INNOVATIVE HVAC SOLUTIONS FOR A HISTORIC BUILDING RENOVATION

Presented by Boggarm S, Setty, P.E., President, Setty & Associates, Ltd.

Planning a 21st Century HVAC Design

In 1997, a radical improvements program was implemented by the Smithsonian Institution to upgrade the HVAC systems in the Patent Office Building, an art museum located at 7th and F Streets, NW, in Washington, DC.

The building is listed in the National Register of Historic Places as a National Historic Landmark. The four-story building has a total gross area of approximately 333,000 sf. This masterpiece of Greek Revival architecture anchors a landscaped central courtyard. The building houses the National Museum of American Art, the National Portrait Gallery, and the Archives of American Art.

The Patent Office Building was built in four phases (Figure 1). The South Wing was built between 1836 and 1840, the East Wing between 1849 and 1853, the West Wing between 1852 and 1856, and the North Wing between 1856 and 1867. It was the largest building to be built by the US Government during the 19th Century. Ownership was transferred to the Smithsonian Institution in 1958 as a permanent home for the National Portrait Gallery and the National Collection of Fine Arts.

The Patent Office Building originally had a vacuum heating system with radiators placed throughout the building. Small chases run in both the interior and exterior walls. It is assumed that these chases were used for hot air ventilation, with coils located in the bottom of the chases and hot air circulated within the chases. In 1968-69, new air conditioning and steam humidification systems were designed and installed. Today, the HVAC system includes two 325-ton chillers with more than twenty-five air handling units. Existing systems do not provide any control of moisture and temperature and humidity requirements.

The very real challenge was to insert new HVAC systems without altering the historic fabric of this Patent Office landmark building.

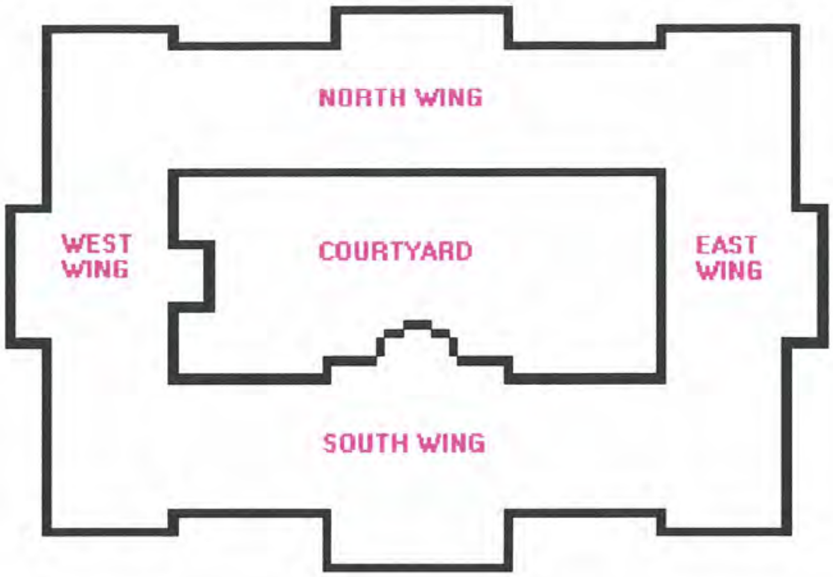


Figure 1 – Typical Floor Plan

Design Objectives

The initial phase of the improvement program required a study be conducted to evaluate existing systems conditions and recommend state-of-the-art HVAC systems that would have the least impact on the National Portrait Gallery aesthetics. Objectives included:

- Maintaining the historic fabric.
- Modernizing the HVAC systems to provide precise temperature and humidity conditions.
- Eliminating condensation on the windows.
- Developing several HVAC alternatives.
- Recommending the best HVAC alternative that provides the necessary temperature and humidity conditions, 70°F ±2°F, 50% RH, ±5% RH.

Building Description and Interiors

Many areas of the building interior and exterior are as originally designed. Significant architectural fabric is in existence and maintained throughout the building. Prominent spaces include:

National Museum of American Art Lobby

This space has marble columns, existing ceiling beams, pilaster claddings with a gray terrazzo floor, and the second floor overlooks the first floor lobby with slender ornamental bolsters and handrails. Finishes are of historically significant materials.

Lincoln Gallery

Built during 1849-52, the third floor of the East Wing has Maryland marble columns, vaulted plaster ceilings, and terrazzo floors. The gallery is used for display of patent models. All of its architectural components are of historically significant features.

Great Hall

The Great Hall dates back to 1880. It is located on the third floor of the South Wing. The Great Hall features the original stone columns, vaulted plaster ceilings, and ornamental ceilings. A fire in 1877 destroyed the North and West Wings, and the original stone columns and vaulted plaster ceilings of the South Wing were removed and replaced with Adolph Craus's design that now exists, which is Scagliola columns and pilasters with red marble, decorative plaster, and ornamental ceilings.

Library and Archives

The Library and Archives of American Art occupy a two-story space. The space was reconstructed after the 1877 fire by Adolph Craus, with cast iron and plaster columns and bronze balcony railings. The mechanical system, which included ductwork, are exposed in this area, and a portion of the room at the fourth floor balcony level has been altered to provide space for the mechanical room. The original space was renovated in 1960.

