Testing Alternatives to Conventional Air-Conditioning in Coastal Georgia

SHIN MAEKAWA, VINCENT BELTRAN, and FRANCIZA TOLEDO

Alternatives to traditional HVAC climate-control strategies were employed at a historic structure in a multiphase study and evaluated based on the resulting interior environments and capital and operational costs.

Introduction

The environmental conditions in which a cultural collection is maintained play a significant factor in determining the lifetime of those objects, especially when they contain organic materials such as wood, paper, parchment, leather, and textiles.[1] Exposure to elevated levels of temperature, relative humidity, illumination, pollutants, and particulates can induce accelerated chemical aging of materials. While mechanical damage may be caused by fluctuations in temperature and relative humidity, prolonged periods of high humidity will promote insect, bacterial, and fungal activity, placing a collection at risk of biological damage.

Both the objects and the interior of the building in which they are housed become acclimatized to the relative humidity of a region. Though subject to multiple threats, collections in hot and humid areas are confronted with an overwhelming risk from biological damage, most acutely from microbial activity.[2] This danger is a consequence of extended wet seasons and the resulting high relative-humidity levels, which infiltrate interior spaces. Since toxic fungicide and disinfectant treatments are now used less frequently due to health concerns, climate control has become the paramount defense against microbial damage, signaling a shift from treatment-based to preventive conservation.[3] Maintaining a collection environment below 75% relative humidity can significantly reduce or halt harm from fungal or bacterial activity.[4]

Fig. 1. Hollybourne Cottage, Jekyll Island, Georgia. Photograph by Harlan Hambright, courtesy of the Jekyll Island Museum.

Collection managers have long relied upon air-conditioning or HVAC (heating, ventilating, and air-conditioning) systems as the primary means of climate control. Although focused generally on visitor and staff comfort, these systems can be modified to address the preservation needs of the collection. The use of a typical HVAC system, however, can present a myriad of problems for cultural institutions. Capital costs can be prohibitive, and high operational and maintenance costs have forced some institutions to restrict their use. Installation of thermal insulation, vapor retarder, and air-conditioning ductwork in historic structures can result in damage to the superstructure and interior of the building. Furthermore, installing an HVAC system may not guarantee the desired collection environment. Specialized air-conditioning systems that moderate these issues may exist, but results from such installations are not available.

Building upon research initiated at the Shelburne Museum, in Shelburne, Vermont, alternative climate-control strategies were developed that were economical, robust, technologically simple, and required minimal structural modification of the historic building.[5] These techniques also emphasized the establishment of an appropriate preservation environment, with visitor comfort a secondary concern. Focused particularly on historic buildings in hot and humid climates, the study integrated the use of ventilation and heating or dehumidification to reduce extreme interior relative-humidity conditions. To limit the occurrence of interior relative-humidity levels above 70% (which is 5% below the microbial-growth threshold), ventilation was utilized to exhaust humid interior air and to supply dry outside air when available. Promoting the movement of warm air can also serve to increase temperatures of dry interior surfaces and thereby reduce the water-activity level necessary for microbial growth.[6] When dry exterior air was not available, heating or dehumidification was employed to moderate the collection climate. Basic use of operational modes was determined by control-logic comparisons between interior and exterior relative humidity.[7]

Hollybourne Cottage, located on Jekyll Island in Georgia, represented an ideal venue for testing this alternative climate-control technique (Fig. 1). Located in the humid Southeast, this multistory historic masonry-and-wood structure exhibited biological damage caused by moisture infiltration, even though essential building-maintenance issues had already been addressed. The general objective for the study at Hollybourne Cottage was to arrest the physical decay of the structure by improving the interior climate throughout the building by means other than conventional HVAC systems.

Following environmental monitoring of the site's climate and the building interior, the initial phase of the climate-control experiment began in June 2000.[8] Five subsequent phases were implemented through October 2005, with each employing different techniques of climate control and visitor comfort. The system configuration and resulting climates during each phase, as well as the associated capital and operational costs, is the topic of discussion for this paper.

Site Description

Constructed in 1890 by bridge-builder Charles Maurice and sold to the state of Georgia in 1947, Hollybourne Cottage is now part of the Jekyll Island National Historic Landmark District. Jekyll Island came to prominence in 1886 when it became the winter retreat for some of America's elite families, including those of J. P. Morgan, Joseph Pulitzer, William Rockefeller, and William Vanderbilt. Situated off the Georgia coast, Jekyll Island is roughly equidistant between Savannah, Georgia, to the north (80 miles) and Jacksonville, Florida, to the south (70 miles), and it lies within the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)–designated warm-and-humid climate region.[9] Hollybourne Cottage has remained vacant since 1947 and does not currently house a collection, though it is open to visitors on a limited basis and has become the focus of a renovation program implemented by summer interns.

Deviating from the timber-and-shingle construction typical of local buildings, Hollybourne Cottage is a masonry structure with a wooden interior structural system. Its external walls are composed of faux tabby, a type of concrete made of cement, sand, shells, and water; a wooden sheathing was used as a pouring mold for the tabby in formation of external walls. Reflecting the engineering influence of its owner, the loads of the second floor and attic are distributed via two simple trusses to the external tabby walls to allow for large open spaces on the ground floor. Basement walls are composed of two parallel brick walls with an internal cavity acting as a capillary break, and the basement floor is a concrete slab.

T-shaped in plan, Hollybourne Cottage has an approximate total floor area of 11,300 square feet and an air volume of 90,000 cubic feet. The approximate floor area for the basement, first floor, and second floor is 3,000 square feet each, with 23,000 cubic feet of air volume. The attic has approximately 2,300 square feet of floor area, with 14,000 cubic feet of air volume.

