A Climate Control System for Hollybourne Cottage, Jekyll Island Historic District, Georgia

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ABSTRACT

The efficacy of a humidistat-controlled mechanical ventilation and space heating system was studied for creating a preservation environment for both objects and historic buildings (such as museums, libraries and archives) that are located in warm, humid climate regions. The goal was to reduce and stabilize the level of relative humidity to avoid deterioration of collections by fungi and bacteria. A low-cost, robust and technically-simple climate control system was designed and tested at Hollybourne Cottage, a 100-year-old, two-and-one-half story faux tabby building. The cottage is located in the Jekyll Island Historic District on the Atlantic coast of the state of Georgia in the United States, within the ASHRAE-defined warm, humid cooling climate region. The efficacy of the control scheme was evaluated through monitoring climates, dust depositions, and microbial activities in the building before and after the installation of the system.

INTRODUCTION

Historically, buildings have been designed with certain architectural features to passively control the interior climate for the health and comfort of occupants as well as for increasing the building's longevity. However, over the course of time, various modifications made to the building's fabric, changes in the use of the buildings, and alterations to those original architectural features and operational considerations may seriously compromise the original structural design for passive control. These building modifications may result from changes in occupant needs, use of the building, local building and fire codes, security requirements, and general lack of maintenance. Such changes can create damp and stagnant areas as well as hot and stuffy spaces, which in turn, can cause severe decay of a building's fabric, not to mention serious health and safety problems for its occupants.

Historic buildings are often converted to cultural institutions to house culturally-important objects. While it is common knowledge that providing a better environment can extend the longevity of the collections (Michalski 1993, Erhardt and Mecklenburg 1994, Ashley-Smith, Umney, and Ford 1994), providing an overly-stringent preservation environment for the collection may simultaneously damage the building. This becomes a serious issue when the building is also "the collection". In such cases, it is necessary to produce a common environment that can better preserve both the collection and the building. This can be achieved by assessing the conditions of the collection as well as the building and understanding the deterioration threats to both (Padfield and Jersen 1990, Kerschner 1992, Staniforth, Hays and Bullock 1994, Maekawa 1999).

In the case of cultural institutions located in warm, humid climate regions, biodeterioration is known to be a major threat to both collections and buildings (Agrawal 1993, Aranyanak 1993). Caretakers of collections in these regions are progressively installing sophisticated air-conditioning systems, but research and experience have proven that, as is often the case in museums housed in historic buildings, the superstructure and interiors of buildings may not withstand the installation and operation of these systems. While air-conditioning systems can control temperature, relative humidity, insects and pollutants, they are often intrusive to the building's fabric, not to mention being expensive to install, operate and maintain. And, even if the system is custom-designed, there is no guarantee that it will produce the desired results.

Because of these issues, there has been a compelling need to find viable alternatives to air-conditioning systems that are economical, robust and technologically simple to operate. The present study was initiated to respond to these needs.

THEORY

In tropical and subtropical climates, moisture content in the outdoor air remains fairly constant throughout the seasons (rainy and dry). However, daily temperature variations range from less than 5°C (9°F) in the rainy season to more than 15°C (27°F) in the dry season. These temperature variations in turn produce inverse levels of relative humidity. Although it may seem that a climate is warm and humid at all times, it is actually always cooler when higher humidity (foggy or raining) is recorded outside. Similarly, indoor areas of higher relative humidity are found in cooler parts of the building (provided that bulk water intrusion is not the direct cause). Basements often have problems resulting from high levels of relative humidity, whereas attics and upper floors typically suffer from heat accumulation and low, as well as varying, levels of relative humidity.

The proposed approach, then, is either to utilize the relatively dry (low relative humidity) outside air to remove moisture accumulated in the building; or to raise the temperature in cooler areas of the building either by warm outside air or heating, rather than cooling the interior air to below its dewpoint temperature in an effort to remove the moisture (and then reheating it). Increasing the temperature causes a necessary reduction of relative humidity in the building, which in turns causes a reduction in microbial activity. The goal is to maintain relative humidity for the collection environment at less than 70%, slightly (5%) less than the threshold relative humidity for significantly increased microbial activity (Brundrett 1990). By providing adequate ventilation that can raise surface temperatures of collection materials to that of the ventilating air, we can reduce water activity numbers on surfaces, arresting microbial activity (Valentín 1998).

The heat accumulation problem can be eliminated (simultaneously improving the overall building ventilation and indoor air quality) by venting hot air away from the upper floors of the building. In a building with multiple floor levels, the climates in intermediate floors are affected by those floors above or below, and can be improved by correcting climates in the extreme floors. If passive features don't produce sufficient ventilation, dry outside air can be brought into the building through an appropriate filter using mechanical ventilators. Heating the building's interiors can be achieved either by a) improved solar heat gain at the problematic area; b) using space heaters; or c) bringing in warm and relatively dry outside air using ventilators.

Mixing necessary for an equilibrated room environment can be achieved by installing fans in strategic locations and rearranging objects in display and storage areas to allow sufficient air movement. This strategy arrests microbial activities, not only in the environment (air), but also on surfaces of the colllections themselves by increasing the surface temperature (reducing the water activity number). We can simply exhaust the accumulated heat by opening vents or installing exhaust fans in higher parts of the building. These improvements can be made without major alterations of the building fabric or design, just reactivating and improving the original (passive) building ventilation features while adapting the least invasive electromechanical devices.

Operating residential or industrial-type ventilators mounted in existing windows and vents as well as convection heaters in open areas can achieve the desired results. These ventilators can be operated with a programmable humidistat control that switches the equipment based on an algorithm, using outputs from relative humidity sensors located both inside and outside of the building.

THE BUILDING AND METHOD

For this study, we selected a historic house in a subtropical region of the United States. The criteria for selection were that the building had to be made of either brick or stone masonry (as are most surviving historical buildings in warm, humid climate regions), and that there was evidence of moisture problems contributing to a high level of microbial activity in the building and its finishes. A third consideration was that the building did not suffer from basic maintenance issues.

In the first year of the study, interior climates and the surrounding site were monitored, allowing us to define climate parameters for both areas. Based upon the collected information, a climate control system was designed and installed. Afterwards, indoor environmental changes made by the system and consequent improvements to the building and its fabric were evaluated.

Local Climate

Jekyll Island is located on the Atlantic coast of Georgia, approximately 129 km (80 mile) south of Savannah and 13 km (8 mile) southeast of Brunswick, in the ASHRAE-defined warm, humid cooling climate region (ASHRAE 2001) at N31°01' latitude and W81°03' longitude. The sandy island is slightly above sea level and mostly flat.

Easterly winds of about 2.9 m/s (6.5 mph) create a maritime influence that modifies summer heat and winter cold. June, July, and August are the hottest months, with temperatures averaging near 26°C (78.8°F). December, January, and February are the coolest months, with temperatures near 10°C (50°F). The average relative humidity is 75%, ranging from about 90% in early morning hours to about 55% in the afternoon (NOAA 1999). Most of the rainfall occurs during the summer months, and the annual average of precipitation (over 30 years) is 1271 mm (50.04 in). The annual average temperature is 19°C (66.2°F), with the average high value being 25°C (77°F), and an average low value of 14°C (57.2°F) (WeatherPost 2001).