Existing HVAC System

The original heating and ventilating system dates back to 1908 or before. A vacuum heating system provided the heating through radiators. The existing chases with heating coils in the lower level provided heating and ventilation air which was a prevalent design during 1908.

The Patent Office Building does not meet ASHRAE 62-89, BOCA, and Smithsonian Institution standards and regulations. Building return air is drawn through the corridors on every floor, and taken back to the air handling units. Return air does not meet BOCA's Air Movement in Egress Elements. The chiller room does not meet ASHRAE Standard 15-1992. The HVAC system does not meet the energy efficiency standards of ASHRAE 90.1 or Executive Order 12902, Guidelines for Reducing Energy Consumption.

Until 1959, the old heating system was repaired on an as-needed basis. The heating system was in very poor condition as a result. In 1964, the entire existing heating system was removed and a replaced with new two-pipe heating/cooling fan coil system. Major chillers and air handling units were installed in the first floor mezzanine and fourth floor mechanical rooms. These units are still in use today. The mechanical system that exists today cannot maintain proper temperature and humidity control in the space, and the existing controls are outdated.

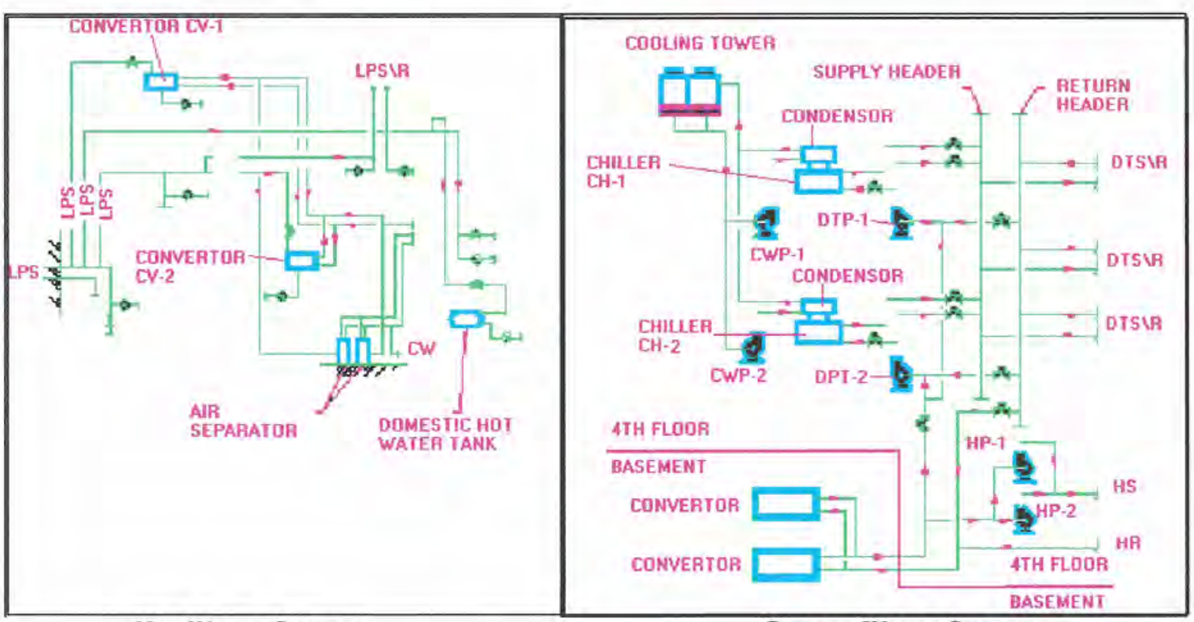
Air handling units are located in the mechanical equipment rooms throughout the building. The units have dual-temperature coils and steam humidification air handlers. The air handling units have been in operation for about 28 years. Retrofitting existing air handlers to meet the new requirements is expensive and may not fit the existing mechanical space.

In 1981, a report was undertaken to propose improvements and modifications to the HVAC systems at the Patent Office Building. The design documents included replacement of chillers and pumps, a new hot water converter, replacement of fan coils units, and replacement of automatic temperature controls. The 1981 modifications to the construction documents do not provide any solution to the existing temperature and humidity problems.

An earlier study in 1979 indicated major deficiencies which included the two-pipe system, the automatic temperature control system, and deterioration of windows and lack of insulation and a vapor barrier, however, no proper solutions were advanced to mitigate the problems.

The existing system has the following characteristics:

- Two 325-ton chillers.
- Steam-to-water converters draw central steam.
- 25 air handling units are located on the third and fourth floors.
- Two-pipe fan coil units.
- One forced draft cooling tower.
- No heating/cooling for interiors.



