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Assessing Methodologies for Detecting Water Intrusion in Wall Systems: Phase 2

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Table of Contents

Table of Figures

List of Tables

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Buildings and Transportation Sciences Division

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1. BACKGROUND

Studies by the University of Florida [1], the Environmental Protection Agency (EPA) [2] and the U.S. Department of Housing (HUD) [3] have revealed that there is a substantial fraction of commercial and residential buildings that have been exposed to moisture resulting in damage or durability problems. Water intrusion into building envelope components leads to a variety of undesirable conditions such as mold, wood rot, corrosion, and aesthetic damage. Tests methods that are presently used to evaluate the amount of water intrusion into a building envelope component are usually qualitative in nature. For example, ASTM E 331, Standard Test Method for Water Penetration of Exterior Windows, Curtain Walls, and Doors by Uniform Static Air Pressure Difference [4] requires that you "observe and record points of water leakage, if any." This test was originally developed to assess the performance of fenestration products but is commonly adapted to evaluate other enclosure assemblies. However, when it is typically used for walls, this procedure is limited to recognizing if the moisture is visually observable from the backside side of the sheathing. It does not address moisture that is absorbed in the layers of the building envelope component, which could impact the durability of the assembly. Clearly a quantitative means of determining water penetration would improve the quality of this type of test and assist with better understanding the resultant impact on enclosure assemblies.

In 2018-20, Oak Ridge National Laboratory, in conjunction with the Air Barrier Association of America, initiated a research project to address this issue [5]. The purpose of that study was to evaluate nine different methods of detecting moisture intrusion through a wall assembly. The wall assemblies included metal frame construction faced with gypsum sheathing and both self-adhered and fluid applied air and water barriers (AWB) were evaluated for this exercise. This project did not test the efficacy of the different AWBs, rather, fasteners were purposely installed in various ways to foster water penetration and activate the different methods of detection. Each detection method was evaluated for five features that included simplicity of use, cost of implementation, whether the method was quantitative or subjective, accuracy, and applicability. A scale of green/yellow/red was used to assess each feature where green was acceptable, yellow was borderline, and red was not to be pursued at this time.

This report covers additional research that has been undertaken to extend the activities initiated in the earlier project with refinements for specific detection methods and considerations for expansion related to field versus laboratory testing standards.

2. SCOPE AND TASKS

The project consisted of five tasks that are detailed on the following sections.

Task 1: Review of Previous Work and Selection of Sensors and Systems to be Evaluated

In concert with staff members from the Air Barrier Association of America (ABAA) and Tremco, Inc., ORNL assisted in the design of the experimental plan.

The group decided to evaluate five different combinations of panel configurations and sensors and that these configurations/sensors would be tested in duplicate. These configurations were identified as A through E and the duplicate configurations identified as A' through E'. The panels were comprised of 5/8-inch exterior gypsum sheathing with 2 x 4 16-gauge steel studs framing installed around the exterior gypsum perimeter held together with # 8 - 1 ¼ long bugle self-tapping screws located 6 inches on center.

was installed with # 8 - 1 ¼ long bugle self-tapping screws located 6 inches on center around the perimeter of the specimens. A 1”x1” angle was installed running horizontally near the center of the panel to use for installing fasteners. A self-adhered water resistive barrier was applied to the exterior gypsum sheathing.

Based on our previous experiments, the group decided to focus on deploying the following sensors:

- Structure Monitoring Technology (SMT) electric sensor tape placed on the backside of the sheathing and between the water resistive barrier and the exterior gypsum sheathing. See Figure 1.
- Embedded moisture pin probes in the sheathing, inserted from the interior side of the gypsum sheathing to meter the moisture content at mid-thickness and the exterior side of the gypsum sheathing. See Figure 2.
- Capacitance-type RH sensors placed on the backside of the sheathing and between the water resistive barrier and the exterior gypsum sheathing. See Figure 2.

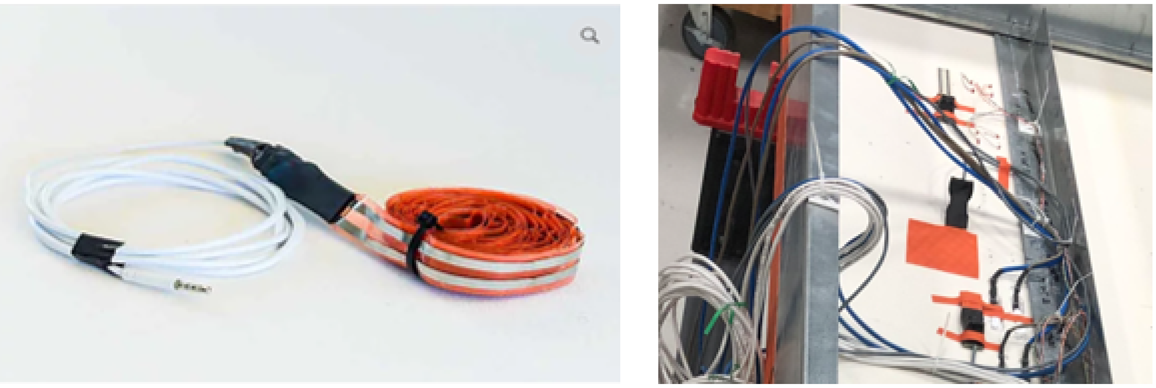

Figure 5: SMT electric sensor tape was placed horizontally on both surfaces of the exterior gypsum sheathing.

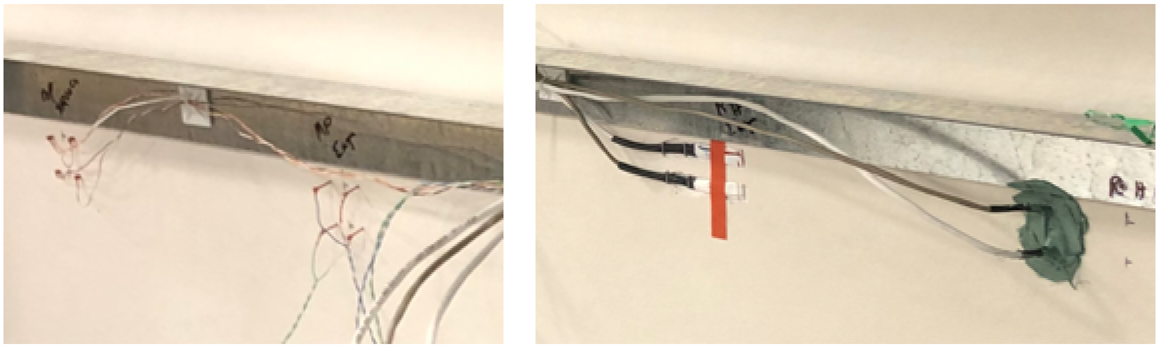

Figure 6: Moisture pin probes (left) and capacitance-type RH sensors (right) are embedded in the exterior gypsum sheathing.

The panel configurations had the following features and sensor types and locations.

Table 6: Sensor type and location for panels A and A'.

Panel ID	Sensor Type	Fastener Type	Sensor Location	Sensing Location
A and A'	Moisture pin 1	Overdriven	0.5-in. below fastener	Gypsum exterior
A and A'	Moisture pin 2	Overdriven	2-in. below fastener	Gypsum exterior
A and A'	Moisture pin 3	Overdriven	0.5-in. below fastener	Gypsum exterior
A and A'	Moisture pin 4	Overdriven	2-in. below fastener	Gypsum exterior
A and A'	Moisture pin 5	Overdriven	0.5-in. below fastener	Gypsum mid thickness
A and A'	Moisture pin 6	Overdriven	2-in. below fastener	Gypsum mid thickness
A and A'	Moisture pin 7	Overdriven	0.5-in. below fastener	Gypsum mid thickness
A and A'	Moisture pin 8	Overdriven	2-in. below fastener	Gypsum mid thickness
A and A'	Capacitance 1	Overdriven	0.5-in. below fastener	Gypsum interior
A and A'	Capacitance 2	Overdriven	2-in. below fastener	Gypsum interior
A and A'	Capacitance 3	Overdriven	0.5-in. below fastener	Gypsum interior
A and A'	Capacitance 4	Overdriven	2-in. below fastener	Gypsum interior
A and A'	Sensor tape 1	Overdriven	4-in. below fastener	Gypsum interior
A and A'	Sensor tape 2	Overdriven	4-in. below fastener	Gypsum exterior
A and A'	Sensor tape 3	Overdriven	4-in. below fastener	Gypsum exterior

Table 7: Sensor type and location for panels B and B'.

