Project No. 02-31 **COPY NO. 1**

ASSESSMENT OF SOUND INSULATION TREATMENTS

FINAL REPORT

Prepared for
ACRP
Transportation Research Board
of
The National Academies

Ben H. Sharp
Yuriy A. Gurovich
Ferdows K. Fazeli
Wyle
Arlington, VA

Eric Miller
Architectural Testing
York, PA

September 2013

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CONTENTS

LIST OF FIGURES AND TABLES

LIST OF FIGURES

LIST OF TABLES

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The opinions and conclusions expressed or implied in this paper are those of the researchers. They are not necessarily those of the TRB, the National Research Council, or the U.S. Government.

EXECUTIVE SUMMARY

This research funded by the Airport Cooperative Research Program of the National Academy of Science is in response to a concern as to whether the acoustic performance achieved in early airport sound insulation programs has met the test of time and still provides the same protection as when it was first introduced. Although no exhaustive studies have been performed, there have been reports that the acoustical performance of treatments applied in early programs might have deteriorated over time. Accordingly, the objectives of the research were as follows:

The objectives of Airport Cooperative Research Program (ACRP) Project 02-31 are as follows:

1. Identify and evaluate the degree and causes of deterioration, and what changes have been made in current programs that reduce the likelihood of deterioration, and
2. Predict the performance of current procedures and provide guidance to help airports determine the expectation of the durability and performance of current sound insulation techniques, treatment and materials.

The project consisted of ten tasks conducted in two phases. In Phase I, a literature search was conducted to develop the chronology of airport sound insulation programs and provide leads to the identification of sources of data. The plan was to use the chronology to identify changes in methods and procedures from early to current programs, and relate these changes to possible degradation in acoustic performance. This effort followed with actual acoustical testing and architectural evaluations of representative sample of dwelling units that were insulated in the early years.

The results from the tests conducted at two sound insulation program sites showed that there has been less deterioration in performance over the years than expected. This is consistent with the lack of reported deterioration in performance obtained from the survey of US programs. In most cases, any deterioration in performance is more likely to be the result of homeowner modifications, poor maintenance, extreme weathering, and in some cases poor installation, and generally not due to deterioration in the products themselves.

This does not imply that there have been no problems with products or installation procedures. Many programs have reported such issues, but to a large extent, these have been identified by the program sponsors (or their consultants) and corrected by the product manufacturers or contractors. The lessons learned along the way have led to changes in products, installation, and quality control procedures that have reduced the frequency of such problems.

In Phase II, the longevity of acoustic treatments was assessed, and guidance material prepared to assist program sponsors in ensuring long-term noise reduction effectiveness. This guidance material is published as a separate, stand-alone document.

CHAPTER 1. INTRODUCTION

It is now 40 years since the first residential sound insulation project was successfully demonstrated in the U.S. as a means of reducing noise impact in communities near airports. At the time, sound insulation was not considered a cost-effective mitigation measure due to the very high aircraft noise levels and hence the requirement for high values of noise reduction. The subsequent phase-out of the early, noisy jets in the 1970s, and the corresponding reduction in aircraft noise levels, improved the cost-effectiveness of the measure, and, coupled with the availability of federal funding in the early 1980s, has led to the implementation of sound insulation programs at most major, and many medium and small, airports.

In the early days of airport sound insulation programs, acoustical products were hard to find, and those that were available were designed primarily for commercial applications. Furthermore, even with the best products specified and purchased, the results were only as good, efficient, and effective as the method of installation. Over the intervening years, as sound insulation programs progressed and became more numerous, the manufacturers responded to market needs, and together with increased contractor experience, many of these initial problems were resolved. The question that remains though is whether the acoustic performance achieved in the early programs has met the test of time and still provides the same protection as when it was first introduced.

There have been reports from homeowners that the acoustical performance of treatments applied in early programs might have deteriorated over time. Although no exhaustive studies have been performed to validate these claims, it is documented (Massaro 2007), that defects have been discovered in some homes treated in the early years of the program. Clearly, each of these defects could reduce the noise attenuation provided by the building envelope, but, to date, no acoustic tests have been performed to determine the magnitude of any reduction, if one exists. Reports of deterioration have also been reported elsewhere, but again, there has been no proof of any degradation in acoustic performance.

In order to assess the performance of the early programs, the objectives of Airport Cooperative Research Program (ACRP) Project 02-31 are as follows:

3. Identify and evaluate the degree and causes of deterioration, and what changes have been made in current programs that reduce the likelihood of deterioration, and
4. Predict the performance of current procedures and provide guidance to help airports determine the expectation of the durability and performance of current sound insulation techniques, treatment and materials.

The project consisted of ten tasks conducted in two phases. In Phase I, a literature search was conducted to develop the chronology of airport sound insulation programs and provide leads to the identification of sources of data. Program data was collected from representative airport programs. A testing methodology was then developed and implemented to assess the current acoustic performance of the early programs. In Phase II, the longevity of acoustic treatments was assessed, and guidance material prepared to assist program sponsors in ensuring long-term noise reduction effectiveness. This guidance material has been published as a separate, stand-alone document.

CHAPTER 2. LITERATURE REVIEW

2.1. Scope of the Review

This literature review summarises the research, technology, regulation, and implementation of airport sound insulation programs in the United States as they have progressed over the past half century.

It is now 40 years since the first residential sound insulation project was successfully demonstrated in the U.S. as a means of reducing noise impact in communities near airports. The advent of these programs has generated an increased interest in the prediction and measurement of the noise reduction of exterior noise in single- and multi-family residences. For the first time, the acoustics of small, absorbent spaces exposed to noise from exterior sources has assumed an importance in the acoustic community that hitherto had been assigned to the interior acoustics of office spaces and multi-family dwellings. The availability of federal funding in the early 1980s has led to the implementation of sound insulation programs at most major, and many medium and small, airports by application of this technology.

The following sections of this literature review chart the advances in acoustical technology related to sound insulation programs, provide the chronology of federal policies and regulations, briefly describe the history of airport sound insulation programs as they have been implemented in the U.S., and assess the effectiveness of these programs. In keeping with the theme of this project, wherever possible the review of the literature is presented in chronological order so that changes in technology, measurement procedures, federal policies, and other factors that may have influenced acoustic performance can be understood.

2.2. Sound Insulation Studies and Research

In the decades from the 1950s through the mid-1970s the subject of architectural acoustics was a hot topic for research, spurred on by the widespread development of multi-family housing in large cities and the associated need for acoustic privacy between dwelling units and office spaces. Significant advances were made in prediction and design principles, as well as in the development of standard acoustic test methods for measuring the sound insulation properties of structures, all in the interest of providing appropriate intra-dwelling isolation. Most of the research and development in those days was directed towards control of interior noise with little attention given to the protection of residents from exterior noise, other than in the design of office buildings (Bishop 1975). A comprehensive description of the state-of-the-art in prediction, design, and measurement as it was in 1980 is described in a report prepared for the National Bureau of Standards (Sharp 1980).

The basic principles of sound transmission are, of course, the same for all structures whether they are intended for interior or exterior (facade) applications, but there are a number of factors that distinguish sound insulation for exterior structures exposed to aircraft noise from that for interior walls between offices, namely (Quirt 1980, Sharp 1994, Bradley 1998):

- The noise spectrum from aircraft noise sources contains more low-frequency energy;
- The exterior sound is incident at different angles of incidence as opposed to a more or less diffuse sound field in a room; and
- An exterior structure usually consists of many elements - walls, roof, windows, doors, etc. - and the overall noise reduction is determined by the combination of these elements.

These differences are not as trivial as they might seem at first sight, as they lead to a reconsideration of design and measurement procedures. Moreover, whereas a large database has been developed for noise reduction (transmission loss) of interior structures, relatively little of such data was available for exterior structures. And in contrast to the interior structure database, that for exterior structures has been gathered from small consulting studies of field situations. This is positive, in that the

data represents real in-situ conditions, but did not provide information on the performance of individual elements.

Early European Studies

Some of the earliest published studies of sound insulation for aircraft noise were for measurements of overall noise reduction of dwellings adjacent to London's Heathrow Airport and associated research of methods to provide a satisfactory interior noise environment (Scholes 1967). The dwellings were all of double brick wall construction. Noise reduction modifications consisted of the addition of secondary windows, attic insulation, sound attenuating ventilators, and the closing of chimney openings. The improvement in overall sound insulation varied depending on the orientation of the dwelling to the aircraft noise, but noise reductions achieved were on the order of 35 to 40 dB without a loss of ventilation.

U.S. Department of Housing and Urban Development

In the 1960s, the Department of Housing and Urban Development (HUD) was responsible for funding a number of noise studies related to exterior transportation noise transmission into buildings. Operation BREAKTHROUGH was this country's first large-scale systematic housing demonstration program, featuring the public demonstration of innovative house designs and site plans. HUD initiated BREAKTHROUGH to encourage more use of industrialized methods. It put these advanced ideas on trial, in prototype form, at nine locations across the U.S.

As part of the HUD program, basic information was gathered on the acoustic performance of existing housing, including noise reduction measurements in several types of single family houses (Bishop 1966a). Bishop compared the data from field measurements with the results of a number of laboratory sound transmission loss measurements of residential type windows and doors, selected since they generally constitute the "weakest links" in achieving effective noise insulation. This and other field noise measurement data for houses in different geographical regions was summarized in a SAE Aerospace Information Report (SAE 1971).

Bishop also selected five houses in three localities and modified them in different ways to achieve more effective reduction of aircraft noise (Bishop 1970). The noise reductions achieved in the rooms most extensively modified were compared with the noise reduction reported for 15 rooms in England. The average noise reduction achieved in both the United States and English houses was quite similar, even though the walls in the English houses were more massive, supporting his previous conclusion that windows and doors were the weakest link. There was little or no benefit from specifying heavier construction for walls or the roof unless sound-transmission paths through windows, floors, or other openings were carefully controlled. A further study demonstrated that the noise-reduction values measured in the field were usually well below those that are calculated on the basis of basic wall or roof structures (Bishop 1966b).

As part of Operation BREAKTHROUGH, HUD sponsored research on the design and development of innovative building elements that provided increased noise reduction at lower weight and thickness than existing structures (Sharp 1973). As in many previous studies, the primary focus of this study was on intra-dwelling insulation, but some innovative exterior building element designs were developed. In 1971, HUD issued their Noise Assessment Guidelines that provided guidelines for assessing exterior transportation noise (HUD 1971), following which they sponsored an additional study to assess appropriate noise attenuation measures specifically for external noise (Sharp 1976). The study included a comprehensive listing of modifications for increasing the noise reduction of exterior structures together with a procedure for estimating energy savings from the various combined treatments.

Operation BREAKTHROUGH ended in 1978 and was generally regarded as a failure as it did not prove the marketability of most of its sponsored housing construction methods. With this cancellation, HUD ended its immediate funding of noise programs.

Los Angeles International Airport

At about the same time, as part of the first phase in a pilot sound insulation program, the Los Angeles Department of Airports sponsored a study to determine the costs and benefits of different modifications to increase the noise reduction provided by typical residential dwellings (Wyle 1968). At this time, there was little data on the transmission loss characteristics of exterior building structures and for individual elements. All that existed were laboratory measurements for a few commercially available window and door assemblies. In order to develop a data base, the first phase of the Los Angeles project was conducted on three test houses in which over 80 combinations of treatment were tested using aircraft as the noise source. The results of these tests provided the first large database of field measured treatments for sound insulation.

U.S. Department of Agriculture

In the early 1970s, the U.S. Department of Agriculture sponsored studies to gain a better understanding of the in-situ performance of building elements. Field measurements in wood-framed buildings showed that the sound insulation was closely correlated (within 3 dB) with predictions based on laboratory test results, provided that close attention was given to controlling sound leaks and flanking transmission (Heebink 1971). Laboratory tests were also conducted in an evaluation of the effect of windows on the noise reduction of a residence (Heebink 1975). Heebink tested operable windows with storm windows added, and studied the effect of sealing. The improvements demonstrated an increase in the combined wall/window STC of between 7 and 10 points. He concluded that, for wood-framed buildings, ordinary windows and well-sealed storm windows were adequate for reducing the indoor reception of exterior noise to levels that are satisfactory.

U.S. Department of Commerce, National Bureau of Standards

In the mid-1970s, the National Bureau of Standards conducted laboratory tests of sound transmission loss, thermal transmittance and air leakage on over 100 typical residential exterior wall constructions with and without window and door assemblies (Sabine 1975). The walls were wood-frame construction with exterior surfaces of wood siding, stucco, and brick veneer. This was a significant database of the laboratory performance of residential structures which provides information on their relative performance.

In a study conducted for EPA, the National Bureau of Standards developed a methodology to measure the cost impacts of acoustical performance requirements for new buildings (NBS 1981). The methodology provides the ability to estimate the change in construction costs resulting from modifications to doors, windows, and exterior walls, and includes a cost minimization model for selecting the least-cost design for a particular level acoustical performance. Although designed for application to new buildings, the principles of the methodology are generally transferable to modification of existing structures. However, it does not appear as though the methodology has been used to any great extent.

National Research Council of Canada

The early 1970s was notable for the start of decade-long research activities at the National Research Council (NRC) of Canada to address aircraft noise and sound insulation design. A number of studies were conducted to develop a database of noise reduction treatments and to develop design procedures for their implementation,

NRC developed a method whereby a dwelling unit may be designed to reduce the noise produced by aircraft to an acceptable level. The individual components contributing to the transmission of sound were chosen so that their effects on the total sound produced were equal (Donato 1973). The total internal sound field may then be calculated by the application of simple weighting factors. The method, although somewhat restricting, had the great advantage that the choice of elements in the design may be made by unskilled personnel. Tables were given showing the insulation factors of various elements and the effect

of their relative surface area on the total sound field. This study was based on estimates of performance of particular components, obtained from laboratory tests and data for exterior walls with some extrapolation of the results for internal partitions.

An experimental study was then undertaken to determine the performance of exterior walls and roofs, and to compare insulation against an isolated source such as an aircraft with that obtained for the reverberant sound fields used in conventional laboratory measurements (Quirt 1978). A composite structure that embodied the main features of typical Canadian housing units was constructed in the NEF 40 zone on an approach path to Ottawa Airport, where it was exposed to noise from a wide variety of aircraft during routine operations. In addition, a Jetstar aircraft was made available for special flights on the four sides of the house to permit a study of the effect of aircraft position on the noise reduction. Several varieties of windows, doors, exterior walls, and roofs were tested, together with tests of special components such as ventilator fans and fireplace flues. First results of the outdoor studies are in agreement with estimates in the guideline document (Quirt 1978).

Design procedures to reduce the interior noise produced by aircraft to an acceptable level were then developed for the Central Housing Corporation (Canada 1981) applying the Acoustic Insulation Factor (AIF) as a measure of the reduction of outdoor noise provided by the elements of the outer surface of a building (Quirt 1980).

In the late 1990s, the Canadian Department of National Defense were concerned over civilian complaints of military aircraft noise and the impact of the noise on on-base housing. In addition, Transport Canada was concerned over the increased noise resulting from expansion of Toronto and Vancouver Airports. These agencies funded NRC to conduct the IBANA project (Insulating Buildings Against Noise from Aircraft). The complete IBANA project included both laboratory and field measurements of building façade sound insulation as well as the creation of computer software to permit the convenient use of this data to design the exterior sound insulation of buildings against aircraft noise.

The project produced a database of over 100 laboratory measurements of the sound transmission loss of building façade components. These included various wall and roof constructions along with some windows and a number of tests to evaluate the effects of vents on sound insulation (Bradley 2000). On the basis of this data, NRC developed IBANA-Calc software to calculate the effect of sound insulation against aircraft noise and to provide the user with indoor noise levels for different outdoor aircraft noises and building constructions (Birta 2001).

Additional work under the IBANA project included measurements on wood stud exterior walls to better understand the acoustic performance (Bradley 2001), and a comparison of laboratory and field measurements of noise reduction where it was demonstrated that the noise reduction of wall/window combinations can be accurately predicted using laboratory measured data (Bradley 2002a).

U.S. Department of Transportation, Federal Aviation Administration

In response to the Airport and Airways Development Act Amendments of 1976, FAA sponsored a study to assess the feasibility and practicality of soundproofing public buildings (Wyle 1977a). The procedures for soundproofing were developed, and the total costs for implementation on a national scale were estimated. The study identified that the threshold of disruption in classrooms is approximately 45 dB, and 40 dB for hospitals. Architectural surveys and acoustic measurements were conducted on 44 school buildings, and modifications were designed and costed. It was determined that noise reduction increases of up to 10 dB could be achieved with the addition of double-glazed windows and by sealing leaks.

U.S., Federal Highway Administration

The feasibility of sound insulating houses from highway noise was studied for the Federal Highway Administration in the mid-1970s, (Davy 1977). A detailed set of guidelines was developed for designing improvements, but no significant implementation has occurred.

U.S. Environmental Protection Agency

As part of an overall systems program conducted by the EPA to examine options for the reduction of aircraft noise impact, a study was conducted to estimate the costs of soundproofing dwellings within the DNL 65 contour at major U.S. commercial airports (Sharp 1981). Housing types were identified for 11 different regions of the US and field surveys were conducted to establish the local characteristics that determine the noise reduction of dwellings. A computer optimization technique was employed to identify the most cost-effective modifications needed to meet the interior criteria of DNL 45.

2.3. Testing Standards

2.3.1. Acoustic Test Procedures

The description of the history of research in architectural acoustics presented in the previous section applies equally well to the development of test procedures for measuring the acoustic performance of building elements and building envelopes. Prior to the early 1980s significant research had been conducted in the development of testing methods for measuring the acoustic performance of individual building elements, but these efforts were concentrated almost entirely on interior building elements, such as wall partitions, leaving methods suitable for building facades to the discretion of the acoustical consultant.

For application to airport sound insulation programs there are three types of required acoustic measurements, namely:

1. To measure the acoustic properties of individual building elements (walls, windows, doors, etc.) to provide basic information for the design of sound insulation treatments;
2. To measure the noise reduction of a building envelope and to determine its eligibility for participation in a sound insulation program; and
3. To determine the increase in noise reduction resulting from the application of building modifications.

The first two of these requires the measurement of an absolute value of noise attenuation; the third requires a measurement of the difference in noise reduction before and after the modifications.

2.3.2. Laboratory Test Procedures

The standard method used in the U.S. for measuring the acoustic properties of a structure in laboratory conditions is the ASTM E90 procedure, first issued in 1955 as E90-55. Periodically updated over the years, with gradually stricter requirements for room design and measurement accuracy, the latest version was issued in 2009 as E90-09 (ASTM 2009). In Europe, the procedure used is defined in the ISO Recommendation 140-3 (ISO 1995). The basic elements of both these procedures are essentially the same.

The sound transmission loss properties of a structure are measured by placing it in the dividing wall between two reverberant rooms, one of which - the source room - is equipped with a source of sound, and measuring the sound level in each room using bandwidths of one-third octaves in the frequency range from 100 or 125 Hz to 4000 Hz. The difference in sound levels, when suitably adjusted for the area of the structure and the absorption in the receiving room, is then equal to the transmission loss of the structure. The adjustment, or normalization, is designed to provide values of transmission loss that are independent of the test facility, so that the transmission loss is purely a function of the structural parameters. The sound transmission loss is a basic acoustic property of the structure alone.

A review of the available data on laboratory measurements of transmission loss shows that, despite efforts to the contrary, there is considerable variation in the values measured in different test facilities (Ferrara 1997, Sharp 1980). The factors responsible for these variations are:

- The spatial characteristics of the sound field in the source and receiving rooms;
- The test structure mounting in the dividing wall; and,
- The size and location of the test structure in the dividing wall.

The ASTM procedure recommends room volumes of at least 80 m^3 for measurements in the one-third octave band centred on 125 Hz, and 125 m^3 for measurements down to 100 Hz. In deference to existing smaller facilities, a room size of 80 m^3 is acceptable but not recommended for new installations. The ISO R140 procedure states that the room volumes should be greater than 50 m^3, with a desirable volume greater than 100 m^3 Thus the ASTM procedure is the stricter of the two and should give more repeatable results at low frequencies.

To increase the diffusion of the sound field, the ASTM procedure suggests the use of randomly spaced diffusing elements or rotating reflectors. A minimum dimension of 2.4 m. is required for the test structure, except for doors and windows, which should be of normal size. Both procedures state that the structure should be installed so that the edge conditions are as similar as possible to normal field installation.

The number of measurements required in the ASTM procedure to sample the sound field in each room is calculated to ensure 95 percent confidence limits of ±3 dB in transmission loss at 125 Hz and 160 Hz, ±2 dB at 200 Hz and 250 Hz, and ±1 dB at higher frequencies. From round robin testing on copies of a reference specimen, it has been determined that the reproducibility standard deviation is about 2 dB or less at all frequencies from 125 to 4000 Hz (ASTM 2009).

2.3.3. Field Test Procedures

Aircraft Overflight Procedure

For airport sound insulation measurements, it would seem that, since aircraft are the source of the noise, and there are usually plenty of these near airports, outside and inside noise measurements should be made with aircraft overflights. This method has the definite advantage of precisely simulating the noise problem experienced by the residents, provided that the measured overflights are representative of the airport's normal operation. If they are, then clearly this may the most suitable method, and in the early years of airport residential sound insulation programs, this was a commonly used technique utilized for the measurement of sound insulation provided by the building envelope (Sharp 1980). The preferred method is to use departing aircraft as the source, as the noise levels are generally higher and the frequency spectrum broader. Exterior and interior noise levels are measured with sound level meters installed outside and inside the building, and the difference between the two sound levels recorded for a number of aircraft flyovers indicates the outdoor-indoor noise reduction.

There are situations, however, that do not lend themselves to this simple approach. If the building to be measured lies directly under the nominal flight path, the normal lateral dispersion of aircraft tracks may result in some rooms being shielded from the direct sound for some of the overflights but not others. The average noise reduction for any given room must then be determined only from overflights that directly impact the room. Another situation is where there are only occasional flights, such as may occur near seldom used runways, or in the vicinity of small airports, although this may be more of an inconvenience than a technical problem.