HOT WATER SYSTEM CHILLED WATER SYSTEM

Figure 2 – Water Flow Diagrams

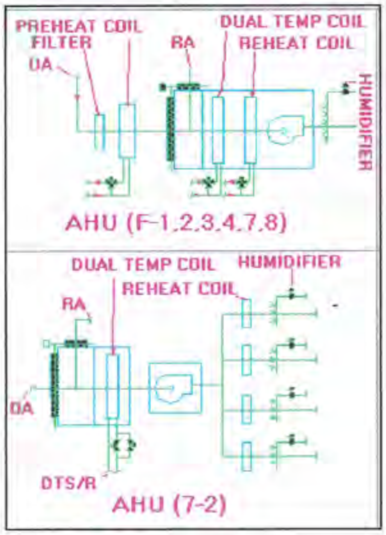


Figure 3 – AHU Flow Diagrams

Existing Chilled Water System

Two hermetic centrifugal chillers are located in the fourth floor mechanical room. Both chillers use refrigerant R-11 (Figure 2). Dual temperature water pumps serve the exterior chilled and hot water systems. Pumps are located in central mechanical room along with the chillers. The cooling tower generates noise, and showers from the tower provide misty, dirty water into the Courtyard.

Hot Water System

The hot water system (Figure 2) is composed of two repeat-heating systems, one serves the reheat coils installed in the air handling units, and the other serves the building hot water system. Reheat pumps are located in the fourth floor mechanical room and the building heating system is located in the basement of the building. A second heating system is part of the dual temperature water system, which is in operation only during the winter, serving the dual temperature air handling units and fan coil units. The hot water requirements for the building are met by two shell-and-tube converters. One converter is in use and the other is a standby unit.

Steam System

The General Services Administration provides the central steam to serve the Patent Office Building. The high pressure steam is reduced to medium pressure and hot water is generated through a set of converters. Fluctuations in steam pressure occur often and limit the production of hot water when needed.

Fan Coil Units

There are approximately 450 two-pipe fan coil units serving the exterior perimeter zone of the entire building. The fan coil units provide constant condensate leakage and drainage problems. They do not provide the necessary humidity control for the spaces. Fan coil units do not meet the new design requirements of year-round, simultaneous heating/cooling and humidity control.

Controls

In 1968, the controls were replaced with pneumatic controls. The pneumatic controls are not effective in maintaining temperature and humidity for the spaces.

HVAC Systems for Individual Floors

Twenty-six air handling units, based on the building zones, provide heating/cooling. Chases located around the in the exterior walls of the building and the interior courtyard are used for duct risers to supply and return air from the air handling units and the spaces.

Testing

Testing measurements using digital probe meters were conducted on all air handling units and pipes. The testing report indicated that all the air handling units were performing at less than 50 percent of their original CFM. The design was 125,995 CFM and outside air was 21,315 CFM. The test results showed 66,891 CFM, and outside air was provided at 5,596 CFM.

Destructive testing procedures were utilized to determine the material properties and longevity. Ultrasonic pipe testing with transducers was performed to determine the remaining thickness of the piping.

Conclusions of the testing determine that all existing piping and AHU's cannot be used for future heating and cooling.

EVOLUTION OF A NEW HVAC SYSTEM

Simultaneous to analyzing existing historic architectural and structural restoration requirements, the HVAC approach was developed. Unique solutions were required to incorporate the new systems into the building's historical fabric.

Historic Architectural and Structural Limitations

Major limitations in the historic buildings architectural and structural systems posed problems in conceiving new mechanical systems. The solid masonry construction of the Patent Office Building limits the options of cutting openings to insert modular building systems. Horizontal duct distribution on every floor was not possible due to restrictions imposed by the architectural historic fabric. For vertical distribution of the ductwork, the simplest operation can be accomplished by chasing walls vertically. Radar and thermography confirmed the existence of the vertical chases both in the exterior and interior walls. These chases are used as much as possible for air distribution in the interior walls. The maximum chase size is 24 inches wide and 8 inches deep.

Insertion of new building systems to meet the new criteria established by the Smithsonian Institution is extremely challenging. Each wing was constructed separately and has its own structural system. The ultimate intent of the renovation effort is to maintain precise temperature and humidity control in all of the spaces, in modules of 400 sf, without disturbing or restoring the historic fabric.

Infiltration and Exfiltration

Both infiltration and exfiltration occur in the Patent Office Building, due to air leakage through the cracks in the window frames, around windows, doors, and through the 24-inch or thicker stone walls. Extensive migration of moisture from the outside to the inside was occurring mainly in the summer months. The Smithsonian Institution requires a conservation standard of humidity control of 50% RH, ± 5% RH, and a temperature of 70°F, ± 2°F, for museum spaces and was very difficult to maintain due to excessive moisture migration. The new HVAC system should be capable of handling the moisture migration, infiltration, and exfiltration in the walls, windows, and doors, while at the same time maintaining distinct temperature and humidity. New innovations in HVAC systems required dewpoint control for every space.

Condensation

Several sources contribute to condensation:

- Moisture penetration through the existing thick walls.
- Visitor and staff moisture and evaporation.
- Moisture infiltration through windows, doors, and openings.
- Outside air ventilation.

Consideration was given to replacing existing wood/metal frame windows with low-E glass, although the historic preservation made it unfeasible. Consideration was also given to embedded electric heating coils in the window frames with electric radiant heating under the windows.

Electric heating cable and electrical radiant coil was controlled by dewpoint sensors located on each of the windows. Water-resistant paint could also be provided to reduce moisture migration (Figure 4).

