The Sistine Chapel: HVAC Design for Special Use Buildings

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Environmental control systems for museums, art galleries and other special buildings typically must control more than just air temperature and humidity, and must often provide much tighter control than is expected from conventional air conditioning systems. The priceless artifacts and art treasures housed in such buildings can be permanently damaged if the environment is not continuously controlled. The comfort of occupants also should be considered. Six principal factors are generally considered in the design of such systems: air temperature, air humidity, light, air circulation, air-borne pollutants, and sound level. This paper discusses these factors and how they were addressed in the design of the air conditioning system for the Sistine Chapel, and provides general guidelines for other special buildings.

General Considerations

Air temperature and *humidity* are the two most important variables which affect objects of art, whether they are made from organic materials such as paper, fabric or wood, or from inorganic materials such as plaster, stone, ceramic or glass. Extreme fluctuations in these variables can cause stress and accelerated wear and aging. High relative humidity, above about 70%, encourages mildew, fungus and mold growth in organic materials and gradual disintegration of inorganic materials due to efflorescence. Very low relative humidity, below about 30%, can cause embrittlement, shrinkage, and cracking. ASHRAE[1] recommends control ranges of 20°C to 22°C (68°F to 72°F) for temperature and 40% to 55% for relative humidity. This is in agreement with others, for example.[2,3,4] Of particular importance is the continuous maintenance of stable conditions, i.e., 24 hours per day. Periodic thermostat setback or setup for energy conservation reasons should not be allowed.

All *light*, whether natural or artificial, can be damaging and should be carefully controlled. Light reacts with oxygen, moisture and pollutants in the air to cause molecular breakdown in organic materials. Ultraviolet radiation is also very damaging due to its ability to cause pigment fading. Control methods include special curtains, shutters and blinds for daylight, and special filters and light elements for artificial lights.

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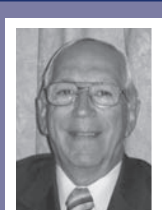


Charles E. Bullock, Ph.D., Fellow/Life Member ASHRAE, served on several Technical Committees and authored numerous technical papers, which appeared in the ASHRAE Journal and other trade publications. When this article was published, Dr. Bullock was an Engineering Fellow with the Carrier Corporation, working in the Advanced Technology Group. At Carrier, he was in charge of several special HVAC projects, including systems for the Sistine Chapel and for George Washington's Mount Vernon Estate. Bullock, now 72, retired from Carrier in 2005, and lives in North Syracuse, N.Y. He continues to do some consulting.

Air circulation is vital in order to maintain uniform conditions. Stagnant spaces must always be avoided, because they lead to poor local control of conditions and also because they can cause mildew, fungus and mold growth. However, high velocity areas can also be very damaging, due to surface erosion and to the deposition of air-borne particles on the surfaces. The actual process by which particles are attracted to and deposited on surfaces has been studied by others who have identified several mechanisms, including thermophoresis (a phenomenon which ties the deposition of particles on a wall surface to the magnitude of the temperature difference between the air and the wall surface—the larger the difference, the larger is the deposit rate), static electricity generated by the passing air stream, and moisture flow. In any case, the need for low air velocities is obvious. Since it is physically impossible and undesirable to have absolutely zero velocities near the surfaces when a ventilating and air conditioning system is in operation, the question is: What is acceptable? ASHRAE[1] generally recommends surface velocities below 0.13 m/s (25 fpm) and overall air circulation rates of 8 to 12 air changes per hour.

Of the common *air-borne pollutants*, sulphur dioxide is potentially the most damaging, because it combines with water to form sulfuric acid which attacks both inorganic and organic materials. Sulphur dioxide can be removed with air washers and special absorbent chemical air filtration units. Oxides of nitrogen as well as ozone gas are also damaging and can be removed by the same means. Electrostatic type air cleaners are not recommended because they generate ozone.

Sound levels should be low, lower than in most office or residential buildings, in order ensure quiet comfort for visitors and staff. This is often a challenge because many exhibit spaces have little sound absorbing surfaces and are acoustically reverberant. Fortunately, a wide variety of sound-absorbing materials and devices are readily available so that acceptable sound levels can be achieved by the experienced system designer. Air- or structure-borne vibrations must also be avoided, particularly those which may cause damaging resonant vibrations within objects on display.

