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Case Studies Illustrating Acoustic Design Guidelines for HVAC Systems in Schools

Robert M. Lilkendey, Siebein Associates, Inc. 625 NW 60th Street, Suite C, Gainesville, Florida 32607, rlilkendey@siebeinacoustic.com

Gary W. Siebein and Courtney McGinnes, School of Architecture, P.O. Box 115702, University of Florida 32611-5702

1. INTRODUCTION

The controlling of noise produced by heating, ventilating and air-conditioning (HVAC) systems is essential to the quality of the listening environment in classrooms. The American National Standards Institute (ANSI) Standard S12.60-2002 – *Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools*, hereafter referred to as "the Standard," documents performance criteria for acceptable background noise levels in classrooms. The Standard calls for a maximum background sound level of 35 dBA for classrooms that are less than or equal to 20,000 cubic feet in volume, and 40 dBA for classrooms that are greater than 20,000 cubic feet in volume[1]. These background noise levels are much lower than most designers have previously considered and what has been published in the literature[2]. Careful attention to the design, selection, and detailing of HVAC systems in schools is required to achieve these levels.

There is an abundance of information in the form of books, journal articles, and professional society publications that designers can reference for guidelines and recommendations to control HVAC noise[2-6]. ANSI Standard S12.60-2002 also includes general guidelines and references for HVAC noise control specific to classrooms. These sources contain a wealth of information and detail related to all aspects of HVAC systems noise control. This paper is not intended to reproduce what has already been written, but rather to focus the design communities' attention on the key acoustical issues related to the design of HVAC systems for K-12 school classrooms. This paper will call upon experience by the authors in designing HVAC systems for over 70 K-12 school projects, designing over 250 HVAC systems with similar design criteria, and recommendations commonly found in the literature, to present eight design guidelines that must be addressed in the design of HVAC systems to achieve conformance with the Standard. It will begin with a review of the five sources of noise in HVAC systems, and conclude with a review of seven case studies of HVAC systems used in schools that demonstrate the need to follow the proposed guidelines.

2. SOURCES OF NOISE IN HVAC SYSTEMS

There are five primary sources of noise from HVAC systems. These sources are present in all HVAC systems, and are common problems among HVAC systems in schools. They are:

1. ***Airborne noise***. Airborne noise is the noise radiated from equipment such as air handling units, fan coil units, heat pumps, through-the-wall heat pumps, etc., that is transmitted through the air and directly through walls, windows, doors or ceilings into adjoining spaces.
2. ***Self-generated noise.*** Self-generated noise, or velocity-generated noise, is produced as air moves through a confined duct system. Noise is generated at points of turbulence such as dampers, diffusers, elbows, and T-fittings, among others, in the ducted air system. Self-generated noise levels increase with velocity and the number of turbulent air points within the system.
3. ***Duct-borne noise.*** Duct-borne noise is produced primarily by the fans in the air handling units that travels though the ducts into rooms. Noise can travel through the supply ducts, the return ducts, the ventilation ducts or the exhaust ducts. Rooms closer to the units usually have higher duct borne sound levels than rooms that are farther from the units.
4. ***Structure-borne noise.*** Structure-borne noise results from vibrations of rotating or vibrating equipment such as fans and chillers that vibrate a part of the building such as a floor slab or

structural frame. The vibration is transmitted through the building structure sometimes over great distances where it vibrates a lighter weight assembly or material such as a ceiling grid or piece of gypsum board that re-radiated the sound into a space.

5. ***Break-out noise.*** There are two types of duct break-out noise. The first is noise generated by high speed or turbulent air in ducts that can cause the duct walls to vibrate and radiate low frequency noise, often called "oil-canning." The second is low frequency noise from a remote source such as the fan in an air handling unit that is transmitted down the duct path, through the duct walls, and into a space. This type of noise is typically perceived as "rumble."

3. DESIGN GUIDELINES FOR HVAC SYSTEMS IN SCHOOLS

All five of the noise sources listed in the preceding section must be controlled to achieve the background noise requirements in the Standard. Eight guidelines are presented for designing mechanical systems in schools to address these noise sources and achieve conformance with the Standard. Most of the guidelines are neither too elaborate nor too expensive to include in a school project and are part of the general knowledge within the field of architecture and building construction, so new technology and expensive, uniquely designed items are not required to implement them. Common sense, pre-planning, and a knowledge of basic principles that can be applied to each individual school project are required of those on the school design, construction and planning team.

1. ***Coordinate mechanical equipment selection with space planning.*** The four HVAC system types serving most classrooms are (a) self-contained, wall mounted air conditioning units; (b) decentralized fan coil units and heat pumps with short duct runs; (c) central rooftop units serving multiple rooms; and (d) central air handling systems with variable air volume controls. Of the four types, only self-contained, wall mounted air conditioning units can not be used in their present form without major noise mitigation design, as it is not possible to achieve the 35 dBA requirement in ANSI Standard S12.60-2000 with this type of unit. The remaining three can be used if all of the other guidelines presented are followed and the equipment rooms/closets housing the units are properly located and constructed. This requires coordination between the mechanical engineer (system selection), architect (space planning), and acoustical consultant (enclosure construction requirements). If located adjacent to a classroom, decentralized fan coil units and heat pumps should be fully enclosed by walls of relatively high mass, and the door to the equipment room should open to a corridor or other non-critical space. Central rooftop units serving multiple rooms should be located over non-critical spaces and an adequate distance from the rooms they serve. Central systems with variable air volume controls should be installed in mechanical rooms that are separated from classrooms by buffer spaces such as closets or bathrooms, have walls constructed of adequate mass, and are separated by enough distance from the classroom to develop adequate duct length. VAV terminal units should be located over corridors, not classrooms.