Innovative desiccant dehumidification systems and dewpoint control of supply air for all the air handling units would provide proper humidity control in the exhibit areas (Figure 5). Constant volume system with positive pressure in the space would provide better control of moisture penetration through the cracks, openings, windows, and doors.

Using a vapor barrier to prevent moisture from moving into or through the wall approach was not possible. The walls are solid masonry, ranging from 24 inches to six feet thick, which would make a vapor barrier too costly to install in the existing structure.

Another possibility was to coat the interior of the exterior wall, which was not practical because it would destroy the historic fabric. However, the building requires dewpoint control for every space, which necessitated desiccant dehumidification control that will eliminate or reduce the moisture migration. Vapor barriers will be installed in the exterior vertical chases to avoid any condensation in the chases.

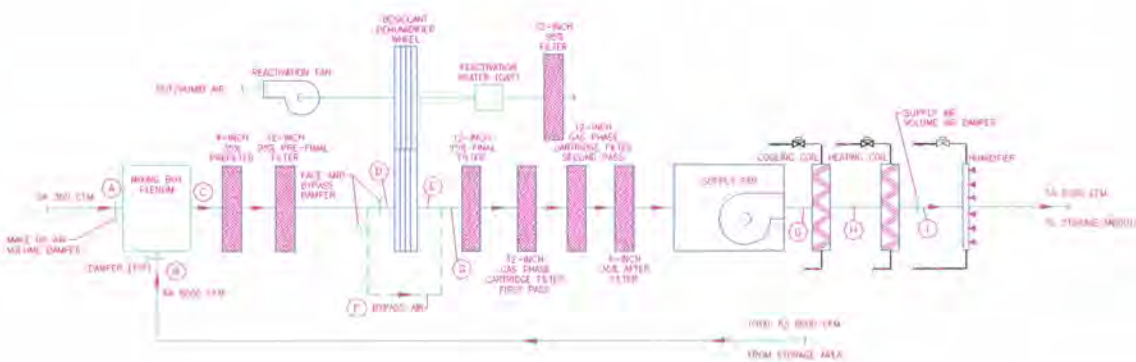


Figure 4 – Packaged Desiccant Dehumidification System

Phasing

Renovation while the building is occupied is very difficult, but not impossible. Several options for renovation of the HVAC systems included closure of the building or phasing by halves (Figure 5). Complete closure would require relocation of the collection, staff, and equipment to a remote location for the duration of the renovation. This would make it much simpler to conceive the new HVAC system and also to install it.

Phasing by halves requires relocation of staff and equipment to one half of the Patent Office Building while the other half is closed for construction. Figure 6 illustrates the procedures involved in shutting down half of the HVAC system while installing the new HVAC system in the other half of the building. This process is cumbersome, more expensive, and may not achieve the necessary results. Due to the extreme difficulties, phasing by halves was not recommended.

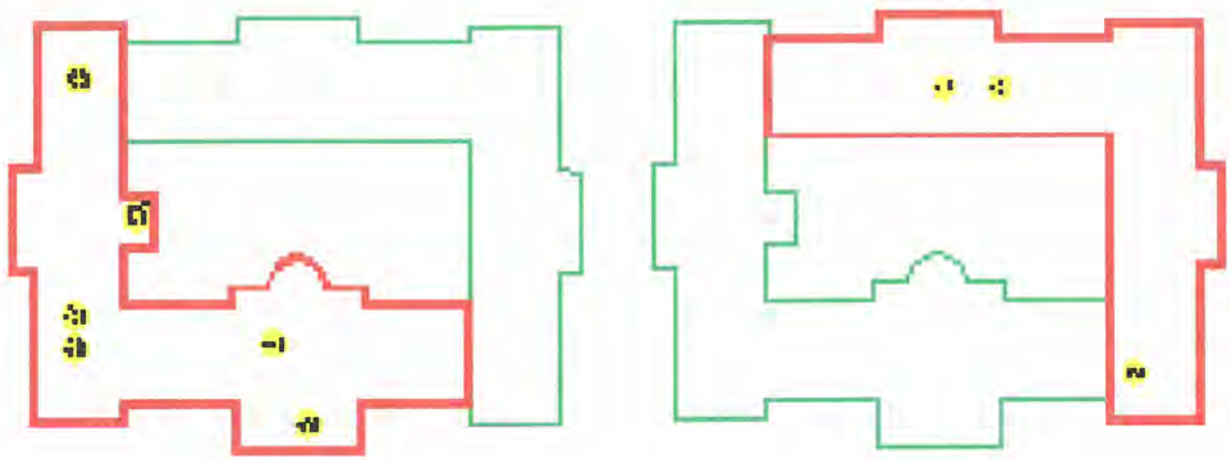


Figure 5 – Phasing Plans

NOTES:

① All central plant equipment will be installed in the southwest parking garage before the existing chillers are removed.

②Existing chillers to be removed after installation of new chiller and temporary piping for hookup to the northeast wing will be provided.

③ Existing cooling tower to be replaced with new cooling tower with minimum down time (during winter).

④ The air distribution system and air handling units serving floors one through four will be removed and replaced with new air handling units and reheat coils. Temporary ductwork and piping will be provided as needed.

