

## **Title: Building Envelope Upgrade at Frank Lloyd Wright's Solomon R. Guggenheim Museum**

### Authors

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### Abstract

The Solomon R. Guggenheim Museum in New York, the last major work by Frank Lloyd Wright completed in 1959, was the focus of a major restoration effort from 2004 to 2008. Throughout its service life, the building has performed admirably, but with some prominent building-envelope flaws. In response to evidence of cracking, the museum undertook an extended study prior to remediation. The principal focus of the remediation was architectural and structural—heat and moisture analysis was part of the overall effort. One part of the heat and moisture analysis was investigation and measurement of conditions in the wall assembly.

Temperature and humidity data was collected at several locations. Results varied, but higher moisture content was documented at one location throughout the winter. On two cold isolated occasions, while the entire wall system was protected from rain by a temporary roof system, liquid water was emitted to the outside through horizontal cracks in the concrete. The analysis of these conditions led to the adoption of measures 1) to control air flow through the assembly; 2) to reduce rain loading on the wall; and 3) to reduce the effect of cold bridging where the exterior walls meet the floor slabs, interior walls and new steel reinforcement. This study will be presented.

The paper will include the transient modeling undertaken during the project. This study focused on investigating the effects of insulation, interior vapor retarding materials, exterior water protection films, and concrete and other components according to the latest boundary conditions specified by *ASHRAE 160P*. Moisture conditions potentially leading to deterioration of the concrete and steel were used as the limiting criteria. This study assisted in specifying exterior coatings and any modifications to the interior insulation or vapor protection.

The final system upgrade included the installation of a new fluid-applied air and moisture barrier and cellular glass insulation on the interior side of the uppermost Rotunda wall, which was exposed to allow for the installation of the surface-mounted interior structural reinforcement.

**Keywords:** Thermal Upgrade, Existing Buildings, Case Study, Hygric and Thermal Upgrade, Internal Insulation Systems.

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## Introduction

The Solomon R. Guggenheim Museum (SRGM) in New York City was completed in 1959, and is the final major work of architect Frank Lloyd Wright. See Figure 1. The main elements were the Rotunda (right)—the main exhibit space, and the smaller glazed monitor seen on the left. The primary structural materials were cast-in-place concrete and shotcrete, then known as gunite. Gunite was used for much of the wall construction. The floors, ramps, structural beams, interior walls and intersecting wall areas were of cast-in-place concrete. A case may be made that the SRGM was the first major architectural work to make use of gunite. A large market for gunite at the time was in the growing industry for swimming pools. A history of shotcrete states that, prior to 1950, its uses were outside the architectural mainstream:

About half of all the (shotcrete) machines that went into service around the world did so in the melting shops of industry: smelters, foundries, chimneys, boilers, refineries, etc. The other half were used to construct water storage and transport systems, protect steel structures and to repair, construct, and support concrete and earth structures for countless industrial and commercial uses.<sup>1</sup>

At Guggenheim, the placement of the gunite involved installation of plywood formwork facing the outside, then metal reinforcement was erected. In the Rotunda, the metal consisted of steel tees at every 10 degrees of circumference, with circumferential bars, and welded wire fabric at the outside and the inside of the vertical and circumferential members. The gunite was projected against the form from the interior. The overall wall thickness was approximately 5 to 5 ½ inches. The impressions of the plywood formwork at the outside of the wall were retained in the final finish. Note the wall condition in Figure 2. This figure shows insulation being installed in 1992.

A specification for the “gun-projected concrete” is among the archived construction documents. The specification calls for best practices and highest standards of the trade, however it is not specific regarding avoidance of cavities or voids in the resulting concrete. In shotcrete, voids are possible since the metal reinforcing can prevent concrete from filling the space immediately behind the steel. See Figure 3 showing correct and incorrect methods of applying gun-propelled concrete.

The exterior of the museum was painted with a primer, then a vinyl acrylic “cocoon” coating were spray-applied to the exterior of the building. See Figure 4. Subsequent to the original construction, several recoating campaigns ensued. The water vapor permeance of the gunite and cocoon were measured by Architectural Conservation Laboratory in 1993.

The recorded values are:

Gunite with all coating layers 0.81 g/m<sup>2</sup>·h (180 ng/m<sup>2</sup>·s·Pa, 3.2 perms at assumed dry cup conditions)  
Uncoated gunite 2.10 g/m<sup>2</sup>·h (466 ng/m<sup>2</sup>·s·Pa, 8.2 perms at assumed dry cup conditions)

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<sup>1</sup> Yogy, George D. “The History of Shotcrete”, *Shotcrete*, Three part series: Fall 2000, Spring 2001 and Winter 2002.

