Environmental Monitoring and Conservation Study of Drayton Hall in Charleston, South Carolina

MICHAEL J. MILLS and GEORGE FORE

Beset by the deterioration of architectural fabric at one of America's great historic houses, the National Trust completed an environmental monitoring and conservation study to serve as the basis for future treatment of the building.

Drayton Hall is one of the great historic houses of North America. Constructed between 1738 and 1742 by John Drayton, it has survived earthquakes, hurricanes, and a civil war. The building retains an extensive amount of original fabric and has additional significance due to the fact that it was never provided with such modern conveniences as electricity, plumbing, or central heating.

The house is owned by the National Trust for Historic Preservation and is open to the public as a museum. Unlike other house museums, there are no furnishings, fabrics, or fine arts on display. Rather, the building itself is treated as the exhibit. Due to the danger of fire, the fireplaces are no longer utilized to regulate interior temperature. The nineteenth-century interior blinds, which modulated light and temperature, were removed for interpretive reasons and to afford a greater level of illumination to visitors. The Trust has the difficult curatorial responsibility of conserving an object fabricated of masonry, wood, plaster, and paint that sits exposed in an open landscape in the South Carolina lowlands (Fig. 1).

Fig. 1. Drayton Hall from the south and west showing the double portico. All photographs courtesy of Ford Farewell Mills and Gatsch, Architects.

Drayton Hall is located in a subtropical area and is in close proximity to the Ashley River and the Atlantic Ocean, which have a moderating effect on the climate. Temperatures may vary from lows of 40° to 50° F in the fall and winter (with occasional freezing conditions) to the upper 90s in the summer, with high relative humidity.

Ongoing deterioration at Drayton Hall has been a constant concern to the curators of the house. In response to those concerns, the Trust issued a request for proposals for architectural, engineering, and conservation services in 1994, listing three component areas of study to be addressed by a conservation report:

- moisture damage to exterior masonry and interior plaster and wood,
- cracking, loss of ornament, and delamination of the plaster ceiling of the Great Hall, and
- fading and disintegration of interior paint finishes.

The project was to evaluate prior reports, undertake field studies and laboratory analysis, and to monitor environmental conditions of the building for a twelve-month cycle. At the end of the project, the Trust desired to have clear recommendations, based on the accumulated data, to deal with the three major problem areas. The interdisciplinary team consisted of Ford Farewell Mills and Gatsch, Architects; Ira Guterman of the Princeton Engineering Group; Robert Silman Associates,

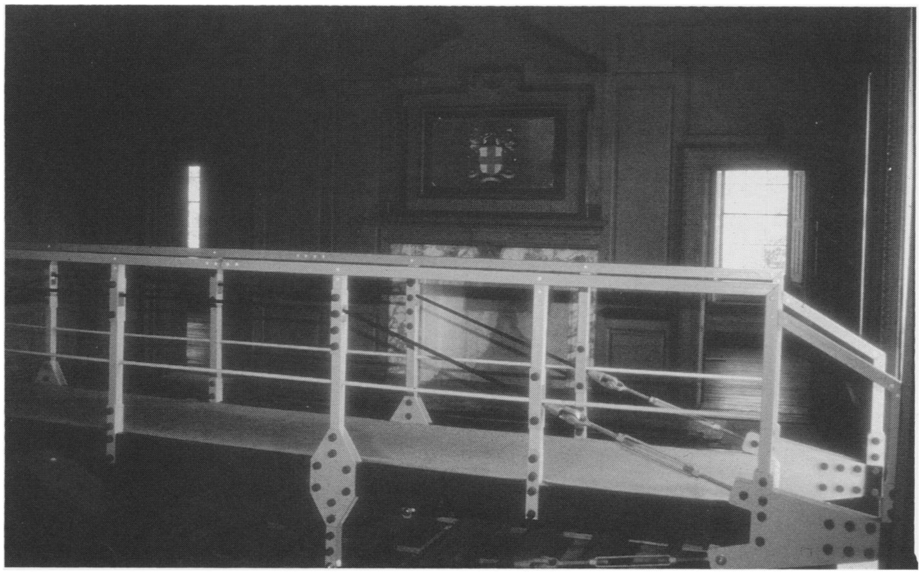

Fig. 2. Temporary suspension bridge in the room over the Great Hall to remove visitor live load from the ceiling.

Structural Engineers; conservator George Fore; and S&ME Associates, Civil Engineers, from Mount Pleasant, South Carolina. James Martin of the Williamstown Art Conservation Center provided analytical support to the team.