Michaelangelo's painting on the ceiling of the Sistine Chapel is among the world's most famous works of art.

The Sistine Chapel System

The Sistine Chapel was built during the period 1480-1484 by the direction of Pope Sixtus IV, hence the Chapel's name. It was built not only as a religious chapel, serving principally as the site of conclaves to elect new popes, but also as a fortress from which to ward off invaders of that time. Because of this, the outer masonry walls are very thick (2 to 3 m [7 to 10 ft]). The interior shape is very simple, being essentially a rectangular box with a vaulted ceiling. The interior dimensions are in the same proportions as those for King Solomon's temple of Old Testament times[5] but slightly larger (40 m L x 13 m W x 20 m H).

The Chapel has six large windows on each long wall, approximately 10 m from the floor, for light and ventilation. The Chapel walls and ceiling were decorated with a wide variety of scenes from the Old and New Testaments by leading artists shortly after the Chapel was completed. However, serious problems with settling of the foundation and shifting of the outer walls caused large cracks to occur in the vaulted ceiling, ruining the original art work there.

After the structural problems were corrected, Michelangelo Buonarroti was commissioned by Pope Julius II to repaint the upper walls and ceiling; this was done over the period 1508-1512 using the fresco technique—painting in water colors directly on fresh plaster. With this technique, the colors are bonded into the subsurface as well as the surface itself. The wall behind the altar was also repainted by Michelangelo during 1536-1541.

All of the frescoed surfaces fell victim to deposition of dust, smoke and other pollutants from candles, combustion heaters, outdoor air, people, etc. Many attempts were made over the centuries to restore the approximately 2000 m^2 (22,000 ft^2) of surfaces, typically using some sort of cleaning process and then applications of a varnish or glue which temporarily brightened the surfaces but eventually turned dark brown. After many layers of dirt and varnish had nearly obscured the priceless frescoes, the Vatican finally decided in 1960 to begin a drastic restoration process. The restoration involved a careful and thorough removal of all the accumulated layers of grime and sealers. First the lower walls were done, then Michelangelo's work on the upper walls and ceiling, and finally the altar wall, which was completed in 1994. The results have been truly outstanding, exposing bright coloring and artwork details which were hidden for centuries.

Prior to the installation of the air conditioning system, the Chapel was ventilated in the spring, summer and fall by natural air flow through open windows and doors and by exhaust fans located under the south windows. This introduced moisture, dust and other pollutants into the space. In winter, heating was provided by a forced-air heating unit in a sub-basement with two outlet grilles in the floor. The heating unit provided very limited heating, but no humidification. The Vatican commissioned a survey of interior conditions in the early 1980s.[6] These surveys showed that: a.) In summer, interior temperatures ranged between about 25°C and 35°C (77°F to 95°F) and relative humidity was about 50% to 60%; b.) In the spring and fall, temperatures were between about 18°C and 25°C (64°F to 77°F) and RH about 45% to 55%; c.) In winter, temperatures ranged between about 15°C and 20°C (59°F to 68°F) and RH was about 35% to 45%; and d.) Vertical temperature gradients of as much as 3°C (5°F) were common.

Using these results to validate it, a dynamic simulation (described below) was used to study interior conditions at all times of the year. *Figure 1* shows typical temperature contours for a day in July. Considerable variation is noticeable in both air temperature and humidity, due principally to the presence of people, during the time when the Chapel is open to the public (10 a.m. to 2 p.m. is shown here. Recently the summer occupancy period has been expanded to be 9:00 a.m. to 5:00 p.m.). Note that the wall temperatures (at the interior surfaces) are very close to the air temperatures, except when the large people loads occur. In addition, significant vertical temperature stratification was observed.

These wide ranges in temperature and humidity conditions were clearly unacceptable for the safety of the frescoes.

The Sistine Chapel is inside the Vatican. It was completed in 1484.

Prior to the restoration, however, the fresco surfaces were somewhat protected by the layers of glue and varnish that had been applied over the centuries. The restored fresco surfaces, on the other hand, have not been protected with any sealant. They will remain in the original state. The Vatican thus recognized the need to protect these art treasures for posterity by creating a "microclimate" around them and sought to provide a suitable environmental control system.