The vapor pressure difference at which these transmission rates were taken was not recorded. If we assume they were the result of standard dry cup tests at room temperature, with RH at 50% and 0%, then the permeance results are those shown in parentheses above.

Over time, there have been several interventions in the building. In 1992, cellular glass insulation was added to the interiors of the Rotunda walls. The cellular glass was installed in 2 ½” thick panels adhered to the walls. The material itself is very impermeable to gas diffusion—even slight abrasion of the material releases hydrogen sulfide gas left from the original material production almost 20 years earlier. An air gap of variable size resulted from the flat panels being applied against the rough, curved wall surface. Mastic was used to seal the joints between the cell glass blocks. Other than the four gobs specified to adhere the insulation to the walls, no mastic was used between the cell glass and the wall itself. See Figure 2. Plaster was applied to structural lath inboard of the insulation. An accumulation of many coats of latex paint was applied over time to the interior plaster.

In 2004, a major restoration effort was undertaken, prompted by concerns over cracks that appeared on the structure. The scope of work was largely architectural and structural, but it included a study of the moisture performance of the building, a portion of which is reported here. (Other portions of the moisture performance work addressed window condensation and air movement within the interior space.) Throughout the study, the museum remained open. The indoor temperature remained approximately 70°F, and the relative humidity was maintained between 40% and 50%. The mechanical system was designed for building pressurization. However, because of large air leaks in the building envelope discovered in the course of the investigation, the building cannot be presumed to have a constant pressurization or depressurization.

### **First monitoring campaign**

For the initial monitoring campaign, four sensors to detect temperature and relative humidity were placed in the wall on Ramp 4. The Main Rotunda has a total of six ramps, and the uppermost ramp provides overhanging protection against rain to the ones below. See Figure 1. The exhibition space between the gunite wall and two adjacent load-bearing concrete walls are known as “bays” (see Figure 2).

Two sensors were installed in south-facing bay 44 and two sensors were installed in west-facing bay 47. One sensor was installed so that it captured the air temperature and humidity of a “bubble” at the inside of the gunite wall panel (named “IWP” location in the reports) and another at the interface of the gunite and the insulation (named “BWP” or behind wall panel in the reports). See Figure 5. Monitoring data was collected from March 2005 to October 2005. There was no scaffolding in place during this time, and the exterior cocoon finish was in place. Thus the results from this campaign represent normal performance of the wall.

Results from this March-October monitoring campaign are shown in Figures 6 and 7. Figure 6 presents a timeline of relative humidity for Bay 47. (Results from Bay 44 were

similar.) The conditions within the gunite wall (IWP) showed stable RH; conditions at the cavity between the insulation and the gunite wall (BWP) were variable, but at lower RH than IWP. Figure 7 shows the same data, with vapor pressure plotted against temperature. As seen in Figure 6, relative humidity at the mid-thickness of the gunite wall remains somewhat constant.

With the cocoon on the outside and foam glass insulation at the inside, the moisture content of the concrete remains practically constant. The concrete buffers the humidity in the wall, and overhanging ramps above provide protection against rain. Given the sorption isotherm relation between moisture content and relative humidity, it follows that the RH would remain practically constant. At the wall-insulation interface, conditions were not as stable. The air at that location was not contained tightly, but rather communicated to both the interior and exterior. Consequently, airflow affected temperature and humidity at that interface.

The preliminary conclusion drawn from this summertime study was that for walls of this type, with a relatively vapor-tight cocoon at the outside, with rain protection from overhanging ramps above, and insulation at the inside, for the months when instrumentation was in place, no problematic high relative humidities should be anticipated. In other words, a highly buffered material such as gunite performed well with very low vapor permeance materials on both the inside (cellular glass) and outside (cocoon coating), provided the material was protected from rain.

### **Second monitoring campaign and observations**

Technical problems prevented data collection during winter 2005-2006. Monitoring resumed in Spring 2006. During the preceding winter, the building was put under scaffold so that no rainwater landed on any of the building walls. Once the scaffolding was complete the cocoon finish was removed down to the bare concrete. Therefore data from the second campaign shows the effect of no rain load and no exterior finish.

Monitoring data for the wintertime of the second campaign are shown in Figures 8 and 9. Figure 8 shows calculated vapor pressure at the BWP location for four sensors at Ramp 4. The cocoon had been removed. What is readily apparent is the fact that vapor pressure in the interface between the gunite wall and insulation is in equilibrium with the outdoors. This holds true for the original sensors and for the new sensors as well. (New and old sensors were paired to ensure similarity of data from the first to the second campaign.)

