EVALUATION OF THE THERMAL PERFORMANCE OF HISTORIC MASS MASONRY WALLS UTILIZING IN-SITU MEASUREMENTS

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ABSTRACT

Energy conservation has become one of the primary goals of architecture and engineering design today, and with this growing awareness for energy efficiency, the need for properly evaluating the thermal and moisture properties of existing and historically significant buildings must be addressed. Without proper evaluation, changes to the thermal and moisture properties of the exterior walls can have serious negative impacts, such as degradation of the existing masonry or interior finishes along with interior air quality and other moisture related issues. To complement current design tools, effective field studies to evaluate existing buildings will improve the quality of data available and analytical results. While many historic mass masonry buildings may not meet the prescriptive minimum insulation requirements of today's energy codes if the total R-value or U-factor are calculated, they do have the inherent ability to absorb, store, and later release significant amounts of heat. This thermal mass provides an intrinsic energy-saving advantage as the materials within the walls absorb energy slowly and hold it for longer periods, reducing heat transfer through the mass wall as compared to framed wall assemblies. A field study and subsequent analysis was performed at two historical mass masonry buildings at the University of Virginia and West Virginia University. Various data logging instrumentation was installed to measure temperature, relative humidity, heat flux, and radiation at critical points within the wall section to determine how heat and moisture were transferred through the wall assemblies. The in-situ thermal resistance of the wall assemblies was evaluated during rain events and periods of high exterior vapor pressure and compared to the overall thermal resistance calculated over the duration of the testing period.

KEYWORDS: *energy performance, historical preservation, in-situ measurements, thermal mass*

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INTRODUCTION

Historic buildings constructed with mass masonry walls have the inherent ability to absorb, store, and later release significant amounts of heat, a property known as thermal mass. The thermal mass of historic masonry walls should be understood before adding insulating materials to meet requirements of building codes. In addition, mass masonry walls rely on the moisture storage capacity of the wall to prevent water infiltration. The drying potential of the wall, along with the storage potential, needs to be evaluated as it will have a direct impact on the hygrothermal performance of the wall. The addition of interior insulation or a continuous air barrier or vapor retarder will affect the performance of the wall assembly. If not correctly designed or installed, these changes can negatively affect the building's ability to adequately manage changes in temperature and moisture. As a further complication, the properties of brick masonry have extreme variability with only a limited amount of published data available for industry reference.

When using the energy code, there are two prescriptive compliance paths for designing the required thermal insulation of mass walls: the prescriptive thermal resistance as defined by assembly type and climate zone; or to determine the U-factor, which is the maximum allowable conductance of the wall assembly. The prescriptive requirements do not fully incorporate the effects of thermal mass and may be inadequate in describing the heat transfer properties of mass masonry walls. As heat flows through the wall, it is dependent on the density of the materials, thermal conductivity, specific heat, and thermal diffusivity. Because mass walls were constructed without a separate layer of thermal insulation, they generally do not meet the prescriptive minimum insulation requirements of energy codes due to the nature of the existing construction of the wall assembly. Implementing changes solely to meet the prescriptive energy code requirements may not benefit the building performance once the thermal mass and the long-term performance of the wall is taken into account.

To gain an understanding of this variability and create a framework for field data collection and data analysis methodologies, two field studies were undertaken. For each study, in-situ measurements were used to assess performance of mass masonry walls and the impacts of moisture and heat movement for both existing and retrofit wall assemblies. The first study was undertaken during the summer at the University of Virginia on a historic Range Room designed by Thomas Jefferson. The second study was performed during the winter months at an academic building at West Virginia University constructed in the early 1950s that has been identified for renovations in the upcoming years to include energy performance upgrades. In both cases, the wall assemblies were observed to be sound and well-constructed.

