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Arnold Schwarzenegger
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BUILDING ASSEMBLIES LABORATORY EVALUATION RESULTS REPORT

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Building Assemblies Laboratory Evaluation Results

Task 3.2 Report

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(GTI Project No. 15485)

for

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Executive Summary

Overview

The overall goal of the work described in this report was to characterize the susceptibility of targeted building components and assemblies to mold growth in the presence of moisture loading conditions (e.g., high humidity, rain, dynamic conditions) in a controlled environmental setting. These evaluations provided experimental data on wall drying rates, propensity for mold growth, and performance improvements associated with innovative wall assemblies, using unique test protocols tailored to meet project goals. Laboratory evaluations under Task 3.2 were intended to provide a technical basis for demonstration home design recommendations in Tasks 3 and 4 and builder guidelines in Tasks 3 and 5.

Laboratory evaluations under Task 3.2 included the following tasks:

1. Characterize the susceptibility of targeted building components and assemblies to mold growth in the presence of moisture loading conditions (e.g., high humidity, rain, dynamic conditions) in a controlled environmental setting;
2. Measure moisture content over time of building assemblies with targeted water-resistive barrier (WRB) and insulation options when the assemblies were subjected to water intrusion events; and
3. Examine drainage capacity and susceptibility to leaks of targeted wall claddings, WRB's, and framing options when subjected to moisture loading conditions.

Susceptibility to Mold Growth Experiments

These experiments characterized the susceptibility of targeted building components and assemblies to mold growth in the presence of moisture loading conditions (e.g., high humidity, rain, dynamic conditions) in a controlled environmental setting. The baseline stucco wall assembly was a 33½" wide x 49½" high wall section with nominal 2x4 wood framing, 16" on center (with double base plate to simulate the wood/concrete foundation wall interface), three-coat stucco cladding, double layer grade D building paper, ½" OSB sheathing, compressed R-19 fiberglass insulation, and ½" interior gypsum panel. Targeted building components compared to the baseline assembly included:

- Mold-Resistant Gypsum Panels;
- Mold-Resistant Sealer; and
- Cellulose Insulation.

Wall assemblies were pre-conditioned with water from a nearby field for a period of 3 to 5 days. Pre-conditioned walls were fully encased in shrink wrap and hung from load cells. Monitoring included visual inspections of visible wall assembly surfaces to check progress of mold growth. Automated data acquisition included all moisture content parameters and changes in wall weight. Water was periodically added to the wall cavity to maintain relative humidity levels in the desired range. Heat lamps were used to drive moisture toward the interior cavity. The duration of each experiment was approximately five weeks, including pre-conditioning. Wall assemblies were then disassembled for a complete visual inspection for mold growth.

Observations from the Susceptibility To Mold Growth experiments include the following:

- For baseline construction, fiberglass insulation experienced visible mold growth on the kraft paper face as well as in the fiberglass adjacent to wood surfaces. More significant mold growth occurred on wood studs and both sides of the gypsum panel. Mold growth on OSB surfaces was visible, but less significant than growth on adjacent wood studs.

- Both types of mold-resistant gypsum panels exhibited significant resistance to mold growth compared to conventional gypsum panels, but only on the surfaces of the panels themselves. The remainder of the wall assembly experienced significant mold growth.
- The areas treated with mold-resistant sealer, as well as fiberglass adjacent to treated areas, exhibited significant resistance to mold growth compared to untreated portions of the assembly.
- Cellulose insulation absorbed and retained much more water than fiberglass insulation and main saturated relative humidity throughout the experiment. The amount of mold growth within the cellulose insulation was less than expected. Both visual inspection and lack of odor indicated little growth inside the cellulose insulation itself except at small spots, and less mold growth on other surfaces than in the other experiments.

Moisture Content Profile Experiments

The Moisture Content Profile experiments characterized the moisture content over time of selected wall assemblies, claddings, and WRB options when subject to water intrusion events. Selected wall assemblies all had OSB sheathing and included:

- Baseline Wall Assembly;
- Higher Perm Housewrap;
- High Drainage Higher Perm Housewrap;
- Exterior Insulated Finish System; and
- One-Coat Stucco.

Wall assemblies were constructed with targeted cladding and WRB options. For all moisture content profile experiments, 3½" R-13 kraft-faced fiberglass insulation was installed in each of the two wall cavities. Each wall assembly had a conventional gypsum panel painted with one coat latex primer and one coat contractor grade latex paint. Pre-conditioning protocols were similar to mold growth experiment protocols. The wall assemblies were closed with all sides except stucco cladding wrapped in plastic, and hung on load cells for the four week duration of the experiment. Automated data acquisition included all moisture content parameters and changes in wall weight. For these experiments, water was not added to the wall cavity after walls were enclosed and hung on load cells. At the end of the third week, heat lamps were directed at the interior side of the wall assembly to provide a thermal driving force for drying through the WRB and cladding.

Observations from the Moisture Content Profile experiments include the following:

- Revised protocols designed to focus wall cavity moisture flow toward the WRB and cladding were successful in providing comparative drying rate data on four different wall assemblies.
- Moisture content data for these four wall assemblies indicated higher initial and final moisture content in the two housewrap assemblies than the two exterior insulation assemblies. The different initial levels were caused by variations in pre-conditioning water levels and amounts, as well as evaporative drying during visual inspections prior to sealing and hanging the assemblies, especially the EIFS assembly. This data illustrated the challenge of providing consistent initial moisture boundary conditions in built-up assemblies, even in a laboratory environment.
- Wall assembly moisture weight profiles showed differences in evaporative drying rates for different cladding and insulation options. Both walls with exterior insulation were similar to each other and dried more slowly than the two walls with housewrap and no exterior insulation, which were also similar to each other. Heating the gypsum panel increased the drying rate slightly.

Drainage Capacity Experiments

Drainage Capacity experiments characterized the drainage capacity of selected cladding, WRB, and framing options when subjected to water intrusion between the cladding and WRB. Wall assemblies included:

- Three-Coat Stucco, Two Layers Building Paper, OSB Sheathing;
- Three-Coat Stucco with Drainage Channels, Two Layers Building Paper, OSB Sheathing;
- Three-Coat Stucco, Higher Perm Housewrap/Building Paper, OSB Sheathing;
- Three-Coat Stucco, High Drainage Housewrap/Building Paper, OSB Sheathing;
- Three-Coat Stucco, One Layer Building Paper, Open Frame (no OSB);
- Cracked Three-Coat Stucco, Two Layers Building Paper, OSB Sheathing;
- Exterior Insulated Finish System, Two Layers Building Paper, OSB Sheathing; and
- One-Coat Stucco, Exterior Insulation, Two Layers Building Paper, OSB Sheathing.

Wall assemblies were constructed with targeted cladding, WRB, and sheathing options. Interior sides of wall assemblies remained open to permit visual inspection for leaks. A 1" high metal trough with a slotted bottom opening was inserted between the cladding and WRB. Each wall assembly was hung from a load cell, and city water was fed into the trough through a flow meter and hose nozzle. For rain simulation experiments, three spray nozzles were directed at the wall assembly to saturate the front side of the cladding to determine the impact on WRB drainage capacity. Monitoring comprised manual readings of equilibrium flow rates and visual observation of drainage profiles and leaks to the interior side of the OSB sheathing or WRB. Duration of experiments for each wall assembly was approximately four hours, including setup, initial drainage capacity and leakage data collection, and supplemental drainage capacity and leakage data with rain simulation.

Observations from the Drainage Capacity experiments include the following:

- Drainage capacities of all stucco wall assembly designs with stucco adhered to the weep screed were an order of magnitude lower than for other walls with full drainage flow channels. Capillary flow through the front of the stucco dominated in these five wall assemblies, and gravity drainage only trickled at the weep screed.
- The open frame wall assembly behaved differently than the other four stucco walls. Capillary flow through the stucco face was much less than the other four walls. In this wall, the majority of the water flow leaked to the interior side of the building paper.
- The wall with two designed vertical drainage channels increased the drainage flow rate significantly compared to capillary-dominated drainage. However, capillary flow continued to dominate drainage away from the two channels.
- Two wall assemblies with designed or inadvertent gravity drainage paths had significantly higher drainage flow rates than the other walls. For the cracked stucco wall assembly, the cracks provided numerous paths for increased gravity drainage, as well as increased capillary flow into the stucco face. EIFS with designed drainage mat and weep screed increased gravity drainage capacity through the designed narrow gap between the insulation and the WRB at the drainage mat. Water was able to flow freely to the weep screed whose holes provided designed drainage functionality. Holes in weep screeds in the other walls were filled with stucco (as was the entire sloped face of the screed) and provided no gravity drainage capability.
- Restricted gravity drainage dominated by capillary flow resulted in visible leaks to the interior side of three of the five affected wall assemblies. Leaks occurred through the OSB sheathing itself, and at staple holes through the OSB. The open frame construction with a single layer of building paper exhibited the greatest amount of visible leakage, but it is not known whether there was similar leakage at the exterior side of OSB sheathing, since that surface was not visible. Neither of the high drainage capacity walls experienced any visible leaks.

Conclusions and Research Recommendations

Data collected during this research project provided evidence of the beneficial impact of mold-resistant materials on mold formation and growth, but only on the materials themselves. The experiments also provided information on drying rates and impact of thermal loading on wall cavity moisture profiles. Finally, drainage capacity experiments demonstrated the importance of providing adequate space for gravity drainage. A capillary break between the stucco cladding and WRB is required for optimal gravity drainage. Additionally, a double layer WRB is essential for stucco walls, with a sacrificial exterior layer for bond break and an interior layer for gravity drainage.

Research recommendations based on Task 3.2 laboratory evaluations focus on three major initiatives::

1. Collect and analyze laboratory and field data on root causes and consequences of building envelope failures to identify and evaluate alternative mold risk reduction strategies for homes with stucco cladding.
2. Develop and evaluate laboratory and field performance test methods for integrated cladding and wall assemblies. The test methods should be realistic and relevant, supported by field data and validated models.
3. Perform laboratory and field moisture content and drying rate measurements of new and innovative building assemblies using consensus test methods to provide additional data to validate hygrothermal models.

Task 3.2– Building Assemblies Laboratory Evaluation Results

1.0 Introduction

1.1 Background

The first technical task (Task 2) of the "Energy Efficient Mold-Resistant Building Assemblies and Construction Practices for California Homes" project was to perform a situation analysis of mold problems and state-of-the-art methods of addressing these problems in the residential new construction market in California. The overall goal of Task 2 was to identify the most challenging mold problems facing California builders and recommend potential solutions for detailed laboratory evaluation and possible use in demonstration homes to be built by the two participating builders. Based on discussions with Commission staff, the project team, Project Advisory Committee (PAC) members, and building industry experts, the highest value areas for this project to address with laboratory testing were water-resistive barrier (WRB) design options (especially around windows), concrete slab installation practices and materials (especially vapor retarder location and fill materials), and drying times for built up wall assemblies.

This focus was intended to provide defensible, repeatable results that advance the understanding of overall wall system performance. Components and subsystems have been tested for mold growth and impact of moisture by building scientists, universities, and manufacturers. The recommended focus built on that testing to provide a better understanding of the behavior of the entire wall assembly as well as collect unique data on the performance of wall cavities and materials as a part of a complete assembly. This approach also allowed flexible and innovative configurations of materials and installation methods to be tested using a combination of available test protocols and new test methods developed specifically to meet project goals.

Specific laboratory tests and protocols developed in conjunction with project team members, builders, PAC members, Commission staff, and industry consultants were summarized in the Laboratory Evaluation Test Plan (Task 3.1). The test plan provided the initial framework for laboratory evaluations described in this report. Based on experience gained during the performance of laboratory tests, the project team updated test goals, protocols, facilities, and test matrix to maximize the value of each test.

1.2 Goal

The overall goal of Task 3 was to perform a systematic laboratory evaluation of conventional and innovative residential building materials, assemblies, and construction practices identified in Task 2. Task 3 laboratory evaluations were designed to provide experimental evidence of moisture loading, propensity for mold formation, and potential performance improvements associated with innovative building assemblies and construction practices.

The goal of Task 3.2 was to test baseline and innovative building assemblies identified in Task 2.4 in accordance with the Laboratory Test Plan developed in Task 3.1. To meet this goal, the project team characterized the susceptibility of targeted building components and assemblies to mold growth in the presence of moisture loading conditions (e.g., high humidity, rain, dynamic conditions) in a controlled environmental setting at GTI's laboratory facilities. These evaluations provided experimental data on wall drying rates, propensity for mold growth, and performance improvements associated with innovative wall assemblies, using unique test protocols tailored to meet project goals. Laboratory evaluations under Task 3.2 were intended to provide a technical basis for demonstration home design recommendations in Tasks 3 and 4 and builder guidelines in Tasks 3 and 5.

1.3 Scope

Laboratory evaluations under Task 3.2 included the following tasks:

1. Characterize the susceptibility of targeted building components and assemblies to mold growth in the presence of moisture loading conditions (e.g., high humidity, rain, dynamic conditions) in a controlled environmental setting;
2. Measure moisture content over time of building assemblies with targeted WRB's and insulation options when the assemblies were subjected to water intrusion events; and
3. Examine drainage capacity and susceptibility to leaks of targeted wall claddings, WRB's, and framing options when subjected to moisture loading conditions.

1.4 Approach

Task 3.2 involved three categories of experiments, each with different protocols to achieve task goals:

- Susceptibility to Mold Growth
- Moisture Content over Time
- WRB Drainage Capacity

Table 1 lists the building assemblies evaluated in these experiments. Wall assemblies included 3-coat stucco cladding, 1-coat stucco cladding with exterior insulation, and Exterior Insulation Finish System (EIFS) cladding with drainage mat. Structural framing options included open-frame construction and oriented strand board (OSB) sheathing. WRB's included asphalt saturated building paper and non-perforated higher permeance housewrap.

Initial moisture content and mold growth experiments were conducted in accordance with the Task 3.1 experiment plan. For moisture content and drying rate experiments, a specified quantity of water was poured into the wall cavity with all edges sealed to characterize drying time toward the interior and exterior wall surfaces. Additional water was poured into the wall cavity to simulate repeated water intrusion events, and by simulating solar and rain effects with heat lamps and spray nozzles. Protocols

Table 1 List of Building Assemblies for Laboratory Evaluation

Building Assembly	Description
Baseline Stucco Wall	Three-coat stucco, two-ply grade D 60 minute building paper over OSB sheathing, or one-ply grade D 60 minute building paper over open frame, 2x4 Wood Studs with kraft-faced R-13 fiberglass batt insulation, ½" gypsum panel, latex primer and finish coat
- High/Low Drainage Openings	Baseline with high/low drainage openings.
- Higher Perm Housewrap	Baseline with DuPont Tyvek® HomeWrap™ for inner layer
- High Drainage Housewrap	Baseline with DuPont Tyvek® StuccoWrap™ for inner layer
- One Coat Insulated Sheathing	Baseline with one coat, insulated sheathing, no drainage channel
- EIFS	Baseline with Exterior Insulation Finish System
- Cellulose Insulation	Baseline with cellulose instead of fiberglass insulation
- Anti-Microbial Gypsum Panel	Baseline with USG Humitek™ gypsum panels
- Fiberglass Gypsum Panel	Baseline with GP DensArmor™ gypsum panels
- Mold Resistant Sealer	Baseline with Foster® 42-42™ mold-resistant sealer

and instrumentation associated with these experiments relied on past efforts at other research organizations, but for the most part they were unique to this project to meet specific task goals. It was expected that this experimental sequence would also facilitate mold growth in susceptible assemblies.

Table 2 describes the wall assembly construction sequence for each type of cladding. GTI staff constructed wall frames and applied the selected WRB to the frame or sheathing. A professional stucco contractor installed metal lath and all stucco and EIFS cladding.

The initial moisture content and mold growth protocols failed to differentiate component and wall assembly mold growth performance adequately. Nor did the protocols sufficiently control boundary layers for use with moisture transport models. The protocols were substantially modified based on consultation with PAC members and building scientists with expertise in moisture loading and mold growth experiments. Special guidance was provided by Anton TenWolde from USDA Forest Products Laboratory, John Straube and Chris Schumacher from the University of Waterloo, and Mark Bomberg from Syracuse University.

The revised protocols were designed to provide more suitable conditions for significant mold growth and comparative drying rates for the WRB options evaluated. For mold growth evaluations, the wall assemblies were fully encased in low permeance plastic (shrink wrap) to maintain high moisture content for an extended period. For wall drying experiments, five of the six sides were encased in plastic to bias vapor flow toward the WRB side. The revised protocols were more successful in meeting task goals.

For drainage capacity experiments, water was discharged through a hose nozzle at a controlled and metered flow rate into a 1" high trough inserted at the top of the wall assembly to measure the equilibrium drainage rate. The trough drained the metered water flow into the wall assembly between the WRB and stucco. Water flow rate for each assembly was adjusted to maintain approximately ½" water level in the trough for 30 minutes. Equilibrium drainage rate and visual evidence of leakage through the WRB toward the interior side of the assembly were noted.

Table 2 Wall Cladding Construction Sequence

Stucco Type	Construction Steps
3-Coat Stucco	Staple Lath to Frame Members (Open Frame) or Sheathing (½" OSB) Apply ⅜" Scratch Coat; Cure for 2 Days; Apply ⅜" Brown Coat; Cure for 5 Days; Apply ⅛" Finish Coat; Cure for 5 Days
1-Coat Stucco	Install 1" Polystyrene Insulation with Taped Seams Over WRB Staple Lath to Frame Members (Open Frame) or Sheathing (½" OSB) Apply ⅜" Base Coat; Cure for 2 Days; Apply ⅛" Finish Coat; Cure for 5 Days
Exterior Insulation Finish System (EIFS)	Install Back-Wrap and Edge-Wrap Mesh over WRB, Folded Install 1" Polystyrene Insulation with Taped Seams Over WRB Fold Mesh over Insulation and Mechanically Fasten to Sheathing Apply ⅛" Base Coat over Insulation and Mesh; Cure for 2 Days Apply ⅛" Finish Coat; Cure for 2 Days

1.5 Wall Assembly Construction

For stucco wall assembly experiments, 33½” wide x 49½” high wall sections were constructed using nominal 2” by 4” wood framing, 16” on center, with double base plate to simulate the wood/concrete foundation wall interface, stucco cladding (3-coat, 1-coat with exterior insulation, or EIFS), double layer grade D building paper, ½” OSB sheathing or open frame, cavity insulation, and ½” gypsum panels (Figure 1).

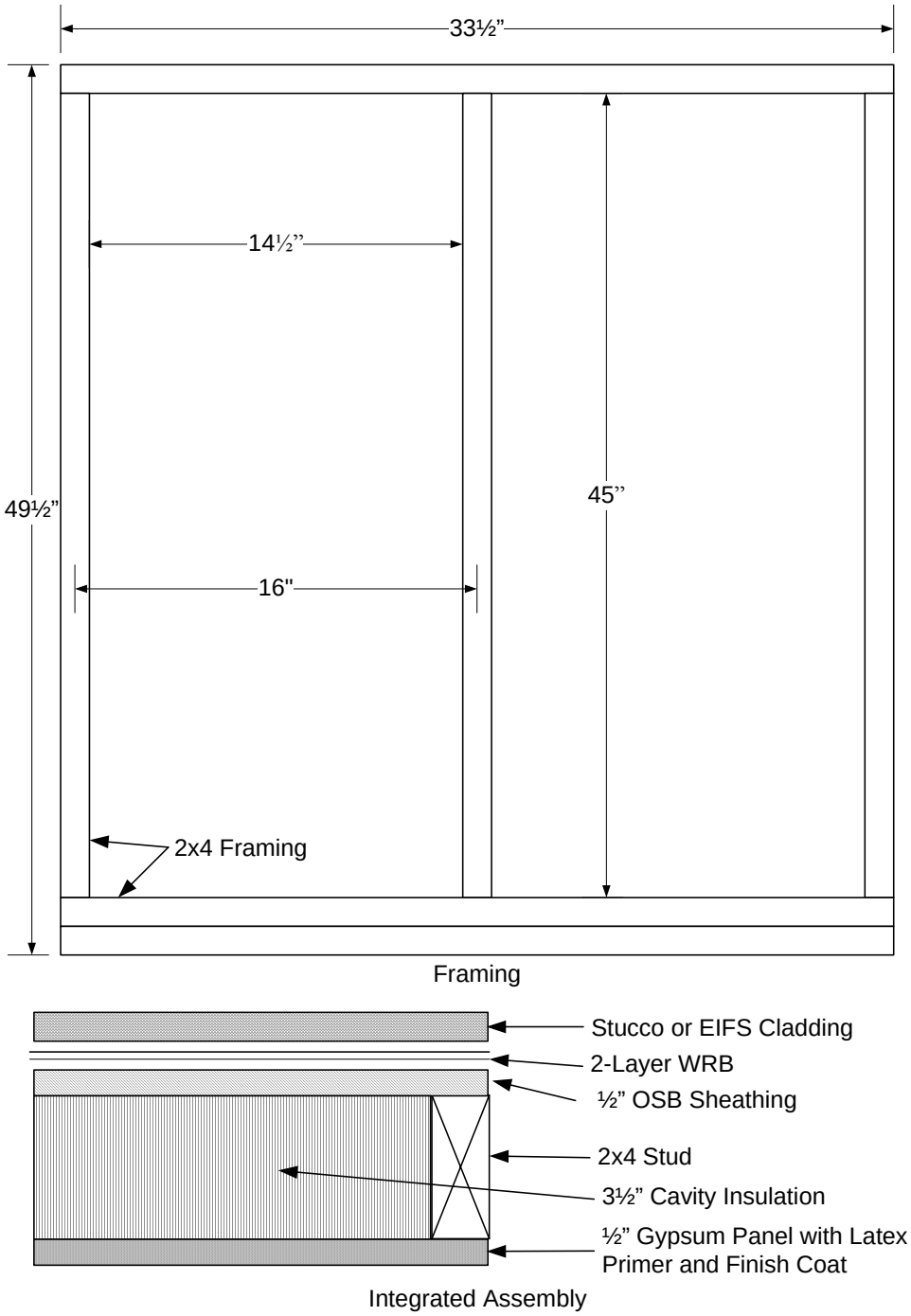


Figure 1 Typical Wall Assembly Construction

1.6 Data Acquisition System

The automated DAS for building assembly experiments was a Campbell Scientific CR10X datalogger with two 64 channel MUX's, power supply, battery backup, and Ethernet access (Figure 2). The DAS and related software were designed and installed by Balanced Solutions to meet on project goals.