In-Situ Noise Reduction Measurements

The first standard test procedure for measuring sound insulation in field (in-situ) conditions is contained in ASTM E336, first issued as E336-71T in 1971. The primary application of E336 is to measure sound isolation between rooms, but general guidelines for measurements of exterior structures with an external noise source are briefly discussed in an appendix. The procedure requires measuring the sound insulation with the exterior noise source at varying angles of incidence, but no guidance is presented as to how this data is to be combined to provide a composite value.

The E336 procedure for field measurement was subsequently revised as E336-77T in 1977 (ASTM 1977) specifying certain conditions that must be met for the results to be as independent as possible of the sound fields in the two rooms and the building in which the structure is installed. For example, the procedure is valid only at frequencies equal to or greater than a lower limiting frequency that is a function of the room volume. For any given lower limiting frequency, the minimum room volume is about one-half that recommended for laboratory facilities in the ASTM E90 procedure. Judging by the results presented by Higginson, whose test rooms would be suitable at frequencies equal to and greater than 250 Hz, this criterion may lead to poor repeatability at the lower and even medium frequencies (Higginson 1972). It is difficult to increase the sound diffusion in small rooms because the size of the diffusing elements necessary to modify the low-frequency modes would be comparable to the room dimensions, leaving very little space for suitable microphone locations. Thus poor diffusion must be accepted in the measurement of field transmission loss (Higginson 1972). As a consequence, the accuracy and repeatability of field measurements conducted in typical dwelling rooms is generally poor unless considerable care and time are taken to sample adequately the sound field in each room. The problem is particularly acute at low and medium frequencies where sound diffusion is low.

The uncertainty of the measurements increases with increasing absorption and with reducing the number of sampling positions. Increasing the amount of absorption actually increases the uncertainty because the sound diffusion is lowered. Test results in rooms of volume 35 to 50 m3 (8’ x 10’ x 15’) indicate that measurements in rooms having absorption typical of furnished dwellings are recommended only if the room volumes are adequately sampled with at least 9 measurement positions. (Nightingale 2001).

If significant flanking transmission exists between the source and receiving rooms, steps must be taken for its reduction before the noise reduction can be measured. The E336-77 procedure provides guidance in determining whether flanking transmission exists by specifying a number of qualitative and quantitative tests. A mandatory test involves adding a temporary shield to the partition and repeating the measurements.

Facade Noise Reduction Measurements

The increasing interest in providing protection for buildings against the external noise produced by highway traffic and aircraft, and in soundproofing existing buildings, led to the requirement for a much more closely controlled test procedure. As a result, the International Organization for Standardization established a standard test procedure, ISO 140-5 (ISO 1978). In 1984, ASTM issued their first standard for measuring the sound insulation of building facades in the form of E966-84 (ASTM 1984). Subsequent versions have since been issued in 1990, 1999, 2002, 2004, with the latest version issued in 2010 (ASTM 2010).

Unlike the measurement procedures for interior building areas, the noise reduction and field transmission loss of building facades depends on the noise source characteristics. The exterior sound field often consists of progressive waves radiated from the source with few reflections from nearby obstacles. For a point source, such as a single vehicle, the sound will be incident on the building facade at a single angle of incidence. For a line source, such as a highway, or for aircraft overflights, sound will be incident

at many angles. Both the ISO and ASTM procedures allow for measurements to be performed using either highway noise or loudspeakers as the sound source.

The E966-84 Standard was developed for the measurement of sound insulation of building facades from highway noise sources; in fact there is no mention of aircraft noise as a possible source (ASTM 1984). Alternatively, measurements can be conducted with an artificial noise source, such as a loudspeaker. The procedure is designed to measure the outdoor-indoor noise reduction (OINR) of an entire building envelope, but can be adapted for measuring individual elements (such as a window) by incorporating measured corrections for flanking transmission of the noise. Such corrections are time-consuming to measure and inaccurate if the element has a high noise reduction itself (as it may after sound insulation modifications are introduced).

If a loudspeaker is used as the source, it is recommended that it be placed to provide incident sound at 45 degrees to the building facade. The volume of the interior room must be at least 40 m^3 to provide sufficient sound diffusion for measurements at the lowest frequency (125 Hz). Furthermore, it is recommended that the room contain hard furniture to increase the sound diffusion. These requirements can only be met in an interior room of size 12 ft. by 15 ft. with little absorption from furnishings, e.g. a dining room, but not a bedroom.

E966-90 issued in 1990 contains a short section on using aircraft noise as the source, and describes what is termed "The FAA Method" (ASTM 1990) in reference to the procedure using aircraft over-flights. However, as the range of vertical angles of incidence from aircraft over-flights can be large, and vary for each noise event, it was recommended that measurements with aircraft noise sources be restricted to components such as roofs, ventilators, and complete structures that cannot be readily tested by other means. If a loudspeaker noise source is utilized, it should be positioned a 45 degree angle to the facade. Measurements of outdoor-indoor level reduction (OILR – a change from OINR in nomenclature only) can also be made at other angles and the values reported at each angle. The recommendation for minimum interior room size was increased to 50 m^3 (1770 ft3).

A subsequent version of E966, issued in 1999, recommended that the integrated average sound level (that is, the sound exposure level, or SEL) of the outdoor and indoor sound pressures be measured simultaneously for aircraft flyover noise, or where natural traffic is sparse.

The next version of E966 was released in 2002 as E966-02 (ASTM 2002) with the only significant change being a procedure for combining the outdoor-indoor level reduction (OILR) measured at different angles into a single angle-averaged value.

The latest published version of E966 was issued in 2010 (an intermediate version E966-04 was issued in 2004 with only minor changes) that contains more information on measuring aircraft noise using individual SEL measurements, but the emphasis is still on traffic noise (ASTM 2010). It is noted that loudspeakers have been used as the outdoor sound source, measuring the level reduction in third octaves and calculating the A-weighted level difference based on a typical aircraft spectrum. As no body of experience in the use of this guide exists at present, it is estimated that the repeatability standard deviation of these test procedure is of the order of 2 to 3 dB, depending on frequency.

Appendix X1 of E966-10 contains information on other measurement methods, including methods used by the Federal Highway Administration and the Federal Aviation Administration. The latter refers to methods using aircraft over-flight measurements, an external loudspeaker, and an indoor-outdoor procedure (Gurovich 2004).

There have been criticisms of the measurement procedure using a loudspeaker as the noise source. The incident sound wave from an aircraft flyover varies in level, spectrum, and angle of incidence as the aircraft moves along its flight track. Since the noise reduction is dependent on both the spectrum and the angle of incidence, it follows that measurement at one single loudspeaker position does not necessarily represent the complete event (Karfalk 1976). It has been demonstrated that variations of up to

4 dB can be observed in measured noise reduction with different angles of incidence, and that an angle of 60 degrees is more appropriate than the 45 degrees as recommended in ASTM E966 (Jonasson 1986). It is therefore difficult to define a single representative location for an artificial source that exposes a building to the same sound field as does an aircraft overflight. The loudspeaker method may be suitable for measuring differences in noise reduction, but even this may not be representative of the real noise situation.

The ASTM E966 procedure allows exterior noise to be measured a) in the free field away from the building, b) at a distance of 2 m from the facade, or c) close to (17 mm) the surface of the facade. Quirt has demonstrated that neither Methods b) or c) give consistent results, and that Method a) is the procedure that should be implemented (Bradley 2002b).

Summary of Field Test Procedures for Aircraft Noise Sources

Currently, there is no standard measurement procedure specified by the FAA or by any of the standards institutions for the measurement of noise reduction for aircraft sources. Measurements using aircraft overflights are representative of the real situation, but results can vary as the noise source is uncontrolled. Loudspeaker measurements would seem to be the answer, but, a review of the data (Sharp 1994, Mulholland 1971) shows that caution is necessary if this approach is to be adopted.

2.3.4. Single Number Sound Transmission Loss Metrics.

The methods described above for measuring transmission loss in the laboratory and level reduction in the field are designed to give detailed data on the acoustical performance of structures as a function of frequency. It is common to present the results in each of 16 or 17 one-third octave bands. This information is valuable to the acoustic specialist so that he can fully understand the change in performance with frequency and can perform detailed calculations on the expected sound isolation in finished buildings, but the data in this form are often confusing to the non-acoustical specialist, such as the architect who has the task of designing the building. To overcome this problem, several methods have been proposed to characterize the sound attenuating properties of a structure in terms of a single number. Such methods can be applied to:

- Rank-order structures in terms of acoustic performance.
- Allow for simplified calculations of noise reduction – such as in a design guide.
- Develop a design optimization procedure that selects the combination of components that achieves a given noise reduction at minimum cost.

One such method involves the use of a grading curve, specifying the transmission loss required in each one-third octave band, against which the measured values for a given structure are compared. The grading curve concept can be used in two ways - it can represent a strict requirement for all structures to be used in a given building type, or it can be adjusted to give a ranking of one structure against another. Since it would be unreasonable to discriminate between two structures whose transmission loss characteristics differed by only one or two decibels in a frequency band, current grading procedures allow for a certain number of deviations below the grading curve.

Several alternative grading curves have been developed or suggested for use in building design. Basically, the curves have been determined by taking the difference between typical source levels in buildings and suitable criteria for acoustical privacy in neighbouring rooms. A comprehensive description of the basis for the different grading curves has been prepared by Yaniv and Flynn (1978). In their review, they conclude that the subjective response data used to establish the requirements for sound levels in dwellings is extremely variable and has led to the development of a number of grading curves that differ by up to 10 dB at some frequencies. The lack of a comprehensive data base on subjective response does not allow an assessment to be made of the importance of these differences. Also, the shape of the grading

curve for partitions is dependent on the typical source spectrum selected for the calculations. As a result, there is considerable uncertainty as to the validity of current grading procedures.

In the United States, the standard grading procedure for the transmission loss of building structures was originally given in ASTM E413-70, Standard Classification for Determination of Sound Transmission Class (STC). Initially, this procedure was intended for application to data measured in the laboratory, and thus provided a single number for ranking the potential performance of structures. The same grading curve is also used to describe the field transmission loss of structures (FSTC) and the noise reduction between rooms (NIC - Noise Isolation Class).

Single-figure rating schemes are intended to rate the acoustical performance of a partition element under typical conditions involving office or dwelling separation. The higher the value of either rating, the better the sound insulation. Thus, the rating is intended to correlate with subjective impressions of the sound insulation provided against the sound of speech, radio, television, music, office machines and similar sources of noise characteristic of offices and dwellings. In applications involving noise spectra that differ markedly from those referred to above (for example, aircraft noise), the STC values are of limited use. Generally, in such applications it is desirable to consider explicitly the noise spectra and the insulation requirements.

Rettinger established that for jet aircraft noises, the necessary insulation of such exterior room boundaries is not well represented by an STC rating as the typical STC curve is lacking in low frequency insulation when it is applied to exterior boundaries (Rettinger 1974). There is actually no simple relationship between the A-weighted sound level and the required STC noise reduction characteristic to achieve a desired interior noise spectrum or a desired A-weighted sound level.

In this respect it should be noted that ASTM Standard E413-70T states distinctly that excluded from the scope of the STC classification system are applications involving noise spectra that differ markedly from the sounds of speech, music, ands similar sources in offices and dwellings. Single-number ratings, such as STC, are often inadequate for the purpose of calculating the required insulation against various types of external noises, although they may be satisfactory for a single type of external noise valuated in a specific way (Rettinger 1974).

A single-number index, called the Exterior Wall Rating, or EWR, has been developed for rating the sound transmission loss of exterior facades (Mange 1978). This index was closely patterned after, but different from, the Sound Transmission Class, or STC, single-number index. The latter provides a fairly reliable single-number rating for the sound transmission loss of interior partitions for typical indoor sounds, but is not suitable for assessing the sound transmission loss of exterior walls to transportation noise sources with high low-frequency content. However, by applying principles similar to those upon which the STC rating was developed, a practical index was constructed which can reliably rate exterior building elements in terms of their ability to attenuate A-weighted sound levels from transportation sources, i.e., aircraft, highway, and railroads. As a method for ranking the performance of exterior facades in terms of subjective response, this method suffers from the same criticisms given to other grading procedures. An advantage of the EWR rating is that the numerical rating value can be used to calculate the interior noise level from knowledge of the exterior level.

Concurrent with the development of the EWR, the National Bureau of Standards developed the Shell Isolation Rating, also intended to predict the A-weighted level reduction (Pallett 1978). The SIR uses a rating curve method similar to E413, but the grading curve is a straight line with a slope of 3 dB per octave from 125 to 4000 Hz.

The EWR index was specifically designed to be used for all transportation sources, so that each structure would have a single rating number. In 1990, the ASTM published Standard Classification for determining the outdoor-indoor transmission class (OITC) for a structure that is applicable for a given

outdoor noise spectrum (ASTM 1990). As with the EWR, the OITC can be used directly to calculate interior noise levels.

According to the ASTM Classification, the rating value only represents the OITC for the given outdoor noise spectrum, so it is a useful method to apply for this or a similar spectrum. However, for practical design purposes, the method can be used for any given spectrum.

2.3.5. AAMA Test Standards for Building Elements

The focus of ACRP project 02-31 is on assessing potential deterioration in the acoustic performance of treatments in the early airport sound insulation programs. The previous two subsections have presented a review of test standards specifically designed to measure and evaluate acoustic performance. However, there are other test standards that, while not directly addressing acoustic performance, do test products for characteristics that can affect the acoustic performance – characteristics such as air leakage, water penetration, hardware cycling, etc. The evolution of these test standards is presented in this subsection.

The first version of ANSI/AAMA 101 voluntary specification was produced by the American Architectural Manufacturers Association (AAMA) in 1985. It replaced the ANSI/AAMA 302.9 "Voluntary Specifications for Aluminum Prime Windows" and the ANSI/AAMA 402.9 "Voluntary Specifications for Aluminum Sliding Glass Doors" standards. The new 101 standard covered 14 different types of aluminum products. This initial standard required operating force, air leakage, water penetration and uniform load structural tests which are the foundation for the standards that superseded it. It also included some forced entry resistance (optional), safety drop, hardware cycling, concentrated load, deglazing and torsion tests for particular product types or components. The three product "Grades" for this standard were Residential (R), Commercial (C) and Heavy Commercial (HC). The Performance Classes covered design pressures ranging from 15 to 50 psf. It also provided basic information and requirements for product components such as the aluminum alloy materials, finishes, reinforcements, fasteners, weather-stripping, glass, insulating glass, glazing materials, mullions and hardware. This document did include dual window (DW) systems and addressed the summer/winter configurations for certain tests.

The next version of ANSI/AAMA 101 was released in 1993. In this revision, Poly Vinyl Chloride (PVC) prime windows and glass doors were included with the aluminum products. Swing (hinged) glass doors, dual action swing doors, dual action windows and side hinged windows were added to the list of products. Architectural (AW) grade windows and doors were added to the existing R, C and HC product grades. Higher water resistance and air infiltration performance requirements were set for AW products than those required for HC products. Architectural products also were required to meet the deflection limit of L/175 for the uniform load test and the Life Cycle specifications of AAMA 910. Thermal Transmittance and Condensation Resistance tests, in accordance with AAMA 1503, were added as an option for product manufacturers. The Welded Corner test was also added since this revision now included PVC windows and doors.

The AAMA/WDMA 101/I.S.2-97 voluntary specification introduced the new "Gateway" term for the first time. Each product type has a set of primary requirements before entry into the product performance class is permitted. A minimum test size is one of the gateway requirements. The product designation now includes the Product Type, Performance Class, Performance Grade and the Maximum Size Tested. For example a 48" wide by 76" high, light commercial, horizontal sliding with design pressure of 25 would designated HS-LC25 48x76. Wood window and door products were also included in this version of the 101 document. Basement (BW), Hinged Egress (HE) and Tropical Awning (TA) windows were added to the list of product types. The Forced-Entry Resistance test was made mandatory for all windows and doors. The maximum air leakage criteria was reduced from 0.37 and 0.15 cfm/ft3 to 0.30 and 0.10 cfm/ft3 respectively, which should help to improve the acoustical performance of some

products. The list of optional tests now included Acoustical Performance which would be performed in accordance with ASTM E1425 or AAMA 1801. These acoustical methods reference the ASTM E90 test method for the sound transmission loss test procedure.

The AAMA 101 voluntary specification, up to this point, was primarily a standard to be utilized by manufacturers, code bodies and specifiers in the United States. The 101/I.S. 2/NAFS-02 document was composed by a task group of representative members from AAMA, Canadian Standards Association (CSA), Canadian Window and Door Manufacturers Association (CWDMA), National Fenestration Rating Council (NFRC), National Research Council Canada (NRC/IRC) and Window and Door Manufacturers Association (WDMA). The goal was to have a single performance standard that could be used by the United States and Canada. However, this goal was not achieved and the standard was only approved by AAMA and WDMA.

The 101/I.S. 2/NAFS-02 document preserved the products designations contained in the previous 101 standard but used SI (Metric) units as the primary designator and IP (Inch/Pound) units as the secondary unit. Skylights (Glass & Plastic), Sidelites, Transom and Specialty Products were added to the list of products. Other materials to be used in the manufacture of fenestration products were added such as Cellular PVC, Fiberglass, Steel, Cellulosic Composite Materials, and Acrylonitrile Butadiene Styrene (ABS). The ASTM E2068 test was now specified for evaluating the operating force of all operable sash or panels. Criteria for the maximum force required to initiate motion of the operable sash or panels from both the fully closed and fully open positions, as well as the force required to maintain motion to the opposite limits of travel were specified. This new NAFS document contained 55 illustrating figures and 80 tables to clarify the requirements of the standard. A Laboratory Test Report section was added to the NAFS-02 document that required a more thorough description of product components and a statement that "horizontal and vertical cross–section drawings of the test specimen were reviewed by the testing agency, and that those drawings matched the tested specimen". Cross–section and component drawings were now required to be stamped and retained by the testing agency.

The AAMA/WDMA/CSA 101/I.S.2/A440-05, Standard/Specification for windows, doors, and unit skylights, was jointly published by AAMA, WDMA, and CSA. This revision retained the five performance classifications (R, LC, C, HC and AW) and the product designations. Four new product types were added to the product list. Test requirements and criteria for side hinged exterior doors were added to this standard specification. The door tests included latching force, limited water, cycle/operation, hardware water, vertical load, forced entry resistance. The air leakage test pressures and criteria are primarily used in the United States; three levels of air infiltration/exfiltration performance criteria are required in Canada for different product types. Impact performance for windows, doors and skylights was added as an optional requirement, and a section included more details to be included in test reports. The acoustical test sizes for windows referenced the gateway performance test sizes of this standard which would require different test sizes for the five performance classes. The test sizes for doors were taken from the ASTM E1408 document, which was withdrawn by ASTM.

The second edition of the AAMA/WDMA/CSA 101/I.S.2/A440 specification was published in 2008 with the following title, "North American Standard/Specification for windows, doors, and skylights". In this revision, the number of window and door performance classes were reduced from five to four by eliminating the C and HC Classes and adding a new class identified as CW. Tubular Daylighting Devices (TDDs) were added to the list of products. There were several revisions and clarifications of the design pressure (DP) and performance grade (PG) terms and some changes to the test sizes. The maximum required force to latch a side hinged door of 65 N (15 lbf) was removed and the required force needed to be measured and reported. This document still did not specify a singular test size for windows, doors and skylights for acoustical performance. Glass and insulating glass units (IGU) descriptions were improved and weatherability, light transmittance, impact strength, smoke density, self-ignition and combustibility test requirements were added for plastic glazing material. The

Framing/cladding materials section was expanded to cover many types of wood, vinyl, aluminum, steel, fiberglass and other types of product components.

The third edition of the AAMA/WDMA/CSA 101/I.S.2/A440 was approved by AAMA, WDMA and CSA in 2012. The standard/specification was restructured so there are separate sections for products, materials and components. The addition of criteria for secondary storm products (SSPs) was added throughout the entire document. This is an important change since many of the sound insulation products have secondary storms. The summer/winter mode test conditions were removed due the addition of SSPs. This standard/specification defines requirements for four Performance Classes. The Performance Classes are designated R, LC, CW, and AW for windows, doors, and secondary storm products (SSPs), skylights, and roof windows. TDDs are not identified with a Performance Class, but are treated in a way similar to specialty products. Both positive and negative design pressures can be noted in the product designations for skylights, roof windows and TDDs. The total number of products has now been increased to 37. This standard now specifies the test sizes listed in ASTM E1425 for products being tested for acoustical performance. These test sizes are nearly identical to the NFRC thermal transmittance test sizes.

2.3.6. Summary

The AAMA 101 document has been significantly improved over the past 25 years. The latest document covers virtually every type of fenestration product that is used in residential and commercial buildings except for curtain wall and storefront systems. Many of the test procedures that are included in this standard require manufacturers to improve the performance of their products. There are optional performance requirements and test procedures that can now be included in product specifications to improve the longevity of products used in residential sound insulation programs.

2.4. Federal Policies and Regulations

In this section we present a brief overview of the development of federal policies and regulations related to airport sound insulation programs, followed by a more in-depth review of the noise criteria established for these programs.

2.4.1. An Historical Overview

Federal policies regarding airport sound insulation programs have been the result of many years of research and experience by a number of federal agencies in the understanding of the effects of aircraft noise on people, and the needs of communities adjacent to sources of transportation noise, such as airports. Federal funding for airport sound insulation programs only became available in the early 1980s, but the history of the legislation that provided this funding goes back to the 1970s.

Federal aviation noise policies are based on the tenet that airport proprietors are normally held responsible for any consequences that aircraft noise may cause as a result of the operation of their airports. Commensurate with that liability is the authority to control those consequences through local use restrictions and other actions that do not violate Constitutional safeguards or federally pre-empted areas. Because airport noise impacts are essentially local in nature, and actions to alleviate those impacts depend greatly on local political and geographical factors that differ from airport to airport, it is axiomatic that noise abatement planning is best accomplished locally by the airport proprietor. The federal government first recognized this concept formally as part of the Aviation Noise Abatement Policy, which was issued in November 1976 by the Secretary of Transportation and the Administrator of the FAA (DOT 1976).

The basic theme of the 1976 policy statement was that aviation noise abatement is a shared responsibility among all elements of the airport community - the federal government, the airport proprietor, aircraft operators, air transportation users, airport neighbours, and local governments. The statement outlined the general responsibilities of each of these elements; and, as one of the federal actions to carry out its responsibilities. FAA established a pilot program of local airport noise compatibility planning known as the Airport Noise Control and Land-Use Compatibility (ANCLUC) Program through

which FAA funded voluntary planning projects at 56 airports across the United States (FAA 1977). These projects were generally well accepted and beneficial.