IN-SITU DATA LOGGING INSTRUMENTATION

Data acquisition instrumentation was installed to gather the data necessary to evaluate the performance of the exterior mass wall assemblies. Interstitial temperature and relative humidity probes were installed at varying depths within the wall assemblies to record the movement of heat and moisture through the wall assembly. To install the probes, ports were drilled into the wall assembly at varying depths. A temporary, impermeable liner was installed in the hole and sealed to the adjacent interior finishes to ensure the moisture measured was only at the end of the liner and not along the length of the port. The probe was inserted into the hole, and an air tight seal was installed between the liner and the probe. The measured temperature and relative humidity values were used to calculate the actual vapor pressure and to develop a vapor drive profile across the wall assembly. The humidity readings were also used to determine the approximate moisture contents of the materials within the wall assemblies using published sorption isotherm curves. Ambient temperature and relative humidity data loggers were also installed at varying locations on the interior and exterior of the building.

Heat flux and thermocouple sensors were installed to determine the approximate in-situ thermal resistance of the assemblies. The heat flux sensors were installed in accordance with the procedures outlined in ASTM C1046 [1]. These sensors were installed at interior surfaces to document the heat flow through the assembly. Thermocouple sensors were installed at corresponding interior and exterior surfaces in close proximity to the heat flux sensor to measure the temperature differential across the wall assembly.

FIELD STUDY OVERVIEW – UNIVERSITY OF VIRGINIA

At the University of Virginia (UVA), the Range Room used for the study was a single room approximately 13 feet by 13 feet in dimension. The walls are comprised of hand molded clay brick with lime mortar and a traditional plaster interior finished with latex paint. The plaster in this building is not original; however, much of the brick and mortar are original. Three different locations within the room were instrumented for this field study: (1) a north facing wall exposed to rain and solar radiation, (2) an east facing wall with covered awning and limited exposure to solar radiation, and (3) an east facing wall with covered awning and limited exposure to solar radiation retrofitted with 2 inches of rigid polystyrene insulation at the interior surface of the wall assembly. The wall sections and location of data logging instrumentation within each of these wall assemblies are shown in Figure 1.

These rooms are typically not air conditioned; however, a window air conditioning unit was installed to provide a significant thermal gradient between the interior space in order to evaluate movement of heat and moisture during the hot and humid exterior summer months in Virginia. The interior temperature in the space was maintained between 69°F and 74°F. Data logging instrumentation was installed from June 17, 2016, to July 25, 2016.