⑤ All existing air handling units in the third floor mezzanine area serving lower levels will be removed. New air handling units with reheat coils will be installed. Also temporary piping will be installed to keep northwest wing in operation.

⑥All existing air handling units located on the fourth floor and serving lower floors will be removed and replaced with new air handling units and reheat coils in their place.

⑦The existing heating system in the basement will be removed and new air handling units will be installed.

⑧All existing ductwork and special area (paint shop, carpenter's workroom, etc.) mechanical equipment will be removed and new individual air handling unit will be installed in its place.

⑨Install new domestic hot water heater in central plant along with new circulating system.

Intake and Exhaust

The historic fabric of the Patent Office Building does not allow any penetration through the walls or roof. Figure 7 illustrates the innovative concept of intake and exhaust systems. In order to maintain the historic fabric while simultaneously adhering to BOCA and AHSRAE standards in conflict with the historic nature of the building, it was decided to take the fresh air at just the bottom of the building near the central courtyard, and discharge the air at the top of the building as required.

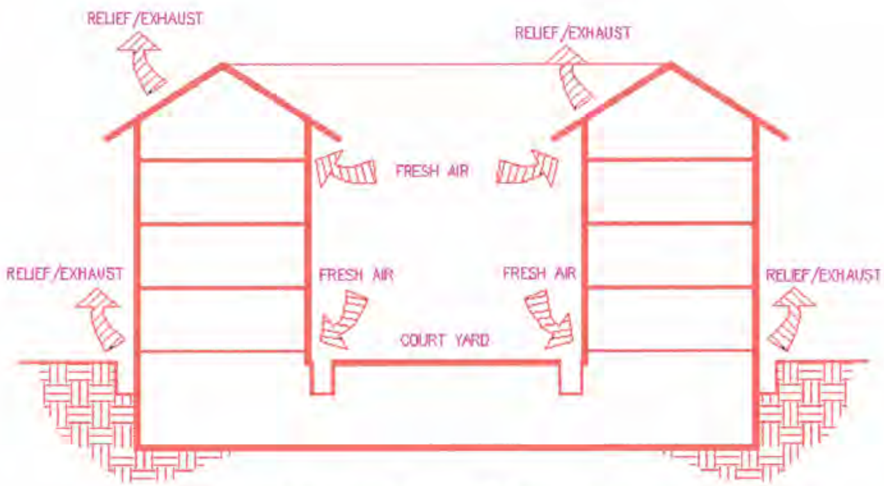


Figure 6 – Intake and Exhaust System

HVAC SYSTEM ALTERNATES

HVAC innovative solutions conceived would provide precise temperature and humidity while preserving the historic fabric of the building. Several alternates were considered and life cycle cost analyses were conducted using DOE-2 computer modeling.

The challenge was to accommodate new vertical chases in each of the four wings as follows:

North Wing: Existing wall chases are utilized to accommodate the small 10 inch x 8 inch duct originally from the mechanical rooms. In addition, it was easy to conceive new chases in a structural style consisting of cast iron beams and shallow brick vaults.

East Wing: A substantial number of existing chases are available for duct distribution. Also, the structural system allows for new chases, even though it is difficult and expensive to install them.

South Wing: The distribution of ductwork in the South Wing is more difficult than in either the North or East Wings. These spaces will be served from perimeter wall chases connected to the basement air handling equipment room and also to the West Wing by new trenches created under the first floor (Figure 7).

West Wing: Providing duct risers to serve the interior zone of the first and second floors of the West Wing will require the reconstruction of a portion of the walls.

Generally, the new HVAC system is comprised of two 1000-ton centrifugal chillers and multiple air handling units with reheat coils, humidifiers, and desiccant dehumidification, all located in the basement central plant mechanical room.

The heating system includes two high efficiency copper fin boilers. The system conceived provides temperature and humidity control for every 400 sf module, with dewpoint control and reheat providing the necessary moisture mitigation, associated with the windows and walls (Figure 8) State-of-the-art DDC control technology provides the necessary PID loops for proper and precise temperature and control. All the alternate systems considered have the above referenced systems.