2. ***Construct the mechanical room/closet enclosure of sufficient mass to isolate the Unit radiated noise from the classrooms.*** Provide massive wall constructions such as CMU or multi-layered gypsum board on each side of single or double studs around mechanical rooms/closets. An acoustical consultant can determine the appropriate construction based on the sound level of the equipment, the transmission loss characteristics of various wall types, the sound absorbing characteristics of the receiving room, and the background noise criteria in the Standard. Enclosure walls must be extended up to the slab above and sealed with caulk. All penetrations through the enclosure must be sleeved and sealed. Routing ducts directly into the adjacent ceiling space over a classroom should be avoided. If possible, route ducts over corridors, storage rooms, bathrooms, or other non-critical spaces before penetrating the envelope of the classroom. Gasketed or STC rated doors to the mechanical room/closet should be installed as required. Doors to the mechanical room/closets should open into corridors or other non-sensitive areas rather than directly into the classroom. For equipment on upper level slabs, thick concrete floors, possibly with floating concrete slabs or resiliently suspended gypsum board ceilings below will have to be considered.

3. ***Follow the guidelines in the literature related to air velocities, air flow, and air balancing for quiet mechanical systems.*** Larger ducts that allow slower air velocities and a duct system

designed to meet ASHRAE and SMACNA guidelines for smooth air flow are required to meet the 35 dBA background noise limit. Reference the literature for in-depth discussions of air movement related noise issues[1,3,5]. In general, the following should be considered:

A. Size ducts not to exceed the air velocities, in feet per minute, given in Table 1, within +/- 50 fpm. Where ducts must be deeper than the ceiling cavity allows to meet the velocities in the table, create soffits to contain the ducts or run multiple ducts of smaller dimension if possible.
B. Use smooth transitions such as radiused or bellmouth fittings at branch takeoffs.
C. Use radiused elbows or square elbows with turning vanes.
D. Install flex duct without kinks or harsh bends.
E. Install volume dampers a minimum of three duct diameters upstream of air terminal devices or design a self-balancing duct system. Avoid opposed blade dampers on air terminal devices if possible.
F. Select air terminal devices with NC ratings of 18 or less.

4. ***Provide a ducted return.*** The return air must be ducted back to the Unit. Open ceiling plenums, open grilles from adjacent closet mechanical rooms, or very short duct runs do not provide sufficient attenuation of fan noise to meet the Standard.

5. ***Install duct-borne noise control devices as required.*** Sound levels from most air moving equipment, if routed through unlined sheetmetal ducts without additional noise control devices, will not meet the Standard. Some combination of glass fiber duct liner, sound attenuators, sound plenums, and acoustical flex duct will be required to achieve conformance with the Standard. The additional system static pressure resulting from the use of these devices can be significant and must be considered in the design of the fan. An acoustical consultant can specify the proper quantity and location of such devices based on an analysis of the sound levels of the equipment, location of the equipment, and the length of duct between the equipment and the classroom.

6. ***Control duct break out noise.*** Break-out noise can be avoided by maintaining proper air velocities and limiting turbulent airflow, and by reducing the sound levels of remote sources through the use of silencers and other noise control devices. Break-out noise can be a problem when fan coil units and/or heat pumps are located adjacent to the classrooms they are serving, or the main duct from an air handling unit serving multiple classrooms is routed over a classroom adjacent to the equipment room. If break-out noise cannot be controlled through reduced air velocities or reduced fan noise, other solutions may include re-routing the offending duct over less noise sensitive areas, lagging the duct with a mass loaded vinyl wrap, or enclosing the duct in a gypsum board soffit.

7. ***Vibration Isolation of HVAC equipment.*** Install vibration isolation devices as recommended in the latest edition of the ASHRAE HVAC Applications Handbook's chapter on noise and vibration control.

8. ***Monitor the value engineering and construction process.*** During the Value Engineering process, of which cost reduction is typically the primary focus, items such as duct liner and sound attenuators are often perceived as luxury acoustical items or "acoustical adds" rather than as integral parts of a standard system design necessary to achieve 35 dBA of background noise in a classroom, and attempts are made to delete these items. During the construction process, walls are often not extended to the deck and penetrations are not always sealed as a result of a contractor's interpretation of what is and is not necessary. Both these processes must be monitored to ensure that the integrity and intent of the design is maintained.

4. CASE STUDIES OF HVAC SYSTEM DESIGNS IN SCHOOLS

The following case studies of actual school projects are used to illustrate how the design guidelines presented can be applied to classrooms to meet the acoustical design criteria in the new ANSI standard on classroom acoustics. Several instances of design approaches that fail to meet the standard are also presented along with potential methods to remedy the situation.

