF AIRCRAFT NOISE AS HEARD NEAR AIRPORTS

The character of aircraft noise heard in communities near airports varies considerably with location relative to runways. Figure 79 illustrates the areas in which three forms of aircraft noise predominate. Table 25 summarizes the general characteristics of these forms of aircraft noise.

In the case of Runway 17/35 at MSP, residential areas of Richfield will be exposed primarily to runway sideline noise, residential areas of Minneapolis will be exposed primarily to departure noise, and (mostly) commercial areas of Bloomington will be exposed to overflight noise.

Location with respect to a runway affects the level, frequency content, onset rate, time pattern, duration, and distinctiveness of aircraft noise. In addition to obvious differences between the noise emissions of different aircraft types, factors that affect the character of aircraft noise as heard in different locations include the flight regime and directivity of aircraft noise emissions, the geometry of an aircraft's flight path with respect to an observer, the slant range between an aircraft and an observer, and the path(s) by which aircraft noise reaches the observer.

Table 25 Summary of general characteristics of overflight, sideline, and departure noise. (Specific location with respect to runway influences all characteristics.)

FACTOR	OVERFLIGHT	SIDELINE	DEPARTURE
Frequency content	Broadband, dominated by mid frequencies	Greater low-frequency content than overflights	Little or no high frequency content
Duration	15 - 30 seconds	30 - 60 seconds	60 - 120 seconds
Onset rate	5 - 15 dB/second	5 - 15 dB/second	About 5 dB/second
Decay rate	5 - 15 dB/second	Strongly dependent on distance	Very slow decay rate
Time history	Roughly symmetric "haystack" with clear 10 dB-down points	Often skewed toward greater duration after peak	Multiple peaks common; 10 dB-down points may be difficult to discern
A-weighted maximum level	Generally greatest	Intermediate	Generally lowest

A.8 DESCRIPTION AND EXAMPLES OF OVERFLIGHT, RUNWAY SIDELINE, AND DEPARTURE NOISE

Figure 80 locates the two sites at which the overflight and sideline noise measurements described below were made.

A.8.1 General Characteristics of Overflight Noise near MSP

Figure 81 illustrates the sound pressure levels, frequency content and time history of a typical departure from Runway 30L at MSP, as heard at a point in northeastern Richfield approximately 4,200 feet to the northwest of the end of the runway. The lower panel of Figure 75 shows the time history of

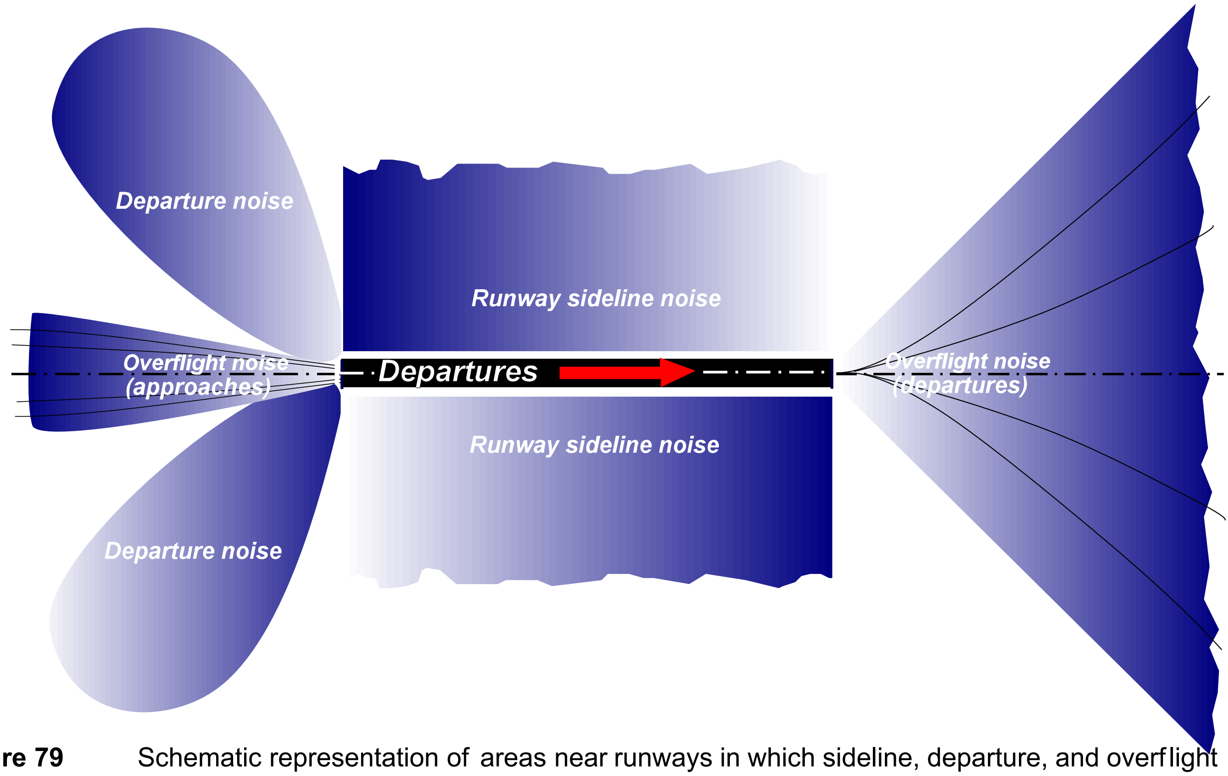

Figure 79 Schematic representation of areas near runways in which sideline, departure, and overflight noise predominate.

the overflight. The passage of time is represented from left to right on the horizontal axis. The A-weighted sound level of the overflight is represented on the vertical axis.

As the aircraft approaches the measurement point, its A-weighted sound level begins to rise from the ambient noise level of about 60 dB (at about 13:19:45) to a maximum of about 88 dB (at about 13:20:22). As the aircraft's flight path continues beyond its point of closest approach to the measurement site, its level decreases to the ambient noise level (at about 13:20:30). The overflight noise remains within 10 dB of its maximum level for about 15 seconds.

Aligned with the same time scale as the lower panel of Figure 81, the upper panel illustrates how the acoustic energy of the overflight is distributed in frequency. Instead of quantifying sound levels in A-weighted units (as in the lower panel), the vertical axis of the upper panel shows sound levels in individual one-third octave bands, coded as colors. Reds, oranges and yellows in the upper panel represent higher sound levels, while blues and greens represent lower sound levels. Thus, the brightest reds and yellows, marking the highest sound levels at frequencies between about 200 and 1,000 Hz, occur at about the time of the A-weighted maximum level.

Figure 76 combines the information presented in the two panels of Figure 75 into a single,

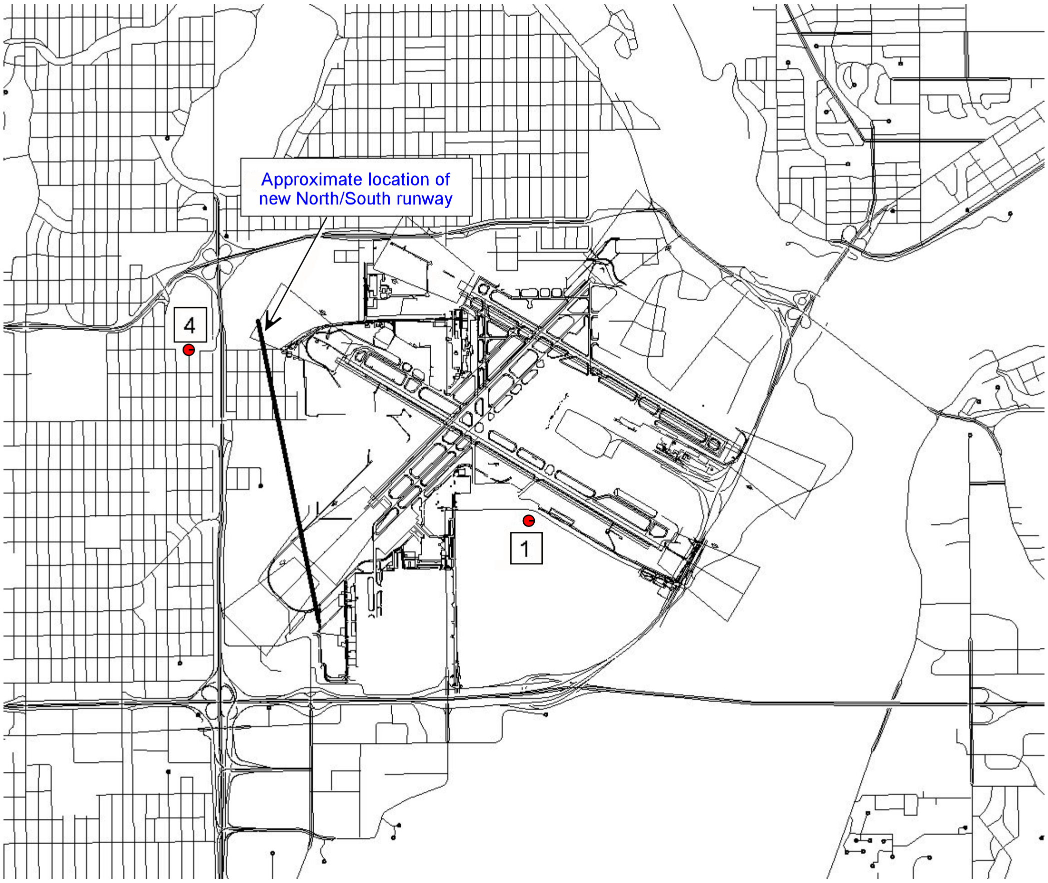

Figure 80 Locations of two aircraft noise measurement sites with respect to MSP.

three-dimensional view. Thus, the series of minor peaks evident in the early part of the time history (lower panel) of Figure 81 are represented as ridges and valleys on the left hand side of Figure 76. As the aircraft approaches the measurement point more closely, the energy in all frequency bands (represented as elevation in Figure 82) rises, to a peak in the vicinity of 13:20:05. As the aircraft flies away from the measurement point after about 13:20:10, the energy in the higher frequency bands (above about 630 Hz) falls off more quickly than in the lower frequency bands.

A.8.2 General Characteristics of Runway Sideline Noise near MSP

Figure 83 illustrates the sound pressure levels, frequency content and time history of a typical takeoff roll of a departing aircraft on Runway 30L at MSP, as heard at a point approximately 1,000 feet to the northwest of the side of the runway. The formats of the graphics in the two panels of Figure 83 correspond to those of Figure 81. Figure 84 combines the information presented in the two panels of Figure 83 into a single, three-dimensional view.

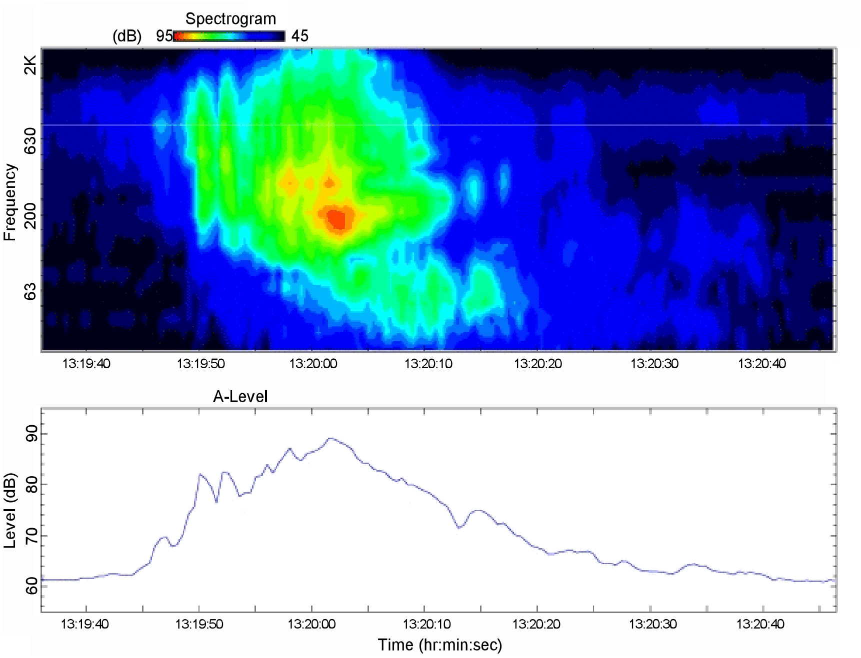

Figure 81 Characteristic time history (lower panel) and spectrogram (upper panel) of an aircraft departure from MSP, as heard in northeastern Richfield (see text for explanation of appearance of figure).

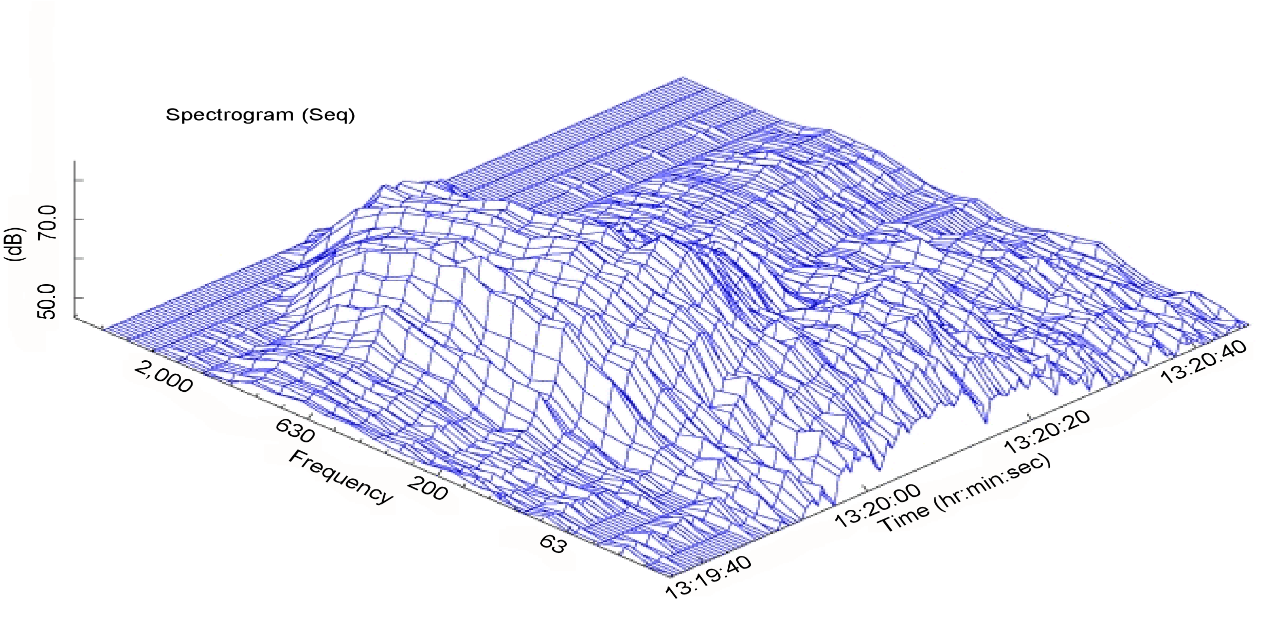

Figure 82 Combined three-dimensional view of time, amplitude, and frequency content of aircraft departure shown in Figure 75 (see text for explanation of appearance of figure).

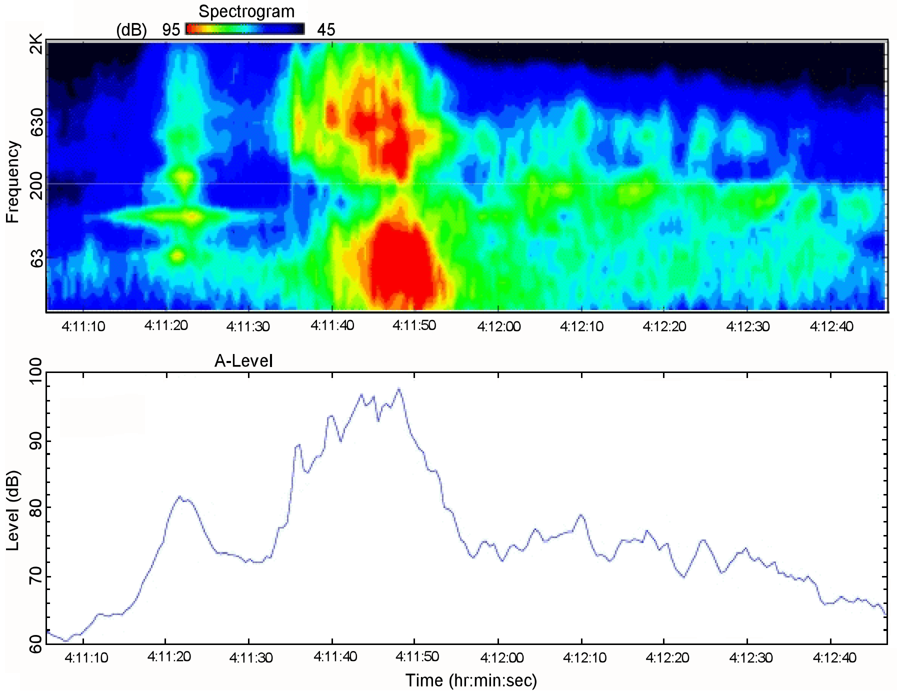

Figure 83 Characteristic time history (lower panel) and spectrogram (upper panel) of aircraft takeoff roll at MSP, as recorded approximately 1,000 feet to the side of the runway (see text for explanation of appearance of figure).

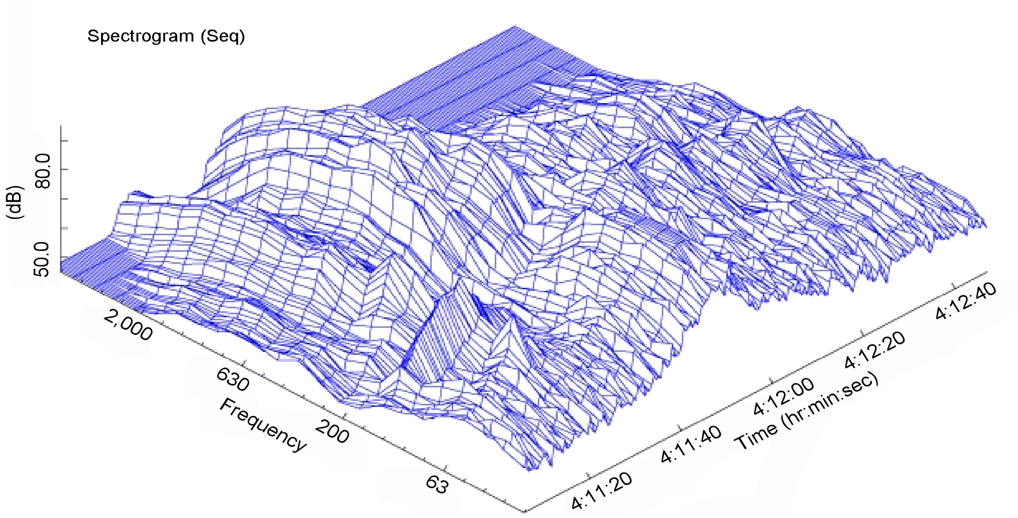

Figure 84 Combined three-dimensional view of time, amplitude, and frequency content of aircraft takeoff roll shown in Figure 77 (see text for explanation of appearance of figure).

Runway sideline noise is considerably less variable in level at a given point on the ground than overflight noise for several reasons:

> Sideline noise is generated by aircraft operating within a few feet of the runway centerline, whereas the slant range from a given point on the ground to airborne aircraft can vary greatly due to complex maneuvering;
>
> Aircraft attitudes and configurations (control surfaces and engine power settings) are less variable for ground operations than for overflights; and
>
> Since slant ranges from runway centerlines to points along runway sidelines are relatively short and constant with respect to ranges from flight paths to the same points on the ground, perturbations of noise levels by long-range acoustic propagation effects are correspondingly lesser.

A.8.3 General Characteristics of Departure Noise

Aircraft departure noise is characteristically described in complaints as a long duration, dull rumbling sound with gradual onset and offset times. Low-frequency noise produced by aircraft departures and other ground operations is not only audible at long ranges, but can also cause secondary emissions (rattling sounds of household paraphernalia) inside residences under some conditions. A- and C-weighted time histories of so-called "backblast" noise show the long duration (approximately two minutes) and double-peak structure frequently observed behind departing aircraft. The second peak is usually attributed to the lesser attenuation of the air-to-ground propagation path after the aircraft becomes airborne than of the ground-to-ground propagation path earlier in the takeoff run. Even though the aircraft is receding rapidly from the measurement point during the departure, its noise level does not decrease as 20 log (distance). Figure 85 shows the return of low-frequency energy in the second peak, about one minute and forty seconds after the start of takeoff roll. Figure 86 is a spectrogram of the aircraft noise event depicted in Figure 85.

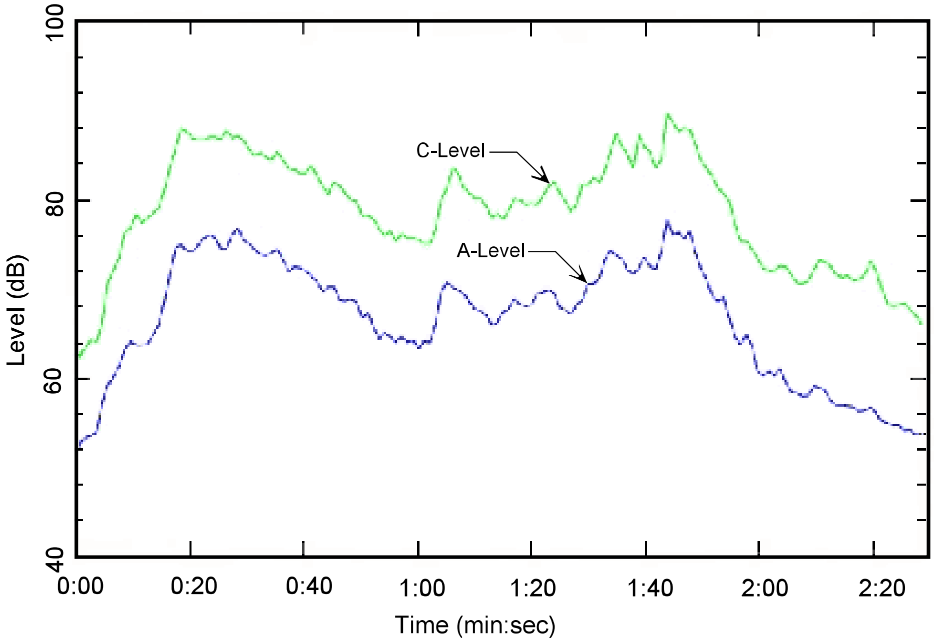

Figure 85 A- and C-weighted time histories of jet aircraft departure measured approximately 1.5 km behind a runway.

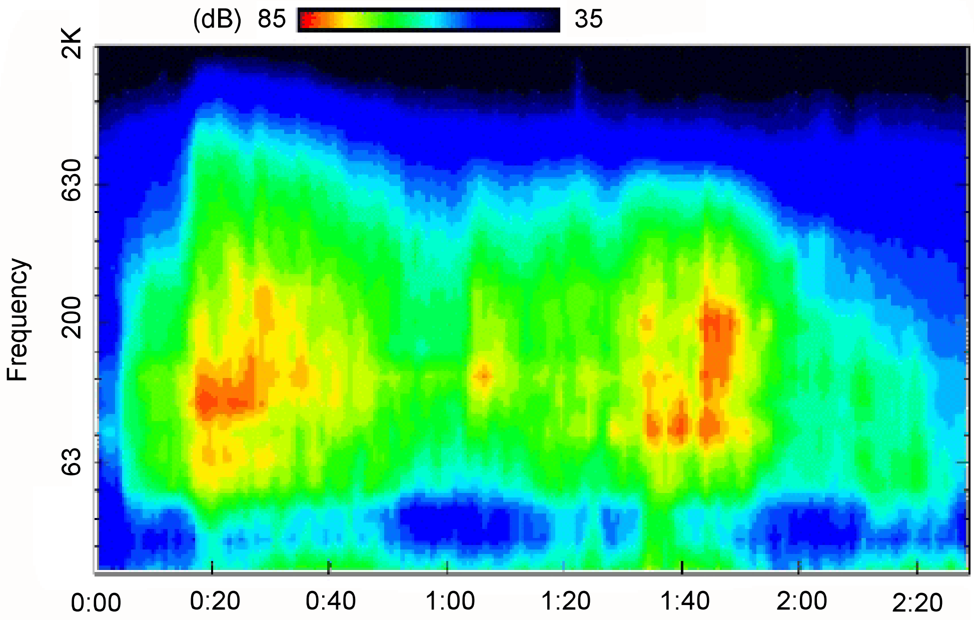

Figure 86 Spectrogram of jet aircraft departure at a point approximately 1.5 km behind a runway.

APPENDIX B REVIEW OF TECHNICAL LITERATURE ON LOW-FREQUENCY NOISE EFFECTS

B.1 SUMMARY OF LITERATURE REVIEW

Except as noted, this section accepted by Expert Panel.

The following conclusions may be drawn from the literature reviewed in this Appendix:

> The primary effect of low-frequency aircraft noise on residential areas near runway sidelines is annoyance due to "secondary emissions": rattling noises and vibration of windows, doors, and household paraphernalia.
>
> Loudness level contours (such as those of Stevens Mark VII) provide a reliable indication of the loudness, noise rating, and direct annoyance of sounds in the low-frequency range of current interest.
>
> People may become aware of low-frequency sound pressure in the octave from about 40 to 80 Hz at sound levels on the order of 70 dB as a sensation of chest vibration. The sensation itself has no adverse physiological consequences.
>
> Levels of aircraft noise in the 25-80 Hz one-third octave bands are in the high 80 to low 90 dB range at low elevation angles and runway sideline distances of about 1,000 ft. Aircraft source spectra contain relatively greater amounts of low-frequency acoustic energy at points closer to the start of takeoff roll than at points successively greater in distance from the start of takeoff roll.
>
> For purposes of predicting sideline propagation of low-frequency aircraft noise from runway centerlines to points on the ground one or two miles distant, geometric ("inverse square) spreading of acoustic energy is the only propagation effect of major concern.
>
> Prediction of low-frequency noise levels produced by aircraft operating on or near the ground requires direct measurement to augment currently available computer models.
>
> Current practical methods for reducing transmission of low-frequency noise into residences are limited in their ability to make substantial improvements. Nevertheless, every possible use should be made of existing design guides and noise reduction prediction models for improvements in low-frequency noise reduction.
>
> Other noise mitigation methods that may be useful in some circumstances include land use planning, use of residential building construction or components designed to minimize rattle, and use of airport operations procedures that minimize low-frequency noise from ground operations.

B.2 INTRODUCTION

This Appendix summarizes the more relevant portions of a large technical literature on low-frequency noise and its effects on people and structures. Many of the U.S. contributions in these technical fields were sponsored by federal agencies including FAA, NASA, the U.S. Air Force and Army, and the Twin Cities Mining Research Center of the former Bureau of Mines. These agencies were concerned with effects of the low-frequency acoustic energy of sonic booms and blast sounds of artillery and mining operations. The technical literature on low-frequency noise effects also includes basic studies of the effects, abatement and control of industrial and other sources of low-frequency noise, such as large power plants.