Based on the experience gained from this pilot program, the Congress, in the Aviation Safety and Noise Abatement Act (ASNA) of 1979, directed the FAA to establish a permanent airport noise compatibility program, to be voluntary at the initiative of each airport proprietor Accordingly, in January 1981, FAA published interim regulations as Part 150 of the Federal Aviation Regulations (FAA 1981) that established a single system for the measurement of airport noise, a single system for determining the exposure of individuals to airport noise, and a standardized airport noise compatibility planning program.

In mandating the establishment of the airport noise compatibility program, which resulted in the issuance by FAA of 14 C.F.R. Part 150, the Congress directed that FAA "identify" land uses which are "normally compatible" with various levels of community noise exposure. The resultant guidelines for land-use compatibility are contained in Table 1 of Part 150 (FAA 1981). Basically, these guidelines identify a DNL less than 65 dB as normally compatible with residential land uses. Values of DNL between 65 and 75 dB may be considered compatible if a community determines such use must be allowed and appropriate sound insulation measures are taken. Above a DNL of 75 dB, residential use should be discouraged.

In developing Table 1 of Part 150, FAA considered earlier compatibility guidelines to assure consistency and validity of its information. In particular, FAA considered the material of the EPA Levels Document (EPA 1974), the Federal Interagency Committee on Urban Noise (FICUN 1980), and the ANSI standard on descriptors for compatible land use (ANSI 1980). FAA also considered basic guidance previously used for earlier noise exposure metrics to assure continuity. These various sources were mutually consistent and compare well.

The Airport and Airway Improvement Act of 1982 established a grant program, the Airport Improvement Program (AIP), with a ‘‘set-aside’’ of funds specifically for noise compatibility planning and projects approved under Part 150[1] including projects that reduce airport-related noise or mitigate its effects. Airports were required to provide a “matching share” ranging from 10 percent to 25 percent of a project’s total cost, depending on the type of project and the size of the airport. For noise-related projects funded under the noise “set aside,” the percentages were established at 20 percent for large airports and 10 percent for small airports. This was an important turning point because partial funding was now available for sound insulation programs. To qualify for AIP funds that are set aside for noise-related projects, an airport must have an FAA-approved noise compatibility program that includes the projects the airport wants funded, except that projects to insulate public buildings used primarily for educational or medical purposes can be funded even though an airport does not have such an approved program.

In 1983, FAA issued an Advisory Circular 150/5020-1 (FAA 1983) providing general guidance for noise control and compatibility planning for airports as well as specific guidance for preparation of airport noise exposure maps and airport noise compatibility programs by airport operators for submission under Part 150. This document remains valid and in effect today. It is understood that FAA is planning to update the document in 2013.

14 C.F.R. Part 150 was revised and made final in January 1985[2]. The program continued to be entirely voluntary on the part of the airport proprietor, but provided the incentive of subsequent eligibility for federal funding, under the Federal Airport Improvement Program, to carry out the approved plan. Funded projects include soundproofing homes and public buildings (schools, hospitals, churches, etc.), acquiring noise-sensitive properties and relocating their uses, implementing noise abatement procedures, and encouraging compatible zoning.

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[1] P. L. 97-248.

[2] 14 CFR Part 150 “Airport Noise Compatibility Planning.

In 1985 FAA issued the first version of the Airport Improvement Program (AIP) Handbook that inter alia specified the requirements and technical criteria for noise insulation projects (FAA 1985). The Handbook has subsequently been updated, first in 1989 (FAA 1989), then in 2002 (FAA 2002), and finally in 2005 (FAA 2005).

Since 1991, airport operators have had an additional funding mechanism to reduce noise impacts. The Aviation Safety and Capacity Act of 1990[3] grants commercial service airports the authority to levy a passenger facility charge (PFC) to assist in financing capital improvement programs[4]. For example, PFCs may be used for airport noise compatibility measures, such as sound insulation, that are eligible for federal assistance, even if the measures have not been approved as part of a Part 150 Program. However, the measures implemented must be consistent with the requirements of Part 150.

The chronological sequence of federal legislation and policies is summarized in the following table.

[3] P. L. 101-508 (title IX, subtitle B).
[4] 14 CFR Part 158, "Passenger Facility Charges".

Year	Month	Event	Reference
1976		Airport and Airway Development Act Amendments of 1976 authorize for the first time the use of federal airport development funds on projects designed to achieve noise relief.	P.L. 94-353
1976	November	FAA Aviation Noise Abatement Policy initiated a pilot project through (up to 25 grants per year) to encourage the preparation of comprehensive noise abatement plans by airport proprietors including acquire noise suppressing equipment, construction of physical barriers, and landscaping for the purpose of reducing the impact of aircraft noise with FAA financial assistance.	FAA ANAP 1976
1979		Aviation Safety and Noise Abatement Act of 1979 (ASNA) directed the FAA to receive voluntary submissions of noise exposure maps and noise compatibility programs from airport proprietors.	P. L. 96-193
1981	January	Part 150 – interim regulation -- implements ASNA	46 FR 8316
1982		The Airport and Airway Improvement Act of 1982 established a ‘‘set-aside,’’ of Airport Improvement Program (AIP) funds specifically for noise compatibility planning and projects under Part 150.	P. L. 97-248
1983	August	Noise Control and Compatibility Planning for Airports – Soundproofing, Para. 345, Section 4	AC150-5020-1
1985	January	FAA Part 150 – final rule	14 CFR part 150
1985	February	Airport Improvement Program (AIP) Handbook – *Cancelled in 1989*	AC 5100.38
1987		Airport and Airway Safety and Capacity Expansion Act of 1987 provided continued funding of noise compatibility planning under AIP.	P. L. 100-223
1989	October	Airport Improvement Program (AIP) Handbook – *Cancelled in 2002*	AC 5100.38A
1990		Aviation Safety and Capacity Expansion Act of 1990 established PFC program.	P. L. 101-508 (title IX, subtitle B)
1993	July	Announcement of Availability Report No. DOT/FAA/PP/92-5, Guidelines for the Sound Insulation of Residences Exposed to Aircraft Operations	AC150-500-9A
1994	July	Announcement of Availability: Passenger Facility Charge (PFC) Application	AC150-5000-12
2002	May	Airport Improvement Program (AIP) Handbook – Sec. 812 Noise Insulation Projects – *Cancelled in 2005*	AC 5100.38B
2005	June	Airport Improvement Program (AIP) Handbook – Sec. 812 Noise Insulation Projects	AC 5100.38C

2.4.2. Criteria for Sound Insulation Programs

Airport Improvement Handbook Guidelines

Following the issuance of the interim Part 150 rule in 1981, FAA issued Advisory Circular AC 150/5020-1 in 1983 (FAA 1983) providing, amongst other things, qualitative guidance for soundproofing projects, including a listing of possible treatments, for buildings in non-compatible land areas, e.g. DNL

65 and above for residences. The Order does not specify criteria for the degree of additional noise reduction to be achieved. According to AC 150/5020-1:

"*The airport cumulative noise metric (Ldn) is useful as an indicator that soundproofing may be required in a particular area. However, when considering any specific building site within a cumulative noise exposure contour (representing significant noise impact) it is recommended that additional analysis via single event maximum sound level and/or sound pressure level versus frequency data be used to determine the necessity (and/or eligibility) for soundproofing.....The A-weighted sound level is more utilitarian than other single event metrics in establishing the need for soundproofing as many of the sleep, speech and activity interference criteria have been developed using LAS levels.*"

The quantitative criteria for federally funded sound airport insulation projects were listed in the 1985 Airport Improvement Program (AIP) Handbook, designated as FAA Order 5100.38 (FAA 1985). In defining the standards to be used in designing modifications to increase the sound insulation of residences, the FAA stated that (FAA 1985):

> *"A 45 dB(A)-48 dB(A) interior noise level is considered a reasonable objective. Federal assistance will not be provided to achieve interior noise levels below 45 dB(A)".*
>
> *"A total noise reduction of 25-35 dB from exterior noise levels to interior levels usually can be achieved with some combination of storm windows, solid-core exterior doors.....and central air conditioning".*

In 1986, FAA issued some additions and changes to the noise criteria of 5100.38 in a version identified as 511.38 CHG3 (FAA 1986), namely that:

> *"The structure must be located within a 65 yearly day-night average sound level (L_{dn}) contour. Normally, unless extenuating circumstances dictate, noise attenuation should not be considered for structures within a 75 L_{dn} or greater noise contour since acquisition is preferred".*
>
> *"A 45 Ldn within the major habitable rooms of a dwelling is considered the reasonable design objective for selecting noise attenuation measures".*

However, the revised 1986 FAA Order added the following provision:

> *"Since it takes at least a 5 dB improvement in Noise Level Reduction (NLR) to be perceptible to an average person, the existing interior noise level of the dwelling must be 50 Ldn or greater to be considered a candidate for noise attenuation".*

With this unusual interpretation and incorporation of the minimum perceptibility concept, FAA took the position that a dwelling exposed to an exterior noise level of DNL 65 could only be a participant if its noise reduction was 15 dB or less – a low value that most dwellings will only exhibit with open windows.

The statement that it takes at least a 5 dB improvement to be perceptible is in keeping with a 'rule of thumb' long held by acoustical engineers that a 5 dB difference in noise level is necessary to differentiate the noise of two separate events, such as aircraft flyovers, from each other when presented sequentially. Surveys of homeowners who participated in airport sound insulation programs at three major airports have shown that a 3 dB increase in noise reduction is considered a 'slight improvement'. A 7 dB increase in noise reduction was rated as 'improved', and a 9 dB increase as 'much improved' (Brown 1990). Further analysis of the survey data indicated that an interior DNL of 43 dB corresponded to a 'slightly improved' response, and 38 dB to an 'improved' or 'much improved' response.

As might be expected, the initial lack of specificity in Order 5100.38, followed by a series of changing requirements, caused a certain amount of confusion in the industry, and led to several different interpretations that were not resolved until the 1989 version of the AIP Handbook was issued.

For example, the wording in AC 150/5020-1 alludes to the use of single-event levels to determining program eligibility, from which it could be inferred that the same type of analysis can be extended to the use of single-event levels to determine the noise reduction required. Stusnick and Wesler (1991) argued that, although the use of the DNL metric may be appropriate in determining eligibility for funding because it has been found to be correlated to the community reaction to environmental noise, experience has indicated that an individual homeowner's annoyance with the noise from aircraft overflights is more closely related to the average sound exposure level (SEL) of overflights (see also Riedesel 1986). For a given value of DNL, the average value of the allowed SEL increases as the number of operations decreases. As a practical example, at Los Angeles International Airport, the measured SEL corresponding to a measured DNL of 70 dB is approximately 94 dB. At Minneapolis-St. Paul Airport, the corresponding measured SEL for a DNL of 70 dB is 102 dB, or 8 dB higher (Sharp 1991).

Thus the use of an interior DNL metric to determine the noise level reduction (NLR) criterion for homes around airports results in higher average interior SEL values in homes around smaller airports than in homes around large airports. In this way, Stusnick and Wesler claimed that the criterion discriminates against small airports. As a result, they proposed that an alternate SEL criterion be used, consistent with the wording in AC 150/5020-1.

Clearly, if the goal of the sound insulation program is to minimize activity interference by maintaining an acceptable interior sound level, a residence near the smaller airport should receive more acoustic insulation than does a comparable residence near the larger airport. This can be achieved by designing acoustical treatment to achieve a given interior mean SEL value of 65 dB (Stusnick and Wesler 1991). At large airports, this is equivalent to achieving an interior DNL of 45 dB. Based on homeowner surveys, Brown found that an average interior SEL of 65 dB corresponded to a 'slightly improved' response from homeowners, and an average SEL of 60 dB corresponded to an 'improved' or 'much improved' response (Brown 1990).

The mean noise reduction for residences with closed windows in the colder climates of the U.S. is 27 dB, and so residences inside the DNL 72 dB contour, on average, will already meet the interior requirement of DNL 45 dB (Sharp 1994). Consequently, only residences inside the DNL 72 dB contour will theoretically be eligible to be included in a federally funded sound insulation program.

The Evolving AIP Handbook Guidelines

There are no available records of any further changes to Order 5100.38 until 1989 when FAA Order 5100.38A was issued to clarify the eligibility requirements:

> *"For residences to be eligible to participate, they must be located within the DNL 65 contour, but outside the DNL 75 contour, <u>although minor exceptions are allowed in certain cases to maintain community integrity</u>." (emphasis added by the author).*

FAA Order 5100.38A also modified the wording of the criteria for noise reduction, now stating it in terms of achieving the requisite NLR when the project is completed. This modification is mathematically equivalent to achieving a DNL of 45 dB in all habitable rooms. However, in this version, the "5 dB improvement to be perceptible" requirement was changed to read:

> *"Since it takes an improvement of at least 5 dB in NLR to be perceptible to the average person, any residential noise insulation project will be designed to provide at least that increase in NLR."*

thus clarifying the earlier statement in 5100.38 CHG3.

The AIP Handbook was later modified and issued in 2002 as Order 5100.38B (FAA 2002). This revision contained more specifics on the design objective, noting that the 'target' interior noise level is 45 dB, as opposed to being a 'reasonable design objective' in 5100.38 CHG3. There is also a provision in

this version that allows some lesser level of acoustical treatment for dwellings that already meet the target interior level.

The latest version of the Handbook, FAA Order 5100.38C was issued in 2005 (FAA 2005) with minor revisions to the requirements. For example, mobile homes are now not eligible for sound insulation treatment. There is also language in this version incorrectly stating that Table 1 of FAR Part 150 sets the interior target noise level at DNL 45 dB. Footnote 1 to Table 1 referring to residential land uses states that, for DNL levels 65-70 and 70-75:

> *".....measures to achieve outdoor to indoor Noise Level Reduction of at least 25 dB and 30 dB should be incorporated into building codes."*

This could be interpreted as recommending a noise level reduction of at least 25 dB for a dwelling exposed to a noise level of DNL 65 dB, which would result in an interior level of (at most) 40 dB.

The Program Guidance Letter of 2012

Historically, it has been widely considered that eligibility for participation in a federally funded sound insulation program has been based on whether a residence is inside or outside the approved DNL 65 noise contour. Those within the contour were considered eligible; those outside were not, unless they were identified as being a contiguous part of the community inside the contour—hence, inside the approved mitigation boundary. Most of the nation's sound insulation programs funded by AIP grants have operated under this assumption for over 30 years, and residents with properties within the DNL 65 contour have been told that they are eligible.

In August 2012, the FAA's Office of Airport Planning and Programming (APP) released a Program Guidance Letter (PGL) 12-09 on AIP Eligibility and Justification Requirements for Noise Insulation Projects reconfirming that the eligibility criteria is in fact a two-step process as described in the AIP Handbook, namely that:

1) Structures must be located within the current or forecast DNL 65 noise contour, *and*
2) Current interior noise levels must be DNL 45 or greater.

According to the PGL, existing programs have until 2015 to transition to the reconfirmed guidelines. New programs must apply the guidelines from the start. The FAA has outlined special circumstances for the treatment of residences that do not meet the two-step eligibility requirements.

a. Neighbourhood Equity (Residences within the modelled DNL 65 contour, but interior noise level is below DNL 45): Where there are a few residences (less than 10%) within a neighbourhood that do not meet the interior noise level requirements, the FAA will allow for a modified design package (Neighbourhood Equity package) which may include improvements such as caulking, weather-stripping, installation of storm doors or ventilation packages.
b. Ventilation Only package for residences with an interior noise level less than DNL 45 that do not have an existing Positive Ventilation System. Residences that rely on open windows for air circulation are eligible for a Continuous Positive Ventilation System package. Sponsors may provide air conditioning in lieu of ventilation only.

The potential impact of the PGL is that many residences may not be eligible for sound mitigation, particularly in the North-East where the existing noise reduction of residences has been increased as a result of homeowner efforts to minimize heat loss in the winter. However, although the PGL was intended to clarify eligibility requirements, it raises more questions than it answers concerning the procedures for determining such eligibility. One thing is certain though, pre-modification noise testing has now been raised to a much higher level of importance than before.

The PGL requires that Airport Sponsors of existing programs to submit reports describing plans and procedures for the transition period that ends in 2015. According to the PGL, the initial step in implementing a Sound Mitigation Program is to conduct a windshield survey of the affected community to identify the diversity of the residences in the noise contour. Information from which housing categories will be established includes: construction type, size, age, number of levels and housing type (single or multi-family). Sponsors are required to submit an Acoustical Testing Plan which outlines the proposed acoustical testing procedures, protocols and test phasing plan. The Plan must be in accordance with the FAA's 1992 guidance on testing, sampling and statistical measures.

Upon completion of the survey, and with ADO acceptance, the sponsor shall select a representative sample of each type of housing to conduct acoustical testing—typically between 10-30% of the surveyed properties. Based upon the test data, the sponsor shall develop a design package for each housing type (e.g. brick vs. sided homes) which will outline the necessary modifications to achieve a Noise Level Reduction (NLR) of at least 5 dB. The Sponsor shall submit the proposed design packages along with the windshield survey and testing results to the ADO for review and approval.

2.4.3. Summary

The guidelines for residential sound insulation programs, and the associated noise criteria, issued by FAA by way of the AIP Handbook, have been confusing from the start, and have led to different interpretations that may have affected design objectives of some early programs. In releasing the Program Guidance Letter in 2012 the FAA has clarified their overall criteria for eligibility. At the time of writing, the FAA is developing additional clarification as to how the PGL should be implemented

2.5. Airport Implementation

At the time of writing, sound insulation programs have been implemented at most major and many medium and small airports in the US – far too many to be discussed in this literature review. Gathering the details of these is described later in Chapter 3. However, in keeping with the objectives of the project, it is useful to describe some of the earlier programs, many of them pilot programs, conducted in the early to late 1980s in order to understand the different approaches and the varying interpretations of the FAA guidance documents.

It was not until the late 1960s, when the problems of aircraft noise were being addressed by the issuance of airport noise standards in California, that the first major sound insulation program was conducted in the U.S. at Los Angeles International Airport. This was a demonstration program conducted in 1969 on 20 single-family houses to assess the technical and economic feasibility of sound insulation as a noise mitigation measure (Wyle 1970). Technically, it was a success, but the costs were considered unacceptably high. Furthermore, even though significant increases in noise reduction were demonstrated, the very high aircraft noise levels in those years meant that interior levels were still unacceptably high. It was to be 13 years before they were to be tried again in Los Angeles when aircraft noise levels had been reduced, and when AIP funds were available for sound insulation.

Apart from school sound insulation programs near major airports, there was little further implementation of sound insulation programs in the U.S. in the 1970s.

Following the availability of AIP funding in the early 1980s, several airports initiated pilot programs, and subsequently, programs were implemented at most major, and many medium and small airports. Table 2-1 shows the chronology of these programs, together with the approximate number of dwelling units completed.

St. Louis Lambert Airport. One of the earliest pilot projects was conducted on six houses in 1981 at St. Louis Lambert Airport (EDI 1981). Modifications were limited to windows and doors and sealing air infiltration openings. It was noted that insulation requirements depended on whether the houses were

exposed to takeoff or landing noise, the former would have required additional treatment to walls and roofs for wood-framed houses inside the DNL 75 noise contour to meet the interior design goal of DNL 45. The conclusion was that it is not generally practical for houses in high noise zones where takeoff noise predominates.

City Of Inglewood, CA. In 1982, as an element to the City's Urban Noise and Community Revitalization Project, the City of Inglewood, California, performed a study to estimate the minimum costs to achieve satisfactory dwelling sound insulation against aircraft noise produced by landing operations to Los Angeles International Airport (Wyle 1982). The design criterion was to achieve an interior CNEL of 45 dB.

When AIP funding became available in 1983, several airports started pilot programs designed to test different methods of sound insulation, and to establish details of project management. Up until then, few large-scale sound insulation projects had been attempted.

San Jose International Airport. A pilot sound insulation project was implemented at San Jose International Airport in 1982 to assess the costs and feasibility of noise mitigation. A total of 10 dwellings were selected covering a range of noise exposure zones from DNL 65 to 75 dB (Hogan 1983). The existing noise reduction of the dwellings ranged from 14 to 23 dB, and was largely determined by poor window design and worn weather-stripping. A design objective based on single-event criteria was considered but rejected as too difficult and expensive to achieve, and so an interior goal of DNL 45 was established. Modifications were limited to windows and doors, with the result that the average increase in noise reduction achieved was 9 dB and all but two dwellings met the interior goal. Applying the same treatments, it was recommended that the future design objective be reduced to CNEL 43 to ensure that all dwellings meet an interior level of 45 dB. But it was to be over a decade before the airport implemented a large-scale program.

Between 1983 and 1987, other pilot residential programs of varying sizes were conducted with goal of providing design and procedural guidelines for larger programs in anticipation of future FAA AlP grants.

TABLE 2-1 Chronology of US Airport Sound Insulation Programs

Airport	1970	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Total
ABE																															562
ANC																															450
ATL																															9500
BAF																															20
BCT																															45
BDL																															50
BFI																															190
BNA																															2500
BOS																															12000
BUF																															
BUR																															2126
BWI																															752
CLE																															3500
CLT																															1032
CMH																															
CVG																															555
DFW																															
DTW																															3000
EYW																															300
FAT																															1010
FLL																															48
GRR																															1
GTF																															72
IAH																															
IND																															350
LAX																															12274
MCO																															24
MDW																															5750
MHT																															1237
MKE																															1477
MSP																															7846
MSY																															
OAK																															558
ONT																															1133
ORD																															7948
PBI																															
PDX																															33
PHX																															1700
PHL																															150
PIT																															359
PVD																															1534
RNO																															3547
SAN																															1820
SAT																															847
SDF																															65
SEA																															9300
SFO																															15118
SJC																															2675
SNA																															382
STL																															1100
SYR																															1070
TOL																															346
TUL																															1484
TUS																															1100

Los Angeles International Airport. Los Angeles was one of the first airports to initiate a further demonstration program and this was conducted on 20 houses in 1983. The merits of the project were demonstrated by before and after comparisons of interior noise levels and by the resident's responses to an opinion survey.