Microbial damage in Hollybourne Cottage was largely localized to the structural members, floor-supporting beam joists, subfloor, floors, walls, and ceilings of the basement and the first floor. A potential cause of the wall damage may have been moisture absorption from the tabby concrete into the wooden-sheathing mold used during the initial construction. Prior damage may have been exacerbated by overflowing gutters, blocked air circulation, and shade from overgrown trees. The presence of a high water table, in conjunction with a partially subterranean basement, lack of drainage away from the structure, and frequent and heavy seasonal rains also may have contributed to the damage. Moisture intrusion into the building was minimized as the result of building and landscape repairs before this experiment began. Throughout the study, liquid water intrusion was not observed in the interior of Hollybourne Cottage. Wooden members in the attic and second floor did not display obvious cracking or decay.[10]

Environmental Monitoring

Since air temperature and relative humidity were the major environmental parameters examined, sensors were placed in locations central to each floor, and one exterior sensor was positioned in protective housing on the north wall. Using concurrent air-temperature and relative-humidity data, the humidity ratio was calculated for each floor and for outside air. Surface temperature was also recorded at the floor and ceiling of each level, though only those of the basement ceiling and the first-story flooring (i.e., areas with extensive damage) will be discussed. A weather station was established in January 1999 in the open space adjacent to Hollybourne Cottage to monitor groundwater level, as well as outside air temperature, relative humidity, and wind.

Climate-Control System

The climate-control system installed at Hollybourne Cottage consisted of sets of supply and exhaust ventilators, as well as convection heaters or dehumidifiers, all of which were integrated with the environmental-monitoring system by control programs. Ventilators were chosen to provide roughly six to eight air changes per hour and utilized existing windows and vent openings. Motorized shutters and antimicrobial filters with an ASHRAE 52.1–rated average efficiency of 25% to 30% were used in

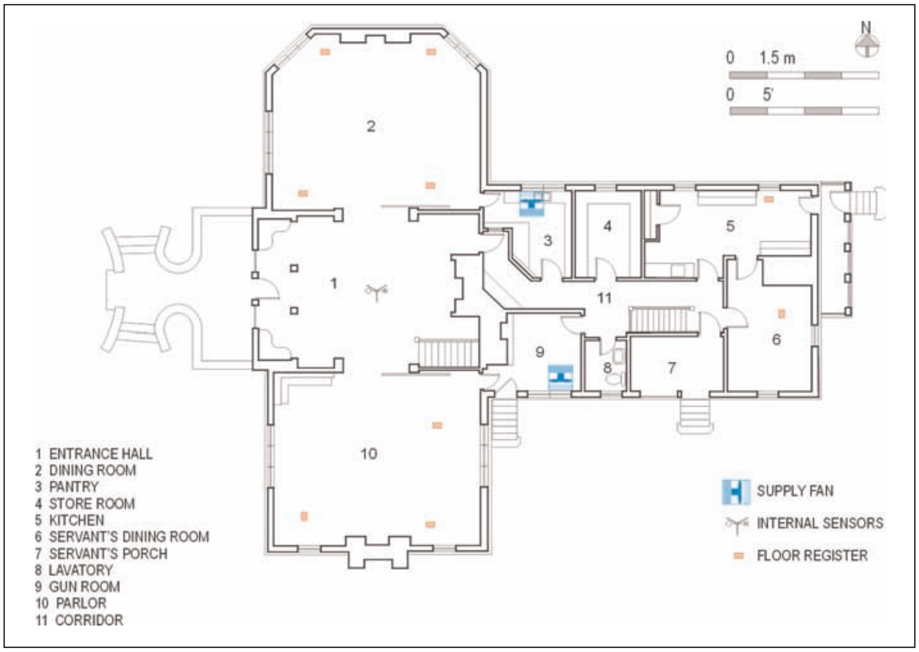

Fig. 2. First-floor plan of Hollybourne Cottage, indicating locations of supply fans, sensors, and floor registers. All images by the authors.

conjunction with supply ventilators, and exhaust ventilators were equipped with gravity-operated shutters. Heaters had the capacity to increase interior air temperatures by approximately 11°F to 13°F, though a programmable maximum-temperature threshold limited their use. Used during latter phases, dehumidifiers installed in the basement in lieu of heaters had an extraction rate of approximately 10 gallons of moisture per 24-hour period.

Phase 1 (June 2000 to February 2001) focused on the extreme areas of the house — the basement and the attic, which represented two distinct climate-control zones, with the first and second floors acting as an intermediate zone without active climate control.[11] The programmable control of the climate-control system compared the internal conditions to those outside to determine the appropriate operational mode. The ventilation mode was operational when internal relative humidity exceeded 65% (low system-deactivation threshold of 60%) and outside relative humidity was less than both basement relative humidity and 65%. Attic ceiling (roof) temperature was also examined for attic or upper-floor ventilation. Throughout most of the study, a slightly higher condition was maintained by the heating mode, which was triggered when both internal and external relative humidity exceeded 70% (low internal threshold of 65%), though a maximum basement air-temperature threshold (approximately 86°F) limited its use.

The first and second floors of Hollybourne Cottage were addressed during Phase 2 (February 2001 to August 2001) with the installation of two supply fans on each floor positioned in central locations (Figs. 2 and 3). First-floor fans were placed near the intersection of the T on the north (pantry) and south (gun room) walls of the east-west wing, while the fans on the second floor were on the east walls of the master bedrooms in the north-south wing. Two additional exhaust ventilators were placed in the basement and one in the attic to balance airflow. Floor registers were also installed between the first floor and basement, allowing for the transfer of air between the two spaces. A convection heater in the attic was mounted in the center of the space to complement existing ventilation. Two climate-control zones were established during Phase 2: the first consisted of the basement and the first floor, and the second consisted of the second floor and the attic.

The next two phases maintained similar climate-control configurations, with the exception of the replacement of three basement convective heaters used in Phase 3 (August 2001 to June 2002) with two dehumidifiers during Phase 4 (June 2002 to July 2003), which remained in use for the remainder of the experiment. Both phases also deactivated basement ventilation, leaving heating or dehumidification as the sole means of basement climate control. The basement of Hollybourne Cottage was again segregated from the rest of the structure and represented one climate-control zone. The first floor also remained independent, while the second floor and attic acted together as the third climate-control zone.