The objective of this microclimate system was to prevent the deposition of any kind of particles or substances on the surface or within the immediate subsurface layers. Without this action being taken, the walls and ceiling would gradually become contaminated once again, principally from the increasingly polluted Roman air and the numerous visitors, as many as 8,000 each day.

Seven system requirements were established before the system was designed:

1. Constant air relative humidity;
2. Controlled fresco temperatures;
3. Still air at fresco surfaces, limited air motion at floor level;
4. Minimal noise level;
5. Minimal pollutants from visitors and outdoor air;
6. Invisible to occupants; and
7. Exceptional reliability.

Constant air relative humidity. For a plaster surface, it is the air relative humidity, not absolute humidity or humidity ratio, that determines its moisture content. Temperature has only a minor influence. This is true of most materials found in museums and art galleries. For the present system, it was decided that relative humidity would be maintained at 55% +/– 5%, for fresco preservation as well as for occupant comfort. In order to establish the performance requirements for the air conditioning system, a dynamic computer simulation was developed.

This simulation included models for the outdoor weather variables (air temperature, solar radiation), transient heat conduction through the massive walls and ceiling, solar radiation and heat flow through the windows, heat and moisture generated by the visitors, radiant heat exchanges between the walls, floor and ceiling, and the mass of air within the Chapel itself. *Figure 2* shows the calculated cooling load profiles for a typical day in July. Of all the factors, the contributions of the visitors, based on a total occupancy of 700 persons, is clearly the most important. Similar calculations were done for other key times of the year. They showed that some cooling was required every day of the year during the occupied period, at least during peak occupancy. During the unoccupied period, the load was either heating or cooling, depending on the time of year. The load profiles showed the severe challenge to the air conditioning system controls in order to respond quickly to the fast load changes and still maintain stable conditions.

The air conditioning system employs an air handling unit, shown schematically in *Figure 3*, comprised of the following main components:

- Air prefilter (90% efficiency)
- Hot water pre-heat coil (with electric back-up)
- Air washer
- Chilled water cooling coil
- Hot water re-heat coil (with electric back-up)
- Chemical filter unit (absorbent, adsorbent, oxidizer)
- Final filter unit (95% efficiency)
- Supply air fan (2-speed motor).

In order to maintain humidity control, several air dew-point sensor units, of the chilled-mirror type, were positioned throughout the Chapel in inconspicuous places. The 55% RH control point is maintained with a special control loop which regulates the operation of either the hot water pre-heat coil or the chilled water cooling coil (whichever is in use at the time).

Controlled fresco temperatures. Several requirements existed here. The fresco temperatures must be above the air dew-point temperature in order to avoid surface condensation of moisture. This is automatically satisfied by the maintenance of 55% RH. Also, the fresco temperatures were required to be "close" to the inside air temperature, in order to minimize the thermophoresis effects (dust deposits). This was accomplished by maintaining the fresco surface temperatures essentially constant using temperature sensors attached directly to the wall and ceiling surfaces and a second special control loop

FIG. 1 Temperature and humidity profiles for a typical July day.

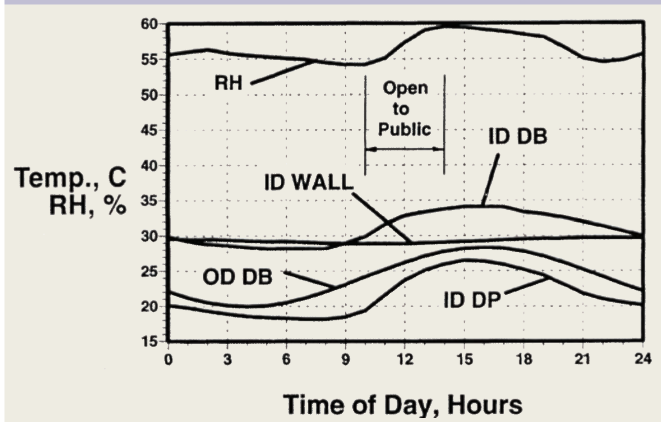


FIG. 2 Calculated cooling load profile for a typical July day. The contribution of the visitors is clearly the most important factor.