From 1974, the time the Trust took ownership, until 1994, numerous studies and preservation projects had been undertaken. These included a 1977 historic structure report by Charles Chase and Kevin Murphy (revised in 1988), site-drainage improvements and archeology, and several materials-conservation projects that included plaster consolidation and structural reinforcement of the Great Hall ceiling in 1979. In response to continued cracking observed in the ceiling of the Great Hall, the Trust convened a colloquium of structural engineers in 1990. This resulted in a conditions survey of the ceiling by the University of Pennsylvania Conservation Laboratory, as well as the design and installation of a bridge over the Great Hall to remove live load from the structure (Fig. 2). In recent years, there have been several memos and letters from structural engineer, David Fischetti, concerning the Great Hall ceiling structure.

Conditions

The team's general observations on the conditions at Drayton Hall were as follows:

Interior paint loss. Paint loss varied from room to room and floor to floor. The pattern was typically greatest from the floor to an elevation of 6 feet. The quantity of loss decreased at higher elevations. The rooms with the most loss are the dining room and an adjoining space on the northwest side of the building. Virtually none of the painted surfaces appeared to be a continuous film. Conditions included losses following the wood grain, crazing, cracking, and losses of alligatored paint (Fig. 3).

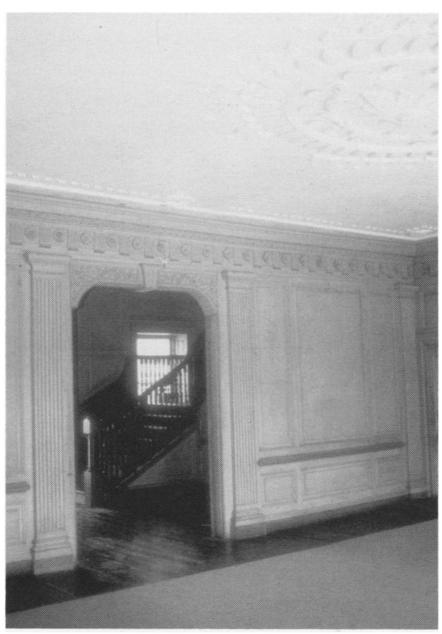

Fig. 3. The Great Hall looking north toward the archway to the stair hall.

Great Hall ceiling. The cracks in the plaster were extensive and were on regular and rectilinear patterns. Also, voids between plaster and lath could be detected by tapping softly on the surface. We had concerns that while the temporary bridge was removing live load from the ceiling, it might be concentrating loads over the arch to the stair hall (Fig. 3).

Rainwater drainage and moisture. Rainwater runoff has long been an issue at the site, and many improvements have been attempted. While the house is not in a particularly damp location and roof leaks are presently not an issue, water runoff has been a concern due to the flat nature of the site. This led to some adjustments in grade around the house in the mid-1980s to encourage better drainage. Of particular concern to us was the basement space at the northwest corner of the building, which felt damp and had salt deposits on the walls and floor. SM&E Associates confirmed that the room was at the lowest point on the site.

Hypotheses. Our observations led to several hypotheses, which included the following:

- The large area of paint loss on the walls may be partly due to abrasion from housekeeping practices before Trust ownership.
- Microclimates and stratification within spaces may be contributing to the loss patterns.
- Rates of paint loss may be related to the physical properties of the paint in each space.
- Changes in relative humidity may lead to dimensional changes in wood and could be contributing to the loss of paint.

- Lack of environmental control may lead to formation of condensation on surfaces.
- Uncontrolled daylight may be accelerating paint deterioration.
- Mortar loss may be due to ground-moisture problems, and pointing mortar used prior to the 1970s may have exacerbated the problem.
- Ceiling modifications at the Great Hall, while stiffening the floor, may have made the entire system more vulnerable to vibration damage.

Based on our observations and hypotheses, a comprehensive monitoring system was designed to gather pertinent information about environmental conditions and to provide data on how the various materials of the building were reacting within that environment.

Design of the Monitoring System

The design of the monitoring system was meant to test our hypotheses by providing information on the temperature, humidity, movement of painted wood, and structural movement of the building. In order to obtain the information, we designed a computer-based system for Drayton Hall having the following components:

- air temperature, relative humidity, and temperature sensors,
- crack monitors to monitor possible structural movement,
- strain gauges to monitor expansion and contraction of the wood and masonry,
- water sensors at window sills to detect surface moisture, and
- contact switches on the main doors.

Locations of the monitoring points were distributed throughout Drayton Hall. Our initial list consisted of well over two hundred measuring points, but it was quickly determined that the installation of such a system would be cost prohibitive. A system with one hundred points could be supported financially by the Trust and would still provide significant environmental data on the critical issues. Twenty of the one hundred points were for special purposes such as monitoring cracks, sensing liquid moisture at windows, and indicating the position of doors. The other eighty were for temperature/humidity measurements and were distributed throughout all rooms in the house at locations to test the various hypotheses. The system was designed, and proposals were sought from several possible suppliers. The successful bidder was Johnson Controls, Inc., of Charleston.