Moisture content sensors included temperature, relative humidity, moisture content, and wood temperature. Temperature and relative humidity sensors were thermistors and thin film capacitance sensors encased in Tyvek® sheathing (Figure 3). Resistance moisture pins and wood temperature thermistors (Figure 4) were designed and fabricated for this project by Balanced Solutions, Inc. Table 3 lists sensor codes to distinguish sensor locations in each assembly. Figure 5 shows sensor locations for all wall assemblies except the mold-resistant sealer assembly. Moisture pins were located in treated and untreated sections in that assembly (Figure 6).

Two load cell fixtures were designed and constructed at GTI's laboratory facilities to provide precise measurements of wall assembly weight (Figure 7). Each fixture included:

- Wood posts for pivot bearing, embedded in concrete casing.
- Pillow block pivot bearing and metal counterweight bar with counterweights.
- Compression load cell (0-25 lb.) attached to wood frame.
- Adjustable wall hanging clips.
- Data acquisition wiring harness and punchdown block.

Wall assemblies were hung from each fixture and counterweights added to provide approximately 5 lb. net weight on the compression load cell when dry.

Table 3 DAS Sensor Codes

Measurement Value	Location in Wall	Location in Layer	Vertical Location
T-Temperature	C-Stud Space	E-Exterior	T-Top
M-Moisture Content	D-Framing	I-Interior	U-Upper
R-Relative Humidity	E-Sheathing	N-Interstitial	M-Middle
			L-Lower
			B-Bottom

Figure 2 Datalogger for Wall Weight and Moisture Content Measurements

Figure 3 Thermistor and Relative Humidity Sensor Installed in Insulation

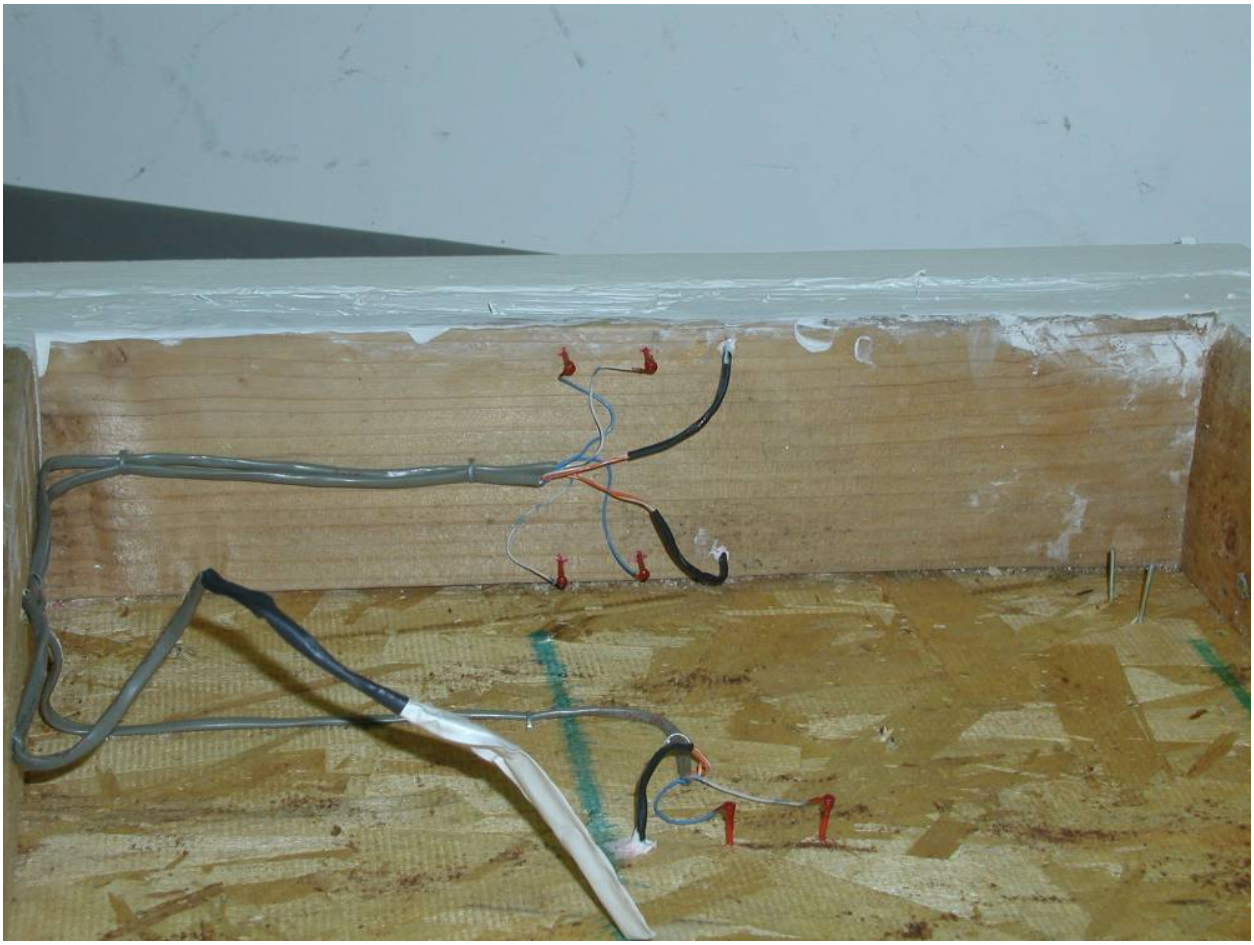


Figure 4 Moisture Pins and Thermistors Installed in Studs and OSB Sheathing

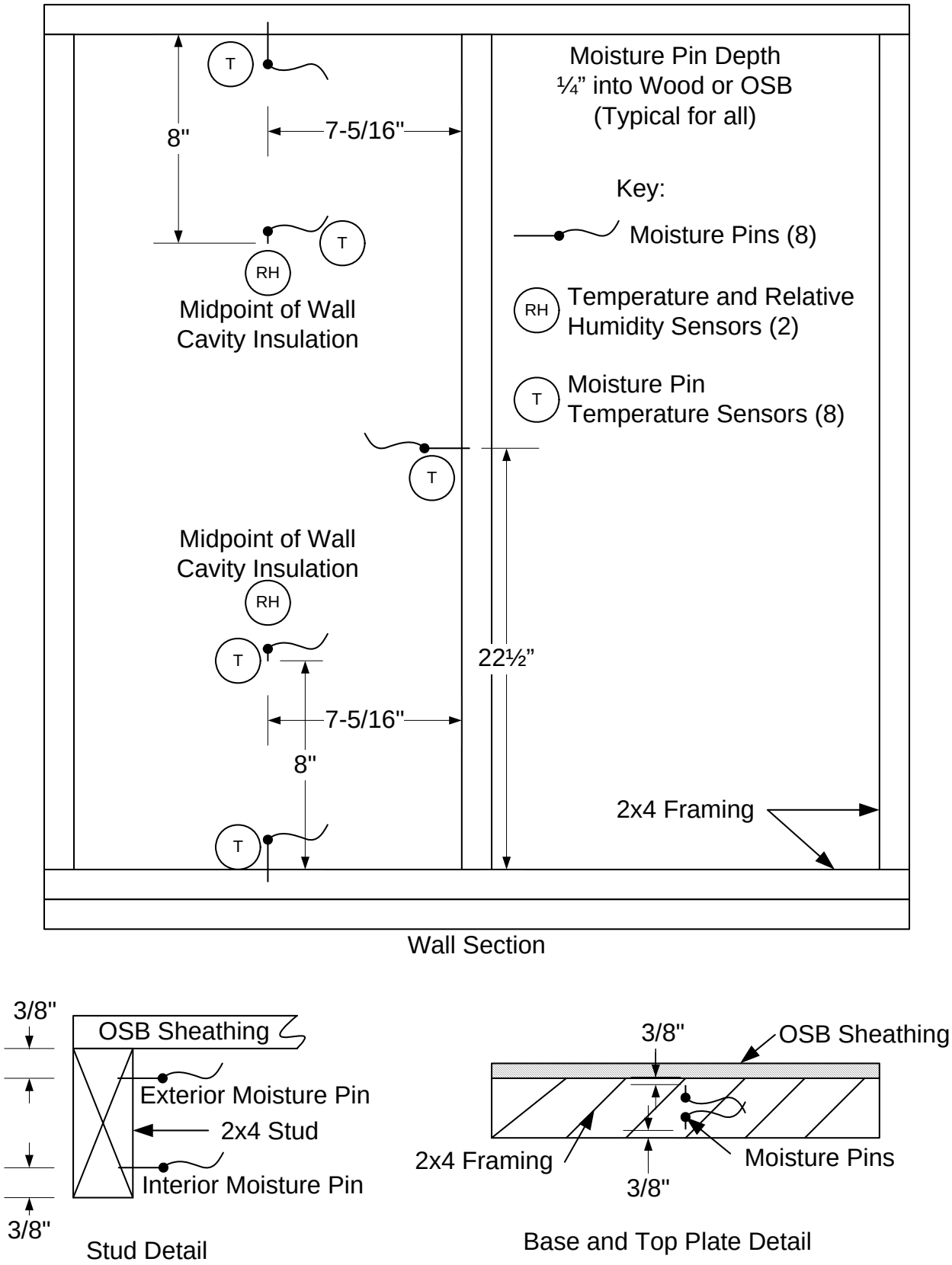


Figure 5 Wall Assembly DAS Sensor Locations

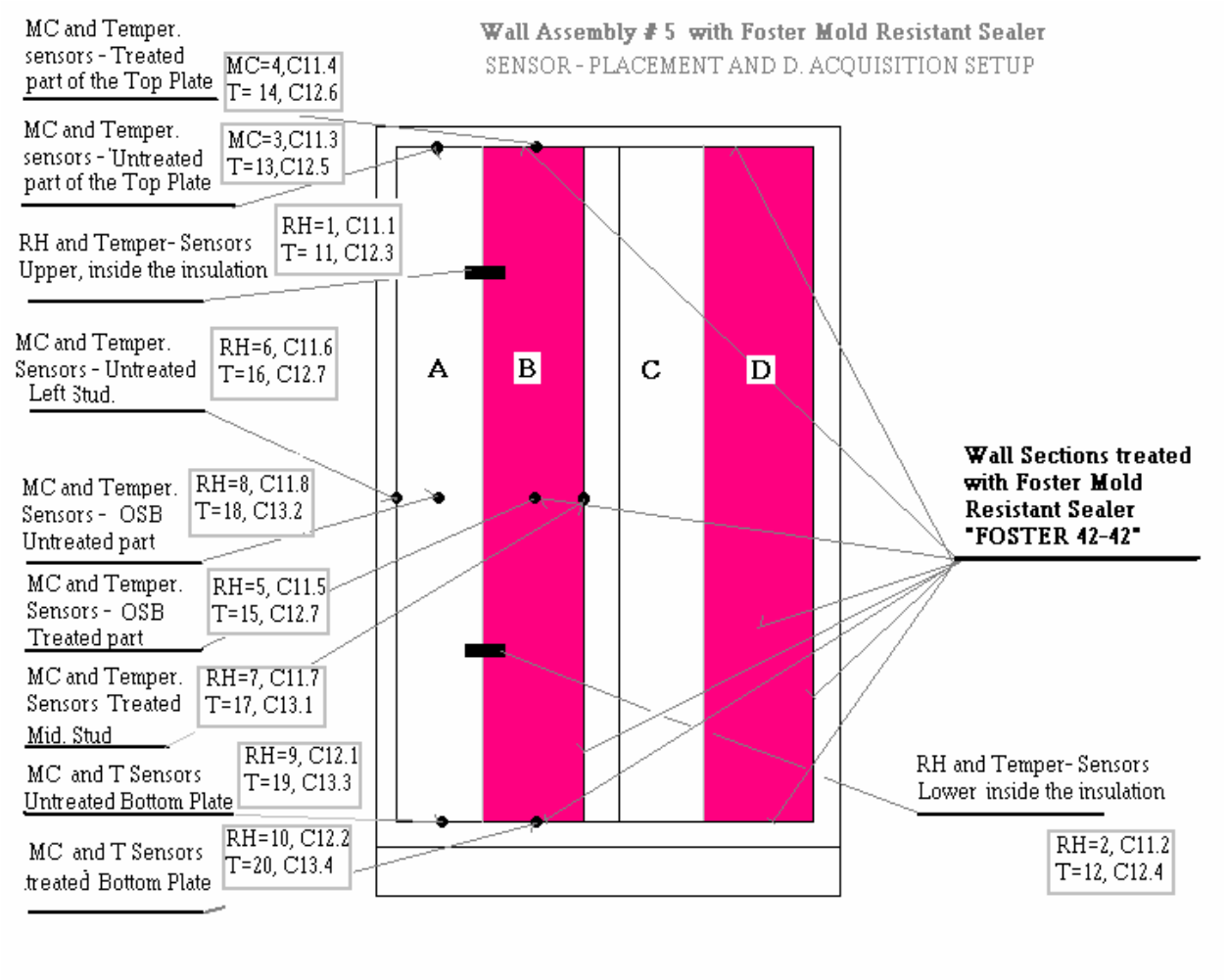


Figure 6 Wall Assembly DAS Sensor Locations for Mold-Resistant Sealer Assembly

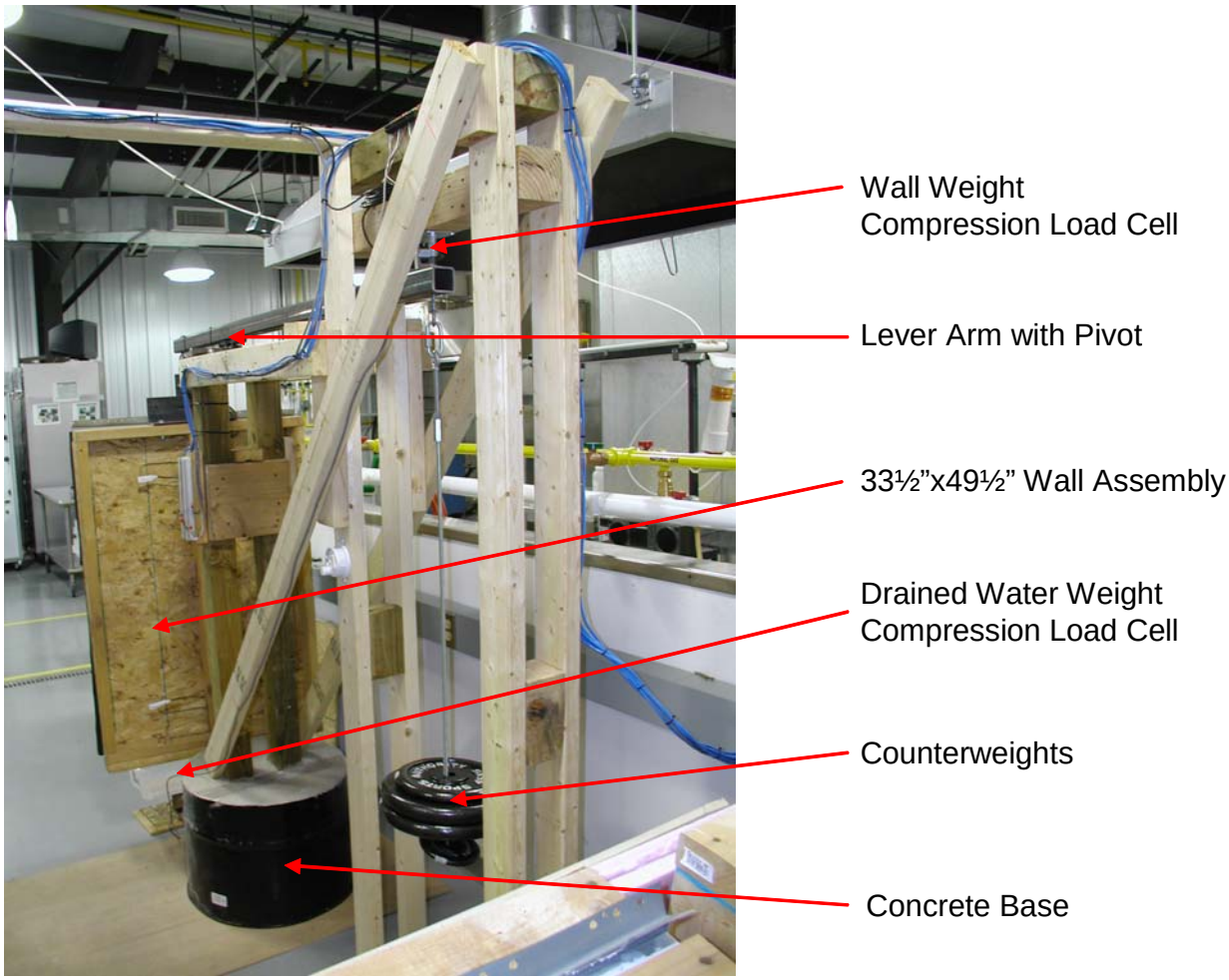


Figure 7 Wall Weight Load Cell Apparatus

2.0 Susceptibility to Mold Growth Experiments

2.1 Goal

The goal of the Susceptibility to Mold Growth experiments was to compare the susceptibility to mold growth of conventional wall assemblies and mold-resistant materials and treatments.

2.2 Scope

The scope of these experiments was to characterize the susceptibility of targeted building components and assemblies to mold growth in the presence of moisture loading conditions (e.g., high humidity, rain, dynamic conditions) in a controlled environmental setting. Targeted building components included:

1. Baseline Fiberglass Insulation;
2. Mold-Resistant Gypsum Panels;
3. Mold-Resistant Sealer; and
4. Cellulose Insulation.

2.3 Approach

The initial approach used for the baseline wall assembly was to pour a specified quantity of water (e.g., 1 pint) into a ½" diameter hole drilled into the 2x4 wood frame at the top of the wall assembly to simulate a water intrusion event. Caulk was applied to wood seams in an effort to make the wood frame/wall interface water-tight. Water pours were repeated at intervals based on wall cavity moisture content and relative humidity in an effort to provide long term relative humidity and temperature conditions considered conducive to mold formation and growth. The wall assemblies were fastened to the counterbalanced compression load cell in each of two stations to measure changes in wall weight over time. Infrared heat lamps and water sprayed on stucco wall surfaces were used to simulate thermal cycling and rain events. This approach was intended to permit both drying rate measurements and mold growth experiments to occur simultaneously and minimize the number of weeks necessary to perform each set of experiments.

This procedure resulted in mold growth predominantly at the base plate and not on the gypsum panels or insulation. Poured water also leaked at an uncontrolled rate after hanging the wall assembly. Heat lamp and spray protocols did not provide suitable boundary conditions to be of value to either wall drying or as inputs to hygrothermal models. This overall approach was not considered suitable to meet experiment goals. Revised experimental protocols described below were subsequently applied to targeted wall assemblies to address these issues. The revised procedures were much more effective in generating mold growth in susceptible assemblies and met experiment goals for the targeted wall assemblies.

2.4 Protocols

Experimental protocols were designed to allow exploration of a number of hypotheses regarding mold formation and growth on wall assemblies, including:

- Mold growth occurs readily with a suitable food source and favorable environmental conditions.
- Water intrusion events in wall cavities provide favorable conditions for mold growth.
- Cellulose materials (wood, OSB, paper, insulation) provide a suitable mold food source.
- Dirt or construction dust on fiberglass insulation provides a suitable mold food source.
- Mold-resistant materials and coatings are effective at delaying mold growth on treated areas or materials.
- Wall assemblies subjected to water intrusion events will not dry out quickly enough to avoid mold growth.

2.4.1 Construction

Exterior edges of the wood frames for all experiments were caulked and sealed with 3 coats of elastomeric paint to minimize leakage during pre-conditioning (Figure 8).

For mold-resistant gypsum panel experiments, 6" R-19 kraft-faced fiberglass insulation was compressed into the 3½" cavity for increased initial water loading. Each wall assembly had 4 vertical gypsum panel sections painted with one coat latex primer and one coat contractor grade latex paint, with edges sealed with Tyvek® tape (Figure 9). Two sections were conventional gypsum panels, and 2 sections were mold-resistant panels. Panels were alternated to provide an interior and exterior stud exposure for the conventional and mold-resistant panels.

For the mold-resistant sealer experiment, 6" R-19 kraft-faced fiberglass insulation was compressed into the 3½" cavity for increased initial water loading. The wall assembly had a conventional ½" gypsum panel painted with one coat latex primer and one coat contractor grade latex paint, with edges sealed with Tyvek® tape. The wall cavity was divided into four sections. Two sections were untreated studs and OSB, and 2 sections were sprayed with mold-resistant sealer (Figure 10). Sections were alternated to provide an interior and exterior stud exposure for the treated and untreated areas.

For the cellulose and fiberglass insulation experiment, the wall assembly had a conventional ½" gypsum panel painted with one coat latex primer and one coat contractor grade latex paint, with edges sealed with Tyvek® tape. The wall cavity was divided into two sections. One section had 3½" R-13 kraft-faced fiberglass insulation. The other section had loose-fill cellulose insulation applied to achieve approximately 3.5 lb. per ft^3 to minimize sagging when wet. The two sections provided an interior and exterior stud exposure for each type of insulation (Figure 11).

2.4.2 Installation and Monitoring

Wall assemblies were laid flat with stucco cladding side down. Water collected from a local field was poured into the wall assembly to a depth of ¼" to soak the OSB for a period of 3 to 5 days, replenishing as necessary (Figure 12). Residual water was drained, and moisture pins were inserted into wood and OSB for moisture content measurement. Sufficient water was poured by hand into the insulation (Figure 13) to wet but not compress the insulation. Insulation was placed into wall cavities and relative humidity sensors were inserted mid-depth into the insulation. Kraft paper was sprayed with water to wet the outer surface (Figure 14). Gypsum panel sections were sprayed with water to wet the back sides only, and installed with screws and washers to allow non-destructive inspection. Edges were sealed with Tyvek® tape. Wall assemblies were wrapped in shrink wrap plastic, except the stucco face, and flipped over, with gypsum panel side now facing the floor. Wall assemblies remained in this configuration for a period of 5 days to pre-condition the insulation and gypsum panels. Walls were opened for visual inspection to check for mold growth and uniformity of wetting. The wall assemblies were closed, fully wrapped in plastic, and hung on load cells for the four week duration of the experiment (Figure 15).