A. Case Study 1: Through-the-wall Heat Pump Units

Case Study 1 actually consists of several classrooms from a number of schools that are served by through the wall heat pump units. The units have a self-contained refrigeration machine that includes a condensing coil that transfers heat to outside air during the cooling mode, a compressor mounted within the unit that compresses the refrigerant, a direct expansion coil where the refrigerant absorbs heat from the classroom air, and a fan to circulate air from the unit to the classroom. The fan must "throw" the air across the classroom from the unit at relatively high velocity. The combination of high velocity air movement and the major noise making devices such as the condenser fan, circulating air fan and compressor located on the classroom wall results in very high noise levels in the classrooms. Noise levels of NC 45 (approximately 50 dBA) to NC 70 (approximately 75 dBA) were measured in classrooms in Florida (Siebein et al, 1999). Under no condition, other than off, was this type of unit capable of achieving a 35 dBA background noise level. Many teachers in the schools surveyed turned off the air-conditioning units when they tried to speak to the class and ran the units when students were out of the classroom at music, art or computers so the noise would not interfere with classroom activities.

B. Case Study 2: Mezzanine Heat Pump System

Case Study 2 consists of an elementary school with classrooms arranged along a central corridor (see Figure 1). The Corridor has a mezzanine with a concrete floor located above the acoustical tile ceiling that runs the entire length of the building. One unitary heat pump for each classroom is located on the mezzanine. This provides individual temperature control for each room independently of the other classrooms. The walls between the classrooms extend to just above the acoustical tile ceiling. There is a large, open attic/plenum space above the classroom ceilings. The heat pumps are water source heat pumps. They dissipate the heat of condensation to a condensing unit located outside the school. There is a fan and a coil in each unit. Return air is brought from the classroom into the unit through a very short return duct. There is a network of supply air outlets spaced evenly throughout the classroom. Noise from the fan travels through the short return duct and is heard at levels of NC 40 to NC 45 (47-52 dBA) in the room. This is combined with casing radiated noise that is produced by the fan located inside the unit. The noise is propagated out of the sheet metal walls of the heat pump into the ceiling plenum, through the acoustical tile ceiling and into the classroom at a sound level almost equivalent to the return air noise. Sound levels propagated through the supply duct are much lower than the return duct and casing radiated noise because of the longer duct run, low air velocities in the supply ducts and small fan sound power level. A background noise level of 35 dBA would likely have been possible if the walls between the heat pumps and the classrooms were of sufficient mass and extended to the roof deck to control the radiated noise, and a greater length of return duct with acoustical lining or a silencer, if necessary, was installed.

C. Case Study 3: Fan Coil Units in Separate Mechanical Rooms

Case Study 3 is a school for profoundly handicapped children. The basic design has a series of buildings consisting of groups of four classrooms arranged around a central corridor. The rooms are air-conditioned by individual fan coil units located in a mechanical room behind each classroom (see Figure 2). The mechanical room walls are constructed of painted concrete block extended to the slab above and sealed with caulk at the perimeter to control airborne noise. The fan coil units are located so there are adequate lengths of ducts running at appropriate air velocities to reduce self-generated noise. There are also sound attenuator, or duct silencers, located in both the supply and return ducts to reduce duct-borne noise to the 35 dBA called for in the Standard.

C. Case Study 4: Primary Air AHUs Plus Fan Coil Units in Closets

Case Study 4 is a two-story school with classrooms lined up on both sides of a double loaded corridor on both the first and second floors (see Figure 3). Fan coil units located in a specially designed closet inside each room are used for heating and cooling purposes only. A primary air AHU (air handling unit), located on the second floor above a classroom with ducts running through the corridor, provides ventilation air for the individual classrooms. An amount of air equal to the ventilation air is exhausted from each room as well.

The primary air AHU has a silencer in the main supply duct serving each wing to reduce duct-borne sound levels. The unit also has external spring isolators to reduce vibration transmitted to the floor slab. The fan coil units are located in a closet in each room. There is a full return duct with a silencer in it that runs vertically from the bottom of each fan coil unit to a return grille in the ceiling. The supply duct moves through a small silencer into a network of ducts serving each classroom. The walls of the fan coil unit closet are constructed of 2 layers of 5/8” gypsum board on each side of 3-5/8” metal studs with 3-1/2” of glass fiber batt in the cavity and sealed at the perimeter with caulk to limit airborne sound transmission into the classrooms. The doors to the closets open into the hallways.

The walls of the Mechanical Room with the primary air AHU are constructed of 8” cmu (concrete masonry unit) with a separate stud wall held off 1” from the cmu wall and consisting of 1 layer of 5/8” gypsum board on 3-1/2” studs with 3-1/2” glass fiber batt in the cavity and sealed at the perimeter with caulk to reduce airborne noise from the air handling unit to the classrooms on either side of the Mechanical Room. The floor of the Mechanical Room consists of a 4" floating concrete floor over the 4" nominal structural slab with a suspended gypsum board ceiling below.