The installation of the system was a cooperative endeavor, utilizing personnel from Johnson Controls, the National Trust, and the consulting team. The system was a digital monitoring system, which consisted of nineteen data-gathering panels each able to accept up to eight input points. The panels were networked with a personal computer located in the basement of Drayton Hall that logged data from the panels to the hard drive every fifteen minutes. By the end of the monitoring year more than four million readings had been logged.

To make sense of the readings, the data that was transmitted in ASCII format was converted into Excel files at our office, making it possible to create graphs and charts necessary for the analysis. Every morning, our computer network automatically downloaded the files at Drayton Hall for the last twenty-four hours. Drayton Hall staff also backed up the information on disk in the event that we lost our link to the house. Several times over the course of the year (most often during weather events), Drayton Hall staff sent disks to us when we had transmission failures.

The physical installation of the sensors was carefully planned to eliminate the possibility of damage to the historic surfaces of the building. On sensitive materials, no adhesives were used nor was penetration of surfaces allowed. Wiring was simply laid on surfaces or attached to clips held in place by pressure in existing crevices. Data-gathering panels were mounted on freestanding plywood backboards fabricated by Trust staff. While it was in operation, the system actually became a temporary exhibit, and used for educational purposes by Drayton Hall staff as part of the building tour (Fig. 4).

Principal Conclusions and Recommendations

The monitoring program provided evidence to support many of the observations and conclusions of the conservation study. Our first conclusion was that the building regulates itself extremely well. It was immediately noticed how rapidly and significantly the relative humidity fluctuates during the day when the building is open for tours. However, the humidity also tended to return to an equilibrium by the beginning of the next

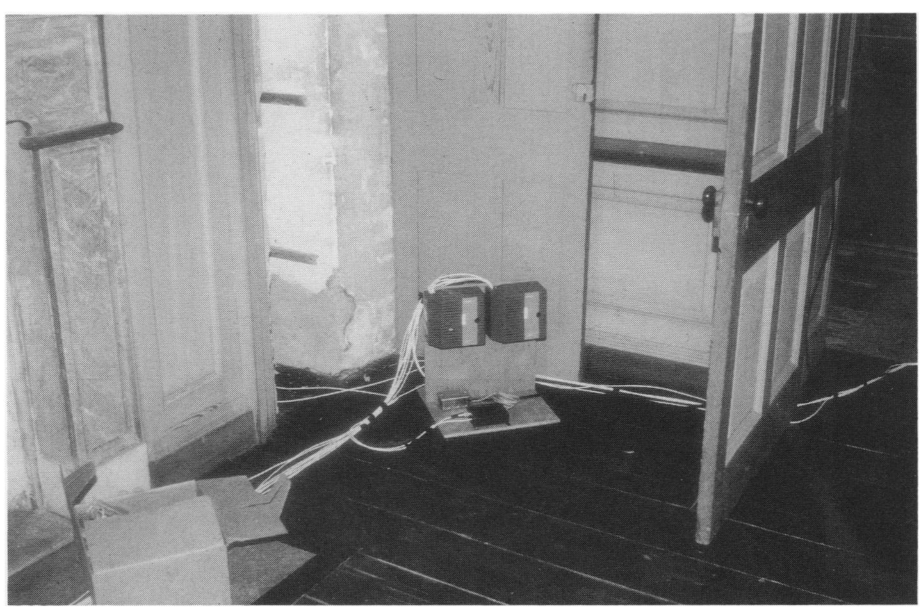

Fig. 4. Typical data-gathering panel.