Panel ID	Sensor Type	Fastener Type	Sensor Location	Sensing Location
B and B'	Capacitance 5	Overdriven	0.5-in. below fastener	Gypsum exterior
B and B'	Capacitance 6	Overdriven	2-in. below fastener	Gypsum exterior
B and B'	Capacitance 7	Overdriven	0.5-in. below fastener	Gypsum exterior
B and B'	Capacitance 8	Overdriven	2-in. below fastener	Gypsum exterior
B and B'	Moisture pin 9	Hole	0.5-in. below hole	Gypsum exterior
B and B'	Moisture pin 10	Hole	2-in. below hole	Gypsum exterior
B and B'	Moisture pin 11	Hole	0.5-in. below hole	Gypsum exterior
B and B'	Moisture pin 12	Hole	2-in. below hole	Gypsum exterior
B and B'	Moisture pin 13	Hole	0.5-in. below hole	Gypsum mid thickness
B and B'	Moisture pin 14	Hole	2-in. below hole	Gypsum mid thickness
B and B'	Moisture pin 15	Hole	0.5-in. below hole	Gypsum mid thickness
B and B'	Moisture pin 16	Hole	2-in. below hole	Gypsum mid thickness

Table 8: Sensor type and location for panels C and C'.

Panel ID	Sensor Type	Fastener Type	Sensor Location	Sensing Location
C and C'	Capacitance 9	Hole	0.5-in. below hole	Gypsum interior
C and C'	Capacitance 10	Hole	2-in. below hole	Gypsum interior
C and C'	Capacitance 11	Hole	0.5-in. below hole	Gypsum interior
C and C'	Capacitance 12	Hole	2-in. below hole	Gypsum interior
C and C'	Capacitance 13	Hole	0.5-in. below hole	Gypsum exterior
C and C'	Capacitance 14	Hole	2-in. below hole	Gypsum exterior
C and C'	Capacitance 15	Hole	0.5-in. below hole	Gypsum exterior
C and C'	Capacitance 16	Hole	2-in. below hole	Gypsum exterior
C and C'	Sensor tape 4	Hole	4-in. below hole	Gypsum interior

C and C'	Sensor tape 5	Hole	4-in. below hole	Gypsum exterior
C and C'	Sensor tape 6	Hole	4-in. below hole	Gypsum exterior

Table 9: Sensor type and location for panels D and D'.

Panel ID	Sensor Type	Fastener Type	Sensor Location	Sensing Location
D and D'	Moisture pin 17	None	0.5-in. below angle	Gypsum exterior
D and D'	Moisture pin 18	None	2-in. below angle	Gypsum exterior
D and D'	Moisture pin 19	None	0.5-in. below angle	Gypsum mid thickness
D and D'	Moisture pin 20	None	2-in. below angle	Gypsum mid thickness
D and D'	Capacitance 17	None	0.5-in. below angle	Gypsum interior
D and D'	Capacitance 18	None	2-in. below angle	Gypsum interior
D and D'	Capacitance 19	None	0.5-in. below angle	Gypsum exterior
D and D'	Capacitance 20	None	2-in. below angle	Gypsum exterior

Table 10: Sensor type and location for panel E.

Panel ID	Sensor Type	Fastener Type	Sensor Location	Sensing Location
E	Moisture pin 21	None	0.5-in. below angle	Gypsum exterior
E	Moisture pin 22	None	2-in. below angle	Gypsum exterior
E	Moisture pin 23	None	0.5-in. below angle	Gypsum mid thickness
E	Moisture pin 24	None	2-in. below angle	Gypsum mid thickness
E	Capacitance 21	None	0.5-in. below angle	Gypsum interior
E	Capacitance 22	None	2-in. below angle	Gypsum interior
E	Capacitance 23	None	0.5-in. below angle	Gypsum exterior
E	Capacitance 24	None	2-in. below angle	Gypsum exterior

Panels A, B, and C were designed to evaluate the impact of overdriven fasteners and removed fasteners (holes) on the output of the sensors. The location of the sensors was also to be analyzed (on interior or exterior of the exterior gypsum sheathing). Panel D was intended to be a control panel with no penetrations in the exterior sheathing caused by fasteners. Panel E was also a control panel; this panel was simply located in the test room to assess whether the sensors in the panels would be impacted by the changing environmental conditions in the room caused by the long-term addition of moisture due to spraying. Panel E was not subjected to any water spray.

To accelerate the testing process, it was decided to combine several of the panels. Panels A and B, Panels C and D, Panels A' and B', and Panels C' and D' were combined. The overall panel size was increased to 72 inches long by 24 inches high. These panels were installed in a wood buck having an appropriately sized aperture with a factory-bonded membrane and sealed in place. An image of the sensors installed in one of the panels is shown in Figure 3. Figure 4 shows the wood buck with panel aperture and installed panel.

Figure 7: Test panel A/B during the application of the sensors.

Figure 8: Wood buck with panel aperture (left) and panel installed (right).

Task 2: Sensor Calibration

Representative moisture pins and capacitance sensors were evaluated to assess the relationship between their output and moisture content. A sample of the exterior sheathing that was being used in the ASTM E331 experiments was instrumented with several moisture pins and capacitance sensors in a similar manner (see Figure 5). Prior to its use, the sheathing board was conditioned to constant weight in a drying chamber maintained at 100ºF and less than 5 percent relative humidity. The instrumented board was placed in an environmental chamber that was controlled at 75ºF and varying levels of relative humidity. A NIST-traceable Vaisala HMP7 temperature and relative humidity probe was used to monitor the hygrothermal conditions within the environmental chamber. The environmental chamber was maintained at ,5, 50, 75, and 95 percent RH for over a week at each condition. After maintaining each condition for over a week, the outputs of the moisture pins and capacitance sensors were recorded. The moisture pin outputs were plotted against the Vaisala HMP7 temperature and relative humidity probe output, was fitted to a logarithmic function, and is also presented in Figure 5. This calibration was then used to process all of the data gathered during the ASTM E331 testing. The outputs of the capacitance sensors were compared with the calibration data supplied by the sensor manufacturer; data collected on the capacitance sensors tested in the environmental chamber agreed well with the manufactured-supplied calibrations. For the ASTM E331 tests, the supplied calibrations were used to process the capacitance sensor outputs.

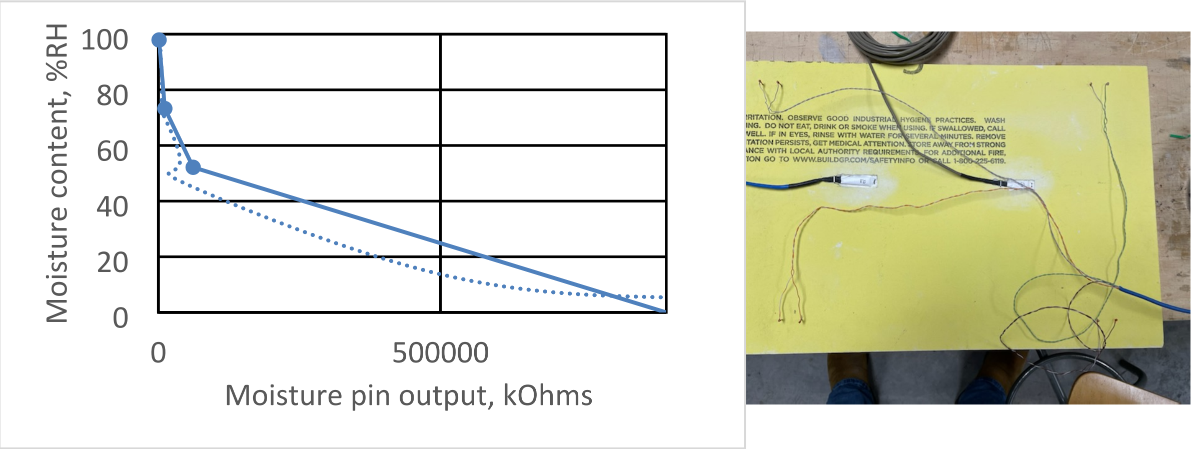

Figure 5: Moisture pin calibration data used for processing moisture pin data and photo of test sample used to collect these data.

Task 3: Laboratory Testing

Each panel was subjected to water sprayed on the surface of the panel in accordance with ASTM E331, Standard Test Method for Water Penetration of Exterior Windows, Curtain Walls, and Doors by Uniform Static Air Pressure Difference using the facilities at Tremco in Beachwood OH. The Tremco Sustainable Building Solutions Test Facility is a state-of-the-art facility for testing of air and moisture infiltration/exfiltration in building enclosures test specimens. Panels A/B and C/D were exposed for 120 minutes while Panels A'/B' and C'/D' were subjected to a 240-minute exposure. See Figure 6.