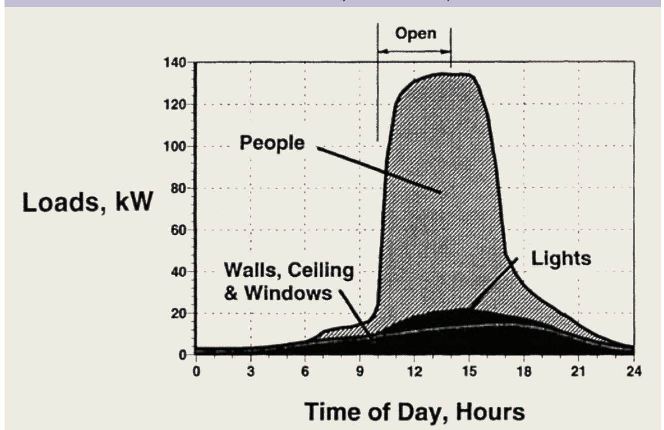
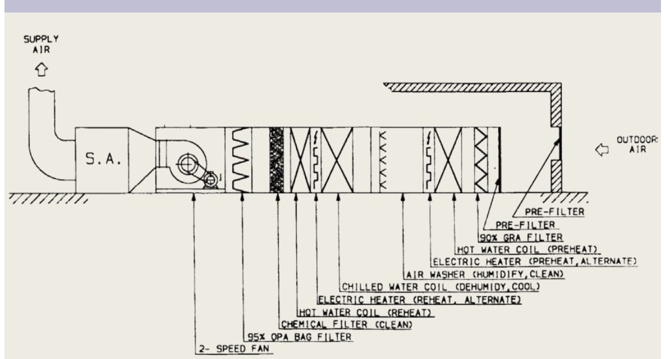


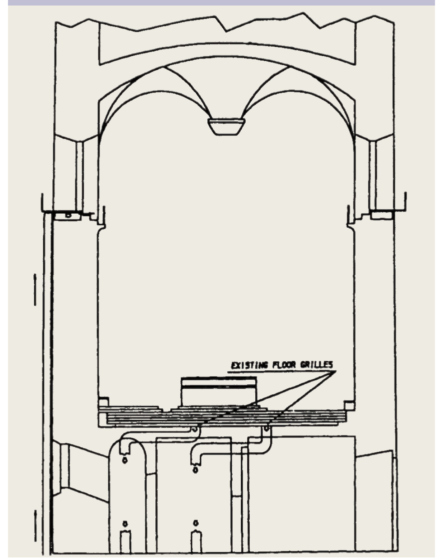
FIG. 3 Schematic shows the main components of the air-conditioning system.



involving the reheat coil. The computer simulation showed that, by maintaining the surface temperatures essentially constant, the adjacent air temperatures would be very close, within 1°C (0.6°F). Air temperature measurements taken near the wall surfaces confirmed this prediction. A third requirement was that the interior wall and ceiling temperatures must be "close" to the exterior surface temperatures, in order to minimize temperature gradients and resulting thermal strain. This was accomplished by allowing the interior temperatures to drift slowly with the seasons, ranging from a low of 20°C (68°F) in winter to a high of 25°C (77°F) in summer.

Still air at fresco surfaces, limited air motion at floor level. The air conditioning system utilizes a forced-air supply arrangement in which air is injected into the space from outlets located directly under windows along one of the side walls. Since practically all of the wall and ceiling areas are covered with priceless artwork, no new openings could be cut in them for air ducts and outlets, leaving only the window sills for this purpose. After mixing with existing room air, most of the supply air is exhausted to the outdoors through grilles located in the floor by an exhaust fan unit. The supply air quantity is larger than the exhaust air quantity so that the space is slightly pressurized, ensuring that no airborne pollutants can enter by infiltration.

FIG. 4 Scheme using supply air from one side only (shown) was chosen over the two-side option.



Although the comfort of the visitors is of course being satisfied, the principal concern is for the safety of the frescoes. In particular, air motion near the fresco surfaces has been minimized in order to reduce the rate at which airborne particles might be deposited on the surfaces. Since ASHRAE recommends velocities below 0.25 m/s (0.82 fps),[1] this was our criterion also.