Boston Logan International Airport. In 1985, Massport completed a residential sound insulation pilot project in four homes in Fast Boston and Winthrop. (Stiffler 1986). The homes were of construction typical of their neighbourhoods and exposed to various types of aircraft noise. The acoustical treatments were implemented for windows, doors, and ceilings achieving increases in noise reduction of about 10 dB (Rosenberg 1993). In high noise areas, Massport implemented a Room of Preference option where extra measures were taken for inner walls and ceilings to achieve an additional 8 to 10 dB of noise reduction.

Atlanta International Airport. In 1985, the Atlanta International Airport initiated a program to soundproof all owner-occupied, single-family residences within the DNL 65 noise contour. The treatments were limited to the installation of storm windows, solid-core and storm doors, weatherstripping and sealing, insulation, and air-conditioning. In consideration of the warm summer climate, noise measurements for the existing structures were conducted with windows open (the assumed normal condition); post modification measurements were conducted with windows closed.

Minneapolis/St. Paul International Airport. The Metropolitan Airport Commission conducted a pilot project in 1985 to assess the feasibility and costs of sound insulation. Two levels of treatment were performed: 1) a low-cost program to include air sealing and vent baffling (10 houses), and 2) to include insulation, air conditioning, and window/door replacement (6 houses). The net measured improvements were 4, 12 dB respectively.

Baltimore/Washington International Airport. In 1987, the Maryland State Aviation Administration sponsored a Pilot Residential Sound Insulation Program for 17 dwellings to determine the feasibility and associated costs of reducing aircraft noise intrusion in residential dwellings (Stusnick 1988). Dwellings within the Baltimore-Washington International Airport DNL 65 noise contour were selected for modification. The modifications included replacement of windows and doors, addition of gypsumboard to walls and ceilings, and installation of new heating, ventilating, and air-conditioning systems. The design goal for this pilot study was to achieve a maximum interior level of 60 dB in bedrooms, and 65 dB in all other habitable spaces. The sound insulation modifications resulted in an average increase in noise reduction of 8 dB. In the subsequent expansion of the program, the design goal as defined in FAA Order 5100.38A was adopted. The energy savings due to the sound insulation modifications resulted in a 3 to 18% cost reduction compared to the existing conditions (Shade 1990).

Seattle International Airport. The Port of Seattle initiated a pilot sound insulation study in 1985 as part of its Noise Remedy Program to abate and mitigate aircraft noise effects (Wyle 1987). Acoustical treatments were applied to 21 dwellings in a range of noise exposures from DNL 72 to 79 dB. The eligibility requirements of FAA Order 5100.38 CHG3 (FAA 1986), namely, an existing interior noise level of at least 50 DNL, were met by at least one room in each dwelling. The design objectives were a) achieving an interior DNL 45 dB in all major rooms, and b) where practical and economically feasible, achieving an interior SEL of 65 dB in living rooms and 60 dB in bedrooms.

San Francisco International Airport. The City and County of San Francisco completed a FAR Part 150 Noise Compatibility Program in 1983 and initiated early sound insulation projects in South San Francisco (Earth Metrics 1986) and in San Bruno (Wyle 1988a). In San Bruno, 48 dwellings in the CNEL 70 to 75 noise contour received acoustically-rated windows and hinged doors, addition of secondary sliding glass doors, and the addition of attic insulation and attic vent baffles. Measurements in ten control homes indicated the project goal of an interior CNEL 45 was achieved in all rooms of the dwellings.

All of these pilot projects were eventually expanded into large-scale projects lasting many years and sound insulating thousands of dwellings. They were joined by most of the other major airports in the 1990s and the 2000s.

2.6. Evaluation of Sound Insulation Programs

Although airport sound insulation programs have now been federally funded for nearly 30 years, there has been little formal effort to assess the effectiveness of the programs in terms of homeowner satisfaction.

As part of residential sound insulation programs, consultants routinely uses a simple "before-and-after" questionnaire to determine how well those programs are conducted and how effective they are perceived by the residents. The "before" questionnaire asks, among other things, just what aviation noise-related factors give rise to disturbance or annoyance. The "after" questionnaire normally presented about three months after completion of the dwelling modifications seeks to determine if there are any perceived changes in those factors.

Surveys of homeowners who participated in airport sound insulation programs at three major airports have shown that a 3 dB increase in noise reduction is considered a ‘slight improvement’. A 7 dB increase in noise reduction was rated as ‘improved’, and a 9 dB increase as ‘much improved’ (Brown 1990).

These rather informal surveys are not scientifically rigorous and do not include responses from a control group of residents from non-modified dwellings. Nevertheless, the responses do indicate a general perception that residential sound insulation is effective and useful in reducing noise-induced disturbances with approval ratings generally in the 80 to 90 percent range.

These surveys are usually conducted within a few months of the project completion, and the homeowner's positive responses may well be influenced by the fact that they now have new windows and doors, and possibly new air conditioning systems. However, in one such survey, conducted at Los Angeles International Airport, the "after" questionnaire was repeated three years later (Wyle 1988a). The 20 homes treated in the 1985 program received an increase in noise reduction ranging from 6 to 9 dB. Comparing the results of the two surveys showed that the opinions of the residents had not significantly changed in the three years since the treatment was implemented. The large majority of the residents still reported that the inside activities which had previously been identified as causing "Very Much" or "Much" disturbance had been "Much Improved" or "Improved" after the dwelling modifications. Almost to a person, the residents thought that installing sound insulation was a "good idea".

One study cast some doubts on the general effectiveness of residential sound insulation as a means to reduce community annoyance with aircraft noise (Fidell 1990). In this study brief telephone interviews were conducted with 941 residents around Atlanta's Hartsfield International Airport. Approximately 63 percent of these respondents lived in houses which had been modified under an airport-sponsored program to improve their sound insulation. Based on the responses to a question involving whether they have been bothered or annoyed by the noise of airplanes while they were at home during the past year, the study concluded that there was no clear evidence of differences in the prevalence of aircraft noise-induced annoyance associated with sound insulation.

The apparent disagreement with the Los Angeles study is difficult to rationalize. It is possible that the Atlanta respondents interpreted their replies from a different viewpoint. They were asked: "While you've been at home in the past year, have you been bothered or annoyed by the noise of airplanes?" These respondents could have interpreted this to mean annoyance while in their yards, patios, or outdoor porches, as well as indoors, and they may have expressed their annoyance from those experiences.

There are published studies on the effectiveness of noise reduction treatments in reducing traffic noise. Utley conducted a study of annoyance after noise reduction treatments had been installed to reduce traffic noise levels (Utley 1985). The overall noise reduction achieved in the program was about 6 dB. The results of the survey indicated that, of the 882 respondents, 84 percent were very satisfied with the treatment in living rooms; slightly less, about 80 percent were satisfied with the treatment for bedrooms.

Amundsen conducted a before-after study to provide estimates of the efficacy of facade insulation in providing an improved indoor noise environment and the effect of this improvement in reducing noise annoyance. (Amundsen 2010). The residents surveyed in the target and the control groups were all exposed to relatively high outdoor road traffic noise levels. After the facade insulation measures were in place, the indoor noise levels were reduced by an average of 7 dB.

The residents were questioned as to their relative annoyance to the exposure using a five-point annoyance scale. After the treatments were installed, 16% of the residents remained highly annoyed (extremely + very). In the target group, the reduction in percent highly annoyed amounted to 26 percentage points, from 42% highly annoyed before to about 16% after the facade insulation measures had been implemented. Most of the residents were still annoyed by the indoor noise level from road traffic, but to a lesser degree than before the noise reduction. The results showed that the exposure-response relationships for indoor noise levels versus indoor noise annoyance estimated on the basis of the before-study explained average noise annoyance reductions well. In other words, the changes in annoyance could be predicted by the reduction in indoor noise levels.

2.7. Deterioration of Building Elements

Deterioration of building structures in general and of various building components such as windows or doors in particular, is related to a subject of durability and life expectancy of building materials and products. Durability is typically defined as the ability of a material, product, or building to maintain its intended function for its intended life-expectancy with intended levels of maintenance in intended conditions of use (NAHB 2002). Somewhat different definitions of durability can be found in the literature (EC 2004, Kesik 2001, Hoff 2009, and Athena 2006), but all of them indicate its dependency on the intended use of the product and its service environment.

Construction deterioration is due to environmental loading and failure of the environmental separation (such as the building envelope) with the result of reduced durability (Sebastian 2011). The manner in which materials and buildings degrade over time depends on their physical make-up, how they were installed, and the environmental conditions to which they are subjected. The Durability by Design Guide (NAHB 2002) lists factors affecting building durability, such as moisture, sunlight (UV radiation), temperature, chemicals, insects, fungi, natural hazards, and wear and tear. Most notable of these factors are moisture, UV radiation from sunlight, and temperature. Other problems, such as mold and indoor air quality, are also related to moisture.

According to various industry surveys summarized in the Design Guide, windows and doors are among the major commonly reported durability issues in new construction, frequency and cost of homeowner warranty claims, and overall expenditures for repairs, maintenance, and replacement. Air and water leakage, glass fogs and frosts are the main performance problems for windows and skylights, while poor weather stripping, checking and splitting of panels, and swelling are widespread problem areas for exterior doors.

Durability and service life expectancy of windows depend to a large degree on the window framing material and assembly details (Vigener 2010). Wood, vinyl and fiberglass are currently the most widely used window frames in residential construction. Aluminum frames, which were often used in the early years of airport sound insulation programs, are now only seen in commercial construction; steel frames are less common.

Wood frames are prone to separation of frame joints from moisture, thermal, structural, and transportation movements, as well as to rot from prolonged contact with moisture, unless they are pressure treated and properly coated. Many new wood windows are protected by a durable exterior finish or cladding that prevents moisture from forming underneath (EWCG 2011).

Aluminum frames are strong and inherently corrosion resistant in most environments if anodized and properly sealed or painted, but readily conduct heat. Condensation and even frost can form. Thermal breaks reduce conduction and improve condensation resistance; however, the durability of thermal breaks varies by type and quality (EWCG 2011). Steel windows depend on an applied coating for corrosion resistance (Vigener 2010).

Vinyl windows provide better energy performance than aluminum due to lower thermal conductivity, and offer welded components that seal the joinery. Vinyl window frames provide good moisture resistance and low maintenance, but tend to expand or contract at temperature changes. Recent designs have improved dimensional stability and resistance to UV radiation and temperature extremes (EWCG 2011).

New wood/polymer composite and fiberglass window frames are strong and dimensionally stable. They provide better moisture and decay resistance than conventional wood (EWCG 2011).

The service life or life expectancy of building components is reported in numerous publications (NAHB 2002, Kesik 2001, Ontario 1996, SHSC 2004, Old 2010, InterNACHI 2010, and Mayer 2005) based on various surveys, and vary significantly between countries, climatic regions, and among building

types. A recent study of life expectancy of home components by the National Association of Home Builders (NAHB 2007) concludes that aluminum windows are expected to last between 15 and 20 years, while wooden windows should last upward of 30 years. Lifespan of window glazing is anticipated in excess of 10 years, while caulking (for sealer) may last from 2 to 20 years. Exterior fiberglass, steel and wood doors will last as long as the house exists, while vinyl doors have a life expectancy of 20 years.

Life expectancy of vinyl windows is estimated between 20 and 40 years (InterNACHI 2010). There is some significant variation in the life expectancy of the windows with some consultants showing a life expectancy of 15 years at the low end, and 40 years at the high end (SHSC 2004). This could be a reflection of the type of window installed in the project and/or proper maintenance over time. The life expectancy from 10 to 15 years is provided in Reference SHSC 2004 for caulking and weather stripping, which are critical elements of window and door installation details necessary for proper integration with adjacent wall components to create a functioning wall system.

From the life expectancy assessments described above, it can be concluded that for the residential sound insulation programs of the mid-1980s, aluminum windows would reach their upper limit of lifespan of 20 years (even with proper maintenance) within the 2005 – 2010 time frame. Based on this, reports of deterioration in the acoustical performance of windows applied in earlier programs may have likely resulted from "normal" (not specific for acoustical units) conclusion of their service life. In the case of acoustical treatments this could lead to defects critical for their sound insulation performance

Such defects have been observed in one early program conducted by the Massachusetts Port Authority (Massport) at Boston Logan International Airport where the treatment consisted of aluminum storm windows (Massaro 2007). Prime door treatments consisted mainly of replacing the door within the existing frame and adding an adjoining storm door. In the years since these treatments were applied homeowners have complained of drafts and increased noise. In some cases, homeowners have applied tape to overcome these problems. Inspection has shown excessively large gaps between window sashes and jamb liners, thermal seals broken with resulting condensation fog, non-existent perimeter seals, and over 60 glazing stress cracks. Over time, noise paths and drafts have increased due to increasing size of gaps between at window sashes and jamb liners. No acoustic tests have been performed to determine if the depreciated treatments have maintained the originally intended noise reduction.

Homeowners have also complained about windows slamming due to loose and broken balances, and of difficulty opening windows due to broken clips, balancers or wheels. Massport does not consider this to be an acoustic failure, but believe it is related to substandard product and the manufacturer's failure to address warranty issues (Massaro 2007). Overall, it would appear that the problems encountered in those early years at Massport could be due to a combination of poor product quality control coupled with inadequate inspection of installation methods. But it must be recognized that the "normal" life span for the products may have also ended between 2005 and 2010.

One of the only field studies of the acoustic deterioration of building elements was a three-year survey conducted in 1997-1999 by the Civil Aviation Bureau of Japan on the performance of soundproofed houses with age (Yamada 2002). In the survey, Yamada conducted a damage inspection of houses due to aging, a comparison of soundproofing performance between 'the present survey' and 'measurement just after the soundproofing work', and a questionnaire survey on re-construction of the soundproofed houses.

Damage on inspected items was related to the time passage after the soundproofing work, it was assumed that the aging of houses caused deformation of window and sash frames, which affected deterioration of sound insulation performance of the soundproofed windows. By comparing the field data with laboratory data, it was determined that the noise reduction had become around 5dB worse in the high frequency region around 1kHz. Looking at the results of the inspection, this deterioration can be ascribed to gaps or openings between window frames and sashes or between sashes generated from the deformation of the houses. According to the survey, 29 percent of the respondents believed that the

insulation had worsened over the years. Yamada concluded that, even though the houses still satisfied the planned targets for sound insulation, it was clear that the sound insulation performance had deteriorated somewhat.

In a laboratory study to determine the relationship between deterioration of insulation performance and window frame deformation in-plane, Yoshimura measured the sound transmission loss of several window sashes by changing the displacement of the window frame (Yoshimura 2002). For the deformation test, a specimen window sash was installed in the test opening of the filler wall with a small clearance along the perimeter of the window frame. According to investigations of actual wooden houses, it is known that there is a little torsion of the window frame over time. Thus, two kinds of deformation were assumed: inclination of the jamb and sag of the sill. The shape of the window frame was changed by applying an external force and the noise reduction measured in the laboratory test facility. It was determined that a 5mm deformation resulted in a decrease of about 2 dB in noise reduction, increasing to 4 dB for a 10mm deformation.

In assessing deterioration, the normal wear-and-tear of windows as they are repeatedly operated over the years must also be taken into account (Peterson 2011). Typical problems that may arise are:

- Weather-stripping begins to wear down, and in some cases pulls out of its track.
- Improper operation of the windows when closing and locking often times result in permanent distortion to the frame.
- If the sash rails in some vinyl window are not reinforced with aluminum rails, over time, the vinyl has a tendency to twist out of shape.
- With a double hung window, if a balance is either disconnected or broken, the result will cause the sash to hang slightly out of kilter, especially with the upper sash. This will leave a gap for noise to penetrate on the same top side where the problem balance is located.
- Poor installation: This is sometimes a problem that shows up years down the road. 1) A poor shimming job and or improper fasteners used, or the window is not properly secured to the house walls will cause the master frame sill to sag and the jambs and head to twist. This will open up noise gaps around the sash. 2) Condensation saturates the loose fiberglass insulation that surrounds the window, resulting in noise 'flanking.' 3) An undersized window leaves excess gaps surrounding the perimeter frame and the construction to seal these gaps are not adequate. 4. Improper sealant such as expandable spray foam is used to seal the opening between the frame and the wall construction, stressing and warping the frame resulting in permanent distortion

Similarly, the normal wear and tear on doors may include:

- Weather-stripping begins to wear down and or pull out. The magnetic weather-stripping has this problem more than most.
- The screw adjustable threshold that raises and lowers the threshold does not stay in the adjusted position. Over time, the standard expander with vinyl sweeps will wear out.
- Improper installation, especially in older homes where the house door frame is out of square and not plumb. The contractor may not do all that is necessary to fit the door properly.

It is important to take these normal wear-and-tear issues into account when assessing deterioration of acoustic performance of sound insulation programs.

2.8. Guidance

Over the years since airport sound insulation programs were introduced and funded through AIP grants, the techniques employed to reduce noise levels inside buildings have become fairly standard – after all, there are only a limited number of retrofit measures that can be employed to achieve the noise reductions required by the FAA policy guidelines. Achieving this level of competence has been assisted

by a series of practical guidelines developed and published for use by practitioners in the design and implementation of sound insulation programs.

The U.S. Department of Housing and Urban Development (HUD) issued guidelines for sound insulation in 1967 incorporating a broad range of criteria for isolating noise in multi-family residential construction (HUD 1967). The topics discussed in the guidelines included different types of noise sources, both interior and exterior, general principles of noise control, and practical solutions to controlling noise in buildings. Special attention was given to the need for educating, training, and closely supervising contractors to ensure that the small details required in applying acoustic treatments are addressed.

The experience gained from a pilot residential sound insulation project sponsored by the Los Angeles Department of Airports in 1970 was published in a guide providing detailed instructions on soundproofing methods for achieving a range of incremental noise reduction improvements (Wyle 1970). This guide was subsequently republished by the U.S. Federal Highway Administration (FHWA 1977).

Based on the results of a number of building noise insulation and house modification studies conducted for HUD (see Section 2.2), a building code for protection from aircraft noise was developed for the U.S. Air Force for application in their Air Installation Compatible Use Zone (AICUZ) program (Bishop 1975). The Code includes a detailed description of the design and construction requirements for achieving different degrees of noise insulation.

In 1986, the FAA commissioned the National Bureau of Standards to develop a manual providing guidance for soundproofing existing buildings around airports in accordance with the goals set forth in the Part 150 regulation (Yaniv 1986b). The manual provides procedures and charts for estimating the noise reduction provided by existing buildings, determining the amount of soundproofing required to achieve an interior level of DNL 45 dB, and for selection of cost-effective retrofit options. There is no record of this report ever being released by the FAA.

Then, in 1992, the Department of the Navy and the FAA jointly funded the development of guidelines for the sound insulation of residences to assist in the implementation of sound insulation programs. The guidelines were published and disseminated by the FAA in 1992 (Wyle 1992). These guidelines were subsequently updated for DOD applications in 2005 to reflect the current building codes and products (Wyle 2005).

These updated Guidelines cover most aspects of a sound insulation program, but by design focused more on technical considerations and less on developing and managing programs. Much of the basic technical data for residences in the 2005 version is still valid, although cost and product information need to be updated and coverage of program issues expanded. There is now a need to update the 2005 Guidelines for FAA noise programs to incorporate additional guidance on program management and implementation which is equally essential in ensuring program success. It is necessary to broaden the scope of the document to include multi-family dwellings, schools, hospitals, nursing homes, churches, and other facilities that may be exposed to aircraft noise, as well as integrate green and sustainable retrofit practices. There is also a need to present the new guidelines in a way that facilitates ease of implementation; hence, the need to provide for a toolkit that leverages new information technology to support both program planning and management as well as field operations., ACRP Report 89 Guidelines for Airport Sound Insulation Programs addresses these issues and provides updated guidance for airport sponsors, consultants, and contractors.

2.9. Summary

A review of the literature shows that the early years of airport sound insulation programs were hampered by a lack of technical knowledge, data, and field experience. The overall impression is that these issues have been largely overcome as more field data has been obtained, testing techniques have to a certain extent been standardized (although not specified by FAA), and experience gained in implementation and program execution. There have been reports of degradation of the acoustic performance of sound insulation treatments in at least one U.S. program, but the extent of such degradation remains to be determined.

CHAPTER 3. SOUND INSULATION PROGRAM DATA COLLECTION

3.1. Introduction

As part of the first phase of the ACRP Project, detailed information was gathered to identify the installation methods, treatments, and materials that were used in early sound insulation programs and those methods, treatments, and materials that are currently being used.

The plan was to define the chronology in the evolution of sound insulation programs in the US, so that changes in methods and procedures from early to current programs can be identified, and related to possible changes in acoustic performance. The chronology was subsequently used to evaluate how program changes may have affected acoustic performance (see Chapter 6). The information was also used to define the airport programs and specific test procedures to be included in the subsequent testing and experimental tasks (see Chapter 4 and 5), which were designed to identify if any deterioration has occurred in acoustic performance over the years.

3.2. Program Data Required

The data collection plan developed for this task included consideration of the sound insulation program features that can affect the acoustic performance.

Program Design – the policies and procedures approved by the airport sponsor and implemented by the program team. The information to obtain includes eligibility requirements (DNL zones), number of units sound insulated, general program management approach (turnkey, separate design, etc.), policies and procedures (allowed - not allowed treatments), and contractor selection requirements.

Acoustic Design – the acoustic criteria for the program and the procedure used to define the acoustic requirements of various building components necessary to meet these criteria. The technical details necessary include design criteria utilized (FAA guidelines, guaranteed 5 dB improvement, modified criteria for special cases, etc.), design procedure employed (STC design, octave-band analysis, measurement based or package design), and testing procedure used (aircraft flyovers, artificial source, sampling scheme).

Treatments and Materials – how the designs lead to the specification of products, including critical structural components such as windows, doors, roof/ceilings, walls and vents. The necessary details for acoustic performance of components to be obtained from the product specifications on the STC and other prescriptive acoustic requirements, thermal and air infiltration requirements, as required in local building codes, and quality control requirements for manufacturer testing.

Installation Methods – how the products were installed and whether the component acoustic performance could be affected by inadequate installation techniques. This information to be obtained from the contractor briefing prior to construction records, uninstalled and installed product test reports, inspection schedule, change order history, inspection list and notes, and project change orders.
Validation – the monitoring of acoustical, thermal and air infiltration performance of the products installed through the in-situ component testing, as well as for the overall sound insulation performance through the full unit tests. The information on sampling procedures and acoustic test results for pre- and post-modification testing to be obtained from the installed product test reports, acoustical test reports, and final technical evaluation report.

