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Status of Low-Frequency Aircraft Noise Research and Mitigation

Prepared for:

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1.0 Introduction

In recent years, concerns over low-frequency noise have surfaced at a number of US airports. Low-frequency noise is generated by the exhaust of jet aircraft, and is particularly noticeable during takeoff operations in the communities located to the rear of departing aircraft. The noise experienced in this area is termed “backblast” noise. Most complaints of backblast noise are related to the rattling of houses and their belongings caused by the noise, and not so much to the noise itself.

It should be recognized that there is nothing particularly new about backblast noise. It has always been present at jet airports, and has not increased over the years - in fact it has decreased in level with the introduction of the high-bypass-ratio engines that are installed on many, but not all, Stage 3 aircraft in operation today. Some observers state that it may be more apparent now that the higher frequency noise has been reduced in Stage 3 aircraft. It is probably more true that the continued presence of the aircraft that only just meet the Stage 3 limits has led to these perceptions, as these aircraft with their low-bypass-ratio engines stand out from the rest.

The question is: “What can be done to reduce backblast noise, or the rattle problems that it induces?”. The concerns at airports are fairly new, certainly compared to those concerning overflight noise, and there is no centralized database of technical literature addressing it specifically. There is, however, literature on low-frequency noise in general. There are also reports on low-frequency noise at airports that cover a range of technical aspects, but do not provide a definitive, overall picture of the phenomenon. Most of these reports have been prepared for very specific and limited purposes, and do not provide a comprehensive technical basis from which mitigation measures can be evaluated.

The objective of this report is to provide a comprehensive review of backblast noise – how it is generated, how it propagates, how it can be mitigated, and where future study efforts and demonstration projects should be directed. The complete process is examined in order to fully understand why certain mitigation measures will work, and why some will not work, so that any current misunderstandings can be put to rest. The previous work of others has provided much of the data included in the report. A listing and brief review of the more relevant documents is given in the Appendix. A final section lists the main conclusions, and presents recommendations on the next steps towards mitigation.

2.0 Low-Frequency Noise Generation and Propagation

2.1 Low-Frequency Noise Descriptor

In discussing low-frequency backblast noise and quantifying the effectiveness of potential mitigation measures, it is necessary to use a descriptor that takes into account the frequency content of the noise as it relates to prediction of effects on the community.

Most people are familiar with the A-weighting network that is used to characterize aircraft overflight noise and many other sources of noise in the community. A-weighting de-emphasizes frequencies below 500 Hz in accordance with the way in which we hear noise – our ears are increasingly less sensitive to noise as the frequency is reduced below 500 Hz. The day-night average noise level, DNL, has been selected by the Environmental Protection Agency and the Federal Aviation Administration as being the most appropriate noise descriptor for community noise, and is used to define the noise environment around airports. It is based on the A-weighted noise levels of individual events.

The noise generated behind departing aircraft – backblast noise – contains most of its sound energy at frequencies below 200 Hz, as shown in the spectrum of Figure 2-1. At these frequencies, noise propagates over long distances, travels quite freely through structures, and can cause these structures to vibrate more readily than does noise at medium and high frequencies.

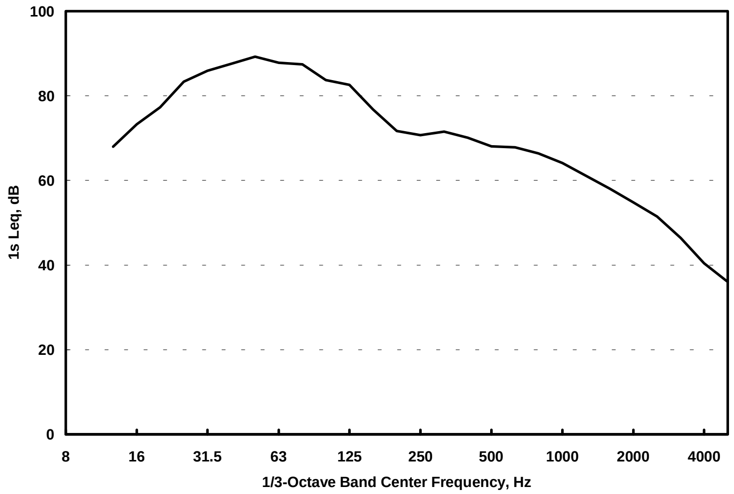

Figure 2-1. A Typical Backblast Spectrum

It is primarily the rattling of structures and bric-a-brac that is annoying to residents and results in complaints. The A-weighting network, with its de-emphasis of low-frequencies, does not adequately represent this noise, and hence should not be used to evaluate its effects or measures to mitigate it.

There are other weighting networks and metrics that have been suggested for use in describing backblast noise. The first of these is C-weighting which de-emphasizes only those frequencies below 63 Hz, and hence covers most, but not all, of the frequency range of backblast noise. The frequency characteristics of A- and C-weighting are shown in Figure 2-2, and the application of these two weightings to the backblast spectrum of Figure 2-1 is presented in Figure 2-3, showing that C-weighting represents an improvement over A-weighting in properly accounting for the low-frequency noise component of the noise.

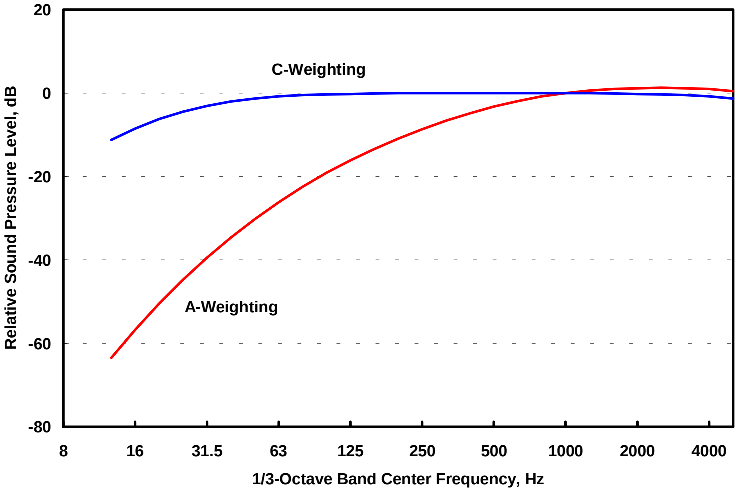

Figure 2-2. Comparison of A- and C-Weighting Networks

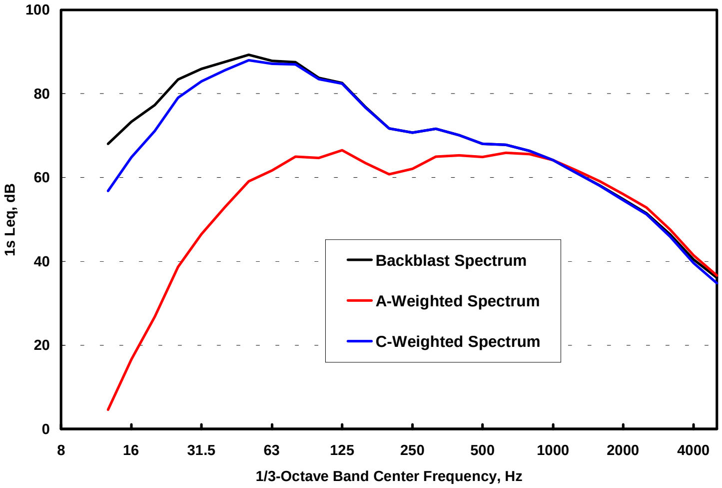

Figure 2-3. The Effect of A- and C-Weighting on Backblast Spectrum

C-weighting is easily measured by most sound level meters, and is used as the most appropriate metric for describing sonic boom and blast noise which contains a significant amount of low frequency energy.

Because of its broadband nature, C-weighting does not discriminate between broadband noises with different low frequency content, although this may not be of concern if all the noises to be considered are low frequency in nature. An alternative metric that has been suggested for describing backblast noise is the Low Frequency Sound Level, or LFSL, which is the arithmetic average of the maximum sound levels of a single event in the six one-third octave bands from 25 Hz through 80 Hz (the frequency range where structures are more sensitive to vibration and rattle). By virtue of its restricted frequency range, the LFSL metric does concentrate on at least part of the frequency range most important for structural vibration in residences, and some studies claim that LFSL correlates better than other metrics with people's reaction to aircraft noise-induced structural vibration and rattle[1].

However, LFSL has not generally been accepted by the scientific community, is difficult to measure, and, contrary to the claims of its proponents, does not necessarily encompass the complete frequency range important to structural vibration and rattle. Further research is required to develop an appropriate metric, but this should not delay the examination of potential mitigation measures. For the present, C-weighted noise levels will be used to describe backblast noise from departing aircraft and for evaluating noise mitigation measures.