Monitoring included visual inspections of visible wall assembly surfaces to check progress of mold growth. Automated data acquisition included all moisture content parameters and changes in wall weight. Water was periodically added to the wall cavity to maintain relative humidity levels in the desired range. Heat lamps were used to heat the cladding and drive moisture toward the interior cavity and gypsum panels (Figure 16). For the mold-resistant sealer experiment, the wall was turned the other way, and the gypsum panel was heated to drive wall cavity moisture toward the sheathing. The goal of these combined protocols was to provide favorable conditions inside the cavity for mold growth.

Experiments were concluded based on visual observation of sufficient mold growth on the gypsum panels. The duration of each experiment was approximately five weeks, including pre-conditioning. Wall assemblies were then disassembled for a complete visual inspection for mold growth (Figure 17).

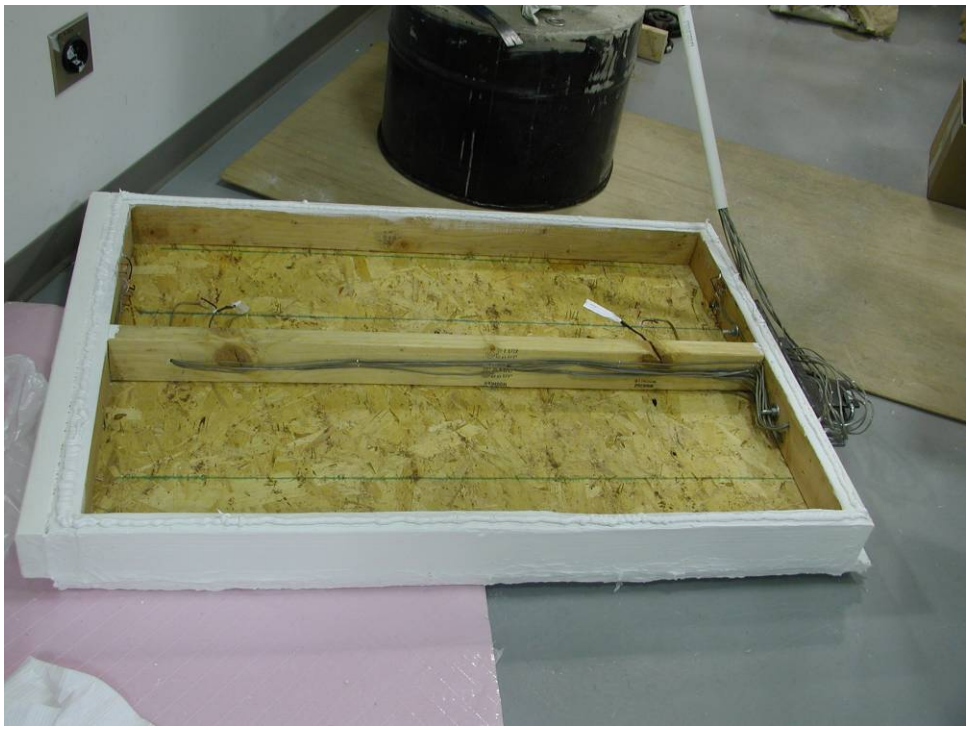


Figure 8 Elastomeric Coating for Pre-Conditioning

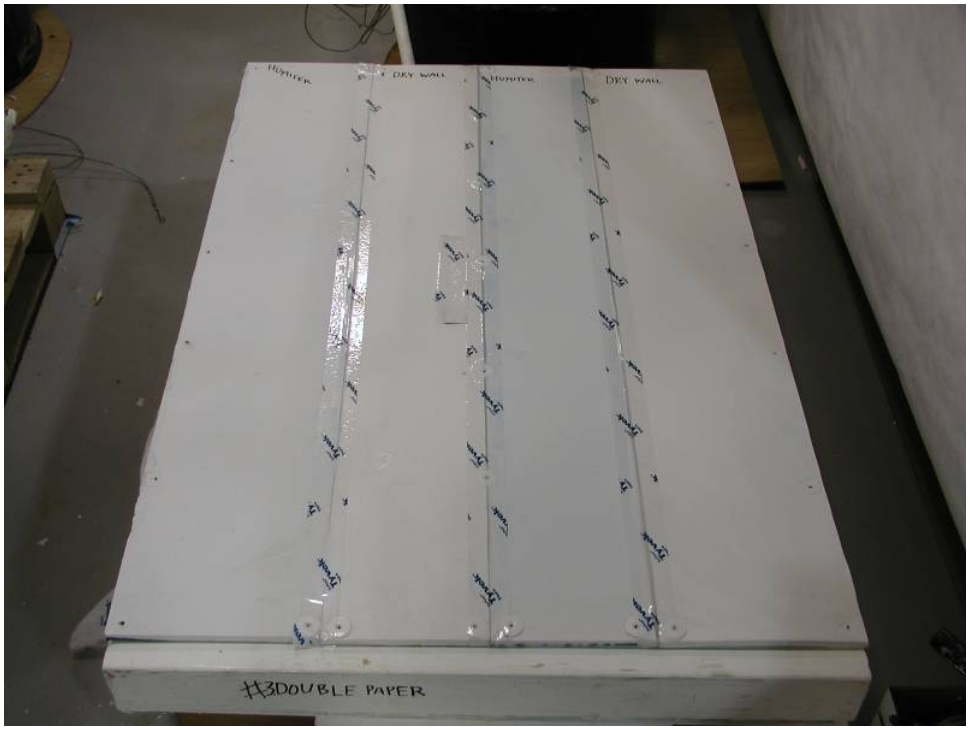


Figure 9 Gypsum Panels Sealed and Taped

Figure 10 Application of Mold-Resistant Sealer

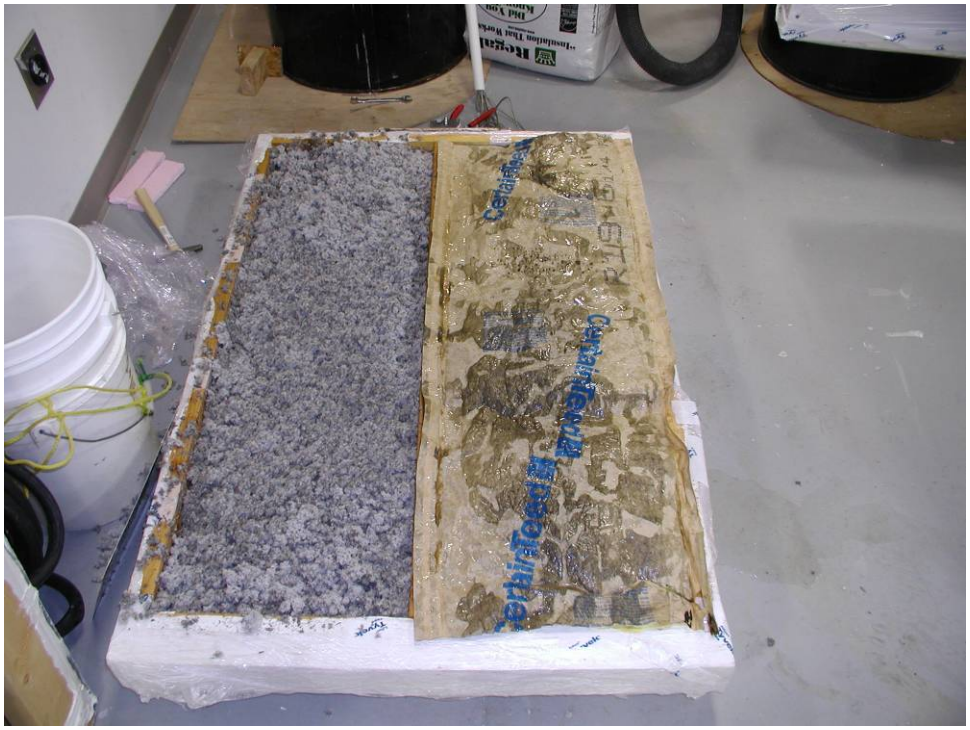


Figure 11 Cellulose and Fiberglass Insulation in Wall Cavity

Figure 12 Water Poured into Wall Cavity to Pre-Condition OSB and Studs

Figure 13 Pre-soaking Fiberglass Insulation

Figure 14 Pre-soaked Fiberglass Insulation Installed in Wall Cavity

Figure 15 Walls Wrapped in Plastic, Hung from Load Cell Apparatus

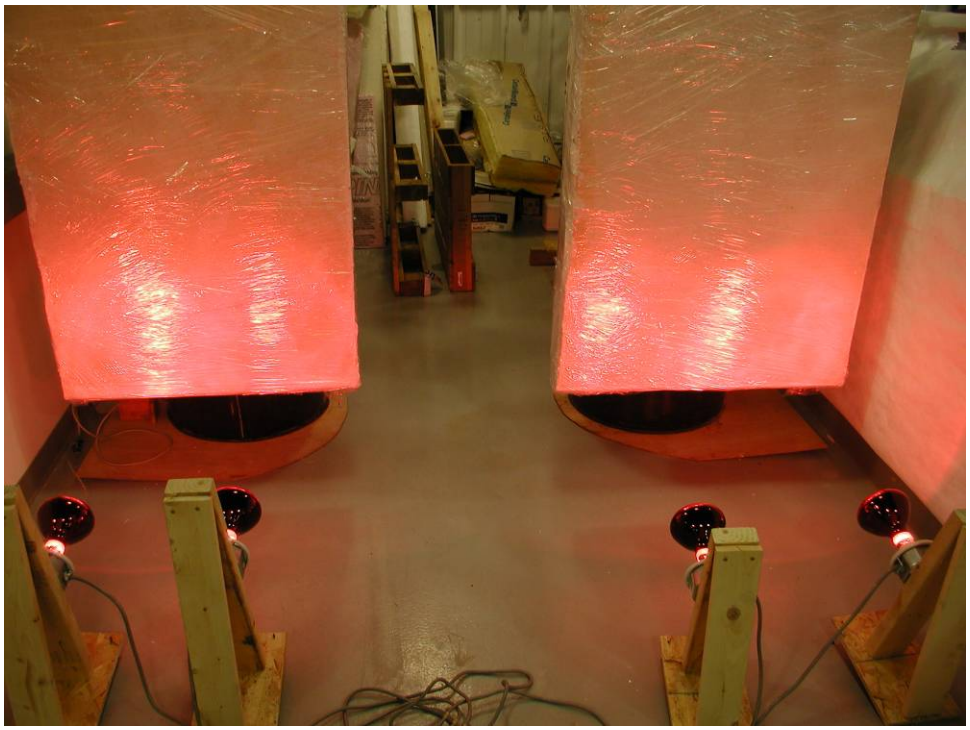


Figure 16 Thermal Loading with Heat Lamps

Figure 17 Disassembly for Final Mold Growth Inspection

2.5 Observations

Initial protocols provided some useful information on wall moisture weight (Figure 18), moisture content (Figure 19), and associated mold growth for baseline wall assemblies. However, using these protocols, relative humidity could not be maintained at high enough levels to promote mold growth, even with periodic water pours (Figure 20).

Revised protocols were more successful in providing suitable conditions for differential mold growth on various surfaces. With the revised protocols, wood and OSB moisture content ranged from 20 to more than 35% (well beyond the upper calibration limit for moisture pins) throughout the experiment period for all experimental wall assemblies(Figures 21 through 24). Periodic water pours were successful in maintaining coincident relative humidity at or near saturated conditions (Figures 25 through 28). Wall weight profiles show the effect of periodic water pours on incremental assembly weight (Figures 29 though 32). In general, the experiments validated initial hypotheses. Cellulose insulation had much less mold growth than initially expected. Successfully growing mold was also very challenging even with seemingly favorable conditions and food sources. The following sections provide more detailed observations for each experiment.

Figure 18 Baseline Wall Assembly Moisture Weight Profile Using Initial Protocol

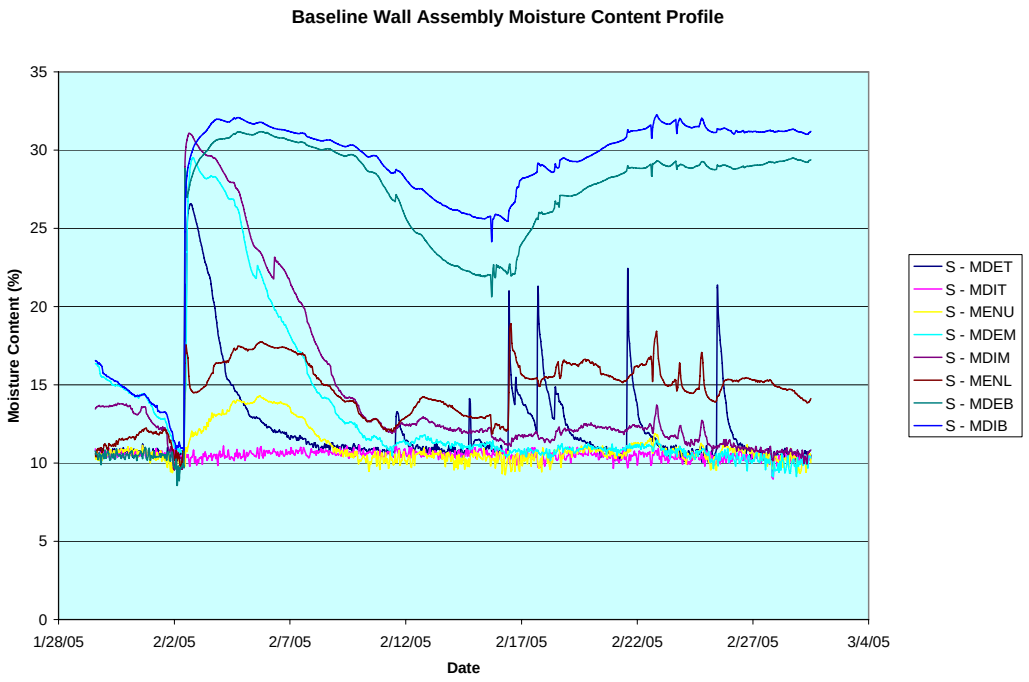


Figure 19 Baseline Wall Assembly Moisture Content Profile Using Initial Protocol

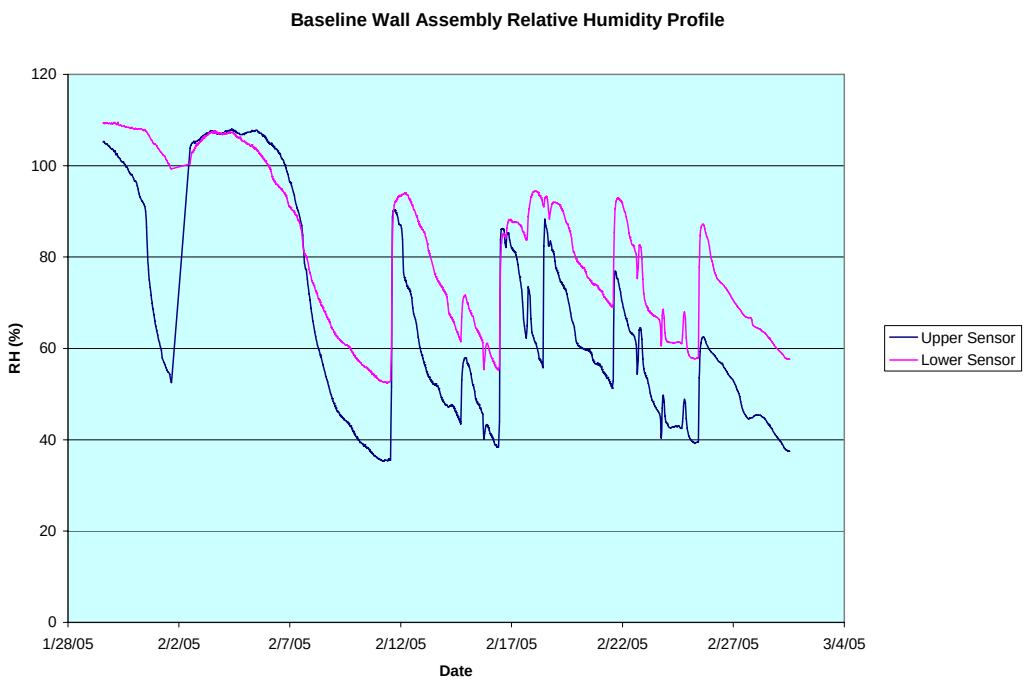


Figure 20 Baseline Wall Assembly Relative Humidity Profile Using Initial Protocol