The climate-control system configuration for Phase 5 (August 2003 to April 2004) included the reactivation of basement ventilation and the rezoning of the upper floors as one climate-control zone. The operational bands for basement dehumidification, attic heating, and ventilation were also merged, extending from 60% to 65% internal relative-humidity; the operational band for heating had previously been set from 65% to 70%.

Phase 6, the final phase of the climate control study (April 2004 to October 2005), maintained the system configuration of Phase 5 but inserted an additional parameter for dew-point temperature into the control logic for basement and upper-floor ventilation. In addition to examining exterior and interior relative humidity, Phase 6 logic further required that basement or first-floor dew-point temperature be greater than or equal to that of the exterior before triggering ventilation, an attempt to reduce elevations in interior relative humidity due to the transfer of exterior air with a higher dew-point temperature.

Results

Site climate. During the study, the overall average values for outside air temperature and relative humidity at Jekyll Island were 67.5°F (standard deviation, or sd: 13.3°F) and 81% (sd: 16%), respectively. The highest average external air temperatures (approximately 70.7°F) were recorded during Phases 2, 4, and 6. The lowest mean temperature (62.5°F, sd: 13.6°F) was observed during Phase 5 (Table 1). Due to an abbreviated time period relative to the other phases that included a prolonged winter and excluded warmer early-summer months, the Phase 5 average temperature was the lowest: 4°F lower than the second-lowest mean air temperature, which was Phase 0, or preinstallation (67.1°F, sd: 12.2°F).

The relative-humidity dataset was affected by comparably less humid conditions during the initial phases of the experiment. Mean exterior relative humidity during preinstallation (Phase 0) was 80% (sd: 17%), followed by a decrease to average values of 79% for Phases 1 and 2 (Table 1). Conversely, Phases 3 to 6 experienced elevated mean humidity values between 82% and 85%. An increase in the moisture content of outside air was also evidenced by elevated average humidity ratios during Phases 4 (104 grain/lb) and 6 (107 grain/lb).

Basement environment. Displaying an average air temperature of 66.3°F (sd: 8.2°F) and a relative humidity of 82% (sd: 11%) during Phase 0, the preinstallation basement environment was plagued by relatively cool and humid conditions during the summer months (Table 1). The 70% relative-humidity level was exceeded during 86% of Phase 0 (Table 2). During this period, a short-term experiment was also carried out, in which relative humidity was recorded beneath a sealed section of the basement floor. Over a period of several days, a saturation microenvironment was observed, confirming a capillary source of moisture.

Installation of the climate-control system shifted the basement to warmer and drier conditions during the summer. Spanning all climate-control configurations, the average basement air temperature ranged from 71.3°F (Phase 5) to 75.3°F (Phase 6) (Fig. 4). Coinciding with the coolest mean exterior temperature, the Phase 5 mean basement air temperature was more than 2°F lower than the second-lowest post-installation average basement air temperature, which occurred during Phase 1 (mean: 73.7°F). The standard deviation of the basement air temperature during the climate-control study ranged from 9.2°F (Phases 2 and 3) to 12.6°F (Phase 1), an increase relative to preinstallation. The temperature of the basement ceiling was approximately 1.2°F cooler than basement air during Phases 1 to 4; surface temperature was not recorded during the final two phases since previous trends in that data were consistent.

Following system installation, mean basement relative humidity ranged from 61% (Phase 5) to 67% (Phase 2) (Fig. 5). The lowest average relative-humidity values were observed during Phases 5 (61%) and 6 (64%). Variability in the relative-humidity datasets was also reduced during the climate-control study compared to preinstallation (sd: 11%): standard deviations ranged from 3% (Phase 4) to 6% (Phases 1 and 3). Phases 1 and 2 exceeded 70% relative humidity, the target maximum level, no more than 11% of the time, while the remaining phases recorded humidity above this threshold no more than 3% of the time (Table 2). During Phases 0 to 3, the mean basement humidity ratio remained similar to that of the exterior. However, basement humidity ratios during Phases 4 and 6 were reduced relative to exterior levels. The Phase 5 humidity ratio was affected by the lack of summer months during its limited study period.

Attic environment. The major environmental concern in the attic space was excessive air temperature caused by heat

Table 1. Statistics for Air Temperature (AT, °F), Relative Humidity (RH, %), and Humidity Ratio (W, grain/lb)