2.2 Jet Engine Noise Characteristics

Aircraft noise is generated primarily from two sources associated with the engines – jet exhaust and internal systems. The hot exhaust gases mixing with the surrounding air creates low-frequency noise behind the aircraft that exhibits the familiar rumbling or roaring sound. Internal noise is generated by the rotating compressor and turbine blades, and is radiated to the front and the rear of the aircraft at medium and high frequencies. Other sources, such as engine shell vibrations and airflow over the aircraft structure do contribute to the overall noise under certain conditions, but are relatively minor and not of interest to this study.

The development of high-bypass-ratio (HBPR) engines, where the exhaust gases are mixed with air taken from in front of the engine through a shrouded thrust-producing fan, significantly reduces the low-frequency jet exhaust noise. The addition of the fan introduces an additional noise source that has the familiar tonal or "droning" characteristic. The directional characteristics of an HBPR engine typical of a Stage 3 aircraft are compared with those of a low-by-pass-ratio (LBPR) engine typical of a Stage 2 aircraft in Figure 2-4

The illustration shows that the low-frequency noise radiated to the rear of the aircraft is reduced significantly in the HBPR engines installed on Stage 3 aircraft. This reduction is quite noticeable for aircraft with noise levels well within the Stage 3 limits, but less evident in aircraft with LBPR engines that only just meet these limits. Typical directivity patterns of individual engines that are installed on Stage 3 aircraft (the HBPR CF6 such as used on the DC-10, and the LBPR JT8D-200 Series on the MD-80 Series) are shown in Figure 2-5, which represent contours of equal A-weighted noise levels – in this case 55 dBA - that would be measured at different points around the aircraft.

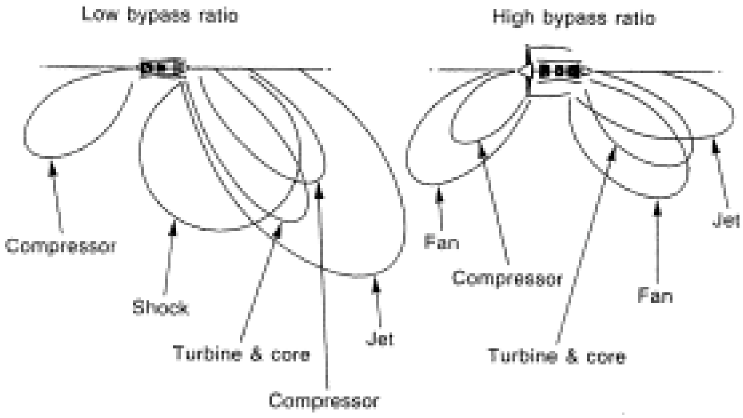

Figure 2-4. Directional Characteristics of Noise Generated by Low- and High-Bypass-Ratio Jet Engines (Illustration courtesy of GE)

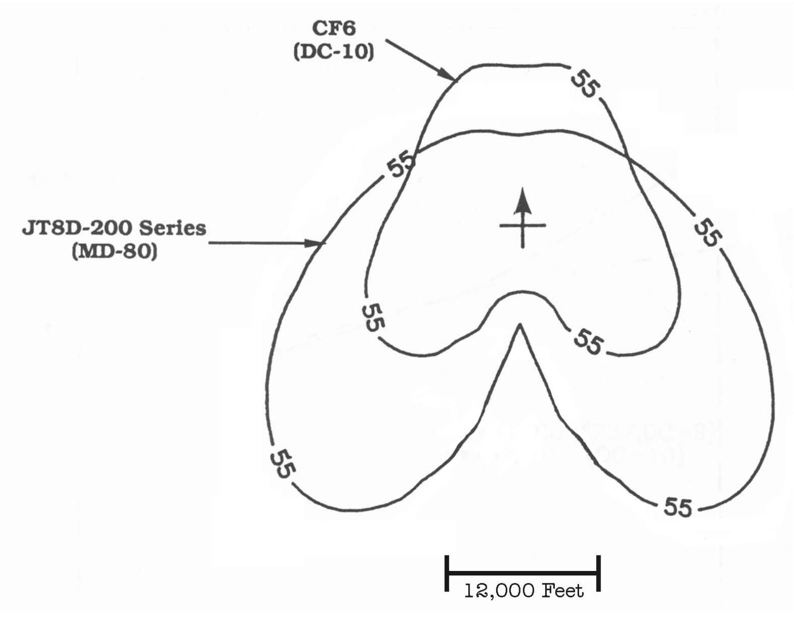

Figure 2-5. Typical Directivity Patterns of the Noise Generated by LBPR and HBPR Engines (the arrow depicts the heading of the engine).

The general shape of the pattern is the same for both engines, exhibiting a distinct lobe at about 45 degrees to the rear of the aircraft that is typical of low-frequency jet exhaust noise. (This figure is a 2-dimensional representation of a 3-dimensional directivity pattern). It should be noted that the noise level changes quite rapidly with angle in the region of the rear lobes, particularly in the case of the LBPR engine, and that there is a significant quiet zone directly behind the engine. This means that the noise levels to the rear of a LBPR engine will be dependent on engine orientation, both horizontally (side to side) as the aircraft moves down the runway, and vertically (up and down) as it climbs. The result is that the noise level at a distant observation point to the rear and side of the runway will vary with aircraft position along the runway as the angle to the aircraft changes. The horizontal variation will be greatest for observers close to, and to the side of, the runway, and will diminish as the observation distance from the runway increases. This effect will be less evident for a HBPR engine where the rear lobe is less pronounced.

The characteristics of the directivity pattern of a LBPR jet engine at low (160 Hz) and high (1000 Hz) frequencies are given in Figure 2-6 for a DC-9 with a hushkitted JT8D-7 engine[2], showing that the majority of the noise radiated to the rear of the aircraft is concentrated at low-frequencies.

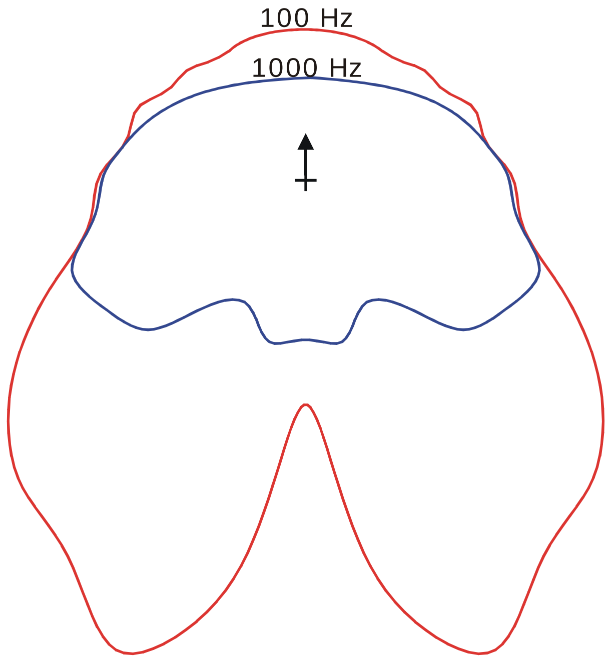

Figure 2-6. Directivity Patterns for a JT8D Engine at 100 Hz and 1000 Hz

2.3 Low-Frequency Noise Propagation

The outdoor propagation of sound has been studied extensively over the years with the result that the basic mechanisms involved are fairly well understood[3,4]. Some of these mechanisms are amenable to calculation by simple models, while others require considerable computer time and extensive data on local conditions to quantify. The major problem in estimating noise levels at great distances from the source is the influence of meteorological conditions on the propagation mechanisms, and the constant variation in these conditions with time. As a result, in practice, it is usually only possible to accurately predict sound levels over relatively short distances from the source.

Most of the existing studies have concentrated on the propagation of sound at frequencies that are important in determining A-weighted community sound levels, while few have been directed at the low frequencies that are characteristic of backblast noise. Despite these limitations, however, it is possible to describe, and to some extent quantify in approximate terms sufficient for this analysis, the mechanisms involved in the propagation of low-frequency noise in the community.

There are four mechanisms that must be considered in the propagation of sound over flat ground with no obstacles – geometrical spreading, air absorption, ground absorption, and meteorology – and these have been discussed extensively in the published literature. Each will be briefly summarized below.

Geometrical Spreading. In the open air, sound waves decrease in intensity as they propagate from the source simply because their energy is spread over an increasingly larger area as the distance increases. In the open air, at distances greater than a few hundred feet, the noise level decreases at the rate of 6 dB per doubling of the distance regardless of the frequency content of the noise. This is the well-known ‘inverse-square-law’ characteristic.

Air Absorption. As sound travels through the air, relative movement of the molecules causes heat to be generated and energy to be removed from the sound wave, which results in the sound wave being attenuated. The attenuation can be significant at medium and high frequencies especially at low relative humidity and moderate temperatures. For example, at 1000 Hz, relative humidity of 20 percent and a temperature of 20° C, the attenuation is about 7 dB per kilometer. This increases to over 20 dB per kilometer at 2000 Hz. This explains why aircraft overflight noise has a rumbling or roaring sound characteristic at large distances.

