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MONITORING OF HISTORIC STRUCTURES FOR WHOLE BUILDING IMPROVEMENTS

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ABSTRACT

A long-term monitoring program was implemented at a historical structure to characterize exterior wall assembly performance and interior operating conditions prior to complete renovation. The purpose of the monitoring system was to analyze the affect interior operating conditions have on historic building enclosure components, which include sandstone veneer walls, exposed concrete walls, skylights, and art deco aluminum frame glazing systems.

The first year of data revealed several interesting facts about building enclosure performance and building operation; namely, past renovations negatively affect the hygrothermal performance of sandstone clad wall assemblies; condensation occurs frequently on glazing assemblies, interior wall surface temperatures are conducive to condensation formation behind displays, the mechanical system creates large pressure differentials under normal operation, and tight control of temperature and RH is a constant challenge.

The measured data was used to calibrate hygrothermal models, and a parametric analysis performed to determine the potential effects adding insulation may have to existing wall performance in order to develop appropriate design solutions for the renovation. Suggestions for implementing large building monitoring programs are provided, as are uses of monitored data in historical building renovation design.

1. INTRODUCTION

A major building renovation is proposed for a historic museum structure located Seattle, Washington. As part of the proposed renovation, the exterior walls will be renovated to be more thermally efficient and the building mechanical systems will be upgraded to better control the indoor conditions. Due to the historical significance of the museum, the scope of the potential repairs, and the sensitivity of the existing wall assemblies, RDH Building Sciences and SMT Research installed long-term monitoring system in the summer of 2008. The purpose of the monitoring study is to understand the in-situ building operating conditions and the resulting performance of the building enclosure components including the exterior sandstone walls, concrete walls, basement walls, skylights, and glazing systems. The results of the monitoring study are used to assist with the design of appropriate enclosure assemblies for the proposed renovation. The focus of this paper is the historic sandstone veneer wall assembly.

2. PROJECT BACKGROUND

Construction of the subject building was completed in 1933 with several additions over the decades. Due to the historical designation of the original building areas, the sandstone veneer walls and front entry glazing system will be retained as part of the renovation. Much of the building enclosure assemblies are original, with the exception of the roof. The sandstone wall assembly at the west elevation was upgraded and restored in 1994. During the 1994 renovation, a self-adhered membrane was added to the interior of the wall assembly behind the drywall, intended to function as a vapor barrier.

Previous reports regarding the sandstone wall condition identified that the particular sandstone used at the building has a history of surface spalling resulting from salt subflorescence and expansion of iron-oxide elements naturally occurring within the sandstone.

3. MONITORING PROGRAM

A long-term monitoring program was designed to monitor the in-situ performance of the exterior wall assemblies and interior operating conditions. The building was monitored using a combination of specifically positioned temperature, relative humidity (RH), surrogate moisture content, pressure, and condensation sensors, depending on the desired assembly and purpose. The sensors are embedded within selected wall assemblies or placed at strategic positions within the museum to measure the desired conditions. The sensors are wired to data-loggers placed nearby, which are in turn wired to a central computer for upload to an internet based server and software review system.

The monitored data collected from the sensors is used to assess the performance of the building enclosure components, and assist with the renovation design. It is also the intention that the sensors will be left in place after the renovation to monitor the new assemblies and interior climate as part of a post-construction quality assurance and commissioning program.

4. HYGROTHERMAL & THERMAL MODELING

4.1 Thermal Modeling

To assist with the design recommendations for the proposed new wall assemblies, the use of hygrothermal and thermal modeling computer software was used. Thermal modeling is used to determine R-values of simple and complex building components and calculate surface temperatures and condensation risk when subject to static design conditions. The two-dimensional thermal modeling software, THERM 5.2 was used for this project to determine interior wall surface temperatures and assess the risk for condensation, particularly behind art-work in the galleries.

4.2 Hygrothermal Modeling

Hygrothermal modeling is the analysis of both heat and moisture flow through a building enclosure assembly, and is used to understand the long-term behavior of assemblies under real climatic conditions and assist with the design of durable assemblies. This project is unique in that the hygrothermal modeling software can be calibrated with the measured data to improve the accuracy of future performance predictions. WUFI Pro 4.2 computer model was used for this project to assist with the design of the renovated exterior wall assemblies to ensure durable long-term wall performance under substantially different interior environmental conditions than the building has experienced to date.

WUFI can account for rain absorption and different water absorption/redistribution for arbitrary material data and boundary conditions. Given the appropriate material data, WUFI calculates heat and moisture flow every hour under the influence of sun, rain, temperature, and humidity. The analysis is however, only as accurate as the assembly data, the material properties, and the interior and exterior conditions input. The accuracy of this analysis is improved by the direct input of the measured weather conditions collected at roof of the subject building.