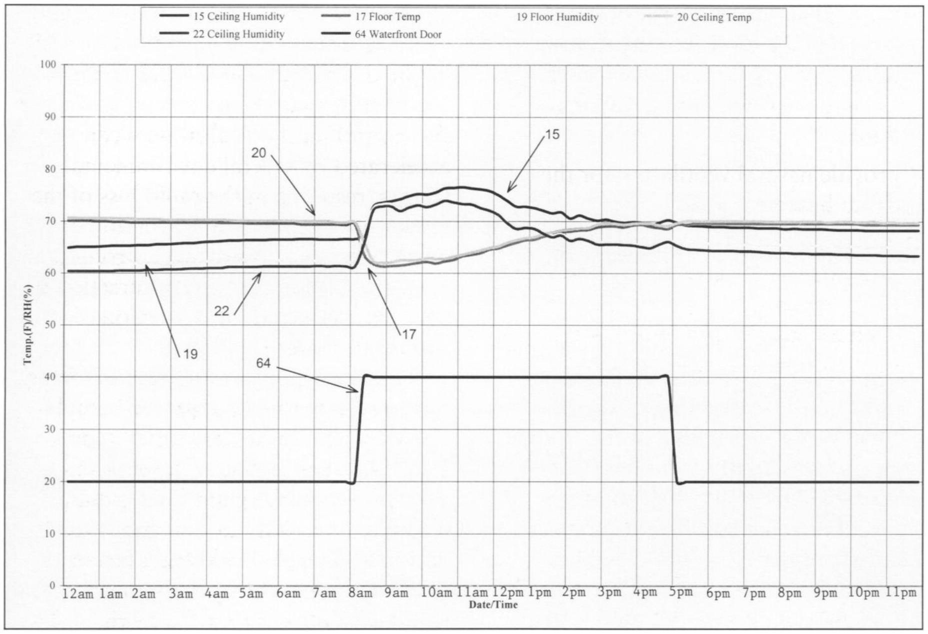

Fig. 5. Temperature and relative humidity plotted on a typical day in October against the opening and closing of the main door (Point number 64).

day. We overlaid the humidity graph on a chart that showed whether the main doors are open or closed, and we documented the correlation. The Trust opens the main doors on either side of the house at 8 a.m. for tours and leaves them open all day. In October, one can see that the temperature dropped and that the humidity immediately rose, which documented the cool, moist morning conditions on a given day. The building then returned to nearly the same interior temperature and humidity conditions by the next day (Fig. 5). In

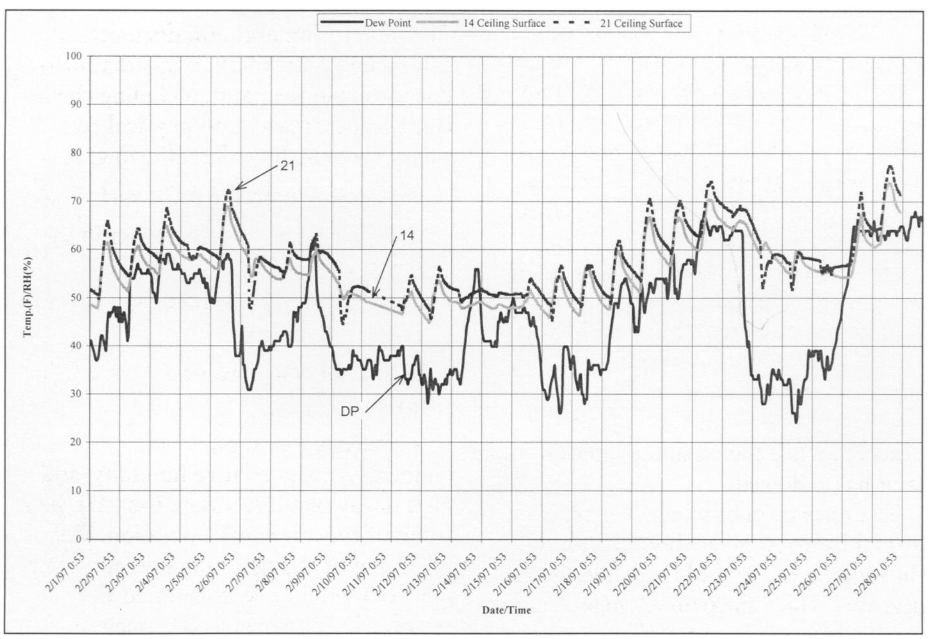

Fig. 6. Comparison of selected surface temperatures and outdoor dew points showing several instances of possible condensation.

August, when temperatures are higher, the opening of the doors has less of an effect on temperature. Rapid humidity changes were still seen during hours of operation but were less precipitous.

Another principal conclusion was the fact that condensation events were occurring in the house during the course of the year. Typically, these occurred in the winter when the building surfaces were cool, the air was moist and warmer, and the doors were thrown open in the morning, as is the custom. The vapor in the warmer air would then condense as liquid on the cool surfaces. An early warning of these conditions is found by examining available weather data. If the ambient dry-bulb temperature of the air is close to the dew point, condensation can easily develop. Thus, cool outdoor overnight temperatures and high relative humidity may lead to possible condensation.

The indoor conditions on February 8, 1997, for instance, were conducive to condensation. The temperature remained low and fairly constant, while the relative-humidity spikes were very high. Condensation occurs when the surface temperature is lower than the dew-point temperature. We compared surface temperatures and outdoor dew points on this graph and discovered that the surface temperature was lower in several instances. Note that this graph shows condensation occurrence on February 8 and on other days in February as well (Fig. 6).

There were seventeen hours of possible condensation at Drayton Hall during the monitoring year, typically occurring during the winter when cool conditions were becoming warmer and more humid. That seemed to us to hold the possibility for a great deal of condensation damage. The year monitored was both cooler and dryer than a typical weather year in Charleston, according to data from the weather service. Therefore, there is potential for even more condensation during more-typical years.

