CLASSROOM

ACOUSTICAL STUDY

August 27, 2007

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I. EXECUTIVE SUMMARY

A. Introduction

1. In 2002 The American National Standards Institute (ANSI) published ANSI S12.60, Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools. This new standard deals with four acoustical issues in classrooms:

   a. Room Acoustics.
   b. HVAC and Electrical Noise.
   c. Classroom Sound Isolation from both interior and exterior sources.
   d. Impact Isolation for multi-story classroom facilities.

2. In order to measure the acoustic characteristics of existing schools and estimate the financial impact of meeting ANSI S12.60 provisions, the Air Conditioning and Refrigeration Institute (ARI) commissioned a study. The study was conducted by the team of Armstrong, Torseth, Skold & Rydeen, (ATS&R), a Minnesota-based Architectural/Engineering Firm engaged in school construction and renovation of school facilities and Kvernstoen, Ronnholm & Associates, Inc., consultants in architectural acoustics and environmental noise control. The objectives of the study were:

   a. To provide a survey of acoustical performance characteristics for existing classroom construction and various HVAC system types in reference to ANSI S12.60.

   b. When classrooms did not meet the requirements of ANSI S12.60, identify the reasons. For these classrooms, potential design solutions were identified and costs were estimated to bring the space into compliance with the requirements of ANSI S12.60.

   c. To verify the design solution(s), we attempted to validate the design for one of the classrooms by actually implementing the solutions we had recommended.

B. Scope

1. Eighteen schools, sixteen of which were located in Minnesota, and two in Phoenix, Arizona, were evaluated in the study. Three classrooms were studied in each school. In addition, a classroom in a school located near an airport was evaluated. A total of 54 classrooms were evaluated for indoor acoustic performance.

2. Due to the northern construction methods, the schools in Minnesota were of heavyweight (masonry) construction and the results may not be representative of other regions in the U.S. Thus, we also studied two schools in Arizona to document how regional (climatic) differences might affect construction to achieve the ANSI S12.60 Standard.

   a. Four HVAC system types were evaluated:

      1) Water Source Heat Pumps, wall and ceiling mounted units.

      2) Central System Air Handling Units (including package rooftop units) remotely located from classrooms.

      3) Central Chiller System, 2-pipe and 4-pipe fan coil units (unit ventilators).

      4) Central Chiller System, desiccant based cooling, fan powered boxes with positive displacement diffusers.

C. Methodology

1. Using a case-history approach, samples of a variety of HVAC types and school types were studied. There were four HVAC types studied in four school configurations, making a matrix of sixteen different schools in Minnesota. The two schools in Arizona made a total of eighteen schools studied. Three classrooms were studied in each school for a total of 54 classrooms. HVAC noise and reverberation times were measured in all of the 54 classrooms. Impact isolation and interior and exterior noise isolation were tested in selected classrooms.

2. Based on the measurements that were taken, design analyses for construction modifications to achieve compliance to the ANSI S12.60 standard were completed. Cost estimates were based on these construction modifications during the design phase not as a retrofit cost estimate.

3. Also included is a verification/validation phase for mechanical noise control (see section XVI) in order to verify that the methods and costs we had recommended were appropriate and accurate. This was done by actually performing the modifications that we had recommended for one classroom.

D. Summary of Results

1. Acoustical Performance Characteristics:

    a. Ambient noise levels in classrooms ranged from 36 to 58 dBA, resulting in only one of the classrooms meeting the ANSI S12.60 requirements. The average classroom ambient noise level was 45.5 dBA.

    b. Many of the tested systems were below specified air quantities. To achieve the design air flow would require larger equipment or larger distribution ductwork, thus either increased installation costs or increased operating costs.

    c. One of the thirteen classrooms tested for interior partition sound transmission met the ANSI S12.60 requirements.

    d. 53 out of 54 classrooms passed the reverberation time requirements of the ANSI S12.60 requirements.

    e. 54 out of 55 classrooms passed the exterior isolation requirements. The exception was the classroom in the school adjacent to an airport. This situation was sought out specifically because of its proximity to the airport.

    f. One multi-story school was tested for compliance with the field impact isolation class of F-IIC 45. It did not pass. It was deemed unnecessary to perform further IIC testing because it was clear from the construction details that all of the multi-story schools would fail the F-IIC 45 standard.

2. Evaluation of Design Solutions:

    a. Evaluation of the design solutions showed that the cost of new construction would increase significantly in order to meet the ANSI S12.60 requirements. Individual classroom cost increases ranged from 4 to 25%. The percentage increase was dependant on the baseline construction chosen plus the upgrades needed. Miscellaneous cost (see miscellaneous section) was not factored into the total cost.

    b. It may not be economically viable to implement all design solutions in renovating existing buildings. The cost increase, on a percentage base, for installing applicable design solutions in renovations is higher than for new construction. In some cases, for renovated buildings it would be virtually impossible to meet the ANSI S-12.60 standard.

c. The table below summarizes the estimated range of cost increases based on the classrooms sampled in the study. The large range is due to the variability of the construction and HVAC equipment design used as a base, and the variable construction type (cost) used as the base for each sample.

Table 1 (Cost Increases to Comply With ANSI S12.60)

Building Type	HVAC Cost per Square Foot	Other Cost per Square Foot§	Total Cost Increase per Square Foot	Percent Increase, %
New Single Story* Minnesota	$2.70 - $12.88	$2.70	$5.40 - $15.58	4 - 12
New Multi-Story** Minnesota	$2.04 - $13.02	$8.70	$10.74 - $21.72	8 - 16
Renovated Single Story*** Minnesota	$2.08 - $12.10	$2.70	$4.78 - $14.80	6 - 19
Renovated Multi-Story*** Minnesota	$1.65 - $9.62	$2.70 - $10.70	$4.35 - $ 20.32	5 - 15
New Multi-Story Arizona ****	$4.66	$2.70 - $18.62	$7.36 - $23.28	8 - 24.5
New Single Story Arizona ****	$2.56	$2.70 - $12.62	$5.26 - $17.18	5 - 19

§ NOTE: Other costs include improved construction except HVAC components.
* Used base construction for new single story at $130 per square foot for Minnesota.
** Used base construction for new multi-story at $135 per square foot for Minnesota.
*** Used base construction for renovation at $80 per square foot.
**** Used base construction for Arizona, single story at $90 and multi-story at $95 per square foot.

E. Conclusions

1. Meeting ANSI S12.60 will require care in the application of HVAC equipment. This includes system selection, duct work layout, vibration control and may require providing separate spaces for air handling equipment versus unitary equipment located in classrooms.

2. The costs of implementing the ANSI S12.60 requirements are significant (4 – 25% for classroom areas) and need to be considered during the planning and design process. In a theoretical large high school scenario, the additional construction cost totaled nearly $5 million dollars without miscellaneous cost.

3. Partition walls that did not meet the Standard failed mainly because of poor construction quality. Closer supervision during construction will be necessary to achieve the expected design. The two Arizona schools had double doors connecting classrooms. Due to excessive noise transmission through gaps and joints around the doors, these did not meet the NIC 45 standard.

4. Almost all classrooms met the Standard for Reverberation Times, although meeting the Standard did not guarantee an acoustically acceptable room. Diffusion, as well as reverberation control was observed to be necessary to achieve an acoustically acceptable classroom.

5. Virtually none of the schools being built today will pass the Impact Isolation Class (IIC) portion of the Standard.

6. We found that during the verification/validation phase of the study for retrofit it was very difficult to reach the required 35 dBA ambient noise level. We were ultimately unsuccessful in reaching 35 dBA in the classroom that was retrofitted for mechanical noise. Given the height and space limitations of that particular classroom, we found that it was virtually impossible to reach the 35 dBA standard. In our experience, difficulty with mechanical noise control is not unusual when there are severe space limitations.

   If the original designer had more flexibility in locating the fan powered boxes into the corridors and used an aggressive sound attenuator selection and double walled ductwork before and after the boxes, it is feasible that the classroom in the validation study could be made to pass. Due to the uniqueness of each ventilation system and the space constraints of each classroom we cannot make a blanket statement about the cost implications to the remaining case studies. In this case study the cost increase would be about 35% more than our original assumptions predicted.

7. A pertinent question will be, "How can we deal with the inevitable cases where a classroom does not meet the Standard?" Fees for design professionals do not allow much leeway in terms of paying for cases where the Standard is not met, nor in many cases even the cost of determining a fix for the problem.

8. An important consideration for any governing body considering the adoption of ANSI S12.60 will be how to apply the standard and who would pay for the inevitable cases where the Standard is not met. In some renovation cases, it will not be possible to meet the standard.

II. INTRODUCTION

A. Background of the ANSI S12.60 Standard

1. Over the past several years there has been a growing realization of the importance of an adequate acoustical classroom environment to support the teaching/learning efforts of teachers/students. In the summer of 2002 the American National Standards Institute (ANSI), along with the Acoustical Society of America (ASA), published a standard titled *ANSI S12.60 -2002 ACOUSTICAL PERFORMANCE CRITERIA, DESIGN REQUIREMENTS, AND GUIDELINES FOR SCHOOLS* to establish a standard for design and performance of school classrooms. The Standard also less specifically addresses teaching spaces such as Swimming Pools, Gymnasia, Cafeterias, Corridors, and Music Rehearsal Spaces. The main focus of the Standard is placed on traditional classrooms.

B. What does the Standard Address?

1. The ANSI S12.60 Standard, published in 2002, is concerned with providing a 15 dB signal-to-noise (S/N) ratio throughout the teaching area. Its total scope is concerned with the noise side of the equation, operating from the assumption that in a typical 900 square foot classroom a teacher's voice would be at a 50 dBA or higher level in most seats. The Standard covers four broad areas of acoustics, as follows:

   a. Room Acoustics:

      1) This is assumed to be largely characterized by Reverberation Times (RTs).

      2) Design Standard

         a) RTs are to be designed to be 0.6 second or lower in classrooms with cubic volumes of 10,000 ft^3 or smaller, at the octave bands with centers at 500, 1,000 and 2,000 Hz. Classrooms with cubic volumes between 10,000 ft^3 and 20,000 ft^3 are to be designed at 0.7 seconds or lower.

      3) Field Test Standard

         a) There is a 0.1 second grace interval, so that rooms field tested are allowed RTs that are 0.1 second above the design standard.

b. Heating, Ventilating and Air Conditioning (HVAC) Noise:

1) This is characterized by simple overall A-weighted and C-weighted measurements at the loudest location in each classroom. Other metrics, such as NC, PNC, RC, etc. are not used.

2) Design Standard

a) The 15 dB S/N ratio presumes HVAC noise of 35 dBA (and 55 dBC) or lower with a signal of 50 dBA. Therefore, the required design level for steady background HVAC noise is 35 dBA. To control the low frequency component there is also a requirement that the steady background C-weighted Ambient Noise Level (ANL) should be no more than 20 dBs higher than the A-weighted level.

3) Field Test Standard

a) There is a 2.0 dB grace interval, so that rooms field tested are allowed ANLs that are 37 dBA at the loudest location.

c. Sound Isolation Between Spaces and From Exterior (Outside) Noise:

1) This is characterized by Noise Isolation Class (NIC) between spaces.

2) Design Standard

a) In the case of adjacent classrooms the required design value of the partition must be STC 50.

b) Exterior noise from traffic or other sources must also be designed to be attenuated to the 35 dBA level in classrooms at the Key location (loudest location in the classroom). An increase of 5 dBs is allowed for the L_{10} Sound Level (Sound Level exceeded 10% of the hour) for the noisiest hour of the day for traffic.

3) Field Test Standard

a) The required field test is Noise Isolation Class (NIC) rather than STC. The field tested NIC required between classrooms is NIC 45.

b) Exterior noise transmitted to the classroom must also not vary more than 3 dBs during the required test period. There is an allowance for the L_{10} Sound Level to be 5 dBs above the 35 dBA level during the noisiest hour of the day.

d. Impact Isolation Class (IIC):

1) IIC is used to characterize the contribution of footfall noise and chair scraping noise from spaces above.