The Historic Building

Hollybourne Cottage dates from 1890 and is part of the Jekyll Island Historic District. It has a distinctive architecture style described as “Jacobethan Revival” (Figure 1), with a building structure that reflects the professional interest of its owner, Charles Maurice, a successful bridge builder from Athens, PA (Watson&Henry 1998). The cottage is situated on the west side of the island, and the surrounding area is flat and filled with overgrown trees taller than the cottage. It was sold by the Maurice family in 1947 to the State of Georgia, and has been vacant ever since.

Figure 1 Main (west) façade of Hollybourne Cottage.

The cottage is a T-shaped, two-and-one-half story structure with a full height basement. The master's area is located in the north-south wing, and the servant's area is in the east wing. Unlike the majority of cottages on the island which are made of timber and shingles, Hollybourne is made of faux tabby (concrete) walls and double brick foundation walls that carry the structural load. The interior of the building is made of wood.

The floors are connected through two staircases: the large main stairway at the center of the building, connecting only the first and second floors, and the steep and narrow secondary stairway, starting in the basement and ending in the attic. The total floor area is approximately 1,050 m_ (11,300 ft_), with an air volume of 2,549 m_ (90,000 ft_).

The cottage's design and architectural details indicate that the owner and the architect were aware of the local climate and took some passive measures to provide a comfortable interior throughout the year. The building used to have a covered deep porch at the end of its south wing as a continuation of the parlor, giving shade and fresh air to that living space. The large window openings on the four facades have externally-located adjustable wooden louvers that allow for cross ventilation while preventing excessive solar heat gains and/or rains in summer. The cottage once had an underground drainage system that carried rainwater to the sea, keeping the foundation walls as dry as possible.

In spite of these original passive climate control features, the cottage has suffered from moisture-related deterioration problems, some being due to the original construction of tabby walls. The wooden wall structures that once served as the form for pouring the tabby concrete absorbed the moisture from the tabby, causing them to soften and later rot (Watson&Henry 1998). This rot extended to the wall panels and floors. The tabby concrete also absorbed water during driving rains and whenever gutters and downspouts overflowed; this moisture must have also contributed to the rotting of wall panels. Other problems were caused by a combination of a high water table, frequent rainfalls and lack of proper maintenance of the gutter, downspout, and drainage systems. All of these conditions contributed to accelerated deterioration of the building materials, particularly its lower parts (floor-supporting beams, joists, sub-floors and structural members of the first floor).

Upper floors of the cottage accumulated heat as all windows were always closed; and the temperature, particularly in the attic, was uncomfortably high in summer months. However, no obvious cracking or decay of wood members is found in the attic.

The Spaces under Investigation

To improve the environment of the whole building, the installation of a mechanical ventilation system was planned for the two most problematic areas of the cottage: the basement, which was the major source of high relative humidity, and the attic, where heat accumulation was a serious concern.

Basement. Figure 2 shows the basement floor plan. Double brick foundation walls with an air gap of about 0.13 m (5 in) create the basement boundary, about 2.44 m (8 ft) high. It has a concrete slab floor that has been broken or lost in several areas. The floor area is approximately 279 m_ (3000 ft_) and the air volume is 651 m_ (23,000 ft_). The walls have a total of 17 identical hinged (operable) windows, measuring 0.6 x 0.9 m (2 x 3 ft), and are symmetrically distributed just above the grade (1.2 m or 4 ft from the basement floor). These windows do not have a louver. During heavy summer rains (in August), water leaks were confirmed at some windows.

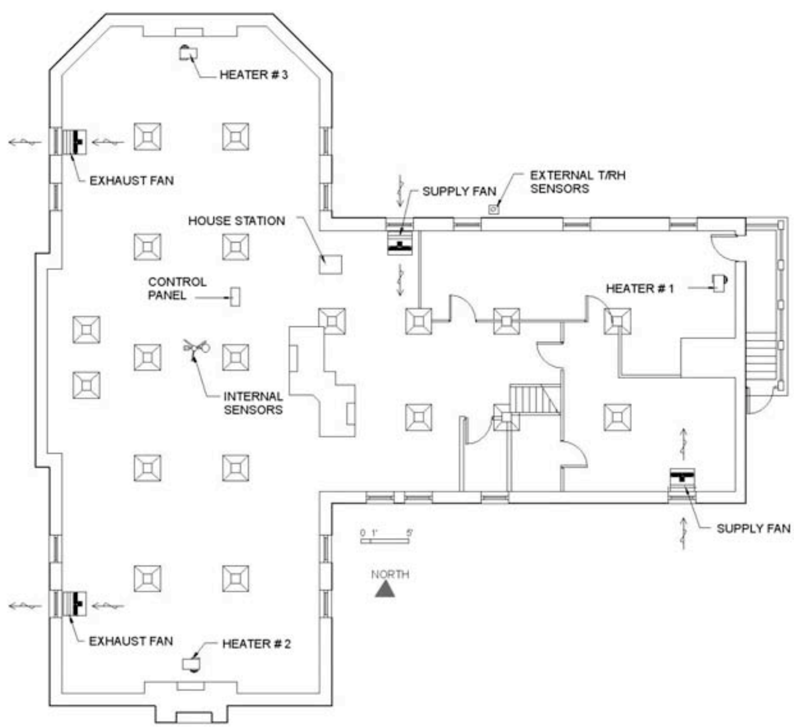

Figure2 Basement plan of the cottage, showing the position of the climate control system and its mechanical units (ventilators and heaters).

This large open space is supported by 20 columns made of plain bricks, which are 0.3 x 0.3 m (1 x 1 ft). The columns are uniformly distributed and bear the wooden structure of the upper floors. Wooden partitions were later added (date unknown) in the east wing of the basement to create a laundry room, ironing room, small storage room and restroom.

In the summer, the basement environment was very humid (nearly 100% RH at all times) and a strong mildew smell permeated the place. Supporting beams and floor joists for the first floor were rotted in many places; the north wing was the worst area. Many parts of the first floor (both the hardwood floor and sub-floor) had decayed, and a large portion of the floor had been lost. Large plywood panels and tarpaper (underlayment for roofing) had been placed on the lost areas to maintain the spatial segregation between the first floor and the basement. Members of the preservation crew from Jekyll Island operated a large dehumidifier in the basement to keep the space dry before the present study was initiated.

Attic. Figure 3 shows the attic space floor plan, consisting of a long narrow finished area extending east-west, with two small rooms at both the west (front) and east (rear) ends, and an unfinished north-south wing. The attic has an area of approximately 214 m_ (2300 ft_) and an estimated air volume of 396 m_ (14,000 ft_). The ceiling height in the midpoint is 2.3 m (7 ft 6 in). It has seven windows of various sizes: two large, rectangular -- 0.9 x 0.6 m (3 x 2 ft), on the east facade; two large, quarter circle with 0.9 m (3 ft) of radius, on the south façade; one small square -- 0.6 x 0.6 m (2 x 2 ft) on the west facade; one small square -- 0.6 x 0.6 m (2 x 2 ft) on the north facade, in the middle; and the last square one -- 0.6 x 0.6 m (2 x 2 ft), facing south, also in the middle of the space. The windows had no louvers. Central and rear chimney shafts penetrated the space.