Case Study 5: Central AHU System with Clustered Plan

Case Study 5 is a school with several two-story buildings that have mechanical rooms located at each end of the buildings with classrooms clustered around the mechanical rooms (see Figures 4a and b). Supply and return ducts move from the mechanical rooms to the ceiling space above each floor. The main ducts were run at high air velocities (2,000 to 2,500 feet per minute) above acoustical tile ceilings in the classrooms nearest the mechanical rooms. The only separation between the ducts and the classrooms was the acoustical tile ceiling. Break out noise from the high velocity air moving through the multiple turns in the ducts was measured at NC 45 to NC 55 in the classrooms nearest the Mechanical Rooms. Rooms farther down the duct path were much quieter. The main ducts had to be enlarged to reduce the air velocity and the breakout noise. The ducts could not be enlarged to the extent required to reach 35 dBA, so a lagging was added to the outside of the ducts to reduce the break-out sound levels. A silencer was added in the supply and return ducts to reduce duct-borne sound levels, the branch duct take-offs were moved farther down the duct path to provide more sound attenuation, and additional inlets and outlets were added to reduce velocity noise.

Case Study 6: Central AHU Systems with Mechanical Rooms Separated from Classroom Buildings.

Case study 6 is a two-story school with classrooms lined up on both sides of a double loaded corridor on both floors. The mechanical rooms are located in separate buildings in courtyards between the classroom buildings (see Figure 5). This provides adequate control of airborne sound transmission between the Mechanical Room and adjoining classrooms. The ducts were designed to run in the structural area beneath a bridge that connected the classroom buildings. The ducts were originally sized for air velocities to meet an NC 30 design criteria. However, the floor-to-floor height of the building was reduced in a value engineering effort to reduce construction costs. This left less height in the open space between the first floor ceiling and the bottom of the second floor. This was the space assigned for the main duct runs from the mechanical rooms to the classrooms. The sizes of the main ducts were reduced to fit into the ceiling space beneath the bridges. The air velocity in the ducts increased to over 2,000 feet per minute resulting in break out noise from turbulent air flow inside the ducts. Sound levels in the first classroom were NC 40 as a result.

Case Study 7: AHU in Mechanical Penthouse with VAV Terminal Units Over Classrooms

Case study 7 is a large school in a city near a major interstate highway. The classroom building is three stories tall with a large Mechanical Room in a penthouse on the roof above a third floor classroom. Main ducts are run vertically through a large chase that is separated by a cmu wall from the adjoining classroom. To isolate the airborne noise and vibration associated with the AHU, the floor of the penthouse consists of a floating concrete slab above the structural floor slab and a spring mounted gypsum board ceiling in the classroom below, in addition to the acoustical tile ceiling. Air distribution is through a variable air volume system with VAV boxes located in the ceiling space of each classroom. The VAV boxes were selected to provide radiated noise levels less than NC 30 in the classrooms. At this time, measurements have not been made to confirm that actual levels achieved in the classroom are less than NC 30. Duct-borne noise is reduced by the length of duct between the air handling unit and the classrooms and silencers located in the supply and return ducts.

5. CONCLUSIONS

Designing classrooms with background noise levels that are in conformance with ANSI Standard S12.60-2000 is possible, but it requires a team effort that begins at the earliest stages of design when critical decisions regarding space planning, system selection, and cost allocation are made. Communication among architects, mechanical engineers, structural engineers, and acoustical consultants must take place early in the design process so that an overall design that integrates the HVAC system and the architectural design in such a way as to work in favor of a quiet system design rather than against. Recognition of the primary sources of noise in HVAC system is essential, and how to reduce or avoid these sources should be considered at all times during the design and construction process. The case studies presented demonstrate that if each of the recommended eight design guidelines for HVAC systems in schools are appropriately addressed during the design and construction process, and the detailed recommendations in the literature are followed, the ANSI Standard S12.60-2000 background noise criteria for classrooms can be achieved, and that failure to address even just one of these guidelines can result in non-conformance with the Standard.

REFERENCES

[1] *Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools*, American National Standards Institute ANSI S12.60-2002 (Acoustical Society of America, New York, 2002).

[2] *ASHRAE. 1999 Handbook – Heating, Ventilating, and Air-Conditioning Applications – Chapter 46*, American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., Atlanta, Georgia (1999)

[3] Mark E. Schaffer, *A Practical Guide to Noise and Vibration Control for HVAC Systems*, American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., Atlanta, Georgia (1991)

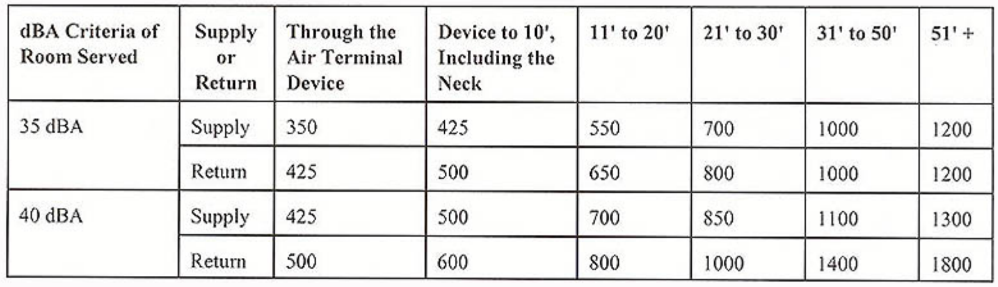
[4] Robert M. Hoover and Warren E. Blazier, Jr., "Noise Control in Heating, Ventilating, and Air-Conditioning Systems," Chapter 42 in *Handbook of Acoustical Measurements and Noise Control, Third Edition*, edited by Cyril M. Harris (Mc-Graw-Hill, Inc., New York, 1999.