2) Design Standard

a) The Standard requires a design value of a floor/ceiling construction to be IIC 50. Carpet may not be used to achieve the IIC 50 category.

3) Field Test Standard

a) A field test of IIC 45 is acceptable.

III. METHODOLOGY

A. Scope

1. We designed a case-history approach, studying an example of each type of a variety of HVAC types and school types. We studied 4 HVAC types in 4 school types in Minnesota and 2 HVAC types in Arizona, making a total of 18 different schools. We studied three classrooms in each school for a total of 54 classrooms.

2. HVAC noise and Reverberation Times (RTs) were measured in all of the 54 classrooms. Sound isolation was measured in thirteen rooms in five schools. Impact isolation was measured in one classroom. Exterior noise isolation was checked for compliance in all 54 classrooms, but was studied specifically in three schools with the following criteria:

   a. One school was near a busy freeway.

   b. One school was near a large metropolitan airport (MSP International Airport).

   c. One school was located in a more typical residential setting, but with a major road nearby.

B. HVAC Noise

1. Table 2 indicates the combination of HVAC System Types and Building School Types studied:

Table 2 (Summary of Case Studies)

Case Study	Type of System	Project
Bldg. Construction Type I: Renovated – multi-story		
1.1	(Equipment Type 1) Dedicated units – located in or next to classroom – water-source heat pumps	K-12 Public School - Renovated in 2002 (Minnesota)
1.2	(Equipment Type 2) Central system air handling unit(s) remote from classroom - Rooftop unit with DX cooling	Education Center - Renovated in 2001 (Minnesota)
1.3	(Equipment Type 3) Central system chiller systems, 4-pipe wall mounted unit ventilator systems	High School - Renovated in 2003 (Minnesota)
1.4	(Equipment Type 4) Central system chiller system, desiccant based cooling (roof top units), fan powered boxes with positive displacement diffusers.	High School - Renovated in 2003 (Minnesota)
Bldg. Construction Type II: New – multi-story		
2.1	(Equipment Type 1) Dedicated units – located in or next to classroom – water-source heat pumps	High School - Built in 1992 (Minnesota)
2.2	(Equipment Type 2) Central system air handling unit(s) remote from classroom - Indoor air handling units	Elementary School - Built in 2003 (Minnesota)
2.3	(Equipment Type 3) Central system chiller systems, 4-pipe wall mounted unit ventilator systems	Junior High School - Addition Built in 2003 (Minnesota)
2.4	(Equipment Type 4) Central system chiller system, desiccant based cooling (roof top units), fan powered boxes with positive displacement diffusers.	High School - Addition Built in 2003 (Minnesota)
2.5	(Equipment Type 1) Dedicated units - located in or next to classroom - air cooled heat pumps.	Elementary School - Built in 2003 (Arizona)
Bldg. Construction Type III: Renovated – single story		
3.1	(Equipment Type 1) Dedicated units – located in or next to classroom – (water-source heat pumps, wall-mounted units, etc.)	K-12 Public School - Renovated in 1992 (Minnesota)
3.2	(Equipment Type 2) Central system air handling unit(s) remote from classroom - Roof top air handling units with DX cooling	Junior High School - Renovated in 2003 (Minnesota)
3.3	(Equipment Type 3) Central system chiller systems, 4-pipe wall mounted unit ventilator systems	Elementary School - Renovated in 2002 (Minnesota)

Case Study	Type of System	Project
3.4	(Equipment Type 4) Central system chiller system, desiccant based cooling (roof top units), fan powered boxes with positive displacement diffusers.	High School - Renovated in 2003 (Minnesota)
Bldg. Construction Type IV: New – single story		
4.1	(Equipment Type 1) Dedicated units – located in or next to classroom – water-source heat pumps	Elementary School - Built in 1990 (Minnesota)
4.2	(Equipment Type 2) Central system air handling unit(s) remote from classroom - Roof top air handling units with DX cooling	Elementary School - Addition Built in 2002 (Minnesota)
4.3	(Equipment Type 3) Central system chiller systems, 2-pipe unit ventilator systems	Elementary School - Built in 1988 (Minnesota)
4.4	(Equipment Type 4) Central system chiller system, desiccant based cooling (roof top units), fan powered boxes with positive displacement diffusers.	Middle School - Addition Built in 2003 (Minnesota)
4.5	(Equipment Type 1) Dedicated units - located in or next to classroom - air cooled heat pumps.	Elementary School - Built in 2003 (Arizona)

2. Three classrooms were studied in each school, for a total of 54 classrooms. Most of the Minnesota schools tested all had similar construction types: Composite walls with concrete blocks, Styrofoam insulation and face bricks. Double glazed windows, and steel deck with bar joist roof construction. New construction typically had a structure height of between 14 feet and 15 feet. Renovated construction ranged in height from 11 feet to 14 feet high.

3. The Arizona schools had steel stud wall construction with brick or stucco veneer and gypsum board interiors, double glazed windows, and wood trusses with plywood decks. The Arizona schools had wooden double doors between all classrooms. Structure height of between 14 feet and 15 feet for these schools

4. While the standard requires 35 dBA maximum SPL at the loudest location in the classroom, (with a 2 dB grace interval) we wanted to find the relative costs of achieving 5 dB increments from 55 dBA down to 35 dBA. We decided to do this would be to measure the SPLs in each room and then determine how much extra it would have cost to get down to 35 dBA, and at the same time determine what the diminished costs would have been had the space been at 55 dBA. For example, if a space measured 45 dBA, we would figure the costs required to bring the level down to 35 dBA (in 5 dB increments, where feasible). As a value engineering exercise, we then determined how money would have been saved if there had been no concern for HVAC noise in the

space. This method was of course not perfect. In some cases there was no plausible way that the classrooms noise level would have been as high as 55 dBA. In those cases we simply took the SPL that would have resulted with no consideration for noise. In one case (a unit ventilator – under window type), there was no feasible way to achieve 35 dBA near the unit, so we simply made the feasible modifications that resulted in an approximate 10 dB noise reduction.

5. Throughout this HVAC noise part of the study we have tried to adhere to the following main precepts:

    a. Follow ANSI S12.60 testing procedures as closely as possible. We have tried to place ourselves in the position of someone testing these schools for compliance to ANSI S12.60. For engineering purposes however, we have gone beyond just testing for compliance, collecting 1/3 octave band data for each of the 6 measurement locations in the room.

    b. We measured three rooms in each school, and we calculated costs based on bringing each of these rooms to the noise levels (35 – 55 dBA). We used cost figures that assumed the work would have been done at the time of the building (or renovation) of the classrooms. We did not try to ascertain what the costs would be to fix noisy systems that had already been installed. We computed costs in two different ways, as follows:

        1) <u>System Wide Costs</u>

            a) There were cases where an RTU was located over a classroom, resulting in excessive vibration and noise through the structure. Although this noise issue affected only a single classroom, we calculated the costs of a concrete pad (and associated additional structure to support it) and spring isolators. This cost was then divided over the total area of all the classrooms served by the unit to develop a square foot cost for each classroom. We did this because it seemed inaccurate to divide the cost by only the three classrooms that we studied. For example, if the modifications for this situation cost $10,000 and there were 10 classrooms served by the unit, we would divide the total cost by 10 to arrive at a cost of $1,000/classroom.

2) Room Specific Costs

a) In other cases there were noise issues that were specific to one classroom, such as a Power Roof Ventilator mounted directly over that classroom. In that situation we estimated the cost to solve the specific problem and charged the total cost to the specific classroom. For example, if the cost to modify the Power Roof Ventilator was $1,000, we would not distribute that cost over all of the 10 classrooms in the example above.

c. We did not typically aim for 35 dBA ANLs, but rather for 2 – 3 dBs below that level, realizing that for a variety of reasons HVAC noise levels are frequently somewhat higher than expected. From a design standpoint if issues were called out in the original design, the costs would be charged to the school, however if modifications were required to bring the spaces to 35 dBA after construction, we would at the least have considerable explaining to do, and might be called to share the cost of the modifications. This was a marvelous method of keeping us focused in this regard.

C. Reverberation Time

1. We tested all of the 54 classrooms for RTs, in six octave bands with centers from 125 Hz – 4,000 Hz, using a balloon as an impulsive noise source, recording three "pops" and averaging the results. All the classrooms but one passed the RT requirement. In that case we charged the cost of a more absorptive ACT to the room and divided this cost between all of classrooms that we studied to come up with a cost/square foot for compliance with the RT requirement.

D. Sound Isolation

1. We tested room partitions in five schools for a total of 13 partitions. Testing was done according to procedures established in ASTM E336 and ASTM E413 to establish NIC. We conducted a visual inspection of the partitions above and below the ceiling for obvious holes or cracks. The workmanship varied greatly, from excellent to poor, as did the resulting NIC's. We charged the extra cost of adding layers of gypsum board in some cases. In other cases the theoretical STC would have been fine, but the workmanship was poor. In those cases, the only add we charged to the rooms was for construction administration, which presumably would have insured that the adequate care would have been realized during construction.

2. In one case, where the workmanship was very good, the theoretical STC was just below STC 50, but the field test was adequate in two of the three partitions. However, we charged each room to add a layer of gypsum board to achieve the theoretical STC 50, since that would have been required by the Standard at the design stage.

3. Finally, in all instances we charged costs for door gaskets and drop seals for classroom doors, since a rating of STC 30 is required for all classroom doors. We averaged the total costs of all the modifications required for the 9 partitions over the square-foot area of those 9 classrooms. We did consider that some of the partitions were not tested (for example, we might have tested the isolation between a central classroom and 2 adjacent ones, but did not test the partition to the corridor, or perhaps also to the classrooms above or below). In the case of floor/ceiling sound isolation we simply estimated that the existing construction would be adequate to meet the NIC 45 Standard. In the case of the corridor walls we assumed that the construction that we observed/tested for the common walls of the classrooms would be similar to the corridor walls.

E. Impact Isolation

1. For this test we followed the procedures established by ASTM E1007-97. We tested only one school for this, because it seemed a foregone conclusion that all classrooms would fail. Whether pre cast planks/topping, Tees, or composite metal deck/concrete with bar joists were used, none of these systems would yield the required Field IIC 45, even with high CAC ACT below.

2. We researched the cost of adding a floating floor system that utilized a relatively thin resilient membrane with 2” concrete topping, and added this cost to all the classrooms that we studied. This was, of course the largest single additional cost that we added. We have added a cost of $6.00/square foot for this feature. The field IIC 45 is strictly required only over core teaching spaces.

IV. <u>PROCESS</u>

A. The process began with studying plans of the school building, locating the HVAC equipment and identifying the likely loudest rooms.

B. We assessed the rooms in a particular area to see which ones seemed to be the noisiest, comparing our aural experience with what we had expected to discover from studying the plans.

C. We determined which rooms to study based on the noise levels we heard and measured. At that point we measured airflow to verify that the rooms were getting the proper amount of air. In several cases we found the airflow to be significantly lower than the design values, so we tried to ascertain in the field if the phenomenon was only occurring in specific rooms or if it tended to be system wide. Air flow also entered into our decision about which rooms to study. However, in several cases we could not find rooms with the specified design air flow. In those cases we used the process described in the two paragraphs above to determine which rooms to study.

D. We studied most of the rooms during the summer months during the hours when school would have been in session. However, in a few cases we also studied schools just after the students had left the building. In all classrooms we measured six different locations, as per ANSI S12.60, finding and designating one location as the key (loudest) location.

E. When still on the site we ascertained the causes of the noise by a variety of troubleshooting methods, including turning various pieces of equipment on and off to determine what the true noise sources were. Having the mechanical plans with us helped immeasurably in this venture. When there was an obvious point noise source that was considerably higher than the surrounding areas, we measured noise levels at 1 meter away from the source.

F. After leaving the site we downloaded the data from the sound level meter and determined more accurately the noise reductions that we might expect to achieve from the measured levels that we had proposed while on site. This included verifying air speeds, and selecting duct silencers, vibration isolation devices, or duct lining, as well as rerouting ducts and changing out diffuser types.