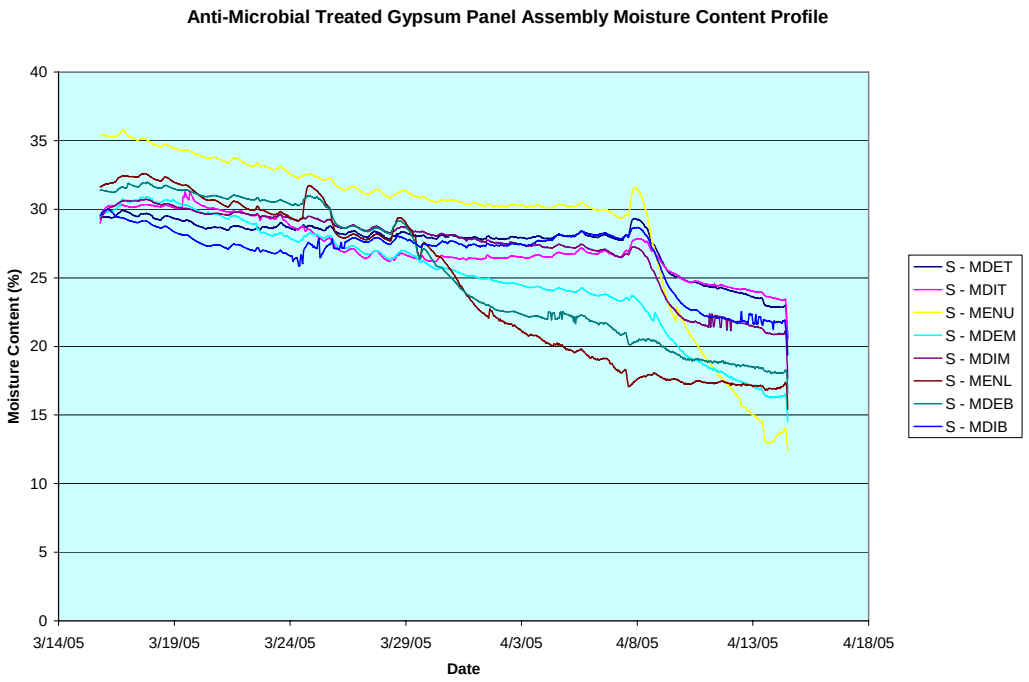


Figure 21 Anti-Microbial Treated Gypsum Panel Assembly Moisture Content Profile

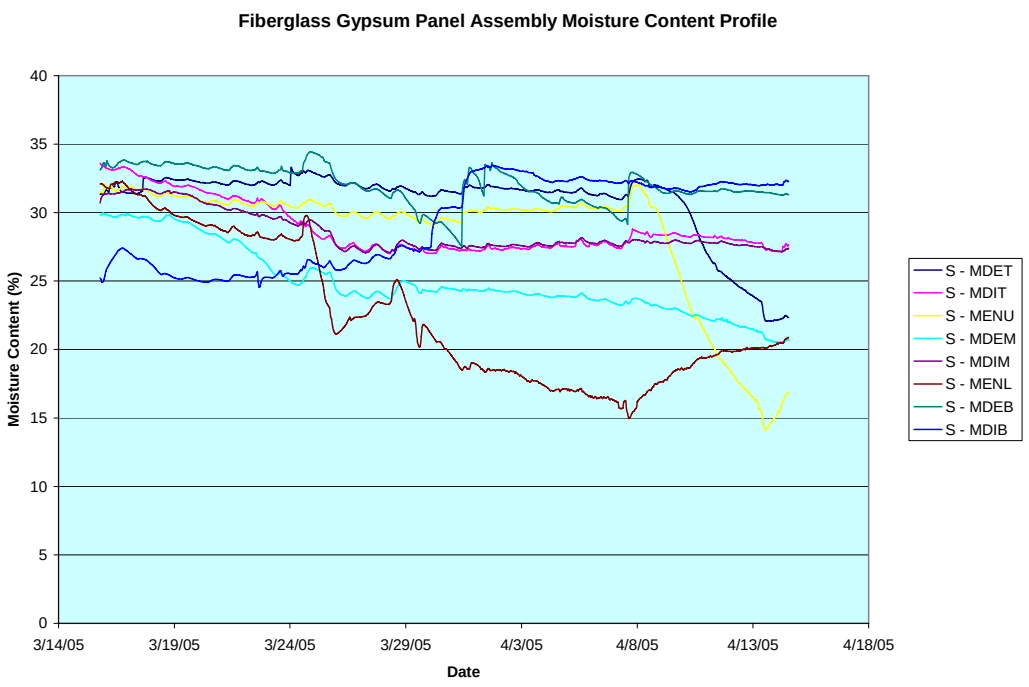


Figure 22 Fiberglass Gypsum Panel Assembly Moisture Content Profile

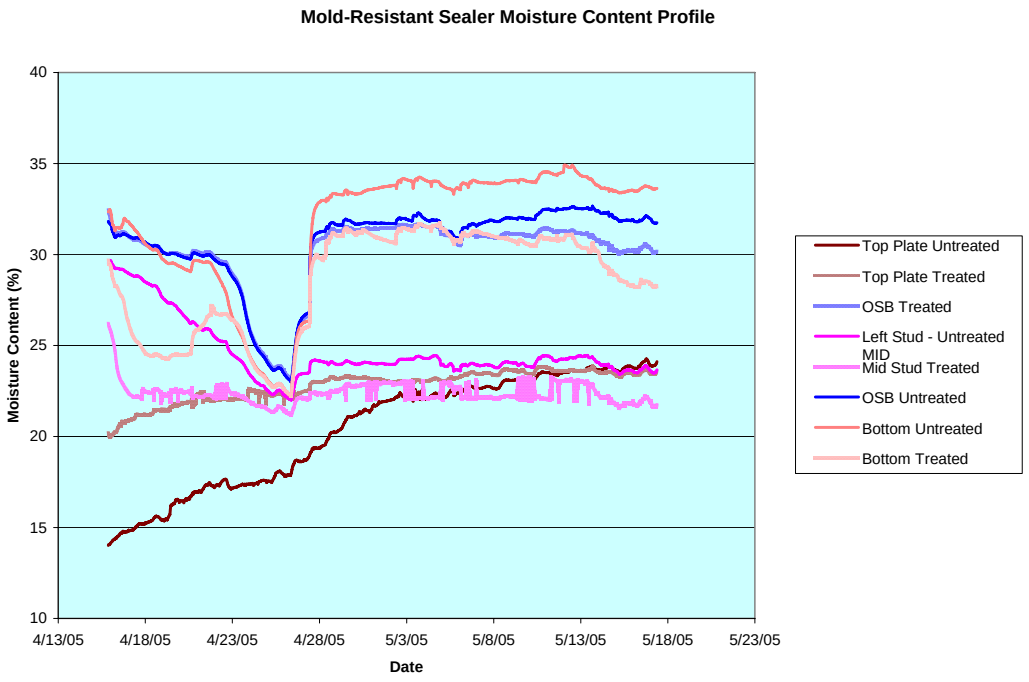


Figure 23 Mold-Resistant Sealer Assembly Moisture Content Profile

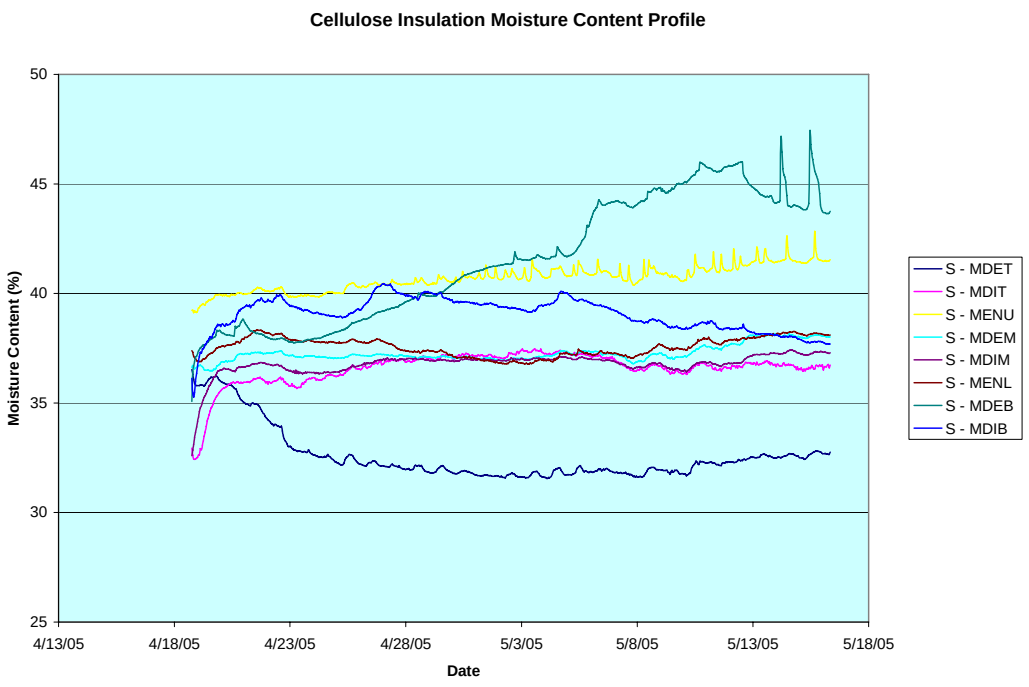


Figure 24 Cellulose Insulation Assembly Moisture Content Profile

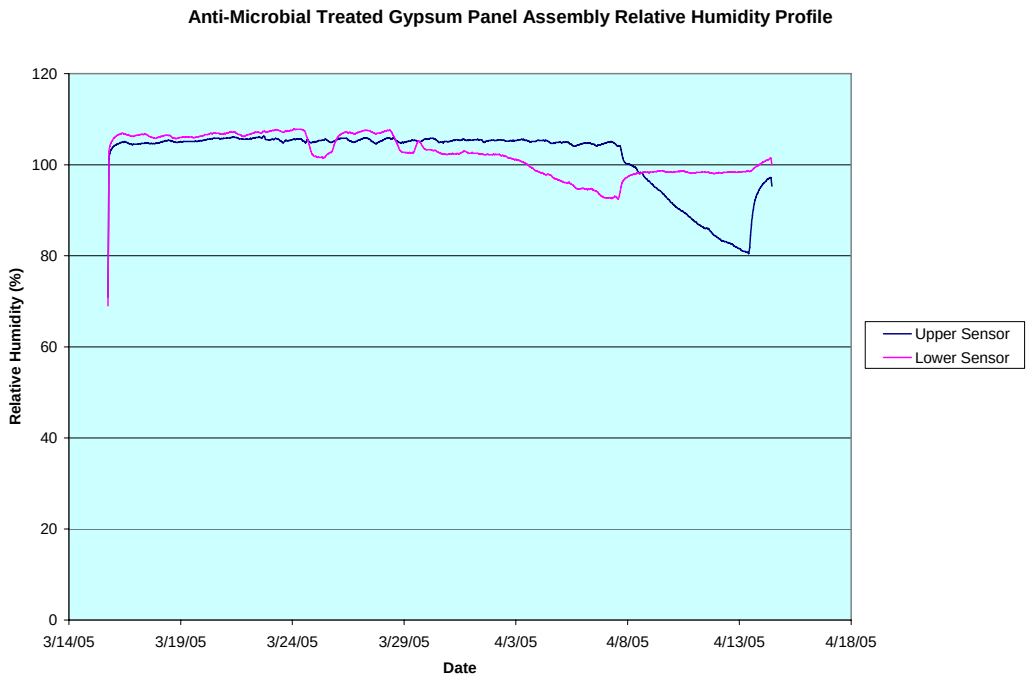


Figure 25 Anti-Microbial Treated Gypsum Panel Assembly Relative Humidity Profile

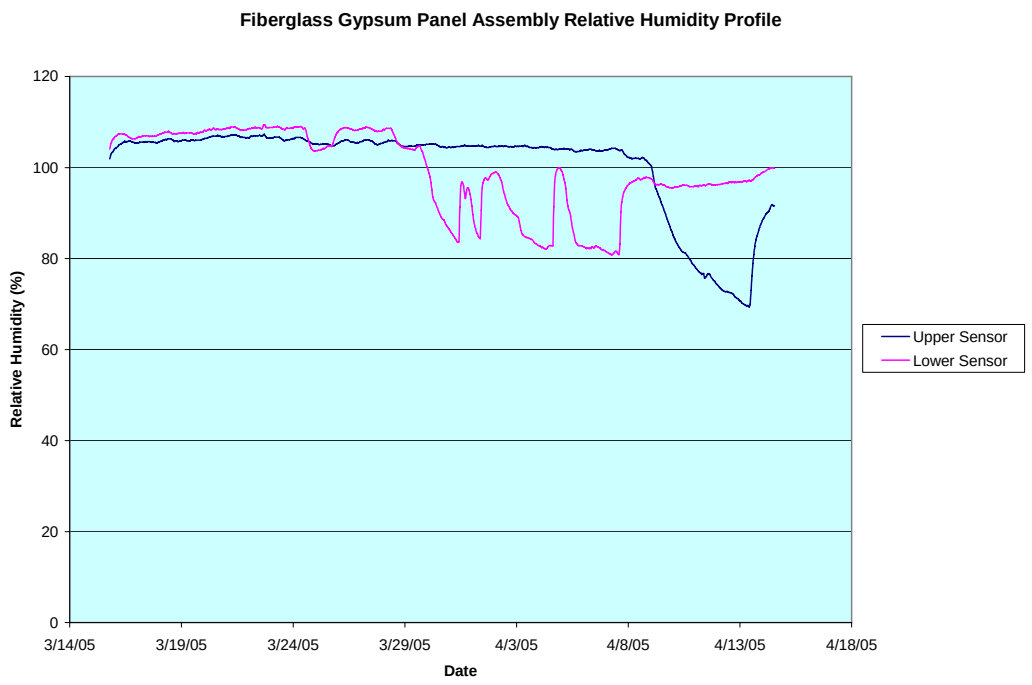


Figure 26 Fiberglass Gypsum Panel Assembly Relative Humidity Profile

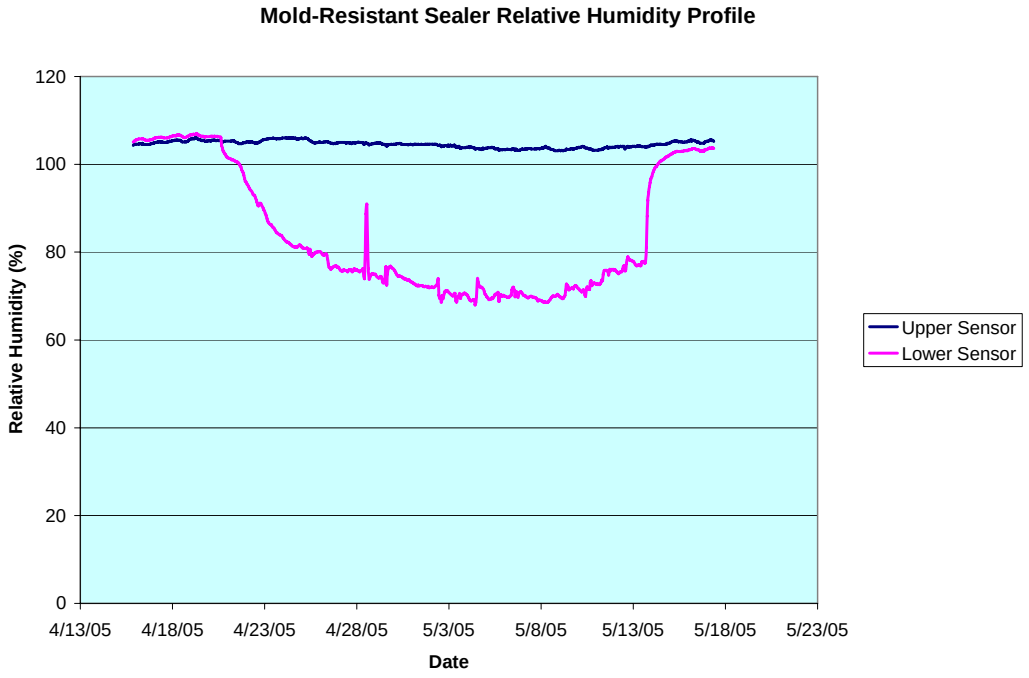


Figure 27 Mold-Resistant Sealer Assembly Relative Humidity Profile

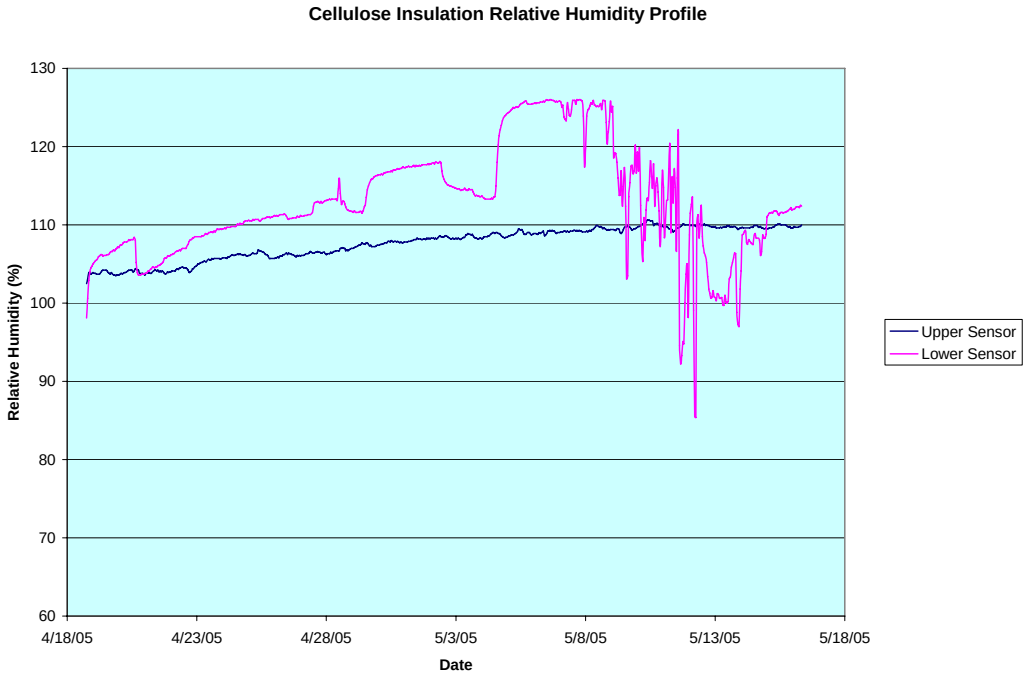


Figure 28 Cellulose Insulation Assembly Relative Humidity Profile

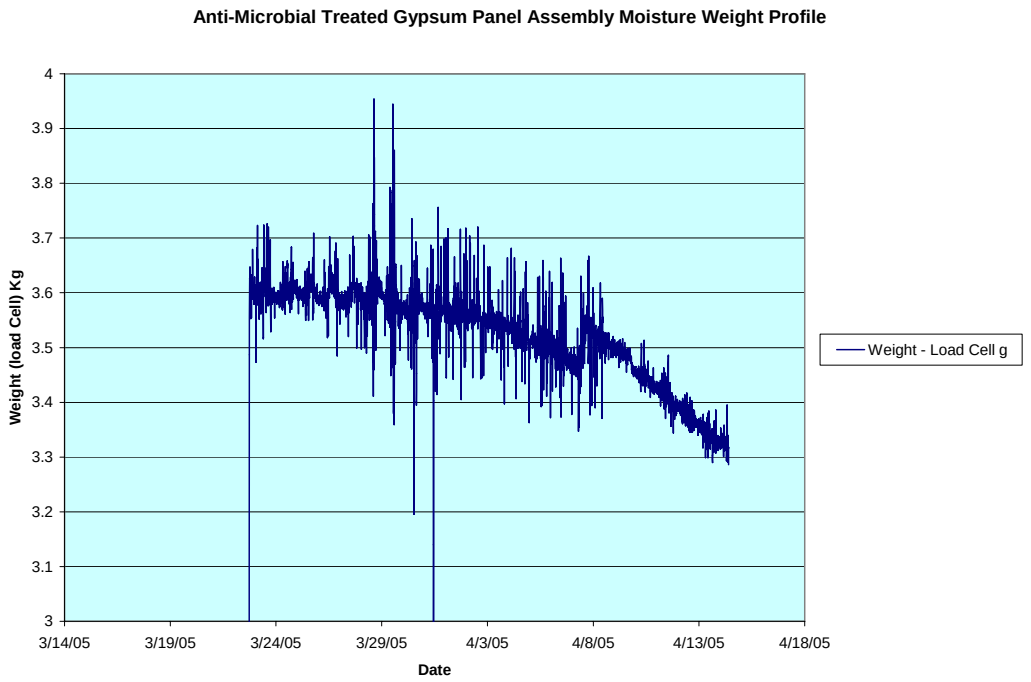


Figure 29 Anti-Microbial Treated Gypsum Panel Assembly Moisture Weight Profile

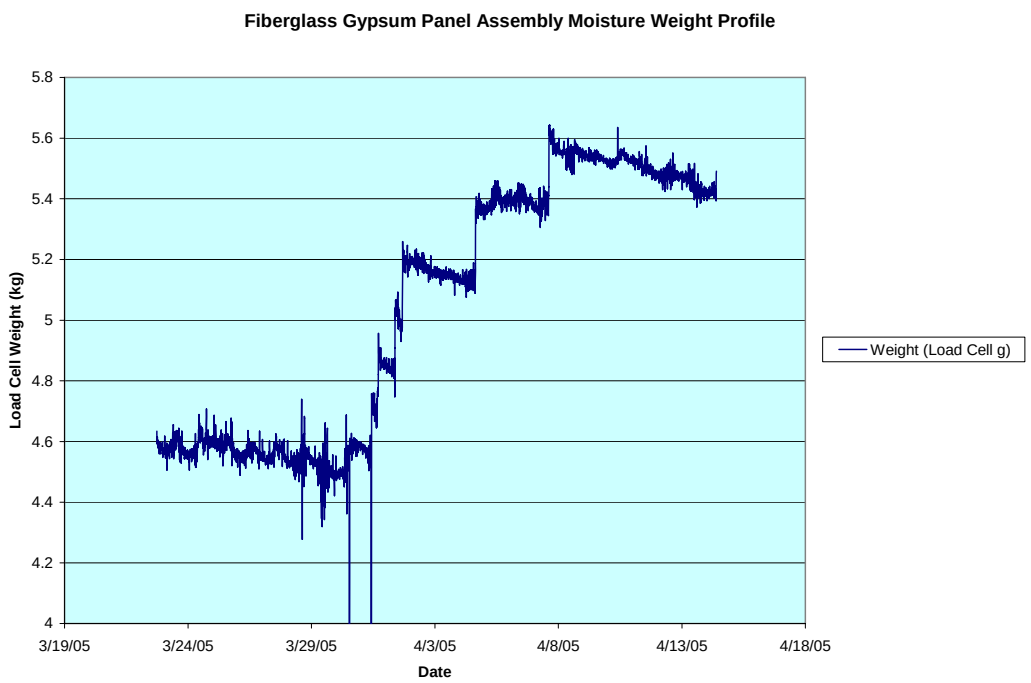


Figure 30 Fiberglass Gypsum Panel Assembly Moisture Weight Profile

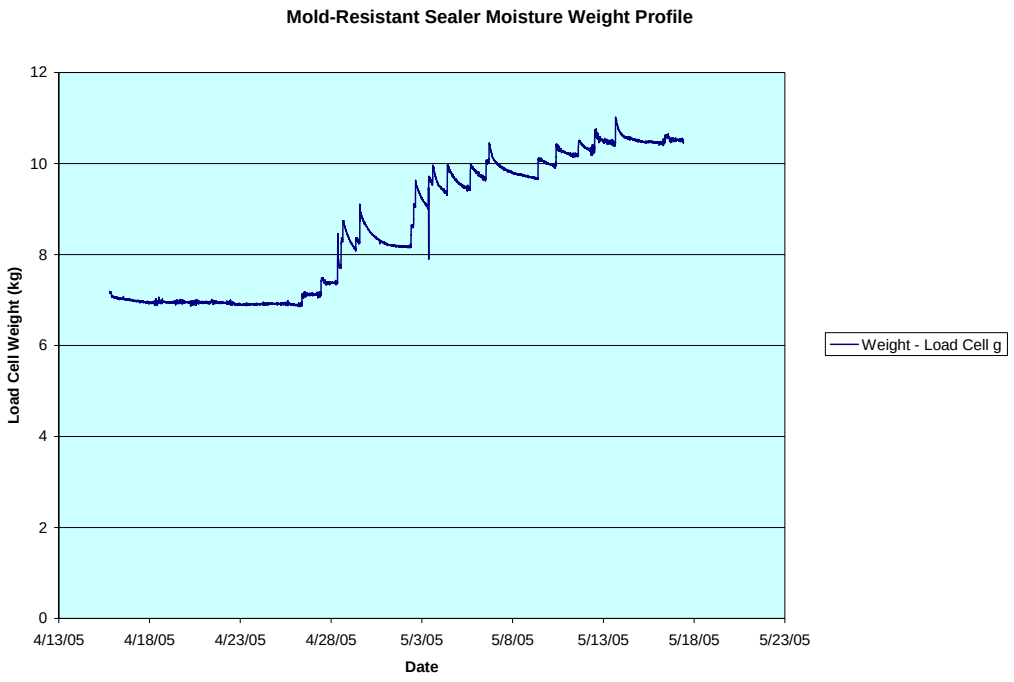


Figure 31 Mold-Resistant Sealer Assembly Moisture Weight Profile

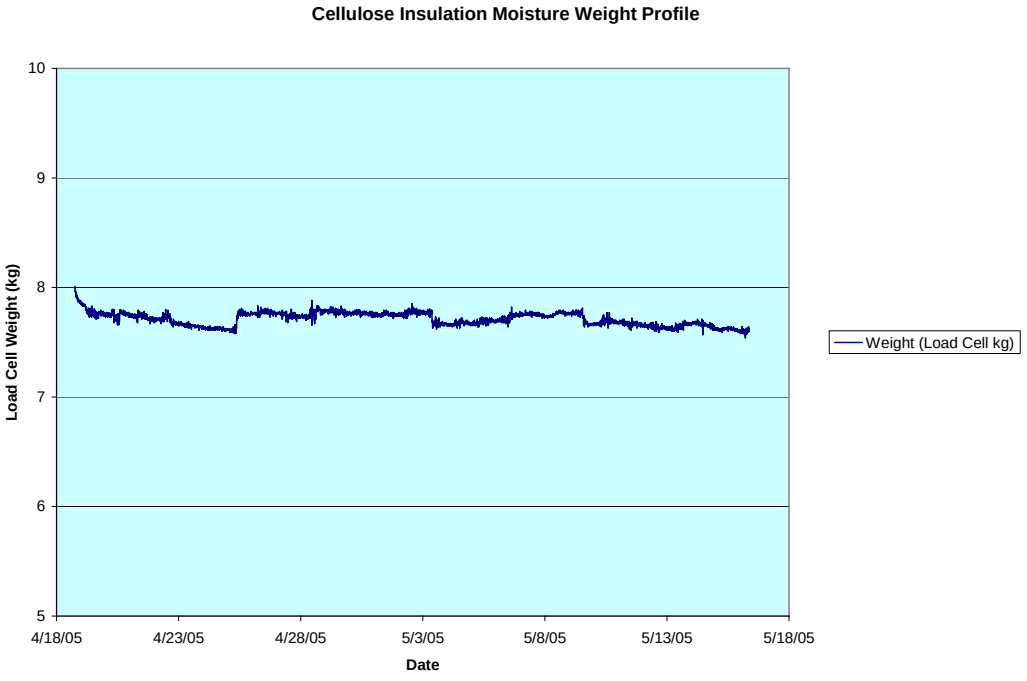


Figure 32 Cellulose Insulation Assembly Moisture Weight Profile

2.5.1 Baseline Fiberglass Insulation

All of the wall assemblies in the Task 3.3 experiments had kraft-faced fiberglass insulation in at least part of the wall cavity. This enabled an evaluation of several moisture loading parameters and scenarios using both the initial protocols and the revised protocols.