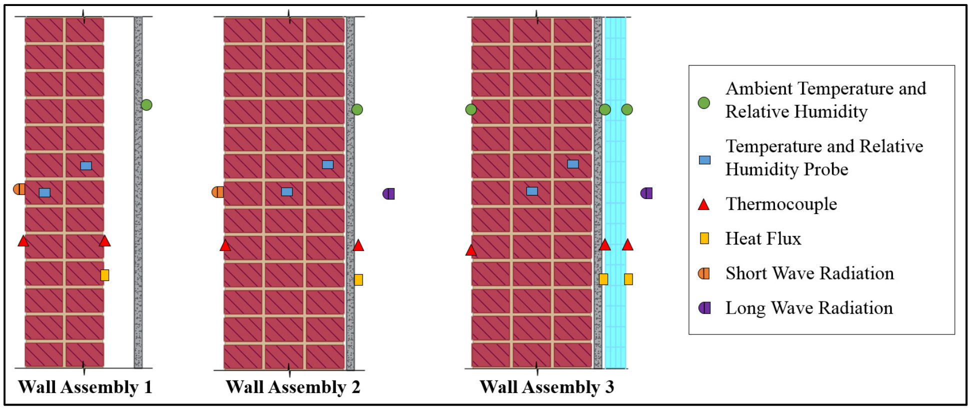

Figure 1: Location of Data Logging Instrumentation within Wall Assemblies

FIELD STUDY OVERVIEW – WEST VIRGINIA UNIVERSITY

The field study at West Virginia University (WVU) was completed in a classroom space. The instrumentation was installed at the north facing exterior wall. The wall assembly was found to consist of two exterior wythes of brick masonry, an air space approximately 8" across, and 4" hollow clay tile finished with interior paint. While the academic building is in use, this particular room was vacant for the duration of the study. Instrumentation was installed from November 14, 2016, through February 14, 2017, and interior conditions were found to be between 70°F and 83°F and 9% and 46% relative humidity. Two different locations within the same space were instrumented for this field study: (1) a north facing wall exposed to rain and solar radiation, and (2) a north facing wall exposed to rain and solar radiation with structural steel embedded within the wall. Because of the variations in the construction of the exterior wall, this study was conducted in two phases, with the second phase incorporating the addition of interior insulation. The second phase of the study is in progress. The typical locations of data logging instrumentation within each of these wall assemblies are shown in Figure 2.

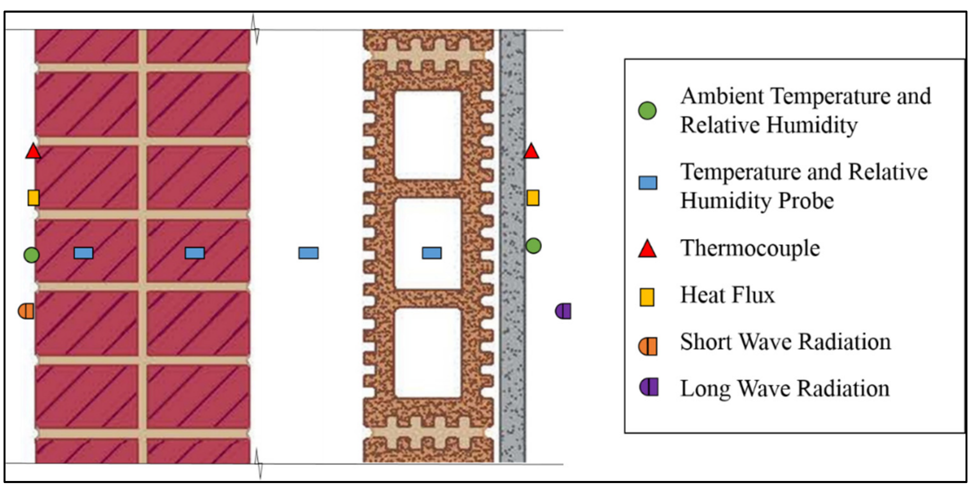

Figure 2: Typical Location of Data Logging Instrumentation within Wall Assemblies

ANALYSIS OF DATA COLLECTED

The data collected from the thermocouple and heat flux sensors was used to determine the in-situ thermal resistance for the assembly in general accordance with the Summation Technique outlined in ASTM C1155 [2]. The in-situ thermal resistance is estimated by dividing the sum of the temperature differential across the assembly by the heat flux within each convergence interval as shown in *Equation (1)*. These thermal resistance values are then further analyzed to evaluate both data convergence and the variance within sets of converged data, which allows for the determination of whether the calculation can provide an acceptable thermal resistance value for the data that was collected.

$$R_e = \frac{\sum \Delta \mathrm{T}}{\sum \mathrm{Q}} \qquad (1)$$

It is challenging to use field methods to accurately determine the thermal resistance of mass masonry walls due to the heat capacity of the wall. The thermal resistance is simply an indication of heat flow through an assembly and does not account for the heat capacity, which provides temporary storage and subsequent release of heat. Due to this thermal lag, the heat transfer through the wall assembly is not precisely accounted for when taking the temperature differentials at a given point in time. Therefore, measurements were taken over several months in an effort to get a more accurate in-situ R-value and to account for the impact of the thermal mass of the masonry.

Determination of Thermal Resistance

While additional scenarios were evaluated, for the purpose of this paper, the analysis was focused on the existing and retrofit walls at UVA at the east elevation of the Range Room and the existing wall assembly at WVU without the steel column acting as a thermal bridge. The data from the other wall assemblies is beyond the scope of this paper.