G. We figured noise reduction as we would typically do in the field while troubleshooting noise issue in that we would generally choose the least expensive means for sound reduction first, moving progressively toward the more expensive fixes until we reached the design goal of 35 dBA or lower. That is one of the reasons that the cost curve generally gets steeper with greater modifications.

H. We then tabulated the cost of the various modifications that we had proposed, (using costs typical for Minnesota) and wrote a project summary for each of the schools that we studied.

I. Finally, we combined the data for each HVAC type to determine typical costs that might be expected by following the ANSI S12.60 Standard.

V. EQUIPMENT USED FOR TESTING

A. We used the same equipment throughout the testing process.

B. For the sound testing we used a Larson Davis Model 824 Sound Level meter, (SN#0764, cal. date 3/16/04) equipped with 1/1 and 1/3 octave filters and a wind screen. The meter was field calibrated directly (Calibrator SN#2366, cal. date 3/15/04) before and after the testing in each school.

C. Balloons were used as an impulsive source for RT testing.

D. For sound isolation testing we used a IVIE IE-20B pink noise source a Mackie M1400i amplifier, and an Electro Voice EV S1202loudspeaker.

E. The tapping machine that we used for Impact Isolation Class testing was a Bruel & Kjaer model 3204 (SN# 1896291).

F. The flow hood that we used was a Alnor Balometer 6463 (SN# 70419253, cal. date 05/04).

VI. EXISTING NOISE LEVEL IN THE CLASSROOMS

A. Below are listed the percentages of the 54 classrooms that fell within each noise category at the key (loudest) location.

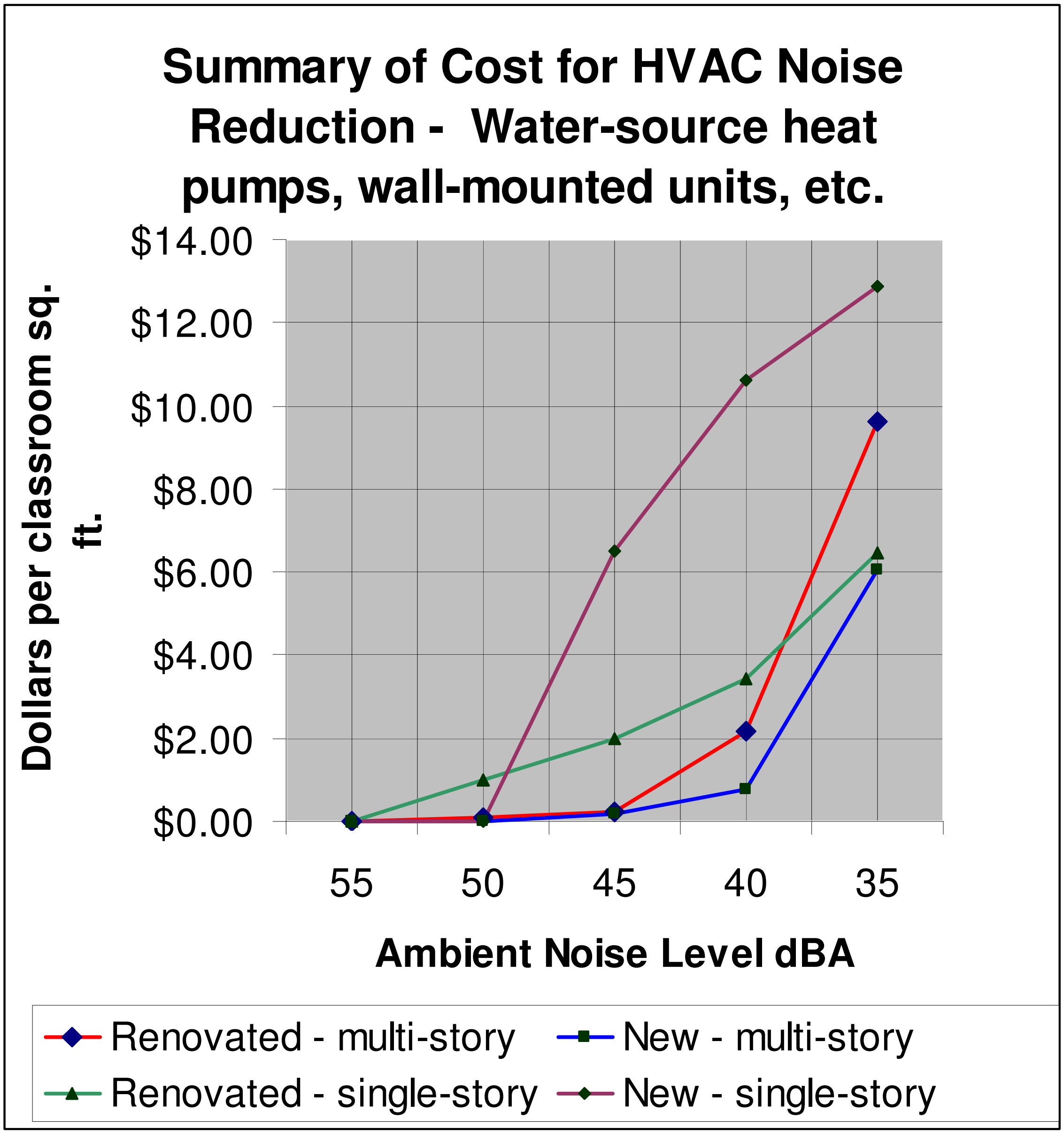
Table 3 (Noise Levels in Existing Classrooms)

Noise Category	Classrooms	Percentage
55 dBA and Over	5	9
50 – 55 dBA	17	32
45 – 50 dBA	12	22
40 – 45 dBA	12	22
35 – 40 dBA	8	15
35 dBA and Below	0	0

B. The above table shows the SPL values for the key location measured in all 54 classrooms. However, it does not show typical noise levels throughout the classrooms. In 24 of the 54 classrooms that we studied, there was a specific point noise source in the space that measured considerably higher than the other locations. This was true in all of the Positive Displacement diffuser classrooms and in all of the unit ventilator classrooms. In these classrooms the noise levels varied greatly depending on how far away from the main source we measured. Noise levels on the opposite side of the classroom were typically 7 dBs lower than the key location.