At frequencies below 125 Hz, however, the maximum attenuation at any reasonable combination of temperature and relative humidity is less than 1 dB per kilometer. In other words, air absorption at low-frequencies is negligible and can be ignored for backblast noise, certainly when compared to other propagation factors to be discussed below.

***Ground Attenuation*.** Sound propagating over the ground is affected by interference between the direct path and that reflected from the ground surface, which usually results in some degree of attenuation[3]. The amount of attenuation depends on the height of the source and measurement points above the ground, the distance, and the properties of the ground surface. The attenuation is greater for soft surfaces, such as grass, than for hard surfaces, such as concrete and water. The effect can be significant at frequencies greater than about 200 Hz, but is usually small at lower frequencies under most conditions. The result is that medium- and high-frequency noise is attenuated more than would be expected from geometrical spreading and air absorption alone, but ground attenuation is not a significant factor in low-frequency noise propagation.

The combined effects of distance, air absorption and ground attenuation on jet engine noise is demonstrated in Figure 2-7. In this figure, the noise spectrum is shown at three distances from the engine – 250, 1,000, and 5,000 feet. At frequencies greater than 160 Hz, the noise levels decrease significantly due to distance, ground effects and air absorption. The dip in the curves at 250 Hz is due to ground interference. At lower frequencies, noise levels decrease due only to the geometrical spreading of 6 dB per doubling of distance. This is a clear indication that distance is the only real factor affecting the attenuation of low-frequency noise in a neutral atmosphere.

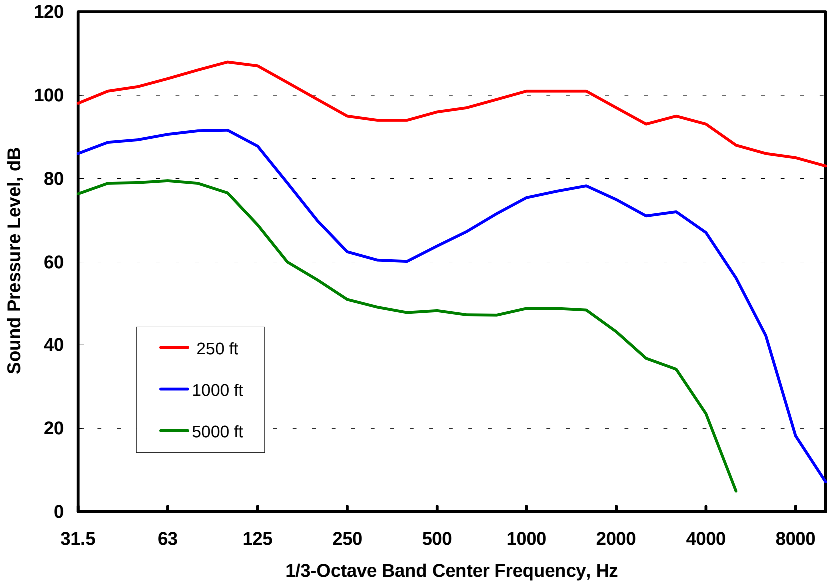

Figure 2-7. Backblast Noise Spectrum at Different Distances from the Aircraft

Meteorological Effects. The most significant effects that can influence the long-range propagation of noise are those introduced by variations in atmospheric conditions – specifically, wind and temperature gradients[3]. By itself, wind has very little effect on noise propagation, other than to increase or decrease the speed of sound, which has no resulting effect. What does affect sound propagation are wind gradients, where the wind speed decreases with decreasing height above the ground. In practice, gradients will always exist near the ground in the presence of a wind due to viscous effects at the ground surface. Changes in sound speed corresponding to a wind speed gradient will refract or 'bend over' the sound waves that would normally propagate into the upper air, and increase noise levels on the ground above those expected from geometrical spreading alone.

During downwind propagation, noise levels at all frequencies are increased over what they would be with no wind - more so as distance increases. Upwind, the sound is refracted upwards, and noise levels can be reduced significantly. But, here is the rub – aircraft always take off into the wind, so that backblast noise is always heard *downwind* of the source where the levels are higher.

Refraction of sound waves also occurs in the presence of temperature gradients, and the results are the same as for wind gradients with the exception that the resulting changes in noise level occur in all directions from the source[3]. If the temperature increases with height above the ground (a temperature inversion), as it sometimes does on cloudless nights and over water, the sound waves will be refracted downwards, and noise levels at a distance will tend to increase. This phenomenon explains why some loud noises are sometimes heard many miles from the source, when they are not heard at intermediate distances. If the temperature decreases with height (a temperature lapse), as it does on a hot sunny day, the sound waves will be refracted upwards, and noise levels at a distance will be reduced.

The effects of wind and temperature gradients are to increase noise levels, at all frequencies, above those expected from geometrical spreading and ground attenuation alone. Figure 2-8 shows the extension of the rear lobes of a single-event contour of an aircraft takeoff that occurs in the presence of a wind and temperature gradient[5].

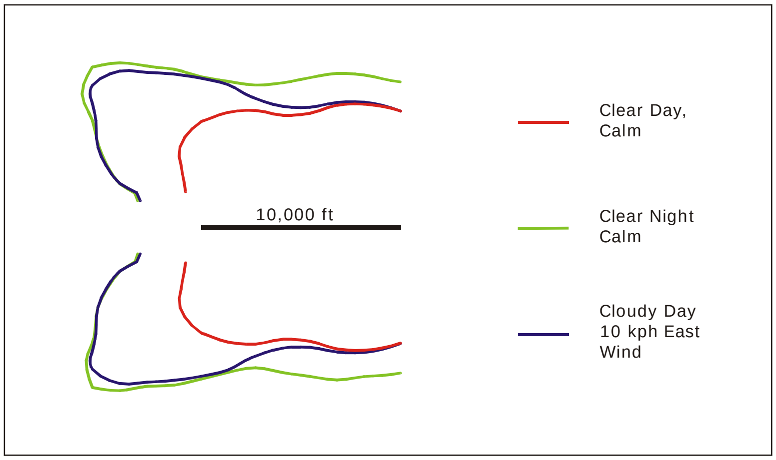

Figure 2-8. The Effect of Wind and Temperature Gradients on Takeoff Noise Contours to the Rear of the Aircraft.

The shift in the rear lobes of the directivity pattern to the left (East in the diagram) downwind of the aircraft are clearly visible. On a cloudy day, temperature inversions are formed, with the result that noise levels increase at a distance from the aircraft. Note that wind and temperature gradients have very similar effects on the contours.

The increase in noise level from temperature inversions depends on the strength of the inversion and the topography. An inversion will tend to increase the sound level more at large distances than close to the source, and more at the bottom of a hill than at the top[6].

Sound can also be scattered when it passes through atmospheric turbulence, or eddies, that is caused by the presence of random local fluctuations in temperature and wind speed. Since the atmospheric fluctuations are random, the scattering of the sound varies with time. Turbulence does not necessarily attenuates the noise, but it introduces a random variation to the level much like the twinkling of light from a star[3].

2.4 Backblast Noise in the Community

With the above background on jet engine noise generation and propagation, it is possible to explain the characteristics of backblast noise experienced in the areas behind departing aircraft.

Most people who live near airports are very familiar with the noise from aircraft overflights, where the noise gradually increases as the aircraft approaches, and then decreases as it flies away. As the aircraft approaches, high-frequency noise is heard from the engine inlet; as it passes, this changes to low-frequency noise from the jet exhaust. People who live near the end of airport runways and to the rear of departing aircraft are exposed to noise that is very different to that from overflights, both in spectral content and duration.

First, the noise to the rear of a departing aircraft has a predominately low-frequency content for the complete duration of the operation, as shown earlier in Figure 2-1. As the aircraft prepares to start its takeoff roll, engine thrust is increased to near maximum and the noise level to the rear increases rapidly to a maximum value. The thrust is maintained throughout the takeoff process, but since the aircraft is moving away down the runway, the noise level changes with time because the distance is increasing, and the orientation of the jet exhaust with any given location in the community is also changing. This time-history characteristic is shown in the left-hand portion of Figure 2-9 for the departure of an MD-80, measured at a distance of 3,200 feet from the runway end at an angle of about 30 degrees to its main axis.

