INVESTIGATION AND REPAIR OF A TERRA COTTA DOME IN A COLD CLIMATE

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ABSTRACT

The investigation and repair of problems associated with a dome clad with a two-layer system of nonoverlapping terra cotta tiles is presented in this paper. The 17-m-diameter dome is located on the Alberta Legislature Building, which was constructed from 1907 to 1913. Water leakage through the dome has been an ongoing problem throughout its life. As a result of an investigation by a provincial government agency to determine a method for reducing water leakage, it was discovered that a serious outward displacement of the terra cotta tiles was occurring. Further investigation and analysis showed that the tiles could be stabilized by means of a retrofit anchorage system without disrupting the outside appearance of the dome. Considerable amounts of condensation, which were found to be forming on the inside of the dome due to air leakage from the interior of the building, were eliminated by the introduction of heat and fan pressurization to the attic space below the dome and by air sealing. Water leakage was controlled by a combination of repointing the terra cotta with lime-rich mortar and by the selective caulking of certain joints. These remedial repairs have been successful in stabilizing the tiles and controlling water leakage and condensation.

INTRODUCTION

The Alberta Provincial Legislature Building was constructed in the city of Edmonton during the period of 1907 to 1913 and is the seat of the provincial government. The main building material for the facade was yellow-brown-colored sandstone that was quarried in the southern area of the province. The most prominent feature of the building is the dome, which rises 54 m above grade and is clad in terra cotta tiles that roughly match the color of the sandstone. The dome has suffered from water leakage and deterioration for much of its life, and various remedial solutions have been attempted over the years. During the last 10 years the dome became the subject of considerable study, which resulted in the repairs described in this paper.

Basic Construction

As shown in Figures 1 and 2, the complete dome structure is composed of three sections:

1. The drum, consisting of vertical brick-bearing walls faced with sandstone.
2. The dome proper, a large curved section of terra cotta tile.
3. The lantern, a windowed structure that crowns the dome, also constructed of terra cotta.

It is believed that the original plans called for the dome to be covered with copper; however, apparently due to delivery problems, more readily available terra cotta was used. The terra cotta tiles were applied in two layers, with the inner layer supported on a riveted steel frame approximately 17 m in diameter. The steel frame consists of eight main curved ribs hinged at the bottom and connected at the top to a crown box beam. The crown box beam also carries the steel substructure for the terra-cotta-covered lantern. The main beams are supported at the bottom on a large reinforced concrete ring beam and tied together with steel plates to resist the outward thrust of the dome. Intermediate ribs and horizontal ring beams span between the main ribs and carry horizontal steel T-shapes measuring 50 mm by 50 mm at approximately 500-mm centers. The T-shapes serve as supports for the inner layer of terra cotta tile. Additional steel angles and threaded rods were added for structural stabilization of the terra cotta, as described later in this paper. Figures 3, 4, and 5 are views of the dome from the interior.

A plaster ceiling is suspended from the main steel frame, forming a large attic space below the terra cotta tiles. This space originally was unconditioned and was accessed through an open stairwell.

Figure 6 shows the original support of the terra cotta tile in more detail. The inner layer of terra cotta tile is approximately 75 mm thick and each tile is about 500 mm by 300 mm in frontal dimension. These tiles, called *booktiles* because of their book-like shape, are set in a mortar bed on the horizontal steel T-shapes. The joints