Following an exterior crack survey, (see Figure 11) greater concerns were raised for the 6<sup>th</sup> floor ramp, the uppermost ramp. For the second campaign, additional temperature and humidity sensors were placed in the walls of ramp 6, in Bays 64 (south-facing) and 67 (west-facing), using the same placement specification as below. Figure 9 shows the measured RH within the wall (IWP location) for the sensors on Ramp 6 and Ramp 4. The inside wall panel sensors for bay 67 remained between 60% and 70% RH until January, when a clear escalation in RH began, terminating close to 80% RH. More striking was the performance of the south-facing sensor, which showed RH at 80% at the start of the

winter, and climbed up to 95% RH by February. At the same time, the RH on the four sensors at the fourth floor ramp remained low, between 50% and 60%. The 6<sup>th</sup> floor ramp wall was performing much more poorly than the 4<sup>th</sup> floor ramps, at a time when it had excellent protection from rain by virtue of a temporary roof, and very high drying potential due to the removal of the cocoon. The fourth floor and sixth floor ramps were at the same temperature, so had the same temperature-driven drying potential.

Two curious wetting events were observed to occur, one in December 2005 and a second similar event in January 2007. See Figure 10. On both occasions, water was seen to be “bleeding” out of horizontal cracks in the wall at the 6<sup>th</sup> floor ramp level, on the southeast side of the building. In both instances the wall was fully protected against rain and snow by a roof that was part of the scaffold. Monitoring data indicates that both “bleeding” events occurred when a severe below-freezing cold snap came to an end.

### **Discussion**

What performance of the wall assembly explains the measured wetting on the 6<sup>th</sup> floor ramp and the “bleeding” events? The following observations contribute to the explanation:

1. Air pressure tends to drive indoor air outward through the wall
  - a. Most museum buildings, and the SRGM is no exception, are maintained at positive pressure by mechanical system design and operation.
  - b. During winter, thermal buoyancy tends to drive indoor air outward through the building envelope at the highest elevations in the building.
  - c. Prevailing winds are from the northwest. The southeast part of the building is on the leeward side, so wind pressure tends to drive indoor air outward. Bay 62, site of the “bleeding” event, is on the southeast side of the building.
2. There were pathways for air flow through the wall assembly
  - a. The gunite wall contains cavities. While best practice would indicate complete filling of the wall with concrete, several factors during construction led to less than complete filling, similar to the incorrect applications shown on Figure 3. This voiding was confirmed by field probes.
  - b. A crack survey (see Figure 11) showed the greatest amount of large cracking at the 6<sup>th</sup> floor ramp, of all the ramps in the Main Rotunda. Most of the cracking was vertical, but horizontal cracks were found, often at the locations of the circumferential reinforcing steel.
  - c. Data indicate that the cavity between the insulation and the wall is coupled to both the indoors and to the outdoors.
3. The indoor air is humidified. During winter, the indoor air was humidified, with a target RH of 50%. Actual RH was between 40% and 50%. Precipitation was excluded as a contributing factor because of the complete roof over the structure at the time.

4. The bleeding phenomenon occurred at the time of the first warm spell following a severe cold spell.

These conditions suggest the following scenario: During cold weather the gunite is cold and may be sub-freezing. Humidified air moves through the network of voids on the “shadow” side of the steel reinforcement. When the surfaces surrounding the exfiltration pathways are above freezing, the moisture content of the concrete becomes elevated, as seen in Figure 9. When surfaces surrounding those pathways are below freezing, frost is formed. With temperature changes, the frost may become water and refreeze to ice. Frost and ice will accumulate during cold spells. With a strong warming trend, the resulting liquid water cannot all be absorbed into the already wet concrete. It drains out of cracks, under gravity and air pressure difference, particularly at the leeward areas.

### **Recommendation**

The recommended repairs for the building as a consequence of this study included 1) treatment for all exposed cracks, and 2) an installation of an air and moisture barrier at the interior of the gunite. The authors’ involvement in the project was limited to the early design phase, so we are unable to report on the execution or performance of the completed wall assembly.

The study did not include the impact of rain on the structure. The first campaign was conducted on Ramp 4 which was protected from rain by overhanging ramps above. The second campaign was done while the building was under a temporary roof structure. Concerns for rain effects on the wall led to the design and construction of an inward-sloped parapet coping to replace the original flat coping. See Figure 12.