Another principal conclusion from the monitoring program was the documentation that relative-humidity levels were higher in the dining room than in any other room in the house. This is also the room with highest level of paint loss. In analyzing the conditions, we noticed that the dining room is directly over the room with the highest moisture in the basement. We discovered that the wood paneling in the dining room has a void behind it that is open to the basement space beneath. Thus, the room with the highest level of paint loss also has the highest relative humidity at its floor and in the wall cavity immediately behind its paneling.

Some of the other conclusions were the following:

- The temperature/humidity measurements showed consistency at all points in the building, leading the team to discount the idea that microclimates and stratification were contributing to patterns of paint loss.
- Soils testing showed that ground water was not a significant contributor to moisture entering the masonry walls; rather, bulk moisture in the form of rain was the most likely source.
- Our strain-gauge readings on wood features showed that dimensional changes are directly related to relative humidity and are almost immediate. The movements are small, typically 0.00012 of an inch, but they occur often and may contribute to paint loss.
- Crack-monitor readings, while affected by moisture and temperature, showed negligible movement; the movement that did occur was cyclical. It was concluded that the building was not in any structural distress.
- We addressed the possibility that the pedestrian bridge was causing excessive deflections of the arch at the rear of the Great Hall. We ran an experiment by loading the bridge with different-sized tour groups and logging the crack monitor readings every second. The magnitude of the displacement, while observable, was less than that due to other causes, such as temperature. It therefore does not seem as though the bridge was causing undue stress to the building.

Several recommendations for dealing with the temperature and humidity effects were identified:

- continue the monitoring of temperature and humidity to ascertain when conditions are favorable to condensation.
- control the opening of doors on days where condensation could occur. On those days visitors may enter through the basement rather than at the first floor.
- provide natural ventilation for the damp basement area.
- provide ultraviolet shading of windows by some means: reinstallation of the nineteenth-century interior shutters, installation of ultraviolet film or storm panels, or addition of roll-down, fabric screens.
- prepare a detailed topographical map of the site around the building to document all drainage patterns. Regrade as necessary to promote better run-off. Repoint open masonry joints with the hydrated hydraulic lime mortar specified in the report.

Conservation of Paint

The Trust's concerns about changes in the appearance of the paint throughout Drayton Hall include the fading of the color in all rooms and rapid loss of paint in the dining room. Originally, it was thought that Drayton Hall had been painted just two or three times since its 1734 construction. Instead, we discovered that the principal rooms contain up to eleven paint layers from at least seven periods.

The investigation of Drayton Hall's paint provided classic examples of both normal aging and accelerated deterioration. The oil and resin binders in the paint are organic and remain reactive to chemical and photochemical processes. The paints respond in well-documented ways to environmental factors such as moisture, light radiation, and changes in temperature. One can see a fairly predictable response of Drayton's 1880s paint to light radiation on a closet door. The paint on the outside is more exposed and has become chalky and bleached, while the oil in the interior paint has yellowed.

The formation of minor crazing is normal for paint layers bound with oil. The initial oxidation of the binder is the means by which the paint changes from a liquid to a membrane. The slow process of oxidation accounts for the gradual volatilization of the binder, resulting in the reduction in volume of the paint film, the division of the paint into small chips, and a slight curling of the paint. Oxidation, secondary chemical processes, and mechanical stresses can be accelerated by several environmental factors, resulting in the rapid loss of the binder and the physical disruption of the paint layers. The source and direction of the stress is indicated by the direction of the paint curls and the formation of surface fractures.

The development of surface fractures can be seen in the dining-room samples viewed with a fluorescent microscope. The cracks are widest at the exposed surface and, as the paint loses volume through oxidation, the fracture extends down through the underlying layers of paint. The pattern of paint loss on the wood is an effect produced by the differential movement between the paint film and the wood substrate as each material responds to changes in relative humidity. Both the paint and wood are hygroscopic and will absorb or lose moisture until each is in equilibrium with the moisture content of the air. As the paint film oxidizes, it shrinks and becomes less flexible, magnifying the stress between the wood and paint and accelerating the paint loss (Fig. 7).

Conclusions and Recommendations

The monitoring program documented several environmental factors that produce stress in the paint, including chemical, photochemical, and physical reactions. These include the following:

- condensation on the paint surfaces,
- moisture from standing water in the basement,
- rapid changes in air temperature and relative humidity, and
- high ultraviolet and near-visible light levels.