For each of these wall assemblies, a one-dimensional U-factor calculation utilizing published thermal properties of the materials within the wall assembly was performed. This calculation was performed in accordance with industry standards and would typically be used to verify compliance with the prescriptive thermal performance requirements in energy codes. These values are shown in Table 1. The purpose of the in-situ monitoring was to determine how conservative these calculated values were, if at all, and how the thermal performance was impacted by the inherent heat capacity and moisture storage properties of the wall.

To calculate the in-situ thermal resistance, the data was analyzed holistically without taking into account convergence intervals. It was theorized that because of the long duration of the testing period and number of data points that were collected, the analysis would essentially normalize over the length of the study. The thermal performance of each of the wall assemblies is shown in Table 1 when analyzed with this method.

Additionally, the data was analyzed in accordance with ASTM C1155 with a convergence interval of 24 hours in order to include a complete temperature cycle. The thermal resistance was calculated within each of these intervals, and the convergence factor for each interval was determined. In accordance with the standard, three consecutive intervals must have a convergence factor less than 0.10, and the thermal resistance values within these data sets must also have a variance less than 10%. For the wall assembly analyzed at WVU, there were four data sets that converged with a value generally less than 0.10; however, the variance between these data sets was 20%. One of these data sets converged to a higher thermal resistance relative to the other data sets, and when excluded, the variance of the remaining data sets was 10.4%. For the existing and retrofit wall assemblies at UVA, there was only one data set for each assembly that converged with a factor less than 0.16 and 0.12, respectively. While these values were not found to converge in a manner that provided an acceptable thermal resistance for the wall assembly in accordance with the ASTM standard, it was noted that the intervals that were found to converge were similar to the thermal resistance found when the entire data set was analyzed as a single interval. The average values of the thermal resistance when the data was found to converge are shown in Table 1.

Table 1: Calculated U-factor Values for Wall Assemblies

Wall Assembly	Theoretical	In-Situ (Total Testing Duration)	In-Situ (Converged Data)
UVA Existing Wall Assembly	R – 2.80 U – 0.357	R – 2.182 U – 0.458	R – 2.254 U – 0.444
UVA Retrofit Wall Assembly	R – 12.20 U – 0.082	R – 6.477 U – 0.154	R – 6.153 U – 0.163
WVU Existing Wall Assembly	R – 3.19 U – 0.313	R – 8.701 U – 0.115	R – 7.249 U – 0.138

The calculated in-situ thermal resistance for the existing wall assembly at UVA was very similar to the theoretically calculated thermal resistance. For the retrofit wall assembly, the added insulation did not appear to translate into as much thermal resistance as would have been expected. This study was conducted during summer months when the temperature differential across the wall assembly is not that high, and as a result, may not provide conditions where the full insulating value of the insulation is realized. For the WVU wall assembly, the calculated in-situ thermal resistance was found to be about double what was calculated theoretically. Because the air space within the wall assembly is situated between masonry materials with heat storage properties, the thermal resistance of this air space may be greater than that assumed for the theoretical analysis.

Because the data was collected during different times of the year, the direction of the heat flux values and the magnitudes of the temperature differential across the wall assembly for each study varied significantly. The heat flux sensors were installed on the interior surfaces of the wall assemblies. For the WVU study, the heat flow was from interior to exterior during the winter months, with the heat flowing into the surface that the sensor was mounted to, resulting in positive readings. For the UVA study, when the heat flow was from exterior to interior during the summer months, the heat flux sensor had negative readings as heat was flowing out of the surface that the sensor was mounted to. It was also observed that the magnitude of the heat flux for the existing wall assembly was much greater than that of the retrofit wall assembly at UVA.

A similar trend was noted for the temperature differentials across each wall assembly. The existing wall at WVU had the greatest temperature differentials, which would be expected since measurements were recorded during winter months. For the UVA study, the existing wall assembly was exposed to limited solar radiation in the early morning each day, resulting in an increased temperature differential across the wall assembly for a short period of time. The additional heat from this exposure could have caused the existing wall assembly to consistently have a greater temperature differential when compared to the retrofit wall assembly which had no exposure to direct solar radiation. Without incorporating the associated date of the measurements and only their sequential order, Figure 3 graphically shows the differences between the heat flux and temperature differential across the wall for each of the wall assemblies that was evaluated.