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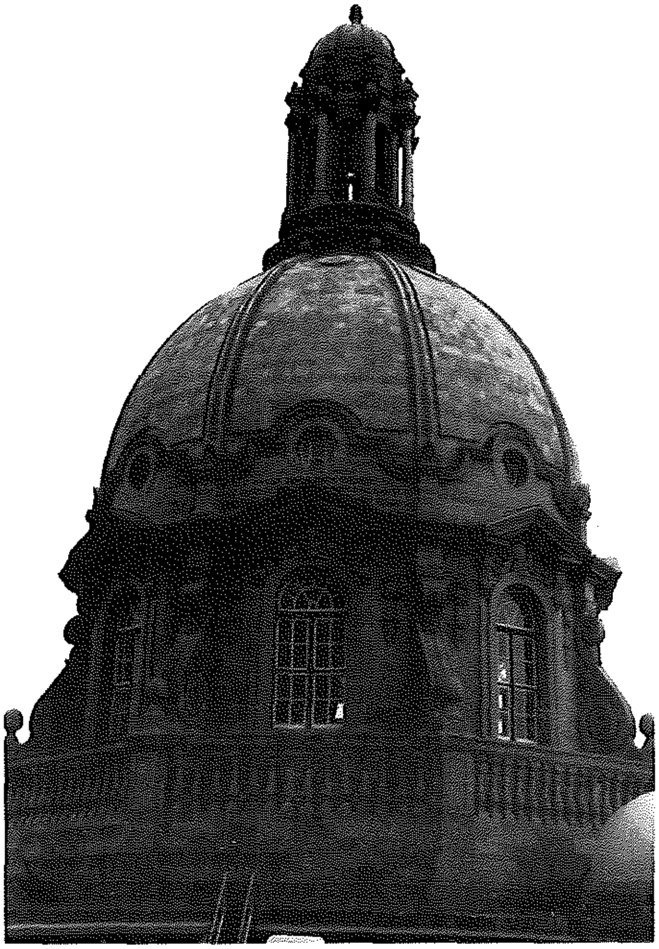

Figure 1 *Alberta Legislature Building terra cotta dome.*

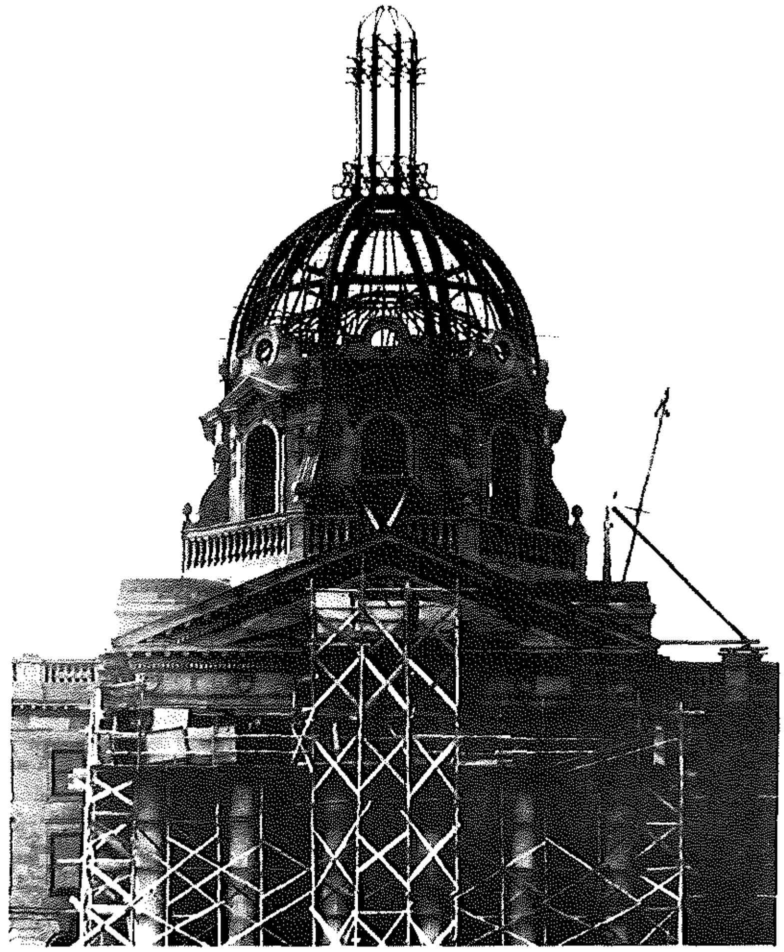

Figure 2 *Original construction photo.*

between the booktiles also are mortared. The booktiles are flat and do not form a spherical surface. The outer tiles are 150 mm in thickness and are about 300 mm by 400 mm in frontal dimension. The cores of the outer tiles were filled with a cement/sawdust mixture, possibly to provide some insulating effect.

The two layers of tile are not connected by ties or bonding units. The outer tiles are supported on an approximately 25-mm-thick setting bed of mortar or *collar joint,* which was placed against the inner booktiles. There are no ties or reinforcement contained within the outer layer of tile as typically detailed by the NTCS.[1]

There are eight raised decorative tile ribs corresponding to each of the eight main steel ribs below. This divides the dome into octants. There are no control or movement joints in either the steel or terra cotta structure.