The interior climate is modeled in WUFI based on the measured conditions observed by the monitoring program. More stringent and tightly controlled operating conditions for a modern museum space are also modeled.

Since it is often not convenient (or even possible) to determine the many material properties necessary for hygrothermal simulations, WUFI includes a database of several hundred common materials. However, as computer models are only as reliable as their input data, and it is often desirable to test a few key material properties and use the results to modify the materials in the database. For the purpose of the museum hygrothermal simulations, samples of the sandstone veneer were collected from spare pieces at the site. These pieces were tested to determine the necessary hygrothermal properties to calibrate material properties for a similar sandstone material included with the WUFI program.

4.3 Sandstone Wall Hygrothermal Performance

The sandstone wall assemblies were monitored to determine the performance of the assembly under the as-built conditions and apply that knowledge to the development and calibration of a hygrothermal model to simulate a proposed thermally upgraded wall assembly.

The sandstone wall assembly was monitored at four locations; three at the west elevation and one at the south. At one of the west elevation locations, the wall sensors were located in close proximity to an exterior fountain where the sandstone is exposed to significant wetting from water splash back when the fountain is in operation from spring through fall.

The existing sandstone wall assembly and location of the installed sensors is shown in Figure 1. The installed sensors include the following:

1 Relative Humidity (RH) and Temperature sensors to measure the RH within the air-cavity behind the board sheathing.

2 Wood Moisture Content and Temperature to measure the moisture content of the >80 year old fir board sheathing.

3 Surrogate Wood Moisture Content and Temperature "Duff Gauges" to measure a moisture level within the sandstone and concrete. The RH within the sandstone and

concrete and can be determined by using the sorption isotherm (relationship between moisture content and equilibrium RH) for the calibrated wood sensor.

4 Exterior and interior wall surface temperature in addition to the temperatures measured at the RH and moisture content (MC) sensors. The temperature at the RH/MC sensor locations are also used to temperature correct the RH and MC sensor outputs.

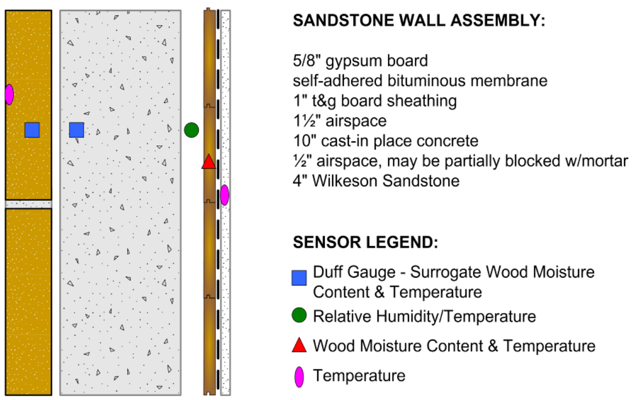

Figure 1. Existing Sandstone Wall Assembly and Installed Sensors

Sensors were installed from the interior of the exhibit spaces, and are typically located within a 1 foot square section of wall. Surrogate moisture sensors were drilled into the wall from the interior and are located 2.5" from the exterior sandstone surface. During installation of the sensors, it was noted that the 1" tongue & groove board sheathing consists of old-growth Douglas fir. Core samples were taken for calibration of the moisture content pins.

Analysis of the sandstone assembly is discussed in the following three sections: Interior Surface Temperatures, Sandstone Moisture Levels, and Board Sheathing Moisture Levels.

5. SANDSTONE VENEER WALLS

5.1 Interior Surface Temperatures

Temperatures are compared to understand the thermal performance of the sandstone and concrete wall assemblies, in particular the interior surface temperature and risk for condensation at the interior wall, and exterior surface temperature for risk of freeze-thaw damage of the sandstone veneer.

Measured temperatures throughout the west facing sandstone wall assembly at the north exhibit space (N1) are plotted in Figure 2 for December 2008, when Seattle experienced record low temperatures and snow accumulation. The measured temperatures at the N1 exhibit space location are representative of typical conditions for the sandstone wall assemblies.

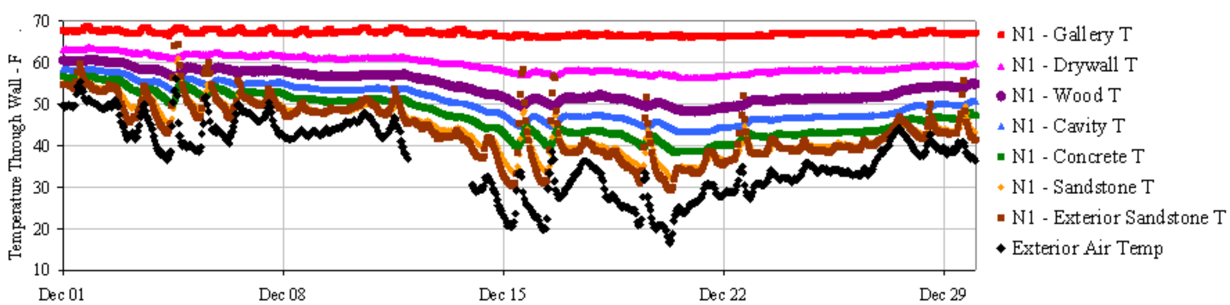

Figure 2. Temperature Profile through West Facing Sandstone Wall at North Gallery, December 2008

The sandstone wall is an uninsulated, but thermally massive wall assembly; therefore, the thermal response of the assembly is slow. The exterior surface is strongly affected by solar heating over all seasons with large daily fluctuation in temperature.