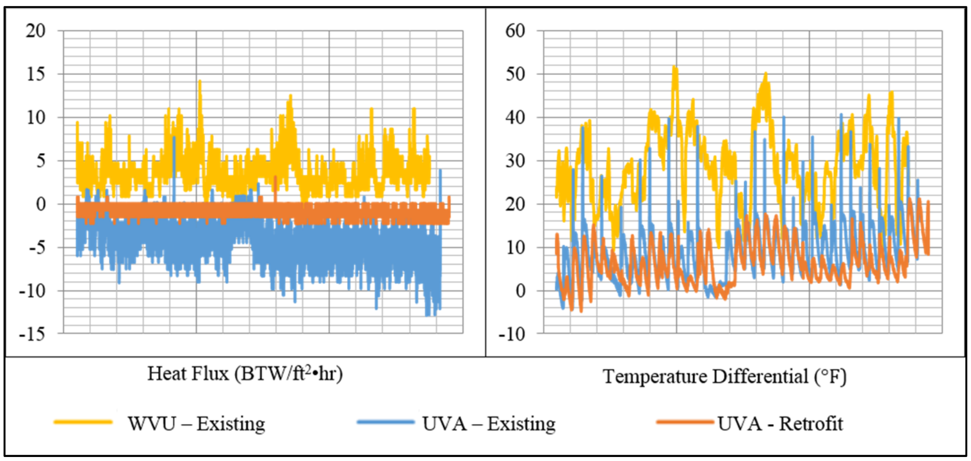

Figure 3: Heat Flux and Temperature Differential Measurements at Wall Assemblies

Impact of Moisture and Exterior Vapor Pressure

Mass masonry walls manage water infiltration through inherent moisture storage properties. When exposed to moisture from rain or humidity, the brick masonry will absorb and store water. In a sound and well-constructed mass masonry wall, a majority of the moisture is stored in the exterior wythe of the masonry assembly, but is expected to migrate to inner wythes depending on the duration of the rain event, amount of moisture absorbed by the brick, amount of direct contact between wythes depending on the condition of the brick and mortar, as well as the vapor pressure gradient across the wall. Because the thermal conductivity of water is much greater than that of brick and mortar, it would be expected that the thermal resistance of the wall assembly would decrease as the amount of moisture stored within the assembly increases.

The relationship between the moisture content within the brick and the relative humidity exposure is given by sorption isotherm curves. Generally, the moisture content of the brick will remain relatively low in the hygroscopic range until the relative humidity values increase to a certain point, after which the moisture content will increase rapidly. While there are published values for these curves, due to the variability of the properties of brick masonry, they may not represent the specific brick being evaluated. For reference, a sorption isotherm curve is shown in Figure 4 utilizing data from a commercially available hygrothermal modeling material database [3]. For these studies, the relative humidity measured at various depths within the wall assembly was considered to determine the approximate moisture content within the assembly.