This literature is reviewed in six areas:

Properties and effects of low-frequency noise on people;

Building response to noise-induced vibration;

Models for perception of noise-induced vibration of structures;

Low-frequency aircraft noise source characteristics;

Aircraft noise propagation;

Other aircraft noise propagation effects;

Reduction of low-frequency aircraft noise into residences; and

Mitigation of low-frequency aircraft noise impact.

B.3 PROPERTIES AND EFFECTS OF LOW-FREQUENCY NOISE ON PEOPLE

The major properties and effects of low-frequency noise as experienced by people at levels germane to the present discussion are:

Loudness
Annoyance (including annoyance of rattle induced by building vibration)
Body vibration
Detection and annoyance of building vibration

This subsection reviews direct responses to low-frequency noise as described in general terms by Johnson, 1976; CHABA, 1977; Broner, 1978; Inukai, Taya, Miyano and Kuniyama, 1986; Berglund, Hassmén and Job, 1996; Nakamura and Inukai, 1998; and Fidell, Silvati, Pearsons, Lind and Howe, 1999.

Major studies in this area have addressed low-frequency noise from the following scenarios:

Jet aircraft and helicopters (Kryter, 1985; and Fidell, Silvati, Lind and Pearsons, 1999a).

Artillery, mining and quarry blasts (Siskind, Stachura and Radcliffe, 1976; Schomer and Averbuch, 1989; Schomer, 1978). (High-energy impulsive sounds are composed primarily of low-frequency energy, which can induce rattle and vibration in buildings comparable to that caused by low-frequency aircraft noise. The annoyance of high energy impulsive sounds is therefore comparable in some ways to that produced by aircraft ground operations.)

Heating and ventilating systems (Blazier, 1991; Waye, Benton, Leventhall and Rylander, 1996).

Miscellaneous industrial noise sources (Nakamura and Tokita, 1981; Gottlob, 1998; Jakobsen, 1998; and Brooks, 1999).

Railways and other ground transportation elements (Passchier-Vermeer, 1998).

Sonic booms (Borsky, 1965; Hubbard and Mayes, 1967; Stanford Research Institute, 1967; American National Standards Association, 1986; Plotkin and Sutherland, 1987; Brown and Sutherland, 1992; and Leatherwood and Sullivan, 1994).

Wind turbines (Stephens, Shepherd, Hubbard and Grosveld, 1982; Shepherd, Grosveld and Stephens, 1983; Kelley, 1987; Wyle Laboratories, 1988).

B.3.1 Loudness

Loudness, perhaps the most basic property of low-frequency noise, is the characteristic of sound most closely related to its physical intensity. The loudness of a sound is sensitive to its frequency content. At commonly experienced sound levels, a low-frequency sound is perceived as less loud than a high-frequency sound of the same sound level. Well-established testing methods make it possible to reliably determine contours of equal loudness on a two-dimensional mapping of the level and frequency for any sound. Figure 87 illustrates the equal loudness contours provided by an international standard (ISO R226, revised 1987). A U.S. standard (ANSI, 1980) describes a comparable set of equal loudness contours.

Continuing interest in methods for assessing effects of low-frequency sound has led to development of loudness models at yet lower frequencies. For example, the Stevens Mark VII Loudness Model extends the contours, in part by extrapolation, to 1 Hz, (Stevens, 1972). Stevens' model summarizes the results of two dozen studies published as of 1972. Other investigators, including Møller and Andresen, 1984, Watanabe and Møller, 1990, and Zwicker *et al.*, 1991, have measured loudness in subsequent laboratory studies at frequencies as low as 4 Hz. Results of some of these later studies are compared in Figure 88 with the ANSI, ISO and Stevens Mark VII Loudness contour models (the latter shown by the purple dash/dotted line). The good agreement of the Stevens Mark VII model with the other loudness measures is apparent. Thus, equal loudness contours such as those of Stevens Mark VII provide a useful descriptor of the subjective intensity of sounds within the low-frequency range of current interest.

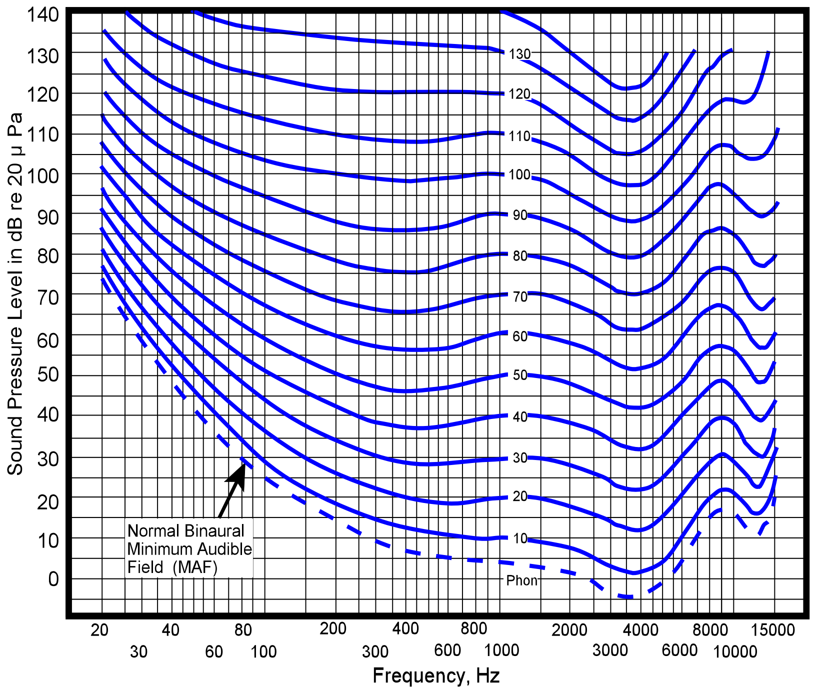

Figure 87 Equal loudness contours at one-third octave band center frequencies, adapted from ISO R226.

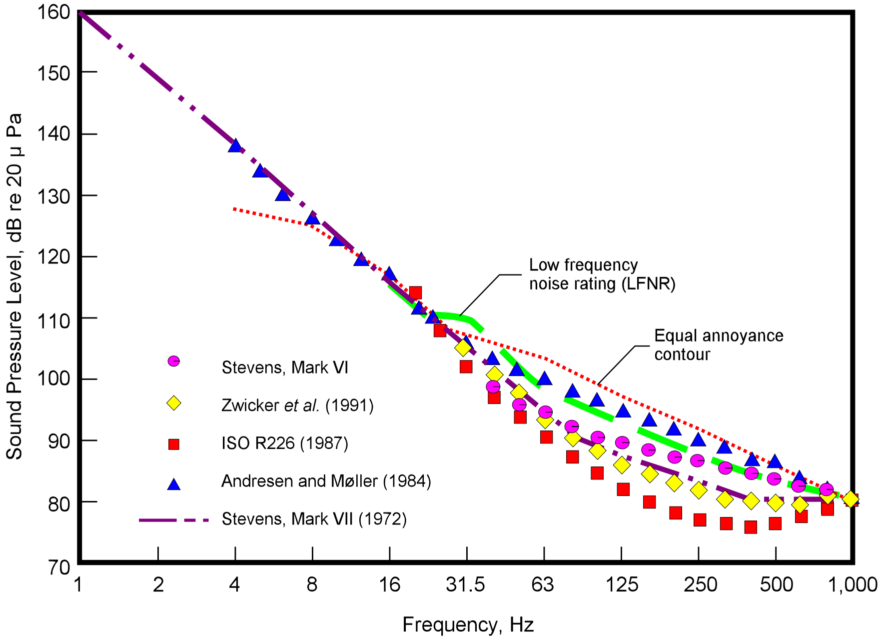

Figure 88 Comparison of equal loudness contours below 1,000 Hz from several investigations for the case where the one-third octave band sound pressure level is 80 dB at 1,000 Hz.

The loudness of low-frequency sounds is not of direct interest for purposes of predicting rattle-induced annoyance for reasons noted in Section 4 of Volume II of this report. One aspect of loudness is noteworthy for present purposes, however: the contours are not parallel at all frequencies. In particular, the difference in sound levels between two adjacent contours of differing loudness is much smaller at low frequencies than at mid to high frequencies. This means that a smaller increase in level of low-frequency sounds makes a greater change in loudness than a comparable changes in sound level of mid- to high-frequency sounds (Fidell *et al.*, 1998). Hence, small changes in low-frequency environmental sound levels can have a greater effect than changes in sound levels of the same magnitude at higher frequencies. Criteria for the acceptability of low-frequency sounds (absent rattle) must therefore recognize this greater subjective sensitivity to changes in low-frequency sound levels than to changes in higher frequency ranges.

B.3.2 Community Response to Low-Frequency Aircraft Noise

B.3.2.1Complaints

Community response to low-frequency aircraft departure noise has been studied in the communities of Millbrae, Hillsborough, and Burlingame near San Francisco International Airport for at least two decades. According to Gilfillan (1999), an initial set of broadband noise measurements was made at SFO by the California Department of Transportation in 1984 (Caltrans, 1984). A 1985 review of this data set suggested that nighttime departures by B-727 aircraft on Runways 01 L/R were a major source of low-frequency noise in areas behind the runways.

Subsequent measurements made at several of SFO's permanent noise monitoring stations in 1986 and 1987 (Connor, 1986; Kesterson, Vondemkamp, and Connor, 1987) confirmed that "The sound of some aircraft departures from Runways 01L and 01R has a character distinct from that of ordinary aircraft noise in that it has relatively more low-frequency content and longer duration." B-727 and B-737 departures were identified as the predominant sources of aircraft noise in areas behind Runways 01L/R.

A review of the 1986/1987 Tracor information completed in 1996 (HMMH, 1996b) identified a C-weighted single-event noise descriptor (a maximum C-weighted sound level of 80 dB) as a reasonable criterion for identifying aircraft departure noise with vibration-producing potential. Further study of low-frequency noise impacts and potential mitigation measures at SFO is presently in progress.

Figure 89 shows the spatial density of complaints (in numbers of complaints per unit time over a six year period) received from neighborhoods behind the main departure runways at SFO. The locations of two complaint foci vary seasonally, but are clearly concentrated in areas corresponding to the major lobes of jet engine noise directionality, at ranges of thousands of meters behind the point of break release. While the size and shape of these concentrations of complaints are clearly affected by local terrain and land use patterns, it is nonetheless clear that the spatial distribution of complaints is strongly influenced by acoustic factors.

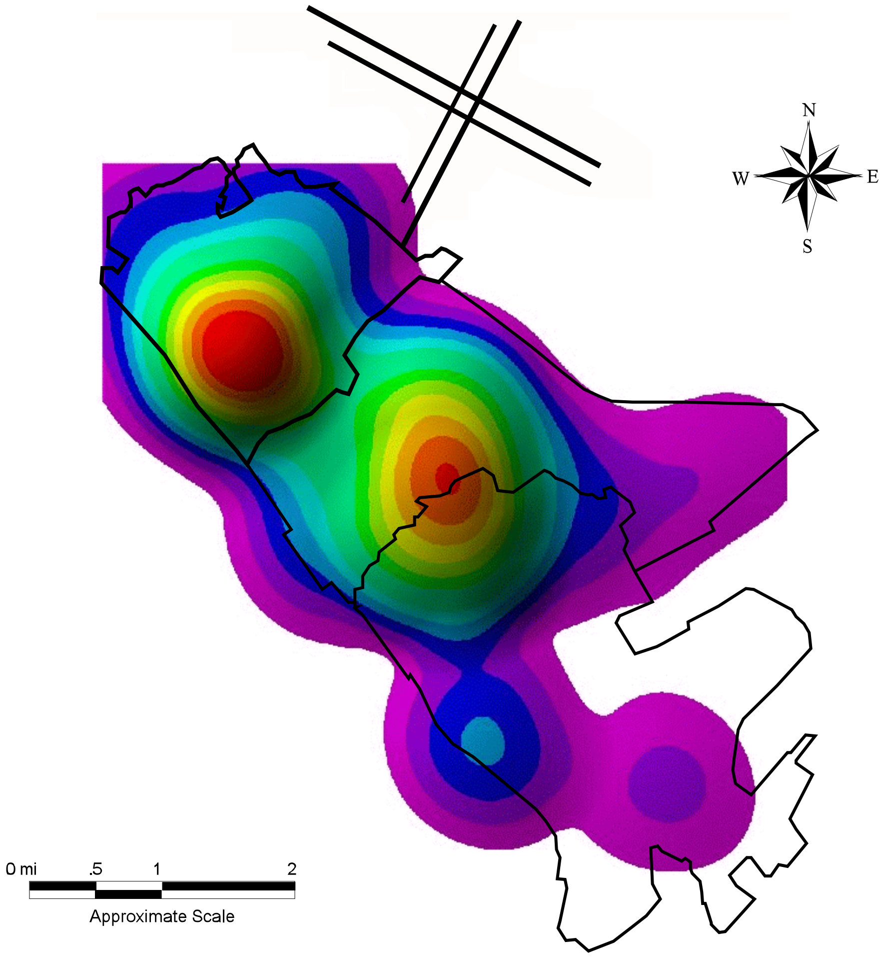

Figure 89 Spatial density of complaints about aircraft departure noise ("backblast") over a six year period, contoured in complaints per square mile per month. (With permission of San Francisco International Airport.)

B.3.2.2Annoyance of runway sideline noise

Fidell, Silvati, Pearsons, Lind, and Howe (1999) describe a social survey of the annoyance of rattle and vibration associated with low-frequency runway sideline noise.[31] Interviews were completed with 644 respondents living in households with LFSL values between 60 and 95 dB in a neighborhood immediately south of Los Angeles International Airport.

Figures 90 through 92 summarize the findings of this study. Figure 90 shows how often respondents were annoyed by rattle produced by aircraft operations. Figure 91 identifies the sources of rattling sounds in the respondents' homes. Figure 92 compares the percentage of respondents who

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[31] Section 4 describes a replication of this study conducted at MSP.

noticed rattle, were annoyed in any degree by rattle, and were highly annoyed by rattle, as a function of outdoor low-frequency sound levels.

Figure 93 shows the locations of respondents who described themselves as highly annoyed by rattling noises produced by aircraft operations with respect to LFSL noise contours. Figure 94 relates the prevalence of annoyance among groups of respondents living in households with similar LFSL values to those values.

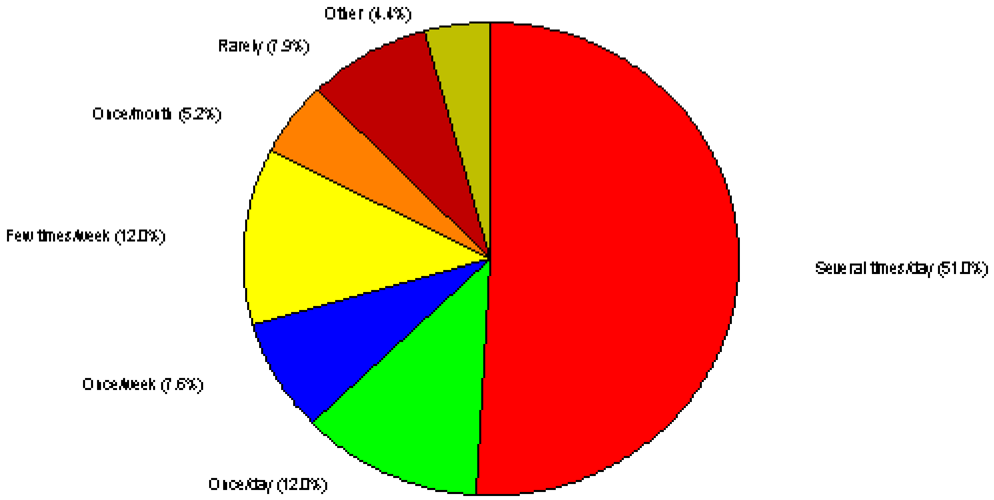


Figure 90 Frequency of notice of rattling sounds in respondents' homes.

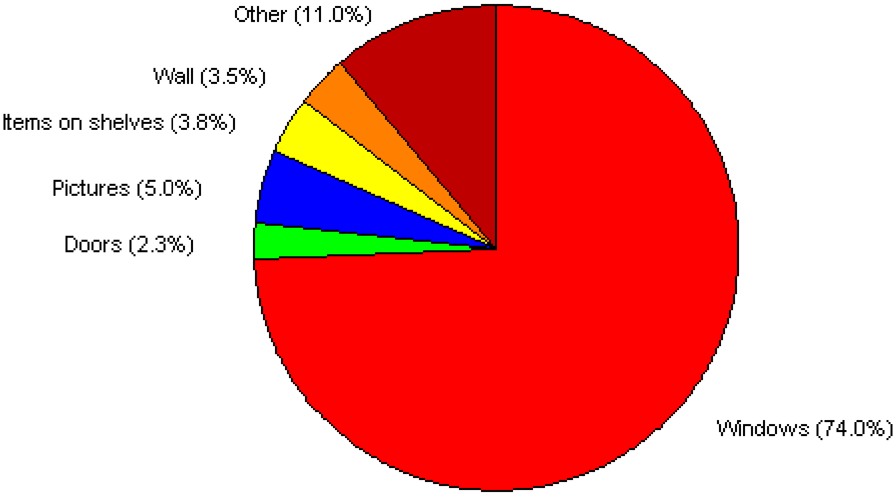


Figure 91 Identification of sources of rattling noises in respondents' homes.

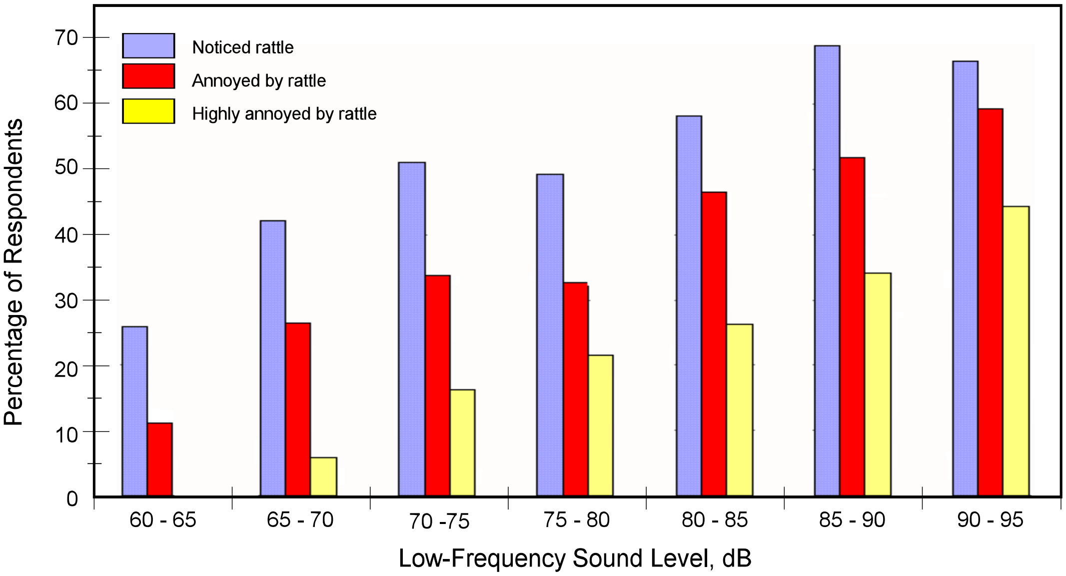


Figure 92 Comparison of percentages of respondents noticing rattle, annoyed in any degree by rattle, and highly annoyed by rattle associated with runway sideline noise.

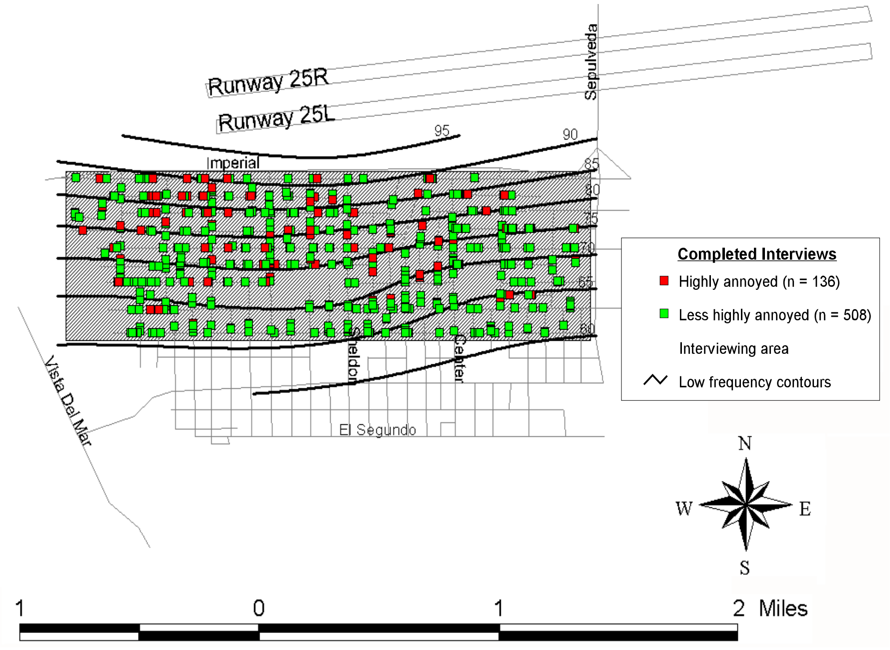


Figure 93 Locations of households in which respondents were highly annoyed (red) and less highly annoyed (green) by runway sideline noise in the El Segundo study at LAX.

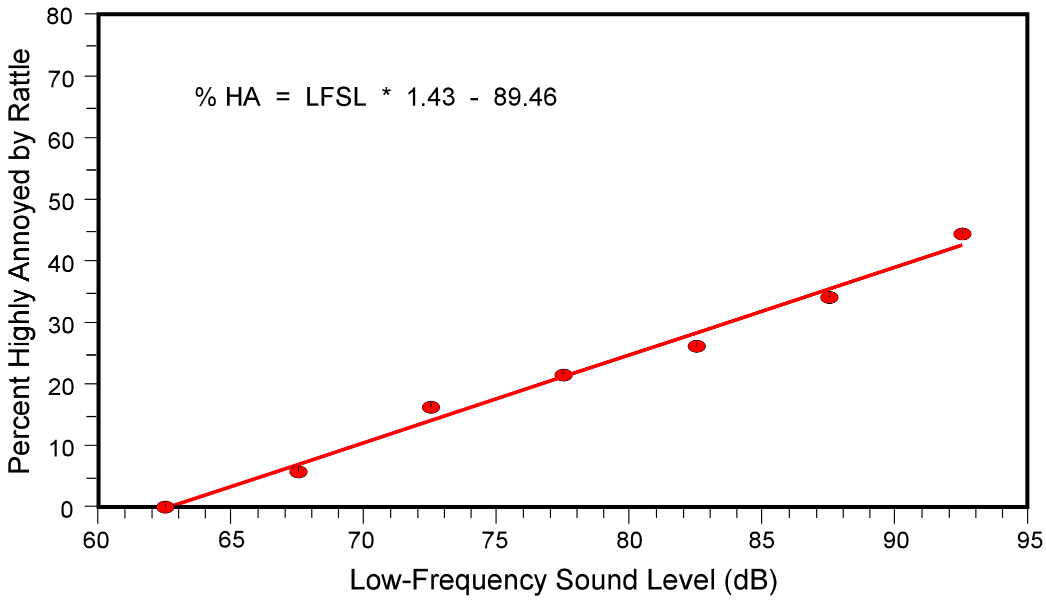


Figure 94 Relationship between outdoor low-frequency sound levels of aircraft ground noise and the prevalence of a consequential degree of annoyance with rattle or vibration in the El Segundo study.

B.3.3 Other Effects of Low-Frequency Sound on People

Many factors other than loudness may affect individual and community response to low-frequency noise exposure. These include situational factors (such as season or time of day); activity interference (such as reading or viewing television); individual differences; and other acoustic and non-acoustic variables, including intensity and frequency of occurrences of low-frequency noise intrusions, expectations, and familiarity with noise sources.

B.3.4 Judged Acceptability of Low-Frequency Noise Exposure

Broner and Leventhall (1983) asked 21 people self-described as particularly sensitive to low-frequency sound to judge the “acceptability” of exposure to 5 Hz bands of noise centered at 25 to 85 Hz. Figure 95 shows the percent of “unacceptable” judgments for this exposure *versus* frequency for three noise exposure levels in each 5 Hz band from 55 to 75 dB. While the results are limited to a small, more sensitive group of subjects, they indicate increased sensitivity to low-frequency sounds at 45 and 85 Hz for this group. The greater subjective sensitivity in this frequency range is consistent with that of three other studies considered next.

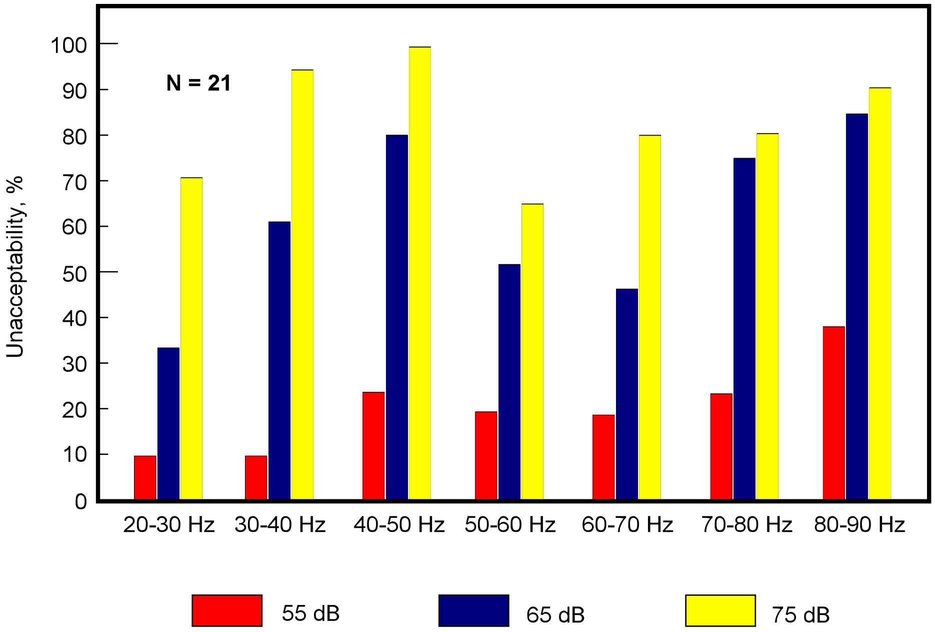


Figure 95 Unacceptability ratings for low-frequency noise exposure for a selected group of 21 low-frequency noise-sensitive subjects (adapted from Broner and Leventhall, 1983).

B.3.5 Chest Wall Vibration

Ollerhead (1968) and Leventhall and Kyriakides (1974) have made direct measurements of vibration of the chest wall in five male and three female subjects due to low-frequency sound excitation. Individual vibration response curves for each of the subjects (the data from Ollerhead, 1968 are averages for two males) are shown in Figure 96. The overall average and one standard deviation for these data are shown in Figure 97.

These data represent the vibro-acoustic transfer function measured on the chest wall as a function of frequency. This transfer function defines the vibration response of the chest wall in units of g (the acceleration due to gravity, approximately 32 feet per second per second) relative to the acoustic pressure on the subject's chest wall. This transfer function is conveniently expressed in decibels re 1 g/20 Pa, where 1 g is a convenient reference acceleration of 1 millionth of a "g," and 20 Pa (microPascals) is the customary reference pressure for sound levels.