At this point in the departure, the aircraft rotates and climbs away from the runway. During the rotation, the jet exhaust is directed at the hard runway surface, and there is evidence that higher noise levels are generated. Furthermore, as the aircraft rotates and climbs from the runway, any ground

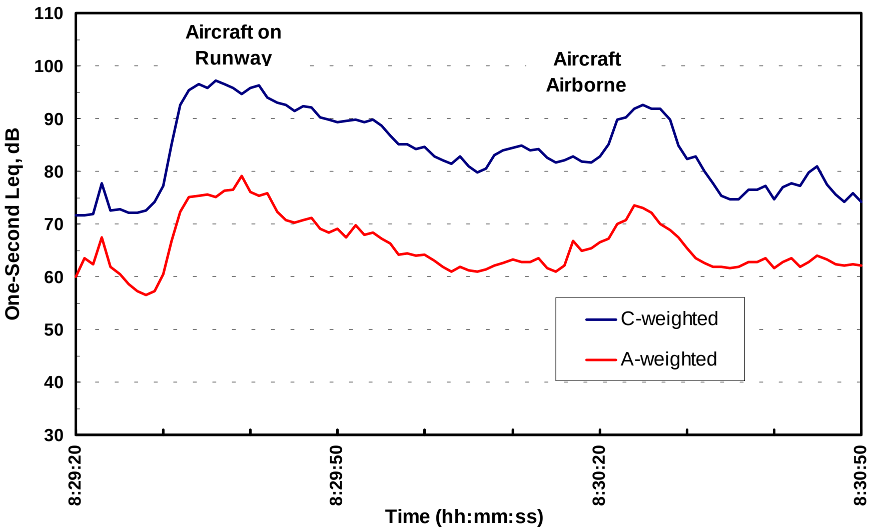

Figure 2-9. Noise Time History of a Single Aircraft Takeoff.

attenuation (although small) will disappear, and the jet orientation will change in the vertical direction, potentially directing the rear lobe of the directivity pattern more towards the ground. It is believed that these are two factors responsible for a sudden increase in noise level, as shown in the right-hand portion of Figure 2-9, introducing a second noise peak. An additional factor may well be the presence of temperature or wind gradients that become significant above a few hundred feet. The spectrum of the noise heard in the community behind the runway end is shown in Figure 2-10 at the times of the two peaks in the time history. The low-frequency content changes little; the higher frequencies are diminished by air absorption.

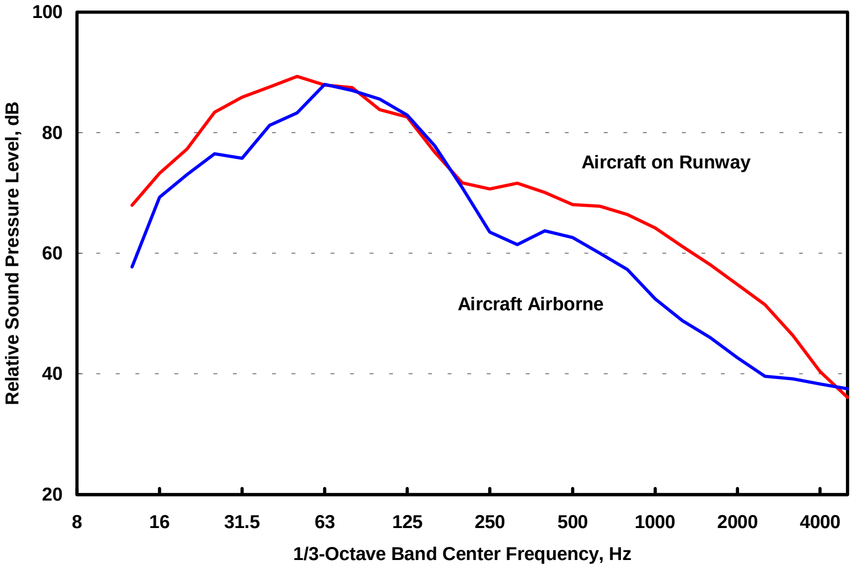

Figure 2-10. Backblast Spectrum from Aircraft on the Runway and Airborne.

This time-history characteristic was noted initially in a 1987 Tracor report[7] and has been mentioned by others in more recent years[8,9]. It is a very important feature of low-frequency backblast noise because, as will be shown later, it limits the noise mitigation measures that can be applied.

The relative magnitudes of the first and second peaks depends on a number of factors, including the distance of the measurement point from the aircraft. The first peak occurs when the aircraft is at the end of the runway closest to the community exposed to the backblast noise; the second peak occurs when the aircraft is 10,000 to 15,000 feet further away. Since the noise level decreases at a rate of about 6 dB per *doubling* of distance, the level of the first peak will decrease much more rapidly with distance away from runway than will the level of the first peak. This is demonstrated in Figure 2-11 which show the noise-time histories at two locations at distances of 7,200 feet (Site 1) and 22,700 feet (Site 15) from the runway end for the departure of an MD-80. At the more distant location, the first peak is hardly noticeable, and yet the second peak has the same level at both locations.

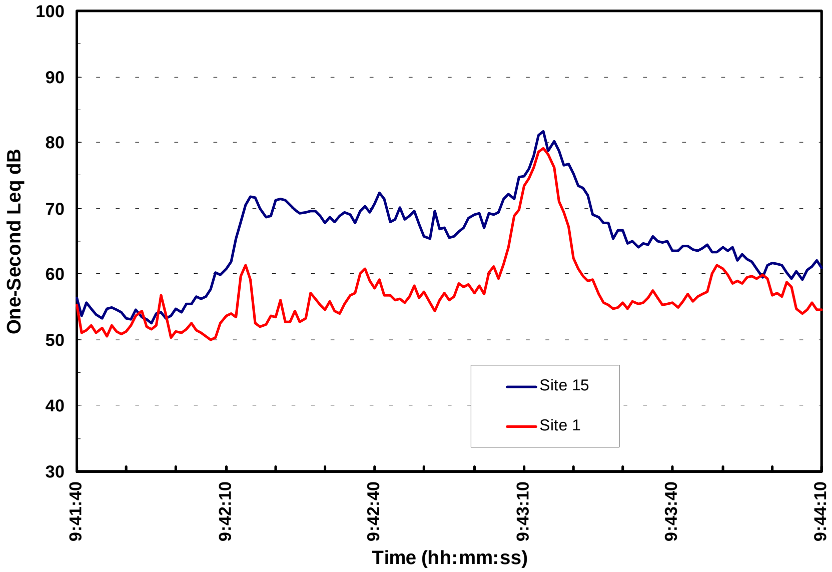

Figure 2-11. Backblast Noise at Two Distant Locations.

The C-weighted noise-time histories at the same two locations for a number of aircraft departures are shown in Figure 2-12. It can be seen that there is little consistency in the relationship between the levels of the two peaks. The last departure on the right-hand side of the figure (a DC-87) is quite different from the others, with the second peak level being higher at the more distant location, while hardly noticeable at the closer location.

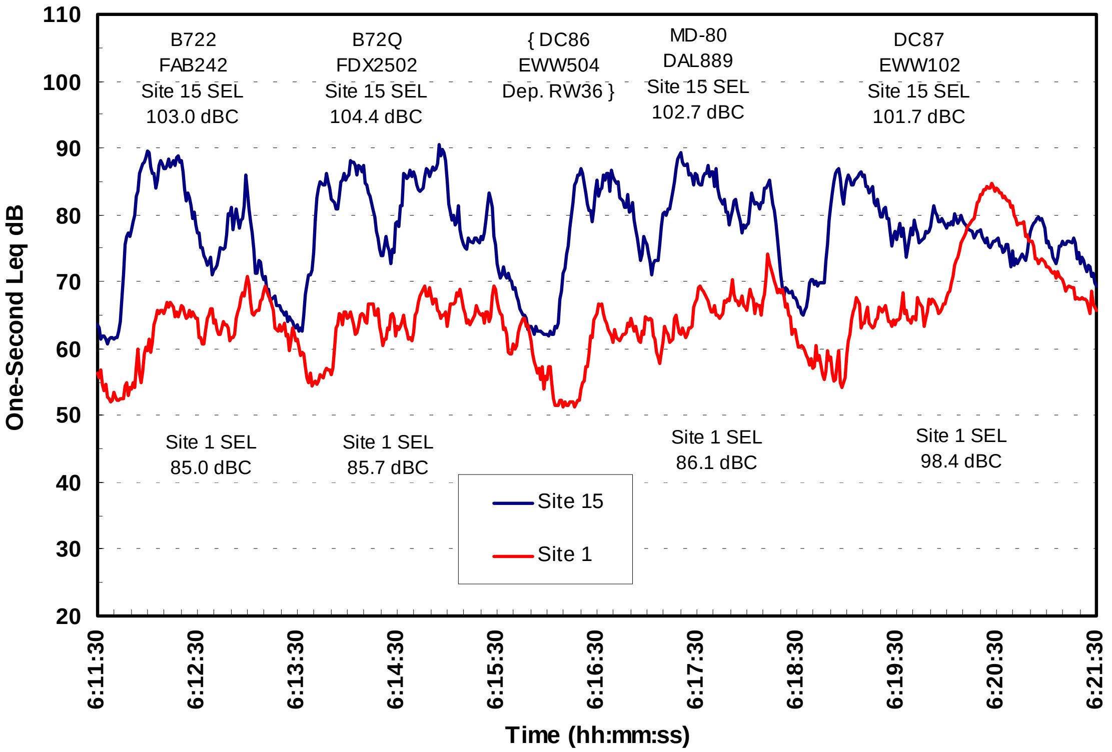

Figure 2-12. Backblast Noise at Two Distant Locations for Multiple Takeoff Operations.