Using initial protocols, local moisture content and relative humidity in the wall cavity affected mold formation and growth significantly. Moisture content at the bottom of the wall assembly was significantly higher than at all other locations. Relative humidity in the insulation was initially high, but fell after one week, and fell quickly after periodic water pours. Mold growth occurred predominantly at the base plate studs (Figure 33). Little visible mold growth occurred elsewhere, including the OSB, higher up in the wall, fiberglass insulation, and gypsum panels. Repeated thermal cycling with four heat lamps followed by application of water sprays on the exterior cladding (Figures 34 and 35) of one baseline wall assembly did not impact mold growth compared to a similar wall assembly that did not use that protocol. Infrared thermography was used to measure the surface temperatures of the stucco during this protocol.

Using the revised protocols, fiberglass insulation experienced visible mold growth on the kraft paper face as well as in the fiberglass adjacent to wood surfaces. More significant mold growth occurred on wood studs and both sides of the gypsum panel. Mold growth on OSB surfaces was visible, but less significant than growth on adjacent wood studs.

2.5.2 Mold-Resistant Gypsum Panels

Both types of mold-resistant gypsum panels exhibited significant resistance to mold growth compared to conventional gypsum panels, but only on the surfaces of the panels themselves. The remainder of the wall assembly experienced significant mold growth.

Initial protocols were abandoned prior to conducting the mold-resistant gypsum panel experiments. Using the revised protocols, significant visible mold growth occurred on the painted exterior side and unfinished interior side of the conventional gypsum panels, while no appreciable amount of mold was observed on either of the mold-resistant gypsum panels (Figures 36 through 39). Significant mold growth occurred on wood studs and kraft paper adjacent to the mold-resistant panels (Figures 40 and 41). Small areas of mold growth were visible on parts of the OSB sheathing and adjacent wood studs (Figure 42). However, mold growth in both areas was much less than on the kraft paper adjacent to the gypsum panels. Mold growth, if any, inside the fiberglass insulation was not visible.

2.5.3 Mold-Resistant Sealer

The areas treated with the mold-resistant sealer, as well as fiberglass adjacent to treated areas, exhibited significant resistance to mold growth compared to untreated portions of the assembly.

Visible mold growth occurred on the painted exterior side of the gypsum panel near the top of the assembly, and two areas on the left and right side near the bottom of the assembly. The highest amount of visible mold growth on the unfinished interior side was in the lower part of the panel. The area of the panel over the base plate was soaked form the repeated water pours, but had no visible signs of mold growth. Scattered sites of mold were visible on the top and several places in the middle of the panel.

The kraft paper face of the fiberglass insulation had visible mold growth near the bottom of each batt The cavity side of the insulation had visible mold exposure primarily on the portion of insulation in contact with the untreated studs in the left cavity, but very little mold growth at the untreated center stud. Visible dark colored mold growth occurred on the side of the insulation that touched the untreated stud on the left outer side of the assembly (Figure 43). No mold growth was visible on any portion of insulation that came into the contact with areas treated with the mold-resistant sealer. A few very small areas of mold growth were visible adjacent to the untreated OSB, with no visible mold growth adjacent to the treated OSB.

Incipient visible mold growth occurred on the untreated OSB sheathing (Figure 44). There was no visible mold growth on the treated half of the OSB.

The bottom plate of the left cavity was soaked, but did not show any significant amount of mold growth. There was substantial visible mold spread on the outside untreated stud. The treated areas of the middle supporting stud did not have any visible mold growth. The top plate had visible mold growth only in the untreated side (Figure 45). Yellow mold growth occurred closer to the top and gray mold growth was visible closer to the bottom of the untreated portion.

The bottom plate of the right cavity was soaked but had little visible mold growth in the untreated portion and no visible mold growth in the treated portion of the stud. The untreated portion of the middle stud showed visible mold growth in several places, especially in the area near the bottom of the assembly (Figure 46), but only a modest amount of a mold growth in the middle and upper portion of the stud.

The top plate of the right cavity again showed contrast between treated and untreated areas. There was a visible black stain in one knot of the treated area. Except in this small area, visible mold in the untreated portion stopped at the junction of the treated area (Figure 47).

The outside stud treated with Foster showed no visible mold growth, except at the edge of a knot that appeared to be oozing tar (Figure 48).

2.5.4 Cellulose Insulation

Cellulose insulation absorbed and retained significantly more water than fiberglass insulation. Moisture content in the OSB and wood studs was at least 10 percent higher than in other experiments using fiberglass insulation in the cavity. Relative humidity data remained above the calibration range of the sensors for nearly the entire experiment, indicating fully saturated air inside the insulation. Sufficient moisture was present throughout the experiment to be considered conducive to mold formation and growth. In spite of these conditions, the amount of mold growth after the four week monitoring period was less than initially expected. Both visual inspection and lack of odor indicated little growth inside the cellulose insulation itself, and relatively less mold growth on other surfaces than in other experiments.

Visible mold growth occurred in spots on the painted exterior side of the gypsum panel primarily near the top of the assembly (Figure 49). The unfinished interior side adjacent to the cellulose insulation experienced more mold growth than the area adjacent to the fiberglass insulation (Figure 50).

There was no mold growth detected (visually or by odor) on the area of the cellulose insulation itself adjacent to the gypsum panel. Visible mold growth was detected in small surface areas of the cellulose insulation adjacent to OSB and studs that had coincident mold growth (Figure 51). No mold growth inside the cellulose insulation was visible away from these surface areas. The cellulose was still quite soggy when the wall assembly was opened for inspection.

The OSB beneath the cellulose insulation showed visible mold growth only in small areas as well, primarily near the base plate (Figure 52). A small amount of mold was detected on the upper stud in the area surrounding the top moisture sensors and on the middle stud in the lower portion of the assembly (Figure 53). No other significant areas of mold growth on the OSB sheathing or studs were visible.

Nominal mold growth occurred on the kraft paper of the fiberglass insulation (Figure 54), with more visible growth on the fiberglass insulation adjacent to the studs and OSB sheathing (Figure 55). The OSB and studs adjacent to the fiberglass insulation showed more visible mold growth than the cellulose side, primarily near the base plate (Figure 56).

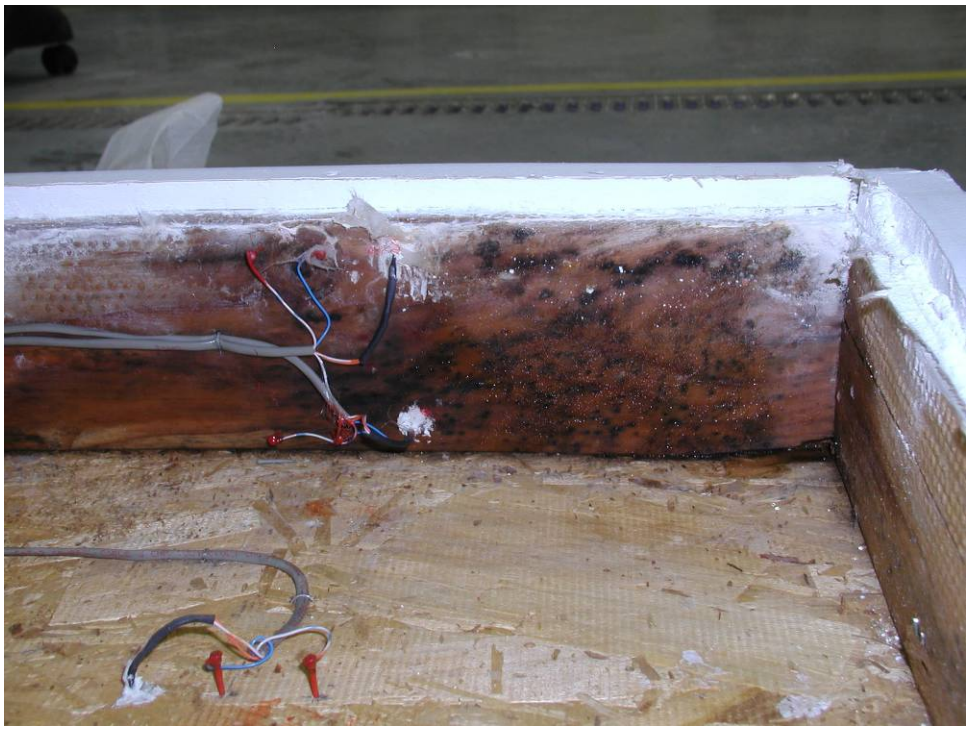


Figure 33 Baseline Wall Assembly Mold Growth at Base Plate

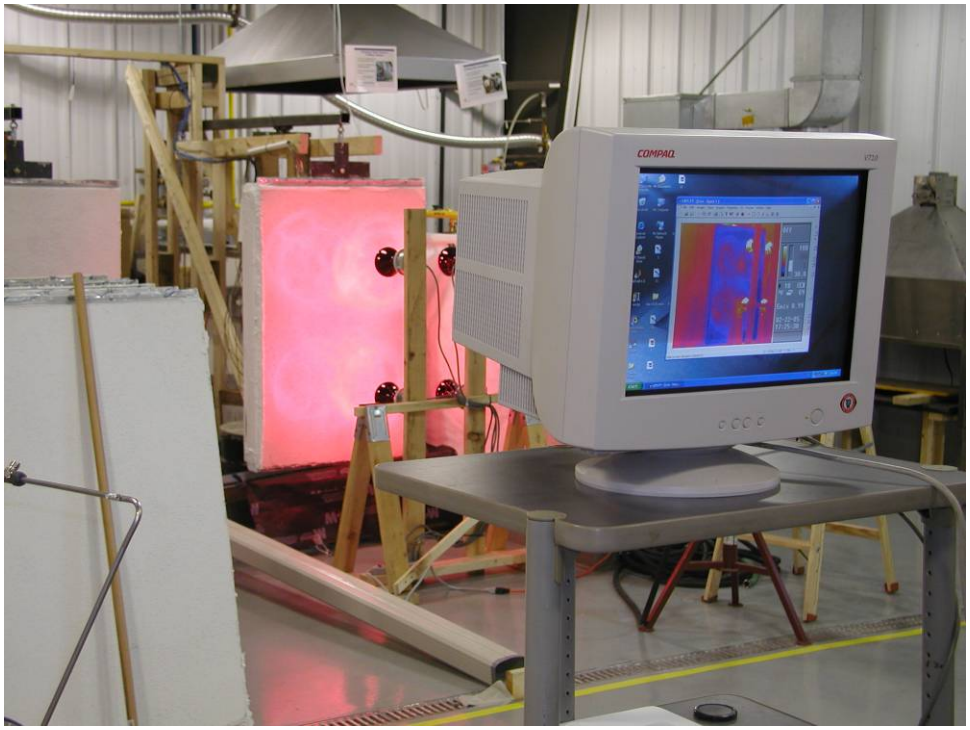


Figure 34 Baseline Wall Assembly IR Image of Thermal Cycling with Heat Lamps

Figure 35 Baseline Wall Assembly IR Image of Water Spray Protocol

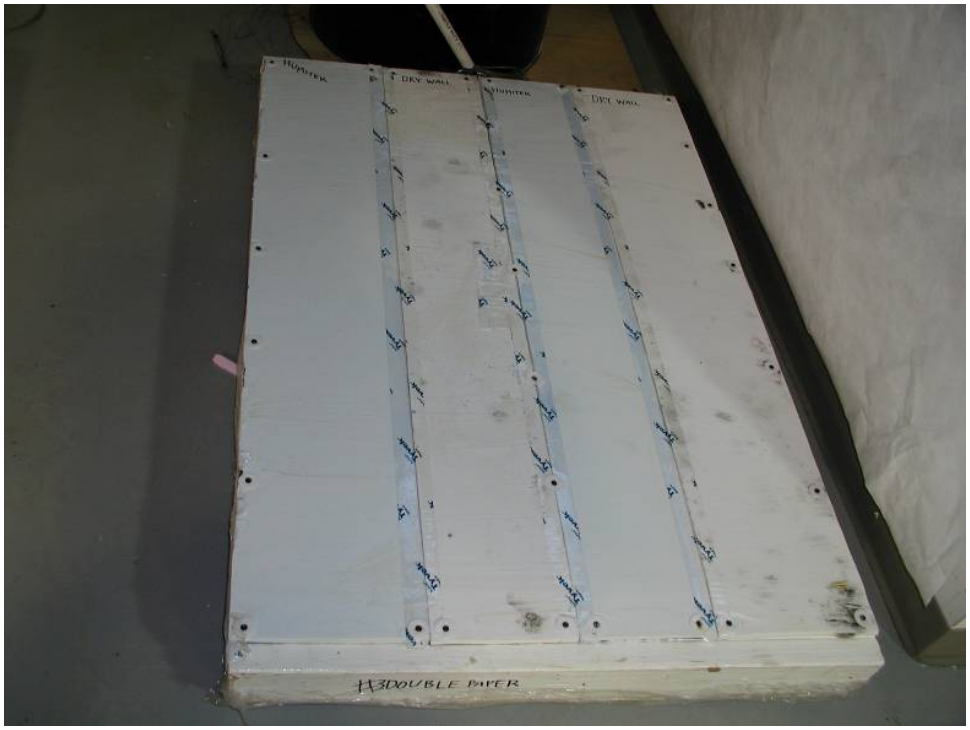


Figure 36 Anti-Microbial Treated Gypsum Panels vs. Conventional Gypsum Panels

(Dark Color on Anti-Microbial Treated Panels is Residual Water)

Figure 37 Back Side of Anti-Microbial Treated Gypsum Panels vs. Conventional Panels

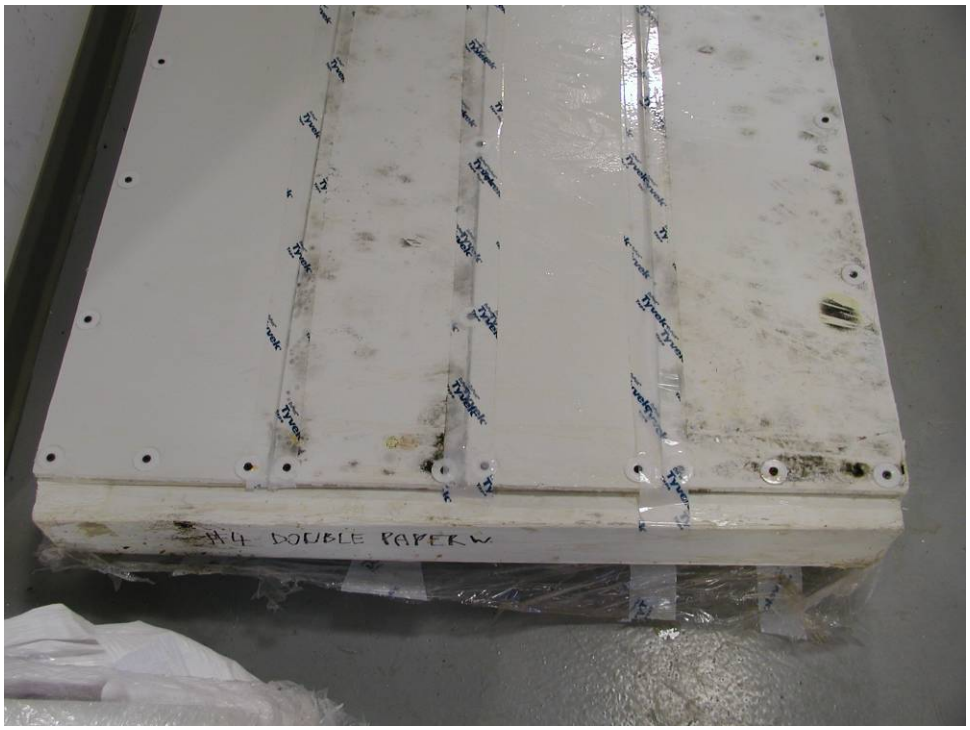


Figure 38 Fiberglass Gypsum Panels vs. Conventional Gypsum Panels

Figure 39 Back Side of Fiberglass Gypsum Panels vs. Conventional Panels

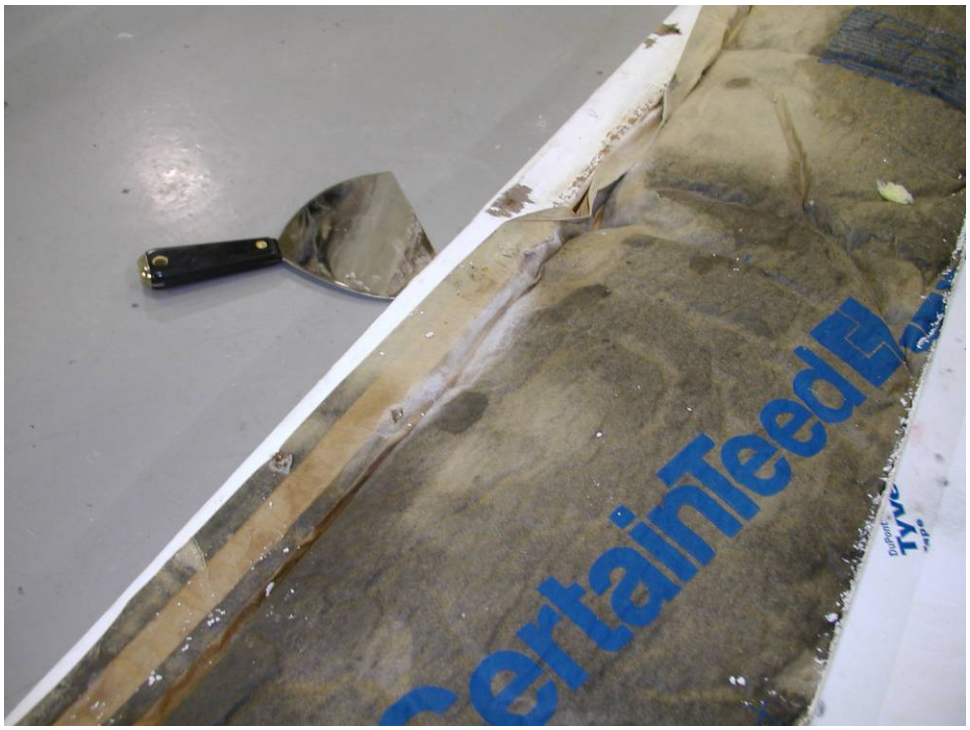


Figure 40 Mold Growth on Kraft Paper under Anti-Microbial Treated Gypsum Panel

Figure 41 Mold Growth on Kraft Paper and Studs under Fiberglass Gypsum Panel

(Discoloration on Base Plate is Water Saturation, not Mold)

Figure 42 Little Mold Growth on OSB and Studs under Fiberglass Gypsum Panel

Figure 43 Mold Growth on Fiberglass Insulation Adjacent to Untreated Stud

(Gray Mold Growth Visible on Untreated OSB only)

Figure 44 Mold Growth Profile on Treated and Untreated OSB

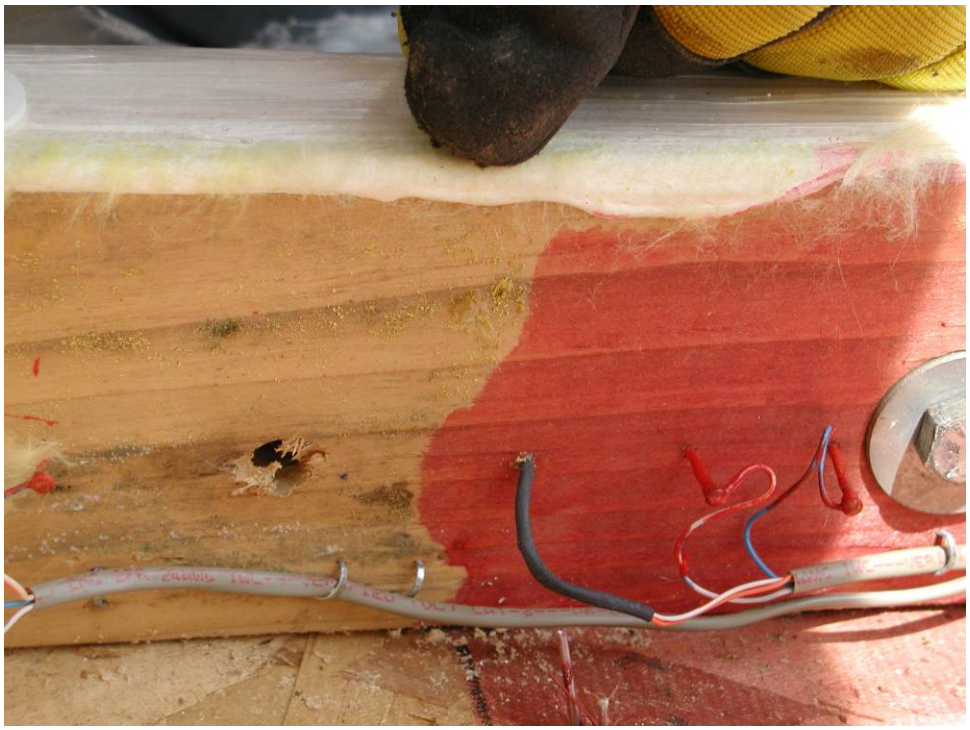


Figure 45 Mold Growth Profile on Treated and Untreated Top Plate Stud, Left Cavity

Figure 46 Mold Growth on Untreated Middle Stud

Figure 47 Mold Growth Profile on Treated and Untreated Top Plate Stud, Right Cavity

Figure 48 Mold Growth in Knot on Treated Outside Stud, Right Cavity

Figure 49 Mold Growth on Exterior Side of Gypsum Panel with Cellulose Insulation

Figure 50 Mold Growth on Interior Side of Gypsum Panel with Cellulose Insulation

Figure 51 Mold Growth on Cellulose Insulation near Middle Stud

Figure 52 Mold Growth on OSB near Base Plate Adjacent to Cellulose Insulation

Figure 53 Mold Growth on Lower Portion of Middle Stud Adjacent to Cellulose Insulation

Figure 54 Nominal Mold Growth on Kraft Paper of Fiberglass Insulation

Figure 55 Mold Growth on Fiberglass Insulation near Base Plate

Figure 56 Mold Growth on OSB Adjacent to Fiberglass Insulation near Base Plate

3.0 Moisture Content Profile Experiments

3.1 Goal

The goal of the Moisture Content Profile experiments was to characterize the moisture content over time of selected wall assemblies, claddings, and WRB options when subjected to water intrusion events.