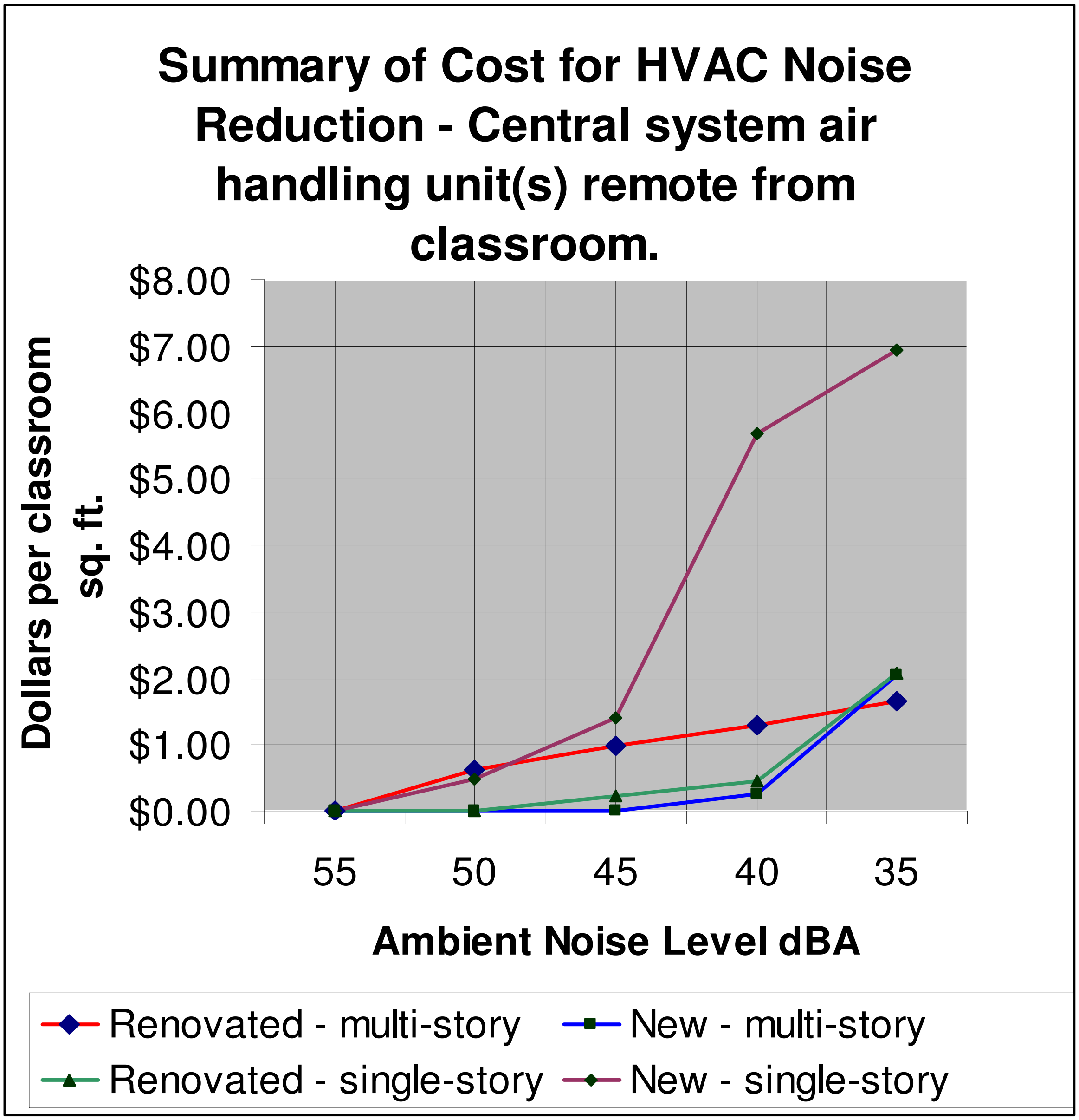
VII. COST FOR HVAC NOISE REDUCTION

A. Cost for Equipment Type 1 (Minnesota)



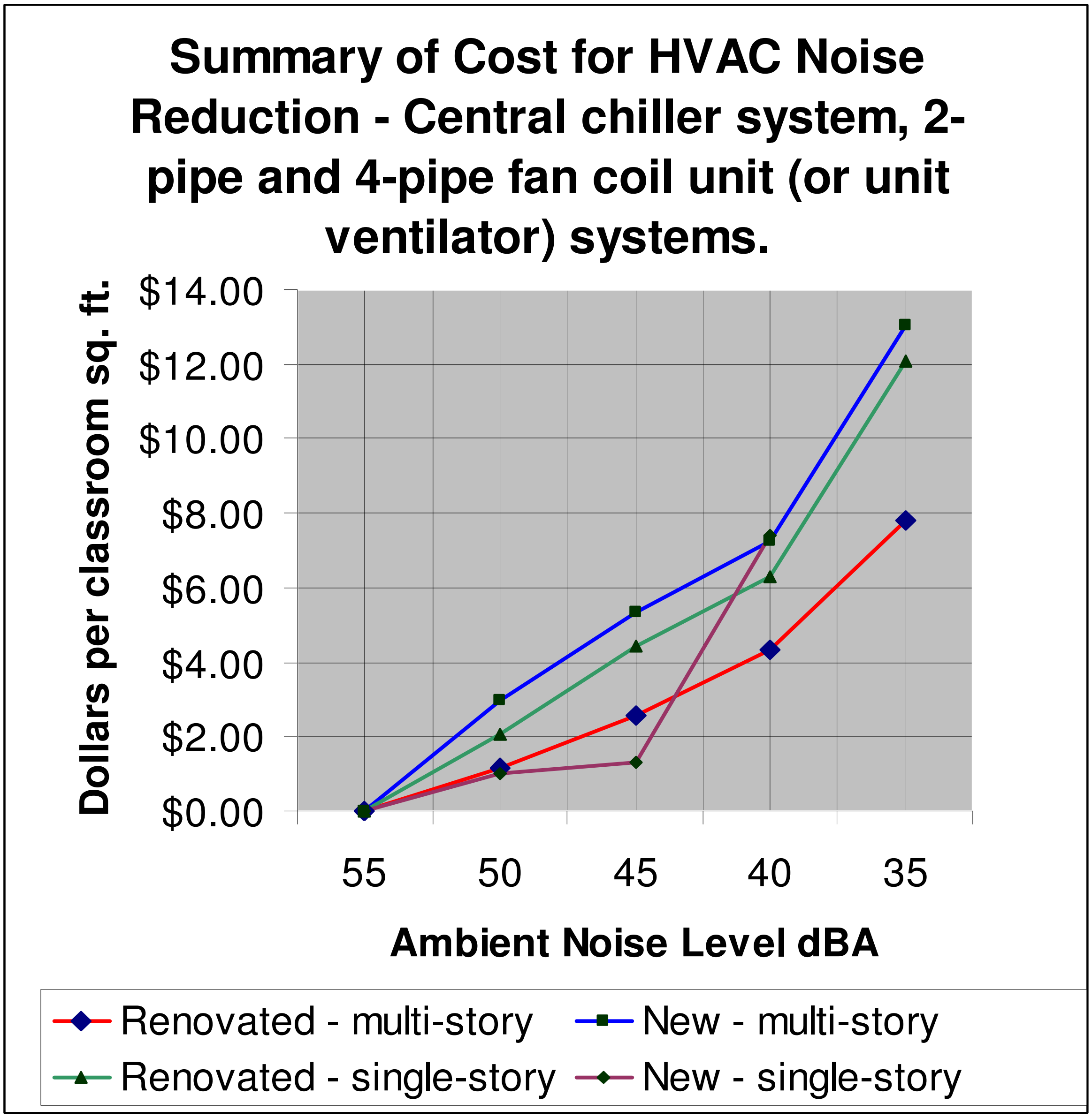
1. The renovated (multi-story and single-story) building and the new – multi-story building have horizontal ceiling mounted water source heat pumps. The new – single-story building has vertical heat pumps in remote mechanical rooms. The increased cost of the mechanical room was included in the new – single story building which resulted in the higher cost for this building type.

B. Cost for Equipment Type 2 (Minnesota)



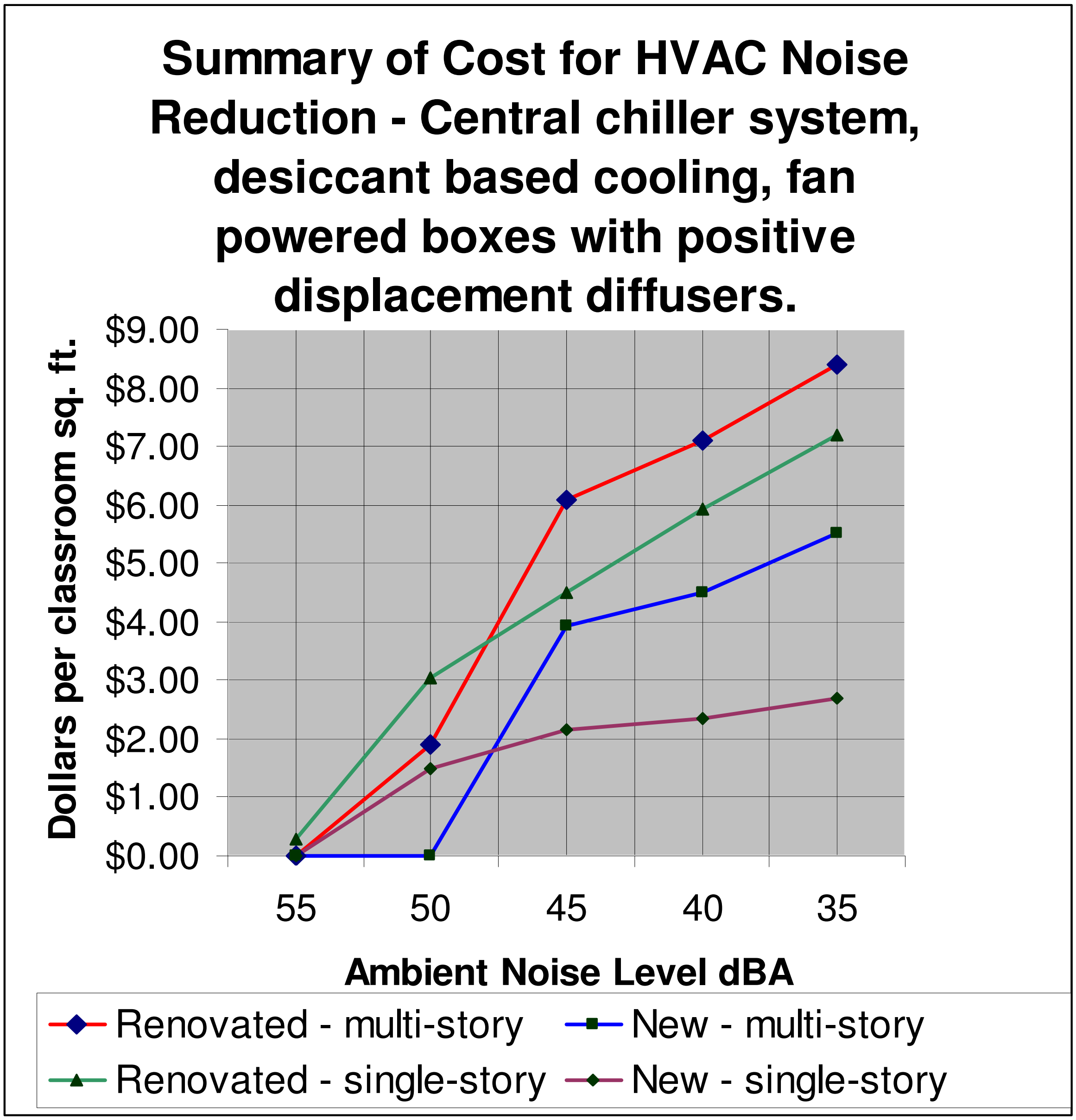
1. The new – single-story project is a small building addition with rooftop equipment indicating higher cost for acoustical treatments spread over a smaller square footage.

C. Cost for Equipment Type 3(Minnesota)



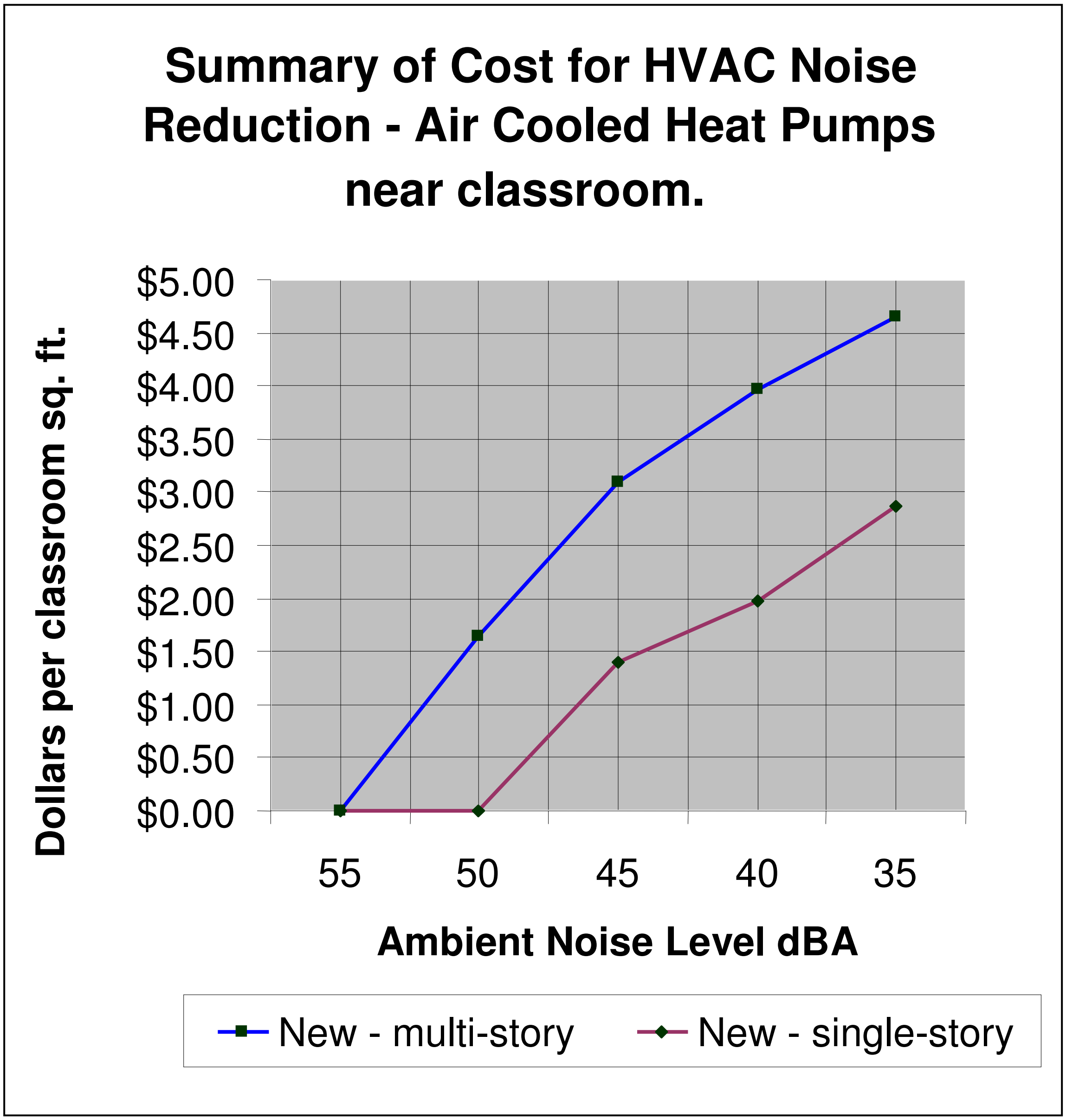
1. The renovated (multi-story and single-story) building and the new – multi-story building are vertical classroom unit ventilators with integral energy recovery wheels. The new – single-story building is a traditional classroom unit ventilator which has a limited capacity. It is unlikely that noise level can be reduced to the required level without significant reduction in system performance.

D. Cost for Equipment Type 4. (Minnesota)



1. Each of these buildings were rooftop Desiccant Based Cooling units with displacement ventilation diffusers and fan powered variable volume boxes. In all four cases there was value engineering that reduced acoustical performance of the systems. These compromises caused the cost curves to be inverted.

E. Cost for Equipment Type 1. (Arizona)



1. New – multi-story building has horizontal ceiling mounted air cooled heat pumps with remote roof mounted condensers for first floor and has roof mounted air cooled heat pumps on corridor roof near the classrooms. The new – single-story building has roof mounted air cooled heat pumps located on roof adjacent to classrooms.

VIII. COST FOR RT REDUCTION

A. All but one of the classrooms tested were in the category of less than 10,000 cubic feet in volume, and thus were within compliance if the RTs at the octave bands with centers at 500, 1,000 and 2,000 Hz were under 0.7 seconds. For the one larger classroom (at 15,000 CF) it was within compliance with RTs of less than 0.8 seconds.

B. Out of all of the 54 classrooms tested, only one failed for RT compliance. This room was somewhat atypically furnished in that it had absolutely nothing in it other than desks. There were no bulletin boards or bookcases or anything else on the walls other than one whiteboard. This space tested somewhat worse than would be predicted by modeling, while all of the other space performed somewhat better than would be predicted by modeling. None of the classrooms that we studied had glass fiber ACT. Typically around 15% of the ceilings were plastic light diffusers. Most had VCT on the floor, but a significant number had carpet.