Homeowner Complaints – the quality and overall performance of the completed project to be assessed based on the pre- and post-modification surveys, subsequent surveys, and homeowner's complaints on workmanship, warranty issues, acoustic performance, deterioration of products, etc.

3.3. Selection of Airport Programs to be Assessed

The overall objective of the project was to assess the degree and causes of deterioration in acoustic performance in early sound insulation programs, and subsequently to provide guidance to achieve longevity in existing and future programs. This was accomplished by examining the details of sound insulation programs conducted since the early 1980s.

The data collected in preparing the Literature Review (Chapter 2) identified 58 U.S. airports at which sound insulation programs have been implemented. These are listed in Table 1 that identifies the chronology of each program together with the approximate number of residences treated. It was not feasible, nor necessary, to review all of the programs listed in Table 1, and so it was necessary to establish criteria for the selection of representative programs which will provide the information identified in Section 3.2. The approach was to gather detailed information from a limited number of programs, combined with a lesser degree of data from a larger set of programs, to provide an overall assessment of the prevalence of deterioration and its causes.

Airport programs in three tiers were selected for data gathering, namely:

1. Tier 1 - to study long-term chronology and potential deterioration in early programs;
2. Tier 2 - to identify product quality control and workmanship issues in later programs;
3. Tier 3 – to examine new program starts which implement the most recent best practices.

Programs in each tier were selected to cover a wide range of climate conditions.

Tier 1 Programs: Early programs that have continued for at least 20 years. The term "early program" was defined as one that was started before the early 1990s, at which time considerable experience had been gained by consultants, product manufacturers, and contractors. It is also a time after which vinyl windows became the most commonly used replacements for existing windows. These programs provided data to cover the entire history of sound insulation and thereby yield a complete chronology of the changes in methods, procedures, and products, as well as providing data on any deterioration of products over an extended period.

Applying the criteria to the airports in Table 1 resulted in a total of eight programs:

- Atlanta (ATL);
- Baltimore (BWI);
- Los Angeles (LAX);
- Seattle (SEA);
- San Francisco (SFO);
- Boston (BOS);
- Minneapolis (MSP); and
- Tucson (TUS).

The selected list includes all the early programs with a wide range of climate conditions. In total, they cover over 50 percent of all residences treated in the U.S. to date. For each of these programs, the data specified in Section 3.2 was requested.

Tier 2 Programs: Established programs implemented after the "early" period, concentrating on complaints and quality control issues.

Initial contacts with airport representatives identified few programs that have received complaints from homeowners specifically related to acoustic performance. However, the mere absence of complaints does not necessarily mean that deterioration in acoustic performance has not occurred. If the original homeowner had moved, the new resident may not have been aware of any changes. Furthermore, the significant reduction in noise levels in the 1990s resulting from the phase-out of Stage 2 aircraft may have matched or exceeded any deterioration in acoustic performance. Several programs have received

complaints on products (windows difficult to open, de-laminated doors, contractor workmanship, etc.) and to a large extent these have been addressed and remedies provided. However, these issues may be indications of (unreported) problems in other programs that have applied the same products and techniques, and which may have resulted in reduced acoustic performance.

Program selection for this tier included those established in the early 1990s, around the time vinyl windows became available, continuing for a minimum of ten years, and insulating more than 500 dwellings, which would allow such programs to experience changes and possible product deterioration

Applying the criteria to the airports in Table 1 resulted in a total of 10 programs:

- Anchorage (ANC);
- Burbank (BUR);
- Cleveland (CLE);
- Detroit (DTW);
- Chicago (ORD/MDW);
- Manchester (MHT);
- Phoenix (PHX);
- Providence (PVD);
- San Diego (SAN); and
- Syracuse (SYR).

The selected list includes programs started after the early years with a wide range of climate conditions. For each of these programs, the focus for data collection was limited to homeowner complaints related to quality of products and workmanship. Specifically, the data requested include:

- Nature of complaint – product, installation, etc.;
- Installation issue;
- Product manufacturer and model;
- Year of construction;
- Year of complaint; and
- Resolution.

If the detailed data described in Section 3.2 was readily available, then it was accepted, but it was not intended to pursue collection of this detailed data with the rigor imposed for Tier 1 programs.

Tier 3 Programs: New programs to identify current best practices.

Established programs with well-defined and successful procedures in place may continue implementing those procedures in favor of adopting current best practices. New programs, on the other hand, are more likely to adopt the current best practices and be more representative of the state-of-the-art. The criteria for selecting new programs were that they should have started within the last five years.

Applying the criteria to the airports in Table 1 resulted in a total of five programs:

- Hartford (BDL);
- Boeing Field (BFI);
- Fort Lauderdale (FLL);
- Philadelphia (PHL); and
- Louisville (SDF).

For each of these programs the detailed data as presented in Section 3.2 was requested.

3.4. Sound Insulation Program Database

Attempts to gather the data listed above had mixed success. Some sponsors provided very detailed information, some provided only outline data, but many provided no data at all. Furthermore, the detail of the data varied considerably. The information that was received was assembled in a database from which categories and trends were established to form the basis for selecting airport programs for measurement surveys (Chapter 4) and defining best practice procedures in the subsequent guidance document.

CHAPTER 4. SOUND INSULATION PERFORMANCE MEASUREMENTS

4.1. Introduction

A major task in the project was to conduct measurements of the acoustic performance of selected dwellings that were insulated in the early years, and to conduct inspections to identify the causes of any deterioration in performance. This section of the report describes the rationale for selection of the dwellings to be tested, the test and inspection procedures that were followed, and the data analyses that was performed.

4.2. Measurement Program Objectives

The objectives of the measurement program were as follows:

1. To identify deterioration in acoustic performance of dwellings insulated in the early programs;
2. To identify the causes for deterioration – products, materials, installation;
3. To correlate inspection data with the acoustic measurements to identify any trends related to product deterioration, installation, or maintenance.

4.3. Airport Selection Rationale and Prioritization

In the Data Collection Plan described in Chapter 3, airport sound insulation programs were classified into three tiers based on initiation date, longevity, and size. Tier 1 programs were those started before the early 1990's and that were continued for at least 20 years. Tier 2 programs were those started after the early 1990's, and Tier 3 programs were those started within the last five years. Tier 1 programs were the 'early' programs for which testing is desirable to identify any deterioration in acoustic performance. The list of Tier 1 airport programs identified for noise measurements is presented in Table 4-1.

The airports listed in Table 4-1 represent the early programs which are the main focus of this ACRP project. However, in gathering the program data described in Chapter 3, it was evident that quality control issues have been present, not only at 'early' airports, but continuing throughout, up to, and including today. There was no indication that these issues have translated into degradation of acoustic performance, but they may well be an indicator of such. This is why the City of Inglewood was included in the above list of potential test sites – the City program was not one of the early programs, but has a complaint history from the years 1998 and 1999.

Each of the airports/cities in Table 4-1 was contacted with a request to conduct testing on insulated residences. For some, data on the early programs was not available (Atlanta and South San Francisco). Not surprisingly, many were reluctant to approve our request for testing (Los Angeles has an on-going program; Seattle is in the midst of a lawsuit). As a result, the main determining factors in the selection of participants were the availability of data and receiving approval for the testing.

One airport and one city expressed an immediate willingness to participate in the testing program (Boston Logan Airport and the City of Inglewood), and promised assistance in contacting homeowners. Others, such as the Cities of Millbrae and San Bruno, CA, gave permission for testing, but despite major efforts, only one homeowner in these two cities offered to participate.

TABLE 4-1 List of Tier 1 Airports Identified for Measurements

Tier	Airport	Years of Interest		Approval for Testing
		From	To	
TIER 1	Atlanta	1985	2000	No records available
	Baltimore/Washington	1988	2011	No
	Boston	1985	2009	Yes
	Los Angeles:			
	Los Angeles City	1984	2011	No
	City of Inglewood	1992	2011	Yes
	Minneapolis/St. Paul	1992	2011	No
	Providence	1991	2002	No
	Seattle	1985	2011	No
	San Francisco:	1985	2011	
	San Bruno	1988	2002	Yes
	Millbrae	1989	2011	Yes
	S. San Francisco	1985		No records available
	Tucson	1992	2011	No

4.4. Selection of Dwellings to be Evaluated

At each of the participating airports/cities, dwellings were selected for acoustic testing and, inspection surveys. Factors that were considered in the selection include:

- Dwellings for which pre- and post-tests were performed and where the test details are available.
- Dwellings in which homeowners have reported a perceived performance deterioration, and/or warranty issue;
- Dwellings in which homeowners have not reported a perceived performance deterioration, and/or warranty issue;
- Preference for dwellings occupied by the original owners;
- Availability for testing (homeowner present during tests).

The actual selection of specific dwellings for testing was developed in conjunction with the airport/city representative, carefully avoiding homeowners with a history of complaints against the airport.

4.5. Homeowner Approach

A critical factor in the test program was gaining the agreement of homeowners to participate. The following letter of introduction was prepared for the airport/city to communicate with the community:

Dear Mr. & Mrs. Homeowner:

On behalf of (Airport/City), I would like to invite you to participate in a national study to assess the condition of products installed in the early years of federally funded airport sound insulation programs. Specifically, we would like to examine the effect of aging, normal wear and tear, etc., on the performance of the acoustic windows and doors that were installed in your home in 19XX.

If you decide to participate, a team of specialists will visit your home to inspect your windows and doors, and perform a few acoustic tests. You should not be inconvenienced for more than 2 or 3 hours. Afterwards, the inspector will answer any questions you may have, and give you some guidelines for proper maintenance and repair of the products as they age. For your convenience, we can schedule the visit for daytime or evening hours, or at weekends if you prefer.

I do hope that you will participate and take the advantage of talking to a specialist about maintaining your sound insulation modifications. The results will also enable federal authorities to continue funding this and similar programs across the nation.

If you would like to accept our invitation, or have any questions, please call me at ...-…-….

Sincerely,
Airport Official

The scheduling of tests was coordinated through airport and city representatives.

4.6. Acoustic Test Procedures

Two types of acoustic measurements were conducted at each selected home, specifically:

1. The exact test procedure used in the original measurements (aircraft flyovers or artificial noise source). The same artificial source location and microphone locations were utilized. Every attempt was made to replicate the original test procedure.
    - The Noise Reduction for aircraft flyovers was determined as the difference between the Sound Exposure Levels (SEL) measured outside and inside the selected room for each event. The outside microphone was located on a pole away from the dwelling to measure the free-field SEL. Two microphones were located inside the room to be measured. The reported noise reduction was the arithmetic average value taken over 10 to 20 aircraft events.
    - The exterior artificial noise source (a loudspeaker) was located in the same location as for the original measurements. The noise reduction spectral transfer function for an artificial noise source installed outside of the room under test was determined as the difference between the average sound levels (L_{eq}) measured outside and inside the selected room. The spectral transfer function was then applied to a representative aircraft noise spectrum (departure of a Boeing 727-200 to represent aircraft of the 1980's) to determine the indoor sound level for the 'representative aircraft' flyover event. The broadband Noise Reduction (in dBA) was determined as the difference between the calculated A-weighted sound levels of the 'representative aircraft' outside and inside the room.
2. Wyle's indoor/outdoor test procedure for diagnostic testing of individual building windows and doors. The test involves placing an artificial noise source (loudspeaker) inside a room and microphone scanning over the inside and outside of a selected element. The Noise Reduction of the element was determined as the difference between the inside (loud) and outside (quiet) sound

levels measured (A-weighted and spectral). The noise reduction of individual elements was intended as a diagnostic tool for comparison evaluation between performance of similar constructions in the same or various houses. It quantified the relative amount of sound energy passing through the element (and through gaps), thus making it a tool to identify faults in the element or installation.

4.7. Inspection Procedure

Wyle's team member, Architectural Testing (AT), established a procedure for classifying building envelope performance, including levels of deterioration, actual performance values through testing, and estimating values for conditions that were not tested. Certainly, material degradation corresponds directly to the types of materials and products. An inspection checklist was prepared to collect the data during the inspections and for sorting and classification upon completion.

AT performed an evaluation of window and door installations to determine the condition of the installed assembly. Using the information provided, AT conducted a site evaluation to check for conformance of the installed assemblies with the available documents as well as the industry accepted standard of care. This was primarily achieved through a close range visual inspection of the window and door systems, as well as the adjacent systems that might affect acoustics. The following summarizes the inspection process.

- Prior to arrival on site, AT collected and review all relative documents and information pertaining to the fenestration assemblies. Relative documents included, shop drawings, architectural drawings, specifications, installation instructions, and associated manufacturers' product literature.
- Upon (or prior to) arrival, building owners were interviewed to review any concerns, maintenance /replacement history, etc.
- Perform a visual inspection, focussed on:
    - Existing fenestration and door systems, and if they were original from initial program installation;
    - Inspection of the interior around the units for signs of damage or deterioration;
    - Existing condition of systems (including function) and components (such as sealants, weather-stripping);
    - Dimensional checks of the fenestration installation to verify installation was within tolerance (size, square, plumb, etc.)
    - Signs of leakage/openings
    – Evaluation of components (balances, hardware, frames, glazing, gaskets, perimeter sealants, etc.) to determine general level of operational performance.
    - Maintenance performed;
    - Identify potential cause of deteriorated system/components (damage, wear and tear, exposure, installation techniques, etc.)

The inspection data was reviewed to determine if any deterioration in acoustic performance was due to:

- Product (window, door) quality control (manufacturer);
- Poor workmanship in installation (contractor); and
- Inadequate maintenance or ill-treatment (homeowner).

CHAPTER 5. NOISE REDUCTION MEASUREMENTS IN RESIDENCES EXPOSED TO AIRCRAFT NOISE

5.1. Introduction

The goal of the acoustical testing was to compare the noise reduction data obtained immediately after the sound insulation was completed with the current measurement data. The selection of houses for the retesting included some with known homeowner complaints related to windows and/or doors, as well as homes in apparently good condition.

5.2. Uncertainty in the Test Results

The results of noise level reduction measured for the same building at different times by different test personnel is subject to uncertainty even when, as in this case, the measurement procedure exactly copies that of the original tests. According to ASTM E966-10, "*No body of experience in the use of this guide exists at present; however, it is estimated that the repeatability standard deviation of these test procedures are of the order of 2 to 3 dB, depending on frequency*".

An earlier version of the E966 standard published in 1990 states that *"… it is estimated that the repeatability of the test procedure is of the order of 2 to 4 dB, depending on frequency"*. Furthermore, it states that "*It is recommended that sufficient data be taken to achieve an uncertainty of ± 4 dB below 200 Hz, ± 3 dB from 250 to 500 Hz, and ± 2 dB above 500 Hz, with a confidence level of 95 percent.* For most building structures the A-weighted noise reduction for typical transportation noise sources is determined by the values in the 250 and 500 Hz octave bands, so this requirement essentially attempts to limit the uncertainty of the A-weighted noise reduction to ± 3 dB.

Accordingly, a difference of less than 3 dB (positive or negative) between the retest noise level reduction (NLR) and final (post-modification) NLR was considered within the measurement accuracy of the tests.

5.3. Boston Logan International Airport

The Wyle/ATI team conducted acoustical testing in homes that were insulated in the early years of the Massport residential sound insulation program in the vicinity of Boston Logan International Airport. Overall, thirty rooms in fifteen houses were tested in June 2012. The complete dataset is presented in Table 5-1showing the house ID, completion year of the sound insulation construction, rooms tested, and the noise reduction measured for the room facades in the initial (pre-construction), final (post-construction) tests, the 2012 retests, and the difference (delta) between the final and retest data.

For the repeat testing, the measurement technique used by the original consultant was replicated exactly. (The engineer who conducted the original measurements was an on-site advisor in these repeat measurements).This included the exterior loudspeaker location (5 ft. above the ground, 25 ft. from the closest point of the building, and at an angle ranging from 0 to 45 degrees), the exterior microphone location (6 ft. from the closest building surface), and the interior microphone location (4 ft. from the interior of the façade). Simultaneous measurements were made of the outdoor and indoor sound pressure levels in octave frequency bands from 63 to 4000 Hz. In place of a simulated aircraft noise spectrum, a 'pink' noise generator producing a flat signal spectrum was used to produce the exterior noise signal. This allowed for a higher signal-to-noise ratio for more accurate measurements at higher frequencies.

The testing procedure was in compliance with FAA standards and generally in accordance with ASTM E966 'Standard Guide for Field Measurements of Airborne Sound Insulation of Building Facades and Facade Elements'. The testing was conducted with calibrated equipment. All windows and doors in each house were closed for the testing, and the air-conditioning was turned off.

The test results are presented in Table 5-1. It can be seen that for the majority of the rooms tested (24 out of 28) where there has been no homeowner modification, no decrease in A-weighted noise reduction greater than -3 dB was noticed between the original post-construction testing and retesting. Analyses for the rooms that exhibited a decrease equal to or greater than -3 dB (identified in red in Table 5-1), or showed significant differences in certain octave bands, are presented below.

House BOS 01, East Boston – Bedroom and Living Room

The sound insulation of the home was completed in 1992, with the initial (pre-construction) acoustical testing performed in May 1990 and the final (post-construction) measurements performed in May 1992. Figure 5-1 compares the results of the initial, final and retest data for the 2nd floor front bedroom.

TABLE 5-1 Acoustic Test Data for Residences in Boston

House ID (Year Insulated)	Room	Test	Noise Reduction (dB)							Overall NLR (dBA)
			Octave Band Center Frequency (Hz)							
			63	125	250	500	1000	2000	4000	
BOS 01 (1992)	Bedroom	Initial	16	22	16	16	23	29	25	17
		Final	21	23	30	40	40	50	42	36
		Retest	17	17	24	31	39	44	45	30
		Delta	-4	-6	-6	-9	-1	-6	3	-6
	Living Room	Initial	18	20	16	25	26	29	32	22
		Final	25	21	24	34	43	43	40	31
		Retest	24	21	24	35	39	43	45	31
		Delta	-1	0	0	1	-4	0	5	0
BOS 02 (1992)	Bedroom 1	Initial	17	21	24	25	31	34	32	26
		Final	17	22	31	35	43	45	43	35
		Retest	20	20	31	39	50	53	54	36
		Delta	3	-2	0	4	7	8	11	1
	Bedroom 2	Initial	17	21	22	26	29	30	29	26
		Final	18	22	32	36	44	58	45	36
		Retest	16	21	33	36	45	51	54	36
		Delta	-2	-1	1	0	1	-7	9	0
	Living Room	Initial	16	20	24	24	28	29	33	25
		Final	20	23	30	34	41	44	44	34
		Retest	19	21	31	37	45	45	47	36
		Delta	-1	-2	1	3	4	1	3	2
BOS 03 (1989)	Living Room	Initial	18	21	26	31	37	42	40	31
		Final	24	26	33	34	41	43	43	35
		Retest	21	25	26	31	41	48	50	31
		Delta	-3	-1	-7	-3	1	5	7	-4
	Dining Room/ Kitchen	Initial	12	26	25	25	33	38	33	26
		Final	20	27	34	36	47	51	49	37
		Retest	14	26	34	38	48	51	53	38
		Delta	-5	-1	0	2	0	0	5	1
BOS 04 (1990)	Dining Room	Initial	22	22	23	20	30	35	31	22
		Final	Data Not Available							
		Retest	19	30	29	42	48	46	49	36
	Living Room	Initial	26	25	24	27	32	37	36	27
		Final	Data Not Available							
		Retest	22	20	27	34	40	43	47	32
BOS 05 (1989)	Bedroom	Initial	18	21	19	17	27	26	26	19
		Final	21	26	36	41	44	39	37	40
		Retest	25	27	42	44	47	50	44	44
		Delta	4	1	6	3	3	11	7	4
BOS 06 (1991)	Bedroom 1	Initial	14	25	21	27	28	26	29	25
		Final	20	33	37	38	45	50	49	39
		Retest	21	34	40	50	57	62	64	46
		Delta	1	1	3	12	12	12	15	7
	Bedroom 2	Initial	22	21	22	23	24	25	25	23
		Final	29	29	31	34	43	47	45	35
		Retest	24	24	34	37	48	50	53	37
		Delta	-5	-5	3	3	5	3	8	2

TABLE 5-1 (cont'd) Acoustic Test Data for Residences in Boston

House ID (Year Insulated)	Room	Test	Noise Reduction (dB)							Overall NLR (dBA)
			Octave Band Center Frequency (Hz)							
			63	125	250	500	1000	2000	4000	
BOS 07 (1990)	Living Room 1	Initial	17	18	25	30	41	47	45	30
		Final	20	21	29	35	42	50	41	34
		Retest	23	26	31	37	50	53	57	36
		Delta	3	5	2	2	8	3	16	3
	Living Room 2	Initial	Data Not Available							
		Final	13	24	32	32	43	46	38	33
		Retest	19	23	32	37	50	56	60	36
		Delta	6	-1	0	5	7	10	22	3
BOS 08 (1992)	Living Room 1	Initial	16	13	20	27	34	33	34	25
		Final	24	33	40	48	57	54	49	46
		Retest	20	26	40	47	55	52	58	44
		Delta	-4	-7	0	-1	-2	-2	9	-2
	Living Room 2	Initial	17	14	20	28	31	32	29	26
		Final	23	32	40	52	59	60	47	47
		Retest	21	25	38	42	49	54	58	41
		Delta	-2	-7	-2	-10	-10	-6	11	-6
BOS 09 (1992)	Living Room	Initial	14	18	18	15	21	18	24	17
		Final	18	21	28	35	40	41	34	33
		Retest	15	28	29	39	41	43	43	36
		Delta	-3	7	1	4	1	2	9	3
	Bedroom	Initial	17	18	22	28	33	39	38	27
		Final	21	24	34	37	44	46	40	37
		Retest	28	21	35	42	49	52	56	39
		Delta	7	-3	1	5	5	6	16	2
BOS 10 (1992)	Bedroom 1	Initial	16	16	17	21	25	26	27	21
		Final	26	26	28	35	44	48	42	34
		Retest	28	29	35	40	48	53	53	39
		Delta	2	3	7	5	4	5	11	6
	Bedroom 2	Initial	15	17	20	19	23	27	28	20
		Final	19	24	30	37	45	50	40	35
		Retest	27	22	36	42	49	52	53	40
		Delta	8	-2	6	5	4	2	13	4
BOS 11 (1992)	Kitchen	Initial	13	25	23	16	29	36	34	18
		Final	15	29	29	30	34	44	40	31
		Retest	6	27	30	30	37	46	50	32
		Delta	-9	-2	1	0	3	2	10	1
	Bedroom	Initial	19	20	20	27	33	38	40	26
		Final	20	24	29	33	43	46	44	33
		Retest	15	24	31	36	47	54	60	35
		Delta	-5	0	2	3	4	8	16	2
BOS 12 (1990)	Living Room	Initial	15	14	20	25	24	26	18	23
		Final	18	23	27	35	37	39	42	33
		Retest	24	27	23	37	42	46	48	31
		Delta	6	4	-4	2	5	7	6	-2
	Bedroom	Initial	20	17	23	26	31	32	31	26
		Final	22	21	28	38	43	40	39	34
		Retest	15	19	28	37	42	47	54	34
		Delta	-7	-2	0	-1	-1	7	15	-1