The water-spray system was configured to deliver water uniformly against the exterior surface of the test specimen at a rate of 5.0 U.S. gal/ft^2·h. The water-spray system had nozzles spaced on a uniform grid, located at a uniform distance from the test specimen, and were adjusted to provide the specified quantity of water in such a manner as to wet all the test specimen and areas vulnerable to water penetration uniformly.

Two panels were evaluated concurrently. Test bucks made of wood was constructed to hold a single test panel. The test buck was coated with a waterproofing material and the test panels were sealed into the buck using flashing tape and waterproofing sealant. The panels were tested with a 6.24 psf pressure difference across the specimen.

Figure 6: Test panels installed in an ASTM E331 apparatus.

Task 4: Observations During and after Testing

Each specimen was observed and photographed during the testing. The moisture pins, electric resistance tape, and the capacitance pins required a data collection system to compile data during the experiments. To accomplish this a Campbell Scientific data acquisition system was set up and used to collect this information. See Figure 7. After the spray exposure was completed, the data collection was continued overnight to examine the drying rate of the panels.

After the test panels completed their exposures, the panels were removed from the apparatus and two handheld moisture meters were used to measure the moisture content of the exterior gypsum from the interior side of the test wall. The first moisture meter that we employed were the Delmhorst BD-2100 and was set on the “gypsum” scale which, according to the manufacturer, measures the moisture content over the range of 0.2 to 50 percent. The second moisture meter used was the Protimeter MMS2. Photos of these meters are displayed in Figure 8.

Figure 7: Data collection systems were used to collect and store data outputs from sensors installed in the test panels. Computers were connected to the data loggers (left photo) for this purpose. Campbell Scientific data loggers were used to collect real time data (right photo).

Figure 8: Delmhorst BD-2100 and Protimeter MMS2 moisture meters used in this study.

Task 5: Results

Task 5a: Handheld Moisture Meter Data

Immediately at the end of the test, each test panel was decommissioned, and all evidence of water intrusion was recorded by photography and documentation. For panels A/B, the Delmhorst BD-2100 and the Protimeter MMS2 moisture meters were used to measure the moisture content of the exterior gypsum from the interior side of the panel. The exterior gypsum was measured approximately 3 inches below the fastener, hole, or below the other instrumentation where no hole was being measured. Two operators (Operator 1 and 2) were used to perform these measurements to gauge the reproducibility of the meters. Prior to performing these tests, both meters measured the moisture content of the Control Panel E (not exposed to any spray). The Delmhorst BD-2100 and the Protimeter MMS2 moisture meters recorded outputs of 0.4 and 14, respectively.

Data compiled with the moisture meters are summarized in Tables 6 and 7 and Figure 9. By plotting the outputs of the two moisture meters against each other, we can assess how their outputs compare. A linear fit was calculated for the 42-point data set and is depicted on Figure 9. Of the forty-two sets of data collected, only three of those data points significantly deviate from the linear fit. Approximately 90 percent of the data collected shows reasonable agreement between the two moisture meters. The three sets of data that are inconsistent with the curve fit were all collected by the second operator.

Table 6: Handheld data on Panels A/B.

Operator	Fastener Type	Measurement Location	Delmhorst	Protimeter
1	Overdriven 1	3-in. below fastener	0.5	16.6
1	Overdriven 2	3-in. below fastener	0.5	17.0
1	Overdriven 3	3-in. below fastener	0.5	16.8
1	Overdriven 4	3-in. below fastener	0.4	16.4
1	Overdriven 5	3-in. below fastener	0.4	16.4
1	Overdriven 6	3-in. below fastener	0.45	16.7
1	Overdriven 7	3-in. below fastener	0.4	16.5
1	Overdriven 8	3-in. below fastener	0.75	22.1
1	Hole 1	3-in. below hole	0.8	21.0
1	Hole 2	3-in. below hole	0.7	19.0
1	Hole 3	3-in. below hole	0.8	20.4
1	Hole 4	3-in. below hole	1.4	27.8
2	Overdriven 1	3-in. below fastener	0.6	18.1
2	Overdriven 2	3-in. below fastener	0.6	19.7
2	Overdriven 3	3-in. below fastener	0.6	19.7
2	Overdriven 4	3-in. below fastener	0.6	20.1
2	Overdriven 5	3-in. below fastener	0.7	19.7
2	Overdriven 6	3-in. below fastener	0.6	19.3
2	Overdriven 7	3-in. below fastener	0.8	60.2
2	Overdriven 8	3-in. below fastener	1.1	26.5
2	Hole 1	3-in. below hole	2.1	23.1
2	Hole 2	3-in. below hole	2.0	26.8
2	Hole 3	3-in. below hole	1.2	23.3
2	Hole 4	3-in. below hole	0.8	21.9

Table 7: Handheld data on Panels C/D.

Operator	Fastener Type	Measurement Location	Delmhorst	Protimeter
1	Hole 5	3-in. below hole	0.6	20.9
1	Hole 6	3-in. below hole	1.1	22.7
1	Hole 7	3-in. below hole	0.6	20.4
1	Hole 8	3-in. below hole	0.6	19.8
1	None 1	3-in. below angle	0.6	18.2
1	None 2	3-in. below angle	0.6	18.0
1	None 3	3-in. below angle	0.6	17.4
1	None 4	3-in. below angle	0.5	17.2
2	Hole 5	3-in. below hole	9.5	25.3
2	Hole 6	3-in. below hole	2.8	33.4
2	Hole 7	3-in. below hole	8.2	100
2	Hole 8	3-in. below hole	0.9	22.8
2	None 1	3-in. below angle	0.7	22.0
2	None 2	3-in. below angle	0.7	21.2
C'/D'	None 3	3-in. below angle	0.6	21.4
C'/D'	None 4	3-in. below angle	0.6	21.3

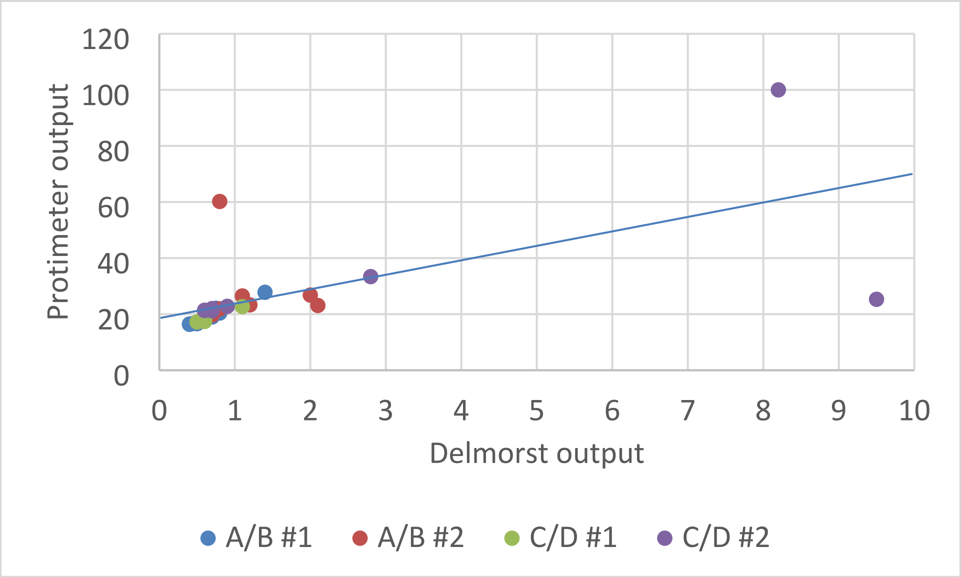

Figure 9: The comparative ouputs of the two handheld moisture meters.

Task 5b: Electric Sensor Tape Data

Electric sensor tape manufactured by Structure Monitoring Technology (see Figure 1) was used to measure the potential for a moisture leak. A short 6-inch length of the tape was installed on the backside of the sheathing and between the water resistive barrier and the exterior gypsum sheathing. The electric resistance output of the tape was monitored during the duration of the ASTM E331 spray exposure. When the tape is exposed to moisture, the electrical resistance of the tape decreases appreciably. The tape acts as "yes/no" sensor indicating the presence of water on the sensor.