Condensation, rapid changes in temperature and relative humidity, and high ultraviolet levels were found to be a result of the museum's operation. The recording of changes in temperature and relative humidity demonstrated the relationship between environmental stress and the opening of the museum doors and windows. High ultraviolet and light levels within the museum

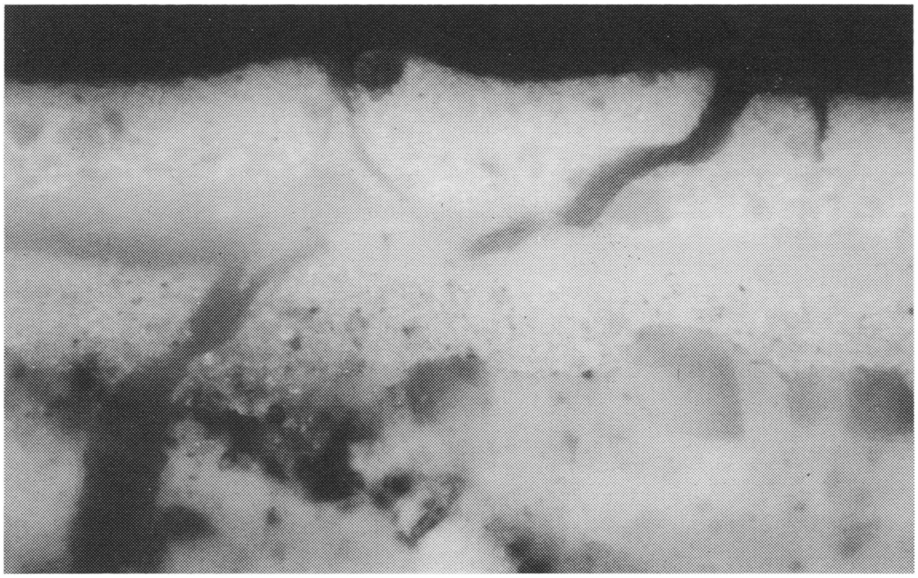

Fig. 7. Photomicrograph showing fractures in the paint film that lead to paint loss.

began when the mid-nineteenth-century interior blinds were removed in the 1970s in order to increase illumination. A review of historic and recent photographs, before and after the Trust ownership, showed the accelerated deterioration in recent years and led us to discount abrasion from prior housekeeping practices as a major contributor to paint loss.

Preserving Drayton Hall's interior paint will be challenging because there is no active environmental-control system. There are several practical procedures that can be implemented to reduce the stress on the paint and conservation treatments that can give the paint more resistance to the environmental stresses:

- new operational procedures to moderate changes in temperature and humidity,
- control of environmental extremes,
- conservation treatments for the paint, and
- permanent monitoring of the interior conditions.

The most direct way of reducing the interior environmental stresses is through use of the existing monitors developed for this study. Monitoring the air temperature, surface temperature, and the relative humidity on the interior and comparing these readings to the exterior air temperature and relative humidity would produce a real-time prediction of condensation. Delaying the opening of the windows until the interior and exterior temperatures are moderated would also reduce thermal and relative-humidity shock to the paint and wood substrate. Straightforward repairs to the windows, which were detailed in the report, would correct deterioration and restore their function.