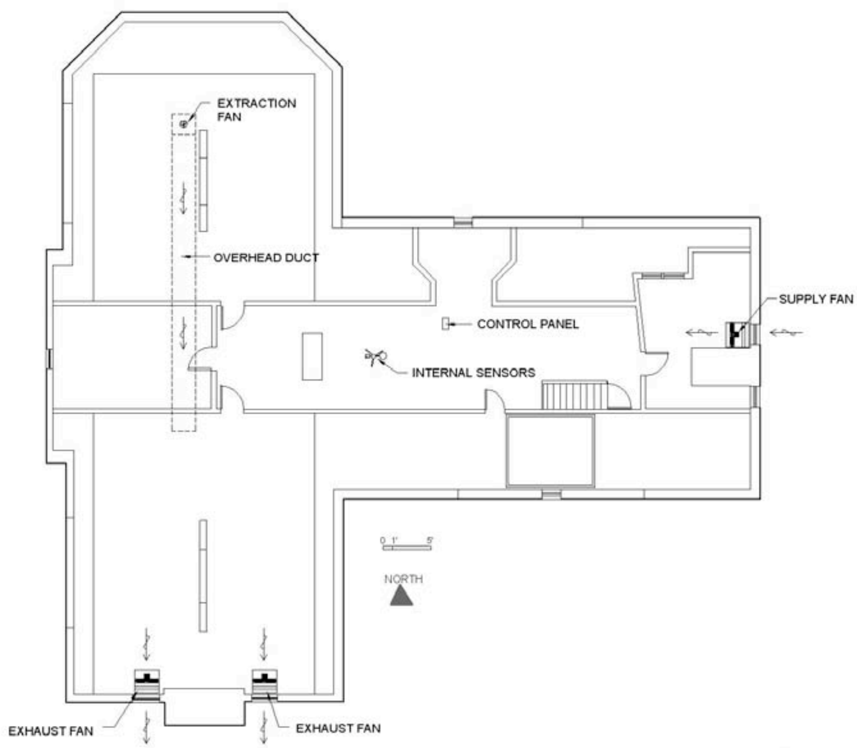

Figure 3 Attic plan of the cottage, showing the position of the climate control system and its mechanical units (ventilators).

The attic was the hottest and stuffiest space during the summer. The wood shingles were considerably weathered and some rain leakage was detected during heavy rains. Water stains were also visible on the wooden floor near the windows on the southern and eastern facades. Bases of the roof, where the roof meets the building's exterior walls, had significant openings; these were plugged to reduce uncontrolled air infiltration.

Climate Monitoring

To monitor the climate, two autonomous stations were installed onsite. One station -- the weather station -- was placed outside at the north edge of the lot, about 12 m (40 ft) north of the building, to assess the exterior climate. The other -- the house station -- was located in the basement of the cottage, with climatic sensors distributed throughout the building to assess the interior climate at all four levels: basement, first floor, second floor and attic.

The weather station measured basic meteorological parameters for characterizing exterior climate: wind speed and direction, solar radiation, air temperature and relative humidity, dew point temperature, and rainfall. In addition, groundwater levels as well as the volumetric water content of surface sandy soil were monitored to establish the relationship between rainfall, soil moisture, and groundwater level.

Inside, the house station measured air temperature, relative humidity, and surface temperatures of floors and ceilings on each floor, recording variations along the floor levels as well as variations (stratification) within each floor. These sensor arrangements also indicated opportunities for condensation to occur on cooler surfaces, either in the basement (summer) or in the attic (winter). In addition, air velocity was measured in the basement to assess air movements generated by air infiltration (before the installation of the climate system), and by ventilators and convective heaters (after the installation). Air temperature and relative humidity were measured at three locations in the wall cavity of the foundation. The same measurements were made in tabby concrete walls at the first floor above the cavity measurements in the basement. These measurements were intended for estimating the moisture migration from the foundation to the structural tabby.

A temperature and relative humidity sensor was placed directly on the slab floor of the basement. Over the sensor, a large (1.5 x 1.5 m or 5 x 5 ft) vapor barrier sheet and fiberglass insulation material were placed to isolate the environment from the rest of the basement's atmosphere. This measurement was taken to evaluate the presence of any moisture evaporating from the slab floor.

The house station also measured volumetric water content of the sandy soil adjacent to the foundation on the north side of the cottage. These measurements were conducted at two depths: at the surface and at approximately one-meter (3 ft) below the surface. These measurements provided clues as to the sources of water migrating to the basement floor and walls. These parameters were measured every 30 seconds, and average values over 15 minutes were recorded at the two stations. These climatic data were periodically downloaded through a telephone line to a base station for analysis.

Climate Control System

The climate control system, installed in June 2000, consisted of sets of supply and exhaust fans for ventilation in the basement and attic, and convection heaters for heating the basement. The volume of ventilation was designed to produce 6-8 air changes per hour in order to ensure moisture removal as well as good mixing (Shari, Wolbrink, Bowen, Neelley, and Sampsel 1979). The heaters were selected to produce a temperature increase of only a few degrees in the space.

Anti-microbial filters (ASHRAE 52.1 Rated Average Efficiency 25-30%) and motorized shutters were installed with the supply fans to control the quality of fresh air during fan operation, and to limit the amount of infiltrating air when the fans were not operated. The exhaust fans were equipped with gravity-operated shutters that opened only during fan operation.

In the basement, two supply fans, two exhaust fans, and three convection heaters (see Table 1 for their specifications) were installed as shown in Figure 2. The supply fans were placed in existing windows on the north and south facades of the east wing, and the exhaust fans were placed far apart on the windows of the west (front) façade of the north-south wing. With this arrangement, fresh air entered from the east (rear) wing and the central area, and then exited from the north and south ends of the basement. The excess amount of supply air was designed to produce slightly positive pressure in the basement in spite of large air leakage paths in the space. The heaters were mounted on floor joists at the three (north, south and east) ends of the basement, to avoid localized heating and to uniformly distribute the heat.

A programmable controller activated the ventilators whenever the outside relative humidity was below 70% and the inside relative humidity was higher than 70%, regardless of indoor and outdoor temperature (as described in the Theory Section). The ventilators ran until the basement's relative humidity was reduced to 65% or less. The heaters were activated whenever both outside and inside relative humidity exceeded 75%. The heater ran until the inside relative humidity was reduced to less than 70%, the outside relative humidity had fallen below 70% (at which time the ventilator would activate), or when the air temperature in that space reached 30°C (86°F). This temperature was estimated based on the moisture ratios found in the basement during 1999.

TABLE 1
Performance specifications for the mechanical units used in the climate control system.