Little could be determined of the origin or manufacture of the terra cotta tiles. The outer tiles are unglazed; however, they display a smooth exterior surface or "fireskin," which is water repellent when undamaged.

[1]Standard specification for the manufacture, furnishing, and setting of terra cotta, National Terra Cotta Society USA.

Problems with the Dome

Historic Records The dome probably has required maintenance ever since completion; however, the first definite reference to repairs appears in an Edmonton newspaper article (*Edmonton Journal* 1943). The article says that old mortar between the terra cotta tiles was being removed and replaced with new mortar to prevent water leakage through the dome.

The next reference (*Edmonton Journal* 1954) describes a major maintenance project to the dome. This involved three components: caulking the joints between the terra cotta, sandblasting the tiles, and applying a seal coating of masonry preservative. Again, the reason for the repairs was said to be water leakage.

In 1977, another restoration occurred that involved repointing of some badly deteriorated mortar joints and the application of caulking over all the joints (SJER 1977). The entire surface of the dome was then sprayed with an acrylic latex sealer that subsequently weathered off over the next few years.

Investigation

In 1983 Alberta Public Works was asked to advise on how to prevent the ongoing water leakage through the

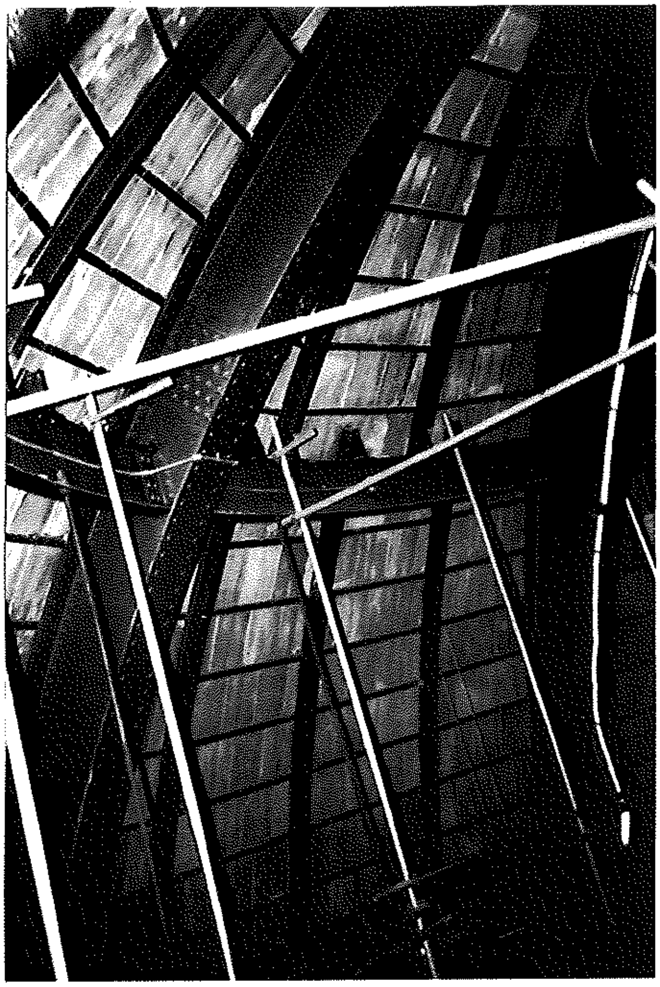

Figure 3 *View of a typical dome octant from the interior. Tube shapes in foreground are construction scaffolding.*

dome. With the assistance of a private consultant, the conditions of the interior and exterior of the dome were investigated.

Observations made from inside the attic during heavy rainstorms confirmed that substantial water leakage was occurring through the terra cotta tile system. The problem appeared worse in the south and west octants. Water dripped from the inner booktiles, thus wetting the steel framework and staining the plaster ceiling below. Water also appeared to be running down inside the collar joint located between the two layers of tile until it stopped on the top of the sandstone/brick drum. From here, the water appeared to be soaking into the masonry of the drum, probably accelerating the observed deterioration of the facing sandstone.