C. Most of the rooms had bookcases, bulletin boards, and other cabinets, equipment, etc. However, since we tested most of the schools during the summer vacation period, we surmised that the amount of extraneous material in the classrooms was probably smaller than usual. We did not typically remove any material from the classroom unless it was obvious that it didn't belong there.

D. For the non-compliant space, we charged the cost of using a glass fiber tile, which would bring it into compliance with ANSI S12.60 RT standards. In a sense this is perhaps the wrong thing to do, because the real problem is a lack of diffusion in the space. However, the space would achieve the letter of the law by using the more absorptive ceiling, and this would likely have been the original design response to achieve the appropriate RTs.

E. Cost Summary For RT Compliance

Table 4 (Cost for RT Compliance)

Total Area of all Classrooms Studied	Total Costs	Price/square foot
46,157 square feet	$632	$0 - $0.70/square foot

IX. COST FOR INTERIOR SOUND ISOLATION

A. We tested partitions between classrooms in five schools, for a total of thirteen partitions. The classrooms were chosen randomly. We did not look for a correlation between HVAC types and sound isolation, although one may exist, since some systems acoustically connect classrooms through the supply and return ductwork.

B. In retrospect, we wish that we had included all of the classrooms in this part of the study, since we did encounter a variety of different types of partitions, from demountable partitions that only extended to the ACT ceiling (not to the deck), to CMU partitions that were well sealed at the deck.

C. There were typically three reasons rooms failed:

1. The partition was not adequate from a design point of view, in that it did not have a theoretical isolation value of STC 50. In one school, 2 of the three partitions passed the field NIC test (barely) even though the theoretical design isolation value was less than STC 50.

2. The theoretical design isolation value would have been adequate, but there was poor workmanship, sometimes with large gaps at the deck and around penetrations. For these rooms we have added in a square foot cost of construction supervision that we posited would have been required to have achieved the level of construction that was called out for in the construction documents.

3. In all cases, the rooms were not equipped with gaskets and drop seals, which are required to achieve the STC 30 for the door that the Standard requires.

D. Of thirteen partitions tested, three passed the NIC 45 field test. However, two of these did not pass the theoretical STC 50 test, so from a design standpoint, twelve of the thirteen partitions would need some modification to conform to the ANSI S12.60 Standard. In each case, we tested all of the classrooms with common walls with the source room (room with the noise source in it). In some cases that was a single room, and in other cases it was two rooms. We also added a cost to consistently use a single structural span across each classroom (rather than occasionally spanning two rooms and having to deal with the penetration/deflection issues).

Table 5 (Cost for Interior Sound Isolation)

Total Area of Classrooms Studied	Total Costs	Price/square foot
7,154 square feet MN	**$18,385**	$0 - $2.67/square foot
Cost including intervening doors between classrooms		
5,354 square feet AZ	**$42,500**	$7.94/square foot *
5,354 square feet AZ	**$56,795**	$10.61/square foot **

*** Cost to upgrade doors to sound doors in for classrooms found in Arizona classrooms were based on 6 classrooms with 5 sets of doors divided by the total area of the six classrooms.**
**** This total includes door modifications plus the $2.67/ square foot cost.**

Note: For the Arizona schools, which had double doors between each room, we added costs for acoustical sound doors between rooms, at $8,500 per classroom. Since the cost may be misleading and wildly skew the figures, we assume that most design professionals would opt not to provide the doors when faced with the high costs.

X. COST FOR IMPACT ISOLATION

A. We measured only one school for impact isolation. We presume all classrooms will fail the Field IIC 45 that is required by the standard, since it would be extremely unusual to provide construction that would pass. As stated elsewhere, it is not acceptable to use carpet to reach the F- IIC 45 level.

B. We researched the cost of adding a floating floor system that utilized a relatively thin resilient membrane with 2" concrete topping (and associated additional structure to support the weight). This cost is obviously only applicable to multi-story schools, and only where a classroom is located under another space which may or may not be a classroom. This was, of course, the largest single additional cost that we added. We have added a cost of $6.00/square foot for this feature.

Table 6 (Cost for Impact Isolation)

Total Area of One Classroom Studied	Total Costs	Price/square foot
806 square feet	$4,836	$0 - $6.00/square foot

C. The floating floor element will meet the impact isolation requirement of the Standard. However, it is probably economically feasible only for new construction. For renovations, adding 2.5" to the classroom floor height would create numerous level change issues. It would also probably require changing the structure to support the heavier flooring load. These issues may make renovations impractical and not feasible from a financial point of view.

XI. COSTS FOR LIGHTING NOISE

A. We studied all 54 classrooms by turning off all HVAC equipment. There was ballast hum ranging from perceptible to annoying in approximately 50% of the rooms we studied, but we did not find any cases where the ballast hum would put the room over 35 dBA by itself, or where the ballast noise was 3 dB above the ambient noise when the lights were turned off. Normally, the difference could be measured only in a few tenths of a dB. This slight variation might easily be attributed to factors other than ballast hum. Therefore we have not added any costs for modifying lighting.

XII. COST FOR EXTERIOR SOUND ISOLATION

A. We checked all 54 classrooms for compliance with the Standard in terms of sound isolation from the exterior, by the means provided by the Standard. The great majority of these passed, having exterior L_{50}'s in the 55 – 60 dBA range and interior noise levels within the 37 dBA maximum mandated by the Standard. We sought out three specific school sites where exterior noise was a definite issue, as follows:

1. One suburban site in line with a major runway at the MSP International Airport.

2. One suburban site 300 feet from a large freeway.

3. One suburban site in a residential area, but within .25 miles of a major highway.

B. Test results and costs associated with the above three sites are as follows. The classroom noise levels must have an L_{10} of no more than 40 dBA during the noisiest hour during the school day.

1. <u>Site in line with a major runway at the Minneapolis – St. Paul International Airport.</u>

   a. This was at a local college located approximately 1.25 miles from the runway. The site was also approximately 0.25 miles from a major freeway. We measured noise levels in the classroom for a one hour period from 2:00 PM – 3:00 PM. This time was chosen as representative of the noisiest time of the day by members of the teaching staff that used the classrooms. The L_{10} in the classroom for that period was 42.2 dBA, which is above the allowable level of 40 dBA. The main 1/1 octave band contributions were in the 250 – 1,000 Hz range.

   b. The classroom studied was on the upper floor of a three story building, with a band of 4' high windows facing the freeway and the airport.

      1) The construction of the wall was as follows:

         a) 4' continuous band of 1" insulating glass.
         b) EIFS construction with 5/8" GWB on both sides of 6" metal studs filled with batt insulation and 2" rigid insulation faced with EIFS finish.

      2) The construction of the roof deck/ceiling was as follows:

         a) 2 X 2 mineral fiber ACT
         b) 2' bar joists
         c) 1.5" metal deck
         d) 6" rigid insulation
         e) Built-up roof with gravel ballast

c. We examined the sound transmission loss of the walls, windows, and ceiling in conjunction with the sound spectrum on the inside of the room and concluded that upgrading the windows would be necessary to meet the standard. We used 3/16" laminated glass for one of the 1/4" panes, which would provide the additional attenuation needed to bring this room into compliance.

Table 7 (Cost for Exterior Sound Isolation)

Total Area of Windows	Price/square foot	Total Costs
160 square feet	$3/square foot	$480

2. Site at 300 feet from Freeway.

a. This was at a suburban elementary school facing the freeway. We measured noise levels in the classroom for a one hour period from 2:30 PM – 3:30 PM. This time was judged to the heaviest traffic during the time that the school was in session. The classroom studied was on the 2nd floor of a two story school.

b. The L_{10} in the classroom for that period was 38.7 dBA, which is below the allowable level of 40 dBA. The exterior L_{10} and L_{50} respectively, were 72.7 dBA and 67.5 dBA. Since this classroom passed the L_{10} test, we did not add any costs for modification. Note: Although this school did pass the L_{10} test for the noisiest hour, it is likely that a prudent designer would provide laminated glass to be on the safe side.

3. Site at 0.25 miles from a major suburban road.

a. This was a high school in a residential area, close to a major suburban roadway. The site was chosen because it was a noisy one. The outdoor L_{50} during the 2:00 – 3:00 period was 61.1 dBA. The school was an older one that had recently been upgraded with 1" insulating windows.

b. The classroom studied was on the upper floor of a three story building, with a band of 4' high windows facing the roadway. In spite of the rather noisy exterior ambient noise level, the classroom met the 37 dBA maximum during the testing, so we did not perform an L_{10} test in the interior classroom. Since this classroom met the standard, there are no costs associated with it.

Table 8 (Summary of Cost/square foot for Exterior Sound Isolation)

Area of Classroom	Total Costs	Price/square foot
1,200 square feet	$480	$0 - $0.40/square foot

XIII. GENERAL OBSERVATIONS

A. In the course of the study, we were confronted with many questions as to how to most accurately detail the costs associated with meeting the Standard. Some issues were fairly obvious, such as the need to implement some kind of duct noise attenuation into a HVAC system, or the need to place vibrating equipment on spring isolators.

B. Other issues were not so obvious. For example, how can the cost of possible over design be assessed? One can readily surmise that the concern of not attaining the dictates of the standard would lead a mechanical engineer or acoustician to employ a "belt and suspenders" approach to acoustical design. But it is difficult to predict accurately the degree to which that concern would encourage over designing the project.

C. Some design elements that are good practice but seldom realized can be expected to become standard operating procedure. It seems reasonable to expect that composite deck/bar joist systems would come to be designed with shorter spans to avoid the penetration of walls by bar joists that may require as much as 2" of deflection. It also seems reasonable to expect that Rooftop Units (RTUs) would routinely come to be placed on concrete as well as vibration isolation curbs. This would be true for units that serve the spaces in question as well as unrelated roof top equipment. This also has implications for the robustness and cost of the structure.

D. Adoption of this standard should not become just one more unfunded mandate. Yet, in pondering all of the issues we cannot help but feel that we have not been able to include all of the costs that will be incurred by adherence to the Standard. There are several spaces, for example, that we have not included, since this study only deals with traditional classrooms, and not with gymnasia, Cafeterias, Corridors, and a number of other spaces. We have also not included additional design fees for the Architects, Engineers, and Acousticians, but it seems that this will also become part of the equation, since the stakes for not achieving the Standard could be high.

E. A question that needs to be asked and answered is, "Who will pay the costs for meeting the Standard if a space fails in some regard?" This will certainly happen. Architects, Engineers, and Acousticians presently do not reflect the cost of the extra time required to sort out the inevitable finger-pointing that occurs whenever there is a complaint. They certainly do not include funds to rectify problems that may have occurred, possibly through no fault of the Architects, Engineers, or Acousticians.

F. While it is noble for professionals to hold themselves to a high standard, it will be a non-existent profession if they are consistently asked to pay for the inevitable shortfalls that will occur. These shortfalls will occur both because of design flaws and construction deficiencies, but as partially demonstrated by this study, these shortfalls will be expensive to fix. It should be kept in mind that this study is about the costs of achieving the Standard in the original design/construction, and not about the costs involved in retrofitting a problem classroom.

G. Background noise levels around 35 dBA without equipment operating were quite common in the classrooms studied and defied any easy identification of a specific source. The upshot of this is that HVAC systems will need to contribute virtually nothing to the noise levels already present in many of the spaces. Without modifications of the current sound level limitations this will make the task of mechanical engineering and contracting very difficult and costly.

H. After visiting all of the classrooms, it became very clear that early planning was the key to achieving the guidelines of the Standard. The most obvious early planning effort must, of course, have to do with the budget. Not to belabor the obvious, but classrooms built to these specifications will not happen unless there is money to pay for it. Then, assuming that adequate money has been appropriated, the physical planning must begin immediately.

I. Structural planning will be exceedingly important, in order to support the larger loads that are a part of the acoustics package. Floating floors and concrete pads must be supported. Careful attention must be paid to where bar joists bear and how much they deflect. Bar joist sizes may have to increase in order to accommodate larger ducts.