An important point to be noted from these noise time histories is that the total duration of the backblast noise is from one to two minutes per event. As the data in Figure 2-12 shows, the noise can be almost continuous at busy times of the day when aircraft are departing one after another.

2.5 Summary of Low-Frequency Noise Generation and Propagation

The information presented in this section can be summarized as follows:

- C-weighting is preferred over A-weighting to describe backblast noise. It is perhaps not the ideal descriptor, but will suffice until additional research identifies a better candidate. The LFSL metric has only a small supporting database, and does not have scientific acceptance.
- Backblast noise is concentrated at low frequencies for the complete departure operation.

- The low-frequency noise radiated by a jet engine is concentrated in a cone at about 45 degrees to the rear axis of the aircraft.

- The rear radiation lobes are more pronounced for LBPR engines, typical of aircraft that just meet Stage 3 requirements, than for HBPR engines, typical of aircraft that are well below Stage 3.

- Low-frequency backblast noise levels decrease by about 6 dB per doubling of distance. The attenuation from air and ground absorption is small.

- Meteorological effects are the major factor affecting sound propagation over long distances. Temperature inversions and downwind propagation will increase low-frequency noise levels.

- Communities exposed to backblast noise are downwind of the aircraft and hence experience increased noise levels.

- The departure noise time history exhibits two separate peaks, the first from the initial aircraft acceleration, the second after it rotates and climbs from the runway. The total duration of the noise event for a single departure can be one to two minutes.

- The level of the second peak decreases less rapidly with distance away from the runway than does the levels of the first peak.

3.0 Backblast Noise Mitigation

3.1 Noise Control at the Source

It is often stated that the most efficient way to reduce noise in communities is to apply noise control at the source. Airports do not have any control over the noise produced by aircraft, although under some circumstances they may be able to persuade the airlines to reduce operations of the noisier aircraft, namely those with LBPR engines. The data presented in Section 2 showed that low-frequency noise levels from HBPR engines are lower than for LBPR engines. There is also evidence in the literature[10] that the low-frequency backblast noise levels of Stage 3 aircraft are on average up to 6 dB lower than for Stage 2 aircraft. Measurements of backblast levels at SFO[8] seem to validate this finding, but the database is very limited. Therefore, removing aircraft with LBPR engines would most probably be a mitigation measure to consider.

The engine manufacturers have achieved significant reductions in jet exhaust noise by increasing the bypass ratio, but there are practical limits to how far this technology can be taken in the future. As a result, future reductions in low-frequency noise, over and above what has been achieved in the transition to a Stage 3 fleet, are uncertain.

An alternative to applying noise control at the source is to modify the operation of the aircraft. There are indications that the second peak of the noise time history may be influenced by the orientation (rotation) of the aircraft as it climbs from the runway. If this is so, then a lower climb rate would reduce the noise level of the second peak. Departure turns might also have a similar effect. Before such procedures could be implemented, it would be necessary to determine if there was any correlation between climb rate or departure track and the low-frequency noise levels in the community.

3.2 Barriers and Buildings

The description of low-frequency noise propagation given in Section 2.3 did not include the attenuation provided by obstacles, such as barriers, berms or buildings, in the path between the aircraft and the community. Barriers have been used extensively to reduce noise levels alongside highways and construction sites, and have been applied in the form of three-sided enclosures to reduce the noise from aircraft runup operations at many airports. It is therefore natural to consider them for reducing backblast noise.

Barriers provide attenuation by eliminating the direct line of sight between the noise source and the receiver. They don’t work quite as well as might be expected, however, because the sound diffracts, or bends, over the top of the barrier, and propagates into the shadow zone behind it, thereby reducing the attenuation. The higher the barrier, and the higher the frequency of the sound, the less the bending, and the higher the attenuation. Sources close to the barrier are better attenuated than those farther away, and the same goes for receiver distance. In fact it is difficult to provide any attenuation from a realistic-sized barrier if the distance between the source and receiver is greater than a few hundred meters[3]. In summary, barriers are most effective when they are tall, when the source and receiver are not too distant, and for high frequency noise.

Taking these facts into consideration, it would not appear as though barriers close to the runway are suitable for reducing backblast noise. First, it is not possible to place a barrier close to the aircraft, and even if it were, it would be quite distant from the community, and the attenuation would be low. Second, a barrier would not attenuate the second peak in the time history. Third, barriers perform poorly at the low frequencies typical of backblast noise. Fourth, the effect of wind reduces barrier effectiveness, and the community exposed to backblast noise by definition will be downwind of a barrier.

Buildings also act as barriers and can be effectively used to reduce community noise. For example, Wyle's Arlington, VA, office is located immediately adjacent to Washington Reagan National Airport with a 13-story building blocking the direct view, and even low-frequency aircraft noise is rarely heard.

A barrier can be effective if it is placed close to the receiver, so the option remains for barriers to be placed in the community itself, adjacent to houses that require protection. To provide even minimal attenuation, the barrier would need to be at least 15 feet tall and located within 50 to 100 feet of the residence.

3.3 Trees and Shrubs

Trees and bushes are known as poor noise barriers and provide little attenuation as a result of shielding[11]. Although foliage may provide a good visual shield, it provides noticeable attenuation only at high frequencies due to scattering of sound, usually above 2000 Hz, where the wavelength of sound becomes comparable to the dimensions of leaves. There is no attenuation due to bare branches or trunks of trees.

The main effect of foliage and trees at low frequencies is to enhance ground attenuation by roots making the ground more porous[3]. The ground attenuation is caused by acoustic interference between direct and ground-reflected sound rays from the noise source to the receiver. The ground attenuation depends on the type of ground surface and under typical conditions exhibits maximum at frequencies of a few hundred hertz. To some extent, the frequency of peak attenuation can be varied by altering the ground[12]. This can, however, be achieved by means other than planting trees.

At frequencies below approximately 100 Hz, attenuation of sound passing over or through each meter (3.28 ft) of tall thick grass or shrubbery is 0.01 dB/m or less[13]. For a band of one hundred meters (330 ft) of such a ground cover, the low-frequency sound levels would be expected to drop by no more than1 dB.

If the foliage is dense like a hedge, a row of bushes or a forest, the additional attenuation of sound propagating through each meter (3.28 ft) of such foliage does not exceed 0.02 dB/m at frequencies below 100 Hz. Moreover, bands of forest are not effective if wider than 200 m (650 ft)[3] or even less[14]. Therefore, the additional attenuation is not expected to exceed 4 dB at low frequencies of interest. To provide the noise reduction, tree heights of over 10 m (30 ft) above the line-of-sight from the source to the receiver are necessary, with the depth of over 10 m of a dense growth[13]. It is also likely to be lowered due to effects of curved ray path over the top of forest produced by vertical gradients of wind and temperature (sound refraction), despite some reduction of such gradients at elevations up to the height of the trees.

A final word on barriers relates to benefits that may be realized through means other than reductions in noise level. It has been noted that people may believe that trees do reduce noise, even though there may be no measurable noise reduction. This may be because people like trees and they tend to "soften" the environment, or that the sound of a breeze through them is pleasing to the ear[15]. It is also possible that in interrupting the view of the airport, trees can lessen the annoyance of noise[16].

3.4 Sound Insulation

The sound insulation of residences and schools exposed to aircraft noise has figured prominently in the noise mitigation plans of many airports both in the US and around the world for many years. Its popularity is partly in recognition of the fact that the technology for achieving reductions in aircraft noise levels will take many years to develop and be introduced into the fleet. By and large, sound insulation programs have been successful, and homeowners have been generally pleased with the results. A-weighted noise levels inside residences have been reduced by at least 5 dB; more in some cases, and the modifications to the homes have often improved their exterior appearance. Many sound insulation programs in warm climates include central air conditioning systems.

It is generally not difficult to achieve the goal of a 5 db improvement in noise reduction in most houses. Standard techniques include installing acoustical windows and doors, adding storms to windows and doors, increased insulation in the attic space, interior wall treatments in some cases, and generally sealing up or baffling any open paths of noise transmission. In order to achieve the noise reduction provided by the house structure, it is of course necessary to keep the windows closed, and so air replacement systems, or air conditioning systems are required. The total cost of the treatment varies with the type and size of the house, but is generally in the range of $15,000 to $30,000 per unit.

Current sound insulation projects are designed primarily to reduce the noise from aircraft overflights – the goals are expressed in A-weighted decibels – and, although they have sometimes been implemented in areas subjected to backblast noise, low-frequency noise reduction has not really been considered in anything other than pilot studies. In fact, FAA's current policy does not provide funding specifically for sound insulation projects directed at low-frequencies.