TABLE 5-1 (concluded) Acoustic Test Data for Residences in Boston

House ID (Year Insulated)	Room	Test	Noise Reduction (dB)							Overall NLR (dBA)
			Octave Band Center Frequency (Hz)							
			63	125	250	500	1000	2000	4000	
BOS 13 (1988)	Living Room	Initial	18	11	20	27	30	34	34	25
		Final	21	21	31	37	41	46	45	36
		Retest	21	24	29	38	44	47	50	35
		Delta	0	3	-2	1	3	1	5	0
	Family Room (h/o replaced window)	Initial	16	25	17	16	27	27	31	18
		Final	22	27	25	31	32	35	35	29
		Retest	20	23	20	30	35	39	42	27
		Delta	-2	-4	-5	-1	3	4	7	-3
BOS 14 (1988)	Living Room	Initial	22	20	21	30	35	37	32	27
		Final	22	23	36	38	46	47	38	38
		Retest	23	24	34	41	48	51	59	39
		Delta	1	1	-2	3	2	4	21	1
	Mech. Room (h/o modified	Initial	15	16	19	29	36	39	34	26
		Final	21	26	31	39	46	52	46	37
		Retest	17	23	30	31	35	40	40	32
		Delta	-4	-3	-1	-8	-11	-12	-6	-5
BOS 15 (1993)	Bedroom 1	Initial	18	20	22	25	35	42	44	26
		Final	19	20	31	44	45	52	43	37
		Retest	20	24	33	39	50	52	51	38
		Delta	1	4	2	-5	5	0	8	1
	Bedroom 2	Initial	24	21	23	28	39	39	41	28
		Final	23	25	27	38	48	50	44	34
		Retest	23	26	26	34	43	48	55	32
		Delta	0	1	-1	-4	-5	-2	11	-2

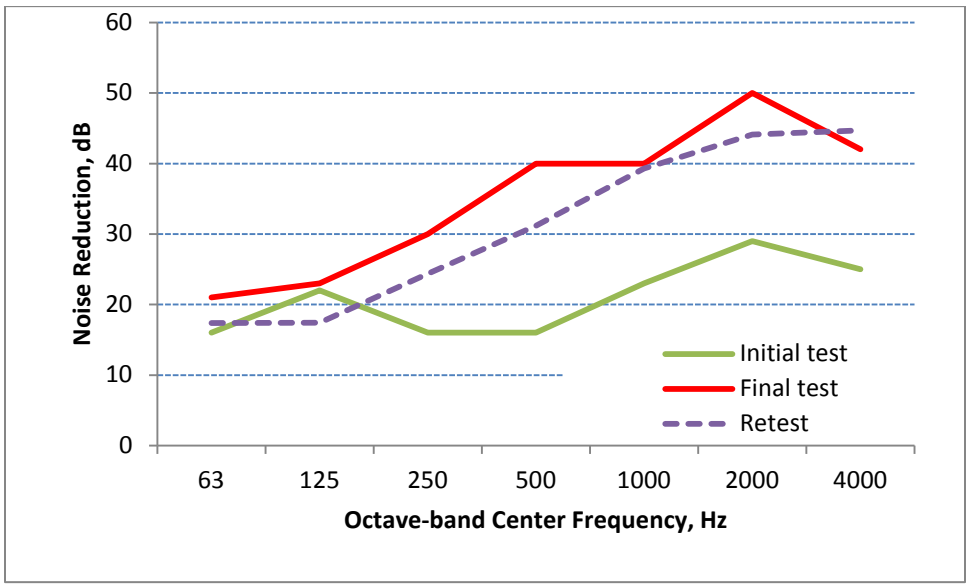

Figure 5-1. Noise Reduction Measured at BOS 01, Bedroom.

It can be seen from the figure that as the result of the sound insulation treatment, the noise reduction of the bedroom façade was increased significantly over the frequency range. The retested octave-band noise reduction indicates a noticeable decrease in noise reduction of up to 9 dB at some mid frequencies.

The house is a two-story frame structure with wood siding. The current owner has been in possession for seven years and reported adding minor caulking of windows, replacing blue board and plaster at the interior of the bedroom exterior walls, replacing carpet, and installing a through-window air-conditioning unit in one of the two windows.

The front bedroom windows installed as part of the sound insulation treatment are of double-hung type with wood frames and aluminum exterior storms. The insulated glass units (IGU) consist of two panes of 3/32" glass with a ¼" air space. The storm window glazing is of 3/32" thick glass.

For retesting of the bedroom, the through-window A/C unit was removed from the second window, and the window was closed. However, the bottom sash of the prime double-hung window was closed not against the window sill but against the remaining wooden bar at the bottom, which was nailed to the sill and could not be removed. This second window condition is shown in Figure 5-2.

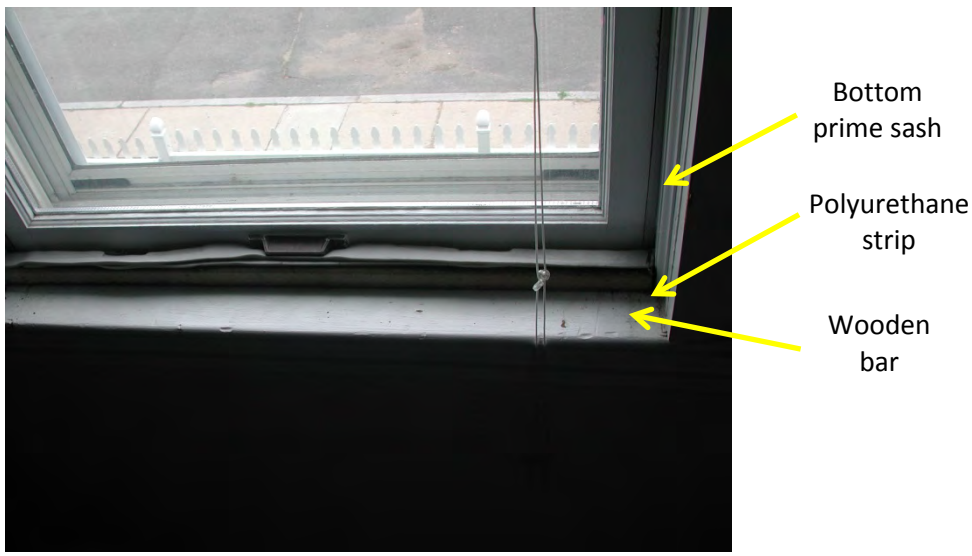

Figure 5-2. Bottom condition of second window for retesting (view from inside of Bedroom).

An indoor-outdoor diagnostic test was performed for the facade, which confirmed the retested noise reduction data shown in Table 5-2. These tests also indicated that the noise reduction provided by the second window was approximately 3 dB lower than the first window throughout the frequency range, probably due to the incomplete closure of the second window as described above.

The home inspection conducted during the retesting showed deterioration and material failure of the window frames, 50% of failed sealant area of glazing seals, completely failed (over 90%) exterior sealant due to inadequate maintenance, general wear and tear/weathering of weather-stripping and frames, and minor deterioration in their operability. The windows appear to be prone to air and water leakage.

The house exterior wall condition is also of concern for this retest. The wood siding and sealant are in completely failed condition and are rotten due to lack of maintenance. The exterior window and wall conditions are shown in Figure 5-3.

Figure 5-3. Windows and walls at BOS 01.

The high degree of the overall structure deterioration is the most likely cause of the diminished noise reduction for the Bedroom compared to the 1992 final testing, as noted above. It is difficult to assign the acoustic deterioration to the replacement window products themselves in this case of apparent inadequate maintenance, when the window wood frames, exterior trim and wall siding have never been painted and the sealant and caulking have never been restored since the sound insulation was completed 20 years ago.

In comparison with the bedroom, the living room in this house showed very little to no decrease in the noise reduction over time. Figure 5-4 compares the results of the initial and final tests, as well as the retest data for the 1st floor living room. The front façade of the Living Room is shown in Figure 5-5.

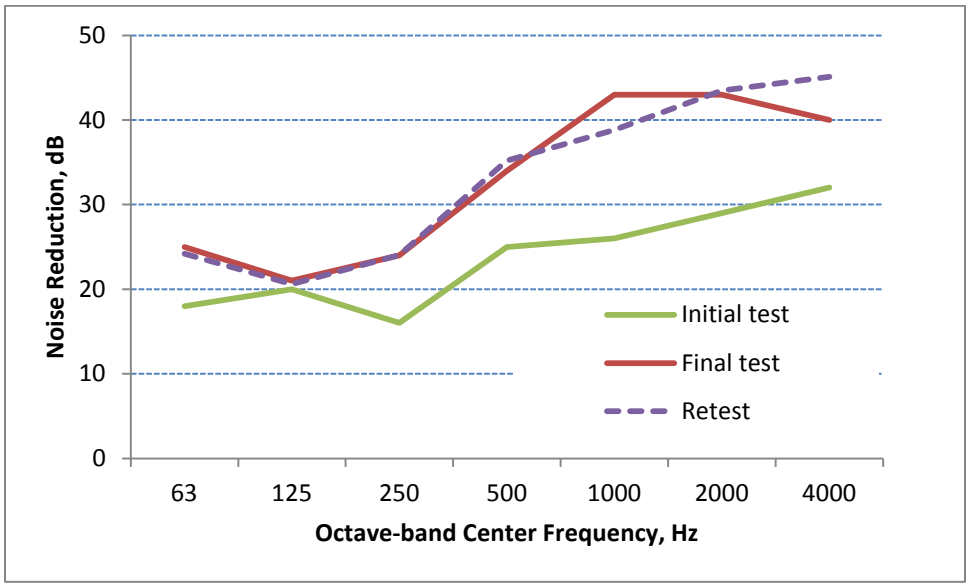

Figure 5-4. Noise reduction measured at BOS 01 living room.

Figure 5-5. BOS 01 living room windows and walls.

The retest results in Figure 4 show remarkable repeatability with the final test data obtained 20 years ago over the entire frequency range. Only in the 1000 Hz octave band, the retested Noise Reduction is 4 dB below the final test. At the high end of the spectrum (4000 Hz), the retest noise reduction is higher than the final test result due to a better signal-to-noise ratio during the retest. (The increase in noise reduction in the octave band centered at 4000 Hz is typical for the final testing in the majority of the measured houses. This is likely due to a lack of high-frequency noise signal indoors during the post modification testing, which resulted in a low signal-to noise ratio). It should be noted that, in general, the noise reduction measured in the final test for the living room was lower than that measured for the 2nd-story bedroom.

During the 1992 sound insulation of the living room, the wood prime units of the windows remained intact, with only new exterior aluminum storm windows added. The home inspection during the retesting showed deterioration and material failure of the window frames, sealant, and general wear and tear similar to that indicated above for the bedroom exterior wall and windows. The degree of such deterioration, especially of the wood siding and frame around the windows, is somewhat lower for the living room, as can be seen in Figure 5. It appears, therefore, that the amount of the wall and window frame deterioration is responsible for the lack of repeatability of the final test data of 1992 in comparison with the retest results.

House ID BOS 03, Winthrop – Living Room and Dining Room

The sound insulation of the home was completed in 1989, with the initial (pre-construction) acoustical testing performed in November 1986 and the final (post-construction) measurements performed in November 1989. The Wyle /ATI team retested the home in June 2012.

The house is a two-story frame structure with vinyl siding. The current owner has been in possession for 12 years and reported replacing exterior siding, window caulking, and drilling extra draining holes for removing storm water penetrated into some windows. Complaints include rotted window framing, drafts, water penetration and wood swelling.

The rear elevation of the 1st floor living room, shown in Figure 6, incorporates twelve awning windows w/exterior "piggy- back" storm windows and interior removable storm panels each. The wood frame awning windows are original and were not replaced during the sound insulation. They are glazed with insulating glass units with two sheets of 3/32"glass at ¼" air space. The exterior and interior storms, glazed with 1/8" single pane glass each, were added to the original awnings as part of the sound insulation treatment.

(a) (b)

Figure 5-6. Windows at BOS 03: (a) exterior views; (b) interior views.

The homeowner typically removes the interior storm windows in summertime. All interior storms were reinstalled for the retesting. Figure 5-7 compares the results of the tests performed for the living room.

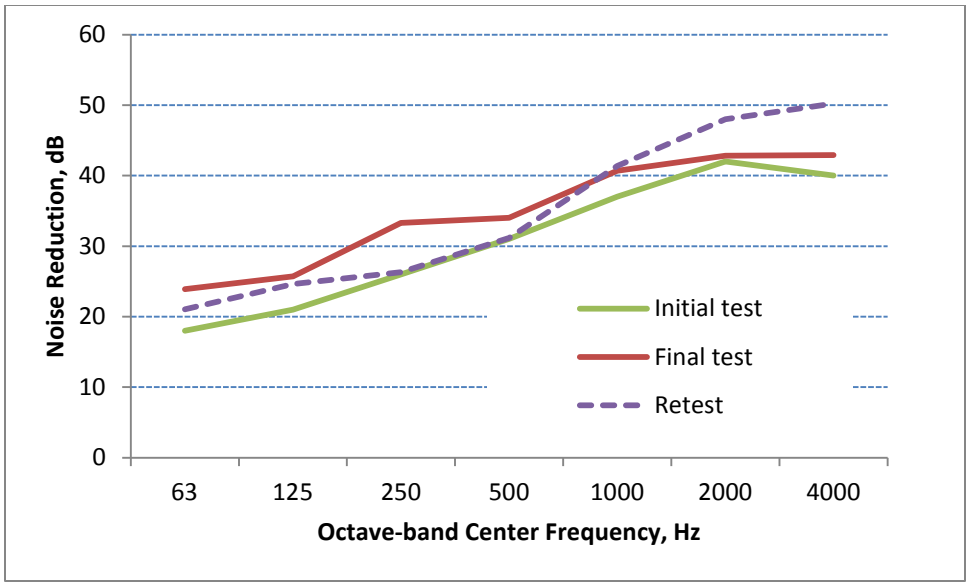

Figure 5-7. Noise reduction measured at BOS 03 living room.

First, it should be noted that the noise reduction improvement resulting from the addition of the exterior and interior storm windows as part of the acoustical treatment was limited, as shown by the relatively small difference between the final and initial tests over the frequency range. The retest of the windows basically confirms results of the final test, with the exception of the 250 to 500 Hz bands, where the storm windows appear ineffective, and the Noise Reduction drops to the initial level tested with no storms.

Additional diagnostic testing performed for the windows indicated that the perimeter seals were likely responsible for the diminished acoustical performance of the windows in this frequency range.

The home inspection revealed moderate window frame deterioration with 50% of areas having failed sealant or weather-stripping, IGU fogging, and material failure in glazing seals resulted from general wear and tear, and weathering.

Acoustical testing was also performed for the horizontal sliding glass door (SGD) in the dining room/kitchen area. The original vinyl prime door was not replaced in the sound insulation program; only the aluminum storm door was added at the exterior. The prime door glazing consists of insulated glass with two sheets of 5/32" glass at ¼" air space. The storm door has a single pane of ¼" glass, installed with a 6" air space between the prime and storm. Figure 5-8 shows the door and Figure 5-9 presents the related test data.

Figure 5-8. Sliding glass door at BOS 03, dining room/kitchen.

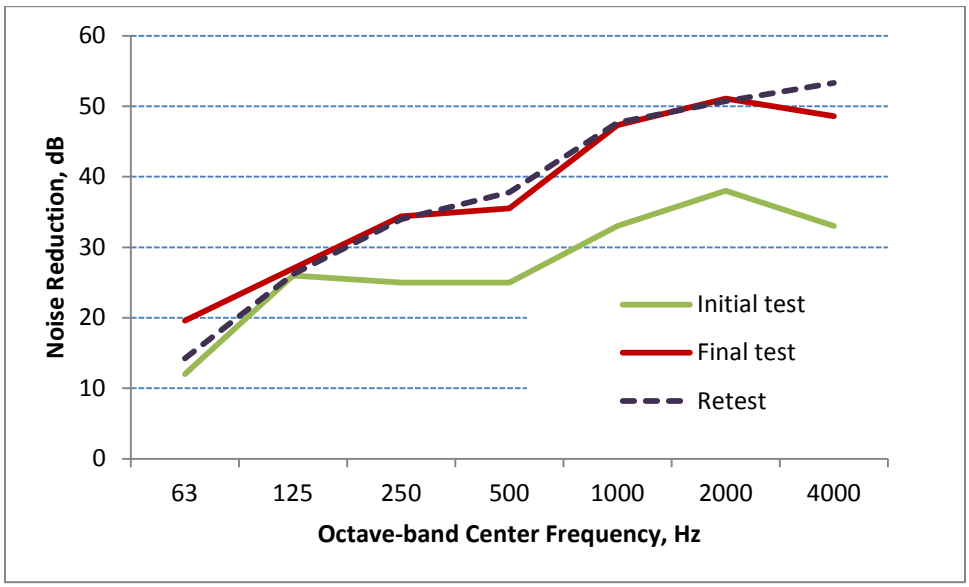

Figure 5-9. Noise reduction measured at BOS 03 dining room/kitchen.

As Figure 5-9 shows, the noise reduction measured for the door shows a very high degree of repeatability between the final test and the retest over the time span of 23 years. This result is especially remarkable since the home inspection revealed moderate deterioration of the frame, minor deterioration of the glazing seals and weather-stripping, and improper installation with no exterior sealant at the storm door perimeter; one of the storm sashes is out of square and racked in the frame.

House ID 08, East Boston – Living Rooms at 1st and 2nd Floors

The sound insulation of the home was completed in 1992, with the initial (pre-construction) acoustical testing performed in January 1991 and the final (post-construction) measurements performed in June 1992. The Wyle /ATI team retested the home in June 2012.

Two front living rooms, one on the 1st floor and another at the 2nd floor of this three-story building, are almost identical in size and shape. Both rooms were selected by the owners as Rooms of Preference (ROP) for the sound insulation treatment. The exterior wall treatment included building up the front and side walls with additional layers of 5/8" blue board on studs on the inside. The front bay windows were replaced with a combination of a double prime window on the outside and a single prime window on the inside, forming a triple-glazed window at each opening. All new windows were of double-hung type, with aluminum frames and single panes of 1/8" glass each. Figure 5-10 illustrates the window construction.

Figure 5-11 compares the noise reduction measured in the initial and final tests, as well as in the retest for the 1st floor living room. Figure 12 provides a similar comparison for the 2nd floor Living Room.

(a) (b)

Figure 5-10. 2nd Floor Living Room Bay Window at BOS 08:
a) outdoor view; b) indoor view.

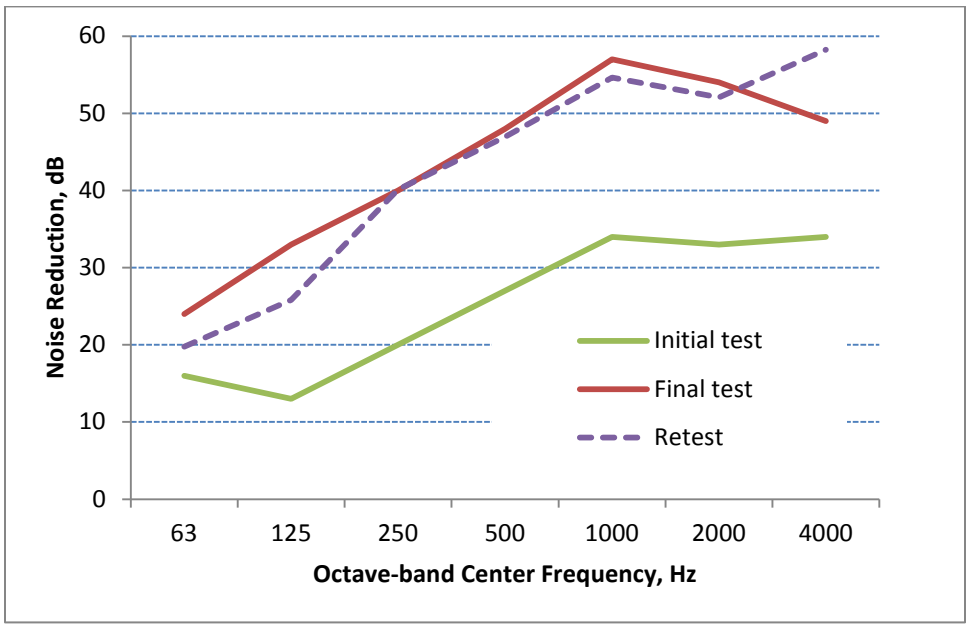

Figure 5-11. Noise reduction measured at BOS 08 1st floor living room.

It can be seen from Figure 5-11 that the sound insulation modifications of 1992 significantly improved the Noise Reduction of the 1st floor living room. The retest performed in 2012 confirms the results in the frequency range from 250 to 2000 Hz (a small variation not exceeding 2 dB is within the accuracy of the measurements). At 4000 Hz, the noise reduction measured in the final test was affected by the lack of a high signal to noise ratio, as described for other testing data above.