[5] *HVAC Systems Duct Design - Third Edition*, Sheet Metal and Air Conditioning Contractors National Association, Chantilly, Virginia (1990)

[6] M. E. Schaffer, "ANSI Standard: Complying with background noise limits," ASHRAE Journal **45**(2), 26-27 (2003)

TABLES AND FIGURES

Table 1. Airflow velocity guidelines for HVAC ducts routed to Classroom Spaces. Values in the Table represent the maximum recommended airflow velocity, in feet per minute (FPM), at a given distance from the terminal device in the space being served by the duct.



dBA Criteria of Room Served	Supply or Return	Through the Air Terminal Device	Device to 10', Including the Neck	11' to 20'	21' to 30'	31' to 50'	51' +
35 dBA	Supply	350	425	550	700	1000	1200
	Return	425	500	650	800	1000	1200
40 dBA	Supply	425	500	700	850	1100	1300
	Return	500	600	800	1000	1400	1800

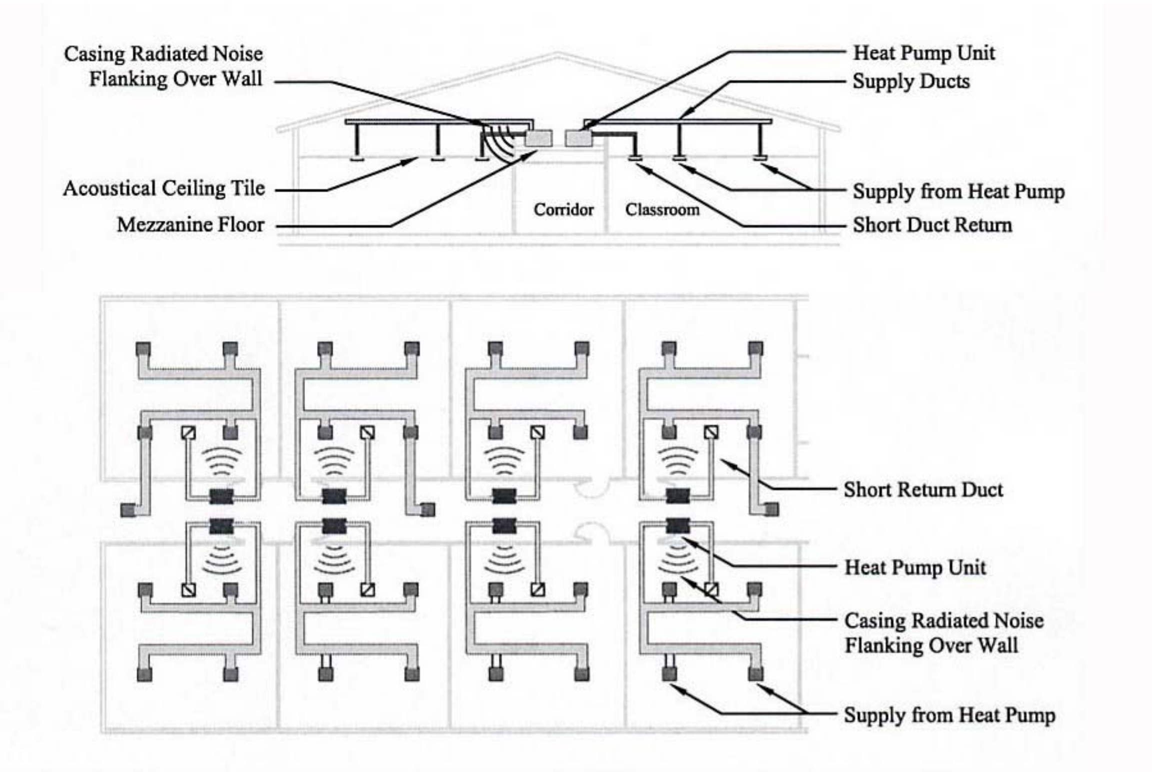


Figure 1. Conceptual section sketch and floor plan of Case Study 2: Mezzanine Heat Pump System.