Cores taken through the booktiles in the lower portion of the dome showed that the mortar in the collar joint was cracked and permeated with voids. In the lower third of the dome, where the collar joint was nearly vertical, compaction of the mortar would not have occurred. Therefore, a continuous bond was not achieved between the inner and outer layers, leaving the outer tiles in this region unsupported.

Severe rusting of some steel T-shapes in the lower third of the dome also was noted. The steel had been converted to rust products, which occupied more volume than the original steel. As much as 50% of the thickness of the T-shape had been lost in one section.

A most disturbing finding was that some of the booktiles were displaced outward as much as 50 mm relative to their supporting T-shapes. The areas most affected by this displacement were the west and south octants. Figure 6 shows an example of the displaced book tile. The book-tile displacement appeared to have increased even during the period of investigation and there were obvious concerns about the stability of the terra cotta.

The general condition of the exterior tiles was found to be good. An occasional tile was cracked, but these cracks appeared to date from original construction. The smooth exterior fireskin had been sandblasted off many of the tiles during previous repairs; however, it did not appear to have caused the tiles to deteriorate. Some tiles had also suffered saw cuts due to careless repointing work in the past.

Investigations of the exterior of the dome showed that the outer layer of tiles was bulging in the locations where

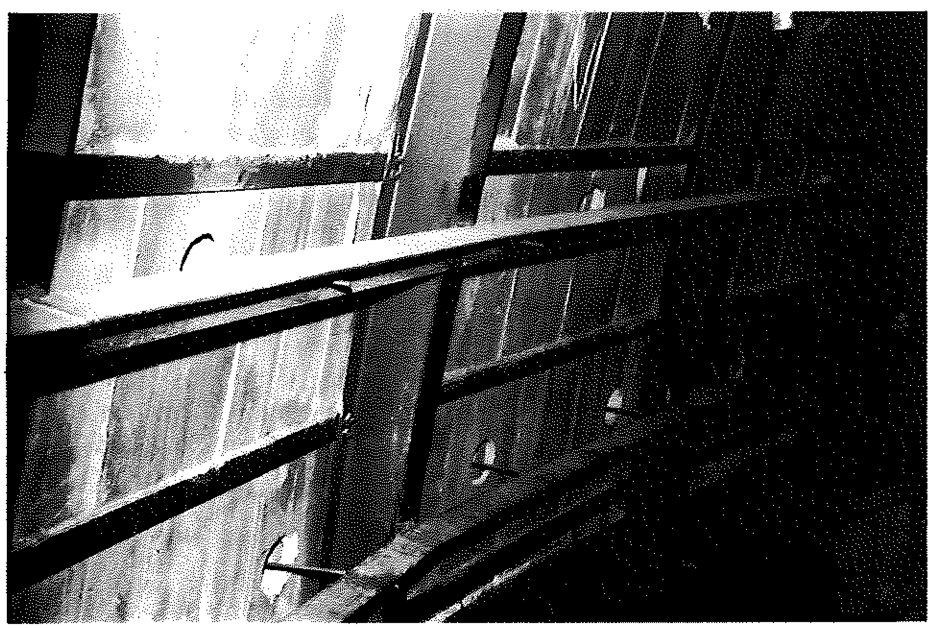

Figure 4 *New structural stabilization added to the existing steel framework.*

Figure 5 *Close-up of the new structure tie-backs. Note inner booktile has been removed to allow viewing of outer terra cotta tile.*

the inner booktiles had displaced. Hairline cracks and separation in the mortar joints could be seen in these areas. In general, the mortar between the tiles near the outer surface was found to be extremely hard, probably because of a high Portland cement content and a lack of lime. There were cracks and separations in the mortar, particularly in the areas where the bulges had been discovered. Smoke leakage tests showed that joints along the ribs also were separated. Ice and frost were observed in some mortar joints. More or less continuous hairline cracks were found in two horizontal joints of the terra cotta at approximately the tenth course from the bottom.

During the fall and winter, heavy coatings of frost and ice on the interior surfaces of the terra cotta were observed. Cores taken through the inner layer of book tile showed frost also was accumulating in the partial mortar-filled collar joint between the two layers of tile. Typical winter air temperatures in the attic space were found to be well below freezing and the relative humidity often was in excess of 75%. Smoke tracers showed a significant amount of air was leaking from the interior of the main building into the attic space, particularly through the open stairwell. It also was learned that several changes had taken place in the recent past that had probably increased humidity levels within the building. These included the introduction of a large fountain/pool in the foyer below the dome and the connection of the building to an underground pedway system. A number of individual offices in the building had also recently installed humidifiers.