		Phase 0 1/99-6/00			Phase 1 6/00-2/01			Phase 2 2/01-8/01			Phase 3 8/01-6/02			Phase 4 6/02-7/03			Phase 5 8/03-4/04			Phase 6 4/04-10/05		
		AT	RH	W	AT	RH	W	AT	RH	W	AT	RH	W	AT	RH	W	AT	RH	W	AT	RH	W
Attic	Mean	72.5	71	91	73.1	69	92	77.0	65	95	73.1	69	89	77.9	65	100	71.7	61	79	80.0	62	103
	Max	106.6	95	224	98.9	92	174	95.2	80	156	97.2	88	165	102.0	81	178	97.4	76	178	101.2	77	197
	Min	38.5	43	22	35.6	36	21	52.4	32	30	39.3	41	21	37.9	45	17	43.5	42	25	42.3	40	21
	SD	13.3	7	36	15.2	7	37	9.8	7	31	11.4	8	32	13.4	4	36	13.2	5	3	12.5	5	38
Second Floor	Mean	70.4	70	104	72.5	65	89	75.3	65	93	72.1	65	82	75.1	59	94	68.8	57	71	76.7	63	97
	Max	94.7	85	246	90.5	82	158	91.8	84	169	90.4	84	151	91.9	82	159	90.1	84	142	92.9	83	167
	Min	40.3	43	18	38.5	50	16	52.7	30	27	41.7	33	18	38.7	26	16	45.4	27	22	44.0	37	19
	SD	11.7	6	51	15.0	5	41	10.1	7	33	10.8	9	31	12.8	8	36	12.5	9	32	12.2	6	37
First Floor	Mean	68.6	73	83	72.4	65	87	74.6	67	91	72.0	68	85	74.0	69	93	68.1	66	75	75.0	69	97
	Max	89.9	87	165	89.7	79	143	90.1	83	149	90.1	84	153	89.9	89	154	88.6	88	149	93.0	89	159
	Min	42.4	43	21	40.0	41	19	52.7	33	27	42.7	33	19	41.3	39	15	46.5	39	24	43.5	40	17
	SD	10.6	8	35	14.4	6	38	9.8	7	32	10.3	8	31	12.1	7	35	12.1	8	36	11.9	8	37
Basement	Mean	66.3	82	85	73.7	65	89	74.5	67	90	73.8	65	85	74.1	66	89	71.3	61	76	75.3	64	87
	Max	81.0	98	155	87.0	77	140	88.7	81	142	89.8	73	147	89.2	72	136	89.6	76	140	89.5	76	140
	Min	48.7	46	25	46.4	43	23	54.8	41	34	51.2	38	25	48.3	46	23	53.0	44	29	51.5	43	25
	SD	8.2	11	34	12.6	6	37	9.2	5	30	9.1	6	28	10.7	3	29	11.6	4	32	10.7	4	32
Outside	Mean	67.1	80	85	67.9	79	90	70.2	79	92	66.7	83	87	70.6	85	104	62.5	82	77	71.8	83	107
	Max	102.6	100	174	106.5	100	163	97.3	100	160	100.5	100	165	97.7	100	177	91.7	100	157	98.4	100	185
	Min	27.3	17	10	21.8	21	10	37.9	23	17	26.1	20	11	17.0	21	6	29.8	24	10	27.3	27	11
	SD	12.2	17	35	16.4	15	41	11.6	16	34	12.3	16	34	13.6	15	40	13.6	16	39	12.6	14	40

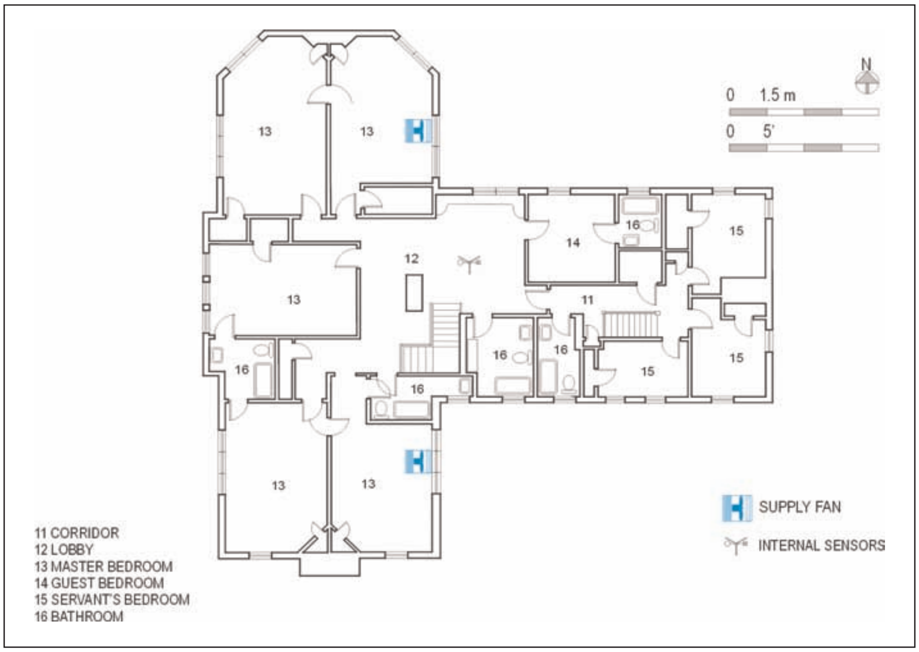

Fig. 3. Second-floor plan, indicating locations of supply fans and sensors.

conduction through the roof and the accumulation of buoyant heated air from lower floors. The preinstallation attic environment displayed a mean air temperature of 72.5°F (sd: 13.3°F) with a maximum value of 106.6°F (Table 1). Average preinstallation relative humidity in the attic space was 71% (sd: 7%), and the 70% relative-humidity level was exceeded during 53% of the period (Table 2).

While temperatures in the attic during Phase 1 (ventilation only) were similar to those of preinstallation, the incorporation of heating beginning with Phase 2 increased average attic air temperatures from 77°F to 80°F during Phases 2, 4, and 6 (Fig. 6). Phase 3 air temperatures were affected by heater malfunction during the bulk of the period, while Phase 5 coincided with much cooler exterior conditions relative to the other experimental phases. The variation of air temperature within a phase during the experiment ranged from 9.8°F (Phase 2) to 15.2°F (Phase 1). Post-installation maximum air temperatures ranging from 95.2°F (Phase 2) to 102.0°F (Phase 4), however, were reduced relative to the Phase 0 peak of 106.6°F.

The installation of attic heating during Phase 2 was prompted by the increase in relative humidity due to the influence of cooler exterior temperatures. Though mean attic relative humidity was 70% during Phases 0 and 1, elevated relative-humidity levels were typically observed during the cold winter months (Fig. 7). Following the addition of heating, mean attic relative humidity was at or below 65% for Phases 2, 4, 5, and 6 (Fig. 7). The variation in relative-humidity data was also reduced during later phases, ranging from 4% to 5%. The 70% relative-humidity threshold was exceeded during only 20% of Phase 2 and no more than 3% of Phases 4 to 6 (Table 2). Despite this reduction in relative humidity, mean attic humidity ratios remained similar to those of the exterior during the climate-control experiment.