The sound insulation treatments described above are more effective at medium and high frequencies than they are at low frequencies, and this is generally true of most structural measures that are used to increase noise reduction. At frequencies greater than about 160 Hz the noise reduction of building elements tends to increase with increasing frequency, and is dependent on three parameters – mass, spacing, and decoupling between elements. The higher the mass, the greater the spacing between interior and exterior wall panels or window panes, and the higher the decoupling between panels, then the higher is the noise reduction. Below about 160 Hz, the noise reduction is compromised by numerous structural resonances which can be shifted in frequency by careful selection of mass and spacing, but they are difficult to eliminate entirely. It is not difficult to increase the noise reduction of a house at medium and high frequencies, but unfortunately, the same treatments have very little effect at frequencies below 160 Hz.

This result has been demonstrated in two sound insulation programs. At Baltimore/ Washington International Airport (BWI), a pilot program to study the application of low-frequency treatments achieved an average increase in C-weighted noise reduction of 4 dB[17,18]. The extent of the treatments was considerable, consisting of major wall modifications and triple windows with an overall thickness of over 12 inches. The costs of the treatment represented a 40 percent increase over those for the standard acoustical treatment.

The Residential Sound Insulation Program at Boston's Logan International Airport exercises another concept, unique for traditional noise insulation programs. In addition to the standard treatment, one room of the dwelling may be designated as the room of preference (ROP). The ROP is a room, selected by the homeowner, that receives special treatment to further reduce transmission of exterior noise. Although not specifically designed for low frequencies, the treatment increases effectiveness of the sound insulation at all frequencies. The supplementary ROP treatments include building the wall in toward the center of the room with additional wall panels and using double-glazed windows 5 to 6 inches thick. An analytical assessment showed that the room of preference treatments increase the C-weighted noise reduction by approximately 5 dB in addition to the improvement achieved

with the standard treatments. The cost of the additional treatments was in the range $5,000 to $6,000 per room[10].

Thus, sound insulation can be increased at low frequencies, but the treatments are costly. In fact, over the years, acoustical engineers have designed numerous structures providing high noise reduction at low frequencies for recording studios, security facilities, and test facilities, such as anechoic chambers. But these have all been fairly massive and expensive structures with double entry doors and multiple windows (if there were windows at all), that would never be considered suitable for residential housing. Some of the homeowners in Boston declined the ROP plan because of the significant reduction in floor space after the treatment was installed.

3.5 Vibration and Rattle

According to the literature, the main complaint of homeowners exposed to backblast noise seems to be related to the rattling of building elements and household articles[20]. The most common examples include rattle noise from windows, doors, pictures, ceiling fixtures, and bric-a-brac. Inside a building rattle can develop when a solid surface of any sort lies close to, but not necessarily in direct contact with an adjacent solid surface. Vibration of these surfaces induced by aircraft noise, especially at low frequencies, can cause them to impact each other giving rise to the annoying sound of rattle.

Extensive literature on the topic of acoustically-induced vibration of building components or furnishings, including measurements, detection thresholds, interpretive criteria and low-frequency effects, have been recently reviewed[20]. For present purposes, of particular interest are studies of the low frequency response of structures to acoustic excitation[21,22,23], and noise and vibration mitigation techniques[24]. These studies consider acoustic loads generated by artillery firing, explosive blasts, sonic booms, and helicopters as sources of low frequency acoustic energy. These acoustic sources have their greatest energy concentrated in the frequency range below 20 Hz (sonic booms), 16 to 63 Hz (transient explosive or artillery blasts), and 50 to 125 Hz (quasi-steady state helicopter noise). Therefore general analytical models, some measurement results, and certain conclusions are applicable to low frequency aircraft noise of interest localized in a similar frequency range.

Since rattle is a secondary noise emission effect resulting from acoustically-induced structural vibration, there are two major mitigation concepts applicable to residential buildings: (a) mitigation by reducing low frequency response of building components and (b) mitigation by preventing impact of vibrating objects against their supporting surfaces.

The aircraft noise-induced structural vibration is a complex phenomenon characterized by resonant vibration response at frequencies well below the usual range of investigations of sound transmission loss of structures. The key parameters responsible for such a behavior are the fundamental resonance frequencies of building structural components, their typical surface weight, and dynamic vibration response factors for acoustically driven structures[21,25]. Based on this data and the basic theory of sound transmission into structures at low frequencies, several areas were identified [5] where mitigation measures might be employed, which include:

- changing the wall structure by increasing mass or decreasing stiffness (staggered studs) to lower the modal frequencies and increase mass law transmission loss;
- changing the air cavity in conventional double wall systems by adding absorption to damp structural and acoustic resonances, and by adding cavity venting to increase transmission loss at panel-air cavity resonance frequencies;
- adding Helmholtz resonators within the wall to reduce wall transmission loss and in the attic to damp lower-order acoustic room modes.

Some of these techniques like cavity absorption or increasing wall mass are well known, normally utilized for sound insulation at frequencies above 100 Hz, and may still be partially effective for vibration and noise reduction at lower frequencies. However, definitive data for low frequencies are lacking. Other techniques like cavity venting and Helmholtz resonators are largely unexplored but promising candidates for future evaluation.

Specific recommendations for minimizing rattle of windows, doors, lighting fixtures, and miscellaneous household items have also been suggested[20,24]. These actions involve rather simple, practical and cost effective solutions that prevent hardware from loosen contacts between structural components by using gasket materials to fill the gaps and to soften the contact points. Simple vibration-isolation pads, washers, etc. added to wall or ceiling mounted hardware, fixtures, etc., floor-mounted cabinets and shelves (or shelf-liners) are also recommended for cushioning the impact of vibrating objects, thereby reducing or eliminating rattle noise.

Again, certain measures from this list are routinely used in residential sound insulation projects as part of gasket weather-stripping utilized in acoustical replacement windows and doors for air-tight installation of glass, window sashes, and door panels. The other solutions like the use of soft isolation pads are lacking experimental demonstration.

In the City of Millbrae, additional treatment was applied to some of the homes in an attempt to reduce low-frequency window and wall vibration and rattle in rooms facing the runway[19]. A secondary interior wall was added, and higher STC windows installed. There are no measured data documenting the improvement, but 38 out of 41 homeowners judged the treatments to be very effective. The costs of the treatment represented about a 20 percent increase over the standard treatment.

In Minneapolis, the majority of all the homeowners who complained about rattling did so because of window rattling. This number drops by almost 40 percent for those who had received the standard sound insulation treatment, which includes restoration or replacement of the windows. It seems clear, and perhaps obvious, that the standard treatment will resolve some, but certainly not all, rattling problems. As simple as it seems, the isolation of household articles from tabletops, walls and shelves with felt or rubber pads eliminates the audible rattle. Many residents affected by low-frequency noise near MSP have taken this measure on their own, and according to survey results, reported it to be an effective measure[20].

3.6 Noise Cancellation

In recent years, localized reduction of low-frequency jet engine noise has been demonstrated using the technology of active noise control (ANC). With traditional, or “passive” noise control techniques, materials such as heavy walls or resilient fabrics are used to block or absorb sound waves. With “active” control, sound waves are modified by electronically controlled loudspeakers, carefully placed between the offending noise source and the affected area. These loudspeakers produce noise that is out of phase with, and hence cancels, the offending noise.

In simple terms, an active noise control system consists of a reference microphone, that monitors the offending noise and passes it on to an electronic controller, that in turn generates an out-of-phase sound that is radiated by a loudspeaker. A second microphone, called the error microphone, is placed where noise reduction is required, and provides feedback to the controller to further refine and minimize the sound level. To work effectively, the system requires that the noise signal received by the reference microphone is correlated well with the noise in the area where the noise reduction is desired.

Initial demonstrations of the application of active noise control to reduce backblast noise from departing aircraft were quite successful[26]. Figure 3-1 shows the low-frequency noise spectrum of the aircraft with and without a simple 3-speaker system in operation. Noise reductions of up to 10 dB were achieved over the frequency range of importance for vibration and rattle.

It is possible to employ ANC in two ways: with the control loudspeaker close to the source or close to the receiver. The former is the most appropriate configuration for reducing noise from engine runup operations where the aircraft is stationary, and it is a configuration that provides the widest coverage. It is not an effective configuration for reducing backblast noise from departing aircraft in communities distant from the runway because, in the process of propagating over a large distance, the correlation between the reference microphone and error microphone signals will deteriorate. The alternative is to locate the system in the community itself, such that the reference microphone monitors the noise that is actually present in the community and the ANC system reduces that noise. A detection system would be incorporated so that the system would operate only during aircraft departures.