At the low frequency end of the spectrum, in the 63 and 125 Hz octave bands, the retested NR is below the final test results. This is not, however, considered a sign of acoustic deterioration of windows since the living room experienced some furniture change and a carpet-to-hardwood floor change in the time between the final test and retest. Moreover, the former exterior wall finish of asbestos cement siding was replaced with vinyl siding for the whole house, which could significantly affect the acoustical performance of the structure. The home inspection revealed only minor deterioration of the glazing seals for the windows, but no exterior sealant at the window perimeter trim, which is improper installation that could have occurred when the wall siding was replaced by the homeowner

In contrast to the 1st floor, the noise reduction of the living room on the 2nd floor appears to have significantly diminished since 1992, as is evident from Figure 5-12. At the low frequencies, the pattern is similar to the 1st floor living room. However at frequencies from 500 to 2000 Hz, the retest noise reduction is up to 10 dB lower than was measured in 1992.

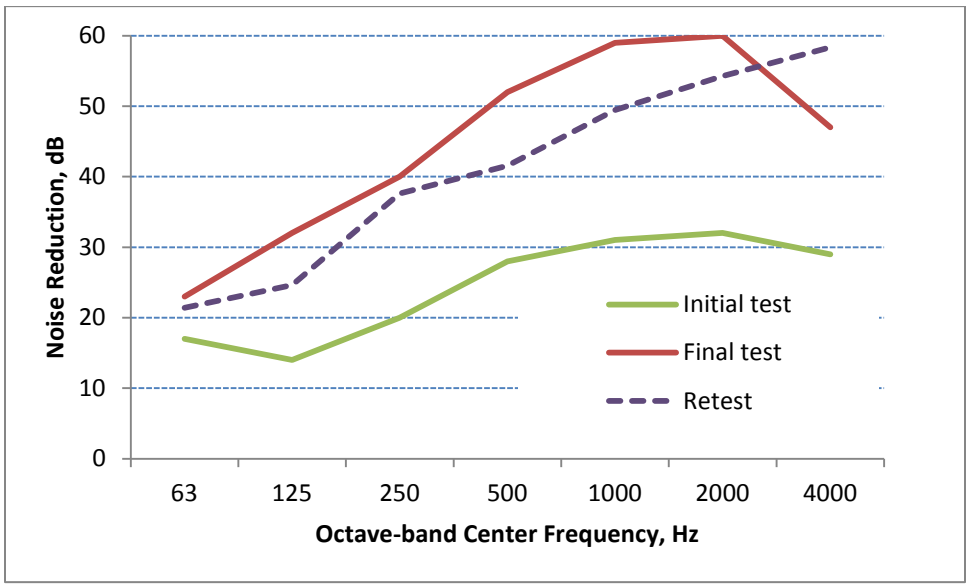

Figure 5-12. Noise Reduction measured at BOS 08 2nd floor Living Room, Windows 19, 20 and 21.

The home inspection of the room discovered construction issues very similar to the ones discussed above for the 1st floor Living Room. No air or water leakage through the windows was identified. However, the 2nd floor Living Room has just undergone renovation that included gypsum board replacement for the exterior walls. During the retesting, the furniture was also still collected in the middle of the room for the renovation – a condition different from the final test. It is not clear whether these variations combined could explain the observed deficiency in the retest noise reduction of the 2nd floor Living Room compared to the final test.

Diagnostic acoustical tests were conducted which confirmed the retested noise reduction data above 500 Hz. It was noted during the diagnostic testing that no window had any obvious sound leaks. There are also no indications that any component of these windows failed beyond what was noted for the

windows at the 1st floor, above. For all these reasons, the results of the retesting for the 2nd floor living room should be considered inconclusive for determining the causes for their apparent underperformance.

House BOS 14, Winthrop – Mechanical Room and Living Room

The sound insulation treatment of the home was completed in 1988, with the initial (pre-construction) acoustical testing performed in October 1986 and the final (post-construction) measurements performed in February 1988. The Wyle /ATI team retested the home in June 2012.

The house is a two-story frame structure with vinyl siding. The current owner has been in possession for 15 years. A small three-season porch at the rear of the house (1st floor) was treated in the sound insulation program. After the sound insulation, the porch was converted by a new owner into a mechanical room with no changes to the windows. Figure 5-13 compares the noise reduction measured in the initial and final tests, as well as in the retest for the mechanical room. It can be seen that, as a result of sound insulation, the noise reduction of the mechanical room was increased by 5 to 12 dB over the entire frequency range. However, the noise reduction retested in 2012 is much lower than the results of 1988, completely negating the prior improvement at frequencies above 500 Hz. Such a significant change is unlikely to occur only as a result of the interior alterations in the room.

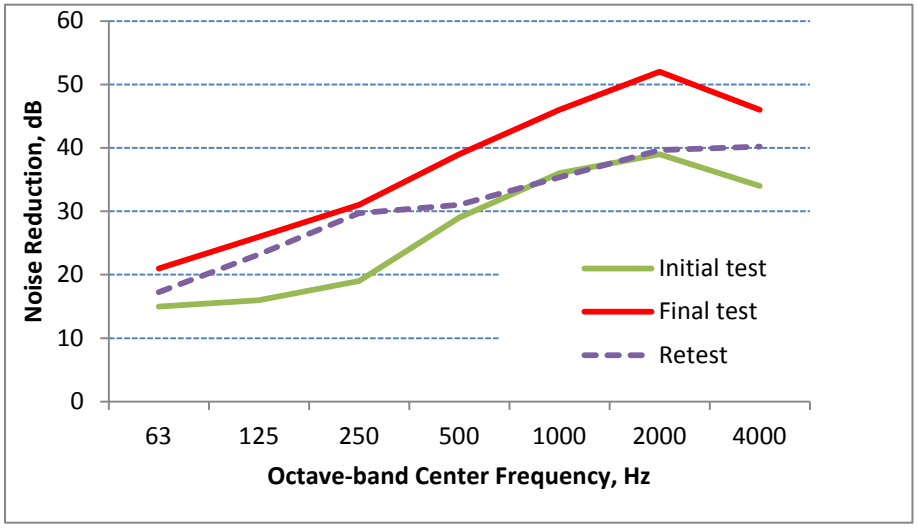

Figure 5-13. Noise reduction measured at BOS 14 mechanical room.

The sound insulation modification of the windows (as well as all other windows in the house) included removing existed double-hung sashes and balance assemblies, insulating weight cavities, installing new wood/vinyl clad double-hung sashes into the existing frames and replacing existing storm windows with new storm windows. The prime window IGU consists of two sheets of 3/32" glass each with ¼" air space in between. The storm window glazing is of 3/32" thick glass. Figure 5-14 illustrates the exterior (a) and interior (b) of the tested rear façade.

(a) (b)

Figure 14. Exterior (a) and interior (b) views of the mechanical room façade at BOS 14.

The home inspection conducted during the retesting showed minor deterioration resulting from lack of maintenance, as well as lack of sealant at all exterior trim work. No air or water leakage through the windows was identified. However, the subjective impression during the sound testing was that the windows and walls in the room sounded 'weak', although no apparent sound penetration spots were revealed.

The noise reduction test results for the front façade of the 1st floor living room are presented in Figure 5-15. For this room, the retest noise reduction closely follows (and even slightly exceeds) the final test data of 1988, up to the octave band centered at 4000 Hz. At the high frequencies, the final test data was likely again affected by ambient noise and did not fully represent the actual Noise Reduction achieved.

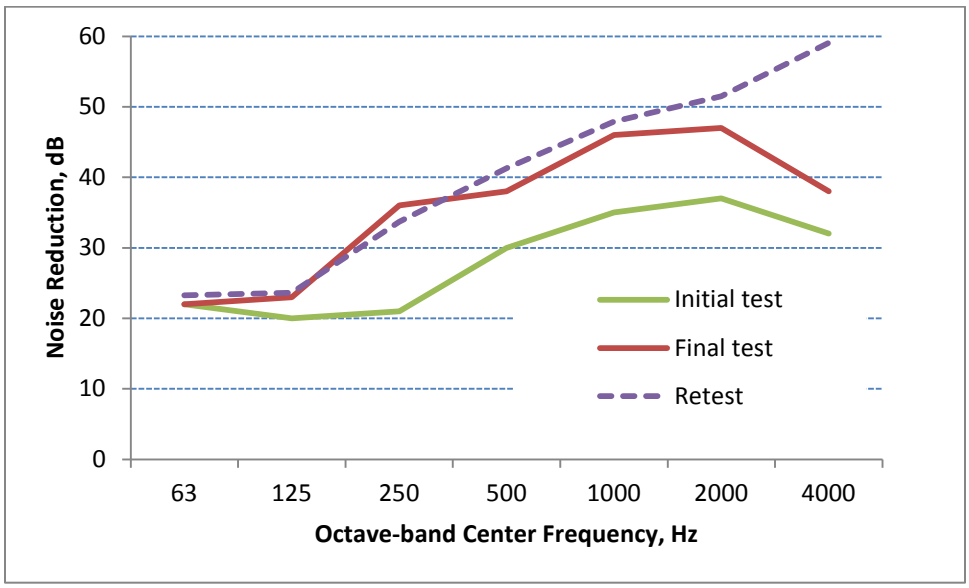

Figure 5-15. Noise Reduction measured at BOS 14 Living Room, Windows 2, 3 and 4.

It is interesting to note that the home inspection during the retest showed the same minor deterioration and lack of sealant as for the Mechanical Room described above. These defects, however, did not result in the lower retest noise reduction that was measured for the living room.

House ID BOS 15, East Boston – Bedrooms at 1st and 2nd Floors

The sound insulation of the home was completed in 1993, with the initial (pre-construction) acoustical testing performed in April-May 1991 and the final (post-construction) measurements performed in February 1993. The Wyle /ATI team retested the home in June 2012.

The house is a three-story frame structure with aluminum siding. The ownership of the home has not changed for 83 years, was present during the sound insulation, and reported cleaning and maintaining the windows.

The front façade of the 1st floor bedroom shown in Figure 5-16 incorporates three separate double-hung assemblies, each including aluminum dual window with the interior and exterior units. Each window glazing unit consists of a single pane of 1/8" glass.

Figure 5-16. Bedroom facade at BOS 15.

Figure 5-16 compares the results of the tests performed for the bedroom.

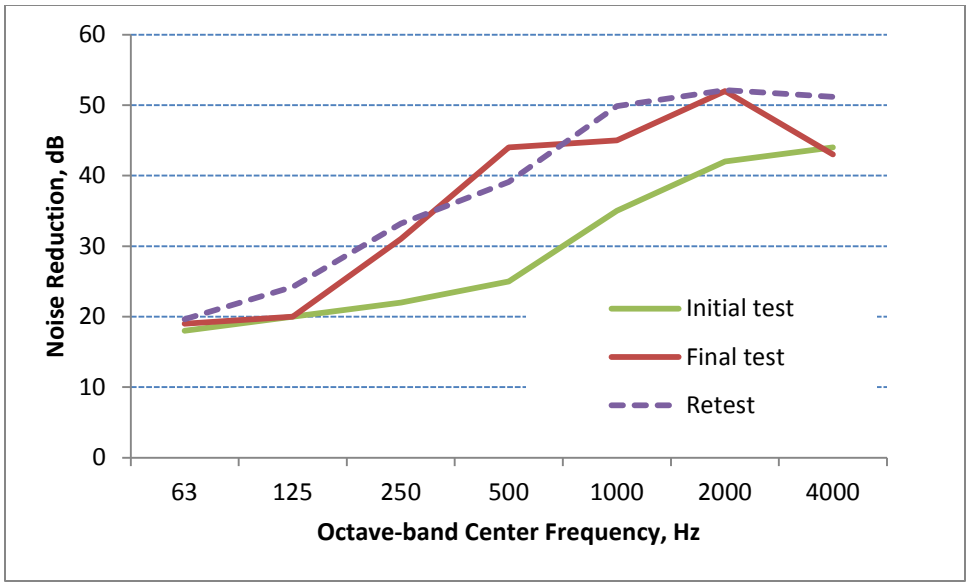

Figure 5-17. Noise reduction measured at BOS 15 1st floor bedroom.

As can be seen from Figure 5-17, the retest noise reduction follows the final test data with minor deviations in several frequency bands, but generally confirming the results of the 1993 test. The variations noted may be explained by the differences in the test setups for this house, such as the location of the outside loudspeaker; for the final test it was placed on the street median, while for the retest it was considered unsafe due to high volume of traffic, and the loudspeaker was located slightly beyond the sidewalk curb, i.e. much closer to the tested façade.

The second room tested in this house was a second bedroom located on the 2nd floor, also at the front façade. The window in this room is an aluminum dual window with the interior and exterior combinations of horizontal sliding/fixed/sliding windows as shown in Figure 5-18. The windows are glazed with single panes of 1/8" glass (all interior and fixed exterior sashes) or 3/16" glass (exterior sling sash).

Figure 5-18. Second bedroom façade at BOS 15.

The results of the tests for the second bedroom are shown in Figure 5-19.

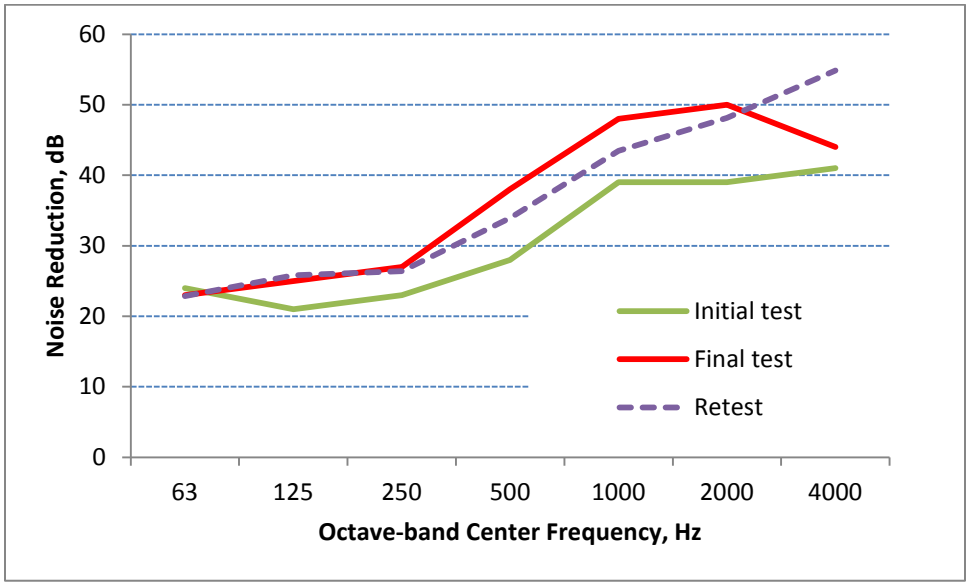

Figure 5-19. Noise reduction measured at BOS 15 2nd floor Bedroom.

As the figure shows, in this case the retest noise reduction is identical to the final test data at low frequencies, but is lower by 3 to 4 dB at frequencies from 500 to 1000 Hz. The home inspection revealed only minor deterioration in isolated areas of the window glazing seals as general wear and tear, and nearly new frame and weather-stripping conditions with no air or water leakage. It is, however, possible that the diminished noise reduction results from the steeper testing angle from the loudspeaker toward the window surface in the retest compared to the final test when the speaker was placed at a larger distance from the structure, as described above. (The sound transmission loss of structures is typically higher for sound incidence angles close to normal than for grazing incidence.)

The diagnostic acoustical testing performed for this home did not provide reliable data due to consistently high ambient noise levels from the street traffic contaminating the results. In the absence of other indicators, it does not appear as though the window fails to reproduce the final test results, and it cannot be concluded that it is underperforming acoustically.

5.4. Conclusion

It can be seen from the analysis presented above, that out of the 28 rooms retested in June 2012 not modified by the homeowner, only four showed more than a 3 dB decrease in the measured A-weighted noise reduction since the post-construction (final) testing. Of those four rooms, the results for only three rooms directly points to deteriorated acoustical performance of the windows due to improper installation, wear and tear, weathering, or inadequate maintenance (BOS 01 bedroom, BOS 03 living room, and BOS 14 mechanical room). This constitutes 11 percent of the rooms retested.

For two rooms with noticeable decrease in noise reduction, there is not enough evidence that the decrease resulted from the window deterioration, while other factors may have affected the test outcome (BOS 08, 2nd floor living room and BOS 15, 2nd floor bedroom). Also, for two rooms (BOS 04 dining room and living room), there is no data available for the final (post-construction) tests to compare with the retest, and for one room (BOS 13 family room), the window tested after construction was later replaced with a different unit by the homeowner.

For the remaining 22 rooms retested, no decrease greater than 3 dB in the related window or door acoustical performance was discovered compared to the final post-construction testing. For many of them,

the post-construction test data were quite repeatable, in some cases despite the evident deterioration in the physical conditions of the product or surrounding structure. Many homeowners indicated poor window functionality - difficulties with opening, closing, cleaning, no tilting, etc. Apparently, physical or mechanical deterioration of windows and doors noted did not necessarily translate into their deficient acoustical performance.

It can be concluded that no wide-spread deterioration of the sound insulation products was found as the result of the testing in June 2012. The few cases of deficient acoustical performance that were discovered, can be attributed to cases of either extreme neglect, extreme weathering, or possibly poor installation. Proper maintenance, similar to regular windows and doors, appears to be a key factor in sustaining acoustical performance of the sound insulation products.

5.5. City of Inglewood

Acoustical testing was performed in homes that were insulated in the Inglewood, CA, residential sound insulation program of 1995 in the vicinity of Los Angeles International Airport (LAX). Overall, 35 rooms in 9 houses were tested between August 14 and 16, and between August 24 and September 12, 2012. The goal of the acoustical testing was to compare the noise reduction data obtained immediately after the sound insulation was completed in 1995 with the current measurement data. The selection of houses for the retesting was based on the availability of houses with previous noise test data and the willingness of homeowners to participate.

The original testing of houses was conducted measuring noise levels of actual aircraft flyovers simultaneously outside and inside the house. The measurements of the overall A-weighted sound levels were performed for several flyovers, and the Noise Level Reduction for a room was determined as the difference between the SEL values recorded outdoors and indoors for each flyover, with subsequent averaging over the recorded events. This technique was reproduced for the retesting. Sound level meter locations were replicated as closely as possible. Other variables include different types of aircraft. However, flight tracks for approach conditions at LAX have not differed significantly over the years.

Table 5-2 provides the noise level reduction (NLR) measured for the rooms in the pre-modification and post-modification tests, together with the house ID, and the rooms tested. Also shown is the difference between the Retest NLR and Final (post-modification) NLR as an indicator of a potential change in the room sound insulation (negative values indicating decrease in NLR from 1995 to 2012).

Diagnostic acoustical tests were also conducted for several windows and doors in the houses. These tests were conducted using a loudspeaker producing high-level noise inside the tested room and measurements performed over the tested element (window or door) inside and outside the structure. The difference between the two sound pressure levels defines the Noise Level Reduction measured in the opposite direction (from inside to outside) than the aircraft noise method described above, and in this case applies to a specific tested element only rather than to the overall room envelope. These measurements were performed in one-third octave frequency bands, as well as in overall A-weighted levels.

A difference of less than 3 dB (positive or negative) between the retest NLR and final (post-modification) NLR is considered within the measurement accuracy. It can be seen from Table 5-2 that the difference exceeds -3 dB for only 3 of the 35 tested rooms. This indicates that no major change in the sound insulation performance has occurred for 32 of the rooms since 1995. The three rooms where the difference exceeded -3 dB were all in a single house. A discussion of the test data for rooms where differences of -3 dB or more were detected is provided below.

Table 5-2 shows that for 6 tested rooms, the difference between the Retest and Final NLR values exceeds +3 dB, i.e. a measured increase in NLR over the years. These variations may have resulted from modifications in the rooms over the 17-year span.

TABLE 5-2 Noise Test Results for Inglewood Program

House ID	Room	A-Weighted Noise Reduction			
		Initial	Final	Retest	Retest - Final
ING 01	Living	30	35	35	0
	Dining	25	35	32	-3
ING 02	Living	29	29	33	5
	Kitchen	28	30	36	6
	Bedroom 1	30	44	43	-2
	Bedroom 2	27	40	37	-2
ING 03	Living	29	38	36	-2
	Kitchen	20	32	33	1
	Bedroom 1	31	40	39	-1
	Bedroom 2	26	40	38	-3
ING 04	Living	23	27	32	5
	Kitchen	25	27	27	0
	Bedroom 1	25	36	37	1
	Bedroom 2	26	33	37	4
ING 05	Living	31	39	35	-3
	Kitchen	24	32	30	-2
	Bedroom 1	34	39	38	-1
	Bedroom 3	20	34	36	2
ING 06	Living	29	34	34	0
	Dining	33	39	41	2
	Kitchen	26	31	32	2
ING 07	Living	26	36	35	-1
	Kitchen	30	32	32	0
	Bedroom 1	29	38	38	-1
	Bedroom 2	28	42	41	-1
	Dining	28	37	35	-2
ING 08	Living	26	37	30	-7
	Kitchen	19	39	32	-8
	Bedroom 1	29	46	38	-8
	Bedroom 3	31	32	35	2
ING 09	Living	27	35	38	3
	Kitchen	21	32	29	-3
	Dining	25	32	33	1
	Bedroom 1	29	38	44	6
	Bedroom 2	30	41	45	4

ING 01

For the Dining Room at ING 01, modifications applied to the existing solid core wooden entry door included additional perimeter seals (no storm door was provided). Since construction in 1995, the door bottom seal has obviously worn out. However, this may not be the only reason for the diminished NLR: after the construction the homeowner installed a through-window air-conditioning unit in the Kitchen that is widely open into the Dining Room providing an additional path for exterior noise.

ING 05

For the Living Room at ING 05, a large window was replaced with an aluminum slider/fixed/slider combination prime window with a storm. Also, a secondary sliding glass door (SGD) was added to the existing prime sliding glass door. Examination of the window revealed that wood blocking was missing on top of the window frame on the inside, leaving about 3/4-inch unsealed gap

between the frame and wall structure over the full width of the window. The gap is not through the stucco wall to the outside, and it is unclear whether it resulted from the improper initial installation or later homeowner modifications. Diagnostic tests performed for the window and SGD using a loudspeaker show relatively low NLR values for both elements – the lowest among the tested elements in this group of homes. Their condition is likely responsible for the apparently deteriorated performance of the sound insulation for this room.