First- and second-floor environments. Preinstallation conditions for the first and second floor of Hollybourne Cottage were roughly intermediate to the more extreme basement and attic environments. During Phase 0, mean air temperatures for the first and second floors were 68.6°F (sd: 10.6°F) and 70.4°F (sd: 11.7°F), respectively (Table 1). The average preinstallation first-floor relative humidity was 73% (sd: 8%), while that of the second floor was 70% (sd: 6%). The 70% relative-humidity threshold was also exceeded 68% of the time on the first floor and 58% of the time on the second floor (Table 2).

Following system installation, the adjacent controlled environments of the basement and attic indirectly affected the first- and second-floor environments. Excluding Phase 5 because of the effect of low exterior temperatures, mean air temperatures for both floors ranged roughly from 72°F to 77°F (Table 1). During the experiment, the mean differential between the first-floor air temperature and the surface temperature of its flooring was roughly 1.2°F. Average relative-humidity levels were also equal to or below 69% and 65% for the first and second floors, respectively. The 70% relative-humidity level was surpassed no more than 50% of the time on the first floor and 30% of the time on the second floor (Table 2). Similar to mean outside humidity ratios during Phases 0 to 3, average humidity ratios for the first and second floor were reduced relative to the exterior during Phases 4 and 6 and remained intermediate between those of the basement and attic.

Operational use and cost. Heating and dehumidification were used far more often than ventilation during the climate-control experiment. Ventilation was utilized between 9% and 19% during Phases 1 and 2, with use decreasing to between 2% and 4% during later

Table 2. Percentile Rank of the 70% Relative-humidity Level

	Phase						
	0	1	2	3	4	5	6
Attic	47	53	80	57	97	99	97
2nd	42	86	73	70	95	92	90
1st	32	84	60	50	53	62	51
Basement	14	91	89	100	99	100	97
Outside	26	28	26	21	15	21	17

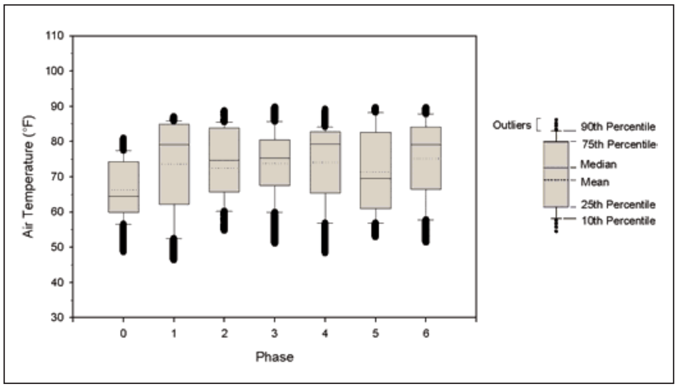

Fig. 4. Box plots showing basement air temperature by phase.

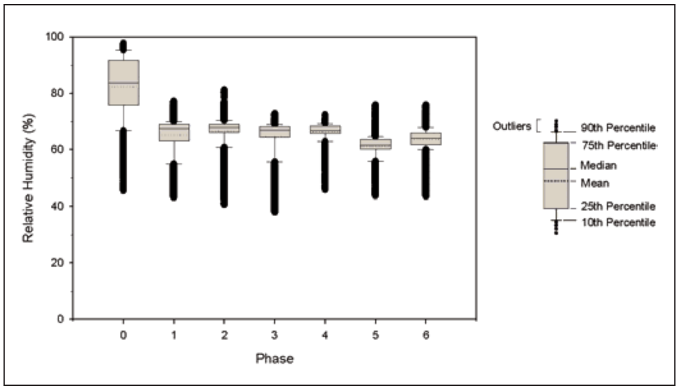

Fig. 5. Box plots showing basement relative humidity by phase.

phases (Table 3). Though heaters were used in the basement during only 13% of Phase 1, basement and attic heater operation ranged from 22% to 40% during Phases 2 through 6. (Phase 3 attic heating use was estimated, as its recorded use was inflated due to heater malfunction.) Implemented in lieu of basement heating during Phase 4, dehumidifier use varied from 34% to 55% of each phase.

Compared to ventilation, heating and dehumidification composed a much larger percentage of the climate-control system's operational cost. At its maximum during Phase 1, supply and exhaust ventilation represented only 11% of the overall cost (Table 4). In contrast, between 88% and 98% of the operational cost during Phases 1 to 3 was due to basement and attic heating use. (Phase 3 attic heating cost was estimated due to heater malfunction). Basement heating, which accounted for 73% to 88% of the operational cost during Phases 1 through 3, was replaced by basement dehumidification during Phase 4, which accounted for only 32% to 52% of the operational cost during the final three phases.

To provide a better comparative index, the cost and energy use for each configuration of the climate-control system was evaluated based on the total floor area of the building (11,300 square feet) and the duration of each phase. During the climate-control experiment, the highest cost and energy indices were observed during Phase 2 ($0.55/ft^2/yr, 59.22 kwh/m^2/yr) and Phase 3 ($0.53/ft^2/yr, 56.7 kwh/m^2/yr) (Table 4). Phase 4 displayed the minimum cost and energy indices ($0.20/ft^2/yr, 21.3 kwh/m^2/yr). The indices of the remaining phases were also relatively close to the minimum.

Capital cost. Assuming a full installation of each phase set-up and disregarding continued use of previously installed equipment, the capital cost of the climate-control system ranged from $11,800 (Phase 1) to $19,100 (Phases 5 and 6). While the cost of sensors and controllers ($4,000) and of electrical components ($2,000) remained consistent throughout the experiment, the cost variation stemmed from the evolving use of ventilators (approximately $700 each), convective heaters ($300 each), and dehumidifiers ($1,500 each) during each phase. Initial installation of the climate-control system also required approximately 200 man-hours, resulting in an added cost of $9,000 per phase ($45 per hour).