Temperatures throughout the mass wall remain more consistent, only slightly affected by daily temperature swings. At the coldest time of the year (<20°F exterior temperatures), the surface of the sandstone drops down to only slightly below freezing, 29-30°F. Depending on the saturation level of the surface of the sandstone, it could be susceptible to freeze-thaw damage. Based on a review of the sandstone façade, freeze-thaw damage does not appear to be an issue, nor is freeze thaw damage typically an issue in Seattle's temperate climate.

Interior wall surface temperatures are much lower than interior air temperatures, with a maximum wintertime difference of approximately 10°F. As a result of the lower temperatures, the RH level at the wall surface will be higher than the exhibit space, and conditions behind artwork may be conducive to organic growth (>80% RH moderate risk to >95% high risk). If the wall surface temperature drops below the exhibit space air dew point temperature of approximately 50°F (the maintained indoor dewpoint at 70°F and 50% RH), then condensation is likely to occur. Interior wall surface temperatures are compared for four sandstone wall locations monitored at the south and north exhibition spaces and are plotted in Figure 3 for the coldest period in December at gallery space S7.

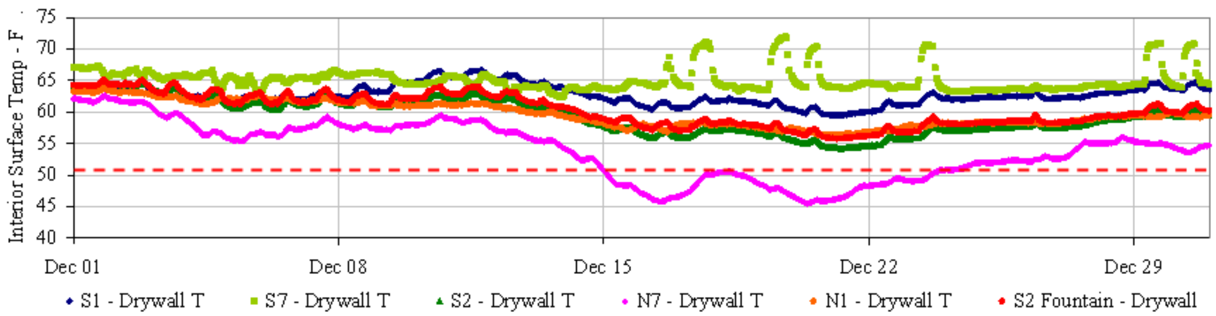

Figure 3. Interior Wall Surface Temperature of Monitored Exterior Walls; Worst Case December 2008 Conditions

5.2 Sandstone Moisture Levels

As no sensor commercially exists to accurately measure the in-situ moisture content of sandstone or concrete for prolonged periods, the moisture level within the sandstone panels and concrete wall were measured using surrogate moisture content sensors made of wood. Wood sensors embedded within the sandstone or concrete reach equilibrium with the moisture level within the stone; based on the known relationship between wood sensor moisture content and RH level, an equivalent RH (also referred to in the figures below as "eRH") within the sandstone/concrete can be determined. Thus, it was determined that RH levels within stone and concrete materials exposed to exterior environments are high (greater than 80% year round), with levels typically slightly higher than the average exterior RH level, based on the amount of wetting from rainfall and other sources.

By using surrogate moisture content sensors, the RH level was measured within the sandstone near mid-depth, 2" to 2 ½" from the exterior surface of the 4" thick panel. The measured wood moisture content and calculated RH levels within the sandstone from July 2008 through June 2009 are provided in Figure 4. The calculated RH levels within the concrete behind the sandstone veneer are presented in Figure 5. Figure 6 presents the calculated driving rain on the west façade, correlating with the moisture contents of the sandstone.