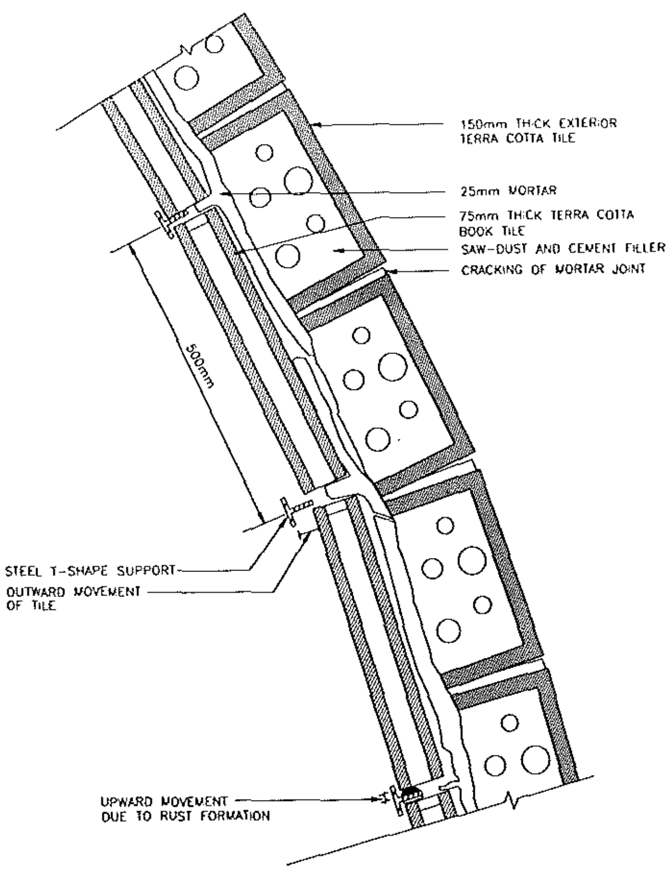

Figure 6 *Original condition of terra cotta tiles at location of maximum displacement.*

ANALYSIS

The discovery of the tile displacement and the unsupported nature of the outer layer of tiles raised concerns about the stability of the dome. It was recognized that the behavior of the dome was complex and involved aspects of structural engineering, materials science, and building envelope engineering. Furthermore, because the dome probably was the most significant historic landmark in the province, any intervention would have to respect historical conservation principles. Based on these reasons and a technical report (Weaver 1984), a team was assembled that included the building's property manager, building envelope specialists from Alberta Public Works, a structural engineering consultant, and a historic masonry consultant.

Research into the detailing of similar terra cotta structures of the period indicated that other terra cotta domes were in existence in the United States; the team decided to visit several such structures in the state of Pennsylvania, including domes in Philadelphia, Harrisburg, Pittsburgh, Washington, and Greensburg. It was found that all the domes suffered water leakage and deterioration problems and that one dome had suffered a partial collapse of the terra cotta, which resulted in recladding of the entire dome.

After returning from the site visits and considering the data accumulated from the recent investigation on the dome, the following conclusions were reached.