A separate analysis of the air circulation patterns within the Chapel with special emphasis on the surface air velocities was thus undertaken in order to:

- Identify areas where velocities would be highest;
- Establish specifications for the design of supply outlets.

Analyses of the heating and cooling loads and the ventilation requirements determined that the total supply air quantity should be highest during the times of peak occupancy, typically 10 a.m. to 2 p.m., as shown in *Figure 2*. At other times, the supply air quantity could be reduced. Originally, two supply air arrangements were considered—air supply from two sides and air supply from one side only. The same total air quantities would be used in both cases.

FIG. 5 Diagram illustrates the double vortex air circulation pattern. The pattern provides a gentle air 'shower' on the occupants at floor level and a weak circulation in the upper vault area.

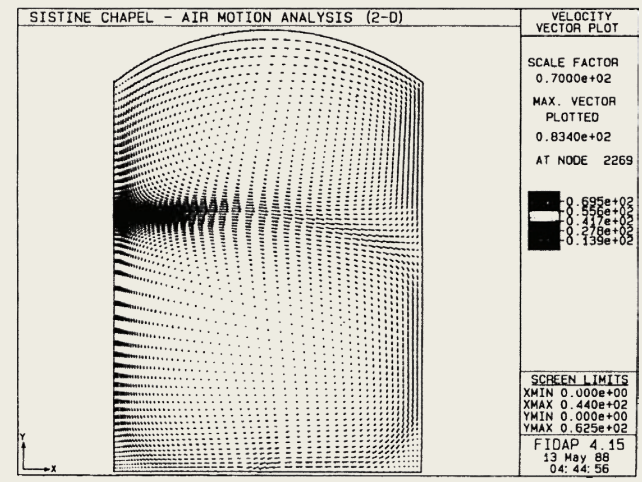


Figure 4 shows the scheme chosen, supply air from one side only. In an effort to keep the aerodynamic noise levels to a

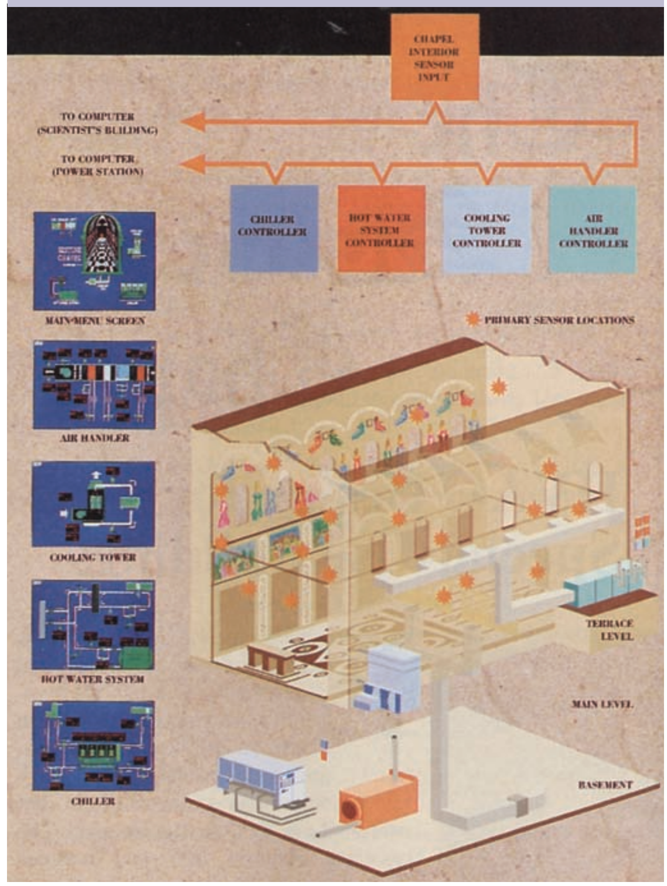
To ensure that art is not damaged, equipment was duplicated so that any failed component can be quickly, often automatically, replaced in operation by its duplicate.

bare minimum, the velocity of the supply air at the outlets under each window was also limited. Air circulation patterns and velocities within the Chapel corresponding to the two candidate air supply arrangements were analyzed with a computational fluid dynamics (CFD) program.[7]

Figure 5 shows a typical result, illustrating the double vortex air circulation pattern, which provides a gentle air "shower" on the occupants at floor level and a weak circulation in the upper vault area. By varying the angle and outlet velocity of the supply air streams, specifications for the outlet devices were established. The devices chosen were specially designed wide-angle diffusers, placed under each of the six windows on the south wall, each diffuser containing numerous adjustable guide vanes and also lined with acoustical insulation.