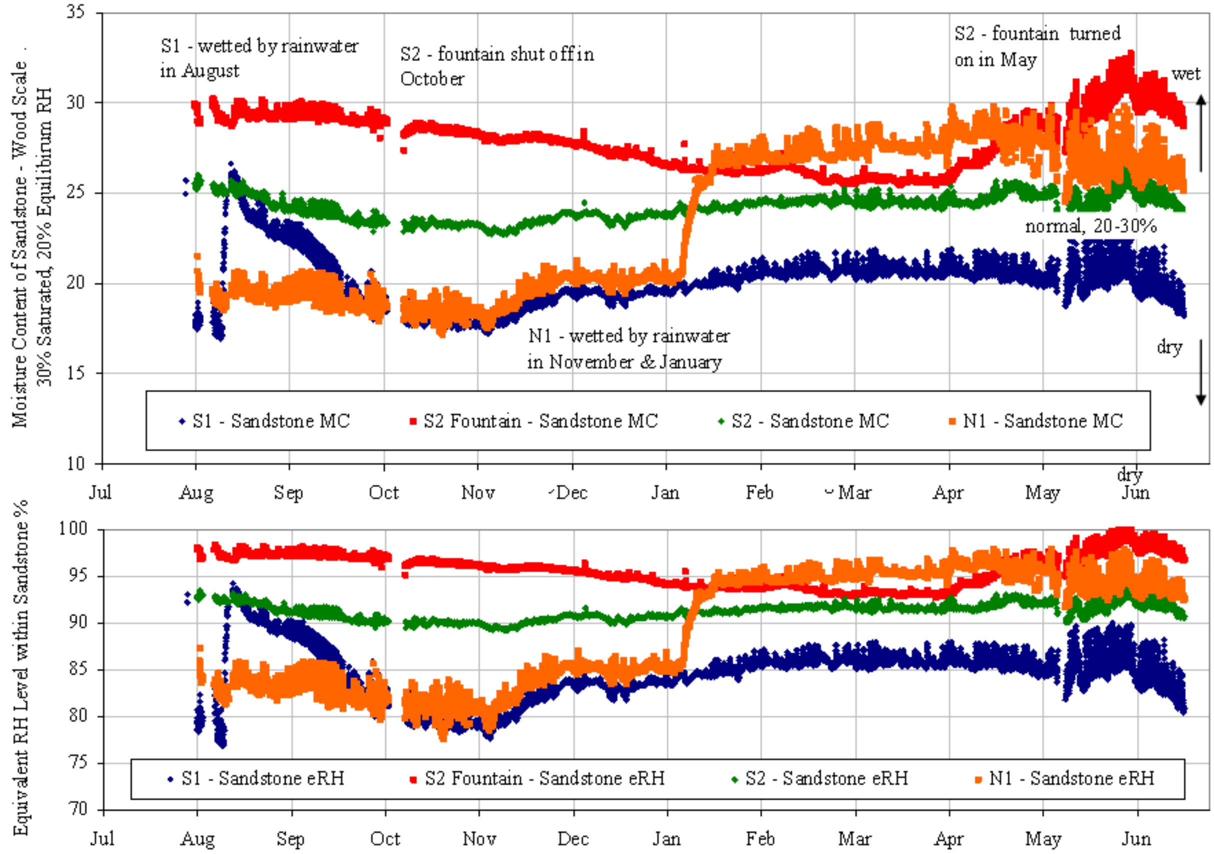

Figure 4. Measured RH within Sandstone Veneer at Mid-depth: July 2008 through June 2009

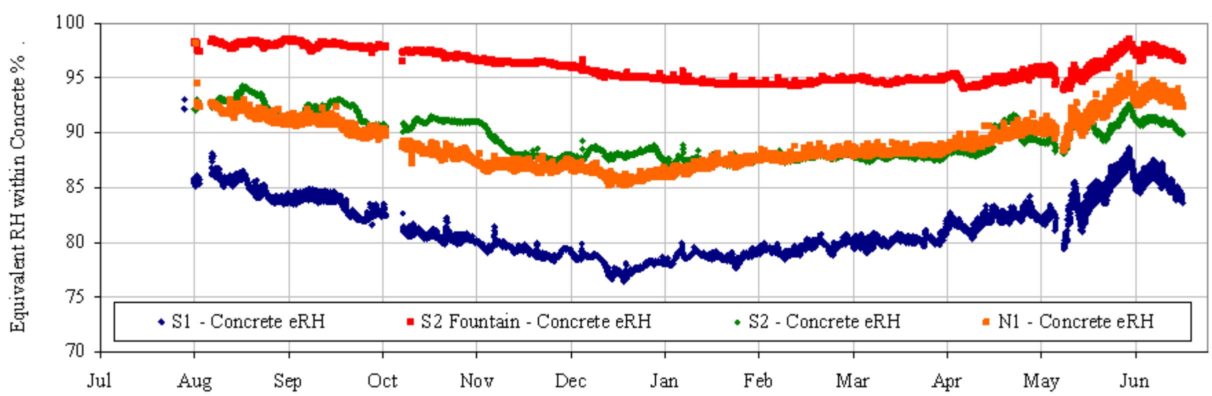

Figure 5. Measured RH within Concrete, directly behind Sandstone Veneer; July 2008 through June 2009