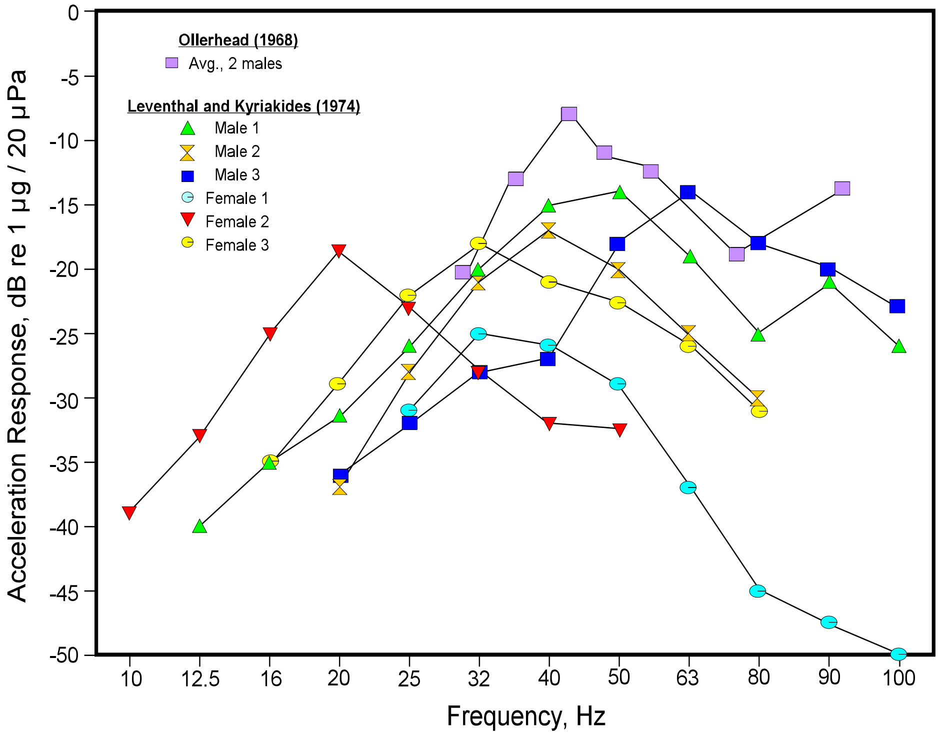


Figure 96 Vibration response of chest wall to acoustic excitation measured on 5 male and 3 female subjects (Ollerhead, 1968; Leventhall and Kyriakides, 1974).

An estimate of the expected threshold of detection of chest wall vibration from low-frequency acoustic excitation of individuals can be derived from these data in the following manner. First, the vibration detection threshold of people exposed to vertical or horizontal mechanical vibration at foot level is estimated from an ISO standard (ISO, 1985 and 1989). This threshold, expressed as the acceleration level in decibels re 1 g, is shown by the solid line in the top panel of Figure 98. Measurements of the decay in vibration of the body from the feet to the chest for mechanical vibration of a standing subject (Goldman and von Gierke, 1969) are then used to estimate the threshold of detection of such vibration at the chest of a person. The resulting estimate is shown by the shaded area in Figure 98.

The low-frequency sound levels expected to cause detectable vibration of the chest can be estimated by combining the latter estimated threshold for detection of chest vibration with the vibro-acoustic response data in the previous figure. This estimate is shown by the shaded area in Figure 99. The range of the estimated threshold reflects the one standard deviation range of the chest wall vibro-acoustic response data shown in Figure 97, and the range for detection of chest vibration shown in Figure 98.

Perspective on these estimates of chest wall vibration may be gained by comparing them with direct measurements of responses of people exposed to low-frequency sound fields, as discussed below.

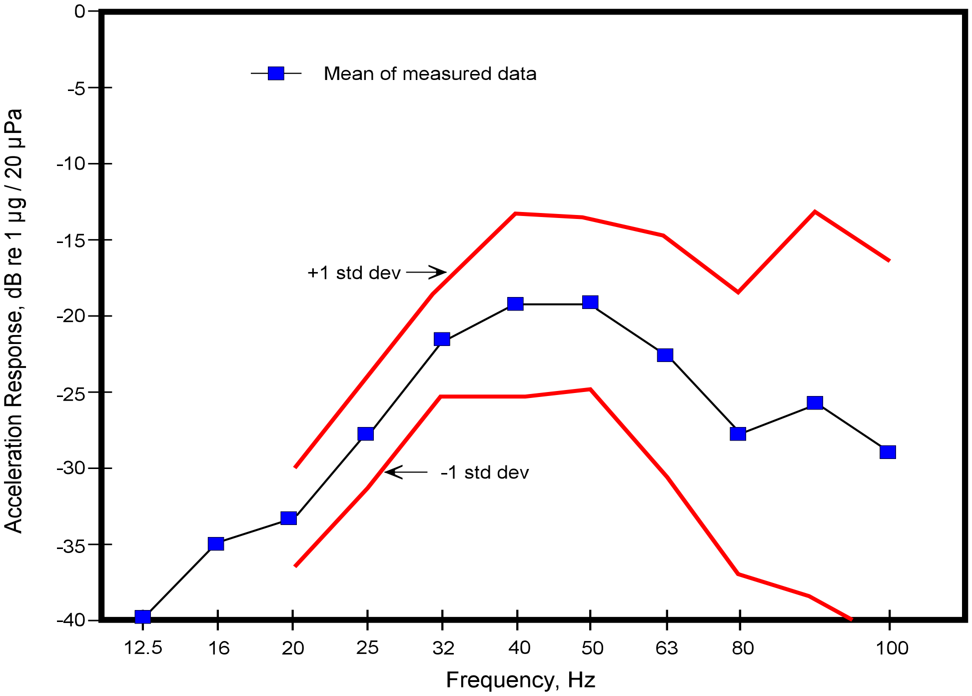


Figure 97 Mean of vibration response to acoustic excitation of chest wall shown in Figure 90, ±1 standard deviation.

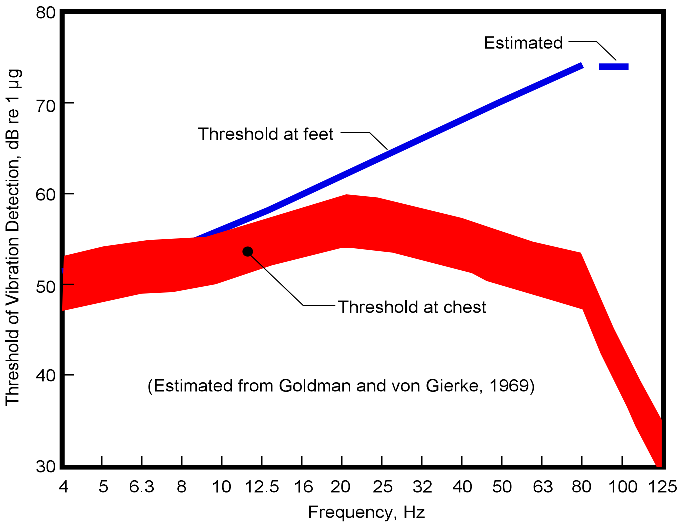


Figure 98 Vibration detection thresholds at the feet and the chest for people based on ISO standards for vibration at the feet (ISO, 1985, 1989) and measured vibration attenuation from foot to chest (Goldman and von Gierke, 1969).

B.3.6 Audibility, Annoyance, and Bodily Sensation of Low-Frequency Noise (Nakamura and

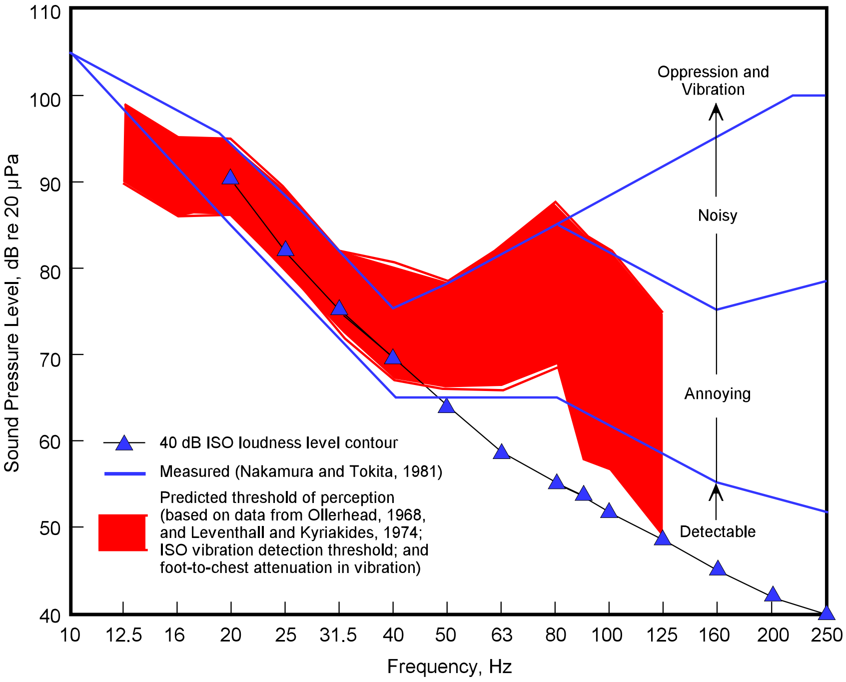


Figure 99 Comparison of predicted threshold for acoustically-induced vibration of the chest based on the preceding two figures and directly measured subjective responses to low-frequency acoustic excitation for 54 subjects (Nakamura and Tokita, 1981).

Tokita, 1981; Tokita and Nakamura, 1981)

In a unique study (Nakamura and Tokita, 1981; Tokita and Nakamura, 1981), 54 students and housewives with normal hearing were exposed in a closed chamber to either pure tone sounds from 5 to 90 Hz, or to one-third octave band sounds from 20 to 630 Hz. Each subject was asked to judge the audibility, annoyance, noisiness, and oppressive feeling or chest vibration of a series of 42 short (20-second) exposures to this low-frequency noise. Approximate boundaries were constructed for each set of judgments, as shown in Figure 99. Agreement is good between the estimated range for detection of chest wall vibration from Figures 96 through 98 and the lower boundary for the measured detection boundary in the data of Nakamura and Tokita.

In summary, several sets of data relating to the low-frequency vibro-acoustic response of the chest show a consistent pattern. The pattern indicates a more sensitive region for such a non-auditory response at one-third octave band levels of about 70 dB (±5 dB) at frequencies of about 40 to 80 Hz. These data do ***not*** suggest any physical trauma from such low-frequency sound, but simply provide a quantitative foundation for chest wall vibration due to low-frequency sound.

B.3.7 Temporal Effects in Exposure to Low-Frequency Sound

Criteria for relatively short-term (*i.e.*, less than 24 hours) temporal integration of exposure to low-frequency vibration (ISO, 1985, 1989; Clevenson, Dempsey, and Leatherwood, 1978) suggest that an equal energy rule provides a useful approximation. Approximately the same response to a 60 minute exposure to an LFSL of 70 dB would be expected as for a 6 minute exposure (1/10 the time) to an LFSL of 80 dB (10 times the intensity but with the same integrated energy). This simplistic model is generally well accepted in standards for community response to environmental sounds (*cf.* American National Standards Institute, 1998). The laboratory study reported in Section 3 of this report confirms its applicability to sounds with considerable low-frequency content.

B.3.8 Response to Combined Noise and Vibration

Several researchers (Sueki, Noba, Nakagomi, Kubota, Okamura, Kosaka, Watanabe and Yamada, 1990; Yamada, Sueki, Hagiwara, Watanabe and Kosaka, 1991) have studied the combined effect of exposure to both low-frequency noise and vibration. Sueki *et al.* (1990) and Yamada *et al.* (1991) documented a pattern of complex interaction between low-frequency noise and vibration. In a study of exposure to noise and vibration from 10 to 80 Hz, Sueki *et al.* found that at high levels of exposure, vibration and low-frequency noise each masked the perception of the other. Annoyance from exposure to both low-frequency noise and vibration was more disturbing than exposure to just one or the other — *i.e.,* their “annoyance” potential was additive. While the noise spectrum involved in this study was not representative of aircraft noise, the frequency range encompassed the range relevant to human response to low-frequency aircraft noise. Thus, these limited data indicate that direct experimental measurement of community response to low-frequency noise exposure may be essential when both noise and building vibration or rattle are involved.

Some limited effort has also been made to define descriptors for exposure of humans to vibration in combination with noise exposure (Passchier-Vermeer, 1998; Passchier-Vermeer and Zeichart, 1998). The social survey by Passchier-Vermeer (1998) of reactions to exposure to aircraft noise and vibration as judged by 22,400 respondents found that:

> The 24-hour A-weighted average noise level (L_{eq24}) was of limited utility as an indicator of vibration annoyance.
>
> Vibration and noise annoyance were reasonably well correlated.

B.4 BUILDING RESPONSE TO NOISE-INDUCED VIBRATION

The direct acoustic effects of low-frequency noise reviewed above are compounded by the vibration of buildings and resultant rattle of building components (*e.g.*, windows) or furnishings (*e.g.*, pictures, mirrors, bric-a-brac, *etc.*). This section summarizes the extensive literature on this topic, including measurements, detection thresholds, interpretive criteria, and effects of such low-frequency noise-induced vibration and rattle.

B.4.1 Measurement of Noise-Induced Vibration in Structures

Studies of noise-induced building vibration have been conducted by NASA, FAA, the U.S. Army, the U.S. Air Force, and the Bureau of Mines. Examples of these studies include:

> For jet aircraft and helicopters: Carden and Mayes, 1970; Langley Research Center, 1976, 1978; Stephens and Mayes, 1979; Hubbard, 1982; Schomer and Neathammer, 1985; Fidell, Horonjeff, Mills, Baldwin, Teffeteller and Pearsons, 1985; Sutherland, 1989; Harris, Miller, Miller, and Hanson, 1998; Fidell, Silvati, Lind and Pearsons, 1999a; and Fidell, Silvati, Pearsons, Lind and Howe, 1999b.
>
> For blast from artillery training or open-pit mining operations: Siskind, Stachura, Stagg and Kopp, 1980a; Siskind, Stagg, Kopp and Dowding, 1980b; Eldred, 1985; and Stagg, Siskind, Stevens, and Dowding, 1984.
>
> For miscellaneous industrial low-frequency noise sources: Tokita and Nakamura, 1981; and Brooks, 1992.
>
> For sonic booms: NASA Langley Research Center, 1967; Benveniste and Chang, 1967; Crandall and Kurzweill, 1968; Sutherland (ed.), 1968; Carden, Findley and Mayes, 1969; Clarkson and Mayes, 1972; Sutherland, Brown and Goerner, 1992; and Sutherland and Czech, 1992.
>
> For wind turbines: Hubbard, 1982.

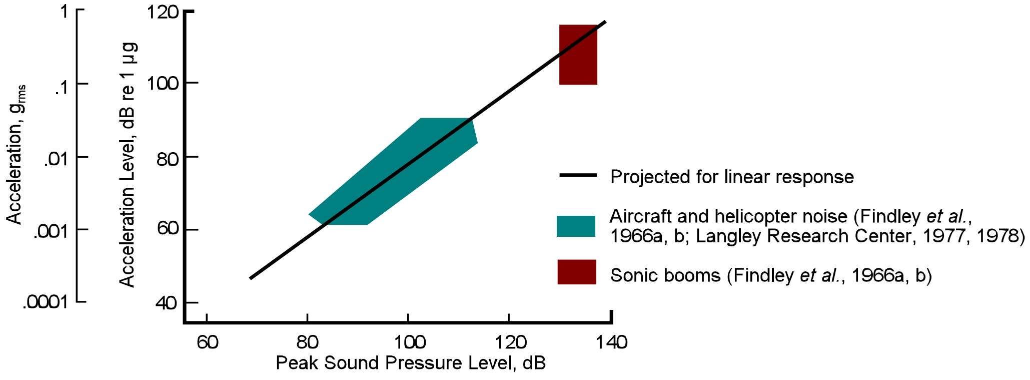
The trend in noise-induced structural vibration response of building components to aircraft, sonic boom, and wind turbine noise established primarily from NASA data (Hubbard, 1982) is shown in the three panels of Figure 100 for walls, floors, and windows, and summarized in Figure 101. The NASA data shown in this figure report only the overall vibration in terms of acceleration relative to the overall peak sound level measured outside the buildings.

It is apparent from the data shown in the top panel of the figure that the measurements from which a general relationship between wall vibration and external sound levels may be discerned have considerable variance. The scatter of the measurements is about 10 dB about the linear trend line relating the acceleration level, in decibels, to the peak sound pressure level in decibels. A similar degree of scatter is observed in a study by HMMH (Harris Miller Miller and Hanson, 1998). This study included measurements of the vibration response to low-frequency aircraft noise on two walls of a residence at a site behind the beginning of takeoff roll at Runway 28 for Baltimore International Airport. In this case, the scatter of the measurements is about 10 to 12 dB about an expected trend line relating the acceleration level, in decibels, to the C-weighted sound level in decibels.

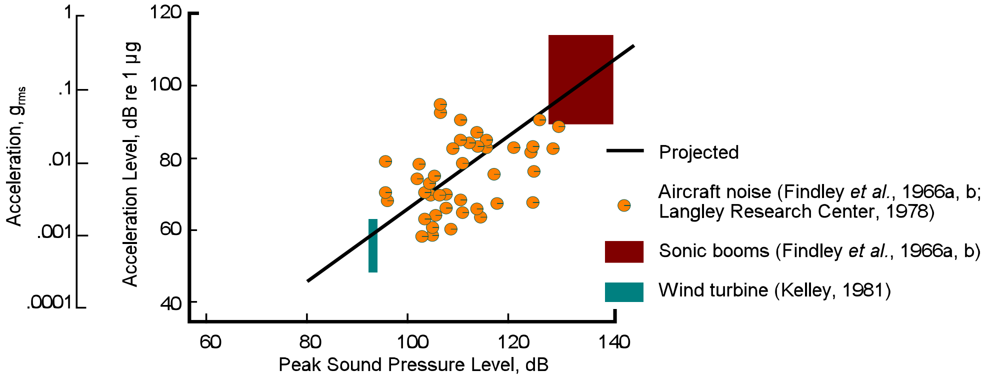
A more detailed description of noise-induced vibration response of (residential) building components is useful for present purposes. In particular, knowledge of the frequency dependence of this noise-induced vibration response is needed to assess the likelihood that the low-frequency aircraft noise will cause building vibration and/or rattle of building components or furnishings. A substantial amount of data is available on measurements of this vibro-acoustic frequency response of building structure and resultant rattle, including the following:

> NASA Langley Research Center studies of building response to aircraft noise and sonic boom (Mayes, Findley and Carden, 1968; Carden, Findley and Mayes, 1969; Carden and Mayes, 1970; Langley Research Center, 1976, 1978; Cawthorne, Dempsey and DeLoach, 1978; Stephens and Mayes, 1979).
>
> U.S. Army Construction Engineering Research Laboratory (CERL) studies of building vibration from artillery blasts and helicopter noise (Schomer and Neathammer, 1985; Schomer, Hottman and Eldred, 1987; Eldred, 1985).
>
> U.S. Bureau of Mines studies of building vibration response to mine blasting operations (Siskind, Stachura and Radcliffe, 1976; Siskind, Stachura, Stagg and Kopp, 1980a; Siskind, Stagg, Kopp and Dowding, 1980b).
>
> Wyle Laboratories studies of building vibration response to rocket noise (Sutherland, [ed.], 1968).
>
> Other studies relating to building vibration response to low-frequency industrial noise (Brooks, 1992) and aircraft noise (Wesler, 1978), and a recent study conducted at BWI airport (HMMH, 1998).

A. Wall responses



B. Floor vertical responses



C. Window responses

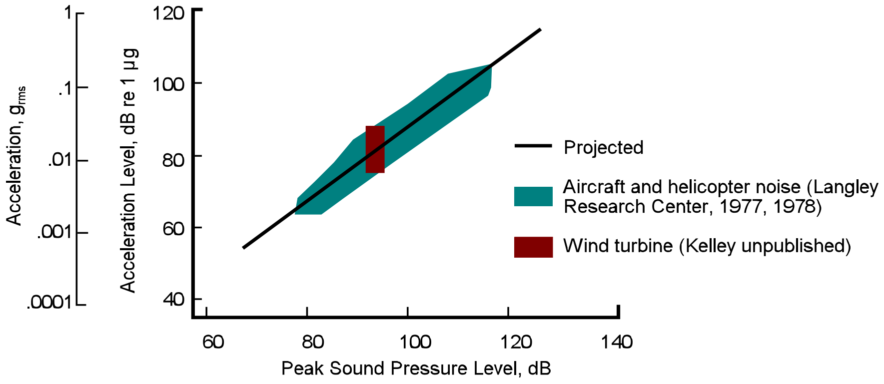
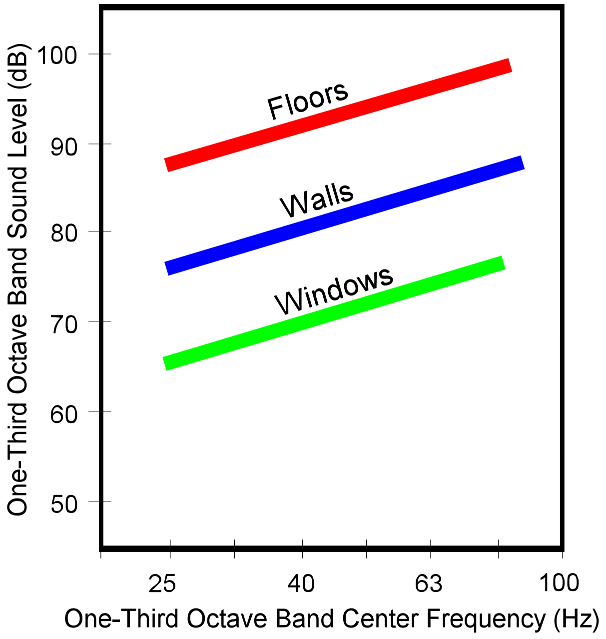


Figure 100 Measured vibration response of residential building walls (panel A), floors (panel B), and windows (panel C) to low-frequency noise from aircraft, sonic booms, and wind turbines. (Figure and data sources cited from Hubbard, 1982.)



Adapted from Figure 9 of Hubbard (1982).

Figure 101 Sound pressure level thresholds for vibration and rattle (after Hubbard, 1982) in the frequency range of current interest.

B.4.2 A Physical Model for the Vibration Response of Structures to Low -Frequency Noise

A simple physical model in useful to illustrate the frequency-dependent vibro-acoustic response character of this response pattern. Such a model is elaborated here for the sake of completeness and for the benefit of interested readers. Others may skip to the discussion of experimental data in Section B.4.3 without loss of continuity.

It has been known since Newton that an object of mass (M) acted on by a force (F) experiences an acceleration (A) proportional to the magnitude of this force and inversely proportional to the mass. In mathematical terms,

$$\text{Acceleration} = \frac{\text{Force}}{\text{Mass}} = \frac{\text{Force}}{(\text{Weight/Acceleration of gravity, g})}$$

The magnitude of the force can be expressed as a pressure (*i.e.*, an acoustic pressure, P) by dividing by the area (S) over which the force (the acoustic pressure) is acting. The weight of the object (*i.e.*, a wall) can also be expressed in terms of the weight, W per unit area, S, as w = W/S. The static acceleration of the mass, indicated by the above expression, must be modified to account for the greater acoustically-driven dynamic or resonance response of a wall acoustically driven at its natural or resonance frequency, in a manner similar to the diaphragm of a drum. This modification is simply made by multiplying the static acceleration response by an acoustic mobility factor, Q. For noise-induced vibration of buildings, this dynamic response multiplier has a maximum value of the order or 5 to 25, depending on the type of structure.

The acceleration response, A, in units of the acceleration due to gravity, g, of a wall acoustically excited by low-frequency noise can be expressed as follows.

$$A(f) = \frac{P(f)Q(f)}{w}$$

Note that both the acoustic pressure, P(f) and the acoustic dynamic response factor, Q(f) depend on the frequency, f, of the acoustic excitation, so that the acceleration response, A(f) also depends on frequency. Note further that by expressing the response in units of the acceleration due to gravity (g), the conversion from mass to weight is inherently included in the above expression for the vibro-acoustic acceleration response, A(f) of a structure to low-frequency noise.

For analytic purposes, it is convenient to express the dynamic acoustic acceleration response in a non-dimensional (scalar) or normalized form as:

$$Q(f) = \frac{A(f)w}{P(f)}$$

The acoustic pressure, P(f) and the surface weight, w, must be expressed in the same units, *e.g.*, lbs/ft^2 (psf), for this normalized expression to be dimensionless.

In decibels, this becomes:

$$10 \log [A(f)\, w/P(f)]^2 = 10 \log [Q(f)]^2$$

B.4.3 Experimental Data on Response of Structure to Low-Frequency Noise.

Experimental data on the vibration response of a 10' x 8' wood-frame residential wall section driven by low-frequency acoustic excitation (Sutherland, Chen and Andriulli, 1968) are shown in Figure 102 in the normalized form indicated by the preceding expression. These response data are presented, in decibels, as a function of frequency relative to the fundamental resonance frequency (about 16 Hz) of the wall. The data are the non-dimensional values of 10 log [A(f)w/P(f)] of the respective one-third octave band values for the mean square acceleration, A(f) and the mean square sound pressure, P(f).

The exterior of the wall was constructed of ¾" x 8" tongue and groove boards over studs covered with tar paper and finished with 1/8" x 12" x 24" asbestos shingles overlapped 1". The interior was constructed of ½" sheet rock with taped joints and mudded nail heads. The total surface weight, w, of the wall was 8.5 psf (Sutherland, Chen and Andriulli, 1968).