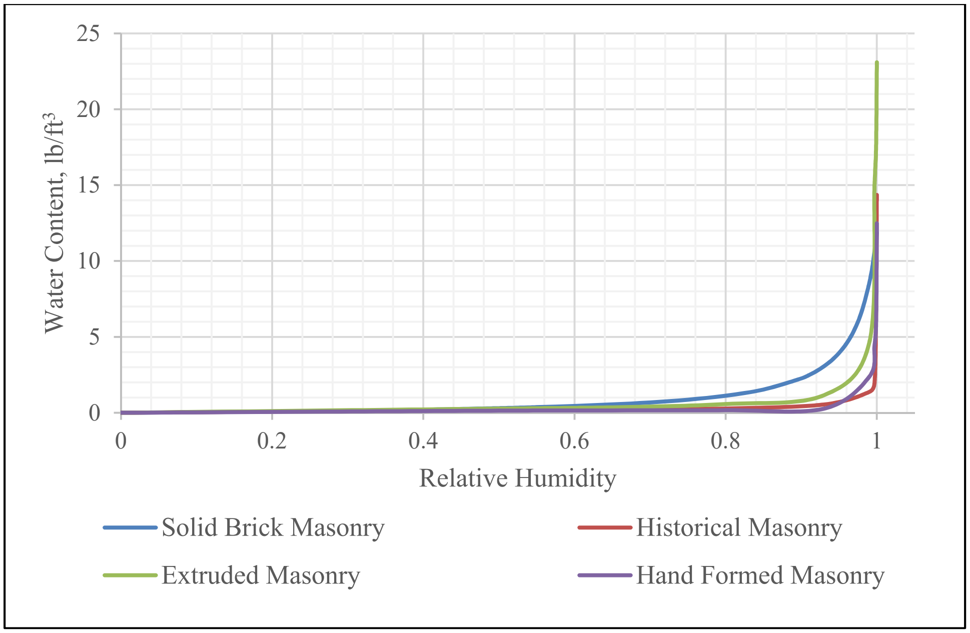

Figure 4: Sorption Isotherm Curve for various types of Brick Masonry

Another method to evaluate moisture storage and movement through a wall assembly is to consider the actual vapor pressure within the brick masonry. This can be calculated by multiplying the saturated vapor pressure at a given temperature by the corresponding relative humidity as shown in *Equation 2*. The difference in vapor pressure across the wall assembly can indicate how moisture is moving through the assembly.

$$AVP = RH \times SVP \tag{2}$$

The moisture within the wall assemblies and the impact on the thermal resistance of the wall assembly was evaluated during rain events. Additionally, the vapor drive across the wall assembly was evaluated based on periods when the greatest vapor pressure differential was experienced across the wall assembly during the testing periods. For the UVA wall assemblies, the exterior vapor pressure peaked during very hot, humid days. The in-situ thermal resistance values calculated for each of these cases is shown in Table 2.

Table 2: In-Situ U-factor Values for wall assemblies during high exterior moisture levels

Wall Assembly	In-Situ (Total Testing Duration)	In-Situ (Rain Event)	In-Situ (High Exterior Vapor Pressure)
UVA Existing Wall Assembly	R – 2.182 U – 0.458	R – 3.15 U – 0.318	R – 2.188 U – 0.457
UVA Retrofit Wall Assembly	R – 6.477 U – 0.154	R – 9.020 U – 0.110	R – 4.085 U – 0.245
WVU Existing Wall Assembly	R – 8.701 U – 0.115	R – 8.437 U – 0.199	NA

A heavy rain event occurred on January 12, 2017, from approximately 5:00 PM to 10:00 PM during the WVU study. The in-situ thermal resistance was calculated during the rain event and was found to be greater than those values calculated previously, which is opposite of what would be expected; however, it was noted that these rain events were not within a data set that converged. Because the theoretical thermal resistance is a function of temperature, if the rain event does not result in changes in the temperature across the wall assembly, the thermal resistance should remain constant. The actual vapor pressure and temperature profiles across the wall assembly during the rain event are shown in Figure 5. While the actual vapor pressures through the wall assembly varied with the exterior conditions, the temperature profile did not appear to be impacted by the rain event in this situation.