J. Space planning, which has always been important, will become more critical under stricter noise requirements. Generally speaking, larger mechanical rooms will be required to ensure room to achieve larger ducts and smooth flow of air. They must also be strategically placed to avoid noise and vibration issues to adjacent spaces. HVAC design will need to be a big part of the early stages of design, in order to avoid transmission of sound between classrooms through the supply and return ducts, and to allow for the extra space needed to ensure smooth airflow and reduce static pressure in the system.

K. Unit ventilators are sometimes virtually the only solution for retrofit situations where there is inadequate deck-to-deck height for central systems. This type of system is, by its nature, much noisier at the unit, and much quieter, (5 – 7 dBs) on the opposite side of the room. In order to accommodate this type of system for retrofit, it may be necessary to change the 35 dBA requirement at 1 meter from the unit if it can be demonstrated that the unit can be placed, for example, 2 meters away from the nearest occupied space.

L. We have observed the following mechanical construction items to be critical to adequately controlling HVAC noise.

1. Installation of air extractors and turning vanes in ductwork can be important to reduce noise. Contractors may not provide these even when they are shown on the plans.

2. Placement of duct silencers is important to avoid creating additional noise through turbulence.

3. Spring isolators are necessary to avoid low frequency vibration transmission. Rubber isolators may not provide adequate low frequency vibration isolation.

4. There are limitations on some equipment (water source heat pumps, unit ventilators, and fan powered VAV boxes) in reducing noise levels. This type of equipment may not be robust enough to handle the static pressure added by attenuation devices.

5. Power Roof Ventilators can vibrate the entire roof structure and sound like much larger equipment.

6. Butterfly dampers in diffusers for rated ceilings can cause 6 – 8 dBs additional noise.

7. Reduced neck size on the supply diffuser will cause turbulence and thus, noise.

8. Unlined ductwork from the fans with no duct silencers will almost certainly result in ANLs higher than 35 dBA.

9. Duct fittings such as elbows, dampers, take-offs, etc. can cause turbulence and therefore noise, particular at higher velocities.

10. RTUs must not be located directly over classrooms, because both noise and vibration problems can be virtually insurmountable in those situations.

11. With the current industry practice of not using duct liner, there is a special importance in using quieter fans and attenuators to reduce noise at the source. We found that internal duct liner, at least in limited use, is necessary to control noise generated by duct fittings as well as the fan itself.

M. In many cases the dedicated systems did not meet the manufacturer's recommendations on airflow. These dedicated units are designed for low first cost and need low static pressure drops to perform well. When available static pressure is exceeded, the units cannot produce enough airflow to meet the rated CFM. When duct silencers or other acoustical obstructions are added to the system the static pressure increases, further reducing the airflow. If a larger motor is added to increase the airflow the result is often more noise. Thus both initial costs and continuing operating costs will increase.

N. The central station systems were typically closer to the design CFM, although some with fan powered VAV boxes were short on air due to the limited capacity of the VAV boxes. In general, the central station systems can more readily have attenuation devices added because they have a wider range of CFM and static pressure available. These systems often are plagued with excessive low frequency noise, which can be difficult to eliminate with conventional means such as duct lining or duct silencers. For such issues, it can be exceedingly important to have the AHUs located far enough from the first classrooms, so that duct breakout can occur in non-critical areas such as storage areas, corridors, etc.

XIV. COST IMPACT TO A SCHOOL CONSTRUCTION PROJECT

A. As stated earlier, this study was based on a case history approach, in which we studied a relatively small number of classrooms (54) to determine ANSI S12.60 compliance, and to determine what additional costs would have been incurred to have brought them to compliance at the design/construction phases.

B. In order to be useful as a planning tool, it may be helpful to look at a few hypothetical school construction projects to illustrate what the cost impact of adopting ANSI S12.60 might be. Of course, each school will differ somewhat from what we discovered in our study, so the following examples should be used only as a guideline.

C. Analysis of school design profiles to determine what percentage of gross square footage of schools are classroom, indicated that for elementary schools the ratio ranged from 38% to 58% of gross square footage. Some of the variance in the percentage of gross square footage is due to more support spaces, wider corridors, more gymnasiums, and other ancillary spaces not directly associated with the classrooms. Applying this information to total building costs may prove to be impractical due to the wide fluctuation of base costs due to building types, features, components, codes, owner's preferences, etc. Therefore we have based the cost per square foot on class room areas only, rather than apply costs to the gross square foot of the building. This cost method would be applied as an addition to normal cost estimating procedures.

D. The following examples provide a range of different cost expected but are not inclusive of all combinations when complying with ANSI Standard 12.60.

1. Example of increased cost to meet the requirements of ANSI S12.60 Standard for a Building Type I (Renovated – multi-story) and Equipment Type 4 (Central system chiller system, desiccant based cooling, fan powered boxes with positive displacement diffusers).

   a. Mechanical Noise Control Most classrooms did not meet the standard, so there will probably be significant extra costs to achieve the standard. We calculated costs of up to $12.88/square foot for this type of construction and HVAC system. In the validation part of the study, we found that costs, particularly for retrofit, may be significantly higher than we had predicted. See Section XVI

   b. Exterior Noise Reduction We found that both in Minnesota and in Arizona that exterior noise was not typically a problem. However, if you have a site that is in the vicinity of an airport, or a large roadway, and with exterior construction masonry, and 1-inch insulating glass you will need to add something for 3/16" laminated glass for on of the ¼" panes of the 1 inch insulating glass of the windows. For the purposes of this example, we have assumed 64 square feet of window per classroom, for an additional $0.40/square-foot cost. If the exterior wall is of lightweight construction and the site is a noisy one, the cost for this issue could rise dramatically.

   c. Room Acoustics We found that most classrooms passed the ANSI requirement in the schools we studied. So, if you are typically using a good quality of ACT (NRC .70 or higher) you probably won't have any additional costs for this issue.

   d. Sound Isolation We found that most partitions did not meet the ANSI Standard, so you will probably need extra materials and increased construction supervision to achieve the required NIC 45 between classrooms. We estimated $2.67/SF to achieve the standard in the schools we studied.

   e. Impact Isolation For the example below, we have assumed a two story building with an equal area of classrooms on both floors, so the square-foot costs would be $6.00/square foot times the classroom area above grade (in this case 50%).

Table 9 (Cost for a Classroom Located in a Renovated – Multi-story Building with Equipment Type 4) – Note that miscellaneous cost is not included.

	Cost ($/Sq. Ft.)
Cost for Classroom Area	Minnesota
Cost for HVAC Reduction to 35 dBA	12.88
Cost for Exterior Noise Reduction($0 - $0.40)	0.40
Cost for RT Reduction($0 - $0. 70)	0.00
Cost for Sound Isolation($0 - $2.67)	2.67
Cost for Impact Isolation $6.00/SF x 50% of total SF	3.00
Total Increased Cost	18.95
Cost for Classrooms Only	
Building Cost for Classroom Renovation (moderate changes)	80.00
Increased Cost to Meet ANSI Standard S12.60	18.95
Total Cost	98.95

f. Based on the above calculations, this would be a 24% increase in construction cost for the classroom only. There may be additional costs, as outlined under section XV of this study.

2. Example of increased cost to meet the requirements of ANSI S12.60 Standard for a Building Type II (New – multi-story) and Equipment Type 3 (Central system chiller system, 4-pipe wall mounted unit ventilator system).

   a. Mechanical Noise Control Most classrooms did not meet the standard, so there will probably be significant extra costs to achieve the standard. We calculated costs of up to $13.02/square foot for this type of construction and HVAC system.

   b. Exterior Noise Reduction For the purposes of this example, we have assumed a quiet residential location in a northern climate with double glazed windows as a base construction, so there would be no additional costs for exterior sound isolation.

   c. Room Acoustics For this example let us assume that the typical standard is ACT with NRC .55. In this case, you will need to upgrade the ACT to meet the Standard at a cost of $.70/SF.

   d. Sound Isolation We estimated $2.67 /SF to achieve the standard in the schools we studied.

   e. Impact Isolation For the example below, we have assumed a two story building with an equal area of classrooms on both floors, so the square-foot costs would be $6.00/square foot times the classroom area above grade (in this case 50%).

Table 10 (Cost for a Classroom Located in a New – Multi-story Building with Equipment Type 3) – Note that miscellaneous cost is not included.

	Cost ($/Sq. Ft.)
Cost for Classroom Area	Minnesota
Cost for HVAC Reduction to 35 dBA	13.02
Cost for Exterior Noise Reduction($0 - $0.40)	0.00
Cost for RT Reduction($0 - $0. 70)	0.70
Cost for Sound Isolation($0 - $2.67)	2.67
Cost for Impact Isolation $6.00/SF x 50% of total SF	3.00
Total Increased Cost	19.39
Cost for Classrooms only	
Base Building Cost for New Classroom	135.00
Increased Cost to Meet ANSI Standard S12.60	19.39
Total Cost	154.39

f. Based on the above calculations, this would be a 14% increase in construction cost for the Minnesota classroom. To estimate costs in other areas of the country, use multipliers such as described below in the City Cost Example. There may be additional costs, as outlined under section XV of this study.

3. Example of increased cost to meet the requirements of ANSI S12.60 Standard for a Building Type IV (New – single-story) and Equipment Type 2 (Central system air handling unit(s) remote from classroom).

a. Mechanical Noise Control We calculated costs of up to $2.00/square foot for this type of construction and HVAC system.

b. Exterior Noise Reduction For the purposes of this example, we have assumed a quiet residential location in a northern climate with double glazed windows as a base construction, so there would be no additional costs for exterior sound isolation.

c. Room Acoustics Using a typical ceiling tile (ACT) with a minimum NRC of .65, there would be no extra costs to meet the ANSI Standard.

d. Sound Isolation We estimated $2.67 /SF to achieve the standard in the schools we studied.

e. Impact Isolation For the example below, it is a single story building, so there are no impact isolation issues.

Table 11 (Cost for a Classroom Located in a New – Single-story Building with Equipment Type 2) – Note that miscellaneous cost is not included.

	Cost ($/Sq. Ft.)
Cost for Classroom Area	Minnesota
Cost for HVAC Reduction to 35 dBA	2.00
Cost for Exterior Noise Reduction($0 - $0.40)	0.00
Cost for RT Reduction($0 - $0. 70)	0.00
Cost for Sound Isolation($0 - $2.67)	2.67
Cost for Impact Isolation (not required – single story)	0.00
Total Increased Cost	4.67
Cost for Classrooms only	
Base Building Cost for New Classroom	130.00
Increased Cost to Meet ANSI Standard S12.60	4.67
Total Cost	134.67

f. Based on the above calculations, this would be a 3.6 % increase in construction cost for the Minnesota classroom. There may be additional costs, as outlined under section XV of this study.

E. ***City Cost Adjust Example***:

1. For example, from Table 11 you can see that the cost for a single story new school for a project located in Minneapolis, Minnesota would be $4.67 per square foot.

2. To determine what this cost would be for other locations in the United States, the follow cost multipliers would be obtained for the 2004 Means Cost Estimating Guide:

   a. City multipliers for regional cost differences.

City and State	Cost Multiplier
Minneapolis, MN	1.13
New York City, NY	1.34
Biloxi, MS	0.78
Phoenix, AZ	0.87

3. Cost Calculations

   a. New York City, NY $4.67 x (1.34/1.13) = $5.54/Square Foot
   b. Biloxi, MS $4.67 x (0.78/1.13) = $3.22/Square Foot
   c. Phoenix, AZ $4.67 x (0.87/1.13) = $3.60/Square Foot

4. School Cost Example showing high end of spectrum: Assume a 450,000 sq. ft. High school in Minnesota with a 2 story classroom wing. Classroom area totaling 55% of floor area equaling 247,500 sq ft of classrooms, 70% of classrooms are exterior, 50% of classrooms are second floor.