Discussion

Environmental comparison. The installation of the HVAC-alternative climate-control system at Hollybourne Cottage resulted in a marked change in the interior environment of the structure. The climate-control system reduced relative humidity and increased air temperatures for each floor. Mean basement relative-humidity levels were reduced from 82% before the experiment began to 67% or less during the study (Table 1). The average climate-controlled relative humidity for the remaining floors was 69% or less, below mean preinstallation levels, which ranged from 70% to 73%. Conversely, mean basement air temperatures during the experiment were typically elevated 9°F over that of preinstallation. Mean first-floor temperatures were increased above those of Phase 0 by approximately 5°F, and the second-floor and attic spaces both displayed an elevation of roughly 4°F above preinstallation levels, reflecting lesser reductions in relative humidity than that of the basement. The similarity between basement and first-floor air temperatures and the surface temperatures of the basement ceiling and flooring of the first floor, which were the most damaged areas of the structure, verified that surface water-activity levels above the microbial-growth threshold would be limited.

Table 3. Operational Use of Ventilation, Heaters, and Dehumidifiers

		Phase					
		1	2	3	4	5	6
Attic	Ventilation use, % of phase	19	11	3	3	3	4
	Heater use, % of phase	-	27	25	22	40	35
Second Floor	Ventilation use, % of phase	-	11	3	3	3	4
First Floor	Ventilation use, % of phase	-	9	4	3	3	4
Basement	Ventilation use, % of phase	11	9	-	-	3	2
	Heater use, % of phase	13	23	24	-	-	-
	Dehumidifier use, % of phase	-	-	-	44	34	55

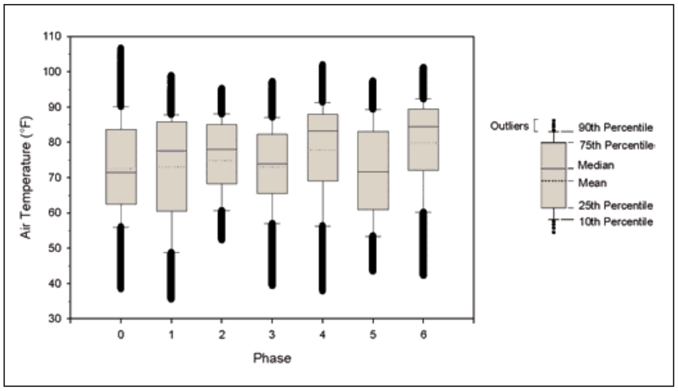

Fig. 6. Box plots showing attic air temperature by phase.

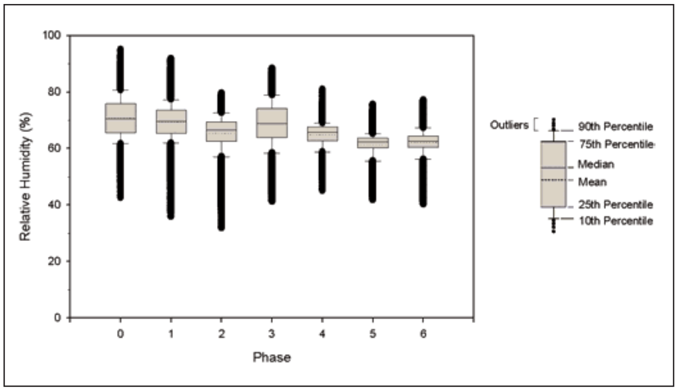

Fig. 7. Box plots showing attic relative humidity by phase.

The dominant factor in preventing microbial growth was limiting prolonged periods of relative humidity above 70%. Reflecting the degree of structural damage, the basement and first floor of Hollybourne Cottage exceeded the 70% relative-humidity level during 86% and 68% of the preinstallation period, respectively (Table 2). Though wood deterioration was not observed in the upper floors, the 70% level was exceeded during 58% and 53% of preinstallation on the second floor and the attic, respectively. Following installation of the climate-control system, the basement exhibited the most drastic change, with the 70% relative-humidity level exceeded during no more than 11% of Phases 1 and 2 and no more than 3% of the remaining phases. Beginning with the Phase 2 heater installation in the attic, the environments of the second floor and attic surpassed 70% relative humidity no more than 20% of Phase 2 and no more than 3% of Phases 4 to 6 (excluding Phase 3 due to heater malfunction). Though high relative-humidity events were also reduced for the first floor, the level of improvement varied widely, due to intermittent visitation and intern work activity, particularly during the humid summer months. Infiltration effects, however, were largely localized, as the basement was isolated and the upper floors were buffered by buoyant, heated air.

Despite an increase in mean attic air temperature, the ventilation mode of the climate-control system was shown to reduce maximum temperatures in the attic during the experiment. Ventilation reduced peak attic air temperatures from a preinstallation maximum of 106.6°F to a range of 95.2°F to 102.0°F during Phases 1 to 6 (Table 1). Though ventilation use is obviously limited with respect to overall air-temperature reduction, the movement of air through the space provided an added element of visitor comfort during periods of extremely warm temperatures in the attic.

The use of dehumidification during Phases 4 to 6 influenced interior humidity ratios, particularly for the basement and middle floors. Prior to Phase 4 humidity ratios for all floors were similar to those outside (Table 1). This similarity is the result of the relatively high rate of exchange of interior and exterior air, which is common for historic structures. The installation of basement dehumidifiers in Phase 4 allowed for the active control of humidity ratio, as evidenced by the reduction of the basement humidity ratio relative to outside levels. This effect seems to have extended to the first- and second-floor humidity ratios, as they remained between the basement and attic values during Phases 4 to 6. The envelope of the attic space was likely the least tight in Hollybourne Cottage and reflected exterior humidity-ratio levels throughout the experiment.

Phase comparison. While Phase 1 addressed the extreme spaces of Hollybourne Cottage, i.e., climate control of the basement and attic, this configuration also served to effectively control the climatic conditions of the intermediate floors from the exterior. The addition of ventilation on the first and second floors during Phase 2 was also important from the perspective of visitor comfort, promoting air movement and introducing fresh air to the most actively used spaces.