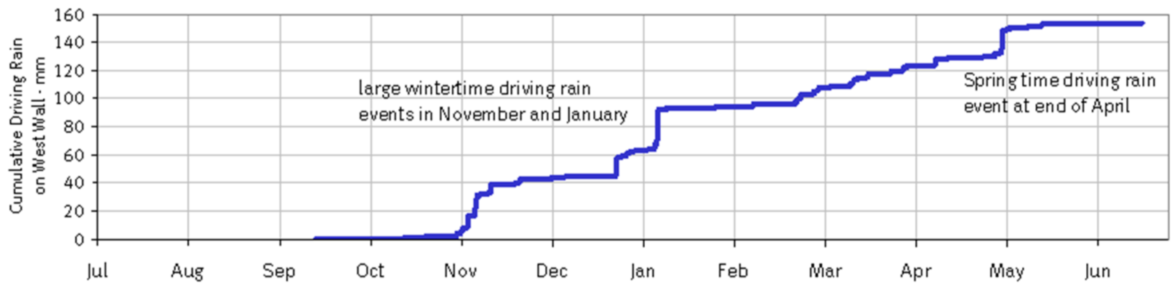

Figure 6. Calculated Driving Rain on West Facing Sandstone Façade: September 2008 through June 2009.

The RH and subsequent moisture levels within the sandstone and concrete remain fairly consistent throughout the monitored period and are at normal levels. As expected, the sandstone and concrete at the S2 exhibit fountain remains the highest as a result of the continuous wetting from fountain water splash back against the wall (Figure 5). When the fountain is shut-off in October the sandstone dries slowly over the winter, until the fountain is turned back on again in May. The moisture levels within the stone and concrete near the fountain are indicative of worst case conditions for the sandstone façade.

The moisture levels within the exposed west facing sandstone veneer remain fairly consistent, however following large driving rain events in November and January (as shown in Figure 6) the monitored locations at exhibit S1 and N1 (exposed at west elevations) are both wetted significantly, resulting in an increase in the overall sandstone moisture content, up to similar levels caused by the fountain.

The monitoring data shows that driving rain has an influence on the moisture levels of the sandstone, and that wintertime rain events wet-up and keep the sandstone wet for the entire winter. Drying is slow and occurs in the spring; but spring-time driving rain events also have a significant effect on the wall moisture levels. Figures 4, 5, and 6 clearly demonstrate that moisture from a driving rain event at the end of April was driven into the wall by solar radiation, which then wetted both the sandstone and later the concrete.

5.3 Board Sheathing Moisture Levels

The moisture content of the board sheathing was measured at each of the monitored wall locations. The condition of the old-growth fir was generally good, however minor evidence of moisture staining and organic growth was observed on the back-primed surface of the sheathing at each of the four monitored sandstone locations. Figure 7 shows the measured relative humidity within the air-cavity space between the fir sheathing and concrete, and Figure 8 shows the moisture content of the fir sheathing. Moisture content sensors were installed on the backside of the sheathing boards.

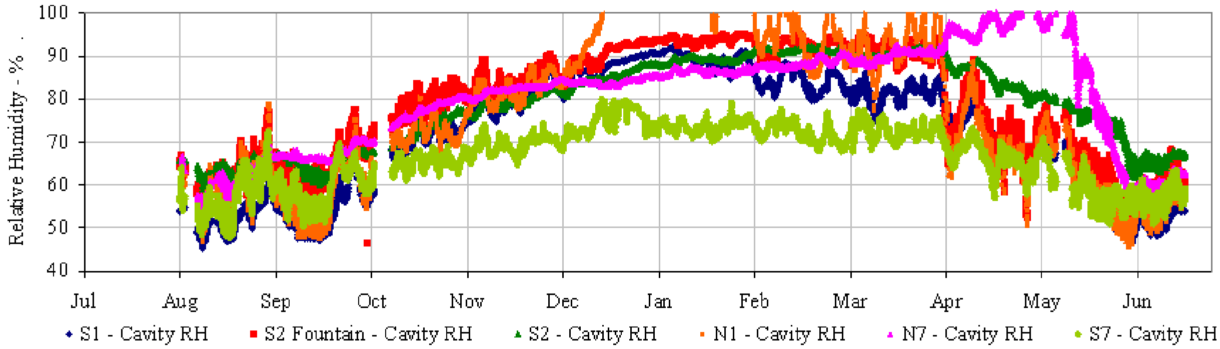

Figure 7. Relative Humidity within Cavity between Concrete and Wood Sheathing Boards: July 2008 through June 2009.