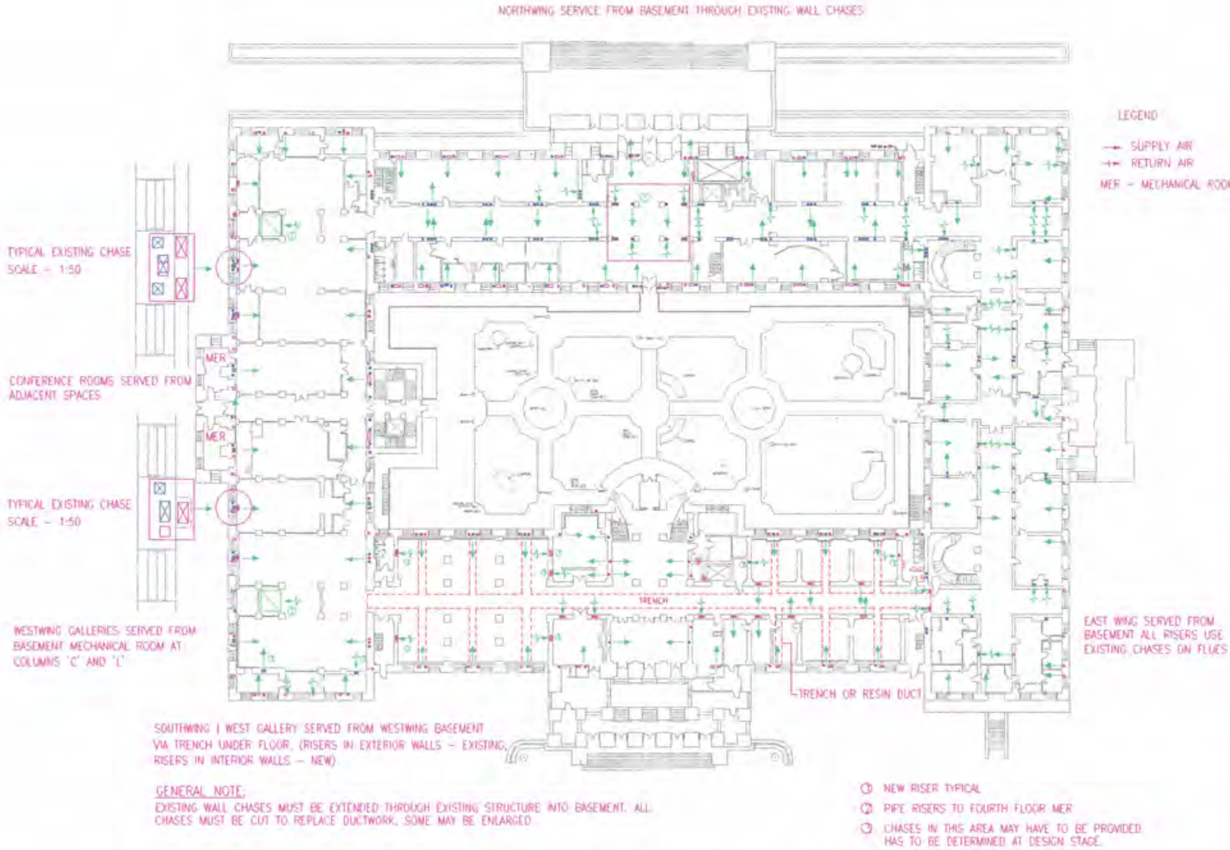


Figure 7 – Alternate No. 1 First Floor Plan

BASIC SYSTEM ALTERNATES

Alternate 1

VAV air valves with reheat coils located in the perimeter spaces. Interior shall be served by VAV reheat boxes connected to the air handling unit located in the basement. Existing vertical chases would be used for piping and ductwork. Chilled/hot water supply, return condensate, and deionized water for the humidifier and primary fresh air would run through existing chases, eventually connected to the variable volume valves. Primary cooling is accomplished at the central air handling units. All the discharged air is reheated to maintain the specified space temperatures.

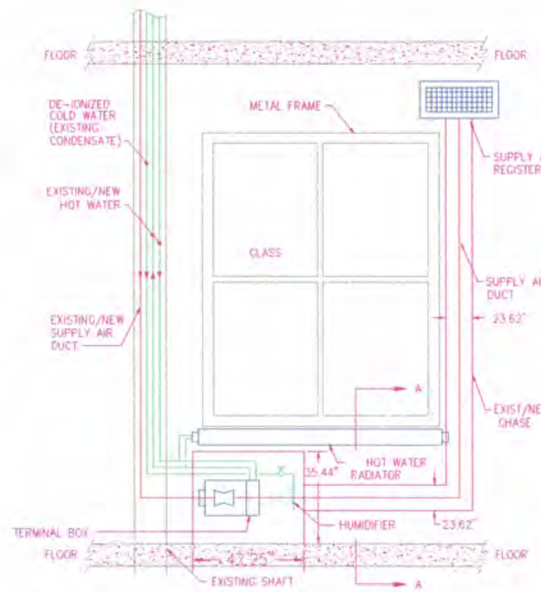


Figure 8 – VAV Air Valves with Reheat Coils

Advantages of this system are central control and ease of operation. Maintenance costs are high to repair air valves in the space, and there will be disruptions in the exhibit areas whenever maintenance or repairs are required. Pipe corrosion may be possible in the pipe chases. The air valve system would not fit into the space between the windows, unless major structural modifications are undertaken.

Alternate 2

All air constant volume system with reheat boxes serving both interior and exterior spaces.

Both perimeter and interior spaces will be supplied by constant volume air handling units and reheat boxes. An electric radiator with an electric coil around the windows would maintain the necessary temperature and conditions in the perimeter spaces. Small ducts would run in the existing vertical chases. Each reheat coil and humidifier box will provide the temperature and humidity requirements. Interior zones would be served in a similar manner as in Alternate 1, where all the air handling units, reheat coils, and humidifiers would be located in the central mechanical room. Existing vertical chases and new chases with a maximum size of 24 inches x 8 inches would serve all interior and exterior modules.