3.2 Scope

The scope of these experiments was to evaluate the drying rate and moisture content of targeted wall assemblies in the presence of moisture loading conditions in a controlled environmental setting. Selected wall assemblies all had OSB sheathing and included:

1. Baseline Wall Assembly;
2. Higher Perm Housewrap;
3. High Drainage Higher Perm Housewrap;
4. Exterior Insulated Finish System; and
5. One-Coat Stucco.

3.3 Approach

The initial approach used for the baseline wall assembly was to pour a specified quantity of water (e.g., 1 pint) into a ½" diameter hole drilled into the 2x4 wood frame at the top of the wall assembly to simulate a water intrusion event. Caulk was applied to wood seams in an effort to make the wood frame/wall interface water-tight. Water pours were repeated at intervals based on wall cavity moisture content and relative humidity in an effort to evaluate repeated moisture intrusion events as well as provide long term relative humidity and temperature conditions considered conducive to mold formation and growth. The wall assemblies were fastened to the counterbalanced compression load cell in each of two stations to measure changes in wall weight over time. Infrared heat lamps and water sprayed on stucco wall surfaces were used to simulate thermal cycling and rain events. This approach was intended to permit both drying rate measurements and mold growth experiments to occur simultaneously and minimize the number of weeks necessary to perform each set of experiments.

This procedure did not provide suitable boundary conditions to be of value to either wall drying or as inputs to hygrothermal models. This overall approach was not considered suitable to meet experiment goals. Revised experimental protocols described below were subsequently applied to the other four wall assemblies to address these issues. The revised procedures were intended to provide more suitable boundary conditions for use in hygrothermal models while focusing on drying rate through the WRB.

3.4 Protocols

Experimental protocols were designed to allow exploration of the following hypotheses regarding moisture content profiles in targeted wall assemblies:

- Moisture content of wall assemblies subjected to moisture intrusion events will be reasonably uniform except at the base plate due to gravity water flow.
- Drying rate through the WRB and stucco cladding will be very slow in the absence of thermal drivers or air movement through the wall cavity.
- Wood moisture content, insulation relative humidity, and wall moisture weight can provide useful information for hygrothermal models only with appropriate boundary conditions.

3.4.1 Construction

Wall assemblies were constructed with targeted cladding and WRB options. For all moisture content profile experiments, 3½" R-13 kraft-faced fiberglass insulation was installed in each of the two wall cavities. Each wall assembly had a conventional gypsum panel painted with one coat latex primer and one coat contractor grade latex paint.

Exterior edges of the wood frames were caulked and sealed with 3 coats of elastomeric paint to minimize leakage during pre-conditioning and provide a continuous vapor barrier along all outside edges of studs.

3.4.2 Installation and Monitoring

Pre-conditioning protocols were similar to mold growth experiment protocols. Wall assemblies were laid flat with stucco cladding side down. Water collected from a local field was poured into the wall assembly to a depth of ¼" to soak the OSB for a period of 3 days, replenishing as necessary. Residual water was drained, and moisture pins were inserted into wood and OSB for moisture content measurement. Sufficient water was poured by hand into the insulation to wet but not compress the insulation. Insulation was placed into wall cavities and relative humidity sensors were inserted mid-depth into the insulation. Kraft paper was sprayed with water to wet the outer surface. Gypsum panels were sprayed with water to wet the back sides only, and installed with screws and washers to allow non-destructive inspection. Edges were sealed with Tyvek® tape. Wall assemblies were wrapped in shrink wrap plastic, except the stucco face, and flipped over, with gypsum panel side now facing the floor. Wall assemblies remained in this configuration for a period of 5 days to pre-condition the insulation and gypsum panels. The wall assemblies were closed with all sides except stucco cladding wrapped in plastic, and hung on load cells for the four week duration of the experiment (Figure 57).

Automated data acquisition included all moisture content parameters and changes in wall weight. For these experiments, water was not added to the wall cavity after walls were enclosed and hung on load cells. At the end of the third week, heat lamps were directed at the interior side of the wall assembly to provide a thermal driving force for drying through the WRB and cladding (Figure 58). Experiments were concluded after four weeks to permit additional experiments. The duration of each experiment was approximately five weeks, including pre-conditioning.

By the end of the EIFS wall assembly five-day pre-conditioning period, substantial mold growth had occurred on both the wood studs and the OSB sheathing (Figures 59 and 60). Mold growth was not an objective of the pre-conditioning period for any experiments. This experience further illustrated the challenges in growing mold in a controlled and repeatable manner. None of the other nine assemblies exhibited any mold growth during the pre-conditioning period.

3.5 Observations

Revised protocols designed to focus wall cavity moisture flow toward the WRB and cladding were successful in providing comparative drying rate data on four different wall assemblies. Two walls used three-coat stucco cladding and one layer of higher permeance housewrap coupled with one layer of building paper as the WRB, and two walls (one-coat stucco and EIFS) used exterior polystyrene insulation combined with two layers of building paper as the WRB. Measurements for the "baseline" wall assembly with three-coat stucco cladding and two layers of building paper as the WRB were conducted with the initial flawed protocol, so no comparable data was available for that assembly option.

Moisture content data for these four wall assemblies (Figures 61 through 64) indicated higher initial and final moisture content in the two housewrap assemblies than the two exterior insulation assemblies. The different initial levels were caused by variations in pre-conditioning water levels and amounts, as well as evaporative drying during visual inspections prior to sealing and hanging the assemblies, especially the EIFS assembly. This data illustrated the challenge of providing consistent initial moisture boundary conditions in built-up assemblies, even in a laboratory environment.

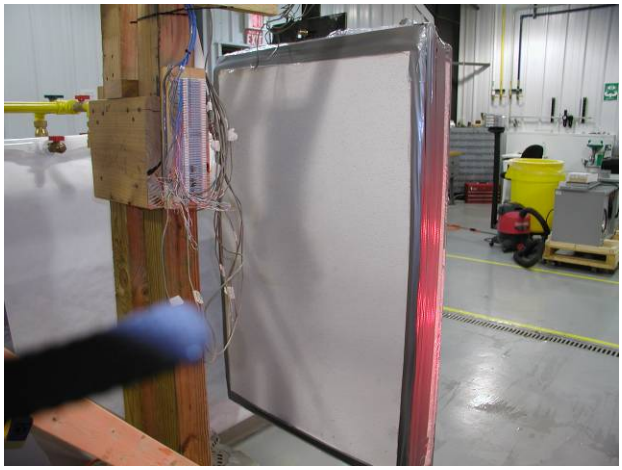
The impact of heating the gypsum panel was also evident from the wall cavity temperature profiles (Figures 65 through 68). Prior to heating, moisture content profiles were fairly random and stable over time. Once heat was applied to the gypsum panels, the temperatures and moisture contents in components closer to the heat source responded more quickly than in other areas of the assembly.

Profiles of relative humidity inside the fiberglass insulation indicated continuously saturated insulation prior to wall heating (Figures 69 through 72), irrespective of initial wood and OSB moisture content. Heating the gypsum panels increased insulation temperature and temporarily drove out moisture toward other assembly components, especially the lower portion of the wall assembly, where 2/3 of the heat was applied. When heating was stopped, insulation again became saturated.

Room temperature in the air conditioned laboratory was reasonably stable throughout the experiment period, with variations in relative humidity based on outdoor conditions (Figures 73 through 76).

Wall assembly moisture weight profiles (Figures 77 through 80) showed differences in evaporative drying rates for different cladding and insulation options. Both walls with exterior insulation were similar to each other and dried more slowly than the two walls with housewrap and no exterior insulation, which were also similar to each other (Figures 81 and 82). Heating the gypsum panel increased the drying rate of each wall slightly.

a) Gypsum Panel and Studs Sealed and Taped



b) Stucco Cladding Open to Environment

Figure 57 Sealed Wall Assembly for Moisture Content Profile without Thermal Loading