Units/Features	Power	Flow Rate	Static Pressure
Supply fan	0.25kW (1/3 hp)	1.130 m_/s (2,395 cfm)	0.062 kPa (1/4")
Exhaust fan	0.12kW (1/6 hp)	0.847 m_/s (1,795 cfm)	0.062 kPa (1/4")
Extraction fan	0.02kW (0.0268 hp)	0.052 m_/s (110 cfm)	
Heater	7.5kW (25,600 Btu/hr)		

In the attic, one supply fan, two exhaust fans, and one residential-type extraction fan (see Table 1 for their specifications) were installed as shown in Figure 3. The supply fan was placed in one of the two windows located on the east (rear) end of the building, and the exhaust fans were placed in two windows at the south façade of the south wing. Fresh air entered from the east end of the building and flowed through the east wing, exiting through the south wing. Since the attic's north wing did not have an outside opening, a ducted extracting fan was placed in the middle of the space at approximately 2 m (6 ft 6 in) from the floor to draw hot stagnant air to the south wing, where the two exhaust fans evacuated the hot air along with air directly flowing from the east wing.

In the attic, since the focus of the climate control was the removal of accumulated heat, control of the relative humidity was not initially considered. Therefore, the controller was programmed to activate the fans whenever the inner temperature of the roof (in its northwestern area) became higher than the outside air temperature and the attic air temperature became equal to or higher than 30°C (86°F). The temperature limit was selected in an attempt to keep the relative humidity in the attic at a stable level. The fans were deactivated when the roof's temperature became lower than 30°C (86°F). The depressurization of the attic was necessary to assist the buoyancy flow of warm air from the first and second floors.

Other Measures and Measurements

Preparations. Steps were taken to ensure the simplest and least intrusive methods for installing the mechanical equipment in the cottage. Once a window had been selected, its windowpanes were removed. Then, an oversized plywood panel with an opening for the fan was mounted over the window, preserving the original windowsills, frames and moldings. The fan was mounted with screws to the plywood panels on a simple stand that bore its weight. A wooden louver was mounted on the outside of the window to camouflage the fans from the outside, although selected windows did not originally have louvers. These louvers were fabricated to reproduce the original appearance found on the first and second floors.

Airborne Particulates. The amount of deposited particulate matter in the cottage was monitored using the quartz crystal micro-balance technique. In this process, quartz crystal plates, measuring 12.7 mm (0.5 in) and 0.178 mm (7 mil) thick each, were coated with grease on both sides to ensure adhesion of the particles, and its natural frequencies were measured. Then, their horizontal surfaces were exposed to the environment at approximately 1.5 m (5 ft) from the floor. On each floor, the crystals were exposed for a period of two months and then retrieved for frequency measurement. The weight of deposited dust was measured from the shift of the natural frequency of the crystal. The method has a sensitivity of 1.4 nanograms.

Airborne Microbes. The objective of the microbial (viable matters) analysis was to provide an evaluation of the indoor air quality that would assist in determining not only the microbial condition in the building prior to improvement, but also evaluate the efficacy of the climate improvement. 28.3 liters (1 ft_) of air samples were impacted to cultural media through an air pump. Malt and soy agars were used to evaluate fungi and bacteria, respectively. Those plates were then transported to a laboratory and incubated for seven days at 30°C (86°F) for bacterial growth; and for 14 days at 25°C (77°F) for fungal growth. Results were given in "colony forming unit per cubic meter" (CFU/m_). For this study, staff members of the local authority performed sample collections at each floor level and outside. Samples were collected every two months on the average, then mailed to a commercial service laboratory for analysis.

RESULTS AND DISCUSSIONS

Measured Outside Conditions

In 1999, the average outdoor temperature was 20.4°C (68.7°F) with a standard deviation of 6.7°C (12.1°F). 25% of the collected data were higher than 25.3°C (77.5°F), and 25% were lower than 15.5°C (60°F). The maximum value recorded was 39.2°C (102.6°F) on August 1st at 4:00 PM, and the minimum was - 2°C (28.4°F) on December 26th at 7:30 AM. The average relative humidity was 82.5% with a standard deviation of 16%. 25% of the measurements taken onsite were higher than 96% RH, and 25% were lower than 73% RH. The minimum relative humidity value measured was 21% on March 2nd at 12:45 PM. Figure 4 shows temperature and relative humidity values recorded at the site, plotted on a psychrometric chart.

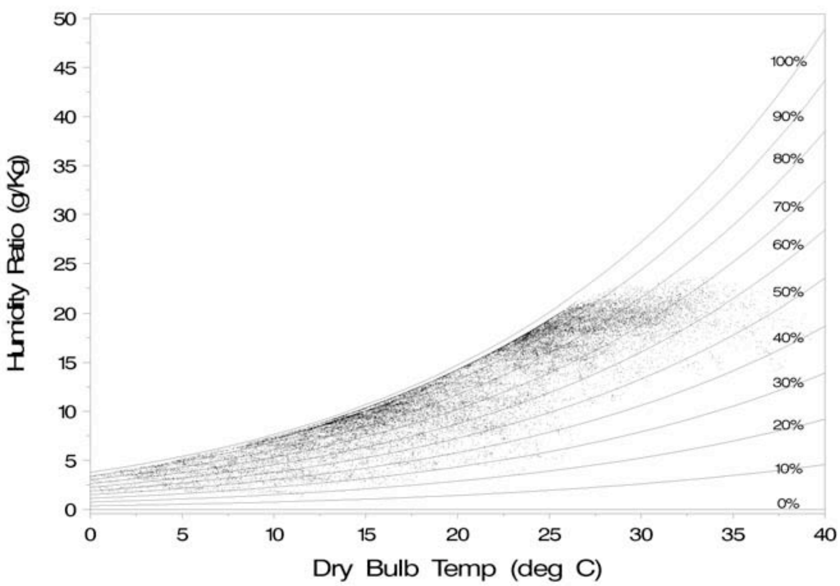

Figure 4 Psychrometric chart showing the measured outdoor air conditions at Hollybourne Cottage, 1999-2000 (15-minute data).

The accumulated rainfall in 1999 was 800.5 mm (31.52 in), with a maximum rate of 23.9 mm / 15 min (0.94 in / 15 min) on June 10th at 7:00 PM. The average wind speed was 0.52 m/s (1.2 mph), from a north-north-east direction. The maximum value was 1.32 m/s (2.9 mph) on March 3rd. There were many calm days.

Climate data for the corresponding two periods, i.e. before (June 1999 - January 2000) and after (June 2000 – January 2001) installation of the indoor climate control system, were compared to evaluate the climatic similarity of the two periods (Table 2). The mean temperature fell from 21.2°C (70.2°F) to 19.4°C (66.9°F), with standard deviations of 7.1°C (12.8°F) and 8.6°C (15.5°F) respectively. The minimum values were - 1.9°C (28.6°F) prior to installation and - 4.5°C (23.9°F) after installation.

The mean relative humidity was reduced from 83% to 78%, with standard deviations of 15.6 and 15.4% respectively. The mean humidity ratio decreased from 13.9 g/kg of dry air to 11.9 g/kg of dry air with standard deviations of 5.3 and 5.2 g/kg of dry air respectively. These statistical values show that the period after installation was slightly cooler and drier than the previous period, although distributions of the data were similar.

TABLE 2

Summary of statistical values for the climatic data collected outside the cottage before and after the installation of the climate control system.