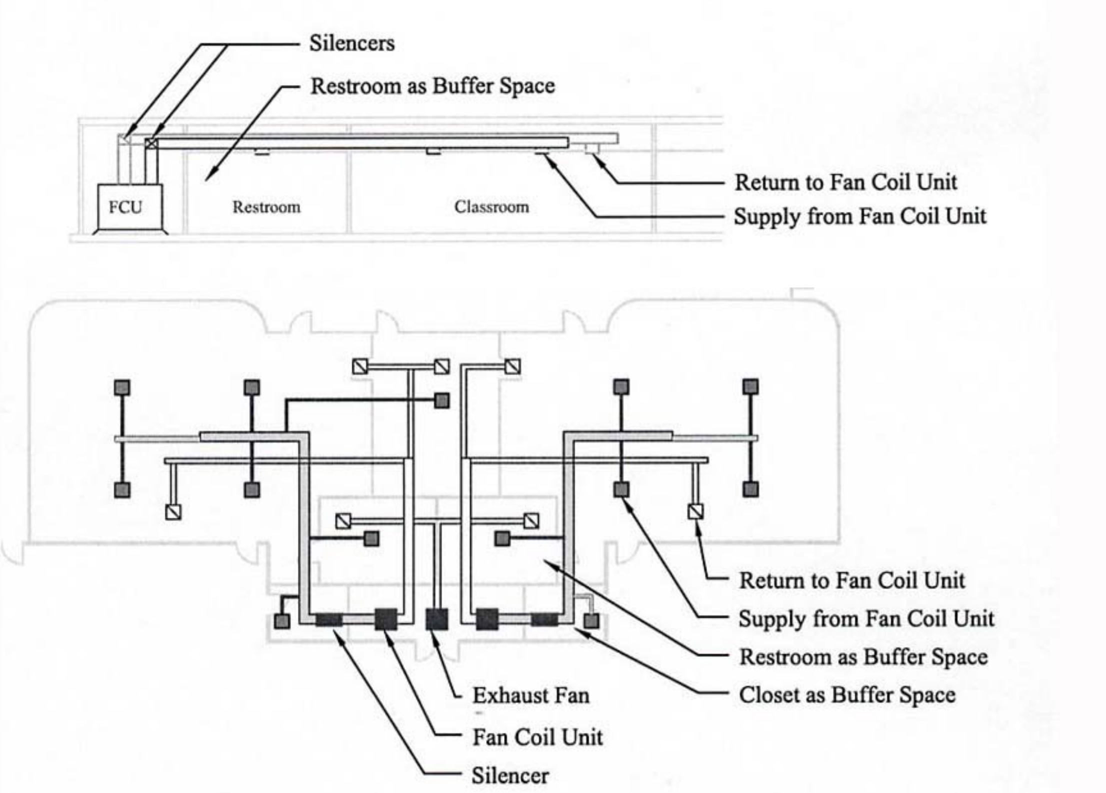


Figure 2. Conceptual section sketch and floor plan illustrating Case Study 3: Fan Coil Units in Separate Mechanical Rooms

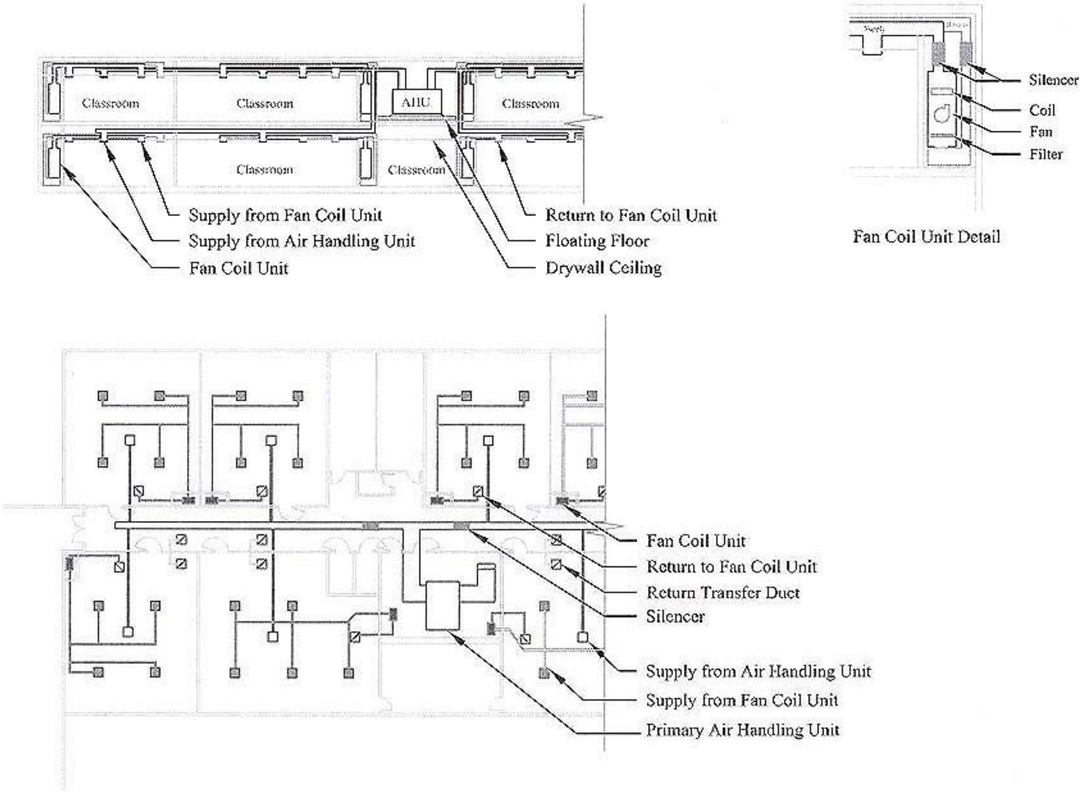


Figure3. Conceptual section sketch, detail and floor plan of Case Study 4: Primary Air AHU Plus Fan Coil Units in Closets