Even with better control of environmental stresses, the more severely af-

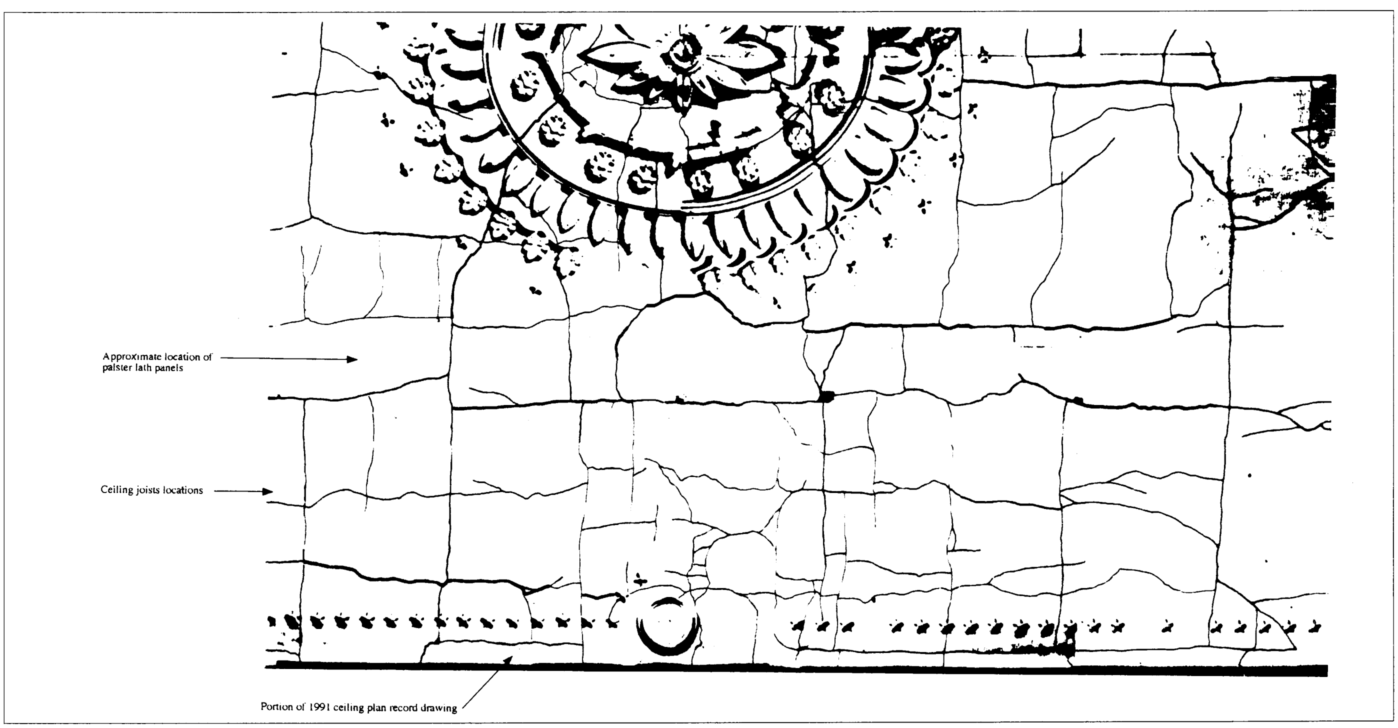

Fig. 8. Great Hall ceiling crack patterns and their relationship to staggered blocks of wood supporting lath.

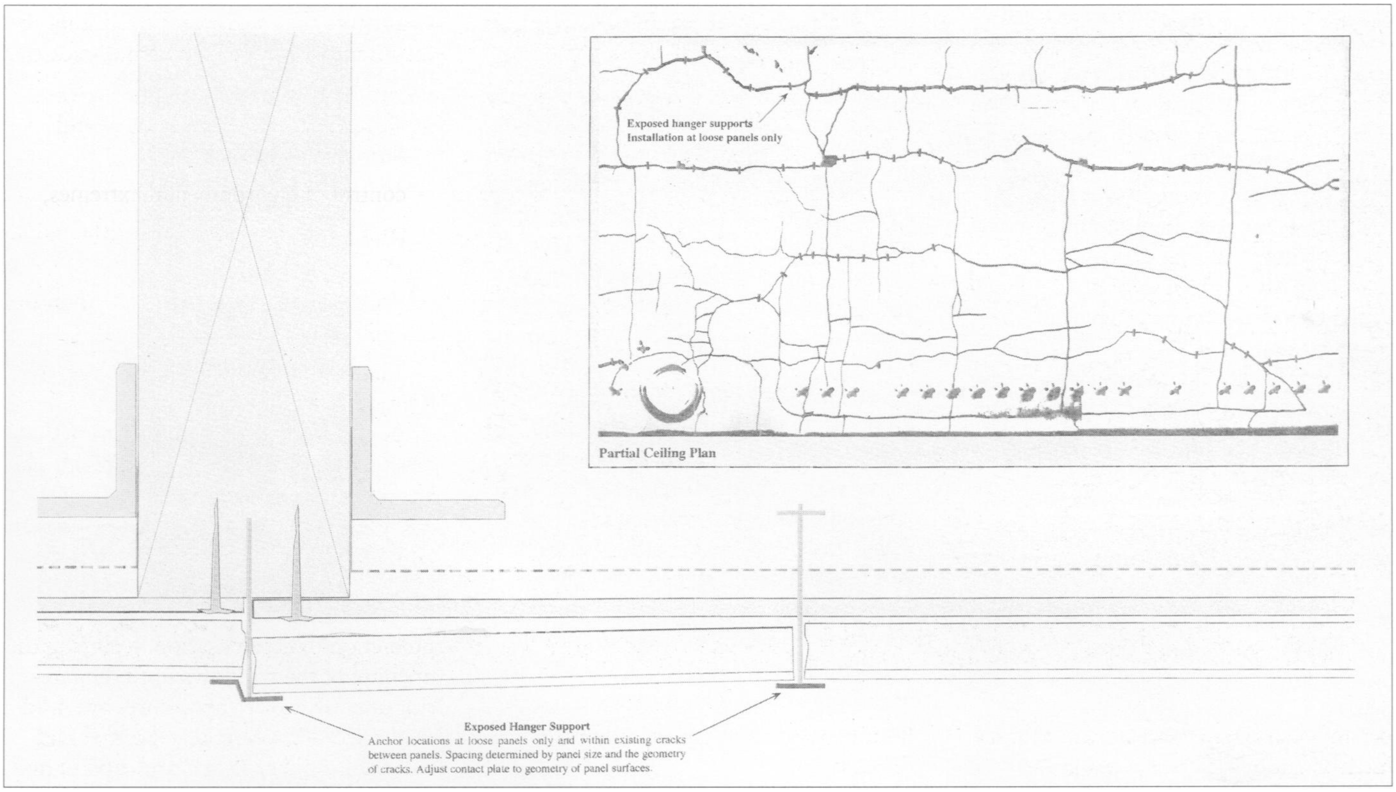

Fig. 9. Section through Great Hall ceiling showing one technique for reattachment of plaster panels.