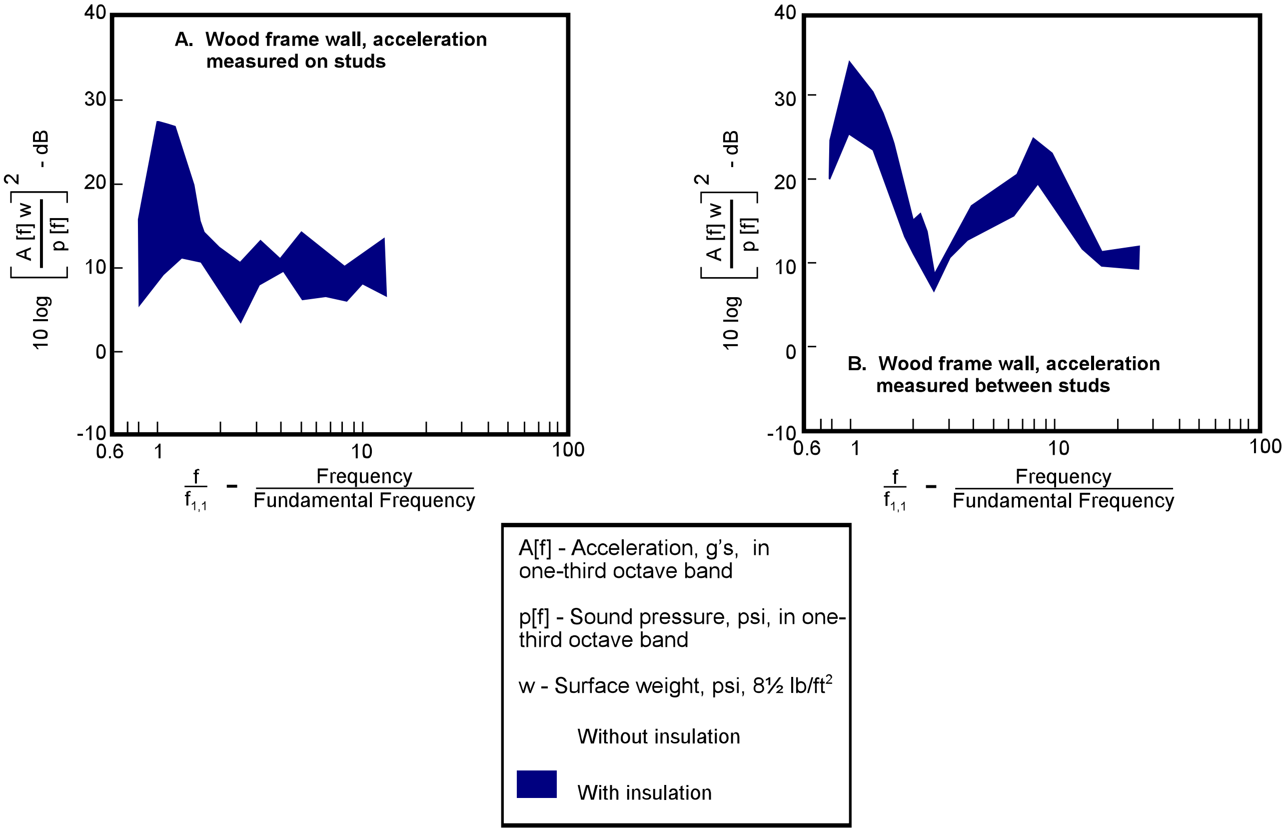


Figure 102 Noise-induced vibration response for residential buildings. (Measurements reported by Sutherland, Chen and Andriulli, 1968.)

The left panel of Figure 102 shows the vibro-acoustic response of the wood stud wall, measured outside the wall over the studs, with and without 2" fiberglass insulation inside the wall. The right panel shows the measurements made outside the wall between the studs with and without insulation. The measurements between the studs indicate the presence of a higher resonance frequency of about 150 Hz for the subsections of the wall between the 16"-spaced studs, as well as the basic resonance frequency of about 16 Hz for the entire wall assembly. *In all cases, the addition of insulation reduced the vibro-acoustic response by about 10 dB at all frequencies.*

Similar structural response data for other types of walls, such as wood frame walls with windows and concrete block walls (see Figure 103) and masonry walls, makes it possible to summarize the key response variables involved in the final expression of Section B.4.2:

the maximum values of the dynamic response factor, $Q(f_o)$, at the resonance frequencies of residential walls of different design;
the fundamental resonance frequencies, f_o, of such walls; and

the typical surface weight, w, of such walls.

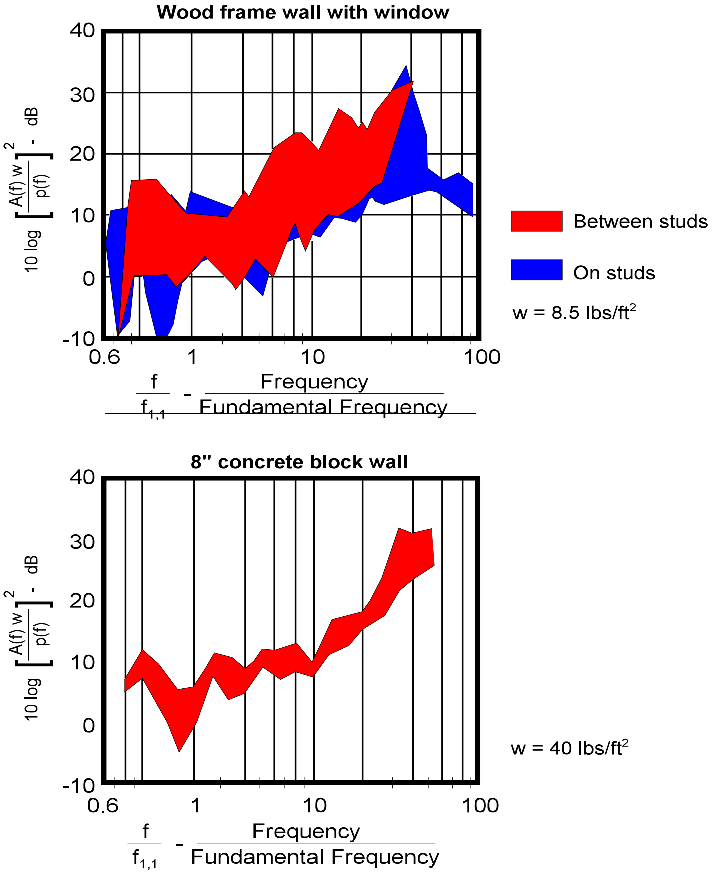


Figure 103 Noise-induced vibration response for residential buildings (continued). (Measurements report by Sutherland, Chen and Andriulli, 1968.)

Table 26 summarizes such numbers based on data published in the literature. Figure 104 summarizes the measured values for the normalized vibration response as a function of frequency for four different wood frame walls. The figure shows the arithmetic average plus or minus one standard deviation from these data for the response parameter, 10 log $[A(f)w/P(f)]^2$.

Table 26 Mean values for building vibro-acoustic response parameters.

		VIBRO-ACOUSTIC RESPONSE PARAMETERS					
		Resonance Frequency (f_o)		Surface Weight (w)		Maximum Acoustic Response (Q(f_o))[B]	
No.	**Building Element**	**Mean (Hz)**	**20 SD[A] (dB)**	**Mean (psf)**	**20 SD[A] (dB)**	**Mean**	**20 SD[A] (dB)**
1	Windows, 2-10', 3/16"	60[a]	2.76[b]	2.35[a]	0.91[b,f]	13.4[h]	5.4[h]
2	Windows, 10-50', 1/4"	15.4[a]	2.76[b]	3.12[a]	0.91[b,f]	13.4[h]	5.4[h]
3	Windows, 50-100', 5/16"	6.2[a]	2.76[b]	3.90[a]	0.91[b,f]	13.4[h]	5.4[h]
4	Brick	12.3[c]	3.30[b]	66.7[c,g]	1.85[b,f]	5.6[h]	3.0[h,e]
5	Concrete block	25.0[c]	2.34[b]	38.0[c,g]	2.50[b]	3.2[i]	3.0[h,e]
6	Wood frame, non-plaster interior (insulated, with and without windows)	15.0[d]	2.50[b,f]	7.20[c,d]	0.91[b,f]	7.1[d]	10.2[i]
7	Wood frame, plaster interior (insulated, with and without windows)	15.0[e]	2.20[b,f]	9.75[c]	0.91[b,f]	5.0[f]	10.0[e]

[A] 20 times the standard deviation (SD) of the log of the log-normally distributed parameter. This parameter, along with its log mean value (specified above) of the log-normal distribution are needed to estimate the probability of occurrence for a given vibration response magnitude (see Sutherland, Brown, and Goerner, 1990 for details of the computational process).

[B] $Q(f_o)$ = maximum dynamic vibration response factor for an acoustically driven structure

$$= \frac{\text{(Structural acceleration, in g's, at resonance frequency, } f_o\text{) (Surface weight, w, psf)}}{\text{(Acoustic pressure, in psf, in same bandwidth, at same frequency)}}$$

The data tabled above are derived from the following sources:

[a] Sutherland, Brown and Goerner, 1990, Table 4-5
[b] Sutherland, 1990, Table 18
[c] Sutherland, Brown and Goerner, 1990, Table 4-2
[d] Sutherland (ed.), 1968 (Appendix A); Eldred, 1985
[e] Estimated
[f] Sutherland, Brown and Goerner, 1990, Table 6-3
[g] Sutherland, 1990, Table 7
[h] Sutherland, 1990, Table 6
[i] Sutherland (ed.), 1968 (Appendix A)

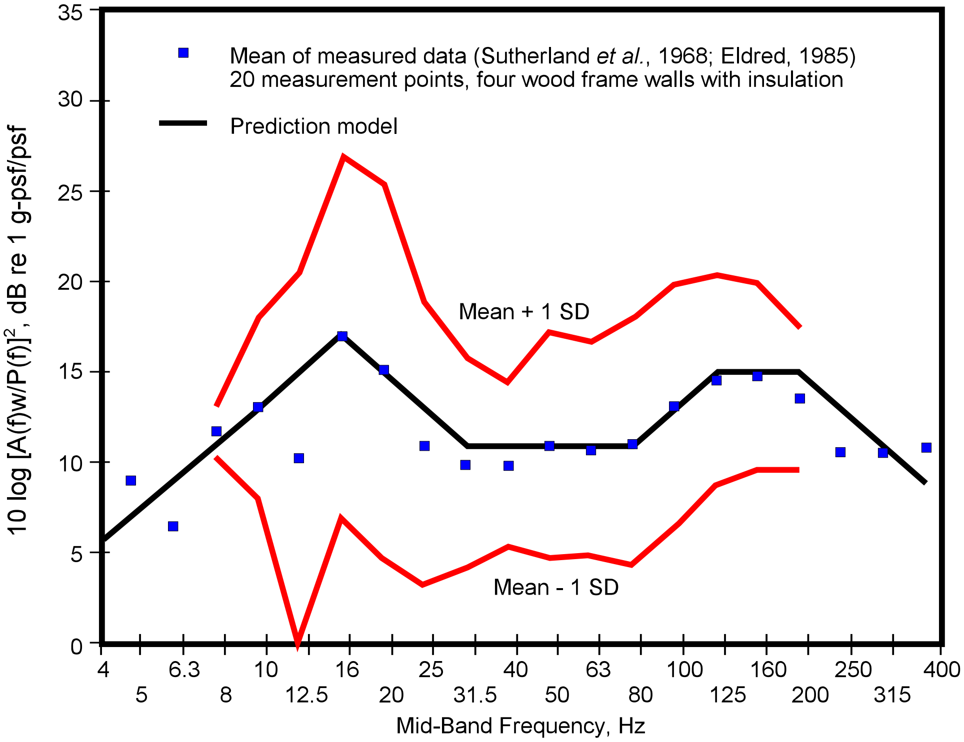


Figure 104 Average vibro-response prediction model for wood frame structure (from data in Figure 96 and Eldred, 1985).

Figure 105 presents the average values for this acoustic response parameter for some of the other structural elements listed in Table 26 in addition to the values for wood frame walls shown in Figure 104. These vibration response parameters for acoustically-driven structure can be considered as prediction models to be used for estimating the vibration response of acoustically-driven structural elements including different size windows, brick walls and standard or conventional wood frame walls with the usual wall board or sheet rock interior as well as wood frame walls with plaster interior. The models illustrated in this figure are based on the type of data presented in Figures 100 through 104 and on more detailed analyses of structural response to sound (Sutherland, 1989; Sutherland, Brown and Goerner, 1990), and draw on the extensive data sources identified in the references listed in Table 26.

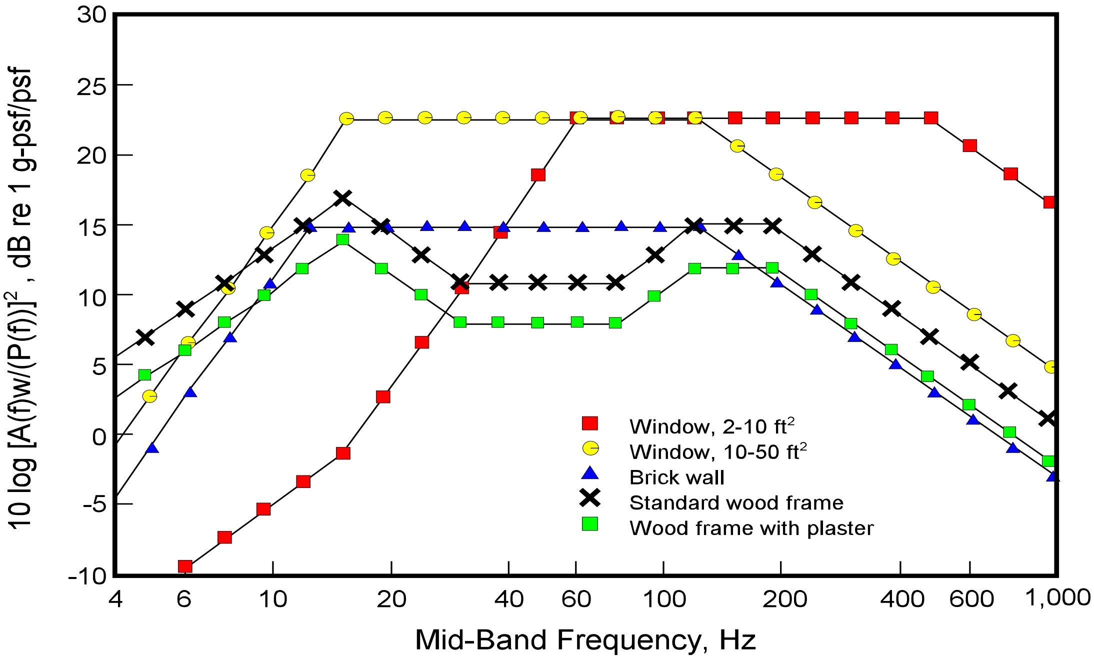


Figure 105 Average prediction model for different types of wall and different sizes of windows.

B.5 MODELS FOR PERCEPTION OF NOISE-INDUCED VIBRATION OF STRUCTURES

This section develops a criterion for detection of low-frequency aircraft noise-induced building vibration by the whole body and through the fingers. The next section addresses the detection of rattle from structure-borne vibration.

The models for estimating noise-induced vibration of residential buildings derived from this review of the literature may be used to develop an alternative to the Hubbard model for vibration detection. This alternative model attempts to account more closely for the frequency-dependent vibration response characteristics of residential building components to low-frequency aircraft noise.

The first step in developing an alternate model is to compare the ISO vibration perception criteria employed in the Hubbard model with other measurements (Goldman and von Gierke, 1961). Figure 100 shows that the latter data on vibration perception is at least 5 to 15 dB higher than the ISO model in the frequency range of 2-80 Hz. Data are also shown in the figure for two studies of tactile perception (through the fingers) of vibration (Goldman, 1957; Verillo, 1962). Figure 100 also shows a suggested criterion for whole body and tactile vibration perception based on a rough average of the ISO, Goldman and von Gierke, Goldman, and Verillo data. This alternative criterion for vibration perception was developed initially for a study of the perception of sonic-boom-induced building vibration (Sutherland and Czech, 1992).

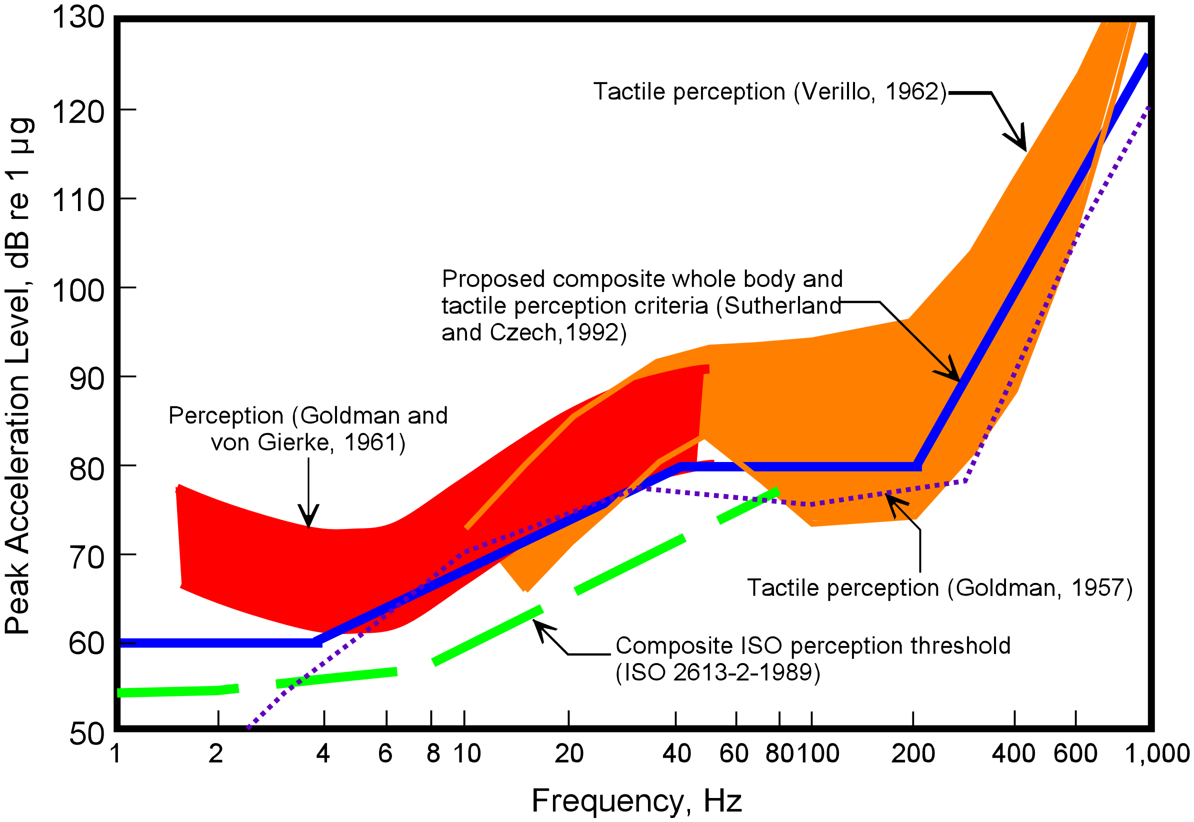


Figure 106 Comparison of the ISO (Hubbard) model for whole body and tactile perception of vibration with Goldman and von Gierke data.

The estimated vibration detection threshold, illustrated by the heavy blue line in Figure 106, can be defined as a function of frequency, f, in terms of the peak acceleration level, $L_{\mathrm{Accel,pk}}$ in dB re 1 μg (1 millionth of a g) as follows:

$$L_{\mathrm{accel,\,pk}} = \begin{cases} 60\ \mathrm{dB} & f < 4\ \mathrm{Hz} \\ 60 + 20\log(f/4) & 4 \le f < 40\ \mathrm{Hz} \\ 80 & 4 \le f < 200\ \mathrm{Hz} \\ 80 + 66\log(f/200) & f < 200\ \mathrm{Hz} \end{cases}$$

By combining the above criterion for vibration detection with the noise-induced building vibration response models in Figures 104 and 105, revised models for detection of such vibration can be developed with the aid of the basic physical response models outlined in Section B.4.2. The results are shown in Figure 108 in terms of the expected one-third octave band sound levels that would cause detectable building vibration for wood frame walls (with and without a plaster interior) and windows of two different size ranges.[32] While the estimated thresholds for detectable window vibration are in rough agreement with the Hubbard model for some windows at frequencies below 80 Hz, the predicted threshold for detectable wall vibration are 5 to 15 dB higher than the Hubbard model at frequencies below 80 Hz (*i.e.*, within the dominant range for the resonance frequencies of typical walls). Thus, the Hubbard model seems to provide a reasonable order-of magnitude estimate for the threshold of detectable vibration of windows, but may be conservative by about 10 dB for estimating threshold levels for detectable wall vibration.

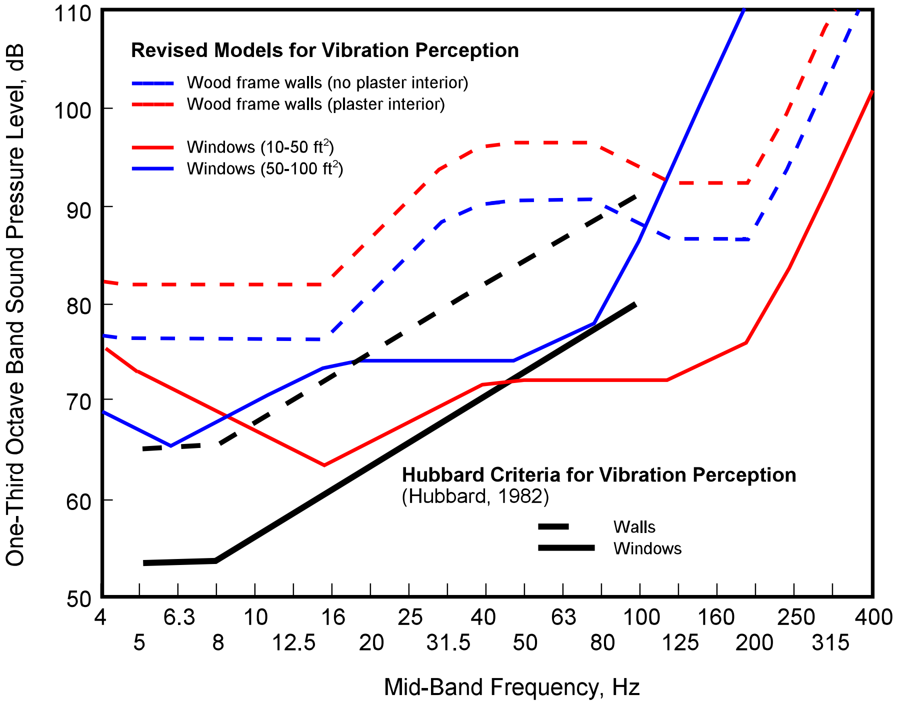


Figure 108 Thresholds for perception of noise-induced building vibration inferred from Hubbard criteria and from suggested models of Figure 105 and criteria of Figure 106.

---

[32] The larger the window size, the lower the fundamental resonance frequency and the higher the surface weight of the glass pane as the glass thickness increases (Haber and Nakaki, 1989).

These predicted threshold values for vibration detection are only mean values about which considerable variation for any one building component is inevitable. This is due to inherent variability in both the vibration response characteristics of building components, and to variability in acoustic excitation.

Published data and engineering models of building vibration response characteristics (*e.g.*, Sutherland, 1989; Sutherland, Brown and Goerner, 1990; Haber and Nakaki, 1990) make possible estimates of the probability of occurrence of noise-induced building vibration. One such an estimate of the probability of detection of noise-induced building vibration may be seen in Figure 109. Over the range of window sizes considered (2 to 50 square feet in area), vibration detection would be expected between 20% and 50% of the time at low-frequency sound levels (25-80 Hz) in the range of 65-72 dB and 72-78 dB respectively. The corresponding noise levels for an average wood frame wall, without a plaster interior, are about 75 dB and 84 dB respectively.

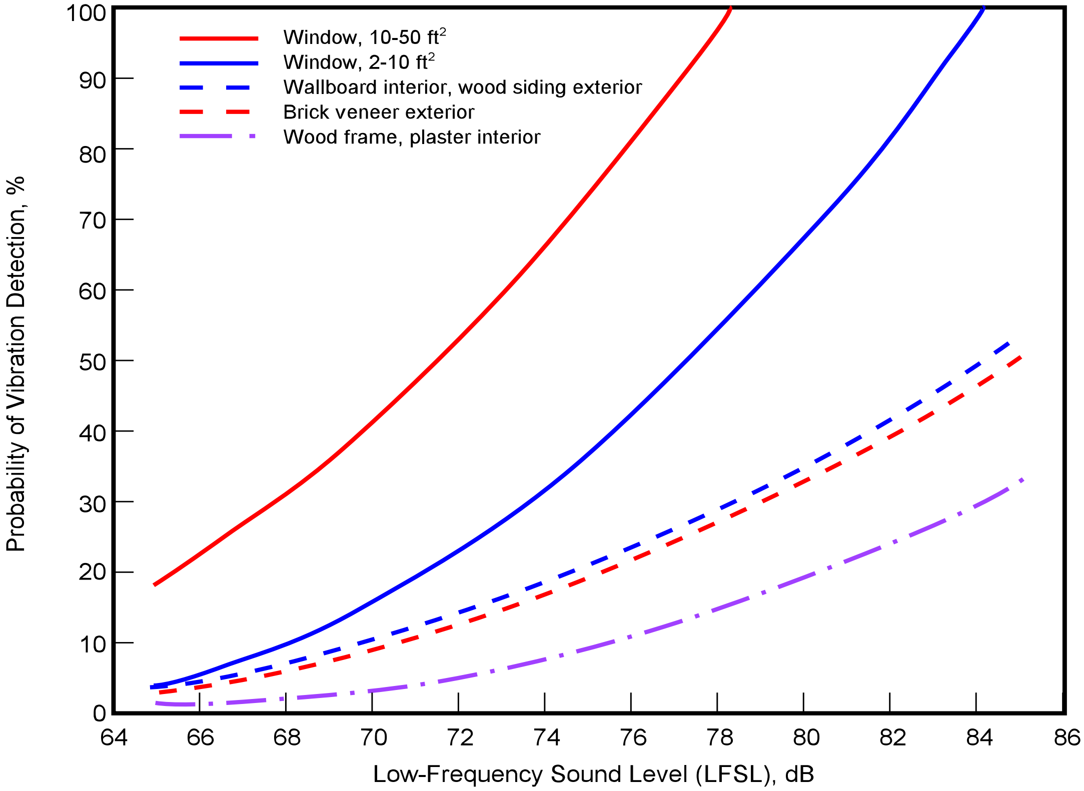


Figure 109 Estimated probability of perception of noise-induced vibration of residential building components.

Although these probability estimates are approximations, they are based on a reasonable database for mean values of building vibration response characteristics, and a reasonable database of the standard deviation of a log-normal distribution (Sutherland, 1989) expressed in decibels of these mean values. Mean values of this distribution are shown in decibel form in the columns labeled 20 SD in Table 26 on page 44.

Variability in low-frequency sound level on the order of 7 to 9 dB can be expected to *increase* the probability of perception of vibration by a factor of about 2.5, or from $p = 0.20$ to $p = 0.50$.

B.6 MODELS FOR PRODUCTION OF RATTLE

The rattle of windows (Crandall and Kurweill, 1968) and other building or interior furnishings (Carden and Mayes, 1970; Schomer and Neathammer, 1985; and Schomer and Averbuch, 1989) is a complex phenomenon characterized by strong dependence on the peak vibration response at resonance frequencies of walls, and non-linear vibration response at levels in excess of a rattle threshold. Some of these characteristics are illustrated in Figure 110 from NASA studies (Carden and Mayes, 1970; Clarkson and Mayes, 1972; and Clevenson, 1978). The aircraft noise-induced wall vibration data in Figure 104 vary with frequency in a complex manner that reflects the influence of the many modes of vibration of a wall. Furthermore, a large increase in wall vibration occurs when a rattle threshold for a wall is exceeded, as indicated by the data in the lower panel of the figure. The increase in wall vibration may be accompanied by an increase in secondary rattle-generated noise emission by pictures or plaques mounted on the wall.