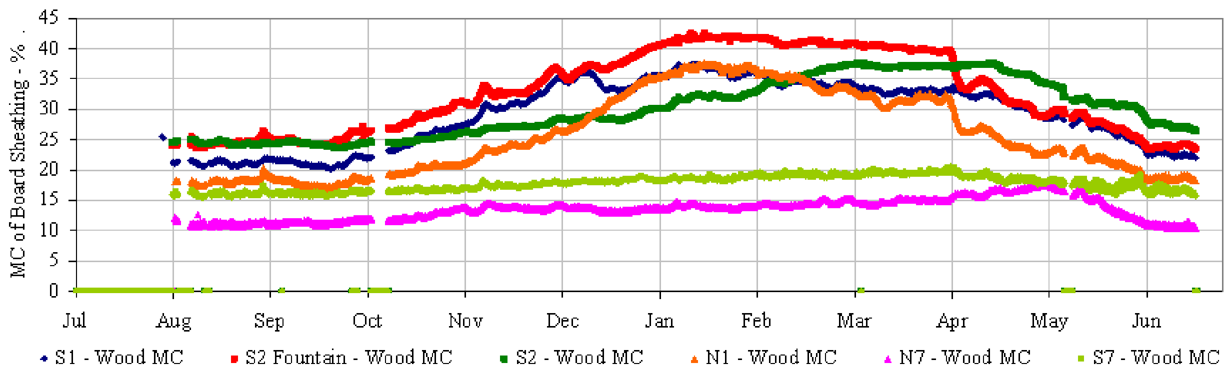

Figure 8. Moisture Content of Wood Sheathing Boards: July 2008 through June2009.

The relative humidity within the cavity between the concrete and board sheathing elevates during the winter months. Consequently, the moisture content of the board sheathing elevates in most locations above fiber saturation. The four sandstone wall locations are noticeably much wetter than the exposed concrete or concrete block assemblies. The sandstone wall assembly contains a vapor barrier on the interior side of the board sheathing, which blocks vapor diffusion towards the interior and prevents the wood from drying. The wall assemblies at exhibit N7 and S7 (exposed concrete and concrete block) do not have a vapor barrier and thus allows the wood to dry towards the interior.

Exterior leaks and vapor diffusion were ruled out as primary wetting mechanisms, leaving interior air-leakage into the cavity between the wood sheathing and concrete as the source of moisture wetting the sheathing. Measured temperatures through the sandstone wall assemblies indicate that concrete and wood surface temperatures within the cavity are between 10 and 20°F colder in winter than the interior air (Figure 2), as the wood sheathing and drywall are relatively insulating in comparison to the concrete and sandstone. The temperatures within the cavity are also at or below the dew point temperature of the exhibit spaces. As a result, when warm moist air from the exhibit area enters the cavity the RH level rises, contributing moisture to the porous concrete and wood surfaces via adsorption. When temperatures within the cavity warm up in the spring, the accumulated moisture evaporates and is removed by airflow through the cavity.

6. HYGROTHERMAL MODELING & CALIBRATION

The performance of the existing wall assembly was modeled using WUFI 4.2 to improve our understanding of the walls' performance and to calibrate the hygrothermal model with the measured data. The calibrated model was then modified and used to perform parametric simulations to predict the future performance of the proposed wall upgrades.

Measured weather data was also input into the WUFI model for simulation to allow for the comparison to the measured data recorded at the various sensors. Measured climatic data from September through April (7-months) was used to calibrate the model and perform the simulations. Initial moisture levels within the materials were set based on the measured data.

The simulations performed found that the WUFI model accurately approximated both the measured moisture and thermal performance of the sandstone wall assemblies. Of most concern for the analysis are the moisture levels and temperatures of the sandstone for freeze-thaw assessment, and the interior wall surface temperatures for condensation risk assessment. Figure 9 compares the modeled to the measured interior drywall surface temperature for a 2-month period during the winter. Small variations are observed between the model and measurements, but the hourly trends are well captured within ±2°F.

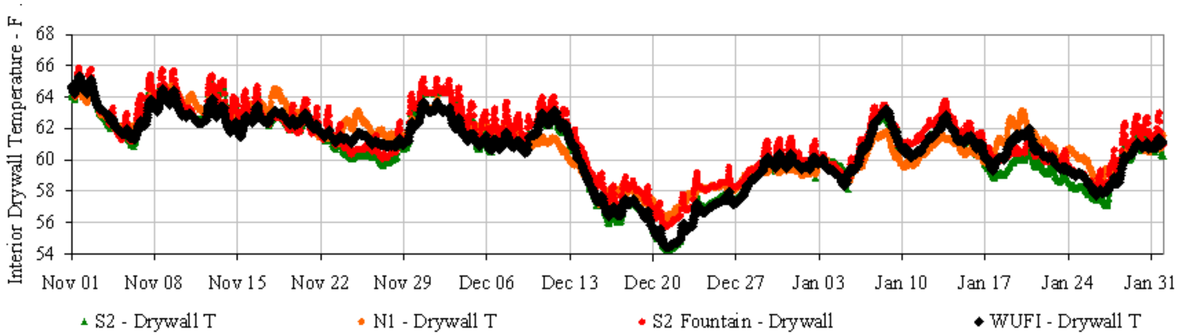

Figure 9. Measured versus WUFI Modeled Interior Drywall Surface Temperature, November 1, 2008 through February 1, 2009