These sensors required a data collection system to compile data during the experiments. To accomplish this a Campbell Scientific data acquisition system was set up and used to collect this information. These data were stored in the memory of the data acquisition system and then transferred to a spreadsheet for subsequent analyses. Prior to the exposure, the data acquisition system was started and collected the electrical resistance of the moisture detection tapes. This data was collected every minute during the experiment and averaged into 15-minute blocks for analysis.

Two electric sensor tapes were applied to Panel A where the two sensors were installed attached to the backside of the sheathing below test sites represented by overdriven fasteners. Panel C was also instrumented with two electric sensor tapes installed between the water resistive barrier and the exterior gypsum sheathing below test sites represented by holes in the water resistive barrier and exterior gypsum board. Three electric sensor tapes were applied to Panel A' where two sensors were installed between the water resistive barrier and the exterior gypsum sheathing and the remaining sensor was attached to on the backside of the sheathing below test sites represented by overdriven fasteners. Panel C' was also instrumented with three electric sensor tapes with a similar distribution below test sites represented by holes in the water resistive barrier and exterior gypsum board.

Figures 10 and 11 summarize the electric sensor tape for exposure tests from 8 March 2022 (two-hour spray exposure) and 9 March 2022 (four-hour spray exposure), respectively.

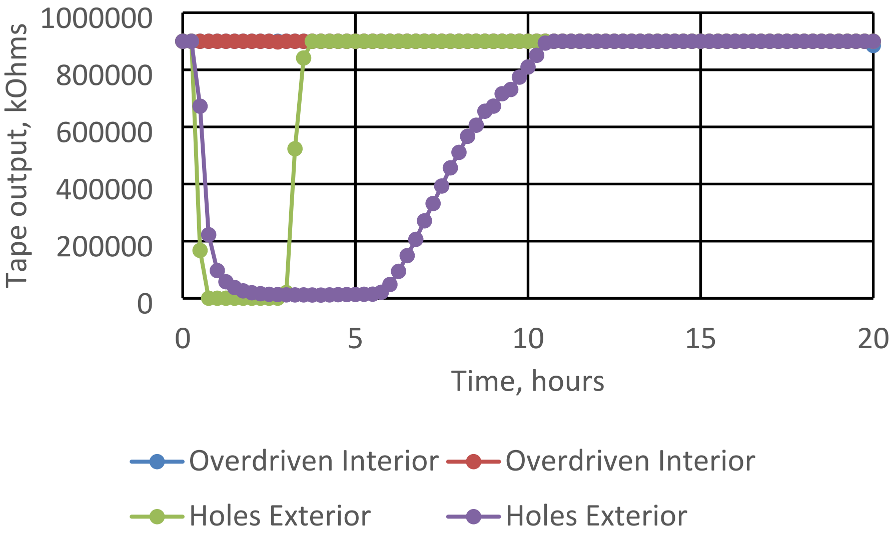

Figure 10: Tape outputs from 2-hour spray exposure experiment.

Data from both experiments show that the tapes used in association with holes in the water resistive barrier and exterior sheathing allow sufficient water to penetrate the into the panel and short circuit the sensor tape causing the electrical resistance to be substantially reduced. The tapes monitoring the overdriven fastener sites do not respond during the spray period indicating that insufficient amounts of water penetrate to these tape sensors. Similar data was collected during the 4-hour spray exposure with sensors monitoring sites associated with holes responding to an electrical short created by the leaking water and the tapes monitoring the overdriven fastener sites not responding.

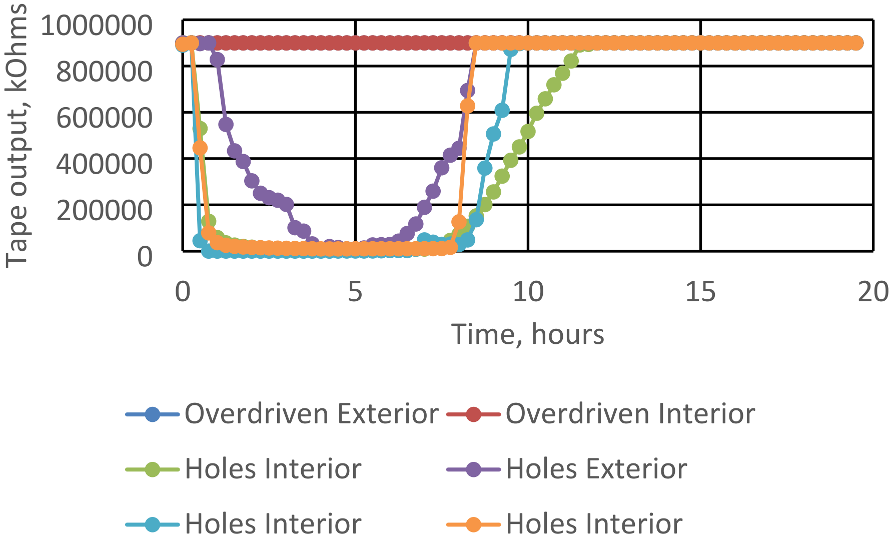

Figure 11: Tape outputs from 4-hour spray exposure experiment.

Task 5c: Capacitance Sensor Data

A capacitance humidity sensor measures relative humidity by placing a thin strip of metal oxide between two electrodes. The metal oxide's electrical capacity changes with the atmosphere's relative humidity. The capacitance type sensors are linear and can measure relative humidity from approximately 10 to 98%. Relative humidity sensors are more precise in measuring smaller moisture incursions as they do not require water to be present to change the electric resistance or to discolor a material. These sensors also required a data collection system to compile data during the experiments. To accomplish this a Campbell Scientific data acquisition system was set up and used excite the temperature and relative humidity sensors and to collect this information. These data were stored in the memory of the data acquisition system and then transferred to a spreadsheet for subsequent analyses.

Figures 12 through 17 depict data that was gathered using capacitive sensors during the 2-hour spray exposure. These sensors were installed between the backside of the exterior sheathing by routing out a small groove in the back surface of the exterior sheathing to accommodate the 1/8-inch diameter sensor. These sensors are coupled with a thermistor so that both absolute and relative humidity can be measured. The sensor combination is surrounded with a protective film made of spun-bonded polyolefin to protect the sensor from direct wetting. The polyolefin is highly permeable to water vapor and therefore does not deleteriously impact its ability to monitor relative humidity.

Note that three of the capacitance sensors failed during the 2-hour spray exposure. All three sensors were near holes in the water resistive barrier. It is theorized that water breached the polyolefin protective film and short-circuited the sensors.

Figure 12 summarizes the test data from the four capacitance sensors located near overdriven fasteners. The data suggests that the location of the sensor with respect to its distance from the penetration and the surface on which it was mounted do not appreciably affect the measured moisture content.

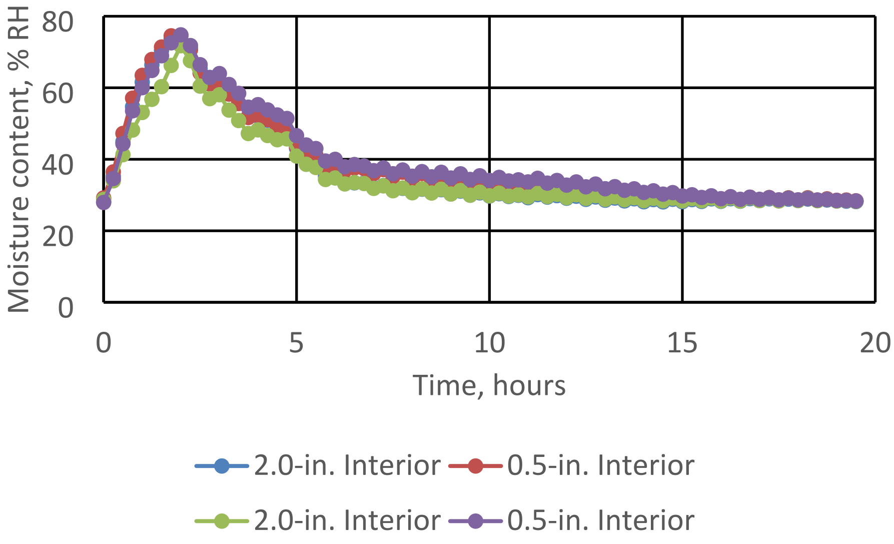

Figure 12: Moisture content measurements from capacitance sensors located near overdriven fasteners.