A limited evaluation of the secondary emission (Sutherland and Czech, 1992) has shown that a rattling picture can generate A-weighted noise levels of the order of 55 to 65 dB at a distance of 1 meter from the rattling picture. Such levels may be well above the usual ambient noise levels inside a residence. Thus, secondary rattling noise can be a very distinctive and intrusive sound that can be a major source of annoyance as a result of rattle occurrence from low-frequency aircraft noise.[33]

Several studies have evaluated the apparent increase in annoyance in terms of the hypothetical increase in noise level that would be required to produce the same annoyance response in the absence of any rattle (Cawthorne, Dempsey and DeLoach, 1978; Schomer and Neathammer, 1985; Schomer and Averbuch, 1989; Schomer, 1991; and Fidell, Silvati, Lind and Pearsons, 1999a). An average value of this effective "rattle penalty" from these studies is about 12 dB with a standard deviation of 6 dB. (The annoyance of rattle is treated in greater detail in Section 4 of Volume II, in a discussion of the results of two field studies conducted in neighborhoods near MSP and Los Angeles International Airport.)

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[33] Even rattle that is not particularly high in level can markedly increase the annoyance of aircraft noise, as described in Section 3.3.4.

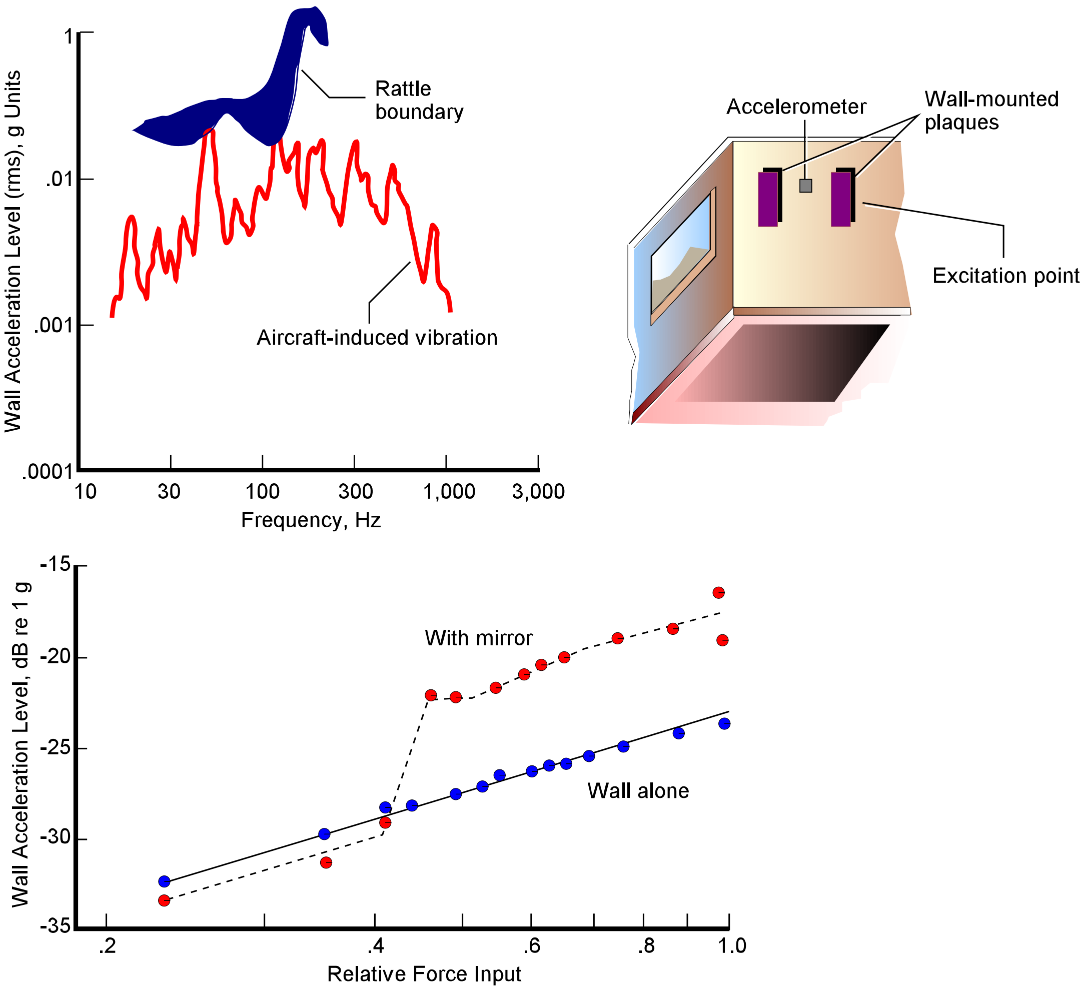

Figure 110 Examples of complex behavior of noise-induced rattle of building components and interior furnishings (from Carden, Findley and Mayes, 1969; and Carden and Mayes, 1970).

A summary of one-third octave band sound pressure levels that can cause rattle of walls, doors and windows is shown in Figure 111 by the two cross-hatched areas (Carden and Mayes,1970; Nakamura and Tokita, 1981). Figure 111 also shows estimated thresholds of onset of rattle for windows and wall-hung plaques. These estimated rattle thresholds are based on the following semi-empirical model for the rms acceleration, A_{rtl}, in g's, at the threshold of onset of rattle. Rattle is assumed to occur when:

$$A_{rtl} = 0.01\ g, \qquad f < f_o$$

$$= 0.01\ (f/f_o),\ g \qquad f \geq f_o$$

where f_0 is the fundamental resonance frequency of the wall or window panel. This expression is in approximate agreement with the trend in measured or calculated acceleration levels at the onset of rattle (Carden and Mayes,1970; Nakamura and Tokita, 1981; and Eldred, 1985).

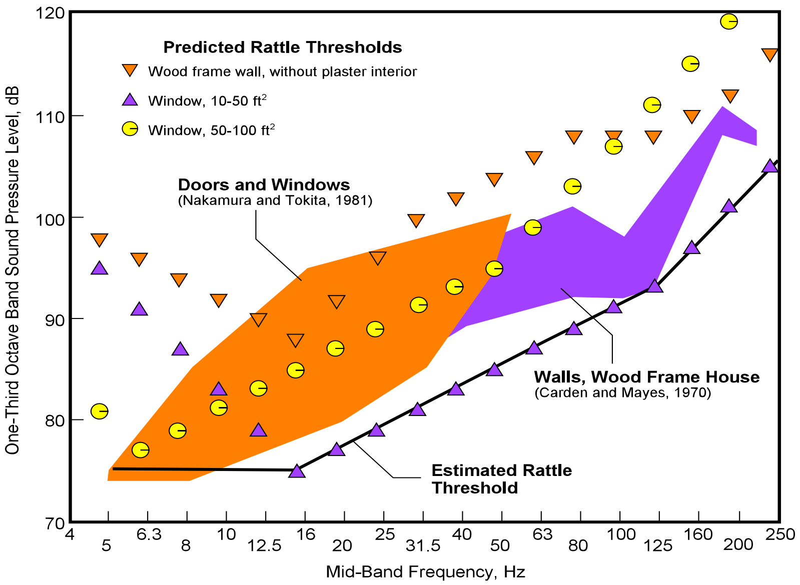

Figure 111 Estimated occurrence of rattle based on the vibration response data and models of Figures 102 through 105, data in Table 26, and the rattle threshold criteria described in Section B.6.

Threshold sound levels for window rattle are the lowest. A single rattle prediction model for one-third octave band sound pressure levels at the threshold of rattle for general application is shown by the single line in Figure 111. This coincides with the predicted rattle threshold for windows between ten and fifty square feet in area, at frequencies at and above the typical fundamental resonance frequency (15 Hz) for such windows. At lower frequencies, the rattle threshold sound pressure level is assumed to be a constant 75 dB.

The process illustrated in Figure 109 has been applied to estimate the probability of occurrence of rattle for the various types of buildings elements considered in Figure 111. Based on the limited data on rattle cited above, the estimated standard deviation for the acceleration level at the onset of rattle is 6 dB. This measure of variability in the rattle acceleration threshold is combined with the other statistical parameters for the structural response and low-frequency excitation to estimate the probability of the occurrence of rattle as a function of Low-Frequency Sound Level (LFSL) shown in Figure 106.

The probability of occurrence of rattle for a window is estimated for the point at which a value of $p = 0.2$ is reached at LFSL values in the range of 68 to 73 dB, and a value of $p = 0.5$ at levels of 75 to 79 dB. The estimates in Figure 106 provide a reasonable indication of the likelihood of occurrence of rattle. Window rattle is the clearly dominant form of secondary emissions.

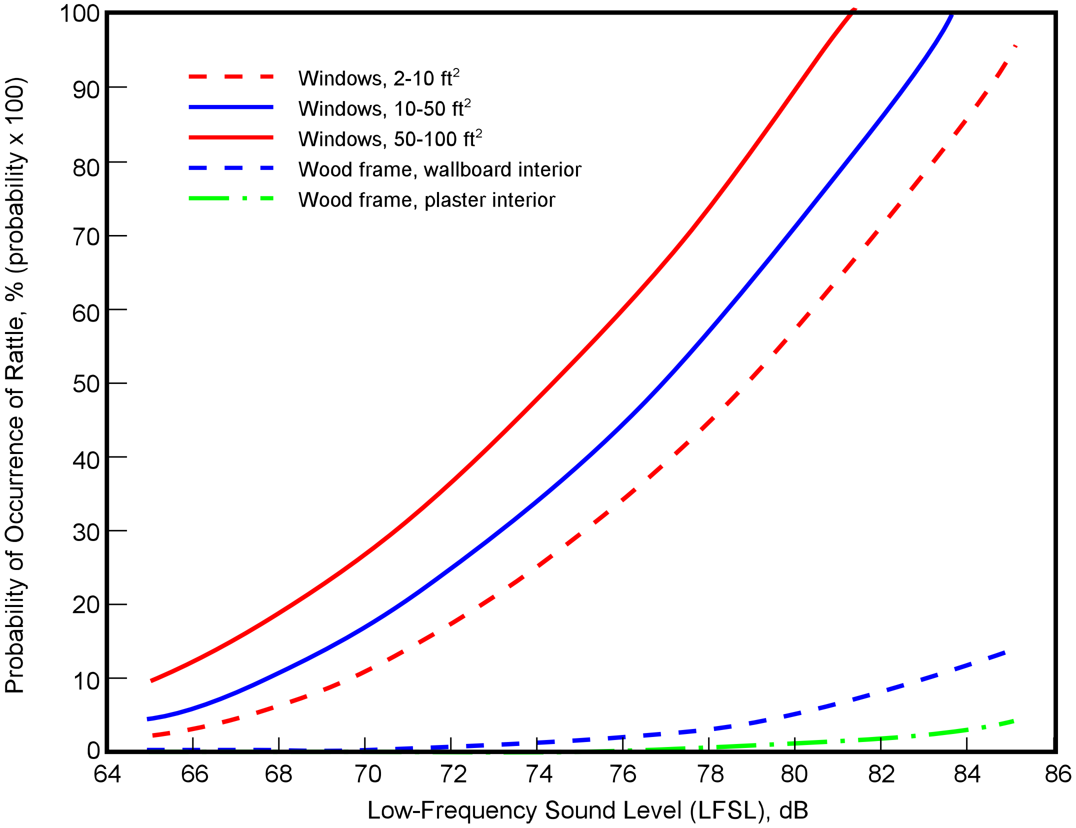

Figure 112 Predicted probability of the occurrence of noise-induced rattle in residential building components.

The prediction models of Figures 111 and 112 are based on published rattle measurements. Other building components, such as doors, ceiling systems, *etc.*, may also be subject to rattle. However, windows are among the most susceptible building elements to rattle from low-frequency aircraft noise. Household paraphernalia (crockery, pictures hung on walls, other bric-a-brac) may start to rattle at other levels.

B.7 LOW-FREQUENCY AIRCRAFT NOISE SOURCE CHARACTERISTICS

This section reviews the literature on measurements and prediction of low-frequency aircraft noise.

B.7.1 FAA's Aircraft Noise Prediction Models

As described in Appendix A, FAA refers to its preferred software for predicting civil aircraft noise as the "Integrated Noise Model" (INM). The current release of INM (Version 6.0) incorporates reference one-third octave band level spectra for a range of commercial jet aircraft. These reference spectra are used to evaluate that component of attenuation of aircraft noise due to atmospheric absorption — a frequency-dependent source of attenuation that is most significant at high frequencies. To evaluate attenuation of aircraft noise over ground, INM 6.0 defines a more detailed grouping of aircraft spectra. Each of 72 classes of aircraft noise, ranging from commercial jet aircraft on departure and approach and helicopters on hover, are specified for this purpose (Fleming, Burnstein, Rapoza and Senzig, 1999). Each spectral class is, in turn, a surrogate reference for evaluating ground attenuation for a number of individual aircraft models.

Both of these aircraft noise spectral models are based on noise measurements made at positions directly under the aircraft. These spectra do not reflect the strong presence of low-frequency noise found at positions to the side and aft of jet aircraft during departure. Figure 113 shows a comparison of spectra measured at a sideline position representative of the type of noise exposure expected for Richfield for operations of the new Runway 17/35, and at MSP at a position close to the takeoff path (similar to typical INM reference spectra). While the absolute levels shown by these data are not necessarily representative of Richfield, the general spectral shape is representative.

Comparison of measured low-frequency sound levels derived from spectra such as those in Figure 113 with computed noise levels using INM Version 6.0 permits empirical adjustments to the INM predictions to provide one approach to estimating future low-frequency noise levels in the City of Richfield. This process is explained in greater detail in Section 5 of Volume II.

B.7.2 Other Aircraft Noise Prediction Models

Other aircraft noise prediction models that were considered for use included:

> NOISEMAP. This is an aircraft noise prediction model developed by and for the U.S. Air Force to predict aircraft noise exposure in the vicinity of military airfields or flight training areas. FAA recognizes NOISEMAP predictions as equivalent to those produced by its own model, INM, for regulatory purposes. NOISEMAP also relies upon reference spectra as building blocks for prediction of aircraft noise levels at points on the ground remote from runways. These spectra have the same limitation as the INM database in that they do not inherently account for the unique low-frequency character of aircraft noise along the sideline or aft of the departing aircraft.
>
> ANOPP. This “Aircraft Noise Prediction Program,” developed by NASA for research purposes, is potentially capable of computing low-frequency aircraft noise emissions. Unlike the empirically-based NOISEMAP and INM models, however, ANOPP is constructed from first principles, and is not optimized for predicting noise exposure in the vicinity of airfields. Its use for present purposes would be both awkward and unprecedented.

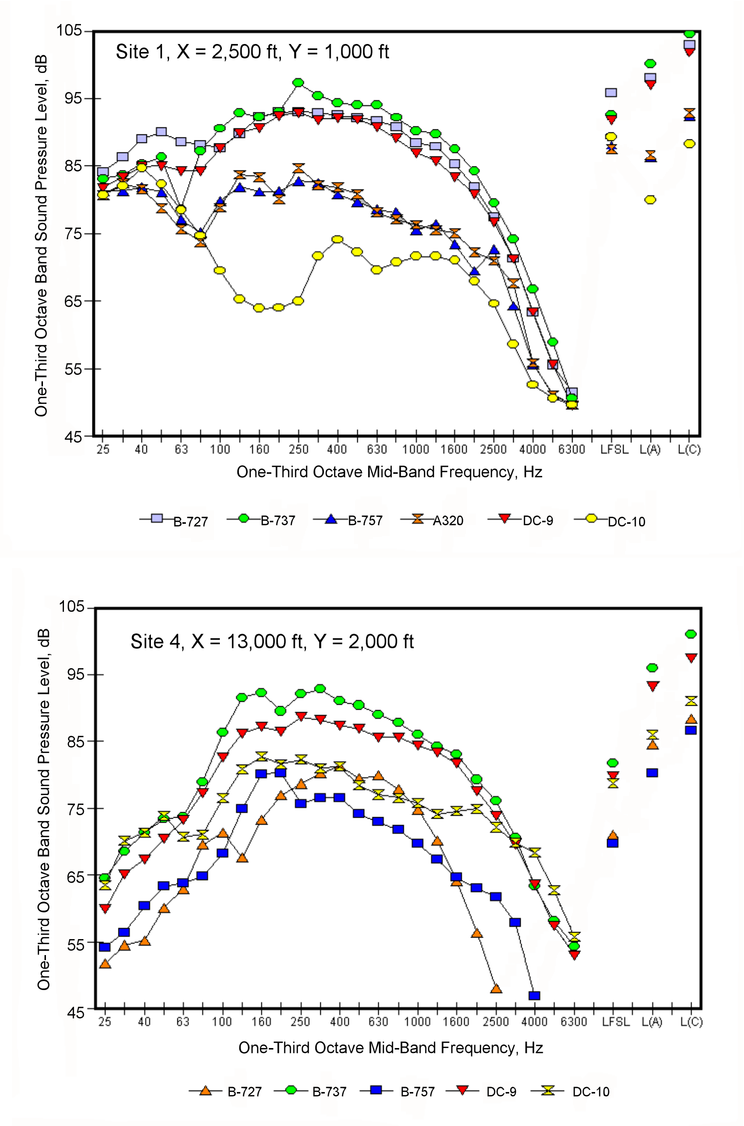

Figure 113 MSP Data at Sites 1 and 4. (Data from Lind *et al.*, 1997.)

Society of Automotive Engineers (SAE) Aircraft Noise Committee's SAE Aircraft Information Report (AIR) 1845, 1986. This publication includes a set of algorithms (not executable code) intended for engineering evaluation of aircraft noise (SAE, 1986). Their use for present purposes is not practical.

Norwegian model (Olsen, Granoein and Liasjo, 1998). Uses of this software outside of Norway are unsupported and of dubious applicability to present purposes in any event.

FLULA2 Model (Thomann and Buetikofer, 1999). This Swiss model is based on an extensive collection of aircraft noise levels along with their spectra measured in many directions, and thus should have been capable of providing very useful information for this program. Efforts to gain access to the model were unsuccessful.

B.7.3 Further Comparison of LFSL and C-Weighted Sound Level

A database was compiled to support further analyses of relationships between C-weighted and low-frequency sound levels. Most of the data were obtained at airports other than MSP with potentially different terrain and ground conditions, and thus may not always be directly applicable for estimating low-frequency for equivalent locations at MSP near Runway 17/35. Nevertheless, they usefully supplement the measurements made in the vicinity of MSP.

Table 27 summarizes the number of measurement points, reference source, airport, number of measurement sites, number and type of aircraft (wide body or narrow body, Stage 2 or 3), number of flights measured, type of flight measured (*i.e.*, takeoff or landing), range of coordinates of the measurement sites relative to the start of takeoff roll or landing threshold, frequency range of the measurements as evaluated, and availability of data for alternative noise descriptors (*e.g.*, C-weighted noise levels, low-frequency sound levels, and A-weighted noise levels) contained in the database.

The data available from the sources listed in this table are very useful for supporting estimates of the low-frequency sound levels needed for present purposes. Examples of this are provided in Figures 114, 115, and 116.

As shown in Figure 113, the spectra along the sideline during departures contains much higher low-frequency noise levels than at other positions. One qualitative measure of the relative predominance of low-frequency sound levels during takeoff is provided by the difference between these C-weighted and low-frequency sound levels. Figure 113 suggests that this difference changes with the distance from brake release.

Just such a pattern is shown in Figure 114 by a plot of this difference, L(C)-LFSL as a function of the distance, X along the runway from brake release. This plot utilizes essentially all of the low-frequency aircraft noise level data for departures available from the sources listed in Table 27. While the data show considerable scatter, a general trend is clear. These show that behind the brake release point, the C-weighted level is only about 2 dB greater than LFSL — evidence of the expected strong low-frequency content in this area. In the immediate vicinity of the brake release point, the average difference [L(C) - LFSL] is less than 1 dB. At positions well past this point, the difference increases as the relative predominance of low-frequency noise, as measured by LFSL, begins to decrease compared to the C-weighted levels. These data can be used to roughly estimate LFSL from C-weighted maximum sound levels computed with INM 6.0. Although the data in this figure are from six different airports, airport-dependent trends are not discernible.

The same sort of information, for landings only, is shown in Figure 109 from a more limited data set for Logan airport (Harris Miller Miller and Hanson, 1996a). In this case, the average of the data indicates that the difference, [L(C) - LFSL] is apparently not sensitive to position along the runway, and is equal to about + 5.0 dB for landings without thrust reversal and about -3.0 dB for landings with thrust reversal.[34] The latter clearly indicates that low-frequency noise will be especially strong, relative to C-weighted levels, during application of thrust reversers on landing.

An alternate method for utilizing the database of Table 27 is illustrated by Figure 116. This shows how the two noise descriptors, LFSL and L(C) are correlated for the same two locations (Sites 1 and 4) at MSP used to obtain the spectral data shown earlier in Figure 113. The two regression lines show, as expected, a high degree of correlation between the two descriptors with about 72% to 81% of the variance explained by the correlation between these descriptors. Thus, starting with predicted C-weighted sound level from INM Version 6.0, regression lines such as those seen in Figure 116 could be used to estimate the preferred descriptor, LFSL, with reasonable confidence in the validity of the estimates.

Further analyses of the relationship between C-weighted and LFSL levels due to aircraft operations within a small area of Minneapolis just north of MSP may be found in Section 4 of Volume II.

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[34] These reverse thrust data for Logan Airport were later found to be unreliable due to probable contamination by wind noise. See Section 6.4 in Volume II for a more complete discussion of thrust reverser noise.

Table 27 Summary of weighted and low-frequency noise level database from measurements near airports.

Points	Reference	Airport	Page No.	Sites	Aircraft Types	WB=W NB=N	Stage 2 or 3	Type Event	No. of Flights	Approximate Range of Coordinates[a]		Frequency Range[b] (Hz)	L_C[c] (dB)	LFSL[c] (dB)	L_{100}[c] (dB)	L_A[c] (dB)
										X (Kft)	Y (Kft)					
9	HMMH, 1996	Logan	15-19	3	6	W,N	2,3	TO	96	0 to +1	0 to 4	16 - 4,000	Y	Y	Y	Y
143	HMMH, 1996	Logan	A2-A7	6	5	W,N	2,3	TO, L	411	-4 to +1	0 to 4	NA	Y	N	Y	Y
2	HMMH, 1996b	SFO	9, 10	1	1	N	2	TO	2	-2.7	2	25 - 4,000	Y	Y	Y	Y
39	HMMH, 1996b	SFO	A9-A50	3	6	W,N	2,3	TO	36	-3 to -14	2 to 13	NA	Y	Y	Y	Y
48	Lind *et al.*, 1997	MSP	11-15	2	7	W,N	2,3	TO	48	2 to 13	1 to 2	25 - 4,000	Y	Y	Y	Y
8	BBN Memo	LAX	6	1	8	W,N	2,3	TO	NA	9.4	2	25 - 250	N	Y	Y	N
300	Fidell *et al.*, 1999	LAX	19, 23	7	8	W,N	2,3	TO, L	NA	9 to 17	1 to 4	25 - 4,000	Y[d]	Y[e]	Y	Y
4	HMMH, 1998	BWI	10-11	1	NA	NA	NA	TO	4	-1.2	3	12.5 - 10,000	Y	Y	Y	Y
3	Shade, 1997	BWI	3, Fig. 1	1	6	W,N	2,3	TO	25	-1.2	3	20 - 4,000	Y[f]	Y	Y	Y
4	Plotkin *et al.*, 1999	DIA	NA	4	1[g]	N[g]	2[g]	TO	1[g]	7	1 to 2	20 - 4,000	Y[h]	Y	Y	Y
Total = 556									Total 623							

NOTES:

[a] X = distance along runway centerline from brake release at takeoff from landing threshold.
Y = perpendicular distance from centerline of runway.

[b] Limited analysis to frequencies 4,000 Hz in some cases to avoid S/N problems in some data.

[c] For BBN data at MSP and LAX, weighted and low-frequency levels are based on energy sum of composite maxima of one-third octave band levels at any time.
For HMMH data at Logan, SFO and BWI, weighted and low-frequency levels are based on energy sum of one-third octave band levels at time of maximum unweighted overall sound level.

[d] Correlation of L_C and LFSL data included.

[e] Contours of estimated LFSL values included.

[f] Average, min and max spectra from 25 flights, including six aircraft types, 20 - 500 Hz data for two Stage 3 types.

[g] Data for B-727; data (not reduced) also obtained for more than 160 additional Stage 2 and Stage 3 aircraft flights.

[h] Full time history available.

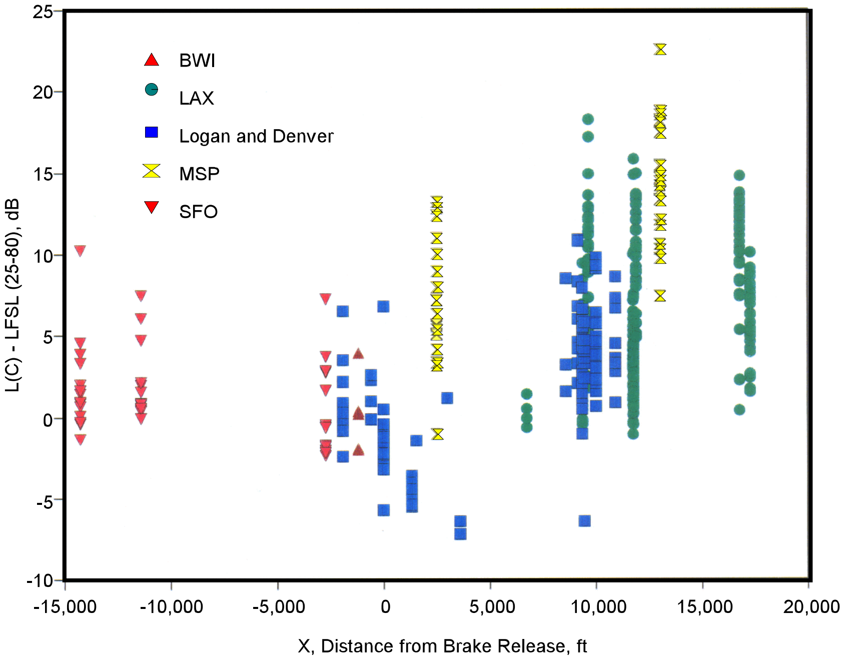

Figure 114 L(C) - LFSL at takeoff measured at six airports (data from sources identified in Table 27).

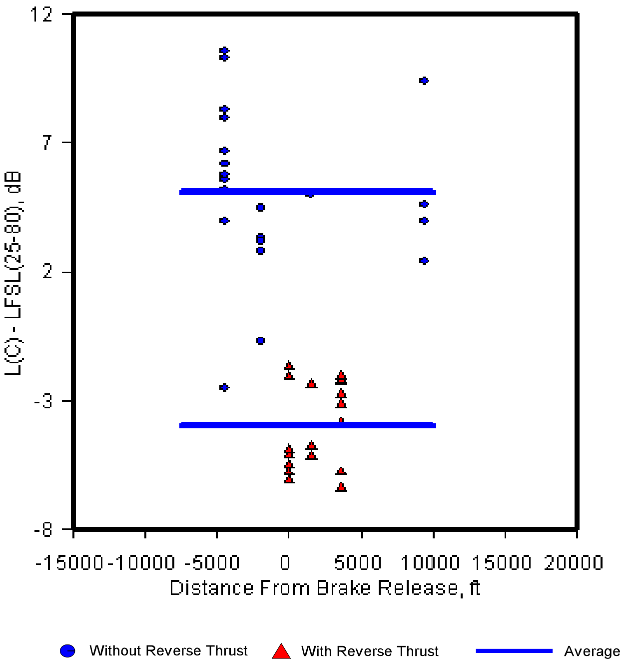

Figure 115 L(C) - LFSL for landings measured at BOS (HMMH, 1996).