- The outer layer of tile was admitting considerable amounts of water into the dome. Besides staining the plaster ceiling below, this leakage was contributing to the corrosion of the steel T-shapes. Although some of the water was soaking through the surface of the tiles, which unfortunately had been sand-blasted during a previous repair, the majority of the water was shown to be leaking through the joints between the tiles, particularly at the ribs and at the tenth horizontal course, where movement in the tile field may have been concentrated.
- The mortar between the tiles was cracked or separated in many locations and, overall, it was extremely hard, probably due to a high Portland cement content. The hard mortar had a tendency to crack rather than accommodate movement in the tile, and water then easily penetrated these cracks. This problem appeared worse at the ribs and lower down on the dome. Various caulking compounds that had been smeared over the joints had not been effective in excluding water.
- The frost and ice that accumulated on and between the layers of terra cotta were largely due to the leakage of warm, moist inside air into the cold attic space and subsequent condensation on the cold surfaces. Several large openings through the plaster ceiling that appeared responsible for the leakage were identified. The condensation also contributed to the corrosion of the steel T-shapes.
- The cause of the outward displacement of the terra cotta was difficult to pinpoint and probably was due to a combination of factors:
  - — Fired clay products have a tendency to gradually expand as they readsorb moisture after leaving the kiln. This process can take several years. The outer layer of terra cotta was completely restrained in its own plane and there were no movement joints provided. The large size of the tiles and the hard Portland cement mortar meant that there was little or no cushioning effect from the joints. To relieve a buildup of in-plane stresses, the exterior terra cotta may therefore have displaced outward.
  - — The bulging also may have been caused by temperature movements caused by temperature differences between the steel frame on the inside of the dome and the terra cotta, which was exposed to the outside environment.
  - — The corrosion of the T-shapes supporting the booktiles also may have contributed to the displacement. Although the corrosion was not severe enough to cause failure of the T-shapes, a "rust jacking" phenomenon may have occurred as the inner layer of tightly placed tiles buckled outward to relieve compressive stresses caused by the growth of the corrosion products. The booktiles would have pushed the exterior tiles outward.
  - — Because considerable frost and ice were found between the two layers of tile, ice-lensing represented another possible mechanism whereby the outer layer of tile was displaced. The growth and expansion of ice between the two layers of tile may have pushed the outer layer outward.
  - — Although a single cause for the outward displacement of the tile was not obvious, it was agreed that the current situation was serious and that immediate remedial action was required to stabilize the dome and to prevent further deterioration.

REPAIRS

In view of the historic and highly visible nature of the building and the generally satisfactory condition of the terra cotta tiles, it was agreed that the best solution would be to maintain the existing appearance of the dome. This excluded such solutions as removing the tile and cladding the dome with copper or lead sheets.

The repair program was started in 1985-1986 and was concentrated in four areas:

- structural stabilization of the unsupported exterior tiles,
- installation of a mechanical system in the attic to prevent condensation and frost buildup on the tiles,
- repairs to the exterior tiles and mortar to reduce water penetration, and
- monitoring of the dome to determine if further displacements were occurring and to determine the effectiveness of the repairs.

The repairs concluded in 1994. The total cost of the program was approximately $700,000 (Canadian).

Structural Stabilization

A structural analysis that modeled the outer layer of terra cotta tiles as an unsupported shell indicated that the lower third of the tiles should be stabilized. In this lower zone, a spherical shell structure has a tendency to push outward. Rather than disrupt the dome's appearance by fastening through the outside, it was decided to tie back the outer tiles from the interior using stainless steel rods anchored in the webs of the tiles. The rods were then connected to new angles, which were welded to the existing steel frame as shown in Figures 4 and 5. An analysis of the frame showed that it was adequate to support all loads transmitted from the terra cotta.

To do this work it was first necessary to build a catwalk platform inside the attic around the perimeter of the dome. This was augmented by scaffolding where necessary. Next, 100-mm-diameter cores were made through the inner booktiles corresponding to each exterior tile on every second horizontal row. This resulted in an anchor spacing of approximately 500 mm by 500 mm. A 13-mm-diameter hole was then drilled into a web on the back of each outer tile. The hole did not extend right through the tile, so the exterior surface of the tile was not affected. New 75 by 75 by 6 mm structural steel angles were then welded to the existing intermediate steel ribs. The hole in the back of each tile was filled with epoxy adhesive and a 10-mm-diameter stainless steel threaded rod was inserted into the hole and fastened to the new angle.

The adhesive anchoring system was selected because of the risk of cracking the tiles with expansion-type anchors. Tests conducted on the site by the adhesive manufacturer showed that the pull-out strength of the rods was more than adequate. The rods were then fastened back to the new steel angles by means of nuts that were tightened sequentially in order to bring the system into a snug position.