WUFI is also able to approximate the moisture levels with the sandstone; however small variations between the modeled and measured data are observed (Figure 10). These differences largely appear to be the result of variable driving rain rates on the sandstone surface. Both locations appear to receive less than the amount predicted by WUFI. Absorption of water into the sandstone will also vary by location, as will absorption of water into the surrogate moisture content sensors. Overall the modeled RH within the sandstone provides a conservative estimate of its performance and likely representative of an exposed location near the top of the building which receives more driving rain.

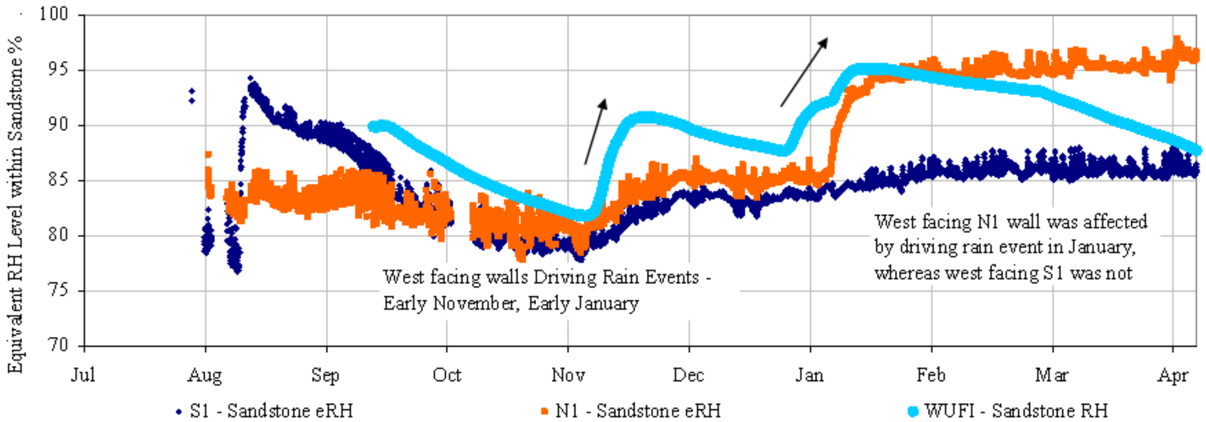

Figure 10. Measured versus WUFI Modeled RH level within Sandstone at West Facing Sandstone Wall Assembly

7. PROPOSED WALL UPGRADE

To improve the thermal performance of the sandstone wall assembly without removing the sandstone from the exterior, it is proposed that insulation is added to the interior of the wall assembly. The proposed wall sandstone wall assembly with the addition of 1 ¾" of closed-cell sprayfoam (R-10.5) is shown in Figure 11.

Insulating the sandstone wall assembly significantly improves thermal performance. In addition to reduced heat-loss and energy savings, interior surface temperatures are improved. The measured data indicates that currently the interior wall surface temperature is low enough that condensation can occur behind artwork. Figure 12 compares the modeled temperature profiles for the existing and proposed wall assemblies visualized using THERM 5.2 and calibrated with the measured data and an exterior temperature of 20°F.

As shown in Figure 12, the interior surface of the insulated wall assembly is significantly warmer than the uninsulated wall, especially behind the artwork. Surface temperatures in the insulated wall are much higher than the air dew point temperature, reducing the potential for condensation.