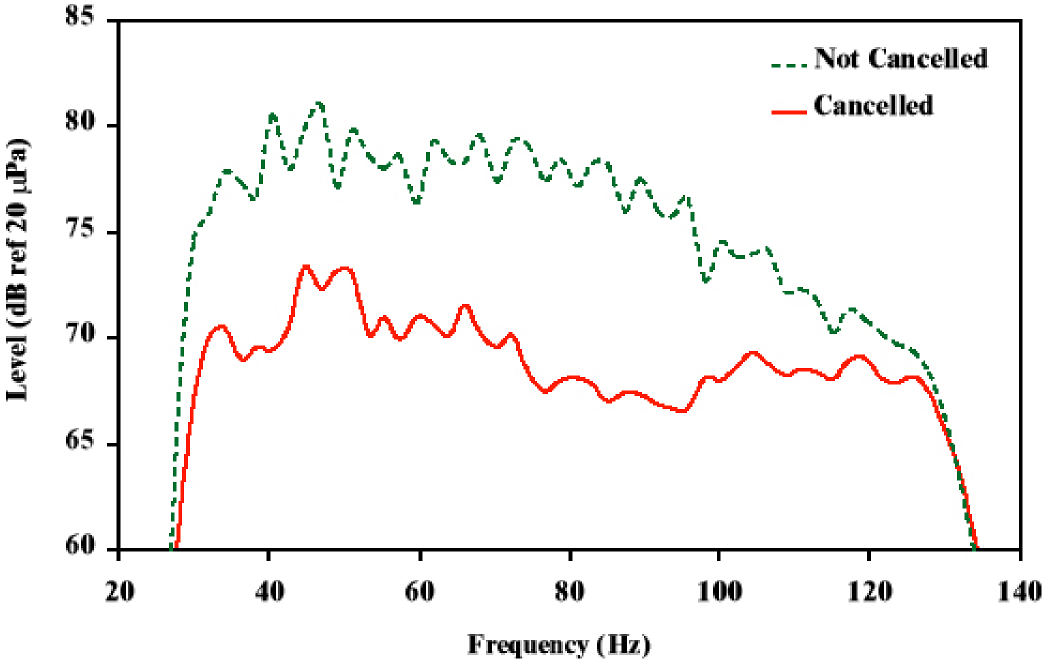

Figure 3-1. Backblast Noise Spectrum With and Without Active Noise Control.

The only items of the equipment that are of any significant size are the low-frequency loudspeakers. The sound power that needs to be generated depends on the distance of the aircraft from the site where noise reduction is required – the smaller this distance, the higher the power, and the larger the speaker assembly. Located in the community itself, the system would not be required to generate high noise levels, so power requirements would be reduced. In a practical assembly, the speakers would be camouflaged to blend in with the surroundings, and would all be at ground level. Properly adjusted, the operation of the system would not be apparent to the local community, except that noise levels would be reduced.

The work conducted to date has shown that ANC can successfully reduce low-frequency backblast noise from a moving aircraft.

4.0 Summary and Recommendations

4.1 Summary of Findings

Noise control at the source is not an option for an airport authority, although removal of the noisier aircraft is possible in some cases. Removal of the noisier aircraft will occur with time due to retirement, and may be accelerated as a result of cutbacks in operations by most airlines due to recent events.

Low-frequency noise levels produced by new-generation HBPR engines will not decrease significantly in the foreseeable future. The “low hanging fruit” of high-bypass-ratio engine technology has already been picked.

Extending a runway, or moving its departure threshold away from a community exposed to backblast noise will reduce the noise level from the start of takeoff, but will have less effect on the second noise peak as the aircraft climbs from the runway.

Barriers do not provide any measurable attenuation unless they are within a few hundred feet of either the source or the receiver. They would only be feasible if placed in the community close to the houses.

Trees and shrubs do not provide any real attenuation, although they may add a sense of tranquility, and, by eliminating visual contact with the airport, may reduce annoyance.

Sound insulation of houses to decrease interior low-frequency noise levels is not practical. Most treatments are too expensive, and aesthetics and livability limit the amount of noise reduction that can be achieved. However, a limited program to replace or renovate loose-fitting windows and doors that have been identified as sources of annoyance by the homeowner could be successful.

Noise cancellation is well suited to low-frequency noise reduction. Initial tests have demonstrated that noise reductions of up to 10 dB can be achieved over a limited area from a moving aircraft. It is not yet been demonstrated in an airport community.

4.2 Recommendations

1. Aircraft with LBPR engines that just meet the Stage 3 limits produce significantly more backblast noise than those with the HBPR engines, and so backblast noise will decrease as these aircraft are retired. After the installation of the proposed new noise monitoring system at SFO, the magnitude of the decrease should be quantified.

2. Displacing the runway threshold away from the community will reduce noise levels of the backblast noise at the start of takeoff roll, and hence

will reduce the total exposure. This should be considered when planning the new runway configuration at SFO.

3. The standard methods employed for mitigating overflight noise are not efficient in reducing backblast noise. The only method that does show promise at low frequencies is noise cancellation through active control, which has had limited demonstration up to this time. A small-scale demonstration covering a few houses would provide the data necessary to validate the concept and allow the scale of the mitigation to be determined.

4. A significant number of residents around MSP reported that a major low frequency noise annoyance factor is rattling windows and doors; and many reported that the problem was cured to their satisfaction when they received replacement windows and doors as part of the standard sound insulation package. However, it is not necessary to implement the entire sound insulation package to achieve the reduction in rattle. It is recommended that a small demonstration program be conducted to test the application of rattle mitigation measures, such as tightening windows and doors, and the installation of felt pads under household articles, to determine their effectiveness and costs. In fact, this is a measure that homeowners could implement themselves.

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Appendix A: Listing and Review of Related Reports

Investigation of Aircraft Departure Noise in Community Areas Behind Runways 1L and 1R at San Francisco International Airport (1986 and 1987)[7,27].

Two reports were prepared by Tracor Applied Sciences in 1986 and 1987 addressing the accuracy of the noise measurement system at SFO[1] and the applicability of using A-weighted levels for describing the noise from aircraft departures[2]. Both reports contain detailed noise data obtained from the noise monitoring system and at other locations.

In the first report[1], attention is drawn to the directivity pattern of low-frequency noise generated to the rear of jet engines, that produces maximum noise levels at an angle 40° to 50° from the jet exhaust axis. Communities located to the rear of departing aircraft, and within this angular range, tend to experience the highest low-frequency noise levels.

The second report[2] describes more of the characteristics of backblast noise and how these differ from the noise of overflights. Specifically, the report notes that backblast noise has more low-frequency content and longer duration than overflight noise. The time history of the noise is also different, being characterized by two separate peak values, one generated as the aircraft starts its takeoff roll, and the second as it climbs from the end of the runway. The latter peak is ascribed to atmospheric conditions and changes in ground attenuation as the aircraft leaves the ground. It is this second peak that prolongs the low-frequency noise exposure.

The study also compared the A- and C-weighted noise metrics with standard descriptors of human judgment, such as loudness level and perceived noise level (PNL) to determine if C-weighting was more appropriate for the low-frequency noise exposure. It was concluded that there was no justification for changing from the A-weighting used in the noise monitoring system.

Although no analysis was conducted, it was noted that secondary noises – such as rattle – could cause an annoyance during departure operations, but that this effect is a relatively minor consideration in assessing noise impact.

Study of the Levels, Annoyance and Potential Mitigation of Backblast Noise at San Francisco International Airport (2000)[8].

This report is largely a forum for presenting the results of laboratory studies and field surveys related to the effects of low-frequency noise on people. It briefly summarizes the spectral and temporal characteristics of low-frequency backblast noise, compares it to overflight and sideline noise, and presents the results of field measurements of low-frequency noise at SFO (see Reference 2). No mitigation information is presented.

The study concentrates on the low-frequency noise environment in the area behind departures on Runways 01L/01R at SFO. The geographical distribution of complaints correlates with the maximum noise levels, which are consistent with the directivity pattern of the engine noise from departing aircraft. It is noted that the time history of the noise from these aircraft is characterized by two peaks – the first as the engine achieves full thrust at the start-of-take-off-roll, the second as the aircraft leaves the runway. The result is that the noise of a departure can last for as long as two minutes.

One of the conclusions of the study is that noise levels in the community may be affected by local meteorological conditions. Specifically, that higher noise levels may be the result of temperature inversions. Evidence that this occurs at SFO is apparent in some of the data presented in the report. Noise levels measured at two locations on consecutive days show an increase that is consistent with the slightly different temperature gradients on the two days. However, while this conclusion is no doubt valid, and is consistent with other studies, it cannot be fully supported by the limited data presented.

Low Frequency Residential Noise Isolation Study for BWI Airport (1996)[17].

The measurements and analyses conducted to determine the requirements for increased low-frequency noise reduction are described in this report.

Noise reduction measurements were conducted on two houses before and after the application of the standard sound insulation modifications designed to increase the A-weighted noise reduction by at least 5 dB. Treatments to the walls are included in the standard program for wood-frame houses. An interior treatment was applied to one house, an external treatment to the other.

BWI Low Frequency Noise Analysis for Allwood Neighborhood (1997)[18].

Measurements of the noise reduction of two typical wood-framed houses modified to increase the acoustic performance at low frequencies are described in this report. The treatments used in the Baltimore-Washington International Airport (BWI) low frequency sound insulation pilot program are summarized below.