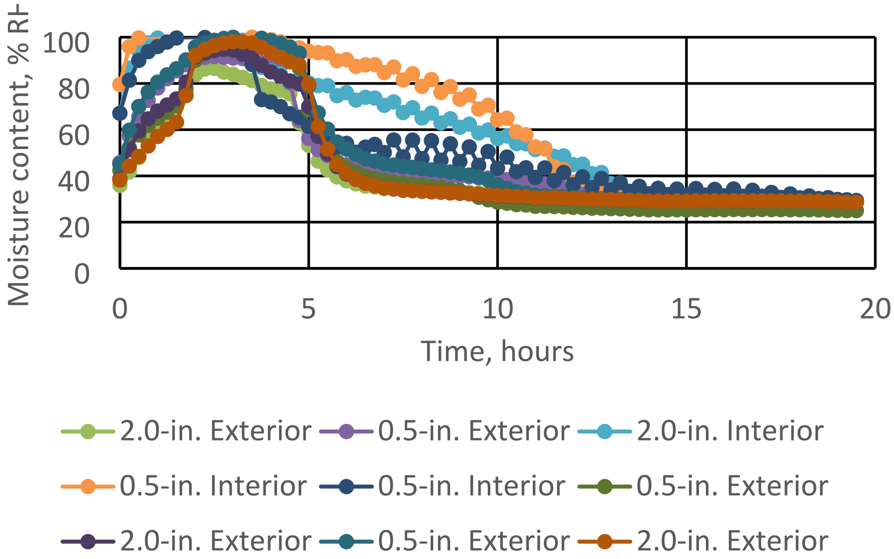

Figure 13: Moisture content measurements from capacitance sensors located near holes.

Figure 13 summarizes the test data from the nine capacitance sensors located near holes. Seven of the sensors reached near saturation (>95 percent moisture contents). After approximately 15 hours, all of the sensors were recording moisture contents near their original "dry" levels.

Figure 14 depicts the average moisture content of the capacitance sensors as a function of the sensor location (distance from the water resistive barrier penetration and the wall assembly surface that the sensor was attached) where there were no holes or penetrations in the water resistive barrier. The interior location is defined as the exterior sheathing surface nearest to the building interior while the exterior location is between the exterior sheathing and the water resistive barrier. The exterior locations appear to sense slightly higher levels of moisture whereas the distance from the penetration appears to have little impact.

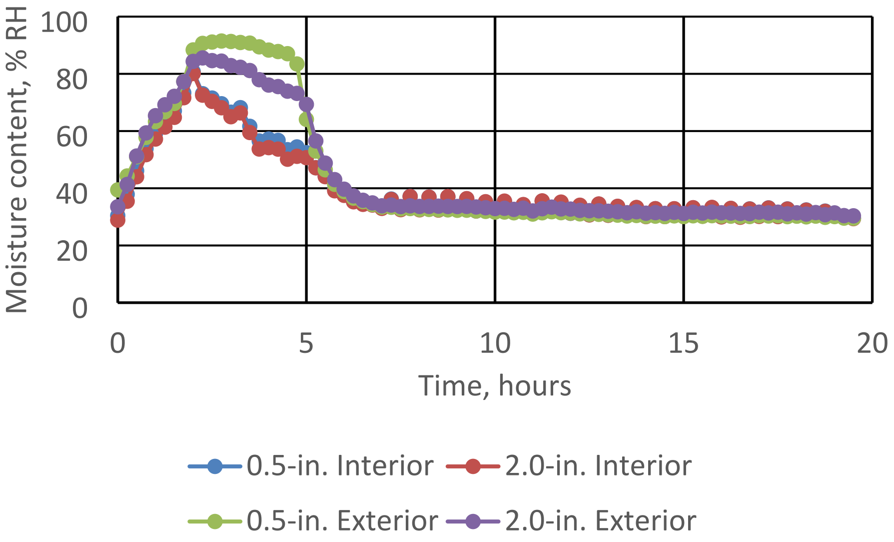

Figure 14: Moisture content measurements from capacitance sensors located away from any penetrations (no holes).

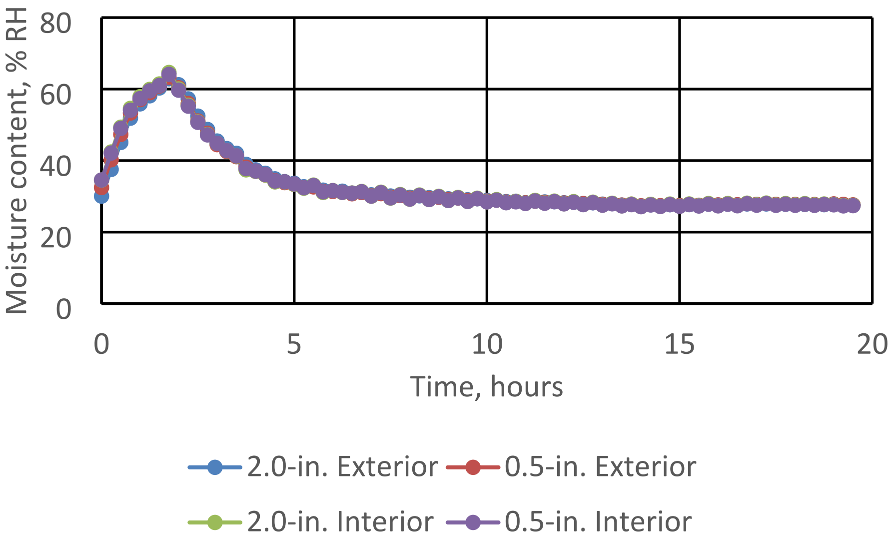

Figure 15: Moisture content measurements from capacitance sensors located away from any penetrations (no holes) in Panel E with no spray exposure.

Figure 15 shows the outputs of the capacitance sensors installed on Control Wall E that was not exposed to any spraying. This data shows that the relative humidity within the laboratory space increases during the testing process and that some of the increase in relative humidity is due to this change in laboratory conditions.

Figure 16 summarizes the average moisture contents measured by the capacitance sensors as a function of the penetration. As anticipated, the sensors located near holes measure higher levels of moisture. Somewhat surprisingly, the sensors located near overdriven fasteners are somewhat lower than those sensors near no penetrations.

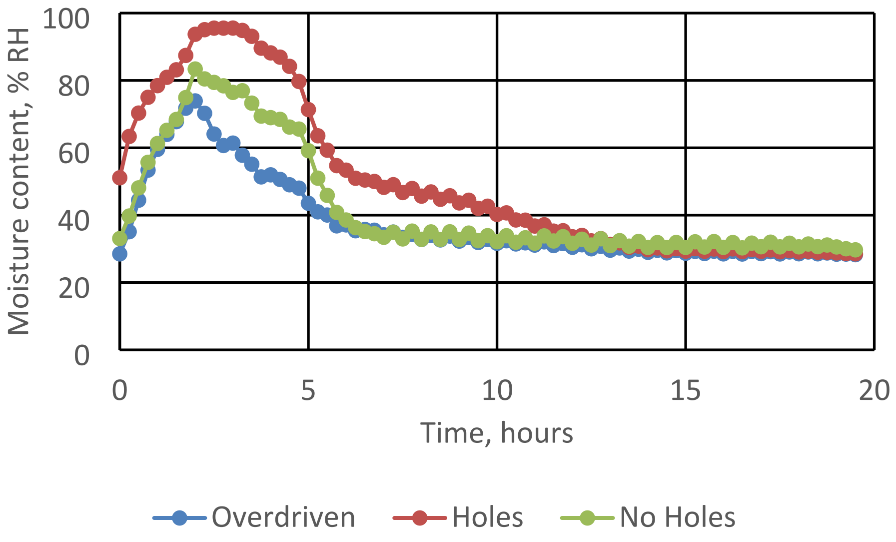

Figure 16: The average moisture content from capacitance sensors located near all penetration types.

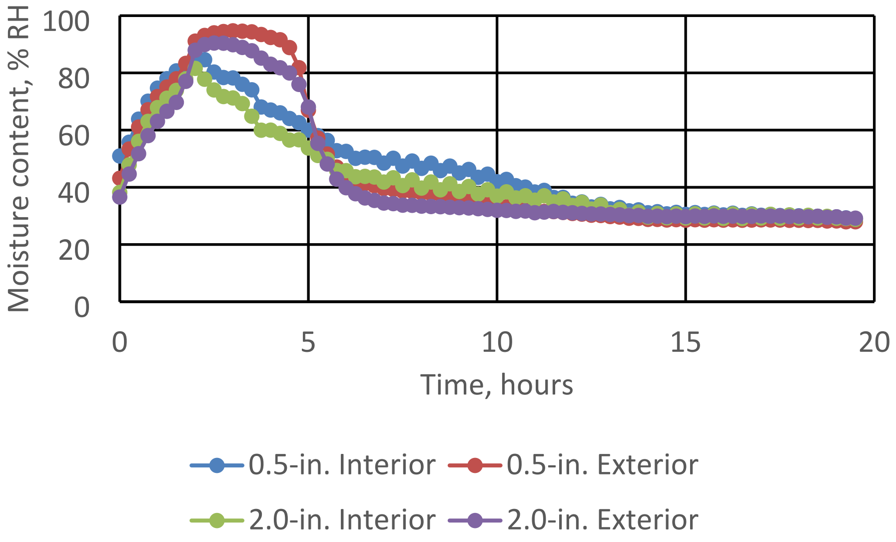

Figure 17: The average moisture content from capacitance sensors as a function of their distance from the water resistive barrier penetration and their installed surface.