Minimal noise level. Although ASHRAE[1] suggests a noise level of RC35 is acceptable, it was decided to design for RC25. This was also a challenge since the Chapel contains no sound-absorbing material, such as carpeting, furnishings or wall hangings. All surfaces are hard. The RC25 level was achieved through the use of a large sound attenuation unit at the air handling unit outlet, a minimum number of turns and area changes in the supply ducts, low air velocities in the supply ducts and outlet diffusers (below 5 m/s [16 fps]), and acoustic insulation in the outlet diffusers. The computer programs for acoustic systems developed by ASHRAE[8] were very helpful here.

▶ FIG. 6 Schematic diagram of the system serving the Sistine Chapel. The primary cooling source is a water-cooled chiller with an output capacity of 210 kW (60 tons).



Minimal pollutants from visitors and outdoor air. Pollutants from visitors (dust, odors, etc.) are minimized by anti-dust carpets at all entrances, the overhead air "shower" and floor level exhaust, which combine to prevent pollutants from reaching the upper vault area. Pollutants from outdoor air are minimized by using 100% outdoor air, the three stages of filtration in the air handling unit and by pressurization of the space.

Invisible to occupants. The only devices protruding into the interior are the six supply air diffuser units. These are positioned under the windows which are 10 m (33 ft) above the floor and are set back from the interior wall surface by about 1 m (3 ft). They are thus completely invisible to occupants at floor level.

Exceptional reliability. In order to ensure that the system operation would not be interrupted by component failures, which inevitably would occur, many of the components were duplicated so that any failed component could be quickly, often automatically, replaced in operation by its duplicate. This included:

- Water pumps—chilled water, hot water, cooling tower;
- Preheat and reheat air coils—electric heating coils are back-ups;
- Water chiller unit—four independent refrigerant circuits. Condenser heat rejection is normally to a cooling tower, but a local water system can be used as a back-up;
- Sensors—the control system employs a total of 92 sensors of various types, 40 of which are back-ups.

In addition, system operation is automatically controlled by a computer system which normally requires no human intervention. Any abnormal condition, such as a sensor failure, causes an alarm notice to appear on video monitors at three separate sites, ensuring that prompt action will be taken. The monitoring sites also have access to real-time reports on all system sensors and can initiate changes in set-points or other system factors if desired. Every component controlled by the computer may be switched on manually (electro-mechanically) in case of emergency.

A schematic diagram of the overall system is shown in *Figure 6*. The primary cooling source is a *water-cooled water chiller unit*, with a nominal output capacity of 210 kW (60 tons). It has four reciprocating hermetic compressors, each with cylinder unloaders for capacity control and independent refrigerant loops for maximum reliability. Condenser heat rejection can be to either the cooling tower or the local municipal water system, as noted previously. Because of the need for precise control of the supply air temperature and the fact that there was only one air handling unit, a dynamic simulation of the chiller/water piping/cooling coil loop was developed. It was found that good stability could be achieved even with rapidly fluctuating loads if a 1000 liter (264 gal) buffer tank was placed in the line between the chiller outlet and the cooling coil inlet. The usual expansion tank also helped. Cooling coil output is controlled through a 3-way water valve at the coil inlet. Water flow is varied in relation to the load—the inlet temperature remains constant. This control scheme is discussed by Haynes,[9] and was found to work very satisfactorily.