Figure 58 Sealed Wall Assembly for Moisture Content Profile with Thermal Loading

Figure 59 Mold Growth on Studs During EIFS Wall Assembly Pre-Conditioning

Figure 60 Mold Growth on OSB During EIFS Wall Assembly Pre-Conditioning

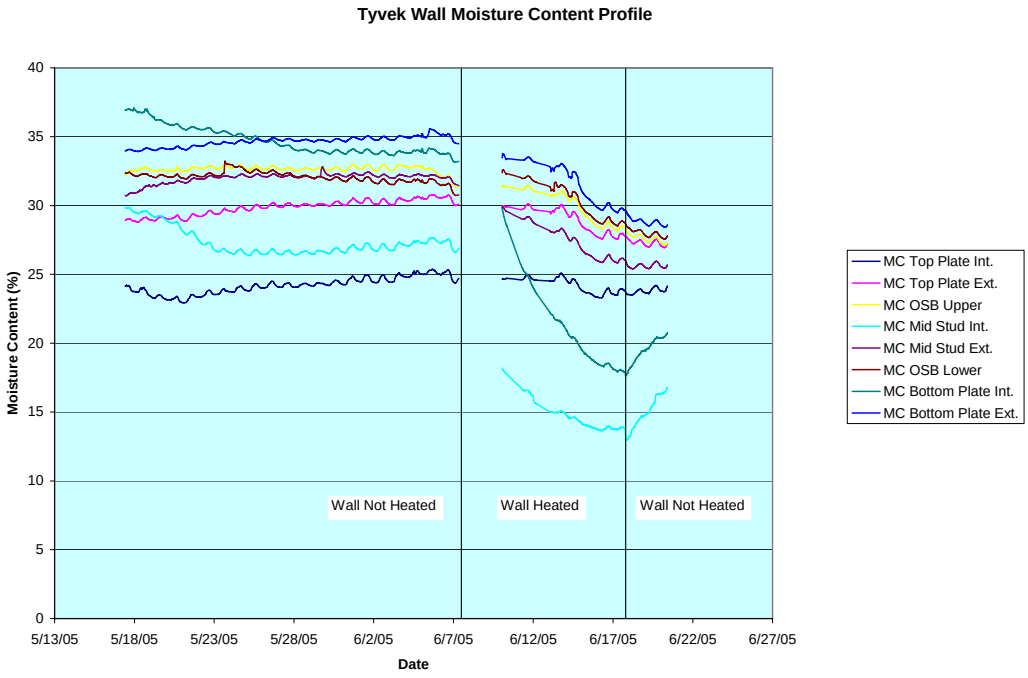


Figure 61 Tyvek® HomeWrap™ Assembly Moisture Content Profile

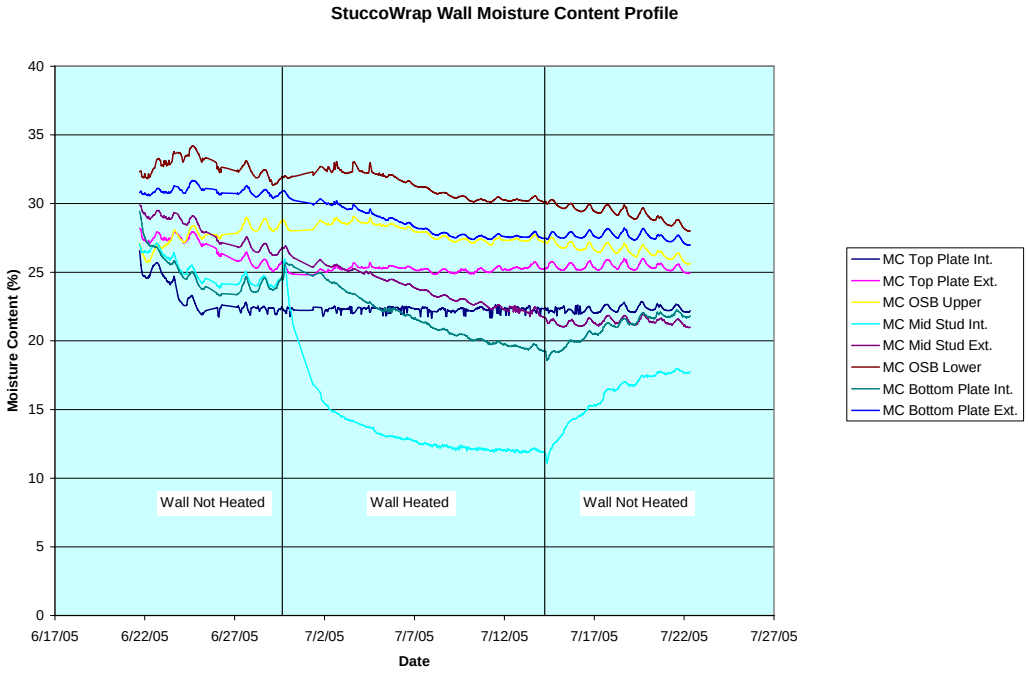


Figure 62 Tyvek® StuccoWrap™ Assembly Moisture Content Profile

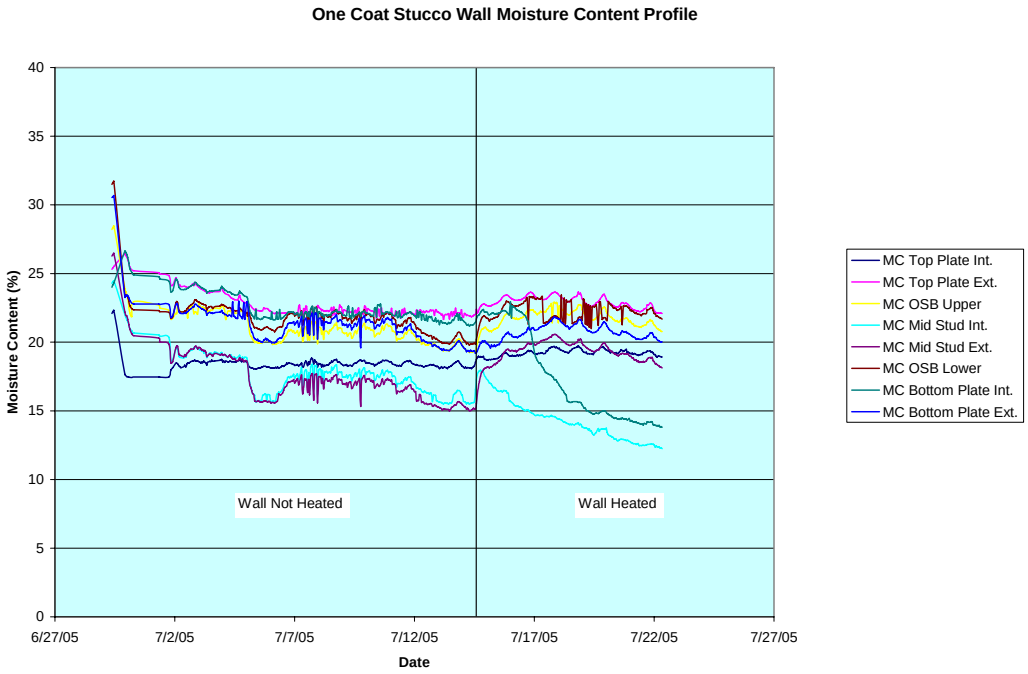


Figure 63 One-Coat Stucco Assembly Moisture Content Profile

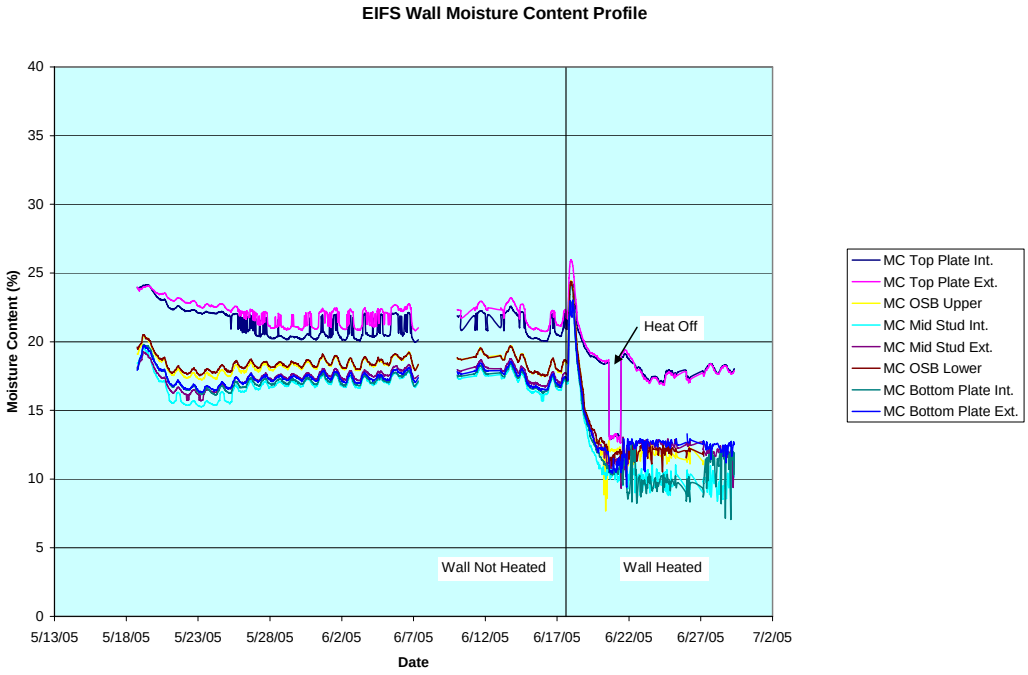


Figure 64 EIFS Assembly Moisture Content Profile

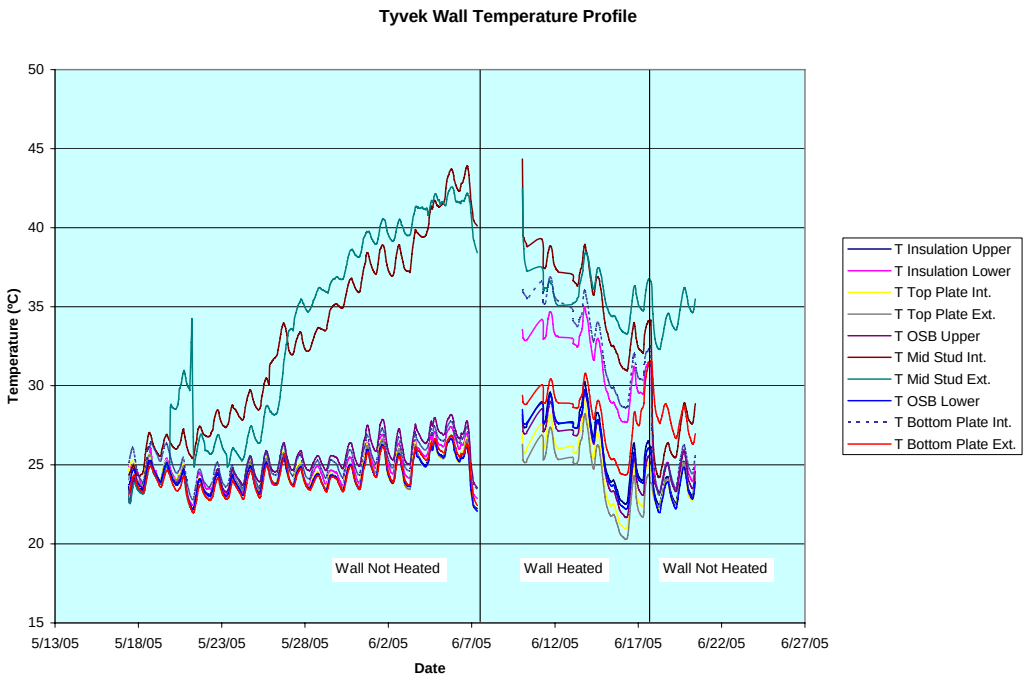


Figure 65 Tyvek® HomeWrap™ Assembly Temperature Profile

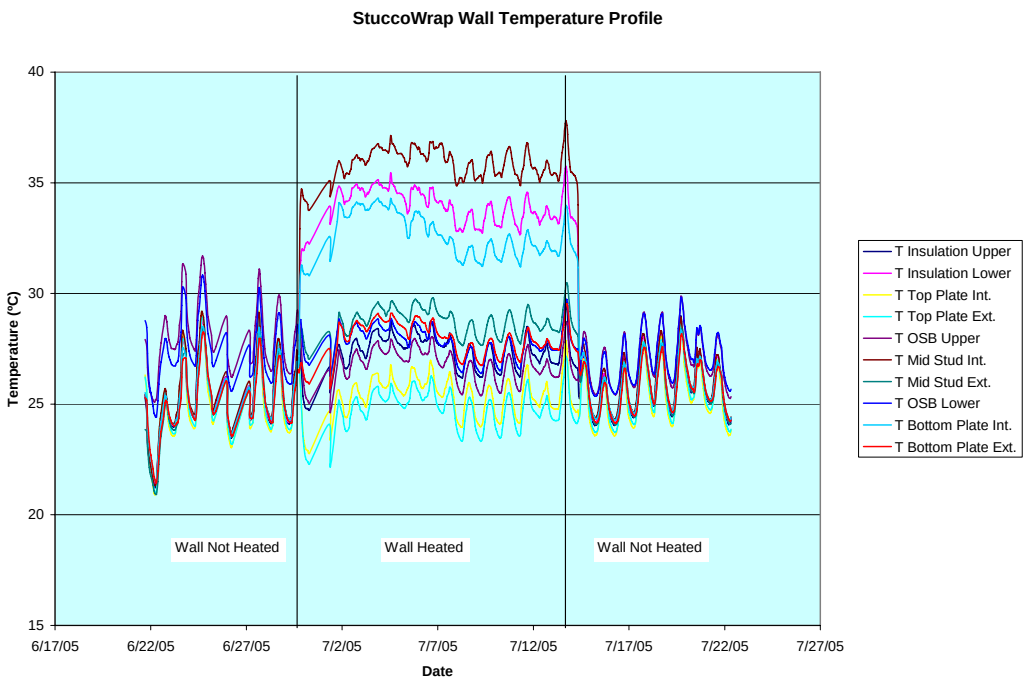


Figure 66 Tyvek® StuccoWrap™ Assembly Temperature Profile

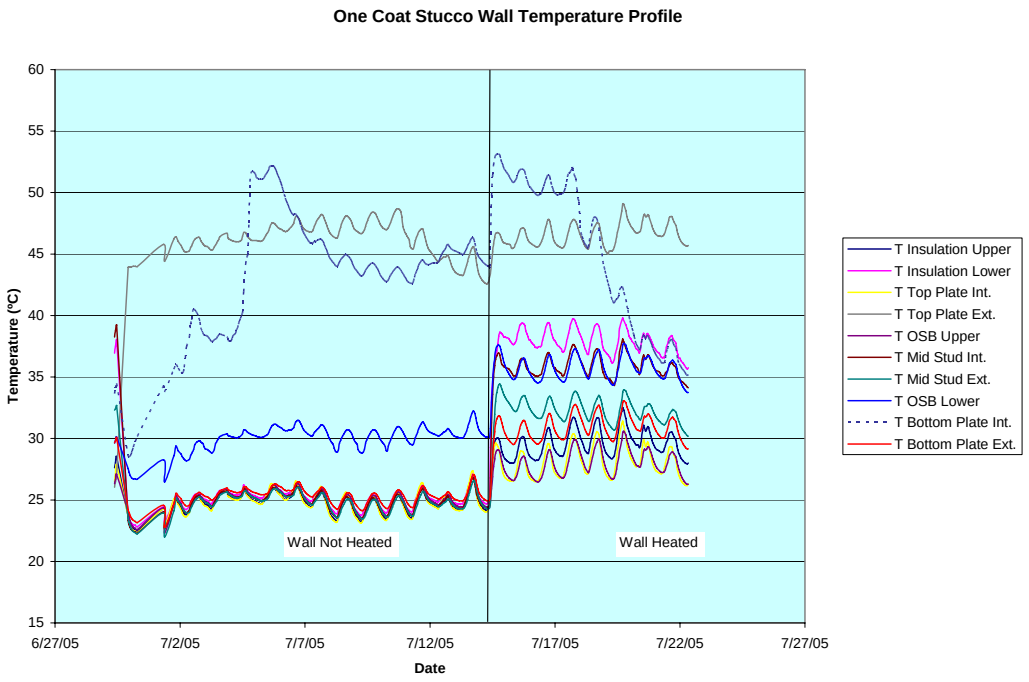


Figure 67 One-Coat Stucco Assembly Temperature Profile

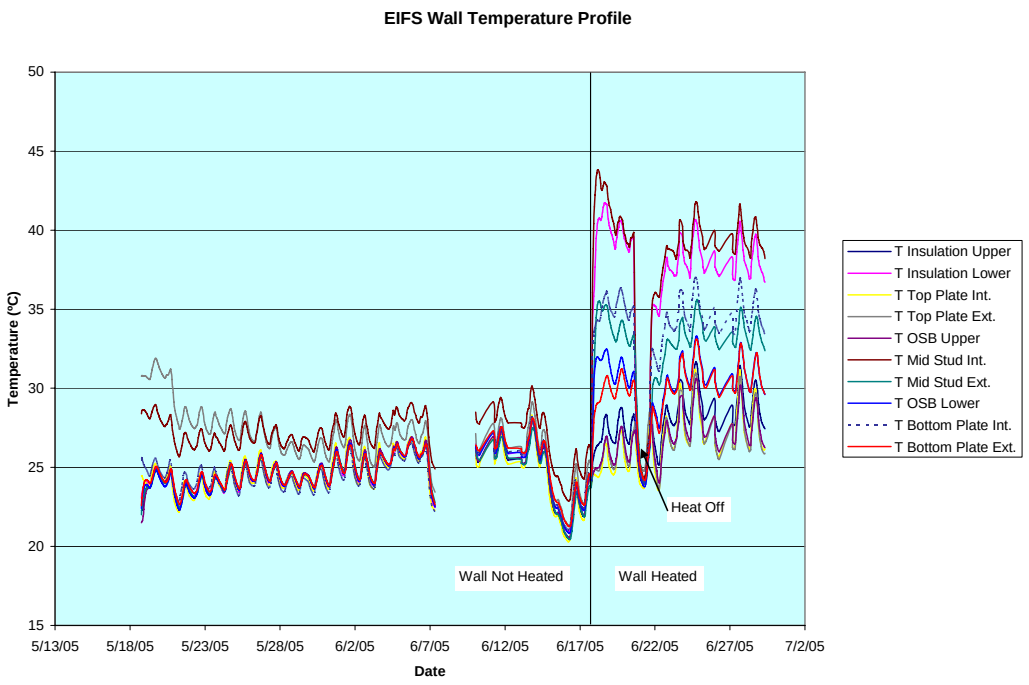


Figure 68 EIFS Assembly Temperature Profile

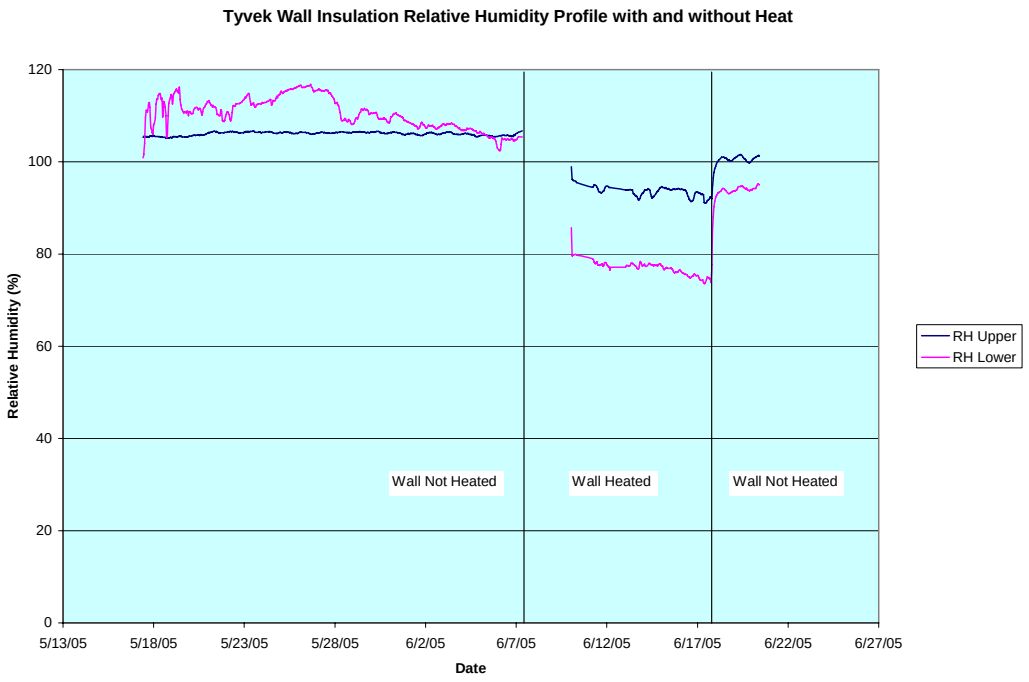


Figure 69 Tyvek® HomeWrap™ Assembly Relative Humidity Profile

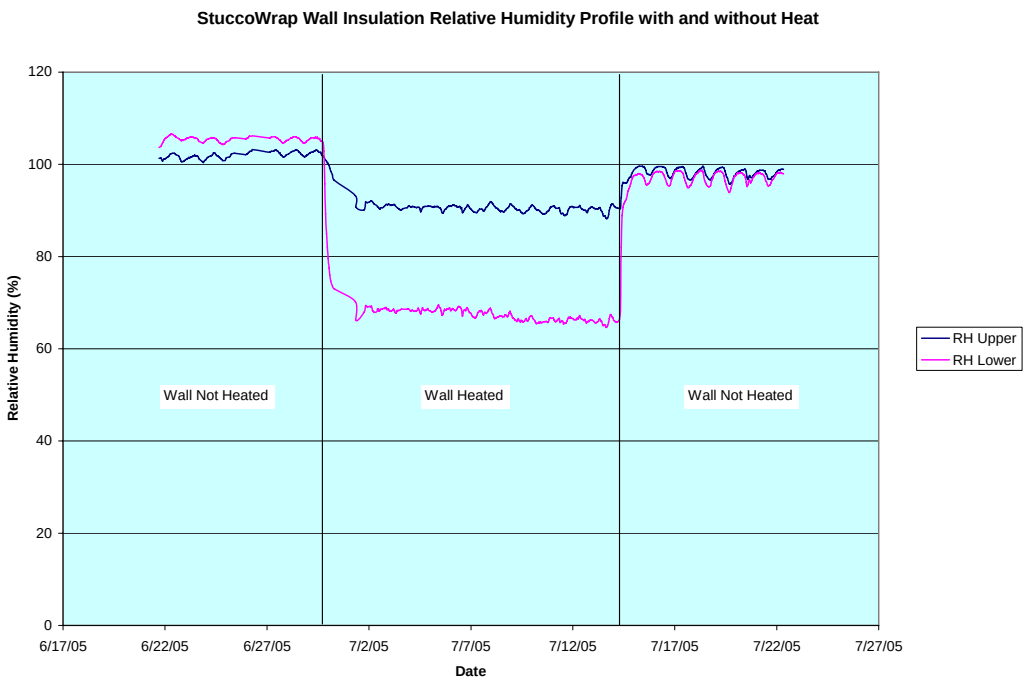


Figure 70 Tyvek® StuccoWrap™ Assembly Relative Humidity Profile

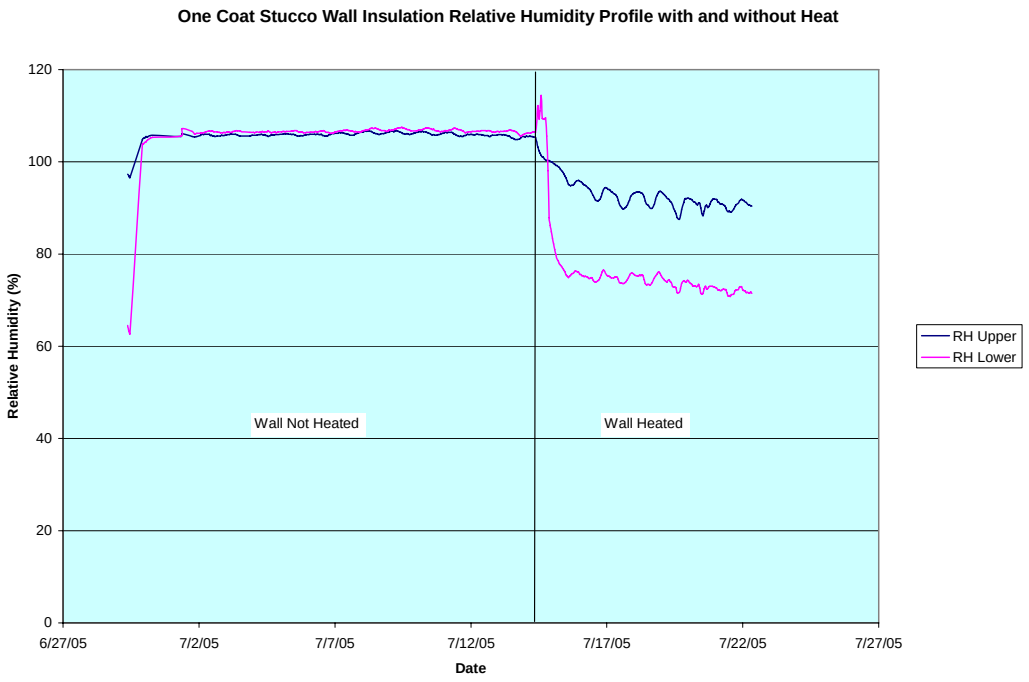


Figure 71 One-Coat Stucco Assembly Relative Humidity Profile

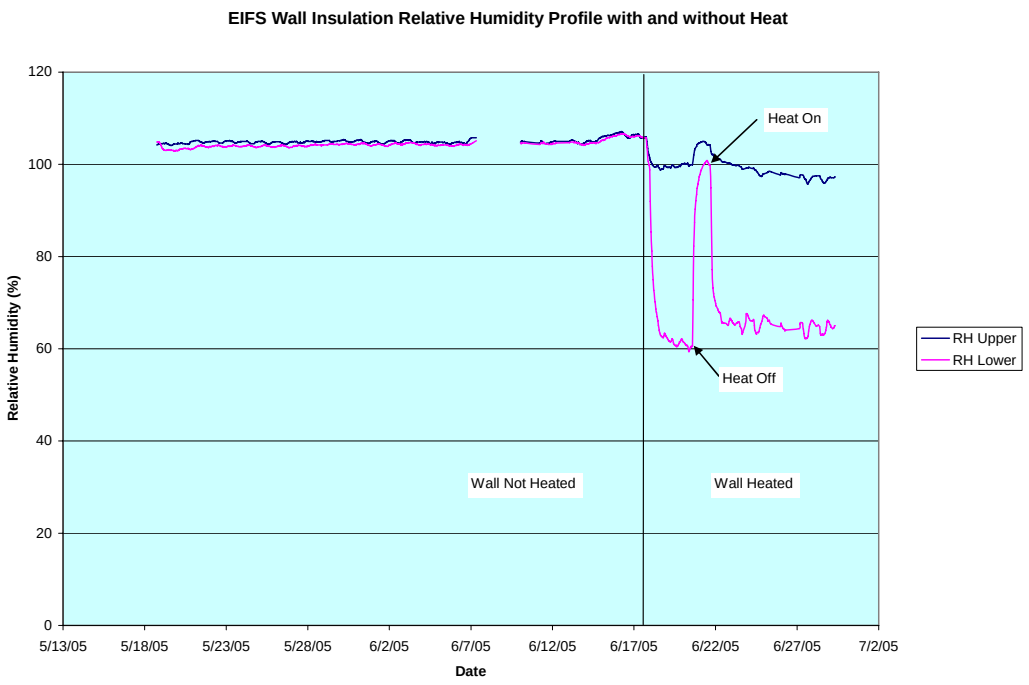


Figure 72 EIFS Assembly Relative Humidity Profile

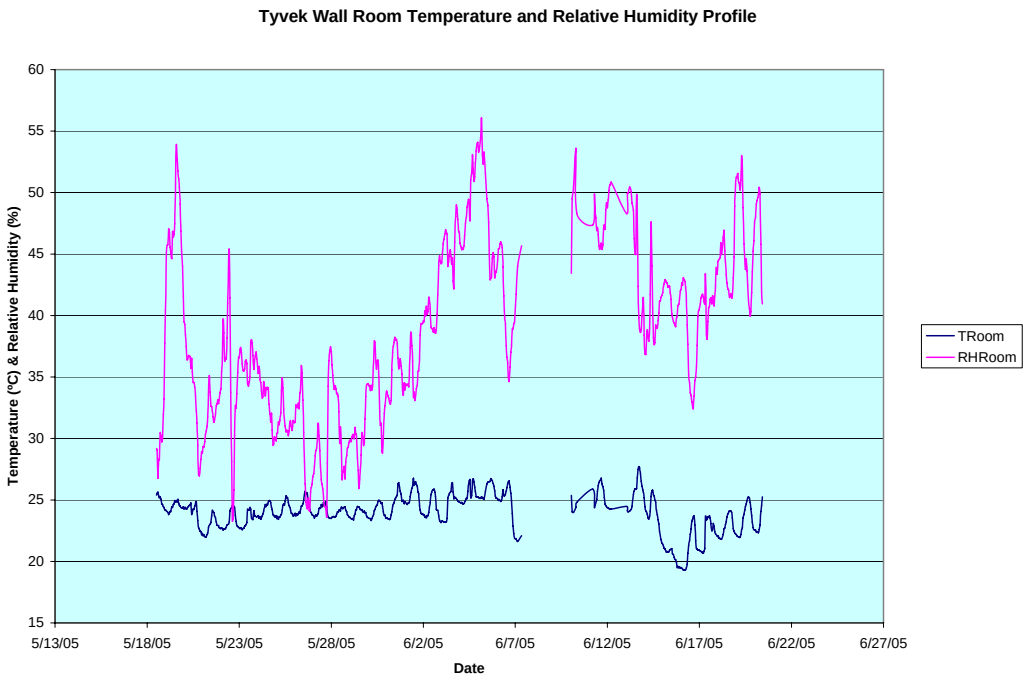


Figure 73 Tyvek® HomeWrap™ Assembly Room Temperature & Relative Humidity

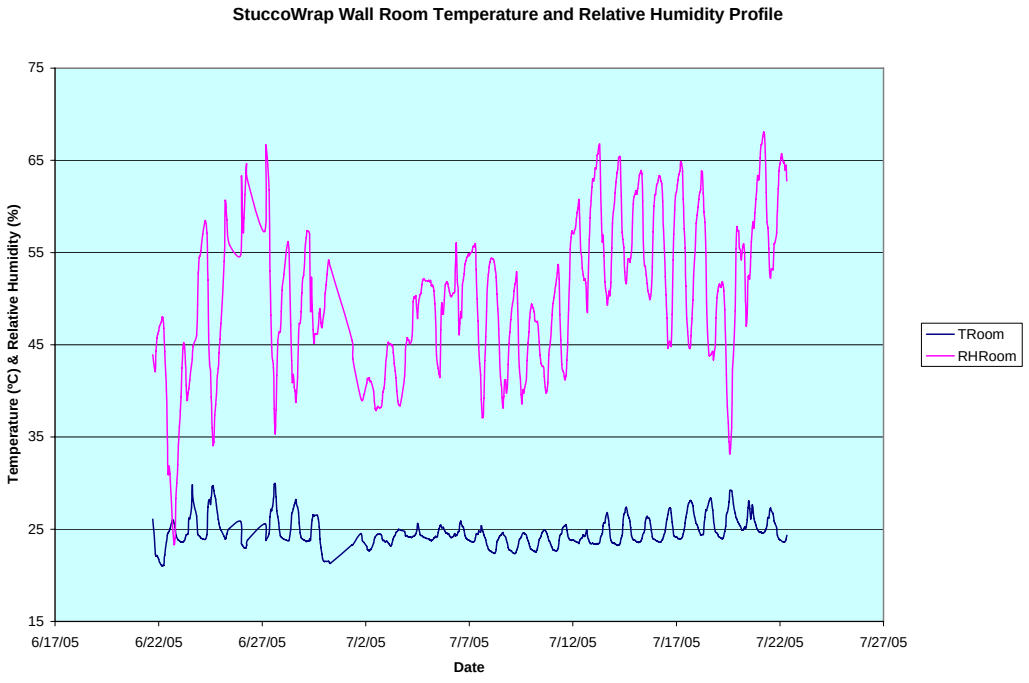


Figure 74 Tyvek® StuccoWrap™ Assembly Room Temperature & Relative Humidity

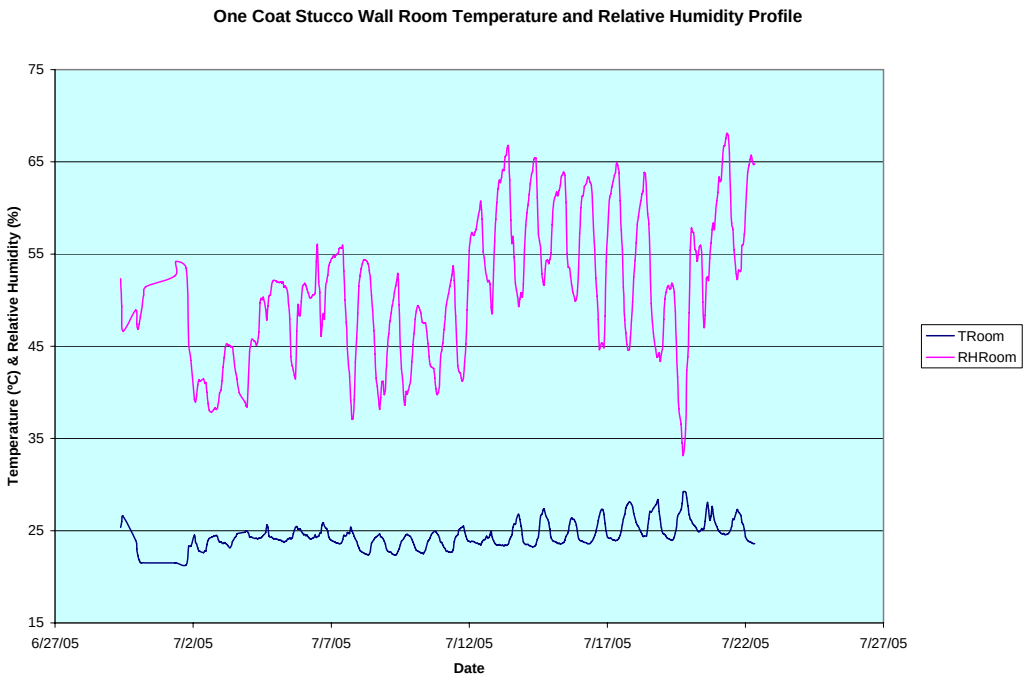


Figure 75 One-Coat Stucco Assembly Room Temperature and Relative Humidity

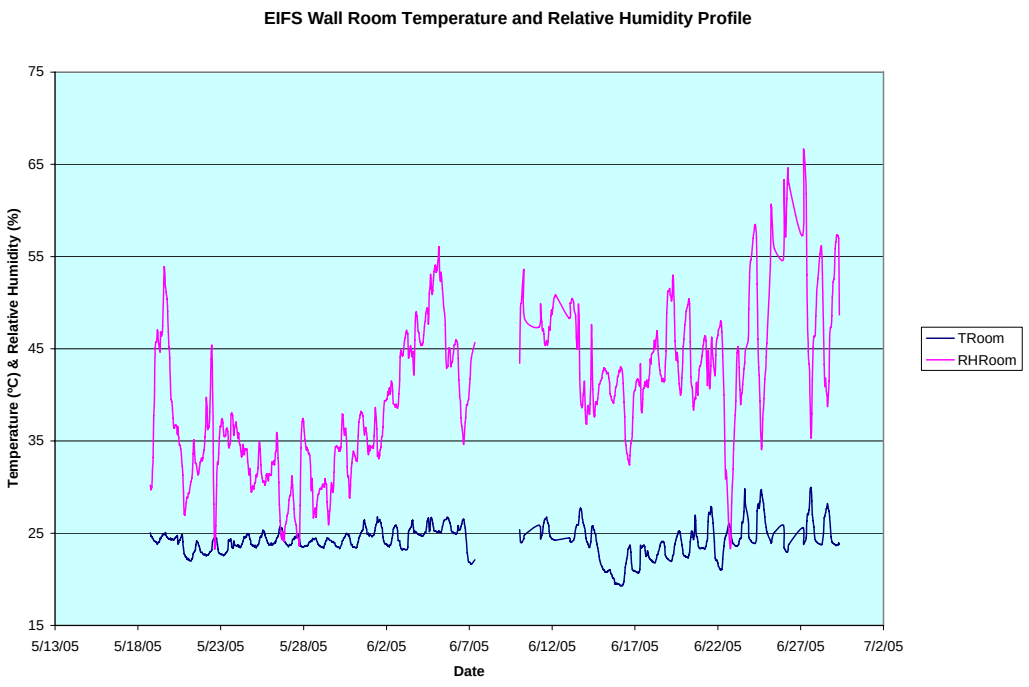


Figure 76 EIFS Assembly Room Temperature and Relative Humidity

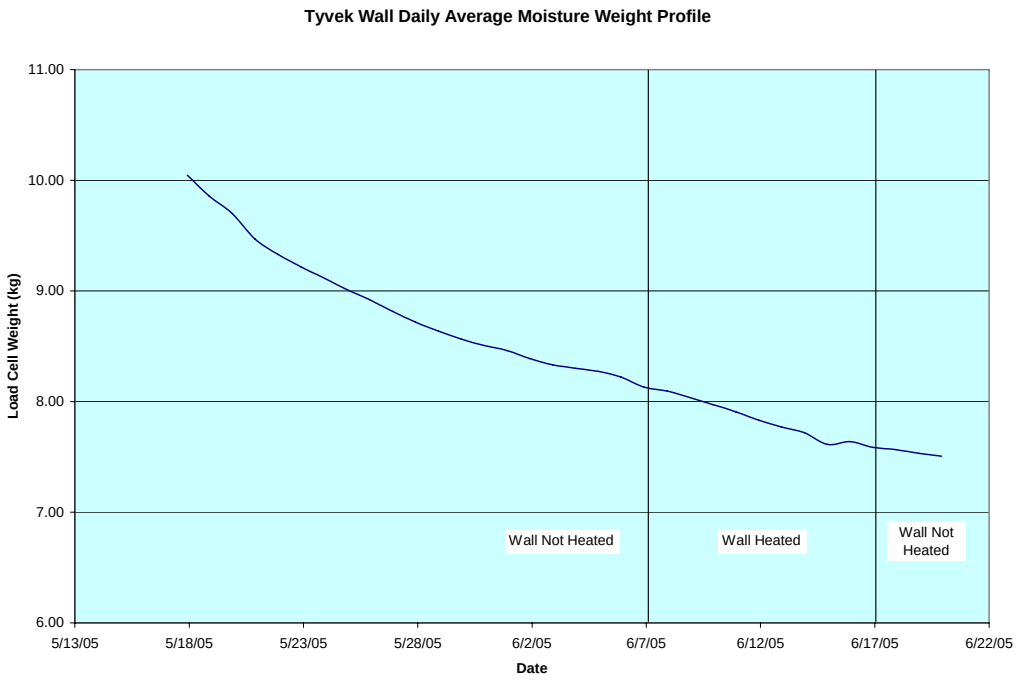


Figure 77 Tyvek® HomeWrap™ Assembly Moisture Weight Profile

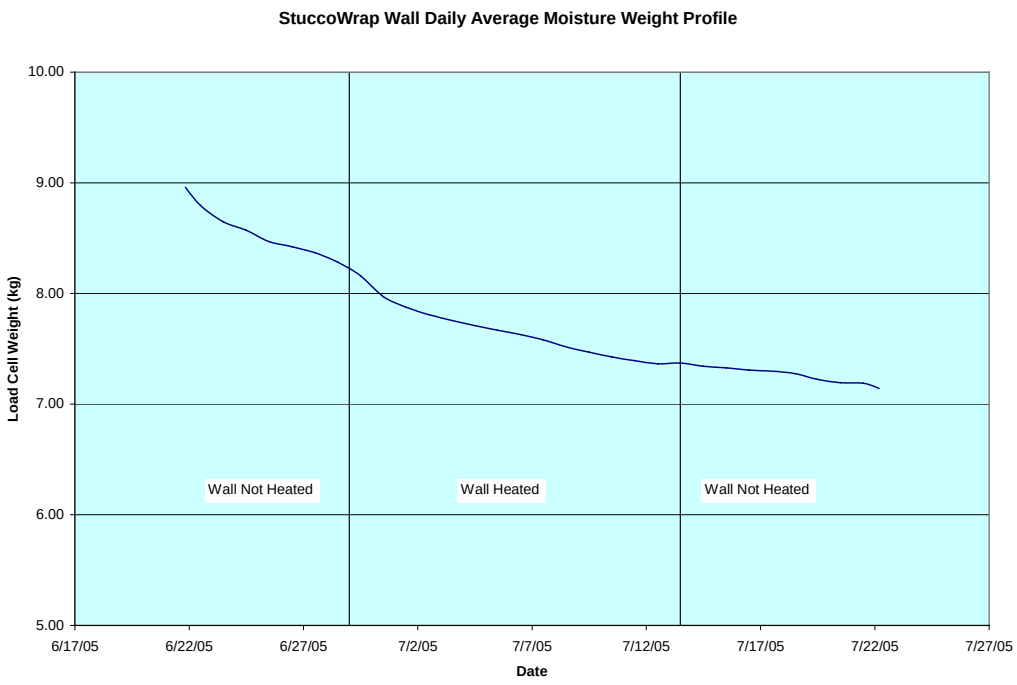


Figure 78 Tyvek® StuccoWrap™ Assembly Moisture Weight Profile

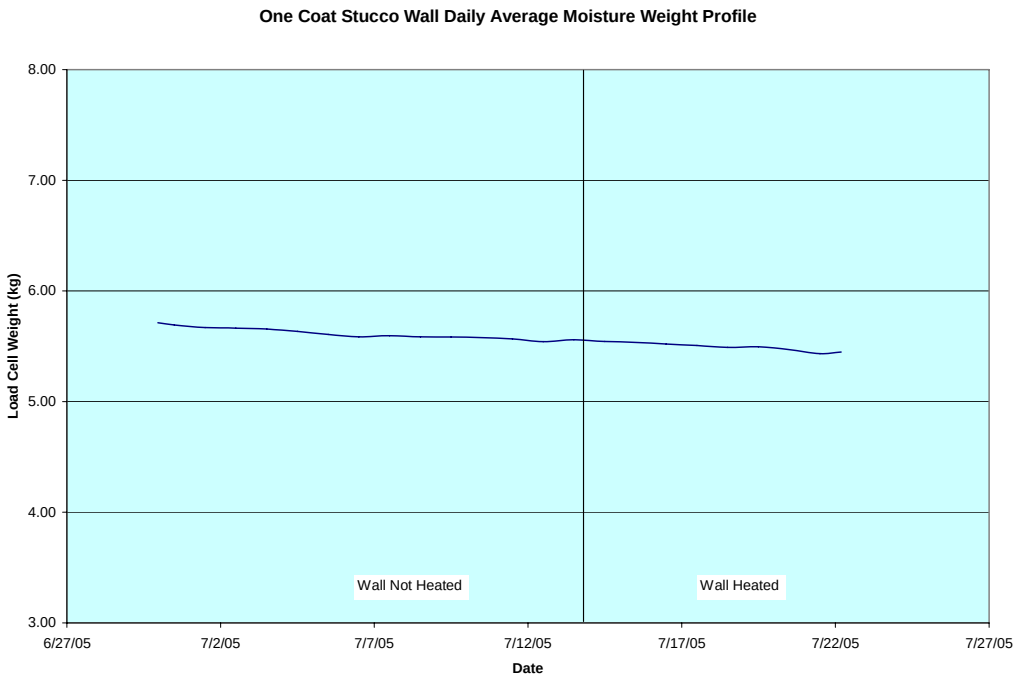


Figure 79 One-Coat Stucco Assembly Moisture Weight Profile

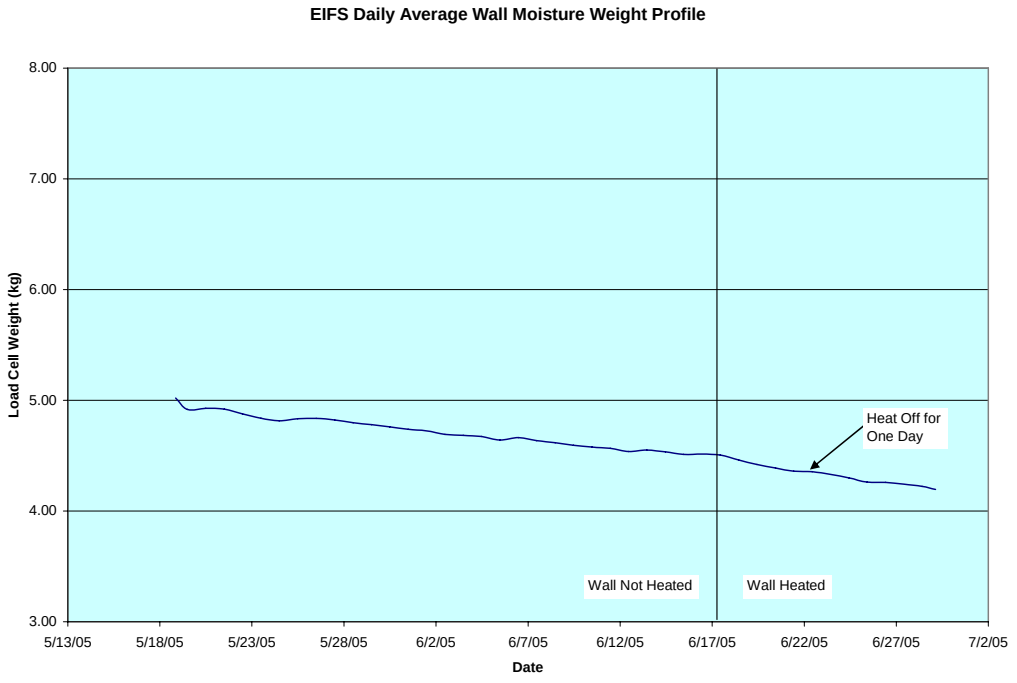


Figure 80 EIFS Assembly Moisture Weight Profile

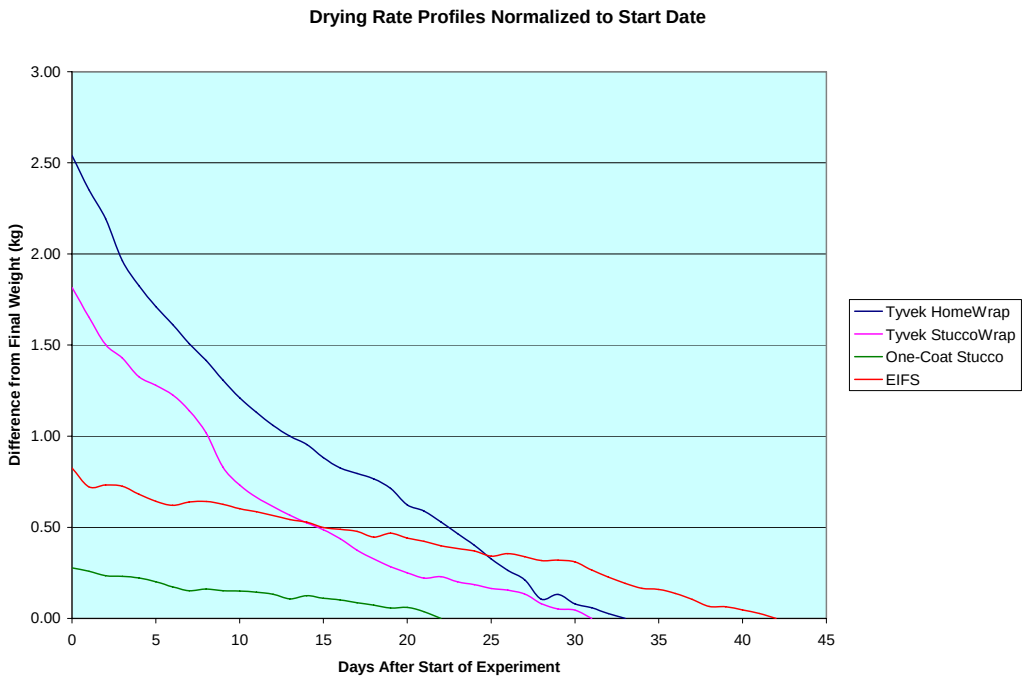


Figure 81 Wall Drying Rate Profiles Normalized to Start Date

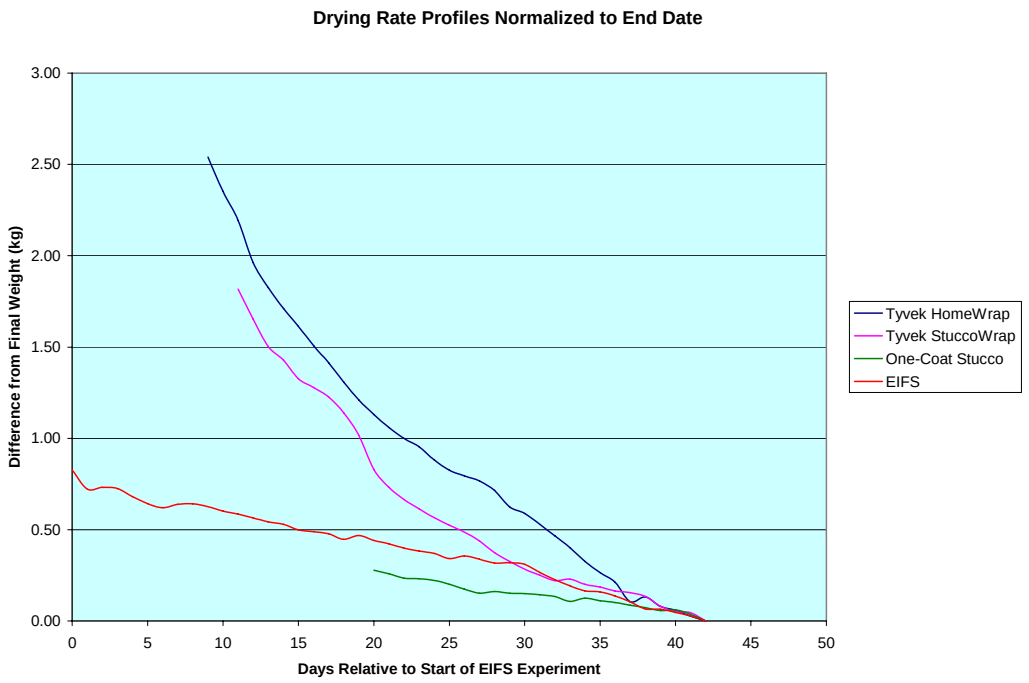


Figure 82 Wall Drying Rate Profiles Normalized to End Date

4.0 Drainage Capacity Experiments

4.1 Goal

The goal of the drainage capacity experiments was to characterize the drainage capacity of selected cladding, WRB, and framing options when subjected to water intrusion between the cladding and WRB.

4.2 Scope

The scope of these experiments was to evaluate the drainage capacities of targeted wall assemblies in the presence of moisture loading conditions in a controlled environmental setting. Wall assemblies included:

1. Three-Coat Stucco, Two Layers Building Paper, OSB Sheathing;
2. Three-Coat Stucco with Drainage Channels, Two Layers Building Paper, OSB Sheathing;
3. Three-Coat Stucco, Higher Perm Housewrap/Building Paper, OSB Sheathing;
4. Three-Coat Stucco, High Drainage Housewrap/Building Paper, OSB Sheathing;
5. Three-Coat Stucco, One Layer Building Paper, Open Frame (no OSB);
6. Cracked Three-Coat Stucco, Two Layers Building Paper, OSB Sheathing;
7. Exterior Insulated Finish System, Two Layers Building Paper, OSB Sheathing; and
8. One-Coat Stucco (Exterior Insulation), Two Layers Building Paper, OSB Sheathing.

4.3 Approach

Water was discharged through a hose nozzle at a controlled and metered flow rate into a 1" high trough inserted at the top of the wall assembly to measure the equilibrium drainage rate. The trough drained the metered water flow between the WRB and stucco. Water flow rate for each assembly was adjusted to maintain approximately ½" water level in the trough for 30 minutes. Equilibrium drainage rate and visual evidence of leakage through the WRB toward the interior side of the assembly were noted.

4.4 Protocols

Experimental protocols were designed to allow exploration of the following hypotheses regarding drainage capacities of targeted wall assemblies:

- Stucco adhering directly to the weep screed without bond break will restrict gravity drainage rate, irrespective of the number or type of WRB layers.
- An engineered drainage system will significantly increase gravity drainage rate.
- Water under any head pressure will leak through staple holes in the WRB.
- Cracks in stucco walls will provide numerous random drainage channels with unpredictable impact on drainage rate and leakage through staple holes in the WRB.

4.4.1 Construction

Wall assemblies were constructed with targeted cladding, WRB, and sheathing options. Interior sides of wall assemblies remained open to permit visual inspection for leaks.

A 1" high metal trough with a slotted bottom opening was inserted between the cladding and WRB and taped and caulked to seal all edges (Figure 83). The slotted opening ran the entire length of the top plate to provide distribution across the full face of the wall. Several small metal wedges were inserted along the length of the slot to maintain a reasonably uniform opening width.