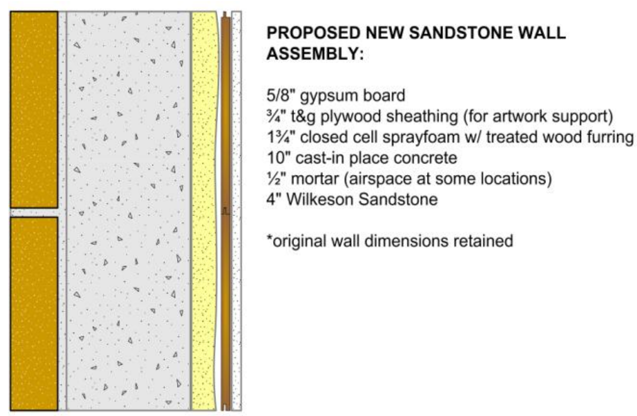

Figure 11. Proposed Sandstone Wall Assembly

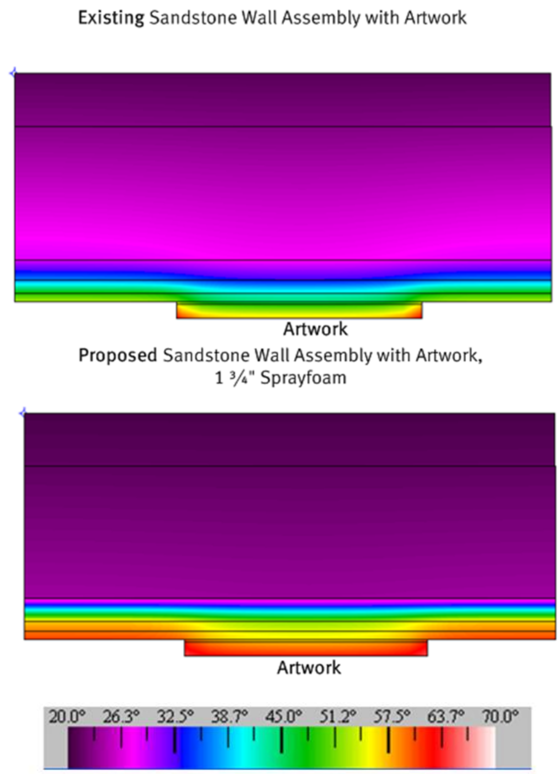

Figure 12. Plan view of existing and proposed wall section showing temperature profile of wall assembly

One of the potential risks associated with insulating the interior of masonry or stone wall assembly is the possible increase in risk of freeze-thaw related damage to the sandstone surface. While rare in Seattle's climate, the analysis was performed as a precaution. Freeze-thaw damage can occur when the surface of the sandstone is near saturation (typically 80% of saturation) and drops below freezing and thaws. Depending on the properties of the stone, spalling may occur. No evidence of spalling caused by freeze-thaw damage was observed on the sandstone façade during our review. Using WUFI, it was confirmed that the number of freeze-thaw cycles the sandstone surface sees in a typical year when saturated is zero (Figure 13). The number of hours that the wall assembly spends below freezing is increased from 123 to 155 hours when simulating 2008 winter data, but no freeze-thaw cycles at critical saturation levels are observed. Therefore the interior insulated sandstone wall assembly does not appreciably increase the already low risk for freeze-thaw damage to the sandstone. Other factors as previously discussed with the sandstone material itself are more likely to cause spalling than freeze-thaw damage.

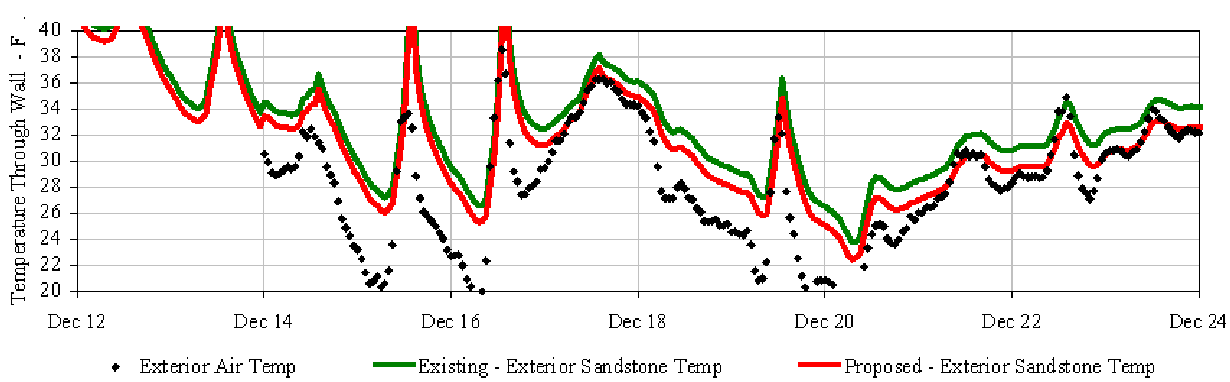

Figure 13 Temperature Profile through West Sandstone Wall at Gallery N1

8. CONCLUSIONS

When planning renovations of historic facilities to improve energy efficiency and air tightness, it is important to understand the pre-renovation hygrothermal performance characteristics of the existing assemblies.

A long term monitoring system was designed to measure key interior operating conditions and hygrothermal performance variables of wall assembly components. Data gathered over the course of one year provided the necessary information to analyze the effect interior and exterior operating conditions have on exterior wall performance. The data was also used to calibrate thermal and hygrothermal computer models used to analyze post renovation proposed wall assembly performance. It was determined that for the historic sandstone veneer portions of the building, adding 1-3/4" of closed-cell spray polyurethane foam to the interior side of the wall is expected to improve interior surface conditions and have little effect on the historic sandstone veneer.

9. ACKNOWLEDGEMENTS

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