Window Treatments – All windows are replaced with high-STC aluminum acoustical window (STC 45) combined with supplementary laminated glass storm windows (STC 30). The combination of glazing weight, lamination in the glazing, and two airspaces, provides an effective barrier to low-frequency sound. The photograph shows a white aluminum window with the inner sash of the prime assembly almost fully open, the second prime window sash partially open, and the supplemental storm window closed.

Door Treatments – Prime door treatments in the BWI program are very similar to the prime door replacement and storm door installation options for the standard sound insulation programs. A heavily glazed full-view storm door is used in combination with a prime door replacement with solid core wood doors.

Sliding glass storm doors are used to complement existing patio doors. The BWI low frequency program requires that acoustically rated (STC 30) doors be used in all installations, and the use of un-rated vinyl patio doors is not permitted.

Attic Treatments – Existing soffits are removed and a complex baffle and insulation system is installed. Within the attic, old insulation is removed and replaced with 3½-inch batts between the joists. Then, a second course of joists is installed parallel to the first set, and one layer of ½-inch cement board is installed over these with additional 6-inch batt insulation on top of new board. This treatment is supplemented by applying two layers of 5/8-inch gypsum board to the interior ceilings of all rooms beneath the attic. Any remaining attic openings and penetrations are sealed or baffled.

Wall Modifications – All perimeter walls are treated. Homeowners are offered either interior or exterior wall modifications. Interior wall modifications include the installation of three layers of 5/8-inch gypsum board over a ½-inch layer of fibrous sound board, applied to the existing interior wall.

Exterior modifications begin with the removal of the home's siding up to the roof line. Tyvek housewrap in installed, followed by resilient channels (7/8-inch) running horizontally. After installing batt insulation between the channels, vertical wood furring (1-inch) is inserted over the insulation to provide a mounting surface for 2 layers of 5/8-inch cement board. Each layer is screwed to the furring strips all the way up to the roof line, through the attic space. Finally, new vinyl siding is applied.

As a result of these modifications, the costs are much higher than for standard sound insulation. The per home costs for low frequency sound insulation at BWI are in the range $40,000 to $50,000, adding about $15,000 to $20,000 onto the normal cost for soundproofing a home.

Acoustical measurements performed in a few residences before and after the modifications (Acoustical Design Collaborative, Ltd., 1996, 1997) indicate that the noise reduction achieved varies considerably with frequency: higher noise reduction was attained at high frequencies and lower noise reduction at low frequencies. This is typical for sound insulation properties of building constructions. Compared to the pre-modification noise reduction in the homes, the post-modification noise reduction shows improvement which also varies for different modification sets and with frequency of sound. When measured in a single-number terms of the A-weighted sound level, the noise level reduction (NLR) improvement for different rooms varies from 9 to 11 dB(A). (Compare with the FAA requirement of 5 dB(A) for NLR improvement in standard noise insulation projects).

Measured in terms of the C-weighted sound level, the NLR improvement achieved in the rooms as a result of the modifications ranges from 2 to 7 dB(C) with an average of 4 dB(C). The measurement data suggest that the improvements in different frequency regions for the two modification sets fluctuate: at some frequencies the interior modifications provide higher noise reduction, at the other frequencies the exterior modifications perform better. The improvements also differ in different rooms. However, when averaged, the overall noise reduction improvements in a given house are similar. On average, the improvement in C-weighted noise reduction is slightly (by 1.5 dB) better for the exterior wall modifications than for the interior modifications.

Development of Single Event Noise Metrics for use in Identifying Aircraft Operations for Possible Mitigation (1996)[9].

This study was designed to suggest noise metrics suitable for describing operations likely to produce adverse effects, and to provide criteria for identifying such operations.

The noise data presented in the report are taken from the 1986 and 1987 Tracor studies of low-frequency noise from aircraft takeoff operations. Using this data, a qualitative argument is made for selecting the C-weighting as most suitable for describing low-frequency departure noise.

The report repeats the findings of the Tracor report related to the occurrence of two peaks in the noise time history, and shows that the relative noise levels of the peaks depend on the distance of the measurement point from the runway. The noise level of the first peak is influenced by ground attenuation, whereas the level of the second peak is not. Thus, the second peak tends to dominate the overall noise time history at larger distances from the runway.

The report does address qualitatively the effect of various mitigation measures, such as using departure heading changes to rotate the directivity pattern of the jet exhaust and hence move the areas of maximum noise level of the second peak.

Study of Low Frequency Aircraft Takeoff Noise at Baltimore-Washington International Airport (1998)[28].

The objectives of this report were to quantify the sound levels generated by aircraft during takeoff, quantify the human judgment of this noise, and measure the propagation of low-frequency noise into the community.

Noise measurements of departing aircraft were conducted at three locations adjacent to the end of Runway 28 at BWI. One of the locations was at a house inside of which the individual noise events were judged by one (sic) resident. Wall vibration measurements were also conducted at this house.

The results from this one-person survey were used to conclude that the C-weighted noise level was the preferred metric over A-weighting for evaluating low-frequency takeoff noise. Furthermore, it was found that the C-weighted noise level correlated better than A-weighted levels with the wall vibration levels. This result is hardly surprising since broadband acceleration levels were measured. By comparing the vibration data with guidelines contained in Reference X, it was concluded that vibration levels become perceptible when outdoor maximum noise levels are higher than 75 to 80 dBC.

Finally, the measured maximum C-weighted noise levels taken at the three locations were used to conclude that noise levels decreased at a rate of 5.6 dB per doubling of distance. The author notes that is close to the theoretical 6 dB per doubling for spherical spreading, but since there is no information on the atmospheric conditions prevailing at the time of the measurements, this conclusion may be valid only for the day of the measurements.

Findings of the Low-Frequency Noise Expert Panel (2000)[20]

The City of Richfield, MN, and the Metropolitan Airports Commission undertook a detailed study of low-frequency backblast noise in communities around MSP, and assigned the task to a Low-Frequency Noise Expert Panel. This report represents the findings of this Panel. It should be noted that there was not always agreement on the findings among the members of the panel. The study included major tasks related to noise effects, which will not be included in this brief review as they are not the subject of the current report. The three areas that will be reviewed are the choice of a noise descriptor, measurements of low-frequency noise reduction, and noise mitigation options.

The Panel concluded that the major effect of low-frequency noise in the community was annoyance due to vibration and rattling of windows, doors and household paraphernalia, and not the noise itself. The noise spectrum of departing aircraft is concentrated at low frequencies throughout the event. They found that C-weighted noise levels were preferable to A-weighted levels in describing the noise, but that C-weighting does not discriminate against different levels of low-frequency noise if the noise is broadband in nature. As a result, the Panel recommended the use of a new metric, the Low-Frequency Sound Level, or LFSL, defined as the sum of the maximum sound levels in the 25 – 80 Hz one-third octave bands during a single aircraft noise event.

Noise reduction measurements were conducted in a number of residences to document the performance at low frequencies. The measurements were conducted on using an artificial noise source as opposed to actual aircraft overflights. The residences included a sample of those that had been modified as part of the on-going sound insulation program. It was found that the LFSL noise reduction of nearly all types of residences was about 15 dB, and that there was no meaningful difference in noise reduction at low-frequencies between residences that had received treatment and those that had not.

Logan Low-Frequency Noise Study (1996)[10]

This study was designed to quantify the reduction in community noise levels between Stage 2 and Stage 3 aircraft, and to determine the effectiveness of sound insulation at reducing low-frequency noise levels.

Noise data from the permanent noise monitoring system at BOS was supplemented by observations, and the noise level data for different operations on different runways analyzed by aircraft type (Stage 2 and Stage 3). Of interest in the current study are the differences noted at locations behind and to the side of departing aircraft. The report concludes that for these locations the average difference (decrease) in noise levels between Stage 2 and Stage 3 operations was 4.2 dBC and 3 dB for frequencies less than 100 Hz. However, one of the locations used in the averaging was directly behind one of the runways where backblast noise is low anyway (see the directivity patterns for jet aircraft in Figure 2-5)). A more representative location (Site 12 for departures on 15) shows an average decrease of 6.3 dBC and 5.6 dB for frequencies below 100 Hz. It would appear that the monitoring sites selected for analysis are not really representative for backblast noise, and that the quoted decreases in noise levels are understated.

The second part of the report is devoted to the low-frequency noise reduction achieved in the BOS sound insulation program. Since the noise measurements reported by the project acoustical consultant were limited to frequencies greater than 63 Hz, it was necessary to make some assumptions about the noise reduction at lower frequencies in order to compute the C-weighted values. The decision was made to simply extrapolate the slope of the noise reduction versus frequency curve to lower frequencies, and with this assumption, it is reported that the increase in noise reduction for the standard treatment was 6 dBC and 4 dB for frequencies below 100 Hz. For the Room of Preference (ROP), the corresponding increases were computed as 12 dB and 9 dB respectively. However, the assumption made does not take into account the fact that structural resonances dominate the noise reduction in this frequency range, and so these numbers cannot be considered reliable.