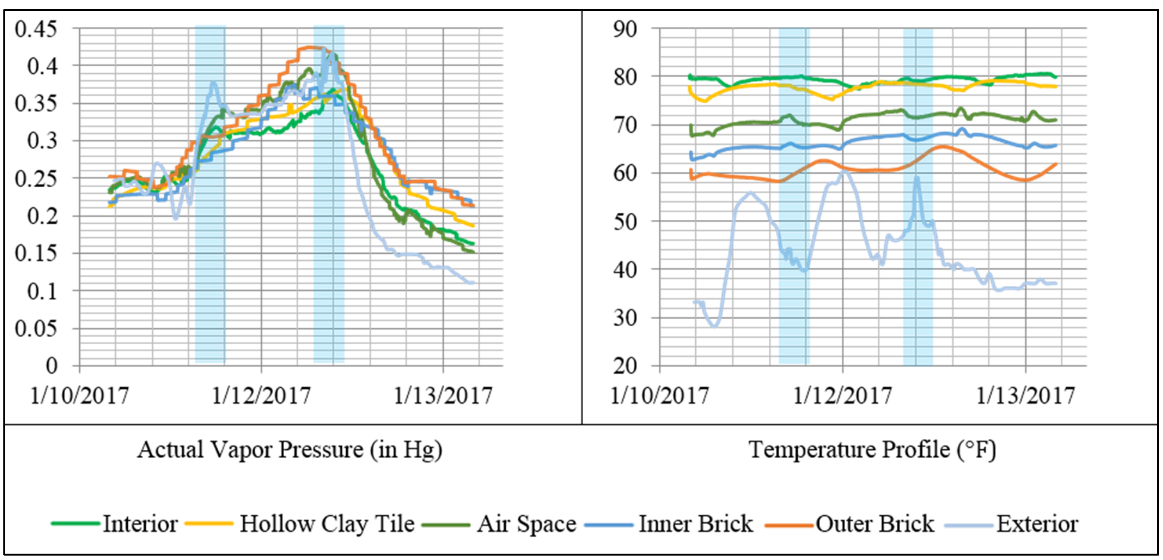

Figure 5: Actual Vapor Pressure and Temperature Profile during Rain Event

A similar comparison was made during the UVA study; however, because the walls that were evaluated as part of this paper were protected by an overhang, they were not directly exposed to rain. Because of the limited impact of the rain event on the performance of the wall assembly, an evaluation was then focused on periods of time when the exterior conditions created the highest actual vapor pressure over the duration of the test period. Most notably was July 24, 2016, when the actual vapor pressure peaked at the exterior. The actual vapor pressure and temperature profiles across both the existing and retrofit wall assemblies were evaluated during this time period as shown in Figure 6 and Figure 7, respectively. While the actual vapor pressure within the wall assemblies was greater than that during the rain event, there was still little overall change in either the vapor pressure or temperature profile across either wall assemblies. The in-situ thermal resistances calculated during these time periods were less than that calculated during other times; however, the peak exterior vapor pressure occurred outside of the data sets that converged.