### **Conclusions**

Initial concerns were expressed for moisture performance of the wall assembly with a relatively vapor-impermeable coating on the outside and insulation at the inside. A first monitoring campaign at Ramp 4 showed stable relative humidity in the gunite at less than 60% relative humidity. A second campaign showed continued good performance at Ramp 4, but unsatisfactorily high RH in the gunite in Ramp 6. Higher air pressure drive and greater flow through Ramp 6 cracks are sufficient to explain the observations.

A “bleeding” phenomenon occurred with the building fully protected from rain and snow. As above, air pressure drive was strong and there were many cracks and voids permitting flow. Accumulation of frost and ice during periods of low temperature is necessary to explain the observation.

Corrective measures to fill the gaps and voids in the gunite and to provide an air barrier at the interior of the wall were recommended. As with many projects of this type, the consultants responsible for making recommendations of this type are not in a position to document the level of compliance with the recommendations. Discussions of indoor humidity settings and mechanical pressurization were conducted in the course of the

work, but are beyond the scope of this paper. **Building Envelope Upgrade at Frank Lloyd Wright's Solomon R. Guggenheim Museum**

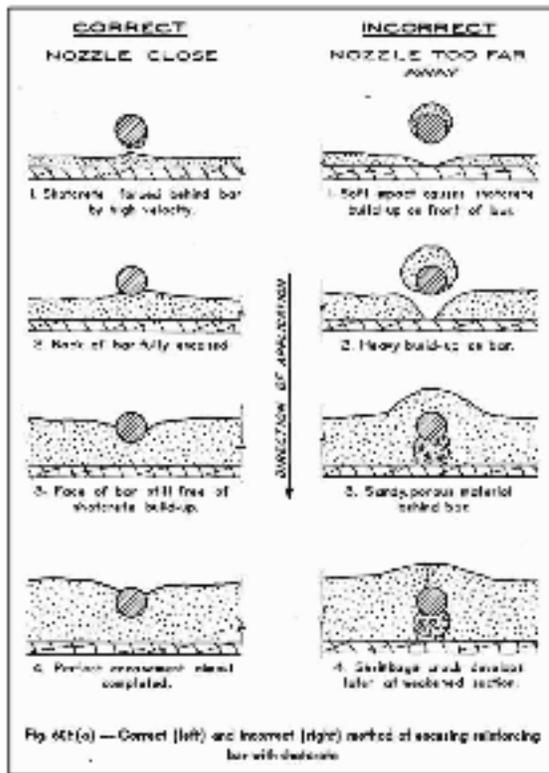
**Figures**



**Figure 1. Solomon R. Guggenheim Museum, New York. ca 1958.  
©William B. Short, the Solomon R. Guggenheim Foundation**



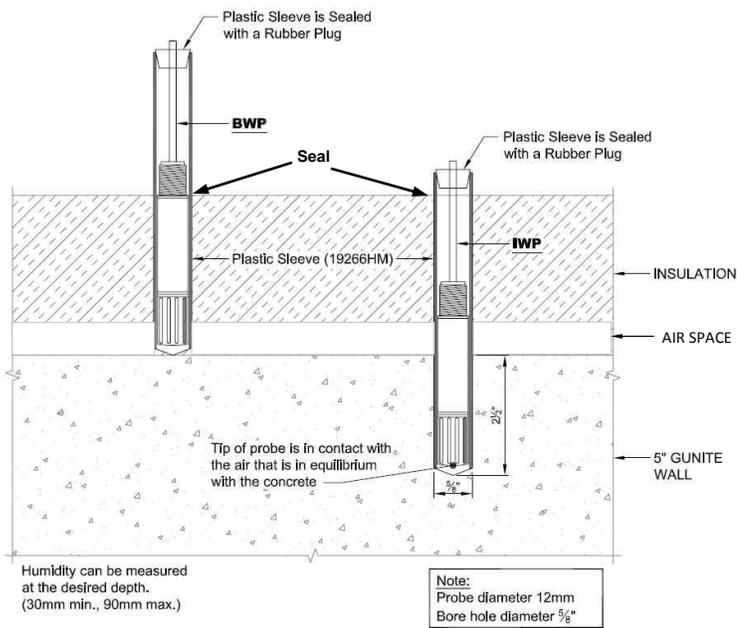
**Figure 2. Placement of cellular foam glass insulation against gunite walls in the Main Rotunda, ca 1992. © D. Heald. The Solomon R. Guggenheim Foundation**