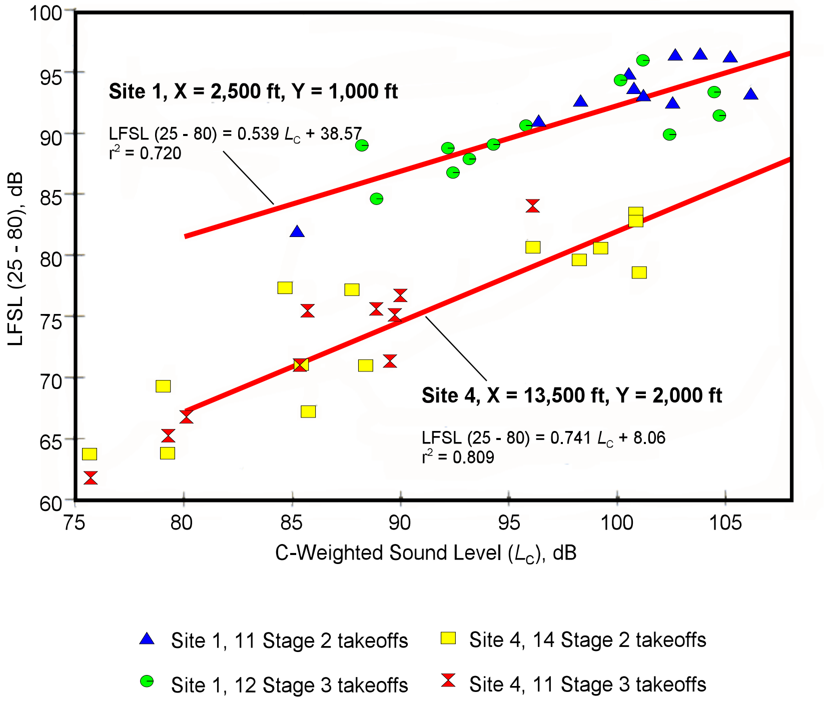

Figure 116 LFSL *vs.* L(C) regression lines for Sites 1 and 4 at MSP (data from Lind *et al.*, 1997).

Similar analyses of some of the data cited in Table 27 are used in Section 4.5 of Volume II to support the estimates of LFSL for areas in Richfield affected by the planned operations on Runway 17/35.

The low-frequency noise level data reported by HMMH are based on one-third octave band levels at the time during an aircraft noise measurement when the C-weighted noise level was greatest. For the data from BOS (Harris Miller Miller and Hanson, 1996a), the low-frequency levels were the energy sum at this unique time of maximum overall level of all the one-third octave bands at frequencies equal to or below 100 Hz. However, an analysis of such data has shown that the resulting maximum sum of the bands 100 Hz is within 1 dB or less of the energy sum of the maximum values in each of the 25-80 Hz bands over a flight event. This sum makes up the preferred low-frequency noise descriptor, LFSL, employed for the BBN measurements (see note "c" for Table 27). Thus, the two low-frequency noise descriptors employed by HMMH and BBN were considered essentially equivalent when evaluating data cited in Table 27.

B.8 AIRCRAFT NOISE PROPAGATION

An extensive literature on the propagation of aircraft noise has arisen from the need to understand how aircraft sound propagates through the atmosphere or over the ground for part of the evaluation of aircraft noise environments. Summaries of some of this literature and citations of the extensive literature on this topic are provided by Piercy, Embleton and Sutherland (1977), Sutherland and Daigle (1997), and Sutherland (1998). The sound propagation phenomena of primary concern briefly reviewed here are:

Refraction by wind and temperature gradients

Ground attenuation

Sound attenuation through built-up urban areas

Fluctuation in aircraft noise due to atmospheric turbulence.

Two other sound propagation effects that should be mentioned are:

1. Basic geometric spreading loss of sound, and
2. Atmospheric absorption of sound.

Geometric spreading is the most fundamental basis for the decrease in level of a sound with distance. As sound spreads out in a spherical wave propagating away from a source, the area through which the sound wave passes increases by a factor of four for each doubling of the radius of the spherical wave, because the surface area of the spherical wave increases as the square of its radius. Since the total sound energy in the spherical is nominally constant, the sound intensity per unit area must decrease as the spherical wave area increases. This leads to the so-called "inverse square law" spreading loss for sound propagation. That is, the sound level decreases by 6 decibels (*i.e.*, the reduction in sound level for a 4:1 reduction in sound intensity) for each doubling of the distance from the source.

Atmospheric absorption is the complex frequency-, temperature- and humidity-dependent sound attenuation mechanism associated with the loss in energy as a sound wave travels through the atmosphere. Although this well-defined process (American National Standards Association, 1995) is very important for attenuation of high-frequency sounds, it is of little concern for the low-frequency sounds of present interest. Over the frequency range of 25 to 80 Hz of the Low-Frequency Sound Level descriptor, and for a range of expected weather conditions in Minneapolis throughout the year, atmospheric absorption would cause a loss of only about 0.011 (±0.005) dB and 0.072 (±0.018) dB, respectively, every 1,000 feet of a sound propagation path. Thus, at a distance of 5,000 feet to the west of Runway 17/35, atmospheric absorption would cause losses of only about 0.05 and 0.36 dB, respectively, at 25 and 80 Hz. Thus, atmospheric absorption can be ignored when assessing low-frequency noise propagation into the City of Richfield.

B.8.1 Refraction by Wind and Temperature Gradients

The major cause of weather-induced variations in aircraft noise on the ground during takeoff is atmospheric refraction associated with non-uniform gradients of wind or temperature. This change in the way sound rays spread out from a source is shown by the various patterns illustrated in Figure 117. The figure shows that the minimum and maximum excess attenuation (beyond geometric spreading loss) occur when the vertical gradient in sound speed is positive or negative, respectively (Piercy *et al.*, 1977).

The minimum excess attenuation from refraction occurs under so-called sound focusing conditions. In the case illustrated, the overall propagation loss for distances beyond about 1,000 ft. from an aircraft noise source can be approximated by cylindrical spreading loss (-3 dB per doubling of distance) instead of spherical spreading loss (-6 dB per doubling of distance).

The maximum excess attenuation by refraction under conditions that cause sound rays to bend upward (away from the ground) can be substantial, reaching values up to 15 to 20 dB at frequencies on the order of 500 Hz (Piercy *et al.*, 1977). Excess attenuation in such sound shadow conditions is limited only by atmospheric turbulence. Lower frequencies are believed to be affected less by upward refraction than higher frequencies.

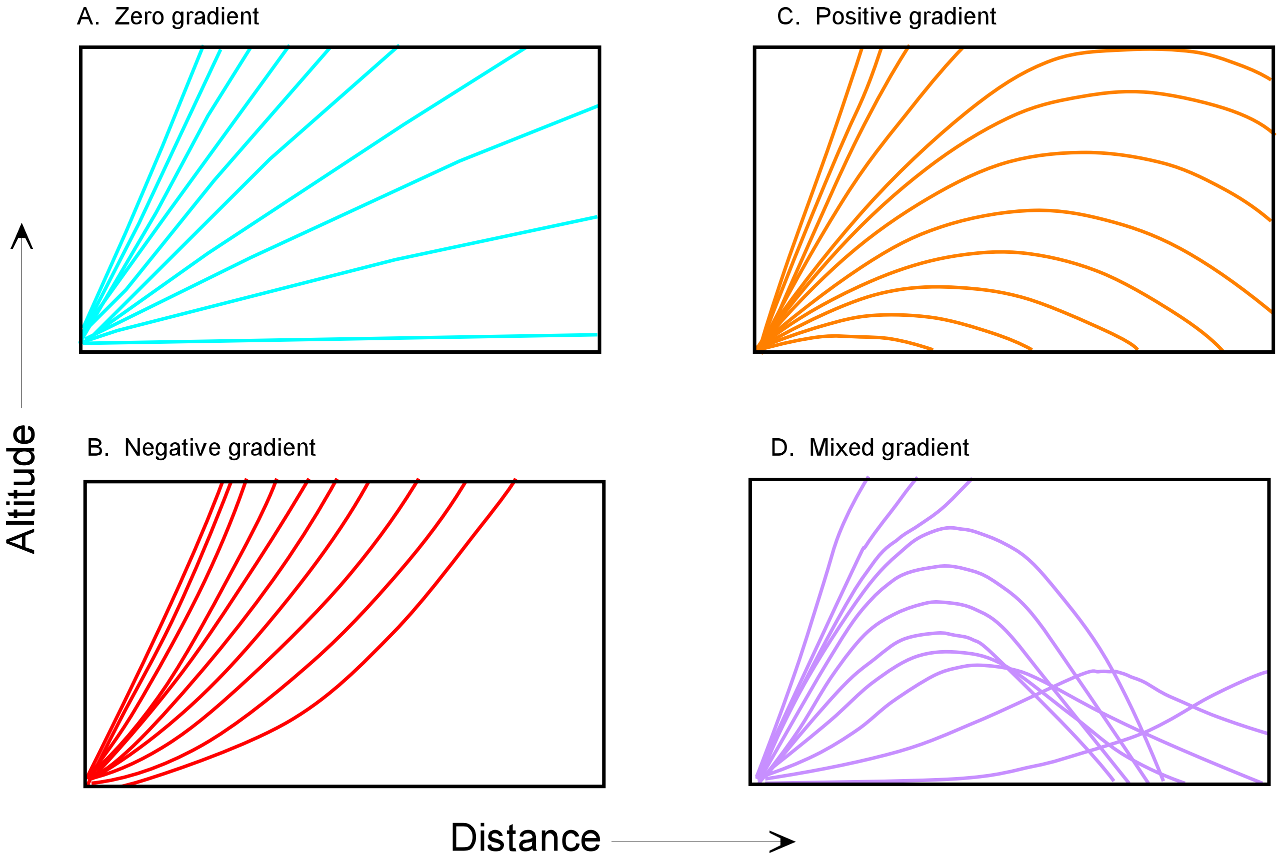

Figure 117 Refraction of sound by wind and temperature gradients.

B.8.2 Ground Attenuation

Theoretical prediction models for ground attenuation are well developed (*cf.* Piercy *et al.*, 1977, and Sutherland and Daigle, 1997). This theory has been recently validated extensively for aircraft noise on the sideline during takeoff (Plotkin, Bradley and Hobbs, 1999).

Ground attenuation depends strongly on frequency and on acoustic impedance of the ground. The latter depends, in turn, on structural-acoustic properties of the ground, including flow resistivity and porosity (see Sutherland and Daigle, 1997 for a summary and references for the original research on this topic). The variation in ground attenuation of low-frequency aircraft noise was evaluated for current purposes from the theoretical models noted above and from an analysis of the relative spectral shape of low-frequency aircraft noise, using the database defined in Table 27 in Section B.7.3 of this Appendix.

The latter data were used to determine the relative spectral shape of the low-frequency aircraft noise so that the frequency-dependent ground attenuation could be computed. This analysis of the low-frequency aircraft data is summarized in Figures 118 and 119. The first figure shows average values of measured one-third octave band levels relative to the low-frequency sound level, for the low-frequency data available, according to Table 27, for six airports. Except for the lowest-frequency one-third octave band levels for the SFO data, these average relative spectra are very similar over all airports. However, based on the results presented in Section B.7.3, variation was expected in the relative low-frequency spectral shape with the position (X) along the runway.

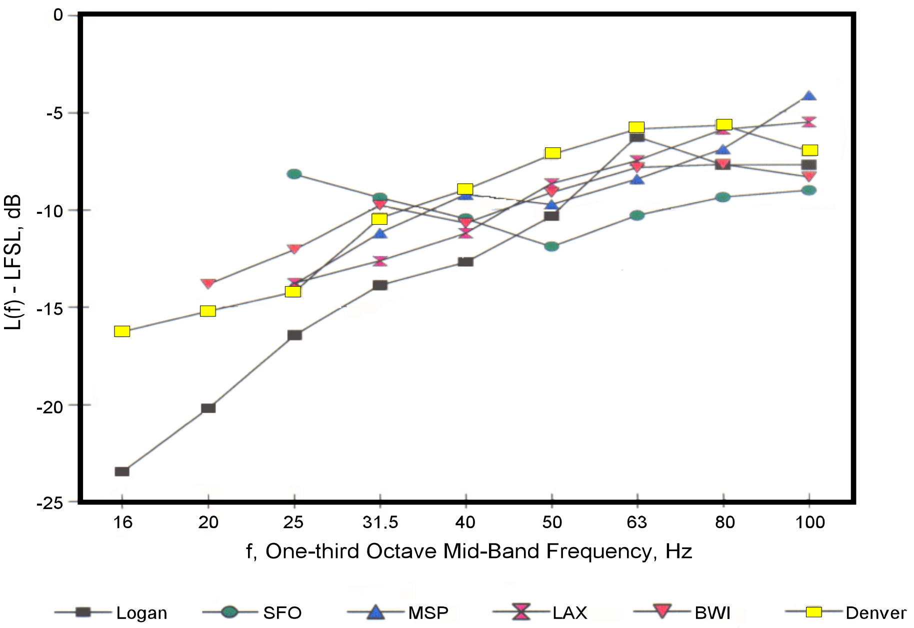

Figure 118 Ground attenuation of aircraft noise: one-third octave band levels, L(f), re: LFSL at 6 airports.

The expected pattern emerged when the relative one-third octave band levels (re: LFSL) were averaged over similar values of the distance X along the runway. This pattern is illustrated in Figure 113 by the average values of the relative spectra *versus* the distance X for the six one-third octave bands (*i.e.*, 25 to 80 Hz) making up the LFSL descriptor. For simplicity and to show a smoothed trend for the data, these relative band levels have been computed for two mid-band frequencies at a time (*i.e.*, 25 and 31.5 Hz, *etc.*). The consistent pattern to these data is approximated in the figure by simple straight line segments.

Given this measure of the relative one-third octave band levels making up the LFSL descriptor, the frequency dependent values of ground attenuation for this descriptor can then be calculated. Omitting the mathematical steps for simplicity, this process provided the computed values for ground attenuation for LFSL shown in Figure 120 as a function of the propagation distance, Y perpendicular to the runway for three different ground surfaces and two different values (0 and 8,000 ft.) for the distance, X along the runway.

Not shown in the figure is the minor effect of varying the source height from 14 ft. to 28 ft — a range encompassing the heights above the ground of wing or fuselage-mounted aircraft engines for current narrow body and wide body fan jet aircraft. This variable was found to have negligible effect (less than 1 dB) on the ground attenuation so the lower engine height of 14 ft was used for the data in

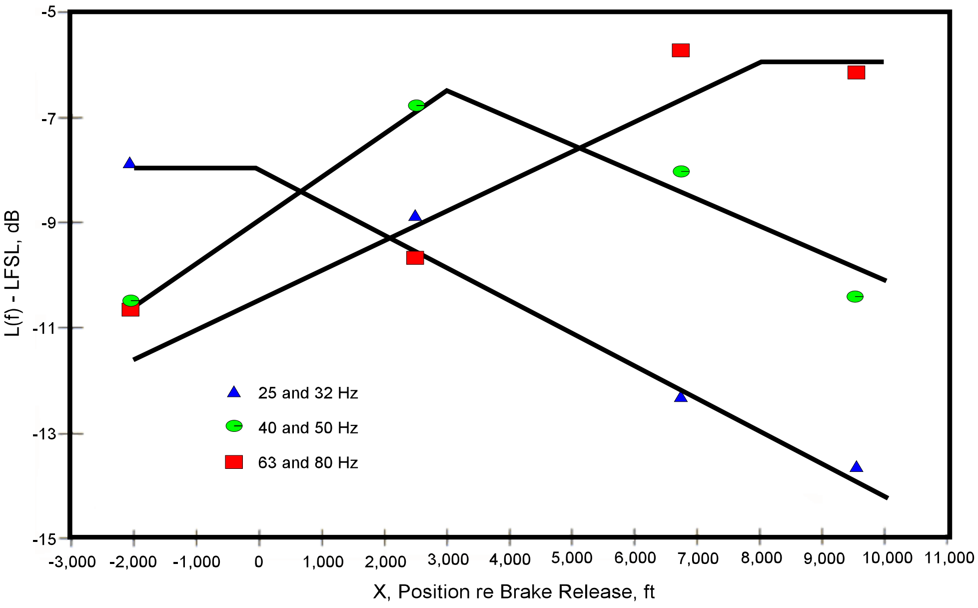

Figure 119 Average values of one-third octave band sound levels relative to LFSL observed at six airports as a function of the distance X, along the runway.

The three different types of ground surface considered were snow, grass and a hard surface, such as packed dirt or concrete. The ground attenuation, or really excess ground attenuation since it is the sound propagation attenuation in ***excess*** of spreading loss or atmospheric absorption, is greatest, as one would expect when the ground surface is an "acoustically-soft" snow cover. For design predictions, however, it is prudent to assume more conservative and more typical ground conditions — somewhere between grass and dirt/concrete surfaces.

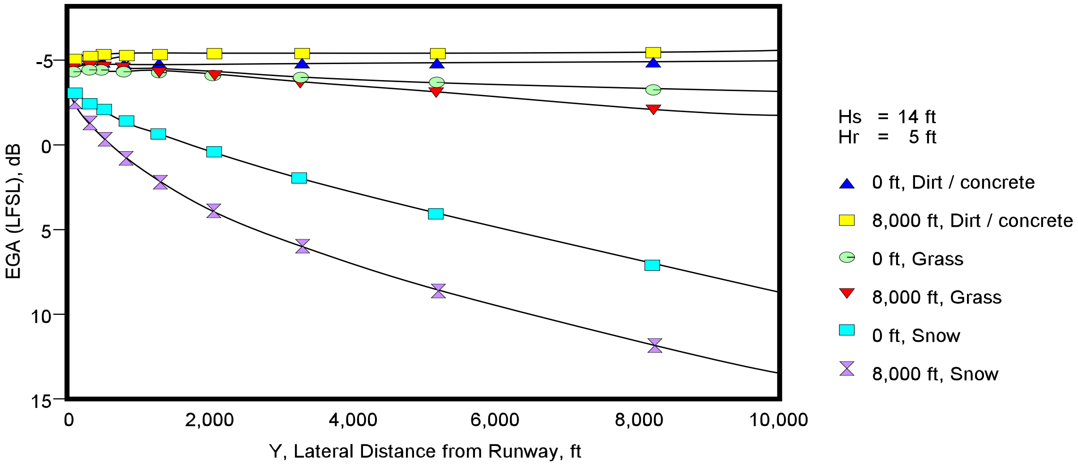

Figure 120 Ground attenuation of aircraft noise: predicted low-frequency excess ground attenuation, Ag(LFSL) *vs.* lateral distance based on relative spectral shape in Figure 113 and the Chien-Soroka theoretical model for ground attenuation (Plotkin, Bradley and Hobbs, 1999).

The values in Figure 120 for the excess attenuation for these two surfaces and "along runway" distances, X of 0 and 8,000 ft. were averaged and then expressed in terms of a value relative to a reference value at a sideline distance of 1,000 ft — a typical minimum distance for the measured LFSL data examined earlier. The resulting average ***relative*** values for the excess ground attenuation for grass and hard surfaces were found to be very small, as indicated in Table 28.

Table 28 Relative values of excess ground attenuation (EGA) for grass and hard surfaces.

Y, Distance Normal to the Runway, ft	0	1,000	3,000	5,000	7,000	9,000
EGA(Y) - EGA(1,000 ft), dB	-0.1	0	-0.2	-0.4	-0.6	0.85
Standard Deviation, dB	0.9	1.0	1.2	1.4	1.5	1.6

With such a small relative change in excess ground attenuation over a range of Y = 0 to 9,000 ft — more than adequate for the range of concern for sideline noise exposure in the City of Richfield — it is reasonable to assume that no allowance be made for ground attenuation beyond that inherent in close-in noise measurements near runways. Thus, only spherical spreading loss must be considered to project the close-in sideline measurements into the City of Richfield. For locations behind the beginning of takeoff roll, estimates can be made by inverse square spreading loss alone to more distant locations along the same azimuth line from the end of the runway.

B.8.3 FAA Model for Ground Attenuation

Versions of INM now under development will include algorithms that account for this ground attenuation in the prediction of A- and C-weighted sound levels (Fleming, Burnstein, Rapoza and Senzig, 1999). The FAA approach combines essentially the same theoretical approach employed above with an empirical data base for aircraft source spectra according to generic types of aircraft (such as two-engine wide body, three-engine wide body, *etc*.). An example from this revised FAA model for ground attenuation of A-weighted sound levels for typical wide body aircraft is shown in Table 29.

Table 29 Example of ground attenuation of A-weighted sound levels from INM Version 6.x.

ELEVATION ANGLE FROM AIRCRAFT TO GROUND	APPROXIMATE GROUND ATTENUATION	
	Hard Ground	Soft Ground
Less than 0.5°	+3	-15
More than 5.0°	0 - 1	0

These results for A-weighted levels cannot be directly compared to the values in Figure 120, since the latter is only applicable for the low-frequency bands making up the LFSL descriptor. However, the two sets of ground attenuation predictions are not inconsistent.

As noted earlier, a major test of the validity of the theoretical model for ground attenuation mentioned above has been carried out recently at Denver airport using an array of microphones extending laterally from 666 to 2,000 ft. to a runway and at a position 6,750 ft from start of take-off roll (Plotkin *et al.*, 1999). The study involved measurements from more than 160 takeoffs of all the types of narrow and wide body aircraft in the current commercial air carrier fleet. The one-third octave band sound levels measured at each lateral position were normalized back to a reference position of 666 ft, accounting for attenuation by inverse square spreading loss, atmospheric attenuation and ground attenuation. The difference between these adjusted levels and the reference level would be zero for perfect agreement between the data and the attenuation prediction models with the largest possible source of error being for ground attenuation. The result of this evaluation is shown for A-weighted levels in Figure 121 as a function of the elevation angle to the aircraft. The scatter in the data is substantial but the mean line through the data is close to zero. As shown in the full report of the study, (Plotkin *et al.*, 1999), the scatter can be attributed primarily to the effects of refraction by wind and temperature gradients shown schematically earlier in Figure 117. However, there is an other effect, considered next, not necessarily included in the analysis which could be the source of the small residual error suggested by the deviation of the average line in Figure 121 from zero for elevation angles below about 10°.

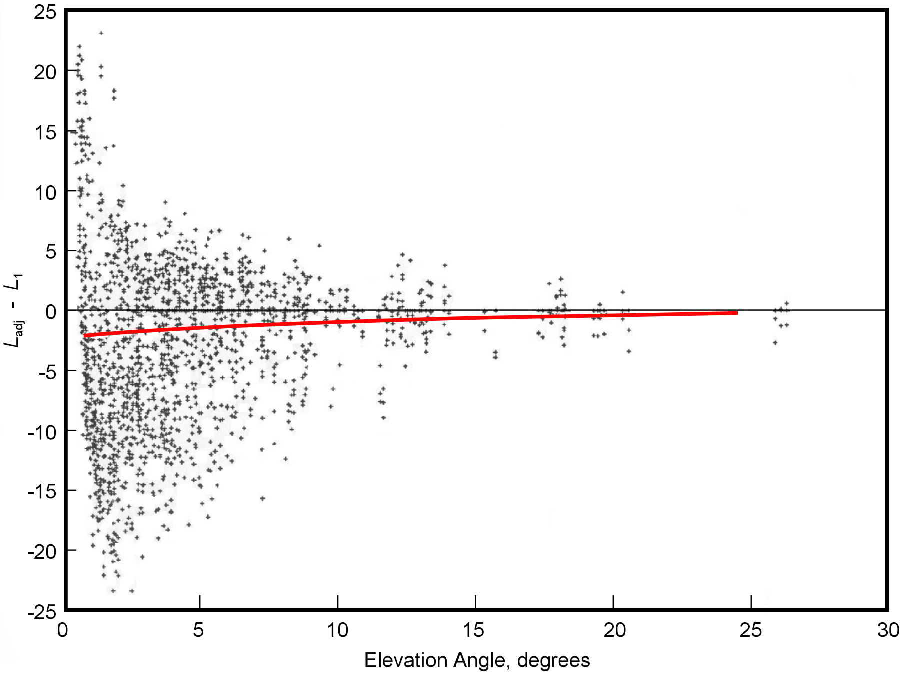

Figure 121 Comparison of measured and predicted A-weighted sound levels along the sideline of Denver International Airport, corrected for ground attenuation. The scatter of data about the zero-wind prediction line reflects changes in sound propagation due to refraction for different weather conditions. (From Plotkin, Bradley, and Hobbs, 1998).

B.8.4 Lateral Attenuation Effects for Low-Frequencies

Another effect is involved in predicting aircraft noise for propagation paths near the ground while the aircraft is on, or close to, the runway. This is the so-called installation effect associated with the shielding or diffraction of the noise from the engines by the aircraft fuselage or wings (Society of Automotive Engineers, 1986). These complex effects are inherently included in any sound level measurements made at positions lateral to the aircraft ground track at low elevation angles between the ground and the sound propagation path to the aircraft. The installation effects are considered insignificant for elevation angles greater than about 50°.

Ground attenuation and installation effects are combined into a single sound source/sound path attenuation factor called lateral attenuation. This lateral attenuation is the sound source/sound path attenuation included in INM Version 6.0 (Fleming, Burnstein, Rapoza, and Senzig, 1999). The FAA model includes estimates of the magnitude of installation effects for A-weighted sound levels. These estimates are based on an evaluation of the differences between measured lateral attenuation data and the predicted ground attenuation using essentially the same theory employed to compute Figure 121 (Fleming, 1999).

A more definitive evaluation of the magnitude of installation effects is still being carried out by the aircraft industry through the efforts, in part, of the Society of Automotive Engineers Committee A-21 on Aircraft Noise. However, the average results of Figure 121 are based on A-weighted sound levels for which the dominant frequencies are well above the low frequencies (25-80 HZ) in the LFSL descriptor. Furthermore, diffraction or shielding effects, which are a primary cause of installation effects, will be much weaker for the longer acoustic wavelengths associated with these low frequencies. Thus, based on all the available evidence in the literature, it can be assumed that attenuation from installation effects is negligible for the low-frequency levels of concern for this study. Considering the very small magnitude of ***relative*** ground attenuation as discussed earlier in Section B.8.2, it is reasonable to assume that both ground attenuation and installation effects (*i.e.*, lateral attenuation) can be ignored for present purposes.

B.9 OTHER AIRCRAFT NOISE PROPAGATION EFFECTS

Three final aspects of aircraft noise propagation considered in this review are the attenuation during propagation through built-up urban areas, the temporal fluctuation of aircraft sound heard on the ground, and ground vibration from direct impingement of sound.

When propagating over and around buildings and large trees in built-up urban areas, noise from aircraft that are on (or very near) the ground is subject to attenuation by reflection, diffraction, or absorption from the buildings (Lyon, 1974; Piercy *et al.*, 1977). For this program, these attenuation effects can be neglected since the attenuation tends to be small at the low frequencies of concern.