Figure 17 depicts the average moisture content of all the capacitance sensors as a function of the sensor location (distance from the water resistive barrier penetration and the wall assembly surface that the sensor was attached) for all penetrations. Again, the exterior locations appear to sense slightly higher levels of moisture whereas the distance from the penetration appears to have little impact.

Similar data was compiled on identical panels that were exposed for a 4-hour spray exposure. The peaks in moisture contents are generally higher due to the extended exposure time and occurred at the end of the exposure time (four hours instead of two hours). During these experiments, four of the capacitance sensors failed when sensing moisture near holes in the water resistive barrier. Again, it is theorized that water breached the polyolefin protective film and short-circuited the sensors. An abbreviated summary of these data gathered during the 4-hour spray exposure are shown in Figures 18 through 19.

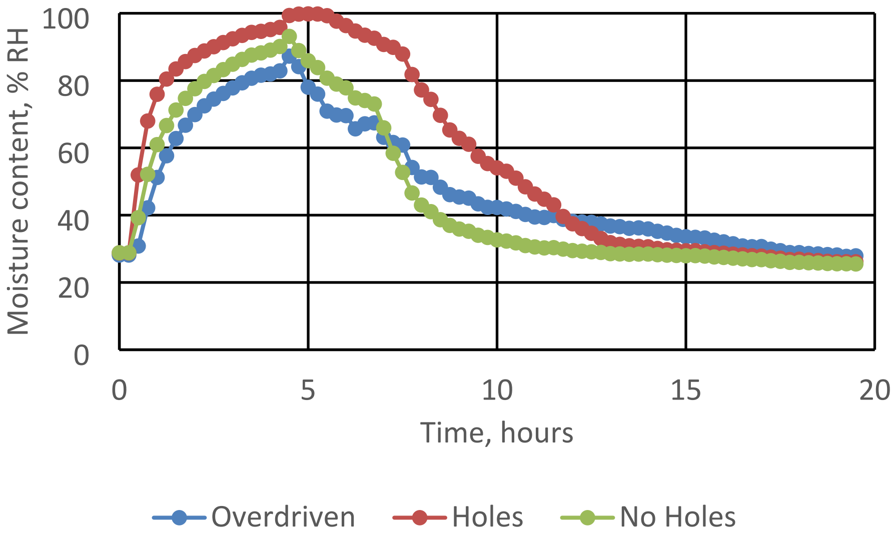

Figure 18: The average moisture content from capacitance sensors located near all penetration types during 4-hour exposure test.

Figures 18 and 19 summarize the average moisture contents measured by the capacitance sensors as a function of the penetration type and sensor location (distance from the water resistive barrier penetration and the wall assembly surface that the sensor was attached) for all penetrations for the 4-hour exposures, respectively. Similar to the 2-hour exposures, the sensors located near holes measure higher levels of moisture and the exterior locations appear to sense slightly higher levels of moisture whereas the distance from the penetration appears to have little impact.

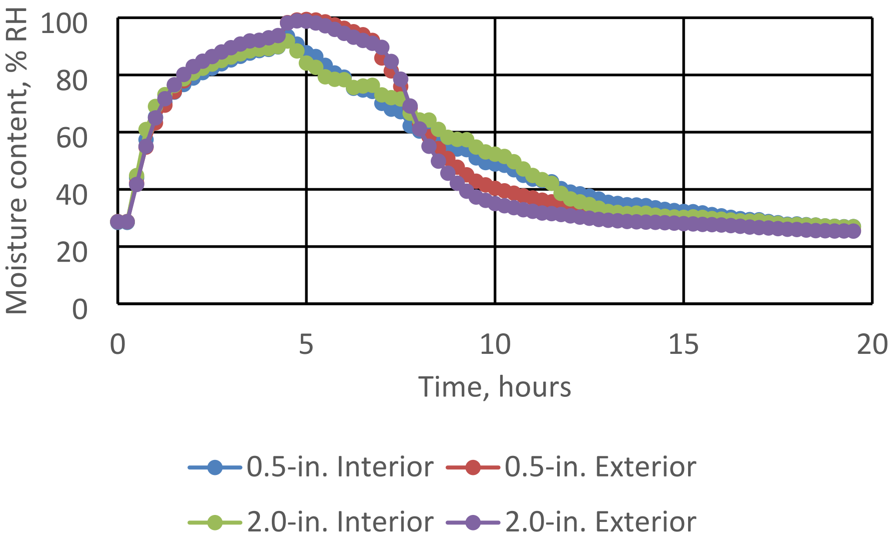

Figure 19: The average moisture content from capacitance sensors as a function of their distance from the water resistive barrier penetration and their installed surface during 4-hour exposure test.

Task 5d: Moisture Pin Sensor Data

The last sensor used to measure moisture content were moisture pins. These measurements are identical to using a portable moisture probe except the pins are inserted into the exterior sheathing and left in place during the test panel exposure. Data is continuously collected over that time interval. The moisture pins measure the electrical resistance between a pair of electrodes that are inserted into the exterior sheathing. Stainless steel nails are used as the electrodes. To electrically isolate the pins, they are coated with an epoxy paint leaving just the 0.25-inch ends exposed. They are physically driven into the exterior sheathing from the interior side and measure the moisture content of the exterior sheathing at mid-thickness. Moisture pins were installed in the exterior gypsum approximately 0.5 and 2.0 inches below each penetration (overdriven fastener, hole, or no hole) to monitor moisture ingress around that specific penetration. The moisture probes were used to measure the electric resistance around each penetration. These sensors also required a data collection system to compile data during the experiments. To accomplish this a Campbell Scientific data acquisition system was set up and used excite the moisture pins and to collect this information. These data were stored in the memory of the data acquisition system and then transferred to a spreadsheet for subsequent analyses.

Figures 20 through 25 depict data that was gathered using moisture pin sensors during the 2-hour spray exposure. These sensors were installed between the backside of the exterior sheathing by driving the fasteners through the exterior sheathing to the surface of the water resistive and to the mid-depth of the exterior sheathing. These data mimic the results from the capacitance sensors displayed in Figures 12-17. Note that the moisture pins were calibrated (see Section 2 Sensor Calibration) over the relative humidity range of 0 – 95 percent relative humidity. Data outside of this calibration range is extrapolated. Some of these extrapolations predict moisture contents in excess of 100 percent relative humidity which is obviously not plausible. If additional work is performed on this research topic, the calibration range should be extended beyond 95 percent relative humidity to include data in the capillary range as the moisture content changes dramatically within this range.

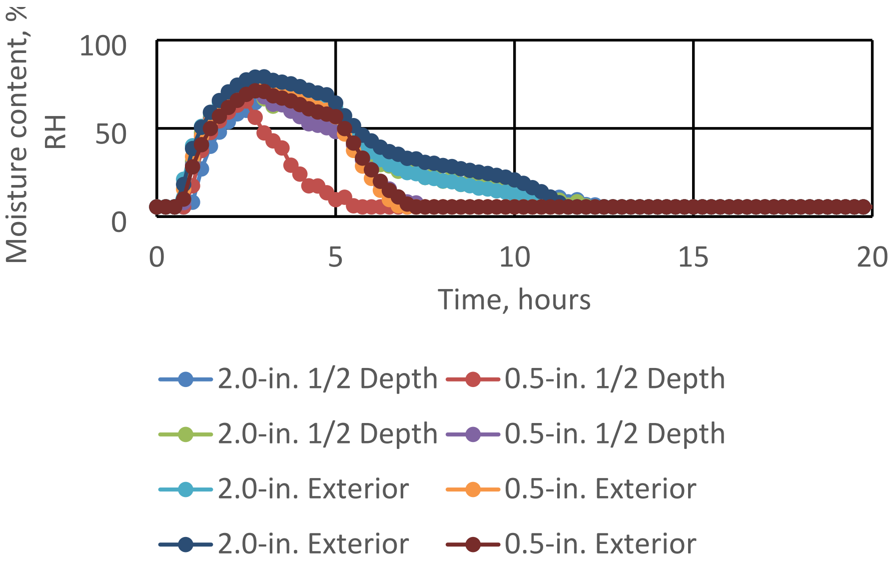

Figure 20: Moisture content measurements from moisture pin sensors located near overdriven fasteners.