	Air temperature		Relative Humidity		Humidity Ratio	
	Before (June 1999 – January 2000)	After (June 2000 – January 2001)	Before	After	Before	After
	°C	°C	%	%	g/kg	g/kg
Mean	21.2	19.4	83	78	13.9	11.9
Standard deviation	7.1	8.6	15.6	15.4	5.3	5.2
Maximum	39.2	39.7	100	99	23.9	21.3
Minimum	-1.9	-4.5	17	19	1.4	1.3

The groundwater level ranged between 0.9 m and 0.35 m (3 ft and 1 ft) below the ground surface between December 1998 and September 1999. But the level dropped below 1.2 m (4 ft) and the well dried in November 1999. It has remained dry to this date (March 2001), with occasional rises due to rain events. The moisture content of surface soil remained dry at less than 5% vol. However, it increased to the 20-30% range during rain. At 0.9 m (3 ft) subsurface, the moisture contents remained stable at 12% throughout the year.

A relative humidity sensor with a vapor barrier sheet, placed on the basement slab floor, measured a vapor-saturated environment, indicating rising dampness through the slab floor. Relative humidity sensors sealed into cavities of the foundation walls again indicated a vapor-saturated environment in the walls. These measurements also indicated that moisture is permeating through walls and slab of the basement into the basement. The amount has been estimated to be much less than since the monitoring started in December 1998, given that the groundwater level was significantly lowered during the second year.

Climate in the Cottage

Operation of the Climate Control System. During the summer, both ventilators and heaters in the basement were activated frequently. The ventilators operated during daytime (from about 10:00 AM to about 4:00 PM), and heaters warmed the basement throughout the night (from about 6:00 PM to about 8:00 AM). With these operations, relative humidity values in the basement were kept below 70% most of the time, while air temperature was kept below 30°C (86°F). Climate in the basement during July 23-27, 2000 while the system was operating is shown in Figure 5. The ventilators were activated during midday when the outside relative humidity decreased to less than 70%. The heaters, to a greater or lesser extent, were activated the rest of the days.

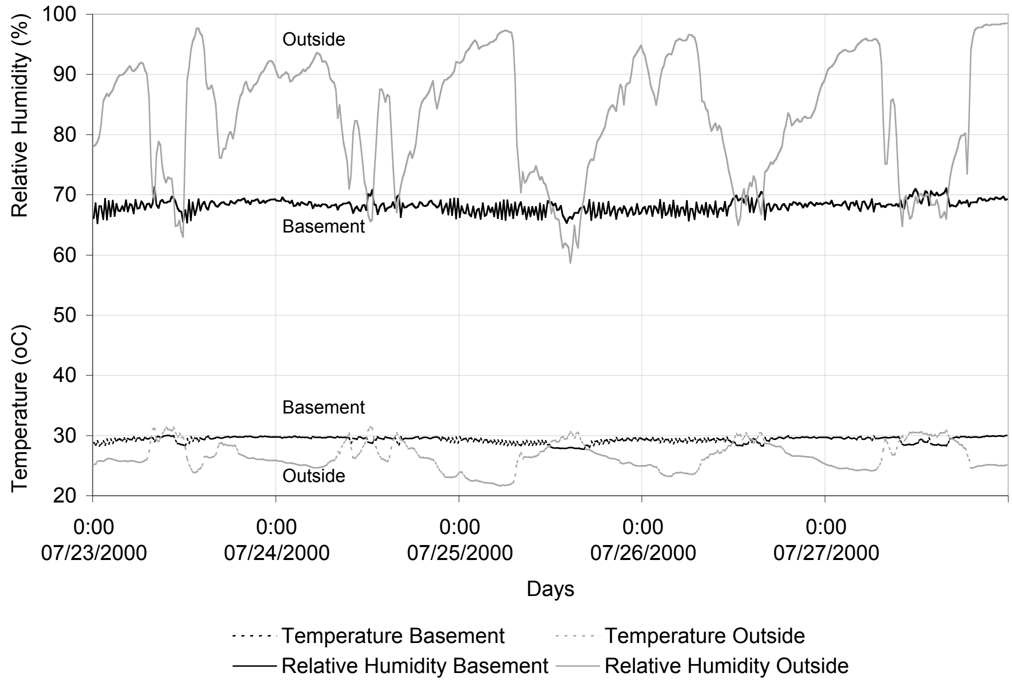

Figure 5 Measured environmental conditions in the basement, while the climate control system was in operation.

In the attic, the ventilators were activated normally in the afternoon until late in the evening (from about 12:00 PM to about 10:00 PM). Their operation was extended on hot days, when the roof's inner surface temperature rose above 35°C (95°F), as occurred on days 23rd and 27th of July 2000 (Figure 6). The attic temperature was kept at a few degrees above 30°C (86°F), while the relative humidity was maintained between 60% and 70%.

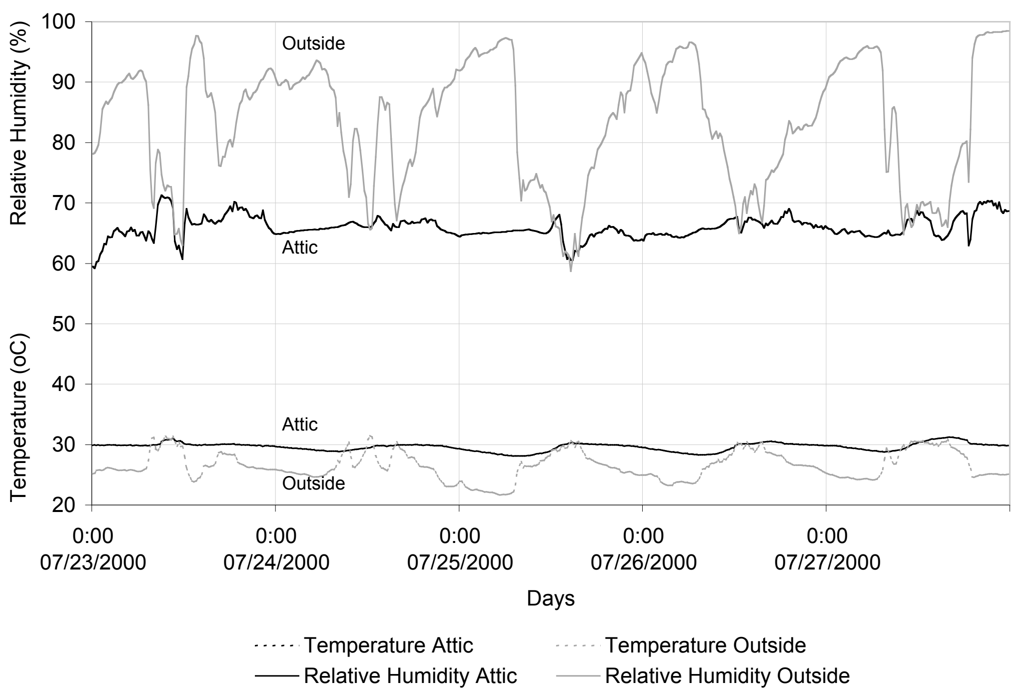

Figure 6 Measured environmental conditions in the attic, while the climate control system was in operation.