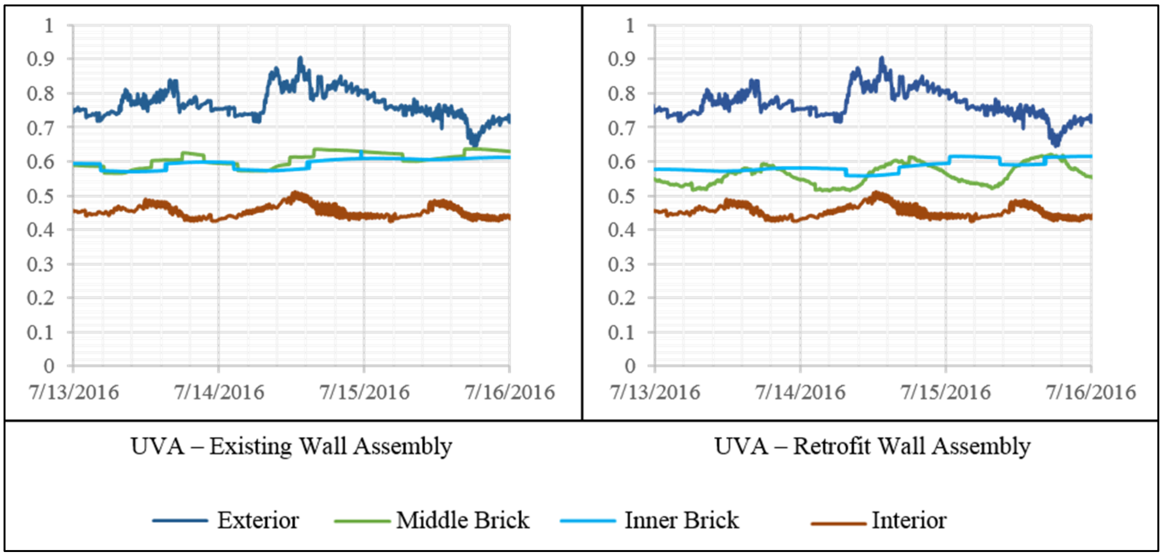

Figure 6: Actual Vapor Pressure (in Hg) profiles during peak exterior vapor pressure

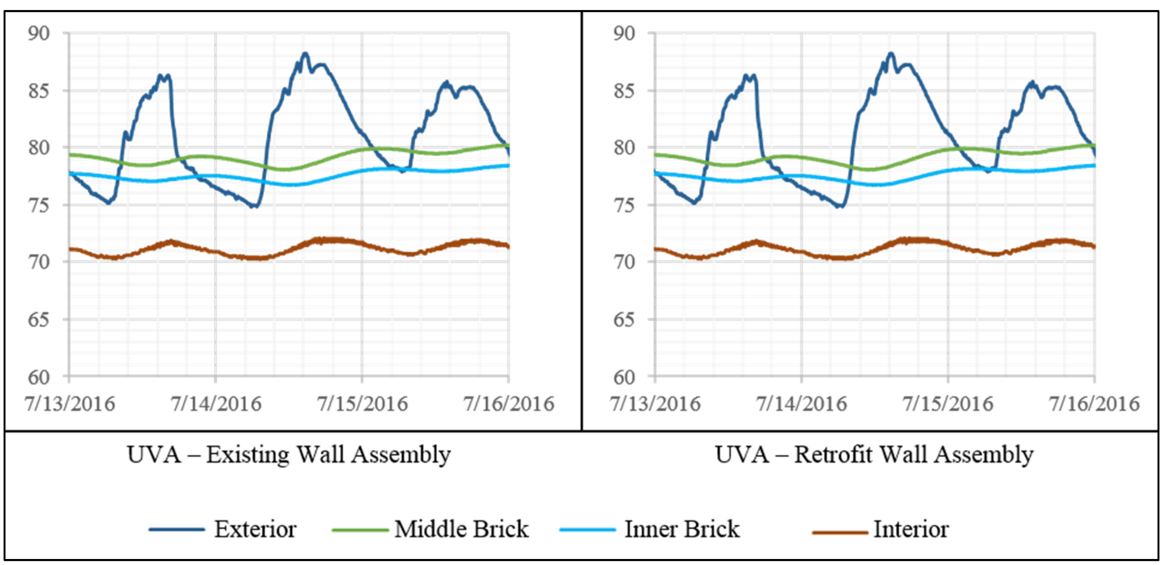

Figure 7: Temperature (°F) profiles during peak exterior vapor pressure

CONCLUSION

Through the use of in-situ data logging instrumentation, an assortment of information can be collected and evaluated to determine the performance of an existing mass masonry wall and the impacts of modifications such as adding insulation. Additional field studies should be undertaken to determine conclusively, how conservative, if at all, predicted thermal resistance values for these types of assemblies are.

These studies indicated that for well-constructed and sound masonry, moisture within the wall did not appear to have a significant impact on the measured R-value for that assembly. It was also found that the winter months proved to be more favorable for determination of an estimated in-situ thermal resistance value. However, due to the duration of the field studies, the thermal resistance of the data set was found to normalize to determine an approximate R-value for different wall assemblies. It was also noted that the theoretical R-values values that were calculated may be conservatively low for certain mass masonry wall types.

In addition to monitoring the thermal performance of the wall assembly, the moisture profile across the wall assembly could be evaluated over time. This data could then be used to verify the initial moisture contents within a wall assembly to determine how the addition of vapor retarders in a retrofit application would affect the ability of the wall to diffuse stored moisture.

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