Figure 20 summarizes the test data from the eight moisture pin sensors located near overdriven fasteners. The data suggests that the location of the sensor with respect to its distance from the penetration did not appreciably affect the measured moisture content. The surface on which the moisture pin monitored measured higher moisture contents on the exterior side of the exterior sheatrhing.it was mounted.

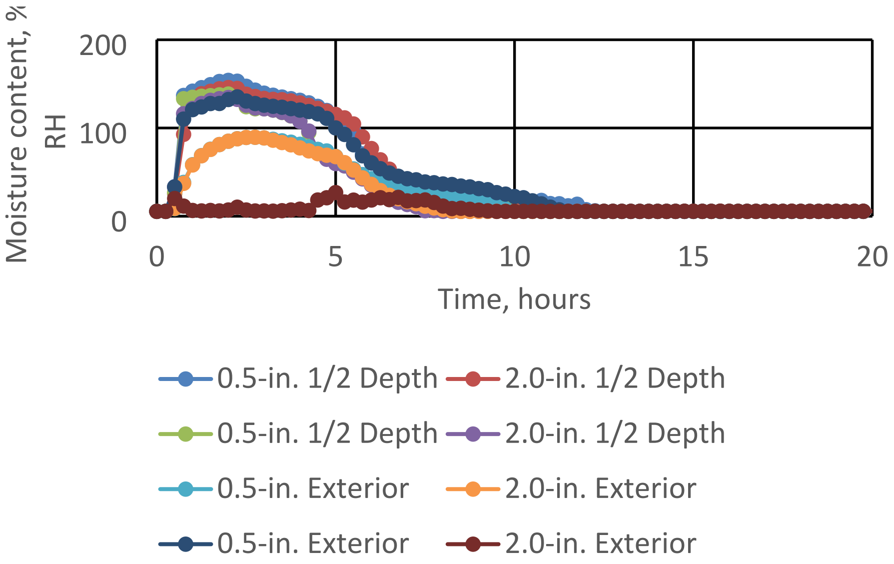

Figure 21: Moisture content measurements from moisture pin sensors located near holes.

Figure 21 summarizes the test data from the eight moisture pin sensors located near holes. One sensor (2.0-in. exterior) appeared to fail probably due to poor electrical contact). Six of the sensors reached near saturation (>95 percent moisture contents). After approximately 8 hours, all of the sensors were recording moisture contents near their original "dry" levels.

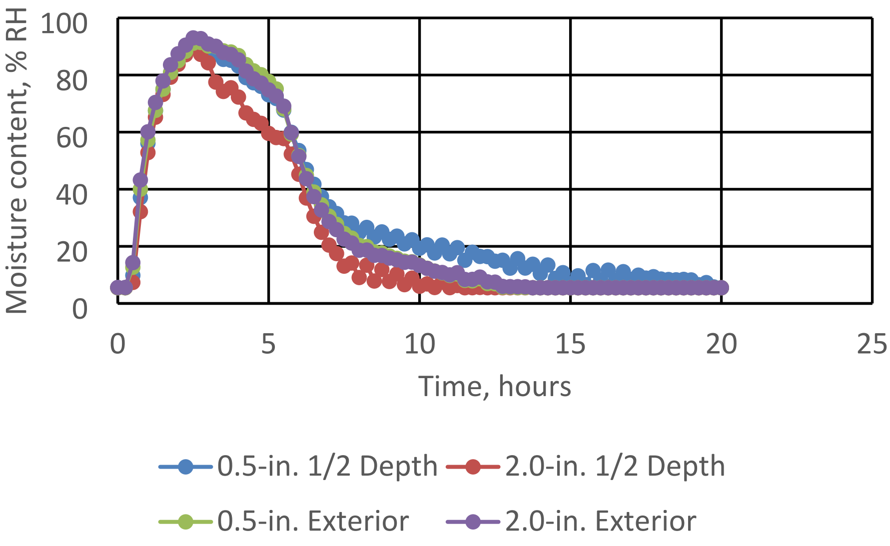

Figure 22: Moisture content measurements from moisture pin sensors located away from any penetrations (no holes).

Figure 22 depicts the average moisture content of the moisture pin sensors as a function of the sensor location (distance from the water resistive barrier penetration and the wall assembly surface that the sensor was attached) where there were no holes or penetrations in the water resistive barrier. The locations and the distance from the penetrations appear to have little impact.

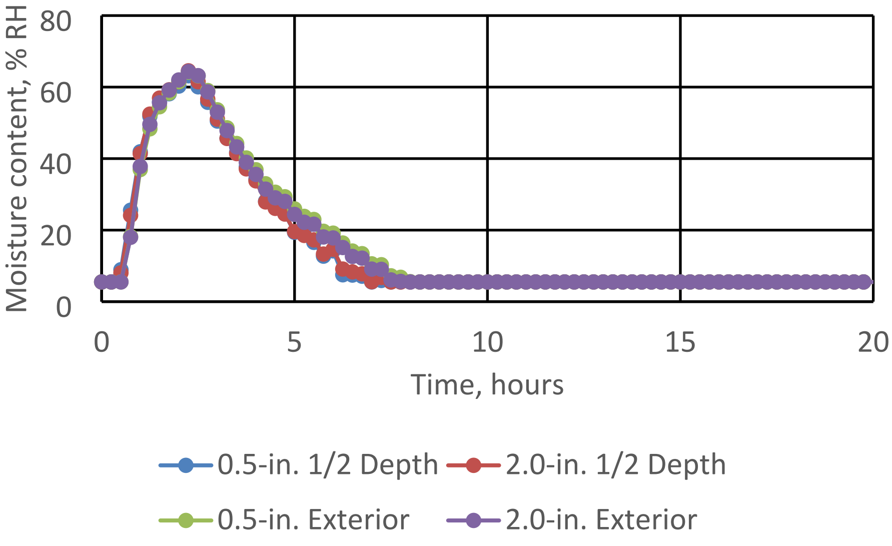

Figure 23: Moisture content measurements from moisture pin sensors located away from any penetrations (no holes) in Panel E with no spray exposure.

Figure 23 shows the outputs of the moisture pin sensors installed on Control Wall E that was not exposed to any spraying. Similar to the capacitance sensors, this data shows that the relative humidity within the laboratory space increases during the testing process and that some of the increase in panel relative humidity is due to this change in laboratory conditions

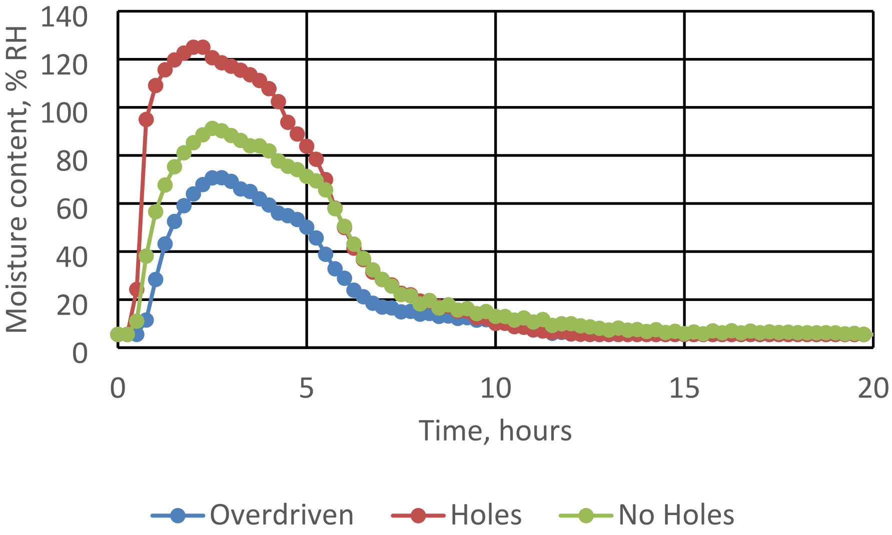

Figure 24: The average moisture content from moisture pin sensors located near all penetration types.