Basement. Table 3 shows a statistical summary of air temperature, relative humidity, and humidity ratio before and after the installation of the climate control system in the basement. In the basement, the mean temperature increased from 21.4°C (70.5°F) to 24.1°C (75.4°F). This temperature increase contributed to the significant reduction of the mean relative humidity, from 87% to 65%. The mean humidity ratio in the basement reduced from 14.7 g/kg to 13 g/kg. This reduction is most likely due to a reduced moisture content of the outside air during the second year of testing (post-retrofit period).

TABLE 3
Summary of statistical values for the climatic data collected in the basement of the cottage before and after the installation of the climate control system.

	Air temperature		Relative Humidity		Humidity Ratio	
	Before (June 1999 – January 2000)	After (June 2000 – January 2001)	Before	After	Before	After
	°C	°C	%	%	g/kg	g/kg
Mean	21.4	24.1	87	65	14.7	13
Standard deviation	4.6	6.2	10.7	5.7	4.9	4.7
Maximum	27.2	30.6	98	76	21.5	19.4
Minimum	11.7	8.9	51	43	4.5	3.3

Histograms of air temperature and relative humidity before and after the installation of the climate control system for the basement are shown in Figures 7 and 8. In the basement, the major change in the temperature distribution was the addition of events for 27.5°C (81.5°F) - 32.5°C (90.5°F), which was the largest occurrence (Figure 7). Prior to the installation of the system, 50% of the data points for relative humidity measurements (Figure 8) were found between 84% and 100% (34% of the data were above 95% RH). Relative humidity values above 75% were eliminated after the installation, and the largest occurrences are now found between 65% and 75%.

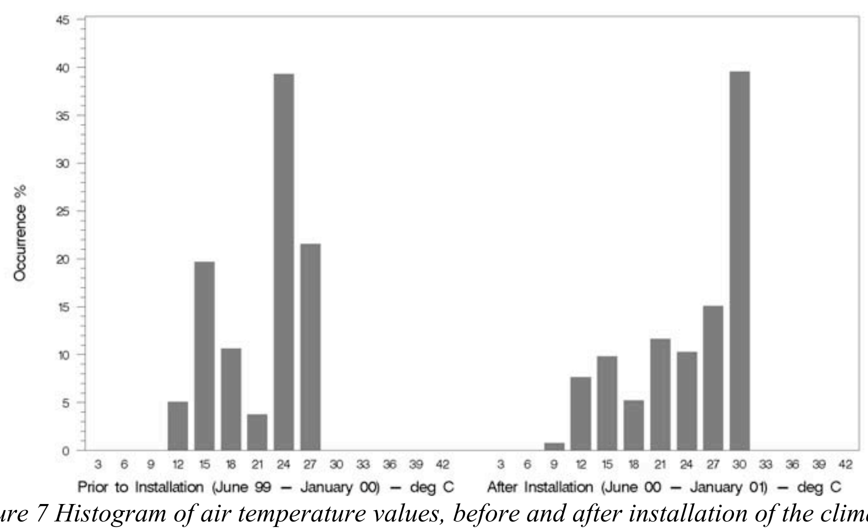

Figure 7 Histogram of air temperature values, before and after installation of the climate control system in the basement.

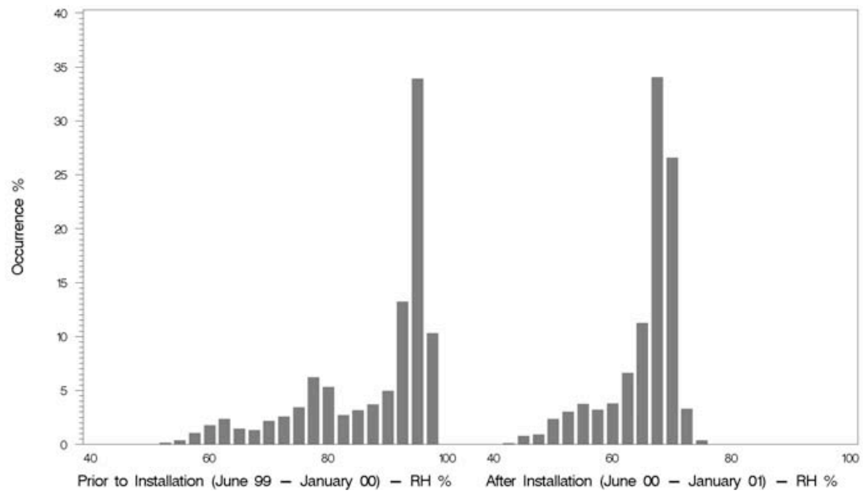

Figure 8 Histogram of relative humidity values, before and after installation of the climate control system in the basement.

Attic. A statistical summary of air temperature, relative humidity, and humidity ratio in the attic is shown in Table 4. Comparisons are made before and after the installation of the climate system. In the attic, the decrease in the mean temperature value was only 1.1°C or 1.9°F (from 24.9°C (76.8°F) to 23.8°C (74.8°F)). However, the maximum temperature dropped from 41.4°C (106.5°F) to 37.1°C (98.8°F). The mean humidity ratio in the attic reduced from 15.1 g/kg to 13.5 g/kg. This reduction may also be due to the reduced moisture content of the outside air during the second year of testing (post-retrofit period).

TABLE 4
Summary of statistical values for the climatic data collected in the attic of the cottage before and after the installation of the climate control system.

	Air temperature		**Relative Humidity**		**Humidity Ratio**	
	Before (June 1999 – January 2000)	After (June 2000 – January 2001)	Before	After	Before	After
	°C	°C	%	%	g/kg	g/kg
Mean	24.9	23.8	72	69	15.1	13.5
Standard deviation	7.9	7.6	6.1	6.4	5.6	4.8
Maximum	41.4	37.1	89.5	92	30.4	23.9
Minimum	7.3	3.4	57.5	36	4.5	3.1

In the attic, the occurrence of high temperature events recorded prior to the installation of the climate system were eliminated or significantly reduced, and the largest occurrence is now found in a range from 27.5°C (81.5°F) to 32.5°C (90.5°F) as shown in Figure 9. This indicates that the effort to reduce high temperature events has been successful. Although the relative humidity distribution at the higher end did not change, more events of lower relative humidity were found (Figure 10). This may be due to ingestion of warm dry air for venting the attic or influenced by the lower outdoor humidity conditions experienced during the post-retrofit period.