The Phase 2 rezoning of the basement and first floor as one climate-control zone dramatically increased operational costs, in large part because the

Table 4. Operational Cost of Ventilators, Heaters, and Dehumidifiers, with Cost and Energy Indices

		Phase					
		1	2	3	4	5	6
Attic	Supply fan, % of total	2	2	1	2	1	1
	Exhaust fan, % of total	3	1	0	1	1	1
	Heater, % of total	-	19	18	43	63	49
Second Floor	Supply fan, % of total	-	2	1	2	1	1
First Floor	Supply fan, % of total	-	2	1	2	1	1
Basement	Supply fan, % of total	4	2	-	-	1	1
	Exhaust fan, % of total	2	1	-	-	0	0
	Heater, % of total	88	73	80	-	-	-
	Dehumidifier, % of total	-	-	-	52	32	46
	Cost/area/year, $/ft2/yr	0.26	0.55	0.53	0.20	0.25	0.28
	Energy/area/yr, kwh/m2/yr	28.3	59.2	56.7	21.3	26.6	30.2

heaters in the basement were also carrying the additional heating load of the first floor. Including the costs of attic heating and first- and second-floor ventilation, Phase 2 displayed the highest operational cost of the climate-control experiment ($0.55/ft^2/year) (Table 4).

The deactivation of basement ventilation during Phases 3 and 4 proved that a reliance on heating (Phase 3) or dehumidification (Phase 4) was sufficient in maintaining the desired environment. The 70% relative-humidity level was exceeded during no more than 0.6% of Phases 3 and 4, suggesting that basement ventilation use may be primarily responsible for episodes of elevated humidity (Table 2).

The replacement of basement heating with dehumidification during Phase 4 resulted in the lowest operational cost for a climate-control configuration ($0.20/ft^2/year) (Table 4). Though dehumidifiers were more expensive initially and required increased operational time compared to heaters, they use 80% less power than heaters (dehumidifiers: 3.0 kwh for 2 units; heaters: 22.5 kwh for 3 units), resulting in overall cost savings. A calculation of simple payback based on the respective Phase 3 and 4 operational costs of basement heating and dehumidification indicated that the investment in dehumidification would be recouped in approximately one year. The increased maintenance costs of dehumidifiers relative to heaters, however, were not taken into account in the calculation.

While the Phase 5 merging of operational bands of interior relative humidity for the ventilation and heating/dehumidification modes suggested that further reductions might be possible, lower relative-humidity levels may not be altogether desirable due to the possibility of salt-related damage. During the study, periodic efflorescence of salt crystals on the basement floor (likely sodium chloride, which deliquesces at 75% relative humidity) indicated that the target relative-humidity level was suitable, as it allowed for crystallization on the slab surface. Reductions to too low of an operational band may cause crystallization to occur within the basement floor.

The inclusion of a ventilation parameter for dew-point temperature during Phase 6 did not appreciably affect ventilation, though this may have been caused by the reduction in ventilation use due to elevated exterior relative-humidity levels. A dew-point temperature control, however, may not be necessary, as short-term elevations in relative humidity (e.g., during a sunny drying period immediately following rain events) would not be sufficient to cause significant microbial activity.

Cost comparison. The operational cost during all climate-control phases represented only a fraction of the energy budget for a typical HVAC climate-control system. Depending on structural use, operational costs for conventional HVAC systems range from $0.75/ft^2/year for a church to $3.00/ft^2/year for a museum, with residences ($1.25/ft^2/year) and offices ($1.75/ft^2/year) representing intermediate levels.[12] Based upon the minimum HVAC operational cost, operational costs for the climate-control system installed at Hollybourne Cottage were 27% to 73% less expensive (Table 4). Furthermore, initial HVAC capital costs range from $10 per square foot for heating only to $50 per square foot for climate control[13]; capital costs for the Hollybourne Cottage system ranged from $1.84 per square foot (Phase 1) to $2.50 per square foot (Phases 5 and 6). While temperature and relative-humidity control of an HVAC system are much more robust than is possible with the Hollybourne Cottage system, the significant capital and operational savings, as well as the effective restriction of high interior relative humidity, suggest that this alternative climate-control technique may present a viable option for cultural-heritage institutions in hot and humid regions.

Conclusion

Though the climatic conditions of each space were adequately addressed during all phases of the study, the system configuration for Hollybourne Cottage should focus on the needs of each individual floor. Continued segregation and control of the basement space, the dominant site for moisture infiltration and a heat sink during summer months, will limit the transfer of air with high relative humidity to other floors. If there is little visitation or work activity, basement climate control can bypass ventilation and rely solely on heating or dehumidification, simplifying the system configuration for establishing a preservation environment. The choice between heating and dehumidification will balance the reduced energy costs of dehumidification versus the lower capital and maintenance costs of heating. In either case, heating or dehumidification should be used as little as possible in order to reduce energy costs and limit the possibility of salt-related damage.

Attic ventilation addressed peak summer temperatures in the space, while heating was used to limit the elevation of relative humidity during the cooler winter months. Though it is limited in its capacity to reduce mean temperature, ventilation was shown to lower maximum attic temperatures. Installation of thermal insulation on the roof would also aid in limiting solar heat gain during the summer and heat loss during the winter. The use of thermal insulation may minimize or even eliminate the need for attic heating.

From a preservation standpoint, the use of ventilation on the first and second floors of Hollybourne Cottage should be avoided, as the intermediate spaces will be effectively protected by the controlled environments of the basement and attic. However, intermittent visitation and summer work, particularly on the first floor, encourages ventilation use for human comfort. Raising the exterior relative-humidity set point for the intermediate spaces or manually activating ventilators during periods of active use would also maximize ventilation. While such actions would likely result in higher interior relative humidity, short-term elevations will not cause significant microbial activity if the exterior set point is returned to less than 70% relative humidity and dehumidification or heating is used during unoccupied hours. Though not introducing fresh air into the interior, the use of air recirculation with particulate filters represents another means of improving visitor comfort.