Figure 24 summarizes the average moisture contents measured by the moisture pin sensors as a function of the penetration type. Similar to the capacitance sensors, the sensors located near holes measure higher levels of moisture while the sensors located near overdriven fasteners are somewhat lower than those sensors near no penetrations.

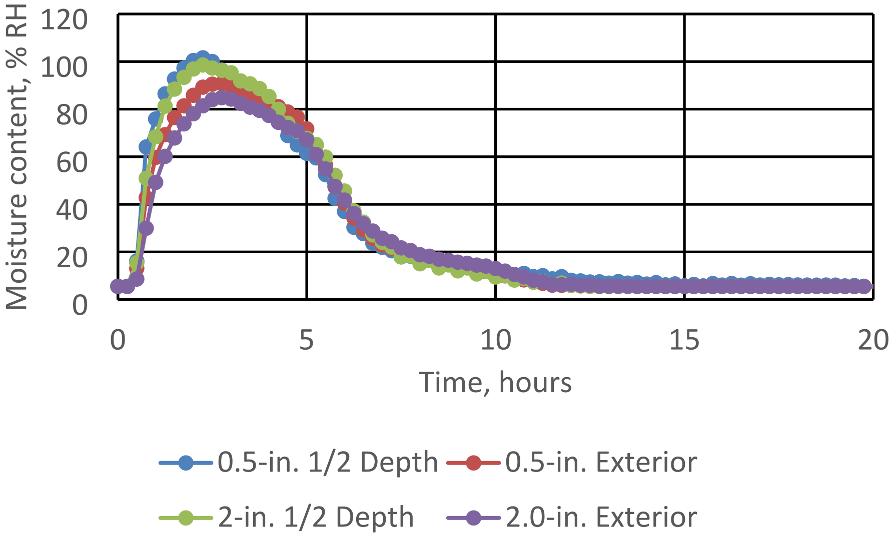

Figure 25: The average moisture content from moisture pin sensors as a function of their distance from the water resistive barrier penetration and their installed surface.

Figure 25 depicts the average moisture content of all the moisture pin sensors as a function of the sensor location (distance from the water resistive barrier penetration and the wall assembly surface that the sensor was attached) for all penetrations. In this instance, the moisture pins located at mid-depth measure a slightly higher moisture content than the exterior locations whereas the distance from the penetration appears to have little impact.

Similar data was compiled on identical panels that were exposed for a 4-hour spray exposure. The peaks in moisture contents are generally higher due to the extended exposure time and occurred at the end of the exposure time (four hours instead of two hours). During these experiments, one moisture pin sensor failed when sensing moisture near a hole in the water resistive barrier. An abbreviated summary of these data gathered during the 4-hour spray exposure are shown in Figures 25 through 26.

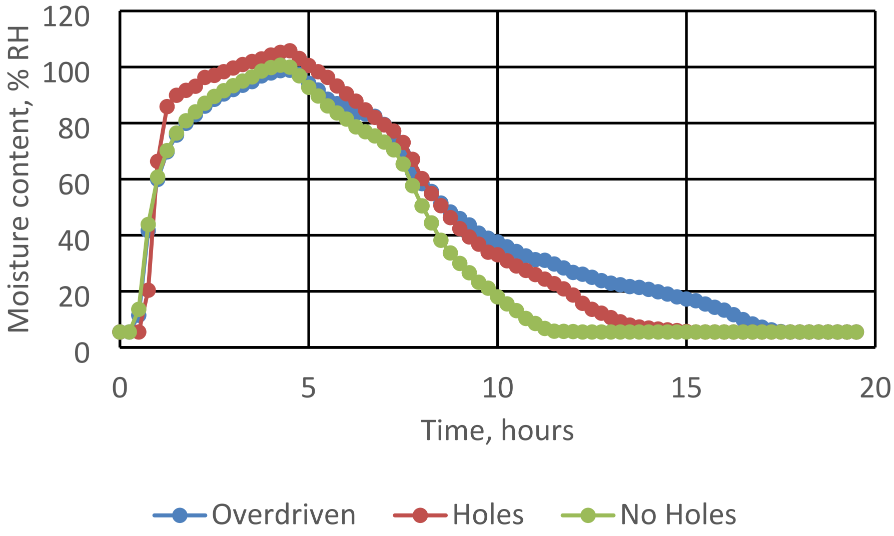

Figure 26: The average moisture content from moisture pin sensors located near all penetration types during 4-hour exposure test.

Figures 26 and 27 summarize the average moisture contents measured by the moisture pin sensors as a function of the penetration type and sensor location (distance from the water resistive barrier penetration and the wall assembly surface that the sensor was attached) for all penetrations for the 4-hour exposures, respectively. Similar to the 2-hour exposures, the sensors located near holes measure slightly higher levels of moisture, the ½ depth sensor locations sense slightly higher levels of moisture, whereas the distance from the penetration appears to have little impact.

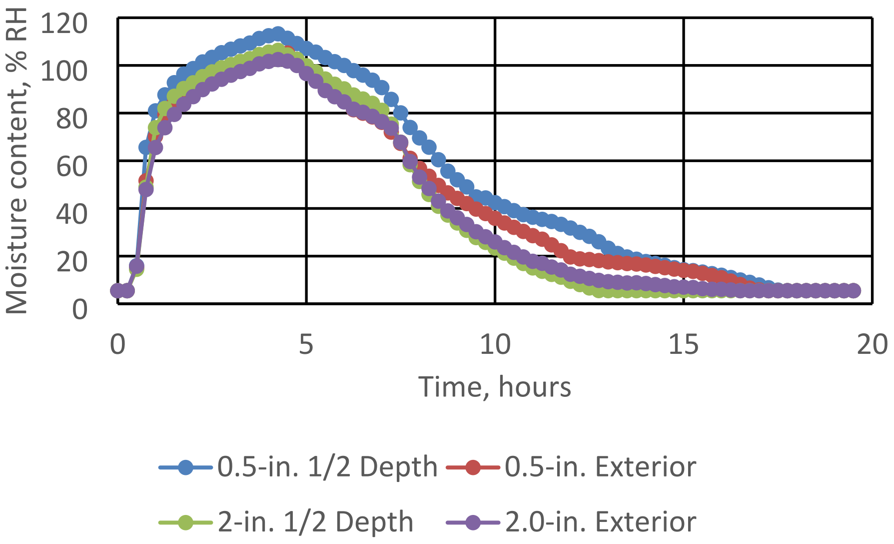

Figure 27: The average moisture content from moisture pin sensors as a function of their distance from the water resistive barrier penetration and their installed surface during 4-hour exposure test.

3. CONCLUSIONS

A family of experiments were performed to evaluate four different techniques for quantifying the moisture pickup of a wall assembly exposed to a water spray as prescribed in ASTM E331. A summary of the observations is listed below.

1. The two handheld moisture meters used in this study gave reproducible results 90 percent of the time. Data was compiled using two different operators. It was noted that the three instances where the data from the two instruments seemed to vary were all collected by one operator.
2. The electric sensor tape seems to only capable of measuring large leaks; the only instances of moisture detection occurred when the tape sensors were monitoring leaks near holes.
3. The capacitance sensors were able to track increases in moisture content during the spray exposure and the subsequent drying that occurred after the spraying was discontinued. Several of these sensors failed during testing, indicating that more care is required to protect them from coming in contact with water. The capacitance sensor data suggests that the location of the sensor with respect to its distance from the penetration and the surface on which it was mounted do not appreciably affect the measured moisture content. As anticipated, the capacitance sensors located near holes measure higher levels of moisture. Somewhat surprisingly, the sensors located near overdriven fasteners are somewhat lower than those sensors near no penetrations.
4. Outputs of the capacitance sensors installed on Control Wall E that was not exposed to any spraying shows that the relative humidity within the laboratory space increases during the testing process and that some of the increase in relative humidity sensed by the panel sensors may be due to this change in laboratory conditions.

5. The moisture pins were calibrated (see Section 2 Sensor Calibration) over the relative humidity range of 0 – 95 percent relative humidity. Data outside of this calibration range is extrapolated. Some of these extrapolations predict moisture contents in excess of 100 percent relative humidity which is obviously not plausible. If additional work is performed on this research topic, the calibration range should be extended beyond 95 percent relative humidity to include data in the capillary range as the moisture content changes dramatically within this range.
6. Similar to the capacitance sensors, the moisture pin sensors located near holes measure higher levels of moisture while the sensors located near overdriven fasteners are somewhat lower than those sensors near no penetrations. The moisture pins located at mid-depth measure a slightly higher moisture content than the exterior locations whereas the distance from the penetration appears to have little impact.

4. ACKNOWLEDGEMENTS

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