fected paint will remain at risk. Paint deterioration is cumulative and not reversible. The conservation of the paint in Drayton Hall should proceed in the same manner as used for art-conservation programs. These procedures include the use of consolidants to stabilize fine surface particles and restore the bond between paint layers, fixatives for bonding the paint system to the substrate, the relaxation of cupped paint layers, and the removal of soil from the paint surface; the consolidation of the paint will produce resistance to mechanical stress, and reduce the reactivity of the paint layers to chemical and photochemical reactions.

In addition to a permanent environmental-monitoring program, we recommended that a photographic monitoring of selected areas of consolidated and unconsolidated paint should be performed on a six-month basis. This will produce a record with which to judge the effectiveness of the consolidation and the stability of untreated surfaces.

Conservation of the Great Hall Ceiling

Observations. The Great Hall ceiling has had a long history of repairs. It is thought that the present system is the second structural system and the third plaster system. The existing plaster was installed in the 1860s. Ours is the fourth study since the Trust acquired the property in 1974.

The ceiling consists of two systems: the structural spanning system, which includes the wood joists and wood braces, and the plaster system, consisting of the plaster and wood lath. In the late 1970s, steel reinforcement was added to the sides of each joist; a plaster of Paris mixture reinforced with wire mesh was cast over the entire ceiling to a depth of 1½ inches. This work was done in an effort to strengthen the joists and consolidate the plaster.

The ceiling still contains many cracks and has a substantial sag. In 1991 these conditions led the Trust to close the room above the ceiling to all foot traffic and to construct a bridge across the second-floor room. It had been thought that the two threats to the ceiling were the stability of the supporting structural system and the response of the plaster to environmental changes. The structural analysis of the ceiling determined that, while the joist system is somewhat flexible, it is not in danger of collapse. However, the dynamic deflection does transfer directly to the plaster.

Observation of the plaster's response to stress found that the plaster responds to vibrations and shock from the structural system but that it is very resistant to changes in temperature and humidity. Plaster is composed of inorganic elements that do not respond to the same magnitude as do the organic components of the paint. In previous studies, it had been believed that the plaster acted as a continuous membrane with a substantial thermal expansion due to changes in temperature.

Instead, our investigation found that the plaster cracks are in a pattern that corresponds both to the wood floor joists and to the staggered blocks of wood lath that support the plaster. The pattern of the cracks and the division of the ceiling into separate panels demonstrate that the ceiling has been more affected by bending stresses than by any other factor. The relatively small panels of plaster divide the larger stresses of structural movement into small components that can be accommodated by the plaster panels without causing additional plaster damage (Fig. 8).

This works well along the length of the joists, but where there is differential movement between adjacent joists, additional plaster cracking has occurred. The flexibility of the ceiling system is such that the conservation treatments must accommodate movement between the panels. Two techniques have been proposed for the reattachment of the three plaster panels: these areas can be reattached mechanically by installing flexible pins from the top of the plaster system or by installing small anchors up through the cracks between panels (Fig. 9).

Recommendations. The long-term goals of the repairs are to stabilize the plaster of the Great Hall ceiling, remove the bridge, reinstall the floor, and allow visitors to walk through the room above the Great Hall to experience more of the house, including its bedchambers. Our recommendations were the following:

- Stabilize the three unkeyed plaster panels that were discovered during the study.
- Reduce the deflection of the floor by stiffening two joists against the stair wall and creating a "stress-skin" system. This system would utilize plywood and screw anchors to create what are essentially "T" beams at the perimeter wall. This design will allow the original floorboards to be reinstalled in their original locations.

Visitors would be confined to the strengthened areas of the floor but would be able to walk through the room without a bridge. This design presents the least disruption to historic fabric, and it is reversible.

Summary

The environmental monitoring and conservation study of Drayton Hall documented that rapid changes in temperature and humidity, the occurrence of condensation, and high ultraviolet light levels were the direct result of the museum's operation. The National Trust is currently embarking on a major conservation project to resolve the structural issues of the Great Hall ceiling, to continue the monitoring of environmental conditions, to modify operational procedures, and to conserve windows, masonry, plaster, and paint. The planned conservation work will be most effective when the building operations are fine-tuned and the environment is better controlled. Based on the long-term environmental monitoring and the conservation recommendations of our team, this project marks a critical phase in the systematic, long-range strategy for the conservation of Drayton Hall.

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