Control of the Attic Environment

Because a substantial amount of the moist interior air was entering the attic space, much of the condensation problem was solved by simply sealing up large leakage holes at the line of the plaster ceiling. However, because it was impractical to locate and seal all air leakage paths, it was decided to artificially pressurize the attic space with outside air and also to provide heat to the space. The pressurization, in effect, reversed the direction of air leakage, which now occurs from the attic to the main building. The outside air used to pressurize the attic

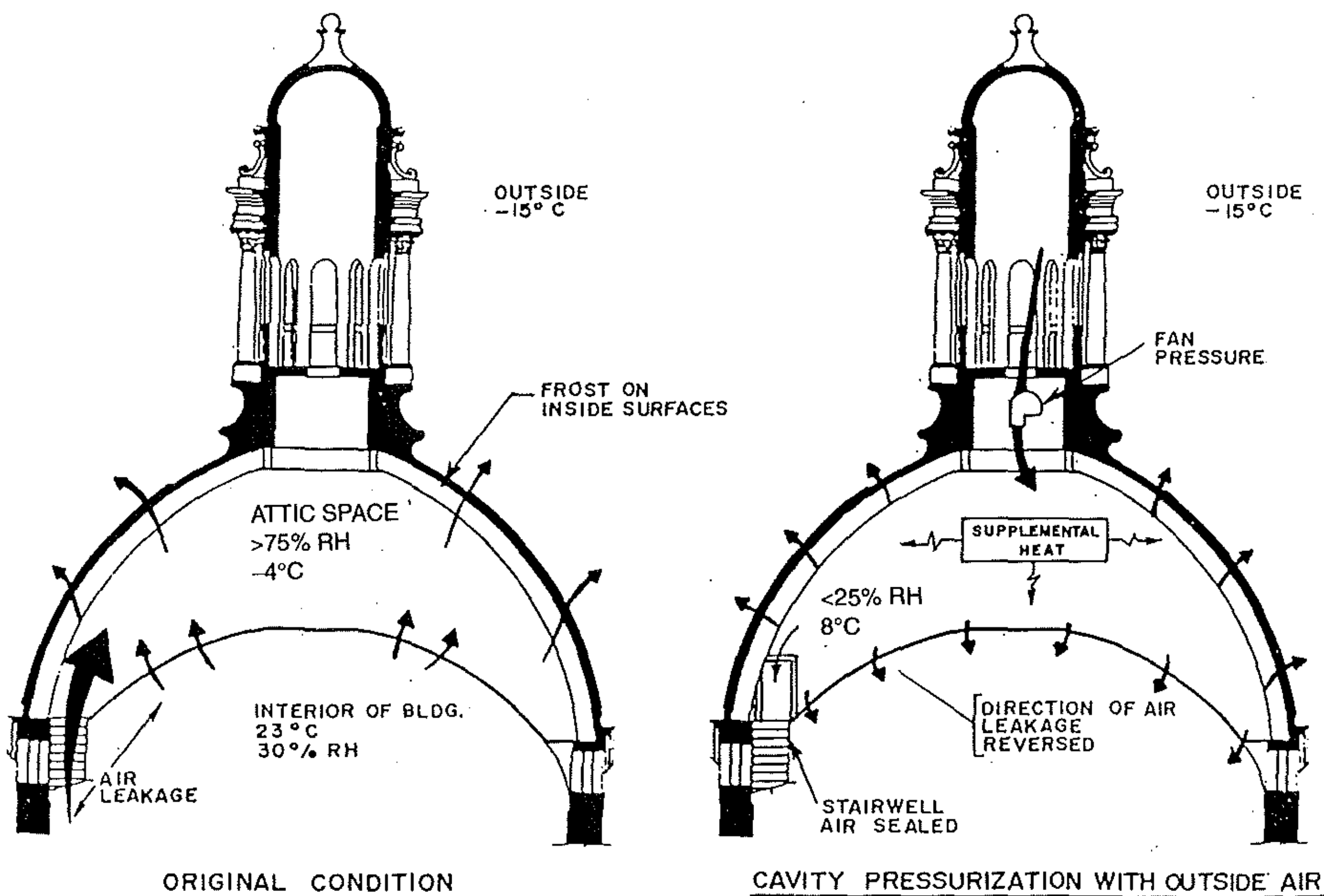

Figure 7 Typical winter conditions in the dome attic before and after repairs.

contains little water vapor and, once heated, becomes relatively dry, eliminating the condensation problem and increasing the drying potential from surfaces in the attic. A summary of the concept can be seen in Figure 7.