The alternative climate-control strategies applied at Hollybourne Cottage posed a significant savings in operational and maintenance costs over those of a conventional HVAC system: a reduction of 27% to 73%. Furthermore, the capital cost (approximately $2.00 per square foot) was approximately 5% of that of a typical air-conditioning system.

Design efforts should also address equipment noise, particularly for ventilation and dehumidification. As sound typically registers between 60 and 80 decibels at each unit, visitation experiences and work efficiency may be negatively impacted by equipment proximity. While double casing and elbow ducts are typically used when ductwork is present, clever placement of equipment and design of visitor path, as well as the positioning of noise reduction forms on wall surfaces, can mitigate noise in historic structures.

SHIN MAEKAWA is a senior scientist at the Getty Conservation Institute and head of its Environmental Studies Laboratory. He holds a master's degree in mechanical engineering and a PhD in conservation science. He is a registered professional engineer (mechanical) in California.

VINCENT BELTRAN is an assistant scientist at the Getty Conservation Institute, conducting research on climate-control technologies for historic buildings and microclimates for the conservation of cultural objects. He earned a B.S. in chemistry from the University of California, Los Angeles, and a master's degree in oceanography from the University of Hawai'i, Manoa.

FRANCIZA TOLEDO, a private consultant based in Recife, Brazil, has authored articles on environmental control in museums, archives, and historic buildings. She received her PhD in museum studies from University College London for studies of the conservation and restoration of movable cultural property at the Universidade Federal de Minas Gerais.

Acknowledgements

This study was conducted under the Alternative Climate Controls for Historic Buildings project of the Getty Conservation Institute. The authors gratefully acknowledge the excellent collaboration of the Jekyll Island Museum and Historic District staff throughout the project, including Warren Murphey, John Hunter, Mickey Gordon, and Brian Robinson.

Notes

1. Stefan Michalski, "Relative Humidity: A Discussion of Correct/Incorrect Values," in *Proceedings of 10th (1993) ICOM-CC Triennial Meeting*, 624–629 (ICOM Committee for Conservation, 1993). David Erhardt and Marion Mecklenburg, "Relative Humidity Re-Examined," in *Preventive Conservation: Practice, Theory, and Research Proceedings of 1994 IIC Ottawa Congress*, 32–38 (London: International Institute of Historic and Artistic Works, 1994). Jonathan Ashley-Smith, Nick Umney, and David Ford, "Let's Be Honest – Realistic Environmental Parameters for Loaned Objects," in *Preventive Conservation: Practice, Theory, and Research Proceedings of 1994 IIC Ottawa Congress*, 28–31.

2. O. P. Agrawal, "Keynote Address: Recent Studies on Biodeterioration of Cultural Property," in *Proceedings of 2nd (1993) International Conference on Biodeterioration of Cultural Property*, 3–19 (Tokyo: International Communications Specialists, Inc., 1993). Chiraporn Aranyanak, "Biodeterioration of Cultural Materials in Thailand," in *Proceedings of 2nd (1993) International Conference on Biodeterioration of Cultural Property*, 23–33.

3. Tim Padfield and Poul Jersen, "Low Energy Climate Control in Museum Stores," in *Proceedings of 9th (1990) ICOM-CC Triennial Meeting*, 596–601 (ICOM Committee for Conservation, 1990). Richard L. Kerschner, "A Practical Approach to Environmental Requirements for Collections in Historic Buildings," *Journal of the American Institute for Conservation* 31, no. 1 (1992): 65–76. Sarah Staniforth, Bob Hayes, and Linda Bullock, "Appropriate Technologies for Relative Humidity Control for Museum Collections in Historic Buildings," in *Preventive Conservation: Practice, Theory, and Research Proceedings of 1994 IIC Ottawa Congress*, 123–128. Shin Maekawa, "Report on the Efficacy Evaluation of Environmental Improvements Implemented in Prentis House, Horseshoe Barn, and Stagecoach Inn at the Shelburne Museum, VT." Getty Conservation Institute internal report, 1999.

4. Geoffrey Wilmot Brundrett, *Criteria for Moisture Control* (London: Butterworth and Co., 1990), 46–59. Nieves Valentín, Rafael Garcia, Oscar de Luis, and Shin Maekawa, "Microbial Control in Archives, Libraries and Museums by Ventilation Systems," *Restaurator* 19, no. 2 (1998): 85–107.

5. Shin Maekawa, "Report on the Efficacy Evaluation of Environmental Improvements Implemented at the Shelburne Museum."

6. Valentín, Garcia, de Luis, and Maekawa, 85–107.

7. Shin Maekawa and Franciza Toledo, "Controlled Ventilation and Heating to Preserve Collection in Historic Buildings in Hot and Humid Regions," in *Proceedings of 13th (2002) ICOM-CC Triennial Meeting*, 58–65 (London: James and James, 2002).

8. Shin Maekawa and Franciza Toledo, "A Climate Control System for Hollybourne Cottage, Jekyll Island Historic District, Georgia," http://www.getty.edu/conservation/publications/pdf_publications/iaq453.pdf.

9. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, *ASHRAE Handbook – Fundamentals* (Atlanta: ASHRAE, 2001), 24.8-24.9.

10. Watson and Henry Associates, "Condition Assessment Survey Report for Hollybourne Cottage, Jekyll Island, Georgia." Getty Conservation Institute internal report, 1998.

11. Maekawa and Toledo, "A Climate Control System for Hollybourne Cottage."

12. Ernest Conrad, "Understanding Mechanical Systems that Support Preservation Environments" (paper presented at the 20th Annual NARA Preservation Conference, Beyond the Numbers: Specifying and Achieving an Efficient Preservation Environment, Washington D.C., March 16, 2006).

13. Ibid.