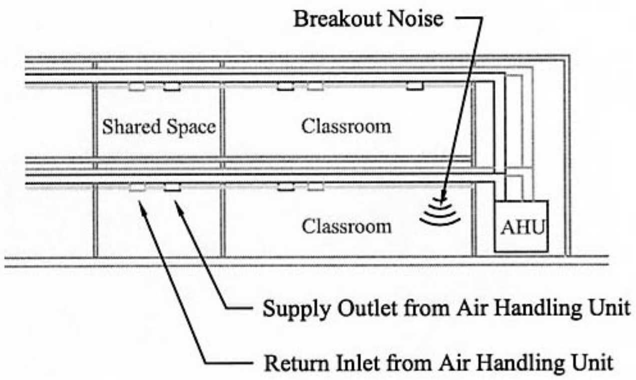


Figure 4a. Conceptual section sketch of Case Study 5: Central AHU Systems with Clustered Plan

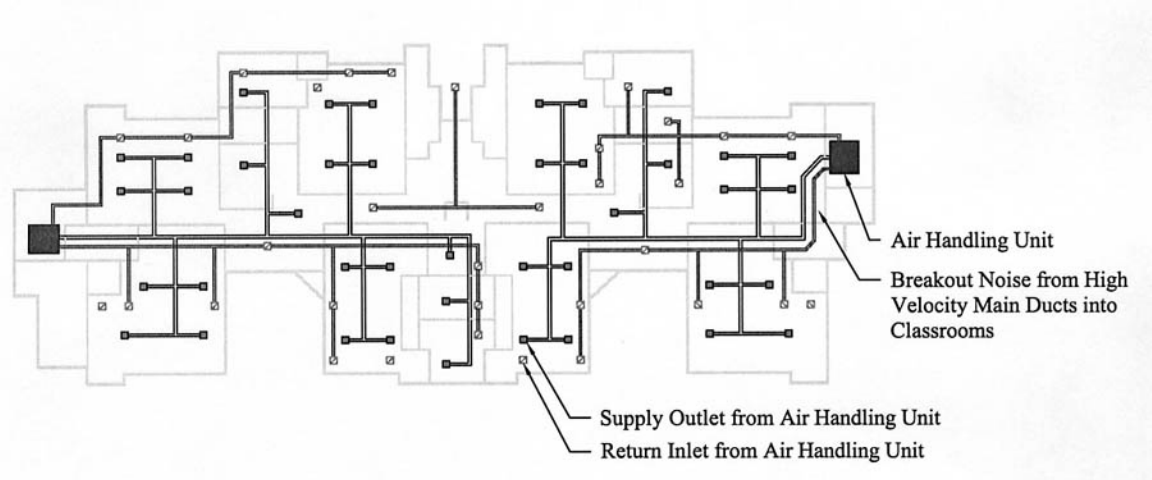


Figure 4b. Conceptual floor plan of Case Study 5: Central AHU Systems with Clustered Plan