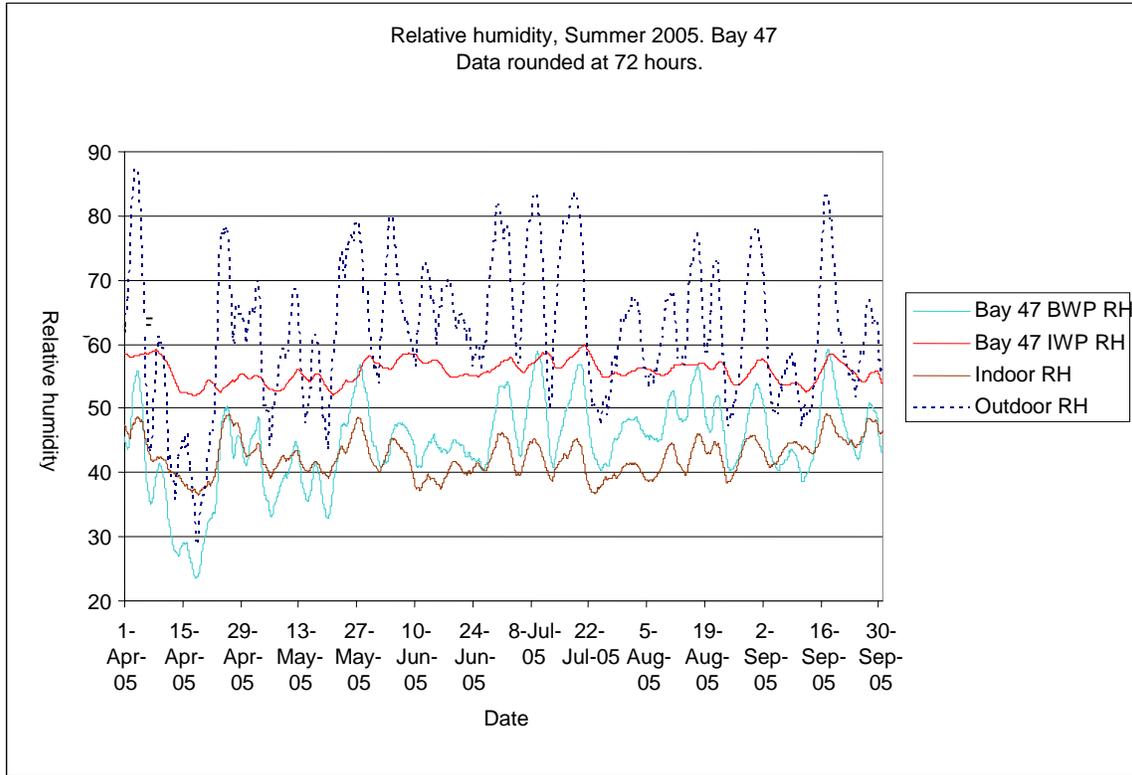
**Figure 3. Diagram from Yogy (2000) showing correct and incorrect methods of application of gunite.**



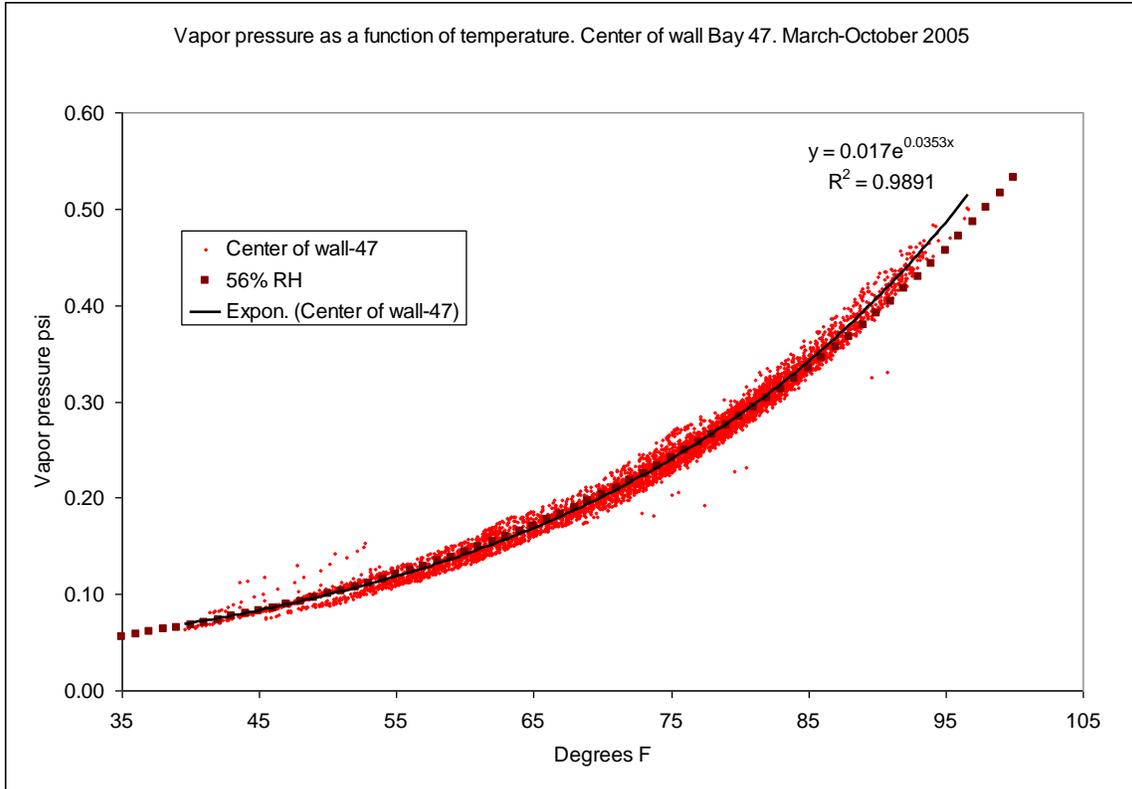
**Figure 4. Application of “cocoon” finish (one of several layers) to the exterior of the Main Rotunda, ca 1958. © William B. Short. The Solomon R. Guggenheim Foundation**