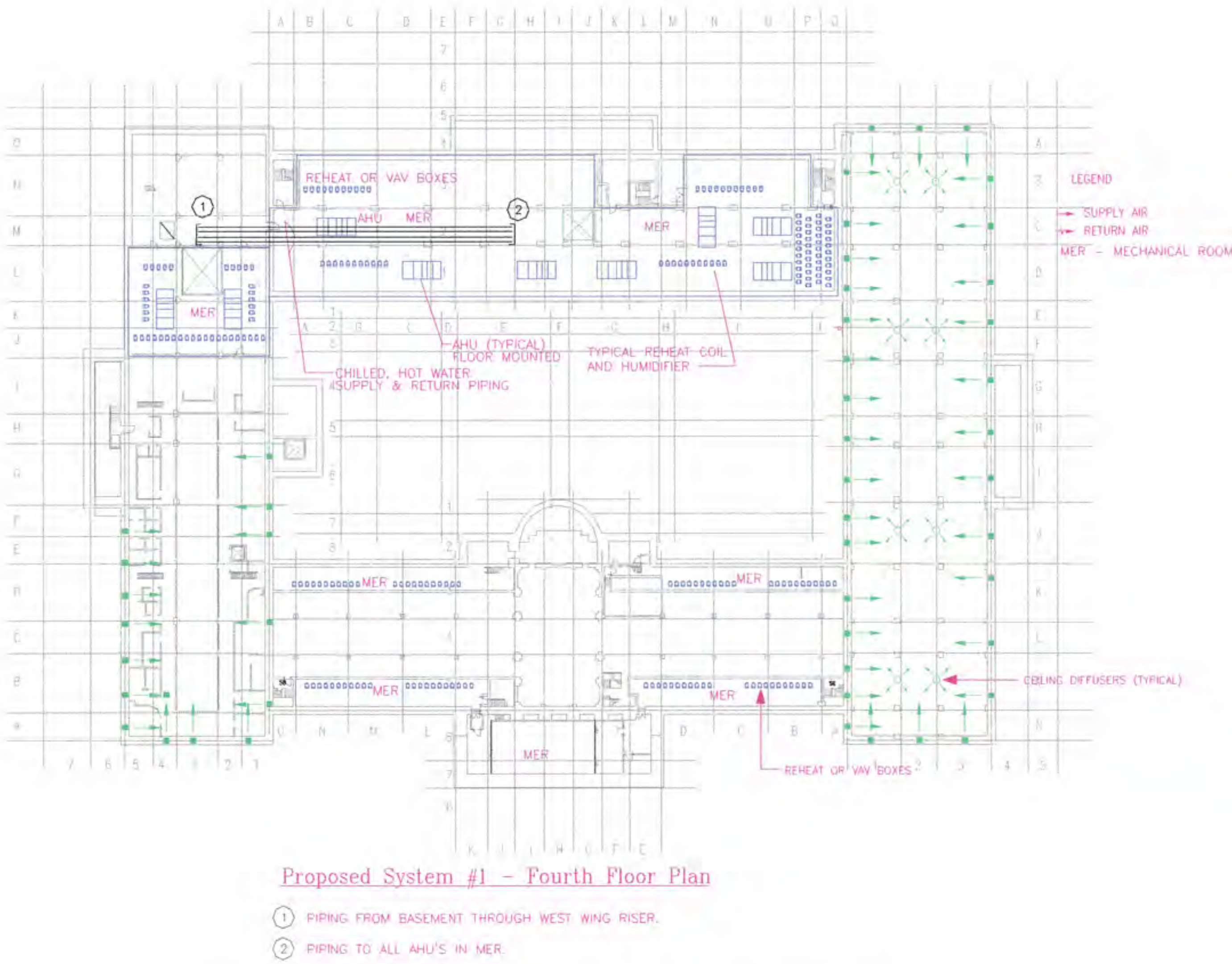


Figure 9 - Alternate 2: All Air Constant Volume System with Reheat Boxes
Alternate 4: All variable volume boxes with VAV reheat boxes.

Alternate 3

Four-pipe fan coil units with reheat. All units shall be located in the perimeter space, and interior VAV boxes located in the basement.

Four pipe fan coil units with reheat coils located in the perimeter walls of the building. For the interior, the system is similar to Alternate 2, with all the units located in the central mechanical rooms. All secondary cooling and heating would be accomplished in the fan coil units based upon the dewpoint requirements of the perimeter exhibit spaces. Reheat coils thermostatic sensors would maintain necessary temperature and humidity: Interior systems would be served by individual reheat coils and humidifiers. Air would be distributed through the interior chases through small, 24 inch x 8 inch ducts (Figure 8). The advantages to this system are as follows: the ducts connecting the fan coil units would be small, and filtration would be accomplished twice, once at the primary unit and again at the secondary unit. The disadvantage of this system are that the control of sensors and humidifiers would be decentralized and require more maintenance, there would be more noise in exhibit areas, corrosion of piping may occur in the chases, high initial cost, and major structural and architectural modifications would be required for repair and maintenance.