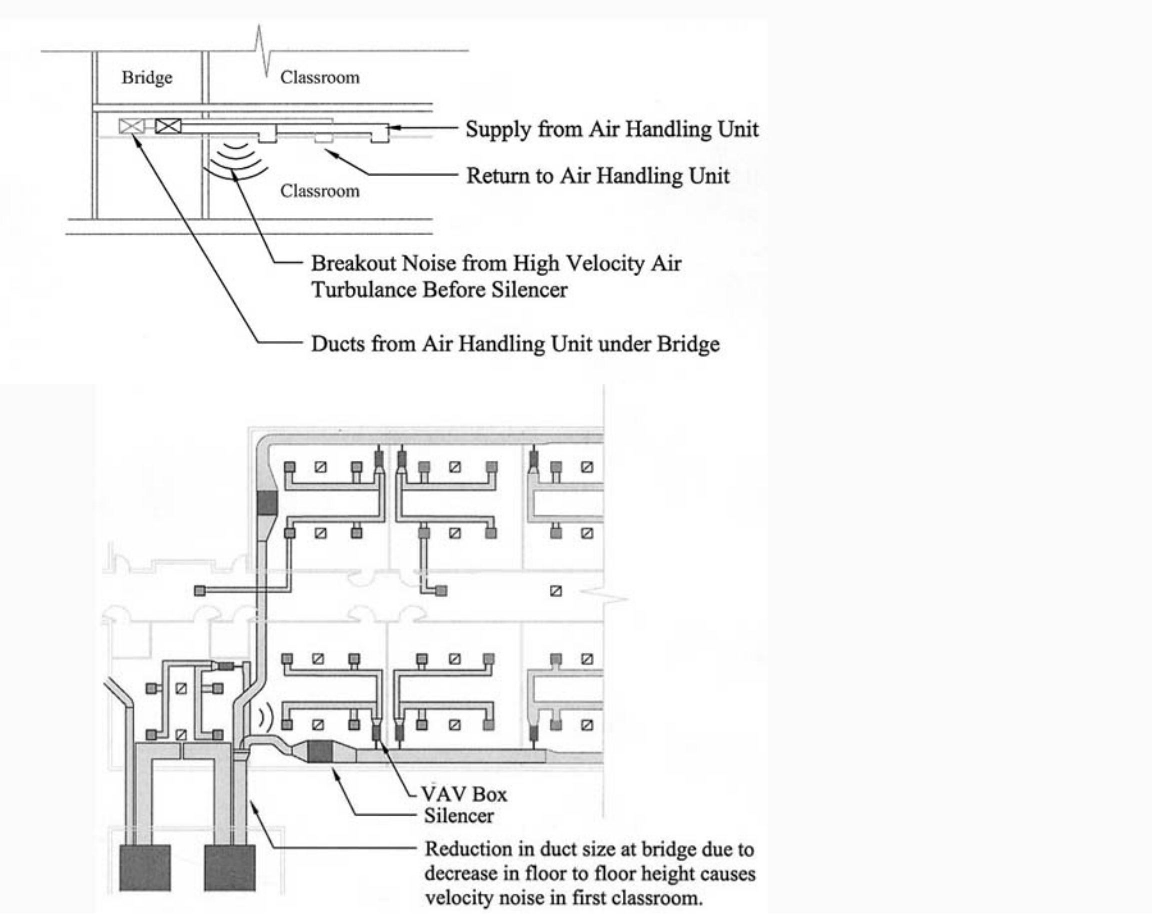


Figure 5. Conceptual section sketch and floor plan of Case Study 6: Central AHU system with Mechanical Rooms Separated from Classroom Buildings.

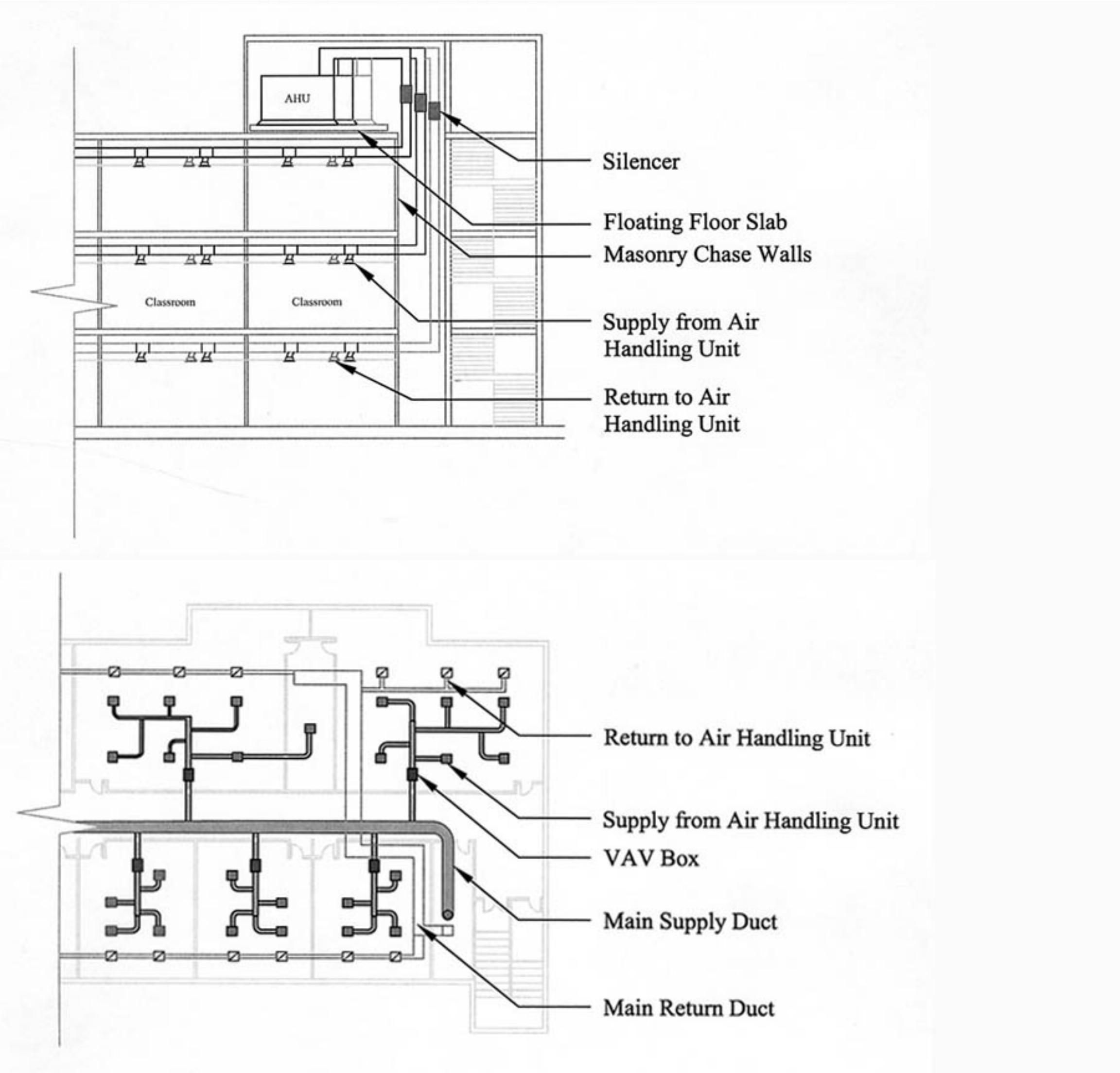


Figure 6b. Conceptual section sketch and floor plan of Case Study 7: AHU in Mechanical Penthouse with VAV Terminal Units Over Classrooms.