The new mechanical system consisted of a fan unit with a flow rate of approximately 235 L/s and an outside air intake located in the lantern. Two electric heaters were installed in the attic with a total output of 40 kW, which was the maximum power available to the attic. These heaters were designed to maintain the attic space at a temperature of 5°C when the outside air temperature is –34°C; they are controlled by an interior thermostat. A glycol heat pump was used to augment the heaters. Continuously running circulation fans also were installed within the space to mix the air uniformly.

Control of Water Leakage

Inner Drainage System To reduce water damage to the sandstone in the drum walls below the dome, the bottom row of inner book tile was removed and an internal gutter was built under the collar joint space between the two layers of tile. This gutter intercepted water that had previously been draining down between the tiles and soaking into the masonry of the drum. Water from each octant was collected individually so that relative leakage could be compared.

Trial Repair Although the fireskin had been sandblasted off many of the exterior tiles, water tests showed that the major proportion of the water was leaking through the mortar joints between the tiles rather than through the tiles themselves. The water tests and observations from within the dome suggested that the leakiest joints occurred adjacent to the ribs. It was concluded that repointing the mortar joints with a softer, lime-rich mortar and installing a properly designed sealant at the ribs would reduce the amount of water penetration to acceptable levels. To assess the effectiveness of this solution, it was decided to repair a single octant and monitor its performance before proceeding with repairs to the remainder of the dome.

In 1986 the west octant, which contained the worst bulging tiles, was repaired. Three different mortar mixes were tried in three demarcated zones; these included cement:lime:sand ratios of 1:1:6, 1:2:9, and 1:3:12. Joint repairs consisted of removing the existing mortar to a depth of two-and-a-half times the joint width and then repointing the joint with new mortar. Special care was taken to use only hand tools, which would not damage the surface of the terra cotta. In some locations where the existing mortar was deteriorated, the full depth of the joint was repacked with mortar.

The joints at the inside of the west octants ribs were sealed with a fillet bead of polyurethane caulking. The fillet legs were approximately 1 in. wide and a bond breaker tape was applied at the root of the fillet to prevent a stress concentration in the sealant.

During the exterior investigations it had been discovered that the small exterior gutters carved into the sandstone located at the base of the terra cotta just above the drum were leaking badly and damaging the stone below. It was decided to include a trial installation of lead flashing in the gutter and the ledge of the west octant as part of the trial repair. Lead was selected because of its proven history as a durable flashing material and its ability to conform to the curved shape of the gutter. A small section of the gutter also was protected with an acrylic latex material reinforced with glass mesh. This material would be a much less expensive alternative than lead should it prove to be sufficiently durable.

Main Repairs The trial repairs to the west octant were evaluated over a five-year period. This included observations made on the interior of the dome and also a detailed exterior inspection that consisted of water testing, as well as visual observations. It was concluded that the repairs to the west octant had provided an adequate level of water resistance but that the performance could be further improved by the addition of more resilient sealant joints. There was no definite conclusion regarding the relative performance of the three different mortar mixes. The 1:2:9 mix, which was of medium hardness, was selected for repointing the remaining seven octants.

The polyurethane caulking in the trial octant had performed well and was therefore used in the remaining octants. In addition to caulking the vertical joints along each of the ribs with a fillet of sealant, the two horizontal joints at the tenth course that displayed hairline cracking were caulked with a butt-type profile.

Apart from a poorly executed reglet detail, the lead flashing appeared to have performed adequately. But, it was decided to use 20-ounce copper sheet for flashing the gutters. This was mainly because a skilled coppersmith was available locally. Based on historical information, copper was felt to be as durable as lead. The acrylic latex material, which also had been tried, performed adequately over the five-year trial, but was felt to be insufficiently durable for installation in such an inaccessible location.

The main repairs lasted approximately four months during the summer of 1994. During this period the entire dome structure was enclosed by scaffolding, permitting the lantern to be inspected and repaired. In addition to repointing and caulking, other minor repairs were executed. These included routing out minor hairline cracks in tiles and filling them with mortar, installing a weathertight clearance light hatch, and creating a slope for drainage on various horizontal surfaces found on the terra cotta. Stainless steel cramps were used to secure larger cracked pieces of terra cotta in a few locations.

Monitoring

Immediately after the structural stabilization of the dome in 1985, "telltales" were installed to measure move-