Due to the effect of atmospheric turbulence on sound propagation, aircraft noises levels can fluctuate rapidly by as much as 5 to 10 dB during propagation through the air, especially when the propagation path is near the ground (Daigle, Piercy and Embleton, 1983). An illustration of such temporal fluctuations for a time history of noise levels during a takeoff is shown in Figure 122. The figure shows these fluctuations for three one-third octave band levels with mid-band frequencies of 12.5, 100 and 1,000 Hz from one flyover record (Plotkin *et al.*, 1999). As indicated in the figure, the fluctuations are generally smaller for the lower frequencies and need only be considered when carrying out measurements of such noise levels.

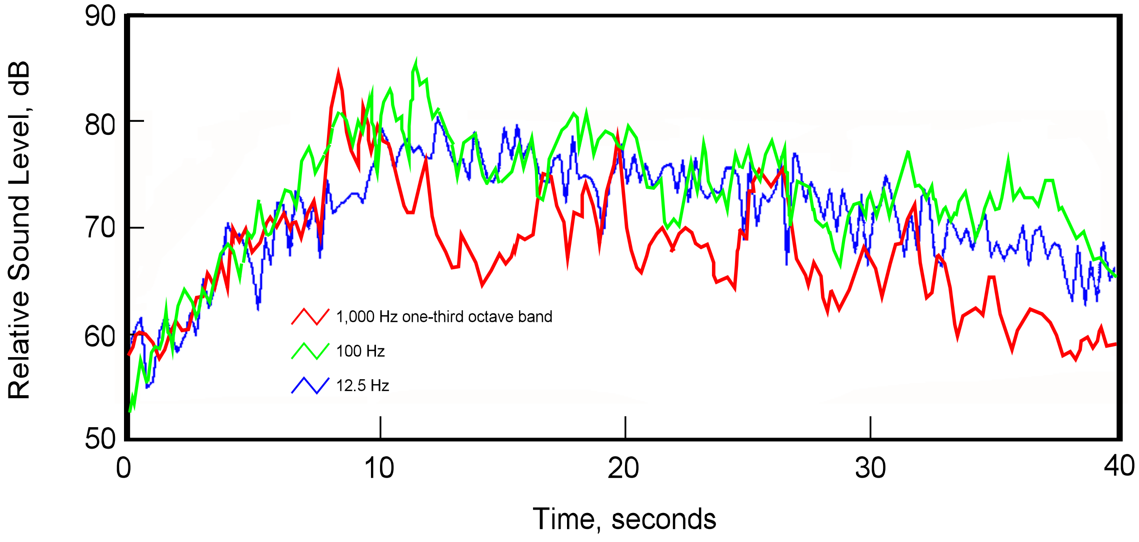

Figure 122 Time histories of low- and high-frequency one-third octave band spectra during the course of an aircraft takeoff roll (adapted from Plotkin *et al.*, 1999).

As a sound wave travels over ground, the ground responds by a vibration in proportion to the magnitude of the sound pressure (Bass and Bolen, 1980). However, the predicted magnitude of this noise-induced ground vibration, confirmed by measurements near rocket launch sites (Sutherland [ed.], 1968), indicates that the levels of ground vibration in the City of Richfield from aircraft operations will be on the order of 20 dB below vibration levels detectable by a person standing on the ground, and well below very conservative criteria for building damage from ground vibration (Siskind, Stagg, Kopp and Dowding, 1980b).

B.10 REDUCTION OF LOW-FREQUENCY AIRCRAFT NOISE INTO RESIDENCES

This section briefly reviews additional data from the literature on noise reduction at low frequencies. While reduction of noise into residences has played a strong part in most studies of major environmental noise sources, and especially reduction of aircraft noise (*e.g.*, Lind *et al.*, 1999), only a few of the many sources of measured noise reduction data are mentioned here.

B.10.1 Measurements of Noise Reduction

Figure 123 compares measured values for low-frequency residential noise reduction reported in the literature with the average noise reduction for treated and untreated homes near MSP presented in Section 5 (see Figures 38 through 46 of Volume II). The MSP data for untreated homes agrees roughly with the measurement data around BWI (Shade, 1997). The wide spread in noise reduction values at high frequencies reflects the trend for lower thermal insulation and hence lower noise reduction values for homes located in warmer climates.

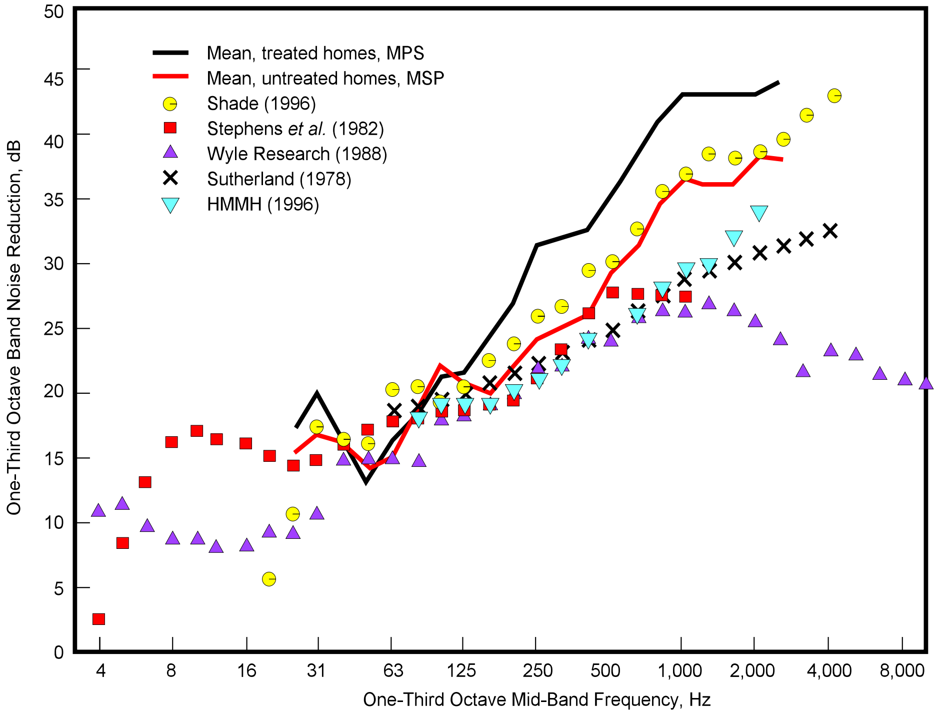

Figure 123 Measured values for low-frequency noise reduction reported in the literature.

Some of the new data in Figure 123 are well below 25 Hz, showing a considerable spread at these lower frequencies. This is consistent with noise reduction into residences at frequencies near or below the fundamental resonance frequency of the walls, and at frequencies that may coincide with internal acoustic resonance frequencies of the measurement room (Gibbs and Maluski, 1998). While the effect of such variations on subjective response of people to low-frequency noise environments is not well defined, the effect is expected to be negligible.

B.10.2 Engineering Prediction Models

While many sources in the literature treat noise reduction design methods for buildings (*e.g.*, Warnock and Quirt, 1991; Lind *et al.*, 1998), fewer treat noise reduction at low frequencies in detail (Sutherland *et al.*, 1983; Brown and Sutherland, 1992; Gibbs and Maluski, 1998; Lind *et al.*, 1999).

Brown and Sutherland (1992) predict the large variation in noise reduction values shown in Figure 123 below 31 Hz using a model that accounts for :

> The influence of "Helmholtz resonances" (*i.e.*, sound generated by blowing on the mouth of a bottle), associated with air leaks through the walls of a building.

The strong influence on low-frequency noise reduction of the lowest resonance frequency of a wall. In this case, mechanical damping inherent in the wall construction can have a significant effect on the corresponding minimum noise reduction at these resonance frequencies.

B.10.3 Criteria and Building Standards

The rapid development of noise insulation programs around airports has stimulated the development of building codes and standards by airports and city and county governments for sound insulation of residences. Examples of such codes and standards include those developed for Seattle-Tacoma International Airport, 1992; Los Angeles Department of Airports, 1995; and the City of Inglewood, 1996. Comparable standards are used for the residential sound insulation program at MSP (Metropolitan Airport Commission, 1997).

These standards vary in detail but typically specify design requirements for critical building components, including:

Exterior windows, both operable and inoperable;

External walls, roofs and ceilings;

Exterior doors; and

Chimneys and outside air ventilation ducts.

The design requirements for external walls, windows, doors and roof assemblies are specified commonly in terms of their Sound Transmission Class (STC), a measure of the basic sound attenuation characteristics of a particular building component (Warnock and Quirt, 1991). In some cases, construction and post-construction inspection verifying testing requirements are also specified. Recommended sound transmission design requirements for new or modified buildings in the City of Richfield are covered in Section 8 of Volume II.

B.11 MITIGATION OF LOW-FREQUENCY AIRCRAFT NOISE IMPACT

Mitigation of low-frequency aircraft noise treated in the literature includes measures applicable at the noise source, along the source-receiver path, and at the receiver (*i.e.*, the residence). These measures are briefly reviewed in the following section.

B.11.1 Mitigation at the Aircraft Noise Source

Substantial progress has been made in reducing noise certification limits for commercial jet aircraft from Stage 1 through Stage 3 (FAA, 1969). Figure 124 illustrates this in terms of the decrease in FAA's FAR Part 36 noise certification noise limits at a position 1,476 ft (450 m) from the runway along the sideline during an aircraft departure. These noise limits increase as aircraft takeoff weight increases.

FAR Part 36 noise certification limits are specified in terms of Effective Perceived Noise Level (EPNL, measured in decibels) a duration- and tone-corrected noise descriptor. EPNL is not directly comparable to A-weighting, and the EPNL values seen in Figure 124 are about 10 to 15 dB greater than comparable maximum A-weighted sound levels. As the figure shows, average sideline noise levels have been reduced by about 16 dB since the first Stage 1 jet aircraft. Corresponding reductions for takeoff and approach noise certification positions are on the order of 18 dB and 12 dB, respectively.

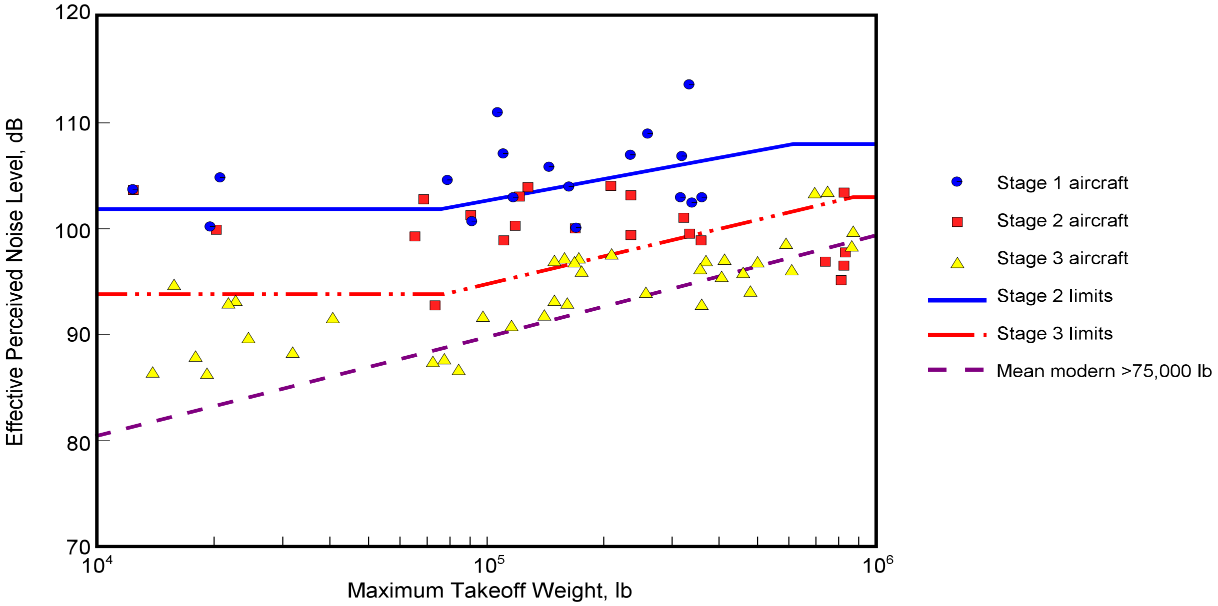

Figure 124 Progress made in reducing noise certification limits for commercial jet aircraft from Stage 1 through Stage 3 (FAR Part 36, 1969).

The requirement that all commercial jet aircraft operating in the continental United States must be Stage 3 by 1 January 2000 has been largely met by most commercial airlines. As can be seen in Figure 124, the quietest aircraft are several decibels below the FAR Part 36 Stage 3 limits.[35]

Airframe noise, which is generated by air turbulence around jet aircraft surfaces during landing and departure (prior to retraction of landing gear), is a low-frequency noise that has received little attention (Hardin, 1976; Crighton, 1991). Due to the large dimensions of commercial jet aircraft, this mixture of aero-acoustic noise sources generates a broadband noise spectrum (Crighton, 1991) with a large component of low-frequency noise. Figure 125 shows the noise spectrum generated by an early, large commercial jet aircraft, the VC-10, under two aerodynamically-different conditions. The VC-10 had a wing area of 2,800 to 2,930 square feet, comparable to that of a BAC A-300 or a Boeing 707-320. It was powered by four pure jet engines on the tail (two on either side) in a configuration similar to that of the McDonnell-Douglas DC-9. The figure illustrates a marked increase of 10 to 15 dB in one-third octave band levels at low frequencies for the aerodynamically "dirty" configuration, presumably with wheels and flaps extended as during ground roll or takeoff, as compared to the "clean" configuration. The low-frequency spectral shape is flatter for the dirty configuration, showing a slight increase as frequency decreases.

---

[35] The aircraft noise reduction achieved under FAA and ICAO regulations is attributable in large part to the design of high by-pass ratio turbofan engines, which are quieter and more fuel-efficient.

This suggests an aerodynamic rather than an engine-noise source for the atypical low-frequency noise reflected by the data in the upper panel of Figure 113 on page 55 of Volume III (*i.e.*, the data in the upper panel reflect increased low-frequency aerodynamic noise associated with ground roll, while the data in the lower panel reflect the propulsion-system noise after rotation and after landing gear and flaps are retracted).

Further evidence of the potential significance of aero-acoustic sources of non-propulsion low-frequency noise can be found in a study of aircraft noise produced beneath high-speed subsonic military aircraft (Sutherland, 1989). Measured low-frequency noise levels under such aircraft tend to exhibit the same, relatively flat spectral shape shown in Figures 113 and 125. Data from this study supported development of a prediction model for low-frequency aerodynamic noise, based primarily on a prior study conducted by NASA on airframe noise (Hardin, 1976). This prediction model was used to make direct estimates of low-frequency noise expected at MSP, and to extrapolate the VC-10 data shown in Figure 125 to conditions applicable to the MSP measurements. These two applications of the model produced estimates of low-frequency noise levels at site 1 at MSP (see Figure 113) that were about 1 to 7 dB below the lower bound of the low-frequency MSP data. This modest agreement is reasonable in the absence of a verified engineering model for aerodynamically-generated low-frequency noise, but suggests the need for further study.

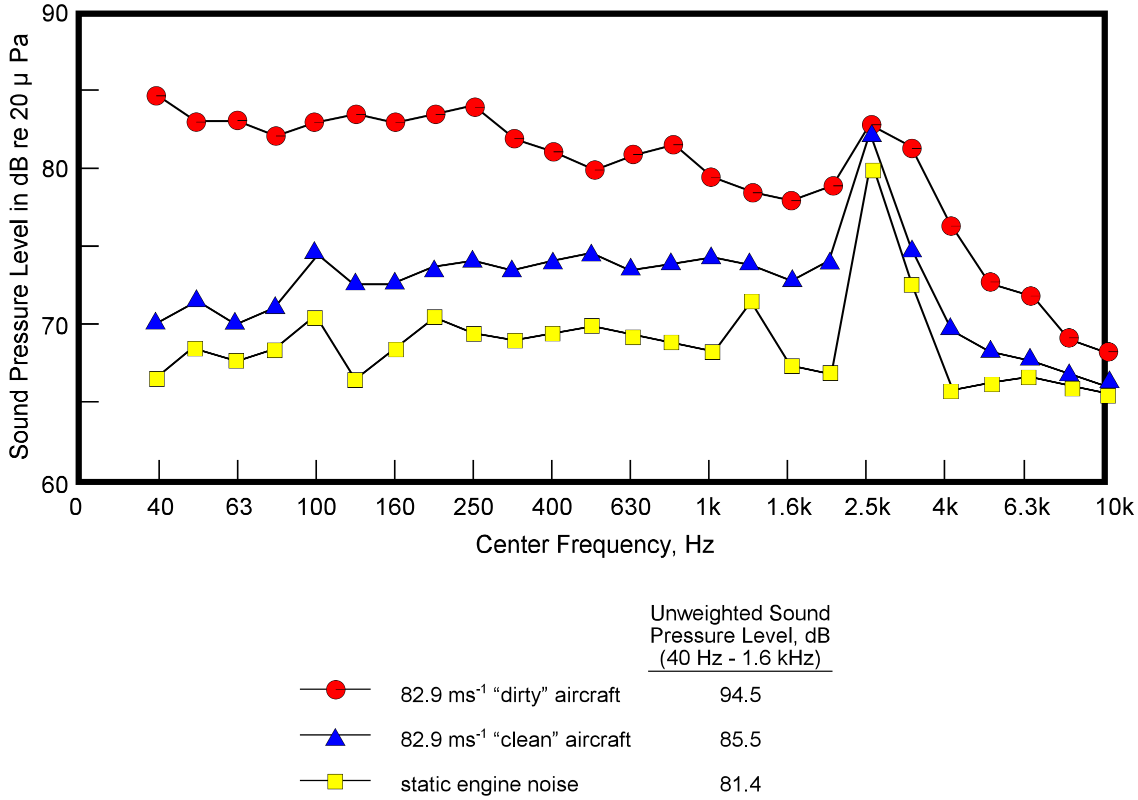

Figure 125 Comparison of one-third octave band airframe noise spectra for "dirty" and "clean" configurations of VC-10 aircraft flying overhead at airspeed of 83 meters per second, and at 183 meters altitude (from Hardin, 1976).

Another source of low-frequency noise that may be present briefly during takeoff is "wall-jet" noise, arising from the impingement of jet engine exhaust on the runway during the few seconds while the aircraft rotates upward on its back wheels and accelerates, just before lifting off the ground.[36] This phenomenon was confirmed in a conversation with a recognized expert in the Boeing Company. While its potential as a significant source of low-frequency noise during aircraft departure has not been determined, based on experimental data (Sutherland and Brown, 1972) on noise of vertically-directed jets (VTOL), jet exhaust into the runway, even for a few seconds, might generate significant low-frequency noise levels for two reasons:

> The "wall jet" formed by impinging jet flow is a fundamentally more efficient source of noise than the free jet, causing increases in sound levels of 10 to 20 dB for vertically-directed jets. A more modest increase in low-frequency noise from this source during aircraft takeoff is very reasonable.
>
> Impingement of the deflected jet exhaust tends to create larger flow dimensions than basic engine exhaust, shifting the frequency spectrum of the aerodynamic noise source downward (*i.e.*, the larger the flow dimensions of an aero-acoustic noise source, the lower its peak frequencies).

While both airframe and wall-jet noise are potential sources of low-frequency noise, neither is amenable to significant noise abatement since they arise from the inherent design or operational features of jet aircraft. A possible exception would be the use of more streamlined wheel well configurations, reducing the airframe noise produced by the deployment of landing gear. Nevertheless, further studies of wall jet and airframe noise might aid in the assessment of environmental impacts of low-frequency noise in communities such as Richfield.

Two final sources of low-frequency noise are (1) noise from thrust reverser operation (see Section 6.4 in Volume II), and (2) noise from ground run-up or ground testing operations. Both sources are unavoidable near airports. Voluntary night curfews on ground run-ups and engine noise reduction facilities can help to reduce the occurrence of low-frequency noise from engine maintenance.

B.11.2 Mitigation Along a Sound Propagation Path by Sound Barriers

Barriers have been employed around some airports, such as LAX, to reduce sideline noise exposure. The design methods for such barriers are well understood (*e.g.*, Kurze and Beranek, 1971) showing that the key design parameters for such barriers are its height and the distances between the barrier and the aircraft source and receiver (*i.e.*, the residence). This is shown in Figure 126 for a barrier of varying height located 1,250 feet from a runway. The results are not sensitive to the engine source height of 14 feet and receiver height of 5 feet assumed for this figure. The barrier attenuation is shown in terms of the theoretical reduction in LFSL using the relative spectrum shapes as a function of runway position, X shown earlier in Figure 119. To provide a conservative estimate of this barrier attenuation, the theoretical lower limit of 5 dB attenuation when the barrier top is on the line of sight between source

---

[36] The slight down angle of the jet engine centerline while resting on the ground is increased by the additional small rotation angle of the aircraft. The resulting increase in down angle is sufficient to cause the engine exhaust, which extends five to ten engine-diameters aft, to briefly impinge on the ground, giving rise to wall-jet noise.

and receiver (Kurze and Beranek, 1971) was not included. This also helps account for the fact that net attenuation of a barrier is less than predicted by theory due to the elimination of the ground attenuation present without the barrier.

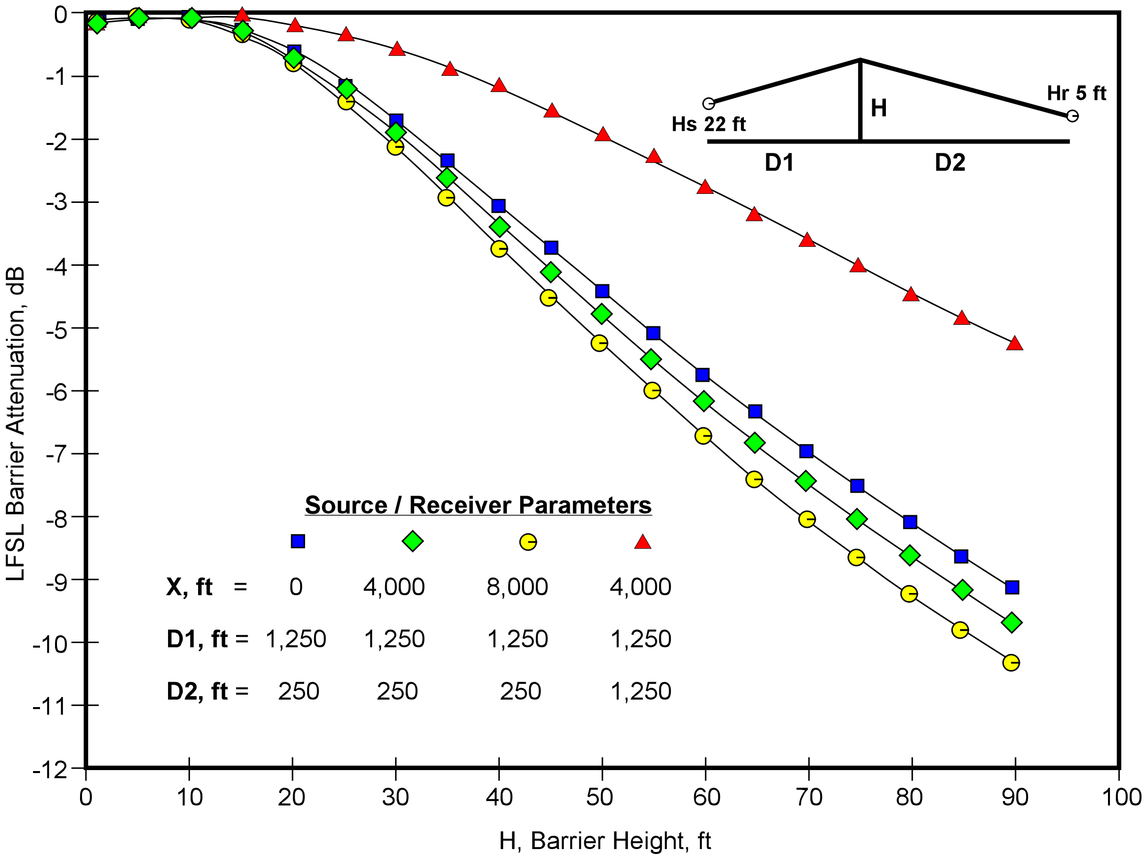

Figure 126 Attenuation of low-frequency sound level (LFSL) by a barrier.

As indicated in the figure, a barrier height of at least 50 feet would provide about 5 dB of attenuation in LFSL for homes located within 1,500 feet from the runway (*e.g.*, D2 = 250 feet) and only about two to three dB of attenuation at homes located 2,500 feet from the runway. While not an insignificant amount of noise reduction, especially at low frequencies, the barrier would be costly, esthetically undesirable and effective only for the time the aircraft is on the ground.[37] Furthermore, the low-frequency barrier attenuation would be subject to some variation depending on the speed and direction of wind at right angles to the barrier.

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[37] ***While the Expert Panel discussed many aspects of barriers and did not limit its discussion to stand-alone barriers, the discussion here is limited to stand-alone barriers. Buildings (i.e., hangers, office buildings and similar structures) can provide beneficial barrier effects and should be considered.***

DeJong and Stusnick (1976) studied the sensitivity of barrier attenuation for upwind and downwind conditions, including a scale model test in a wind tunnel. The latter showed the barrier attenuation increasing or decreasing by up 3 to 5 dB at high frequencies for a runway crosswind of 11 miles per hour in the direction of sound propagation. Thus, for this worst case wind condition, nominal barrier attenuation could be nearly eliminated.

B.11.3 Mitigation at the Receiver

Noise impact mitigation measures that can be taken at receivers (*i.e.*, at residences) include reduction of the noise and vibration or rattle in the home, changing the land use in the close vicinity of the airport, or providing compensatory economic incentives to residents. Each of these measures is briefly considered here.

B.11.3.1 Mitigation by increasing noise reduction

The first step in increasing noise reduction into residences would be the application of the noise insulation design and construction standards mentioned earlier in Section B.12.3. However, additional measures not necessarily included in such programs can be considered.

Since the weakest link in achieving high noise reduction into a residence is usually the windows, further improvements in the window design may be cost effective. Such further improvements can include (Schomer, 1991):

> Upgrading the edge seals around the window periphery using a tighter seal and more weather-resistant materials
>
> Increasing the window thickness
>
> Using double-pane construction with an air space between each pane

The next place to look for improvements in noise reduction will usually be the walls. Innovative techniques to increase sound attenuation through the walls have been extensively explored experimentally and analytically in one benchmark study (Sharp, 1973). Key conclusions of the study include:

> Simple design algorithms developed to support improved design concepts and increased sound transmission loss for single and multiple panels, especially those with undesirable structural sound transmission bridges that can limit achievement of high noise reduction.
>
> Careful design and fabrication taking full advantage of the basic mass law (*i.e.*, increasing the surface weight of the wall) for improving sound transmission loss, but over a wider frequency range than normally achieved in standard construction.
>
> Use of nontraditional building materials offering higher sound transmission properties. This approach usually requires support and participation by the building industry in the development of such cost-effective building materials in a practical form.

Similar concepts suitable for high transmission-loss walls and windows can also be applied to improving sound transmission through doors — another weak link in noise reduction into residences.

Other building components that need careful consideration for improvement in noise reduction can be recognized in:

> Poorly insulated or lightweight roof or ceiling systems
>
> Inadequate acoustic "traps" for penetrations into a house such as chimneys, pet doors, mails slots, air vents, *etc.*

More detailed studies of benefits or requirements for sound insulation near airports are also available (*e.g.*, Shade, 1996; Lind, Pearsons and Fidell, 1998).