ING 08

For three rooms tested at ING 08, the difference between the Retest and Final NLR values in Table 5-1 falls well below -3 dB, indicating a significant reduction in the sound insulation of the rooms. Since the original sound insulation of the house, several alterations have been made by the homeowner: carpet was replaced with hardwood flooring in all the rooms except for kitchen, and the solid-core front door was replaced with a hollow acoustically non-rated door. These alterations can be largely responsible for the measured reduction in NLR. Also, one of the windows in the Living Room could not be completely closed.

Inspection of the house revealed that several windows in the kitchen were missing the inside top blocking, similar to the case of the Living Room at ING 05. Although there were no gaps to the outside, they may have contributed to the loss of the measured sound insulation if the original construction included the blocking which was later removed. A diagnostic test using a loudspeaker supports the conclusion that the gaps contribute to lowering of the noise reduction in the room. However, it is unclear whether missing blockings resulted from improper initial installation or from later homeowner alterations.

In Bedroom 1, the top outer sash in one of the two windows could not be sealed completely upon closing. This is definitely a contributing factor to the loss of the noise reduction in the room, and is the result of improper operation of the window. A diagnostic test using a loudspeaker performed for another window in the room, one with a properly sealed sash, showed an NLR of 41 dB. This value, which was likely lowered by sound transmission through the adjacent window with the incompletely sealed sash, is to be compared with the Final NLR value of 46 dB for the entire room. The retest NLR value for the room of 38 dB is 8 dB lower. We can conclude that the unsealed window condition is responsible for the deteriorated performance of the sound insulation for this room.

5.6. Summary of Acoustic Performance Measurements

Acoustical measurements and architectural testing was performed in homes that were insulated in the early years of the Massport residential sound insulation program in the vicinity of Boston Logan International Airport, and the Inglewood, CA, program of 1995 in the vicinity of Los Angeles International Airport (LAX). The goal of the acoustical testing was to obtain current room noise reduction information and then compare it to the noise reduction data obtained immediately after the sound insulation was completed. The selection of houses for the retesting included some with known homeowner complaints related to windows and/or doors, as well as homes in apparently good condition.

It can be seen from the analysis that only 6 of the 65 rooms tested showed signs of acoustical deterioration, and some of these may have been due to homeowner modifications. The majority of tested rooms did not show any noticeable decline in measured noise reduction compared to the post-construction (final) testing. Therefore, no wide-spread deterioration of the sound insulation products was found as the result of the testing. A few instances that were discovered to have deficient acoustical performance can be attributed to cases of extreme neglect, extreme weathering, or possibly poor installation. Proper maintenance, similar to regular windows and doors, appears to be a key factor in sustaining acoustical performance of the sound insulation products. Many homeowners indicated poor window functionality such as difficulties with opening, closing, cleaning, etc. Apparently, physical or mechanical deterioration of windows and doors noted did not necessarily translate into deficient acoustical performance.

CHAPTER 6. EVOLUTION OF THE SOUND INSULATION PROCESS

The data collection task described in Chapter 3 was designed to gather detailed information to identify the installation methods, treatments, and materials that were used in early sound insulation programs and those methods, treatments, and materials that are currently being used. The results of this task were used to define the chronology in the evolution of sound insulation programs in the US, so that changes in methods and procedures from early to current programs could be identified, and related to a possible reduction in deterioration of acoustic performance.

The results from the limited noise tests conducted at two sound insulation program sites show that there has been less deterioration in performance over the years than expected. This is consistent with the lack of reported deterioration in performance obtained from the survey of US programs described in Chapter 3. In most cases, any deterioration in performance is more likely to be the result of homeowner modifications, poor maintenance, extreme weathering, and only in some cases poor installation, and not due to deterioration in the products themselves.

This does not imply that there have been no problems with products or installation procedures. Many programs have reported such issues, but to a large extent, these have been identified by the program sponsors (or their consultants) and corrected by the product manufacturers or contractors. The lessons learned along the way have led to changes in products, installation, and quality control procedures that have reduced the frequency of such problems.

6.1. Product Problems Encountered

In the early days of airport sound insulation programs acoustical products were hard to find, and those that were available were designed primarily for commercial applications. As a result, early programs used a combination wood or aluminum prime window with an aluminum storm, or double aluminum-frame windows. Doors were heavy, and fitted with inappropriate seals, and for the most part they were incapable of providing the required STC ratings. Sliding glass doors also could not provide the necessary STC rating and programs opted to specify combination of primary and secondary sliding glass doors.

As sound insulation programs progressed and became more numerous, the manufacturers responded to market needs, and many of these problems were resolved. The following table describe some of the reported issues related to the performance of doors and windows and the corrective actions adopted by the programs and manufacturers.

Issue	Resolution
Delamination of doors – Delamination of the doors is one of the main issues from the early years of the programs that continues to cause problems today. The acoustical wood doors are comprised of different layers of insulation material and veneer bonded together. This combination is susceptible to moisture which can cause the door to delaminate. Delamination is not exclusive to wood doors, but has been experienced with aluminum metal prime doors where there is a full glass storm door over a dark colored door in full sun exposure.	One action has been for sound insulation programs to include finishing instructions for the door leaf in the technical specification. The field conditions under which the door finish is applied is equally important. Many programs require pre-primed doors, or application of sealer/primer and first coat in a warehouse, in a dry, controlled environment. Inspection of the door finish, especially at the door edges and holes cut through the door for hardware, is an important step that must be followed strictly during the door installation by a seasoned construction manager in order to minimize the occurrences of this issue

Issue	Resolution
	Additionally, as the technology advanced, the construction of the door core and the way it is bonded to the door skin has improved. This has allowed the door manufacturers to increase the warranty period from 1-or-2 years to 5 years. There is a restriction in the warranty language requiring 4' overhangs or the installation of a storm door in order to protect the wood doors. The vulnerability of the acoustic wood doors to moisture is an ongoing issue and requires further improvement or design change..
Warpage of the entire door panel –About 25% of all complaints on door issues are related to door warpage. Warpage occurs due to numerous factors, including the condition of the wood products, the manufacturing process, environmental conditions at the site, including temperature fluctuation and moisture, the environmental conditions of the warehouse where the door was stored before installation, faulty finishing, and/or faulty installation.	As discussed in the delamination discussion above multiple improvements have been made to alleviated this issue, including advances in technology to design an improved core, improvements in manufacturing process for attachment of the door skin to door core, and improvement in technical specifications to include finishing instructions, and specifying how doors are to be stored in the warehouse. Also, incorporating seasoned construction managers to make sure the requirements of the technical specifications are followed. Incorporating these changes has reduced the number of warpage issues.. Manufactures routinely honor the warranty of the door if warpage occurs during the warranty period, provided that other requirements of the warranty language are met.
Automatic door bottom seals – Automatic bottom seals were a continual problem in early sound insulation programs. They required regular maintenance, or they would lose their tightness, alignment, and/or would break entirely.	As a result of numerous complaints in all programs, most have replaced automatic door bottom seals with alternative fixed in-place seals.
Difficulties of installing door leaf within existing door frame – During the early years of sound insulation programs, only door leaves were replaced. This practice caused many issues during the installation phase. In many instances, it was difficult to fit the new door within the existing frame or to add the necessary air/acoustic seals.	Pre-hung doors are now specified, including both door leaf and door frame. The new details consider modifying the new door frame to accommodate kerfed-in seals.
S-88 smoke seals or bulb seals peeled off easily – During the early years, programs received complaints regarding this seal peeling off and leaving a gap for noise to penetrate inside the dwelling units.	To overcome this problem, many programs discontinued the use of this seal and replaced it with a combination of rigid seals and kerfed-in seals. This, alongside with the issues mentioned in the previous item required specifying new door frames which could accommodate the kerfed-in

Issue	Resolution
	seals. The use of S-88 (smoke seals) was limited to garage access doors for meeting the requirements of building codes.
Misalignment of aluminum windows. Early acoustic windows were aluminum, tended to be somewhat flimsy, and were subject to misalignment as screws were tightened during installation	Specification of aluminum frame alloy and/or thickness. Most programs now specify vinyl windows.
Improper operation of hardware interfering with closure of doors and windows.	There have been numerous advancements in hardware technology, and manufacture dealt with this issue on the spot or incorporated changes in their manufacturing process, quality control, and/or design to minimize problems related to hardware malfunction
Weather-strip deterioration – Weather-strips are vulnerable to wear and tear and need regular maintenance.	Due to improvements in technology, manufacturers now use more durable weather-strips in acoustical window products.
Condensation in double window assemblies	Improved edge sealing to exclude air and moisture infiltration.
Sagging of casement windows - During the early years, sagging of the casement windows, which translated into problems closing the windows and loss of acoustical effectiveness, was a major issue. Although sagging is inherent in the construction of this type of the window because of its weight, there were two other major contributors to this issue. There were times that the windows were specified without consideration being given to the maximum size set by the manufacturers. The limits set for the size of these windows were too high, contributing to additional weight and, as a result, sagging.	Programs began specifying solid continuous blocking along the whole length of the window in order to completely support the window at its sill, and the construction managers/contractors now make sure the window is securely attached to the structure at window jambs according to manufacturers' written installation instructions. Additionally, similar to the door warpage issue, the performance of the contractors directly affects the window sagging. Programs with the highest standard in construction management have most effectively controlled this issue. In addition programs and or manufacturers have dictated size limitations for casements windows in order to deal with windows weight.
Dirt buildup on sliding tracks of horizontal slider windows and sliding glass doors which could cause difficult operation.	To address dirt build-up in window tracks, a simple approach is to bring the issue to owners' attention during the design or construction phases. Although the major aluminum and vinyl window manufacturers did not take this issue into consideration for any design changes, one window manufacturer provided a design where the roller sits on a rail rather than rolling on a flat surface of the window track. This design alleviated the issues related the roller and dirt build-up in the track
Oversized windows – Similar to the issues	Refer to resolution for dealing with sagging at

Issue	Resolution
experienced with casement windows, these windows experienced issues with sagging or operation and consequently lead to decrease of acoustical performance.	casement windows.
Thermal break failure in some early aluminum windows. The material used to create the thermal break deteriorated over time and broke down in climates with weather extremes, leaving gaps in the gasket that water could leak through. In wet weather conditions, water would run down the glass, into the gaps in the deteriorated gasket, and into the wall.	The thermal break in some aluminum windows created issues in programs with colder climates. This issue appeared in the thermal barrier of a series of popular acoustical windows which were installed on commercial projects. Laboratory reports were examined, site visits of the affected facility conducted, communicated with the window manufacturer to hear their explanations, and ultimately made the decision to prevent the use of that type of window in sound insulation projects located in colder climates. At the same time some programs specify iso-bar thermal breaks and are moving away from poured and de-bridged thermal breaks.
Incorrect maximum sizes for 3-lite sliders, which caused the frames to deflect.	New windows of a different configuration had to be installed.
Incorrect glass thickness was detected in windows where 1/8" glass was substituted for 1/4" glass in the full-lite self-storing storm doors	Storm doors replaced by manufacturer.
Failure to install tension clips on self-storing doors.	Clips were installed after construction was completed.
Corrosion of aluminum windows in close proximity to salt water - aluminum frames installed in areas close to the coast showed corrosion due to the salt-laden air.	Improvement in aluminum coating is an ongoing matter. With advances in technology, more effective and longer lasting coatings have become available often and the manufacturers take advantage of these improvements to add to the longevity of their products and specifically deal with this issue.
R-values of products deteriorating over time due to settling. The compaction of loose cellulose fill reduces the volume of air spaces within the fiber and its insulation value.	To address the reduction in R value due to attic insulation settlement some programs use fiberglass batt insulation in ceilings whenever possible.
Compliance with building codes and other applicable local or Federal regulation.	It is imperative that the Specifications and inspections require that the product installed meet or exceed the applicable requirements, and any updates and changes in these requirements. Mandates have been placed on air infiltration, water tests, and structural tests including the maximum force required opening windows/sliding doors were added to technical specifications. There are only a few programs that use field testing on

Issue	Resolution
	installed products. This seems like an effective quality control measure at identifying window manufacturing problems. One program has removed two manufacturers because of test failures.
Similar to previous items there are air exchange requirements within codes and regulations in order to ***achieve a healthy interior environment***	Incorporating relief vents/or mechanical ventilations to overcome the pressurized interior space in order to guarantee the code required air exchange between exterior and interior and provide fresh air into dwellings. Therefore improving the interior environment of the dwelling unit and reducing the need for the residents to open the windows/doors. Similarly, the addition of Energy Recovery Ventilation Systems in every home has reduced moisture problems without causing acoustic problems.
Double sliding glass doors are massive and difficult to open	STC-rated sliding glass doors have become available and have been introduced into projects. This advancement eliminated the necessity of adding storm doors to existing sliding glass doors which was an unpopular treatment within airport communities.

The significant evolutionary changes in sound insulation products are as follows:

- High STC-rated vinyl window products were introduced in the late 1980's. At first, the new products were not universally accepted, partly because the first versions were much thicker than existing aluminium products they had been using, and partly because they were unsure of whether vinyl (read "plastic") windows would be acceptable to the public. Within years, however, the popularity of vinyl windows has increased due to their acoustical and energy-saving performance.
- Specification of aluminum frame alloy and/or thickness.
- Specification of vinyl frame thickness.
- Improvements in the design and manufacture of wood doors. The changes in how the core is manufactured and the material used in the core have resulted in much lighter door with the same or better acoustical performance. The lighter doors also are also much easier to install and therefore minimize the potential issues related to installation or future sagging of the door.
- Introduction of high STC-rated sliding glass doors to projects vs. adding storm doors.
- Installation of Energy Recovery Ventilation to enhance air quality and meet certain Code issues. Although this item does not directly affect the performance of the products, but as a secondary cause can contribute to product's deterioration. Without improving the air quality, the chances for moisture built-up and mold increases and this results in speeding up the process of wear and tear on the wood frames, or sealants which in return contributes to failure of performance as intended.

6.2. Quality Assurance and Control in Manufacturing

Quality Assurance/Quality Control (QA/QC) plays an important role of sustaining product quality long after a manufacturing process is completed. Manufacturers over time have developed QA / QC procedures, and invested in this phase. The quality control process can be lengthy, and sophisticated. Some manufacturers have incorporated procedures such as:

- Developing quality control plans,
- Developing control charts,
- Incorporating product inspections process,
- Testing products to uncover defects
- Hiring quality control engineers
- Emphasizing on competence, such as knowledge, skills, experience, and qualifications
- Obtaining recognized certifications in QA / QC process such as ISO 9001, international standard for design and manufacturing excellence or incorporating ASTM or AAMA requirements for manufacturing.

Another process that seems to be incorporated in some of the manufacturers control procedures is vertical integration, which is the degree to which a firm owns its upstream suppliers and its downstream buyers. Contrary to horizontal integration, which is a consolidation of many firms that handle the same part of the production process, vertical integration is typified by one firm engaged in different parts of production.

At least two for the window manufacturers take advantage of this process. Excerpts from one manufacturer's website indicates:

"XXX *controls quality every step of the way by making our own Insulated glass units, Vinyl frames and components, Fiberglass and wood components and Tempered glass. To ensure top quality from start to finish, XXX precisely controls our vinyl compound formulation to withstand harsh climate conditions. We extrude our own frame material and fabricate all vinyl windows and doors to order, giving us the tightest quality control."*

Similarly, another manufacturer is taking advantage of vertical integration:

"*We design and extrude all of our aluminum profiles in-house, including custom trims, sills, receptors and structural mullions. We pour and debridge our own polyurethane structural thermal barriers and offer polyamide strips as part of a comprehensive thermal technology package. We fabricate our insulated glass units according to ASTM E 2190 using warm-edge spacers and computer-controlled automated glass cutting and insulating equipment. We also electrostatically paint in-house architectural finishes that meet AAMA 2605 quality standards, with warranties to meet your project requirements."*

By controlling the extrusion of components, integrated widow manufacturers are able to lower their raw material costs as well as better control their supply chains. In addition, integrated producers can better control quality by monitoring the process from raw materials to components to finished products.

6.3. Quality Control During Construction

It is not only the acoustic products have changed and improved. The best products can be specified and purchased, but are only as good, efficient, and effective as the method of installation. With experience from the early programs, installation methods have improved by introducing more rigorous

training for contractors, and more detailed inspection procedures throughout construction. Whereas contractors in early programs tended to regard jobs to be just the same as any other house upgrade, they now realize that sound insulation construction requires much more attention to detail. Furthermore, the procedures for addressing existing code violations have become more rigorous in deciding eligibility for sound insulation treatment.

In the early years, poor contractor performance contributed to problems during and after construction. Specifically, the contractor or their subcontractors did not follow the plans as intended, thereby increasing the risk of products not performing as intended. Example of such issues during construction and their resolution are as follows:

- Not supporting the windows sill completely at sill. Technical specification or design documents included requirements for fully supported sills, and the construction managers are now paying close attention to this item.
- Inadequate attachment of the window to the building structure at jamb locations. Design documents and details included requirements to address this issue such as following the manufacturers written installation instructions, mandatory trainings by the manufacturers, and specifying adequate installation experience for window installers.
- Requirement of a minimum number of days per house for construction so that the contractor will not schedule construction to be performed at an unrealistically fast pace without regard to the required attention to detail.

  Early instances of contractors attempting to complete a house in a single day forced the trade to work very quickly and the quality of the work was difficult to maintain at an acceptable level without constant supervision. Time requirements put in place to avoid this situation and proper supervision by the programs and experienced construction mangers/building inspectors keeps contractors accountable for the quality of their installations and adherence to plans and details.
- Improper finishing of the wood doors. Wood doors are susceptible to moisture damage and proper finishing is extremely important in avoiding moisture damage or doors delamination. Some programs included finishing/sealing instructions in their technical specifications including requirement for finishing and sealing all six edges of the doors, and any cut holes. Some other programs made it mandatory for doors to receive the primer and the first coat in warehouse under dry, controlled environment. In addition the manufacturers of the wood door list the finishing requirements in the warranty language so that he programs and contractors pay close attention to this item.
- To deal with quality control of delivered products, modern programs have incorporated detailed product inspection. During the product inspection phase, one random window in each style and one random door, sliding glass door, storm doors will be selected and thoroughly inspected. All features compared with approved product submittals and construction documents to make sure the submitted products are matching the approved products.
- The performance of thorough product inspections are now implemented during the pre-construction phase, taking advantage of special laser micrometers to be used to measure the glass and air gap thickness, and to detect the presence of lamination in glass.

Tools and procedures that have been introduced over the years have included:

- RFI/RFCO tools to be utilized
- The oversight of the construction process and contractor performance is crucial in appropriate installation and finishing the acoustical products and, in return, enhances the products' performance. Accordingly, all current programs employ experienced construction managers to ensure contractors' performance.

- As a quality control measure, programs are required to conduct detailed pre-bid and pre-construction meetings to communicate the specific acoustical goals of the program with the contractors.
- Requirement to specify liquidated damages if the contractor does not finish the project on schedule.
- Requirement to specify prevailing wage requirements. Because contractors were required to pay much higher rate to the employees they would hire the best in the trade to have a smooth construction phase with minimal issues arising from the workers performance.

6.4. Building Codes and Testing Standards

Credit for improvements in programs must also be given to the changes in building codes which, over the years, have imposed additional requirements for thermal and air/water infiltration testing - there were no thermal requirements in effect 25 years ago. In colder climates, new wood-frame construction has changed from 2”x4” studs to 2”x6” studs and includes additional insulation; hence, newer houses exhibit better acoustic performance than older construction.

Accompanying changes in building codes has been a corresponding update of testing procedures by ASTM and other organizations, as well as a plethora of guidance material from the National Association of Building Sciences and the National Association of Home Builders. While many of these test standards do not directly address acoustic performance, they do test products for characteristics that can affect the acoustic performance – characteristics such as air leakage, water penetration, hardware cycling, etc. The evolution of these test standards is presented in Chapter 2 of this report.

The first version of ANSI/AAMA 101 voluntary specification for these characteristics was produced by the American Architectural Manufacturers Association (AAMA) in 1985 and has been significantly improved over the past 25 years. The latest document covers virtually every type of fenestration product that is used in residential and commercial buildings except for curtain wall and storefront systems. Many of the test procedures that are included in this standard require manufacturers to improve the performance of their products. There are optional performance requirements and test procedures that can now be included in product specifications to improve the longevity of products used in residential sound insulation programs.

Many states in recent years have adopted energy efficiency measures that have directly affected the design of some products or the creation of program policies. An example is the Building Energy Efficiency Standards, comprising Title 24, Parts 1 and 6, of the California Code of Regulations, which is mandatory state-wide. The standards require lower U-values and Solar Heat Gain Coefficient (SHGC) for the windows and doors compared to what was specified in the program specifications.

In addition to the standards, during the construction process, the general contractor or specialty subcontractors are required to complete various construction certificates. The purpose of these certificates is to verify that the contractor is aware of the requirements of the building energy standards, and that they have followed the Energy Commission-approved procedures for installation and the installation work is done in accordance with the approved plans and specifications. This requirement adds an unprecedented level of quality assurance by the general contractor and specialty contractors during construction phase. The improved quality control process will reduce the product performance issues arising from improper installations.

Some States including California and Pennsylvania have introduced mandates to put a cap on emission of construction material to minimize the negative health effect of off-gassing and to improve indoor air quality. Toxins such as Volatile Organic Compounds (VOCs) enter the interior spaces from the paint, flooring, stains, varnishes, plywood, carpeting, insulation and other building products used in their construction. These substances are released into the air through a process called off-gassing. As part of this mandate, the parties involve in construction have to specify/utilize building products that are

minimizing the off-gassing of pollutants such as (VOC) and Formaldehyde. These changes may effect in revising installation instructions and/or post construction care of products such as wood doors that need be made with new standards Formaldehyde emissions and finished with low VOC limiting coatings.

6.5. Summary

The evolutionary changes in airport sound insulation programs relating to product design, installation, test procedures, and building codes have been briefly described based largely on information obtained from the survey of programs described in Chapter 3. This information together with information from other chapters is summarized in the form of practical guidelines in a separate stand-alone document that can be applied by airport sponsors, designers, and contractors to provide guidance on best practice for:

- Program eligibility requirements;
- Design criteria and procedures;
- New and improved products – performance and laboratory testing;
- Building code recommendations;
- Preparation of bid documents;
- Quality control in installation;
- In-situ testing procedures; and
- Homeowner maintenance.

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