**Figure 5. Temperature and humidity sensor placement in the walls of the Main Rotunda, Ramp 4 and Ramp 6.**

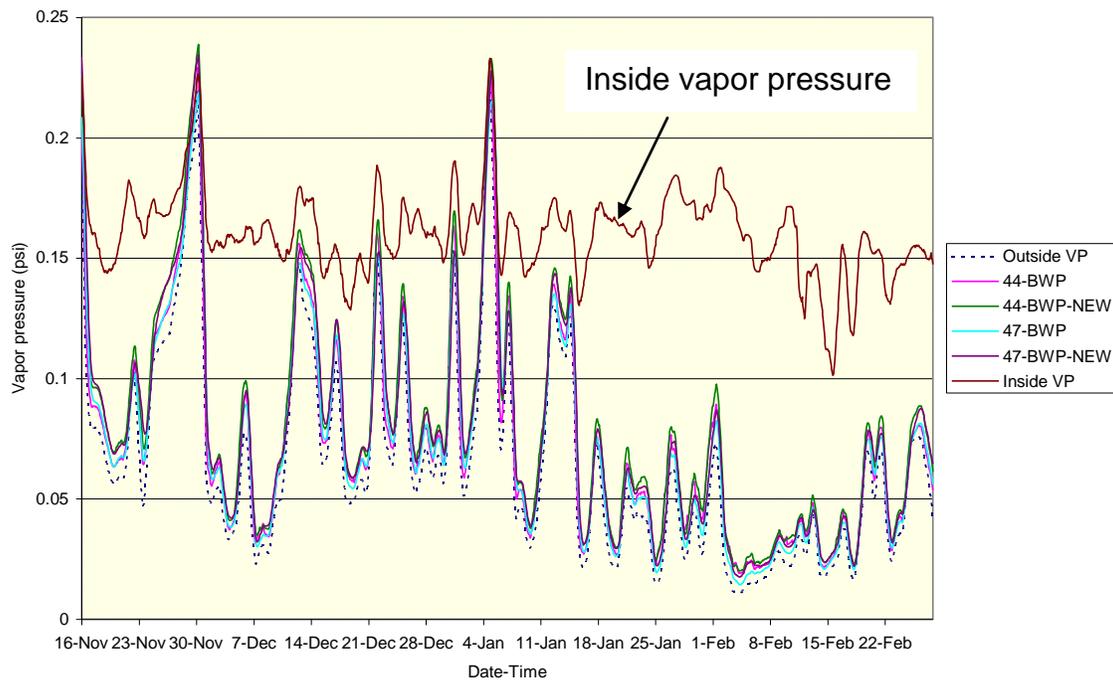


**Figure 6. Timeline of relative humidity measurements, April to September 2005, Bay 47. Exterior “cocoon” finish was in place.**