B.11.3.2 Mitigation by reducing vibration and rattle

Rattle can occur inside a building when a solid surface of any sort lies close to, but not necessarily in direct contact with an adjacent solid surface. Acoustically-induced vibration of these surfaces can cause them to impact each other giving rise to the annoying sound of rattle (Sutherland, 1982; Schomer and Neathammer, 1985).

Specific techniques for minimizing rattle and assessing the annoyance benefits of such action have been carefully studied by the U.S. Army Construction Engineering Research Laboratory (CERL). While these techniques are intended for application to residences exposed to blast sounds from DOD artillery weapons training areas (Schomer, Hottman, Kessler and Kessler, 1987a; Schomer, Hottman and Eldred, 1987b; Schomer, 1991), they would still be effective for reduction of aircraft noise-induced rattle. Recommendations for minimizing rattle of building elements excerpted from Appendix B of Schomer, Hottman, Kessler and Kessler, 1987 are reproduced here in Tables 30 through 33. These recommendations address seven basic types of windows (fixed, casement, awning, sliding, double-hung, jalousie, and pivoting), multiple door types (swinging, bypass sliding, surface sliding, pocket sliding, and side-hinge folding; flush, paneled, french, glass, sash, jalousie, louvered, shuttered, screen, and dutch), ceiling systems, bric-a-brac, wall hangings and other building components.

Table 30 Steps to minimize window rattle due to low-frequency aircraft noise.

POSITIVE ACTIONS	ACTIONS TO BE AVOIDED
Use a fixed window if outdoor air is not required.	Don't allow the jalousie window opening mechanism to become loose or worn. All shafts should rotate in soft plastic bushings. All gear clearances should be minimized. Linkage should be encased in soft plastic sleeves.
Use a casement or awning window which can be secured firmly against a gasket.	Don't allow window hardware to loosen. Inspect the hardware periodically and apply preventive maintenance.
Use gasket material liberally to reduce the gap between the sash and track and to soften the impact when these two components make contact. A second advantage is the improved reduction in heat loss.	Don't use a sliding, double-hung, jalousie, or pivoting window as a new or replacement window due to the gaps which exist between the sash and track.
Encase the double-hung window sash weights in a soft plastic jacket to soften the contact when the weight vibrates Apply a small felt disk to the lower edge of each jalousie window element to prevent window-to-window contact. Manufacturers should bond a soft plastic sleeve to the window edge to prevent heat loss and rattle.	

Table 31 Steps to reduce or prevent rattle in ceiling systems due to low-frequency aircraft noise.

POSITIVE ACTIONS	ACTIONS TO BE AVOIDED
Ensure that enclosed lighting fixtures are well made with minimum gaps. Ensure that the sheet metal housing is stiff and well secured at its contact points.	Don't use a dropped acoustical tile ceiling. If one is used, insure that contact between vertical wires and joist and metal frame is eliminated. Don't use light fixtures that hang from the ceiling by a chain or similar device. Also, avoid light fixtures with loose elements.

Table 32 Steps to reduce or prevent rattle of doors due to low-frequency aircraft noise.

POSITIVE ACTIONS	ACTIONS TO BE AVOIDED
Use swinging paneled doors for the home exterior. Swinging and side-hinged folding doors should be used in the home.	Don't use lightly constructed screen doors. Enclose the safety chain in a soft plastic sleeve and insure that the hardware is tight and in good repair.
Use a single rather than a multiple-element garage door. Weatherstrip the building jamb and allow minimum clearance between the overhead track and roller. Encase the springs in soft plastic jackets.	Don't use sliding doors, particularly the pocket sliding type. If sliding doors must be used, don't hang the door loosely from the ceiling, use a bottom track also. The gap between the track and the door should be minimized. A track liner of soft plastic or weather stripping-like material will minimize contact.
Avoid french, dutch, jalousie, louvered, and shutter doors. If used, separate the door elements using soft plastic foam or weatherstripping-type materials.	
Use a plastic screen instead of a metal screen.	
Insure that the door hardware is in good repair. Minimize the gaps in lockset tongues where the tongue fits into the jamb. Insure that hinge pins are tight and coated with plastic. Place a soft plastic foam or felt strip on door mail slots to prevent hard contact.	

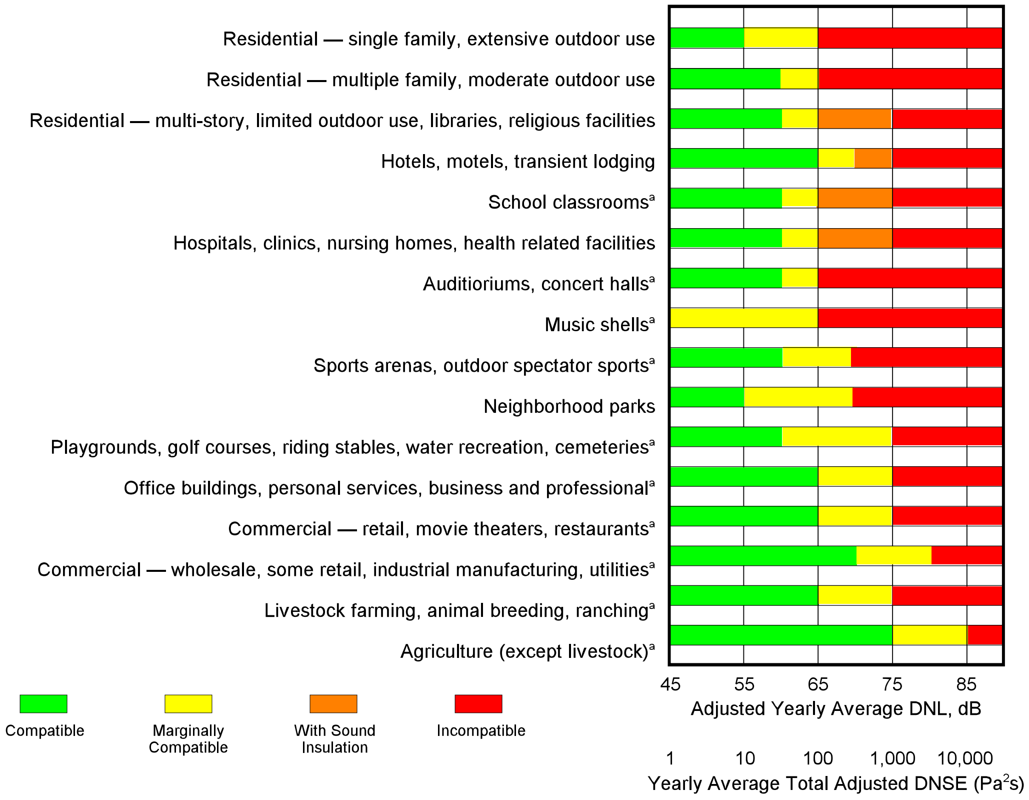
Table 33 Steps to reduce or prevent rattle of miscellaneous household items, including bric-a-brac, due to aircraft noise.

POSITIVE ACTIONS	ACTIONS TO BE AVOIDED
Install soft plastic foam or weather stripping-like material to the lower edge of the back of hanging mirrors and picture frames to prevent direct contact by the frame or mirror with the wall.	Don’t allow home heating ducts and registers to loosen. Use duct tape around all seams.
Separate small items from the surfaces of shelves, in closets, or on other horizontal surfaces by using small felt or foam disks or strips glued to the underside of the item.	
Separate plates placed horizontally on shelves using soft plastic foam doilies.	
Ensure that window air-conditioners are installed properly. The refrigeration coils should be separated. Air intake and exhaust louvers should be separated by foam strips or disks.	
Keep downspouts and gutters in good repair. Ensure that all seams are tight and covered with duct tape.	

Some of these tabulated recommendations to prevent or reduce rattle in homes subject to high levels of low-frequency noise are suitable for incorporation into building design codes, while others might be included in an advisory guide to homeowners to minimize acoustically–induced rattle of building components or furnishings.

B.11.3.3 Mitigation by land use planning

Land use planning can help to minimize future incompatibilities between as-yet undeveloped land and current or future aircraft noise. It can also guide re-development of existing land in ways that minimize future incompatibilities. Figure 127 shows a recommended guideline for compatible land use in noise-impacted areas that is contained in Part 5 of ANSI S12.9-1998 (ANSI, 1998). The guide is not necessarily valid for areas exposed to low-frequency aircraft noise. Appropriate revisions to the standard, based on the material presented in this report, may need to be considered in and around the City of Richfield where low-frequency noise is a unique element of aircraft noise exposure.



[a] *Receiver locations at which it may be appropriate to use Day-Night Sound Exposure, in (Pascal)^2 • seconds, and Sound Exposure Level, in decibels, without inclusion of special adjustments (from Part 4 of ANSI S12.9).*

Figure 127 Land use planning guidelines for noise exposure (from American National Standards Institute).

B.11.3.4 Mitigation by economic incentives

The final mitigation measure considered here is economic incentive. While application of economic incentives does not reduce noise, it may make the noise environment more palatable. A unique survey of such measures was conducted in 1996 by BBN (Fidell, Silvati and Howe, 1996) for the MSP Noise Mitigation Survey Group. This telephone survey reached 2,880 respondents from a sample of 11,700 households in 19 regions around MSP, including 787 respondents in northern and southeastern Richfield.

The measures posed to the respondents included four purely economic incentives (free airline tickets, reduced property taxes, paid neighborhood improvements, and financial support to residents who wished to sell their homes), one for noise reduction treatments (acoustic insulation of their homes), and two purely operational noise reduction measures (*i.e.*, one- to six-hour periods during the day when no aircraft would operate, or fewer aircraft operations per day). While the operational measures were not economic incentives, they allowed the survey to rank the preferability of different kinds of noise mitigation measures.

The results of the survey are shown in Figure 128 in terms of the average percent of positive responses to the various alternatives as a function of average A-weighted DNL at respondents' residences. Except for an increased preference for acoustic insulation as DNL approached 65 dB and higher, there was no apparent effect of noise exposure level on preference for any particular incentive. The operational changes, however, were preferred over any of the economic incentives. Financial assistance with selling one's home was the least preferred incentive, suggesting a strong commitment of most of the respondents to their existing homes. Finally, the acoustic insulation measure was clearly preferred over any of the non-acoustic, economic incentives. These results tend to validate the effectiveness of the sound insulation program being carried out around MSP.

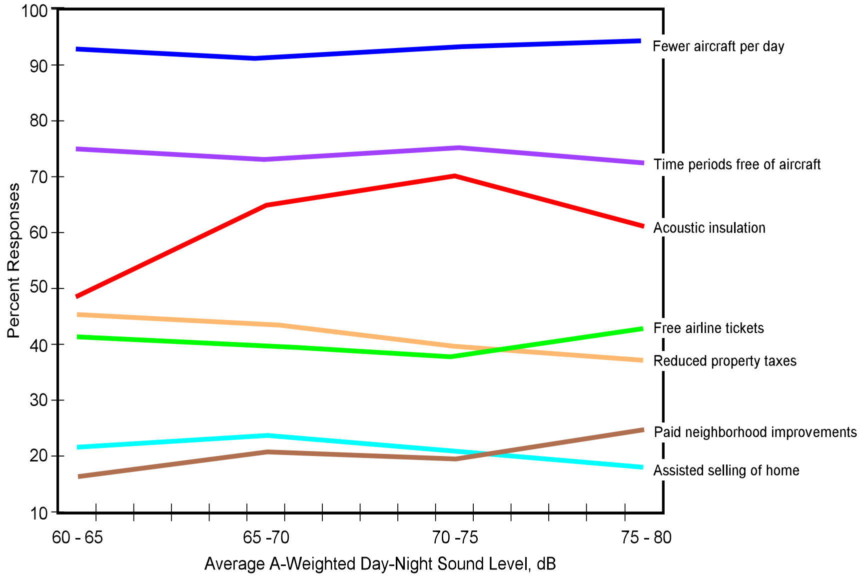


Figure 128 Responses to economic incentive options.

B.12 SUMMARY OF HUMAN RESPONSE TO LOW-FREQUENCY NOISE

Key findings of this review of the literature on human response to low-frequency noise are summarized in the following sections.

B.12.1 Low-Frequency Aircraft Sound Levels

Available aircraft noise models are not adequate to predict low-frequency sideline noise — direct measurement is still required.

The low-frequency sound level descriptor employed for this study (LFSL) is readily measurable with current acoustic instrumentation, and can be roughly estimated from C-weighted sound levels.

Measured LFSL, relative to C-weighted sound level, shows a consistent pattern of variation as a function of the distance along the runway from brake release. Lower frequencies predominate at positions closer to brake release.

Weather-sensitive refraction conditions play a major role in the stability of runway sideline noise levels. For example, at very low elevation level angles of the sound propagation path from aircraft to receiver (*i.e.*, less than 10°), downwind and upwind propagation of A-weighted sound levels can vary by as much as +15 dB and -15 dB, respectively. This type of weather-sensitive variation may be less for lower frequency noise levels.

Ground attenuation of low-frequency sound levels is not expected to be significant for most ground surface conditions, with the exception of fresh, deep snow.

B.12.2 Subjective Measures of Low-Frequency Noise

While loudness calculation methods offer the most accurate way to assess aircraft noise, simpler noise assessment descriptors employing more commonly used instrumentation are preferred.

A limited assessment of low-frequency acoustic excitation of the body (*i.e.*, the chest wall) presents a consistent pattern, indicating a threshold for perception of acoustically-induced (physiologically harmless) chest wall vibration occurring at one-third octave band levels of about 65 dB at frequencies of about 40 to 80 Hz.

B.12.3 Perception of Acoustically-Induced Low-Frequency Vibration and Rattle

Current methods to predict threshold levels for perception of noise-induced building vibration may be too conservative at frequencies below 16 Hz.

Well-established models for predicting building vibration and associated human response have provided a more reliable measure of threshold levels for human vibration detection and annoyance.

One-third octave band sound levels at the threshold for onset and detection of acoustically-induced vibration of windows are in the range of *68 t*o 72 dB at low frequencies (*i.e.*, 25-80 Hz). These thresholds are roughly comparable to widely employed threshold levels for detection of acoustically-induced window vibration. Corresponding LFSL values threshold values for detection of window vibration would be about 78-80 dB.

One-third octave band values at the threshold for onset of acoustically-induced window rattle vary from about 78 dB at 25 Hz to 88 dB at 80 Hz, or 10 to 15 dB greater than that for detection for vibration of windows.

B.12.4 Summary of Human Response to Low-Frequency Noise in the City of Richfield

According to the respective criteria for the thresholds shown in Figure 129, anticipated low-frequency sound levels (LFSL) in the City of Richfield may exceed subjective levels of perception as follows:

(1) 70 to 75 dB for perception of chest wall vibration;

(2) 78 to 80 dB for perception of window vibration; and

(3) 88 to 96 dB for onset of window rattle.

B.12.5 Noise Mitigation Measures

Only limited reduction may be possible for airframe noise.

Full use should be made of existing design guides and prediction models for maximizing noise reduction of residences. However, current state of the art methods offer relatively little noise reduction of low-frequency noise into residences.

Practical steps are available to homeowners and builders to reduce acoustically-induced building vibration and rattle.

While other economic incentives to reduce noise impacts around airports are possible, application of acoustic treatments is likely to be the most attractive alternative, short of reducing numbers of aircraft operations.

Figure 129 summarizes the low-frequency noise criteria for human response.

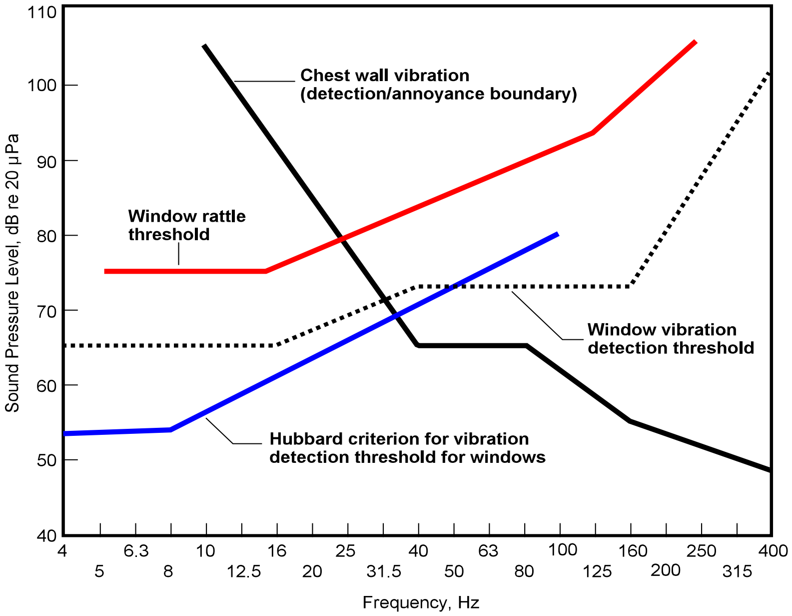


Figure 129 Summary of criteria for human response to low-frequency noise.

APPENDIX C REVISED PLAN OF WORK FOR THE EXPERT PANEL ON MSP LOW-FREQUENCY AIRCRAFT NOISE

Section C.1 contains the revised Plan of Work approved by the Policy Committee in March, 1999. Section C.2 contains a further revision of the Work Plan approved by the Policy Committee in July, 1999.

C.1 REVISED PLAN OF WORK

1 March, 1999

PURPOSE:

A Low-Frequency Noise Policy Committee (the "Policy Committee") was established by an agreement between the Metropolitan Airports Commission and the City of Richfield. The agreement charged the Policy Committee to conduct a comprehensive study of low-frequency aircraft noise. The agreement charged the Policy Committee to convene an Expert Panel to provide technical input and information to the Policy Committee. The Policy Committee requested that the Expert Panel draft a Plan of Work containing those tasks required to provide the Policy Committee with the technical information that it needs to fulfill its responsibilities under the agreement.

PREAMBLE:

A Draft Work Plan was prepared by the Expert Panel as the basis for discussions with the Policy Committee on 17 February, 1999. The Expert Panel met on 25 February, 1999 to revise the Draft Work Plan. This Revised Work Plan is submitted for discussion with the Policy Committee during the meeting of 3 March, 1999. Revisions include refinement of individual task descriptions and development of proposed schedules for completion of tasks and presentations to the Policy Committee.

During the meeting of 25 February, 199 the Expert Panel completed substantive work on some tasks. The task descriptions include the results of that work (*e.g.*, agreement that annoyance is the effect of low-frequency noise that the Expert Panel is addressing).

TASKS IN WORK PLAN:

The Work Plan proposed by the Expert Panel consists of the following nine tasks:

Task 1. Review literature on audibility, noticeability, and effects of low-frequency noise on individuals and communities

The documents to be reviewed include those listed below. Additional documents that the Expert Panel believes will improve the information base will also be reviewed. The completion date for Task 1 is 23 April, 1999.

Berglund, B., Hassmén, P., and Job, R.F.S. (1996). "Sources and effects of low-frequency

noise," J. Acoust. Soc. Am., 99(5), 2985-3002.

Blazier, W. (1991). "Noise Control Criteria for Heating, Ventilating, and Air-Conditioning Systems," Chapter 43 of Harris, C. (ed.), Third Edition, Handbook of Acoustical Measurements and Noise Control, McGraw-Hill, Inc., New York.

Broner, N. (1978). "The effects of low-frequency noise on people — a review," J. Sound and Vib., 58(4), 483-500.

FAA Engineer's Report (1998). "Residential Sound Insulation at Baltimore/Washington International Airport," AIP 3-24-0005-39.

Fidell, S., Silvati, L., Pearsons, K., Lind, S., and Howe, R. (1999). "Field study of the annoyance of low-frequency runway sideline noise," J. Acoust. Soc. Am., in press.

HMMH Report 294090, (1996). "Development of Single Event Noise Metrics for Use in Identifying Aircraft Operations for Possible Mitigation."

HMMH Report 293810.04, (1996). "Logan Low-Frequency Noise Study."

HMMH Report 294730.300/293100.09 (1998). "Study of Low-Frequency Takeoff Noise at Baltimore-Washington International Airport."

Hubbard, H. (1982). "Noise Induced House Vibrations and Human Perception," Noise Control Engineering Journal, Volume 19, No. 2, pp. 49-55.

Lind, S., Pearsons, K. and Fidell, S. (1997). "An Analysis of Anticipated Low-Frequency Aircraft Noise in Richfield Due to Operation of a Proposed North-South Runway at MSP," BBN Report 8196.

Task 2. Identify relevant noise effects and descriptors

The Expert Panel shall describe the purposes for which low-frequency noise descriptors are needed and compare the utility of C-weighted and other measures of low-frequency aircraft noise for these purposes. The Panel shall also identify means for converting disparate low-frequency noise descriptors into comparable units, and if possible, reach agreement on a single preferred noise descriptor for present purposes. The completion date for Task 2 is 31 March, 1999.

During its meeting of 25 February, 1999 the Expert Panel decided that there is a very high probability that annoyance is the only effect of consequence from present or future low-frequency noise in the vicinity of MSP. While the literature review (Task 1) will be relied upon to confirm or reject that thesis, the Expert Panel will begin its work focusing on issues associated with annoyance.

Task 3. Determine existing and predicted low-frequency noise levels in the vicinity of MSP runways

BBN and HMMH have both estimated low-frequency noise levels due to future operation of Runway 17/35, although the two studies used different descriptors to describe the noise environments. In this task, the Expert Panel will undertake two subtasks: (1) determine current ambient and aircraft-related low-frequency noise levels; and (2) resolve any differences between BBN and HMMH estimates of future noise levels. In the first subtask, the Expert Panel will measure and map existing low-frequency noise levels in Richfield and in other areas in the vicinity of MSP selected for comparison with areas in Richfield. These would include areas in Minneapolis and Bloomington as appropriate. (The measurements will be conducted at the same time as the measurements for Tasks 5 and 6.) In the second subtask, the Expert Panel will map predicted noise levels based on existing data using the descriptor selected in Task 2. The completion date for the second subtask of Task 3 is 23 April, 1999.

Task 4. Identify criteria for acceptability of low-frequency noise in residences

The Expert Panel shall identify a rationale for assessing the acceptability of low-frequency aircraft noise intrusions. This effort will include require conduct of listening tests under controlled conditions. The rationale shall take into consideration the relative annoyance of overflight, departure and ground noise of aircraft operations, the prevalence of annoyance due to aircraft ground operations, and such other factors as agreed by the Expert Panel. The rationale shall permit inferences about the efficacy of alternate treatments for increasing low-frequency noise isolation in residences, and to the extent feasible, generally resemble the rationale for mitigation of the effects of overflight noise. Four levels of noise reduction will be tested: typical (unmodified) residential construction and construction that provides 3 dB, 6 dB and 9 dB of noise reduction improvement at low frequencies. The completion date for Task 4 is 4 May, 1999.

Task 5. Determine low-frequency noise reduction provided by typical residential construction in the vicinity of MSP

Little objective information is available about low-frequency noise reduction of typical residences in the vicinity of MSP. The Expert Panel will define a program of measurements to document the low-frequency noise reduction of such residences. The measurements will be undertaken by the Expert Panel or with the assistance of personnel of MAC and the City of Richfield. The measurements will be conducted at approximately five houses of each type of construction typical of the housing stock around MSP. The completion date for Task 5 is 18 June, 1999.

Task 6. Determine low-frequency noise reduction provided by residences subsequent to treatment in the MSP Residential Sound Insulation Program

This task is similar to Task 5, but is for residences that have been treated in the MSP Residential Sound Insulation Program. The Expert Panel will define a program of measurements to document the low-frequency noise reduction of such residences. The measurements will be undertaken by the Expert Panel or with the assistance of personnel of MAC and the City of Richfield. The measurements will be conducted at approximately five houses of each type of construction typical of the housing stock around MSP. (The construction types will be the same as identified during Task 5.) The completion date for Task 6 is 18 June, 1999.

Task 7. Evaluate the acceptability of low-frequency noise environments in residences without and with treatment from the MSP Residential Sound Insulation Program

Based on the noise reduction information from Tasks 6 and 7 and future low-frequency noise levels from Task 3, the Expert Panel will estimate interior levels of low-frequency noise in residences without and with treatment from the MSP Residential Sound Insulation Program. The Expert Panel will then compare the estimated levels with acceptability criteria identified in Task 3. The measurements will be conducted at approximately five houses of each type of construction typical of the housing stock around MSP. The Expert Panel believes that this task will identify the need to improve the noise reduction of at least some construction types beyond the level achieved by treatment from the MSP Residential Sound Insulation Program to achieve compatibility. For that reason, it is recommended that the laboratory portion of Task 8 be undertaken as part of this Work Plan. The completion date for Task 7 is 16 July, 1999.

Task 8. Determine the types of treatment required to improve the noise reduction and achieve compatibility of the low-frequency noise environment

In this task, the Expert Panel will identify construction techniques appropriate to achieve the noise reduction required to achieve acceptability. Before use of the techniques in a mitigation program, the Expert Panel believes that they should be analyzed using the following methods: (1) testing in a laboratory environment, and (2) application to several residences in the vicinity of MSP. The Expert Panel proposes that the laboratory analysis be conducted within this work plan. However, because of the time required for field modifications and testing, the Expert Panel recommends that application to residences in the vicinity of MSP occur after completion of this Work Plan. The completion date for Task 8 is 14 May, 1999.

Task 9. Prepare reports to the Policy Committee documenting the work of the Expert Panel

The Expert Panel will undertake all tasks in this Work Plan in a manner to facilitate regular progress reports to the Policy Committee. To achieve this goal, the Expert Panel will prepare interim and final reports documenting each task. At the completion of Tasks 1 through 7, a consolidated report will be prepared. The completion date for Task 9 is 30 July, 1999.

PROPOSED SCHEDULE OF PRESENTATIONS TO THE POLICY COMMITTEE

The Expert Panel proposes that the results of each task be discussed at meetings with the Policy Committee shortly after completion of the individual tasks. The proposed schedule of meetings is listed below. Please note that the schedule of meetings differs from the initial schedule distributed on 17 February, 1999. While the number of meetings is the same, a total of 8, the dates of individual meetings have been changed to fit the schedule for completion of tasks. The Expert Panel believes, however, that the overall schedule of tasks and meetings is consistent with an ambitious, but achievable, schedule for completion of the technical work.

Meeting Date	**Topic**
31 March	Task 2: Noise Effects and Descriptors
28 April	Tasks 1 and 3: Literature Review and Predicted Levels of Low-Frequency Noise
19 May	Tasks 4 and 8: Criteria for Acceptability of Low-Frequency Noise in Residences and Types of Treatment Required to Improve Low-Frequency Noise Reduction
23 June	Tasks 3, 5 and 6: Measurements of Ambient Low-Frequency Noise and Low-Frequency Noise Reduction of Residences without and with Treatment from the MSP Residential Sound Insulation Program
21 July	Task 7: The Acceptability of Low-Frequency Noise Environments in Residences without and with Treatment from the MSP Residential Sound Insulation Program
Fall, 1999	Task 9: Final Report

C.2 FURTHER REVISION OF PLAN OF WORK

At the suggestion of FAA's Office of Environment and Energy made during a meeting with the Expert Panel in July, 1999, additional field measurements of low-frequency aircraft noise were made in the social survey interview area described in Section 4.2.4 of the report.