The use of chilled water coils appears to be superior to direct-expansion coils for precise temperature control, at least in this situation. The *hot water preheat and reheat coils* are supplied from either the district hot water supply or an auxiliary gas-fired boiler. Control of these coils is also achieved with 3-way valves. Water flow is constant through each coil when it is in use—only the inlet temperature is varied. It was found that good stability in the hot water loop could also be achieved with rapidly fluctuating loads if a 1000 liter (264 gal) buffer tank and the usual expansion tank were placed in the line between the boiler and the heating coils.

The *supply air ducts* required special attention. Because no particles of any kind could be introduced into the supply air stream, there could be no exposed insulation within the duct work, which would be gradually eroded by air flow. This required that the ducts have double-wall construction, with thermal insulation placed between the stainless steel inner and the aluminum outer walls.

This provided thermal insulation and some acoustical attenuation. A third, outer painted steel sheet metal covering was added for further protection and also as camouflage. The wide-angle outlet diffuser units were constructed in a similar way, with the acoustical insulation by perforated metal and a protective plastic film. Due to severe space limitations, the chiller unit, chilled water pumps and valves, and the auxiliary gas boiler were placed in a second sub-basement storage room. This location was also preferred because it was not directly under the Chapel and would not transmit potentially harmful structural vibrations to the Chapel. The air handling unit was placed on an outdoor terrace, then covered with a brick and tile enclosure so as to blend in with the original building architecture.

The cooling tower was placed in an inconspicuous location near the air handling unit. The air handling unit and the cooling tower were also located away from the main Chapel structure in order to avoid vibration transmittance. The exposed supply air duct work was also painted to blend in with the existing building, as noted previously.

The new exhaust air unit was located in a separate room in the second sub-basement and connected with the same ducts previously used by the old under-floor heating unit. Finally, sensors were located at numerous locations within the Chapel interior, on the water chiller, on the air handling unit and other key points. A variety of sensors were used: temperature; humidity (dew point); pressure; On/off.

SUMMARY

• **Establish the basic specifications for the specific application.** The six principal factors generally considered in the design of such systems are: air temperature, air humidity, light, air circulation, air-borne pollutants, and sound level. The guidelines suggested by ASHRAE[1] are good starting points. Modifications to meet the requirements of a specific job may be necessary. For example, buildings or areas that primarily house rare books or documents should have lower humidities, e.g., 30% RH, compared to others with art work.

• **Analyze the building characteristics, including all heat and moisture flows.** If the building is of conventional construction, load calculation methods described by ASHRAE[10] are recommended, and are available via several computer programs. Not only the building envelope but also the internal loads (people, lights, equipment) must be analyzed.

• **Analyze air circulation patterns in all internal areas.** Locate the supply and return air devices. For cases where high accuracy is not deemed appropriate, this may be done by simply studying the architect's drawings and sketching in air flow paths. In cases where space condition control is very critical, computer analysis of the air flow paths with a CFD type program is strongly recommended.

• **Select the air conditioning system type and components.** The ASHRAE HVAC Systems and Equipment Handbook[11] contains much helpful information. For most jobs, where humidity levels common to most typical comfort air conditioning jobs are needed, conventional all-air systems are satisfactory. However, for cases, such as book or document storage facilities, where very low humidities are needed, systems employing desiccant type equipment may be required. Harrison[12] has useful information on this type of system. Thermal storage systems should also be considered for cases in which rapid load changes due to sudden appearances and disappearances of visitors are common and are repeated each day.

• **Analyze the control system.** Of particular importance is the selection of humidity sensors. For long term accuracy and reliability, chilled-mirror dew point type devices are recommended. However, several less expensive devices are available. In any case, frequent (at least annual) sensor inspection and re-calibration, if necessary, are strongly recommended. Temperature sensors are available in a variety of forms. *The 1993 ASHRAE Handbook—Fundamentals*[10] has a good review of instrumentation options and control system basics. Haynes[9] also has practical information on control system design.

The status of each sensor is recorded in the computer at 8 or 10 minute intervals, for archival use and later analysis.

The system was started on July 6, 1992, and has been operating automatically since then. No significant equipment problems have occurred. Interior space conditions have been very satisfactory—temperature and humidity control have been very good and there has been minimal vertical temperature stratification.

The air flow patterns are generally as designed and expected. Air quality is very good even during occupied times. The computerized system monitoring, data collection and storage system has performed very well.

Acknowledgments

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