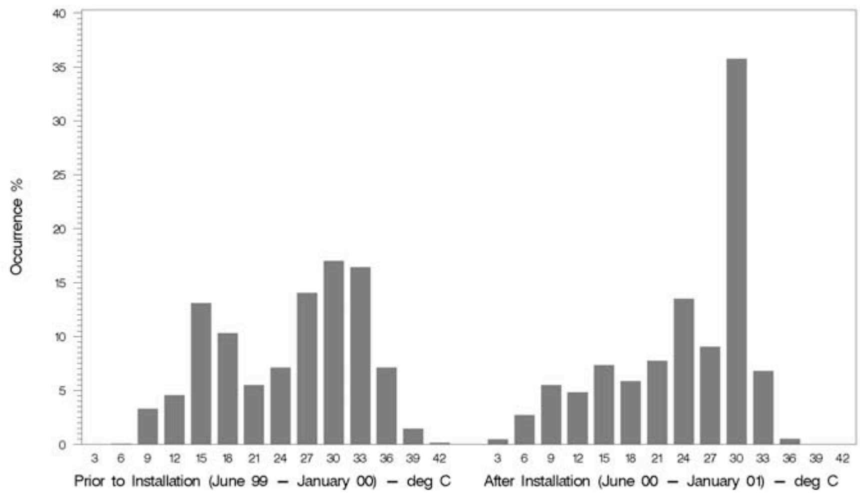

Figure 9 Histogram of air temperature values, before and after installation of the climate control system in the attic.

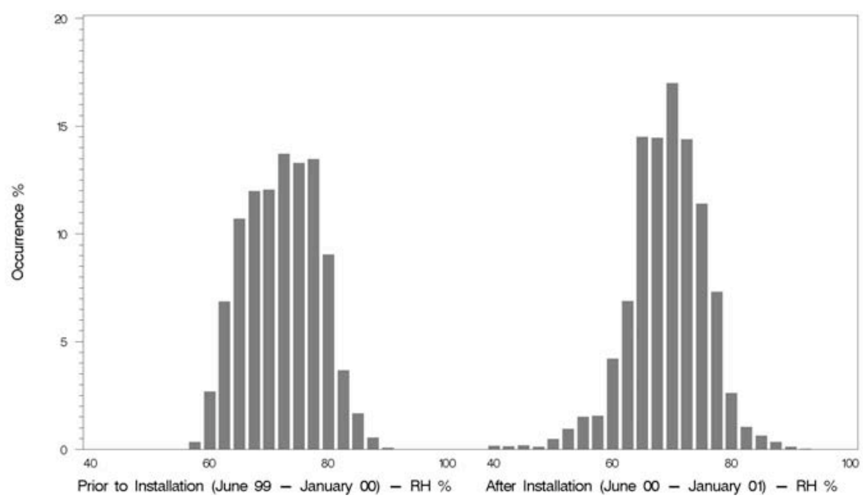

Figure 10 Histogram of relative humidity values, before and after installation of the climate control system in the attic.

First and Second Floors. The improvements achieved in the basement and attic positively affected the first and second floors. An average condition of 23.5°C (74.3°F) and 65% RH was produced on both floors after the installation of the climate system. On the first floor, the average temperature increased from 22.8°C (73°F) to 23.5°C (74.3°F) with a larger standard deviation from 6.1°C (11°F) to 7.8°C (14°F). The average temperature was reduced from 23.8°C (74.8°F) to 23.5°C (74.3°F) with also an increased standard deviation from 6.9°C (12.4°F) to 7.5°C (13.5°F) on the second floor. However, most importantly, the relative humidity reduced from 75%, the threshold value for an increased microbiological activity, to 65%, a safe level, with a significantly reduced standard deviation of 5.6% on the first floor. A similar improvement with even a smaller standard deviation of 4.8% RH was achieved on the second floor. Averages of the humidity ratio also reduced on the floors, but those may be due to a reduction of the moisture content of the outside climate.

Dust Deposition. Dust deposition has been monitored in the cottage since it was swept clean in early December 1998. So far, there have been 12 samples taken on each floor as shown in Figure 11. As a general rule, the amount of particles in the building followed a seasonal pattern. The amounts were less in the wet season (see samples of 9/21/99 and 10/10/00) than in the dry period. Smaller amounts of particulate matters were present in the environment during rain and highly humid days, resulting in lower deposition rates. In the period prior to the installation of the system, the first floor produced the highest average value (22.7 ng/day), followed by the attic (18.6 ng/day). The basement and the second floor presented similar values (16.4 and 15.4 ng/day). After the installation of the system, the trend was maintained, with lower figures, except for the attic. The dust level in the basement was reduced to an average of 11.9 ng/day, 16.5 ng/day on the first floor, 14.5 ng/day on the second floor, and increased slightly to 18.7 ng/day in the attic.

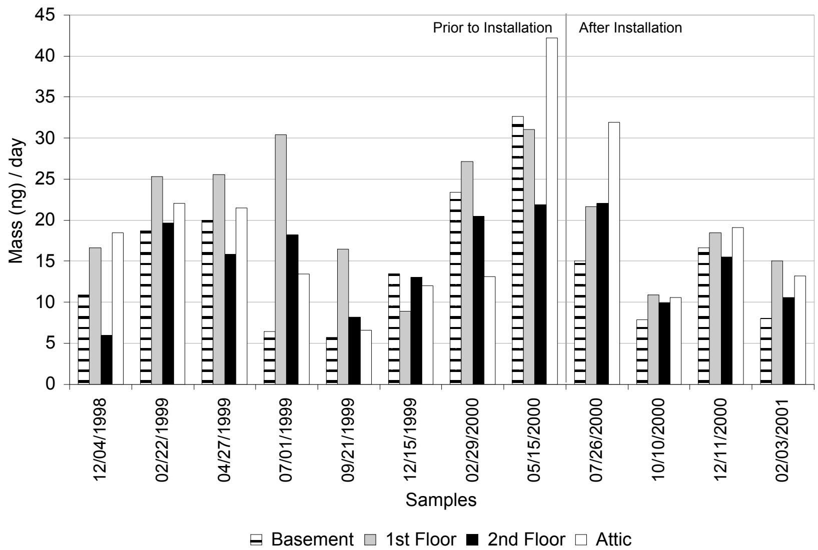

Figure 11 Dust monitoring results for Hollybourne Cottage.

Prior to the installation of the climate control system, preparation work was performed in the cottage. The highest deposited values occurring in May 2000 coincide with the work, and the high deposition rate continued for the following two months. However, in the months after that, the rates reduced and stabilized to those levels recorded prior to the installation. Variations that existed prior to the installation among floor levels were significantly reduced, indicating that mixing of the climate in the building by the climate system was effective.

Although the cottage was cleaned prior to start of the dust monitoring, dust sources in the building could not be eliminated. Rotted wood pieces continued to shed a dusty powder, and interior paints on walls and ceilings had long lost their binder and were peeling and flaking from minute disturbances in surrounding areas. These deterioration conditions are considered to be contributing factors for the high levels of dust deposition rates. It is unlikely that a significant amount of dust was introduced to the building by the ventilation system, since fresh air had been filtered before it was brought into the building.

Microbial Contamination. Bacterial activity in the cottage followed a seasonal pattern, with figures increasing toward the middle of the year, and decreasing toward February. This may be due to higher levels of temperature and relative humidity in summer. Consistently higher bacterial activities were recorded in the attic and the second floor, and they remained stable in comparison to the rest of the cottage. The reason for this is unknown, but it is likely that animal intrusion, such as squirrels, contributed to those high, steady figures there. The last sample (5/31/01) showed that bacterial activity decreased on the second floor (530 and 282 CFU/m_), and increased on the first floor (177 and 318 CFU/m_), in relation to the same period last year (5/3/00). In the basement, the activity could not be compared, since there was no bacterial growth in the first sample (0 and 247 CFU/m_). As for the attic, the last sample seemed to be contaminated (707 and 3286 CFU/m_). The most common bacteria were *Bacillus subtilis*, *Bacillus pasteurii*, and *Streptomyces* (PureAir 2001).