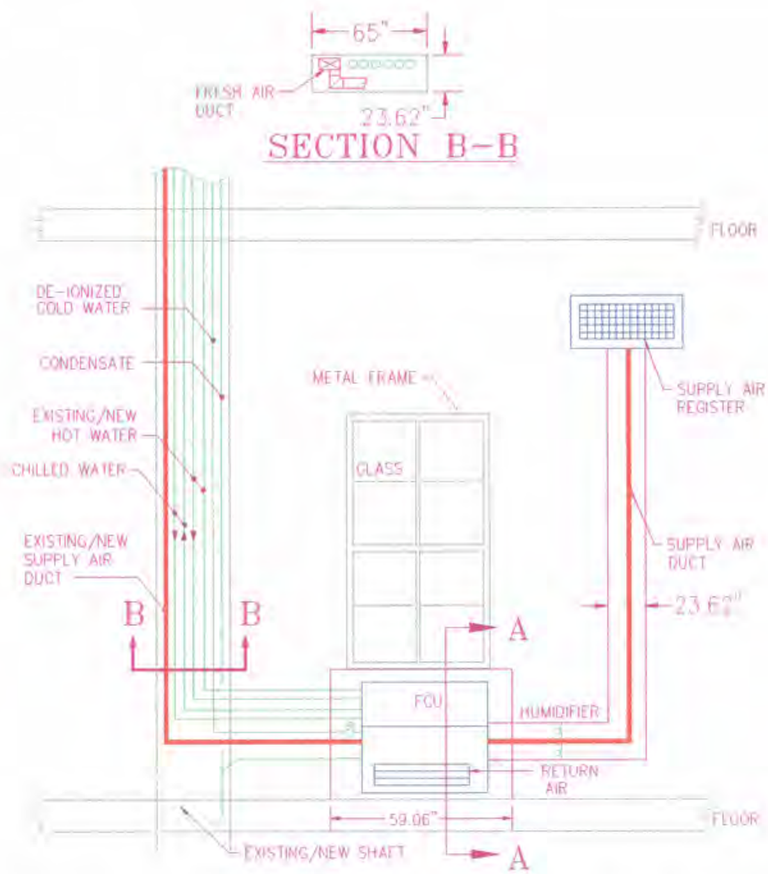


Figure 10 - Alternate 3: 4-Pipe Fan Coil Unit with Reheat Coils in Perimeter

Alternate 4

Alternate 4 is similar to Alternate 2, (Figure 8) with the exception that the variable volume boxes provide conventional air as required to meet the cooling or heating demand of the space. All the central plant air handling units and associated reheat coil boxes and humidifiers would be located in the central plant mechanical rooms. Interior zones would be similar to exterior zones, and all the air would be supplied through existing or modified chases. Advantages of this system are that control of temperature and humidity would be centralized, ducts connecting the diffusers would be small, maintenance costs would be low, no repairs or maintenance would be required in the spaces, and the operating costs would be low. Disadvantages of this system are that at times, less air would be in circulation in the spaces, it has a higher initial cost than Alternate 2, and less energy savings.

Energy and Economic Analysis

To recommend the best alternate, energy and economic models were developed using existing public domain programs. A detailed energy and economic analysis was needed to evaluate the energy consumption of the alternates, and finally, the National Institute of Standards and Technology's Building Life Cycle Costing (BLCC) program was utilized to determine the life cycle of each of the systems. The program utilizes 24-hour operation and calculates the energy consumption of each system. With BLCC, the life cycle costs of the alternate systems are computed to determine the lowest life cycle cost. The methodology utilizes maintenance and replacement costs as determined by GSA standards. The present value of each system is analyzed, and the best system recommended (Table 2). Only Alternates 2 and 4 are analyzed, since Alternate Nos. 1 and 3 are not feasible without disturbing the historic fabric and structural integrity of the building.

Results are based on first cost and resent value of two alternates over a twenty-five year cycle. Savings achieved using Alternate 4, the variable volume system are insignificant.

Historically, variable volume Alternate 4 consumes less energy than Alternate 2. However, the initial cost is higher. Under low load conditions, boxes will drop down to 30 to 40 percent of the full load capacity. When the system are controlled to maintain the required humidity under low load conditions, the systems will switch back to constant volume reheat mode, and the anticipated savings will be substantially reduced.

Alternate 2, a constant volume reheat system, is energy-intensive and provides a good circulation rate. It also meets ASHRAE Industrial Quality Standards. It is easier to maintain precise temperature and humidity conditions through dewpoint control.

Table 1 – Life Cycle Cost Analysis

	Alternate No. 2	Alternate No. 4
Initial Cost	22,724,550	23,995,870
Annual Recurring Cost	5,478,403	6,190,941
Energy Cost	11,832,700	9,738,823
Present Value Life Cycle Cost	40,035,660	39,925,640
Net Savings Over 25 Years	0	110,020

CONCLUSION

Alternate 2 recommend evolved to be inserted into the historic building without impairing the historic fabric of the building. Also, constant volume reheat system mitigates the existing problem of maintaining temperature and humidity in the building. Alternate 2's unique HVAC distribution systems were evolved to fit in the existing chases and also to maintain architectural and structural integrity.

Desiccant dehumidification and reheat systems with dewpoint control provide the necessary solutions in maintaining temperature and humidity in every 400 sf module, and electric cable and perimeter radiant heat eliminate the condensation.

eric:\mydocs\employees\bogi\ASHRAE Dublin Ireland Nov 2000 POB Paper