Item	Sq. Ft.	Cost/Sq. Ft.	Total Cost
HVAC Noise Reduction	247,500	$13.42	$3,321,450
Exterior Noise Reduction	173,250	$0.40	$69,300
RT Reduction	247,500	$0.70	$173,250
Sound Isolation	247,500	$2.67	$660,825
Impact Isolation	123,750	$6.00	$742,500
		Total	$4,967,325

Cost for city (Minneapolis) $4,967,325
Adjust for city (Phoenix) $4,967,325 x (0.87/1.13) = $3,824,400

XV. MISCELLANEOUS COST Note: None of these costs were factored into the case studies

A. *Low Velocity Duct Design*: To design the ventilation system at a maximum velocity of 800 feet per minute may require the designer to add height to the building to accommodate larger ductwork. Each additional block course (8 inches) in height that is added to the building can increase the cost of the building by $6.07 per square foot.

1. An example would be as follows: To increase the building height from 14 feet 6 inches by two block courses (1 foot, 4 inches) would increase the building cost by $12.14 per square foot.

B. ***Design Fees***: With the increase in building costs, the professional design fees would rise proportionally if the costs are included in the building budget estimates. As may often be the case, the estimates would not include the extra costs and the project would bid higher than the estimated budget. This would cause the building team to explore value engineered cost reductions to bring the project back into budget. This value engineering could compromise the acoustics and also cost the design professional billing hours. There will also be a design cost associated with meeting the Standard. Additional meetings and coordination between design disciplines, as well as construction supervision and testing at commissioning will be necessary to ensure that the requirements are met.

1. Although the costs outlined above are very difficult to quantify, we believe that there would be few who would deny that they are real costs. They could vary hugely from project to project, but it seems prudent to include some notion of what these costs might be. Based on the above discussion, an additional $2/square foot for each classroom space could be a reasonable number to assign to those costs. This may be high for some projects and low for others, but assigning such a number at least is helpful in identifying a ballpark figure for design and design assurance costs

2. *Special Acoustical Inspection*: To ensure that acoustical treatments have been installed properly, the design professional would need to inspect wall and floor/roof joints, sleeving and sealing around piping and conduits to verify that noise separation integrity was maintained. Cost could be between $0.05 to $0.20 per square foot of classrooms.

B. Operating Costs: Some upgrades would cause an increase in operating costs due to higher static pressure which would increase the motor horsepower. Assume a one horsepower increase for a fan operating 16 hours a day, 5 days a week, 52 weeks a year. At $0.06 per KWH the cost would equate to approximately $250.00 per year per horsepower. In retrospect, increasing duct sizes to maintain a maximum duct velocity of 599 feet per minute could off-set some acoustical treatment static pressure changes.

C. Design Assurance:

1. If under a mandate to achieve the performance standards of ANSI S12.60 the prudent acoustical, architectural, or engineering professionals will want to ensure that the costs are borne by the client in the original building cost, rather than by themselves, which might be the case if the completed building does not meet the Standard. Thus, an extra measure of design assurance, which might be called over design, is likely. How much of an issue this might be is extremely difficult to quantify. Thus, we have provided a discussion of each of the four acoustical issues with which the Standard deals.

2. Room Acoustics: All but one of the 54 classrooms that we studied met the Reverberation Time (RT) requirement of 0.6 seconds. Thus, it seems clear that most permanent construction materials for classrooms will meet the Standard, assuming that ACT ceilings are used. This is due in part to the extra absorbing materials typically found in the classroom, such as books, bulletin boards, chairs, etc. Still, it is quite possible that acousticians and architects will tend to use premium ACT just to make sure, so there may be costs of $0.50 - $1.00/square foot additional for classrooms, even though this would not be required by the Standard.

3. Sound Isolation:

   a. A wide variety of partition types have been tested, so there would not seem to be a great likelihood for over design for this building element. However, most of the failures in sound isolation between spaces come about as a result of inadequate workmanship in sealing up penetrations, cracks, and junctions between the partition and the deck, so close construction supervision will be mandated.

   b. Another issue is that 8" concrete block is quite commonly used as a construction material for partitions between classrooms. While a properly sealed 8" CMU wall will almost certainly pass the NIC 45 field test, it does not meet the Design STC 50 value that is required by the Standard. Most sources list sealed standard weight 8" CMU as STC 49, therefore sand, grout, or other fill material would have to be added to meet the design value of STC 50.

   c. All classrooms we studied met the field standard for exterior sound isolation except the classroom located next to the airport. Possible issues in northern climates would tend to be about whether or not to use laminated glass as one of the panes in an insulated window. This may have farther reaching implications than just for classroom windows. Since the laminated glass has a slightly different exterior appearance, architects may opt to use the laminated glass on an entire façade, rather than just on the classrooms.

4. HVAC Noise:

   a. This is probably the area where the most extra money would be spent to ensure compliance with the Standard. Larger capacity equipment costing more money may be specified to ensure slower, quieter equipment operation. However, larger capacity equipment may increase operating costs and adversely affect dehumidification operations in addition to increased up front costs. To reduce operating cost, duct layouts should be scrutinized particularly carefully to ensure the smooth flow of air.

b. In cases where there are Roof Top Units (RTUs) over a metal deck system, it would be best to place these units on concrete pads. This would absolutely be required in some instances, for example when the units are adjacent to, or even over a classroom. In other cases the units may be more remote, but as a designer, it would be a temptation to place even remote units on concrete pads to make sure that there would be no vibration issues.

5. Impact Isolation: While the floating floors required for impact isolation are a large additional cost for multi story schools, it seems likely that the costs will be quite predictable. That is, over-designing by putting floating floors where they are not needed seems unlikely. Therefore, over-design in this area is probably not an issue.

XVI. VALIDATION OF ASSUMPTIONS FOR CASE STUDY 3.4 (Equipment Type 4, Renovated – Single Story Building)

A. Summary

1. For this portion of the study, in one classroom (Room D117) we actually implemented our recommendations from the first part of the study. This was done to determine if the recommended modifications actually reduced noise to the extent that we had predicted. A work plan and budget were prepared, and we performed acoustical testing and air flow testing at each phase of the work. Although we came reasonably close, we did not succeed in reducing the noise levels to ANSI S12.60 standards, due to low ceiling height and other space restrictions.

B. Introduction

1. The purpose of this portion of the study was to verify that the modifications that we proposed for the earlier phase would be effective in reaching an ambient noise level of 35 dBA at 1 meter from the loudest noise source in the classroom. In the earlier phase, we proposed modifications to the HVAC systems and estimated the costs for the modifications that would be required to reach 35 dBA.

2. In this phase we modified the HVAC system in a similar way that we had proposed, proceeding in the same stepped manner that we had proposed in the first phase. The modifications proposed to the systems were as follows:

C. Validation Original Recommendations

1. Recommendations from the original study to meet the 35 dBA standard by the following measures Room D117 is a 1,060 square foot science room:

    a. Room D117 needs VAV boxes moved and soffits extended to provide sound attenuators in supply and return ducts (58 to 40 dBA)

    b. Ducted HVAC noise from the rooftop units was significant. Add duct silencers at each RTU just downstream of the fan. Since the rooftop ducts were double wall ducts, they could have been perforated for the first 20' downstream of the duct silencers, along with 5' of duct at every drop to the individual rooms (40 to 35 dBA)

D. Validation Planned Changes

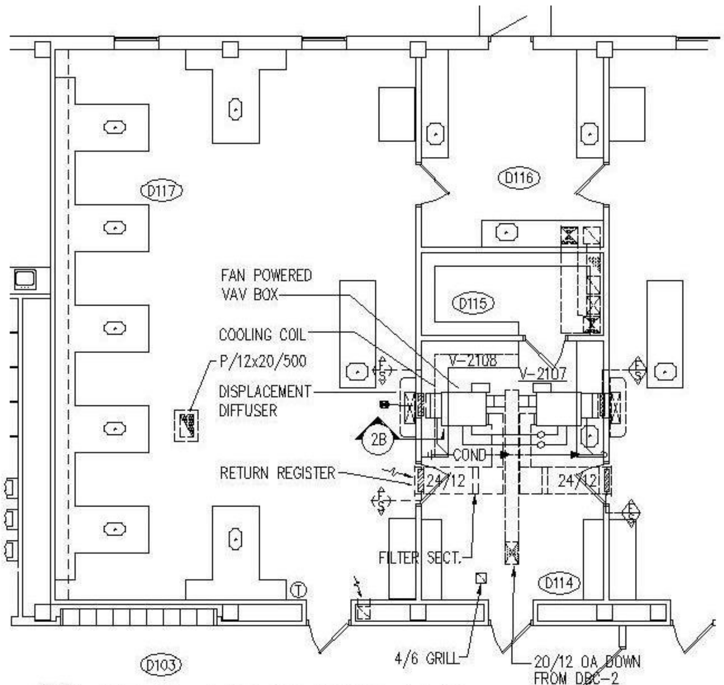
1. Changes were planned in steps, with testing between each step as follows.

    a. Increase VAV Box speed.
    b. Relocate fan powered VAV box and add attenuators in supply and return ducts.
    c. Replace power roof ventilators.
    d. Replace a portion of rooftop unit ductwork.

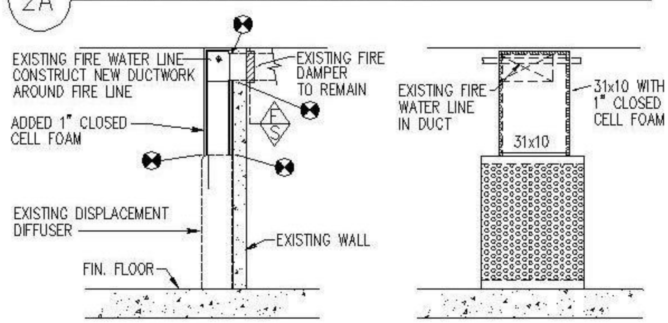
2. Total contractor cost was quoted at $30,435, while testing and design time estimate was $12,975. Total planned cost was $40.93 per square foot.

E. Actual Validation Modifications Performed

1. The chosen room (D117) was a science room with a displacement ventilation diffuser, a fan powered VAV box in an adjacent room with a remote rooftop DBC ventilation air handler and a separate roof mounted exhaust fan. The displacement diffuser was fed from a fan powered VAV box that was 3 feet away from the drop to the diffuser. Between the VAV box and the duct drop is a duct mounted cooling coil and a motorized fire/smoke damper. The duct drop had a restrictive angle cut-off at a 45 degrees to avoid a sprinkler pipe. The fan powered VAV box was sized for 1200 CFM and is located in an adjacent storage/prep room with a second box that feeds another science room. The building has a roof structure that is about 11 feet above the floor, which causes a height restriction for mechanical installation.



2A FLOOR PLAN OF ROOM D117



2B SECTION THROUGH DISPLACEMENT DIFFUSER

2. The noise level as measured at the beginning of the study was 59.5 dBA at 1 meter from the loudest noise source (displacement diffuser) and a design air flow of 1200 CFM. During the testing process, additional steps were taken compared to the original recommendations to allow for more data collection and analysis of each corrective action implemented. Some re-evaluation occurred to address new noise sources that were masked by higher noise levels. The following modifications were incorporated into the system with the acoustical results as noted in the table below:

Table 12 (Modifications Performed for Room D117)

Step	Description	dBA	Note
1	Sound level with air flow at design	59.5	
2	With VAV box off, exhaust fan received sound attenuator Exhaust fan operating only, to determine exhaust fans noise contribution to room.	35.4 **	
3	Changed duct drop in classroom to displacement diffuser, added 1" closed cell foam liner to a new duct drop and reconfigured the elbow to incorporate the pipe.	55.4	
4	The fan powered VAV box was rotated 90 degrees and moved away from the diffuser, elbow attenuators were added on supply and return ducts and closed cell foam duct liner was added to the ducts.	41.8	A
5	1 1/2" of mineral wool was added to solid portions of displacement diffuser	39.2 *	B
6	Return grille was replaced with a large free area style grille and 1 1/2" mineral wool was added to the supply attenuator	38.9 *	
7	Additional area of supply duct received 1 1/2" mineral wool liner	36.7 *	C
8	Added side air flow nosing to reduce duct turbulence at flat surfaces. Questioned accuracy of air flow readings	38.2 *	D
9	Attempt to reach 35 dBA, Fan powered VAV box was replaced with a larger model to increase air flow and potentially reduce noise, more accurate air flow reading was taken (traversed supply duct drop with a balancer) and VAV box calibration indicated air flow at 1,187 CFM	39.6	E
10	At this point the design is at a physical end point at which practical attenuating means and methods have been utilized. Space constraints and effects on adjacent classroom systems do not allow continued study. More radical approaches may reduce noise to the space, but are not deemed acceptable for the spaces (classroom) involved		

Note A Due to sound attenuation added to duct, noise from rooftop DBC unit was no longer a factor. Re-evaluated noise sources. Revised modification list.