Figure 12 shows a bar graph of the fungal activity in the cottage before and after the installation of the climate system. Contrary to bacterial activity, no seasonal trend was detected for fungal activity, although a general decrease in activity was noted for the last sampling performed (5/31/01). The most ubiquitous fungi in the cottage were *Cladosporium cladosporiodes*, *Penicillium frequentans*, *Chaetomium species*, followed by *Geotrichum candidum*, *Aspergillus fumigatus*, *Trichoderma viride*, and *Alternaria alternata* (PureAir 2001). After the installation of the climate control system, the average fungal activity decreased in all floors, except in the attic (from 141 to 749 CFU/m_).

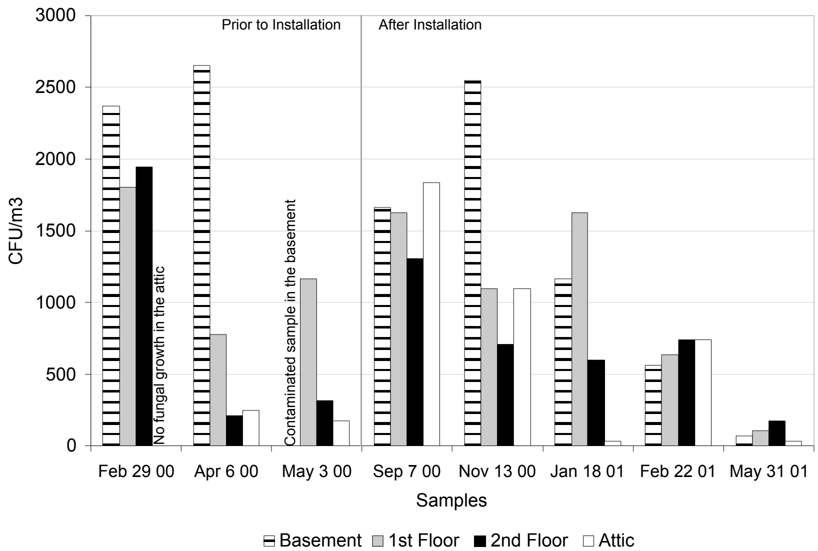

Figure 12 Microbial monitoring results for Hollybourne Cottage (fungi).

Cost Analysis.

- Capital cost. The estimated cost of an air-conditioning system for the entire cottage is between $100,000 and $120,000 US. (This cost was estimated based on previous installations in historical buildings in the district). It would require a 7.5-ton unit for the lower part of the building and a 10-ton unit for the upper part. An extensive ductwork system (cleverly hidden from view) would have to be installed. To compare, the material cost of the tested climate control system was less than $12,000 US. $4,000 of this total was spent on sensors and the controller, the cost of which does not change much for larger applications. Ventilator fans ranged from $600 to $800, and convective heaters cost $300 each. Approximately $2,000 was used for electrical components. A highly programmable controller was used that also worked as a data acquisition device for the climate monitoring; therefore, it was significantly more expensive than a simple controller device needed for this application. (A suitable unit may cost less than $500). System installation was very simple and required less than an estimated 200 man-hours, which amounts to $ 9,000 (@ $ 45.00 US/hr). It is a completely automated and robust system, and in one year of operation, there has been no need for maintenance or repair.

- Energy cost. In the basement, the climate control system operated either the ventilators or heaters almost continuously between June and October 2000. Then the system reduced the operation to mainly heating from October onwards. The ventilators ran a total of 642 hours and the heaters, 749 hours, throughout the year, particularly in September when strong rains fell. In the attic, the ventilators operated for the total of about 312 hours, just between June and September. The seven-month cost (June - December) in energy consumption by the system amounted to $ 1,351.44 in 2000 (@ $0.07 US/kW-hr). In the basement, the ventilators cost $ 81.66 to operate, and the heaters, $ 1,180.60. The ventilators in the attic cost $ 89.18 to operate.

CONCLUSION AND FUTURE WORK

The concept of an economical and technologically-simple climate control system for preserving both historic buildings and their collections in warm, humid climate regions was tested in Hollybourne Cottage in the Jekyll Island Historic District in Georgia, USA.

Prior to the installation, environmental monitoring was conducted over a one-and-a-half year period to characterize climates of both the outside and interior of the building. The exterior climate was recorded as mild in temperature but very humid. The basement was the major source of high humidity, and the attic was a space for heat accumulation.

A custom-designed climate control system, consisting of humidistatically-controlled ventilators and heaters, was installed in the two most challenging interior areas to document the climate improvement achieved. After operating the system for nearly one year, the following conclusions were drawn to evaluate the performance efficacy of the system.

In the Basement

- seasonal temperature variations were significantly reduced;
- only a few events where relative humidity reached above 75%;
- a significantly reduced number of events where the relative humidity reached above 70%;
- humidity ratio was similar to that of the outside;
- temperature slightly increased while relative humidity values considerably decreased, at the cost of slightly higher daily temperature and relative humidity variations;
- dust deposition rate was slightly higher but eventually stabilized;
- environmental microbial count stabilized;
- predominant use of space heating with some energy consumption.

In the Attic

- temperature slightly decreased while relative humidity values remained the same, at the cost of slightly higher daily temperature and relative humidity variations;
- dust deposition followed a seasonal pattern, with this space presenting the second highest figure;
- environmental microbial count slightly increased – reasons unknown;
- extended use of ventilation, however, low energy consumption.

For the majority of time, the climate control system successfully produced and maintained the proposed environmental condition of less than 70% RH throughout the building most of the time. In addition, an acceptable display and storage environment of 65% RH (with less variations) was achieved on the two intermediate floors by allowing higher temperatures as well as larger temperature variations. Moreover, by improving conditions in the extreme floors (basement and attic), we were able to improve the overall climate conditions on the display floors (first and second). The installation was possible with minimum window modifications. The system is simple, inexpensive and requires low maintenance.

We anticipate that the system is capable of producing even better climate conditions (lower relative humidity) in the attic if some heating is provided in that space, particularly during the rainy period. We also foresee a reduction in energy consumption if either another type of heating, such as a natural gas heater, becomes available; or some intervention is implemented on the building fabric (such as the application of vapor barriers and thermal insulation in the basement and thermal insulation of the roof in the attic).

Presently, Hollybourne Cottage is closed to the general public, and so we did not deal with the issues of thermal comfort, noise or vibration. However, we expect that the cottage will be open to visitors in the future, and so these issues are currently being investigated as part of the next phase of this project.

ACKNOWLEDGEMENTS

The authors wish to thank Mr. Warren Murphey, senior director of operations and museum; Mr. Mickey Gordon, former superintendent of preservation; and Mr. John Hunter, chief curator; all three senior staff and the preservation team members of the Jekyll Island Authority for their assistance and support throughout the project both on and off the site, and Mr. Deven Hamilton, of the Getty Conservation Institute, for processing climate data.

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