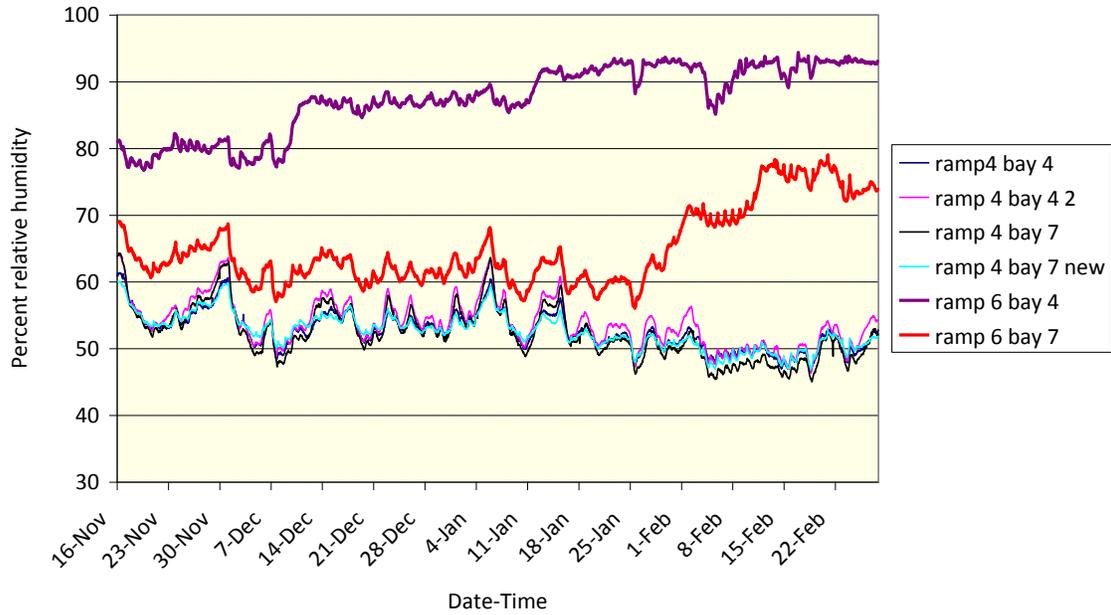
**Figure 7. Temperature and humidity results, March-October 2005, bay 47, within the thickness of the gunite wall (IWP position).**

Vapor pressure measured at the BWP location, four sensors, Ramp 4, Winter 2006-2007, 72-hour rounding



**Figure 8. Timeline of relative humidity measurements at the interface between the insulation and the gunite (BWP position) for winter 2006-2007, Bays 44 and 47. Exterior “cocoon” finish had been removed.**

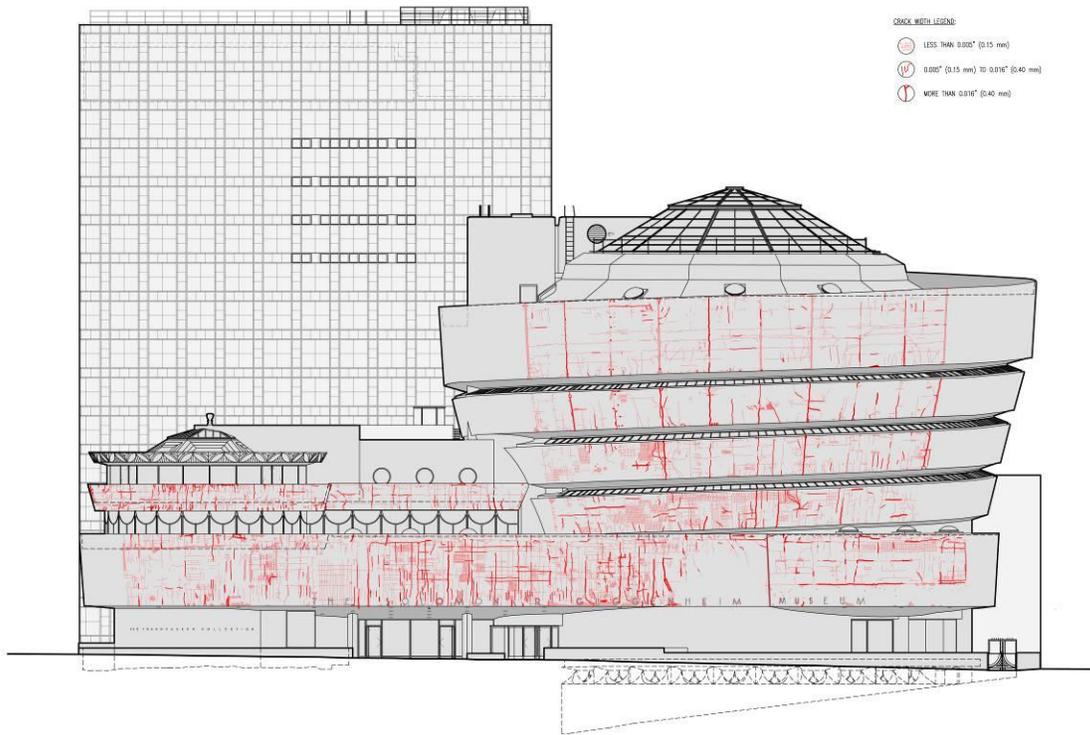
Relative humidity at Guggenheim wall locations  
November 2006 to February 2007