Note B Discovered noise emanating from return grille and supply register.

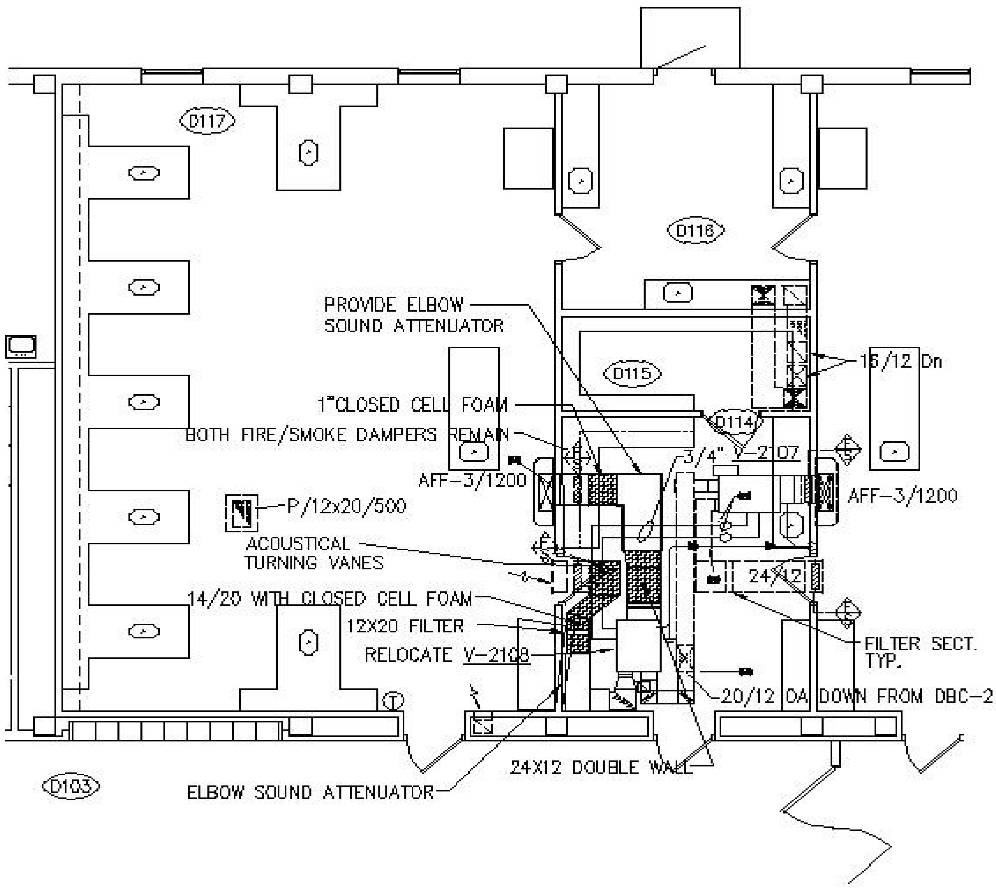
Note C Discovered the supply attenuator was installed backwards

Note D Added side deflector nosing at inlet to supply attenuator.

Note E Verified air flow with larger box, Calibrated box CFM readings with Balancer.

* Airflow: Could not reach design airflow. Static pressure drop exceeded fan powered VAV Box capacity.

**(The exhaust fan was tested independently of the VAV box to allow for evaluation of noise reduction effectiveness from a separate noise source.)



3 UNIT 'D' PLAN RELOCATE UNIT & NEW DUCTWORK

3. In approaching the validation portion of the study, we broke the attenuation attempts down to smaller pieces to allow for more data to be collected. In all, we made 12 trips to the site, trying to tweak the system to reach 35 dBA. Changing the diffuser duct drop gained 4 points, while moving the VAV box and adding attenuators gained 14 additional points. After the initial 18+ point drop from 59.5 to 41.8 dBA the amount of attenuation gained for each change became more difficult. New noise sources were identified (return diffuser, exhaust fan) as louder sources were quieted. Additional corrections were implemented to reach 36.7 dBA but the airflow was found to be below acceptable quantity. A larger fan powered VAV box was provided and airflow was verified at design (1189 CFM) with a 39.6 dBA reading. At this point, we had reached a dead-end, and the practical limits of attenuation for the physical constraints at this test location prohibit achieving the target noise criteria of 35 dBA.

4. Problems encountered:

    a. The Fan powered VAV box was located too close to the diffuser.

    b. The structure is low, thus limiting the mechanical system installation.

    c. The room where the VAV box is located was cramped, thus limiting the options for attenuating the mechanical system.

5. Actual costs: During the process of arranging the corrective work the decision was made to break the changes into as many steps as possible to gain more insight into which changes gave the most noise reduction. In doing so the negotiated price with the contractor was updated as new approaches were identified and others were eliminated. Some labor was performed by the contractor, while other was performed by the testing agents. The contractor costs wound up reduced from the planned cost, while the design and testing costs were more. Total actual cost stayed within the original planned cost of $40.93 per square foot while reducing the noise level from 58 dBA to 39.6 dBA

F. Lessons Learned

1. When dealing with noise issues, the design professionals must take a calculated approach in analyzing the noise sources and the amount of correction required. When multiple sources are encountered, each source must be studied both separately and cumulatively to determine the best course of action.

2. Many unforeseen and unpredictable obstacles often occur during the installation process that can and do affect the acoustical performance of the system. A generous safety factor (5 dB) should be used to assure that the target noise level is met. Our original safety factor of 3 dB was not sufficient.

3. Relatively small fans (in fan powered VAV boxes, fan coil units, etc.), can produce relatively high noise levels (59 dBA) when placed near the classrooms they serve. When space constraints limit the options to attenuate these noise sources, there is very little chance to achieve such a low (35 dBA) noise level. This is further complicated by the capacity and noise limits of the fan powered equipment available and the physical size and attenuating capabilities of the sound attenuators available.

4. When analyzing sound data the designer should use octave band data and calculate the attenuation in the system for his project to determine the actual performance of the system.

5. The total cost to bring a classroom up to compliance after construction can be in the $30/SF to $50/SF range as compared to $4.35/SF to $20.32/SF during the design phase Thus, the cost to reduce sound levels in a problem School with 247,500 Sq Ft of classroom at $30/Sq Ft to $50/Sq Ft could equal $7,000,000 to $12,000,000.

6. The practical implications for this study include the following:

    a. Costs could be significantly higher than planned. Even after spending large amounts of time and resources trying to bring our retrofitted classroom to a mechanical noise level of 35 dBA, we were ultimately unsuccessful. It is difficult to say how much more we might have spent to reach the 35 dBA level, since in our case, the physical limitations of the building (particularly floor-to-floor height) made it virtually impossible to reach the 35 dBA level.

    b. Start with a very conservative design, particularly for retrofit situations, but also for new construction. More intense study and modeling of noise and attenuation throughout the design process is essential. All noise sources must be considered and analyzed, even small fan powered equipment.

c. While it is not uncommon to design and reach 35 dBA in a few spaces in a school building (e.g. the Auditorium, or remote learning spaces) these low noise spaces may often be achieved at the expense of the other spaces. That is, higher static pressure, larger duct sizes, greater distance from the HVAC units, etc. can be reasonably accommodated for a few spaces, but it is very difficult to achieve these low noise levels consistently when space constraints or equipment configurations or locations are problematic.

d. For retrofit projects, it is recommended that you at least triple the amount of design time you think you will expend to reach 35 dBA. Space constraints and existing conditions can limit available design options, thus forcing compromises that can limit the designers' ability to achieve 35 dBA throughout the building.

e. For new construction, plan for a considerable cost contingency for fine tuning the systems once they are built. Buildings are unique entities that may have similar designs, but are often custom built and rarely have identical characteristics. Things have a way of going wrong during the construction process, and if you have a school with 30 or 40 classrooms, it is certain that a few of them will require additional work and commissioning to reach the 35 dBA level. It will need to be established at the beginning of the design process/contract negotiations as to who would pay for this, because it could be a considerable expense.

XVII. APPENDIX

A. Glossary Of Terminology

A.F.F.	Above Finished Floor
ACT	Acoustical Tile
AHU	Air Handling Unit
ANSI	American National Standards Institute
ASA	Acoustical Society of America
AUX CL RM	Auxiliary Classroom
cfm or CFM	Cubic Feet/Minute
CMU	Concrete Masonry Unit
dBA	Decibels - A weighted scale
dBC	Decibels - C weighted scale
DBC	Desiccant Based Cooling
DER	Dedicated Energy Recovery Unit
DIFF	Diffuser
DIST	Distance
DTL	Detail
DX	Direct Expansion
ERU	Energy Recovery Unit
EXH REG	Exhaust Register
FC	Forward Curved
ft^3	Cubic Feet
GYP	Gypsum Board
HP	Horsepower
HVAC	Heating Ventilating Air Conditioning
Hz	Hertz
LAG	Cover duct with two layers of gypsum board
NC	Noise Criteria
PNC	Preferred Noise Criteria
PRV	Power Roof Ventilator
RA or R.A.	Return Air
RC	Room Criteria
RET DIFF	Return Diffuser
RM	Room
RT Test	Reverberation Test
RTU	Rooftop Unit
SA	Supply Air
SF	Square Feet
SF/dB	Square Foot per Decibel (dBA)
PWL	Sound Power Level
SPLS	Sound Power Levels
SUP DIFF	Supply Diffuser
T.A. Duct	Transfer Air Duct
T12	1-Inch Diameter Fluorescent Lamp (Magnetic Ballast)
T8	5/8-Inch Diameter Fluorescent Lamp (Electronic Ballast)
TRAN GRL	Transfer Grille
TYP	Typical
UV	Unit Ventilator
VAV	Variable Air Volume Terminal
VCT	Vinyl Composition Tile
VFD	Variable Frequency Drive
WK	Work

B. Team Credentials

1. Study Team

    a. Project Manager – James Lange, P. E.
    b. Architectural Lead – Rod Erickson, FCSI/CCSI/CDT
    c. Mechanical Lead – Gary Grenzer
    d. Electrical Lead – Gaylen Melby, P. E.
    e. Acoustical Consultant – Project Manager: Steve Kvernstoen
    f. Acoustical Consultant – Technical Support: Sari Rönnholm, DMA and Katerina Bergeron, PhD

2. James Lange, P. E. is a Partner (Director of Mechanical Engineering) for Armstrong, Torseth, Skold & Rydeen, Inc. (ATS&R), Minneapolis, Minnesota.

3. Gaylen Melby, P.E. is a Partner (Director of Electrical Engineering) for Armstrong, Torseth, Skold & Rydeen, Inc. (ATS&R), Minneapolis, Minnesota.

4. Gary Grenzer is a senior mechanical designer for Armstrong, Torseth, Skold & Rydeen, Inc. (ATS&R), Minneapolis, Minnesota.

5. Rodney Erickson, FCSI/CCSI/CDT is a Partner (Specifications) for Armstrong, Torseth, Skold & Rydeen, Inc. (ATS&R), Minneapolis, Minnesota.

6. Steve Kvernstoen, principal, heads the Acoustics Design Group for Kvernstoen, Rönnholm & Associates, Minneapolis, Minnesota.

7. Katerina Bergeron, PhD is a consultant in Architectural Acoustics for Kvernstoen, Rönnholm & Associates, Minneapolis, Minnesota.

8. Sari Rönnholm, D.M.A is a consultant in Architectural Acoustics for Kvernstoen, Rönnholm & Associates, Minneapolis, Minnesota.