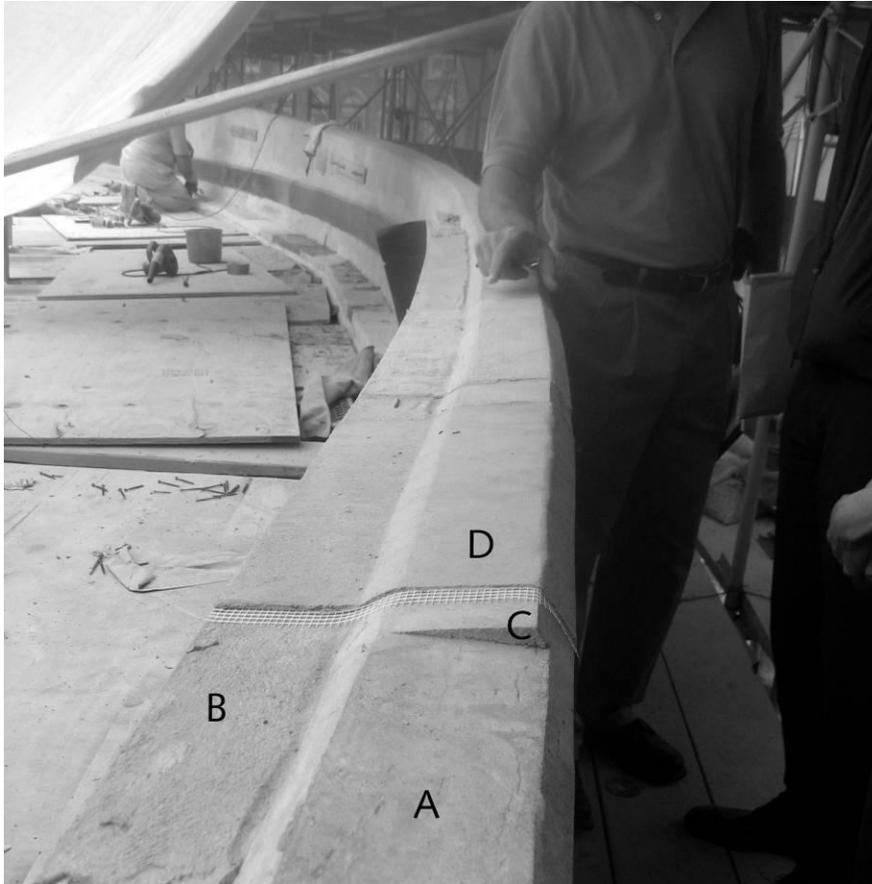
**Figure 9. Relative humidity measurements in bays 44, 47, 64 and 67, winter 2006-2007, at the center of the wall thickness (IWP position).**



**Figure 10. “Bleeding” event at the exterior surface of Bay 62. Scaffold roof provided full protection against rain and snow at the time of the photograph.**



**Figure 11. Extent of exterior wall cracking at the Guggenheim's Fifth Avenue (West) façade. @ WASA/Studio A.**



**Figure 12. Onsite mockup of new cementitious topping along full-length of Rotunda parapet. © A. Ayón, WASA/Studio A, 2007. Observers in the foreground are standing on the scaffold, facing the exterior of the Rotunda roof parapet. The worker in the foreground is facing the interior (roof side) of the parapet.**

**A: Top of existing outward-pitched Rotunda roof parapet.**

**B: Top of new inward-pitched stucco covering surface-applied structural reinforcement.**

**C: New inward-pitched resin-based mortar over top of existing parapet.**

**D: New reinforced fluid-applied waterproofing membrane over new top of parapet.**



**Figure 13. The Solomon R. Guggenheim Museum after completion of the work  
© D. Heald, The Solomon R. Guggenheim Foundation, 2009**



**Figure 13. Detail of Rotunda wall showing original formwork marks after exterior conservation work. © A. Ayón, WASA/Studio A, 2009**