Exterior edges of the wood frames were caulked and sealed with 3 coats of elastomeric paint to prevent leakage between the wood frame and cladding (Figure 84). This was necessary to ensure that all water that was fed into the trough drained only down the WRB or out the front face of the cladding.

4.4.2 Installation and Monitoring

Each wall assembly was hung from the north load cell to facilitate experiments and to enable moisture weight measurements if desired (Figure 85). City water was fed into the trough through a flow meter and hose nozzle (Figure 86). The nozzle was sized large enough to provide acceptable water velocity into the trough at peak flow rates. Based on flow rates experienced and use of metered water, wall weight measurements using the load cell were not considered relevant. For rain simulation experiments, three spray nozzles were directed at the wall assembly to saturate the front side of the cladding to determine the impact on WRB drainage capacity and leakage (Figure 87).

Monitoring comprised manual readings of equilibrium flow rates and visual observation of drainage profiles and leaks to the interior side of the OSB sheathing or WRB. The automated DAS provided wall weight data throughout the experiment period. The originally planned protocol was to characterize moisture capacitance and drainage capacity by feeding small amounts of water into the trough and collect the drained water in a bucket at the bottom of the wall assembly. By comparing readings from the wall weight load cell to the water weight in the bucket, information about the wall capacitance and drainage rates was to be obtained. However, after initial experiments revealed other parameters of interest for these experiments, this protocol was abandoned in favor of the manually read flow meter.

Duration of measurements for each wall assembly was approximately four hours, including setup, initial drainage capacity and leakage data collection, and supplemental drainage capacity and leakage data with rain simulation.

4.5 Observations

Experimental data supported each of the initial hypotheses. Table 5 lists equilibrium flow rates into the trough for each wall assembly without rain simulation. Rain simulation did not impact flow rates for any of the wall assemblies, but did impact leakage through the open frame wall assembly. Flow rates for all stucco wall assembly designs with stucco adhered to the weep screed were an order of magnitude lower than for the two walls with full drainage flow channels. Capillary flow through the front of the stucco dominated in these five wall assemblies, and gravity drainage only trickled at the weep screed (Figures 88 through 92). The open frame wall assembly behaved differently than the other four stucco walls. As shown in Figure 91, the capillary flow through the stucco face was much less than the other four walls. In this wall, the majority of the water flow actually leaked behind the building paper.

The wall with two designed vertical drainage channels increased the flow rate significantly compared to capillary-dominated drainage (Figure 93). However, since these channels did not provide full face gravity drainage at the weep screed, its total drainage capacity was still much lower than the EIFS and cracked stucco wall assemblies, and capillary flow continued to dominate drainage away from the two channels.

Two wall assemblies had significantly higher drainage flow rates, with the maximum measured rate limited not by the WRB capacity, but by the nozzle velocity and the trough slot width. One high drainage capacity assembly was a three-coat stucco wall that had accidentally fallen over onto the stucco face as the finish coat was drying. This cracked the stucco in an unknown way, but provided an opportunity to investigate the impact of stucco cracks on WRB performance. The cracks provided numerous paths for increased gravity drainage, as well as increased capillary flow into the stucco face (Figure 94).

The other high drainage wall assembly was the EIFS with designed drainage mat and weep screed (Figure 95). In this case, the increased gravity drainage capacity was a function of the designed narrow gap between the insulation and the WRB at the drainage mat. Water was able to flow freely to the weep screed whose holes provided designed drainage functionality. This weep screed still provided a screed at

the base of the EIFS assembly, but the drainage holes were not plugged by stucco and were able to drain the water very effectively. Holes in weep screeds in the other walls were filled with stucco (as was the entire sloped face of the screed) and provided no gravity drainage capability (Figure 96). Options to address this issue for conventional weep screeds include de-bonding the stucco from the weep screed, and changing the weep screed detail to provide a clear drainage path.

Restricted gravity drainage dominated by capillary flow resulted in visible leaks to the interior side of three of the five affected wall assemblies. Leaks occurred through the OSB sheathing itself (Figure 97), and at staple holes through the OSB (Figure 98). The open frame construction with a single layer of building paper exhibited the greatest amount of visible leakage (Figures 99 and 100), but it is not known whether there was leakage at the exterior side of OSB sheathing, since that surface was not visible. Neither of the high drainage capacity walls experienced any visible leaks.

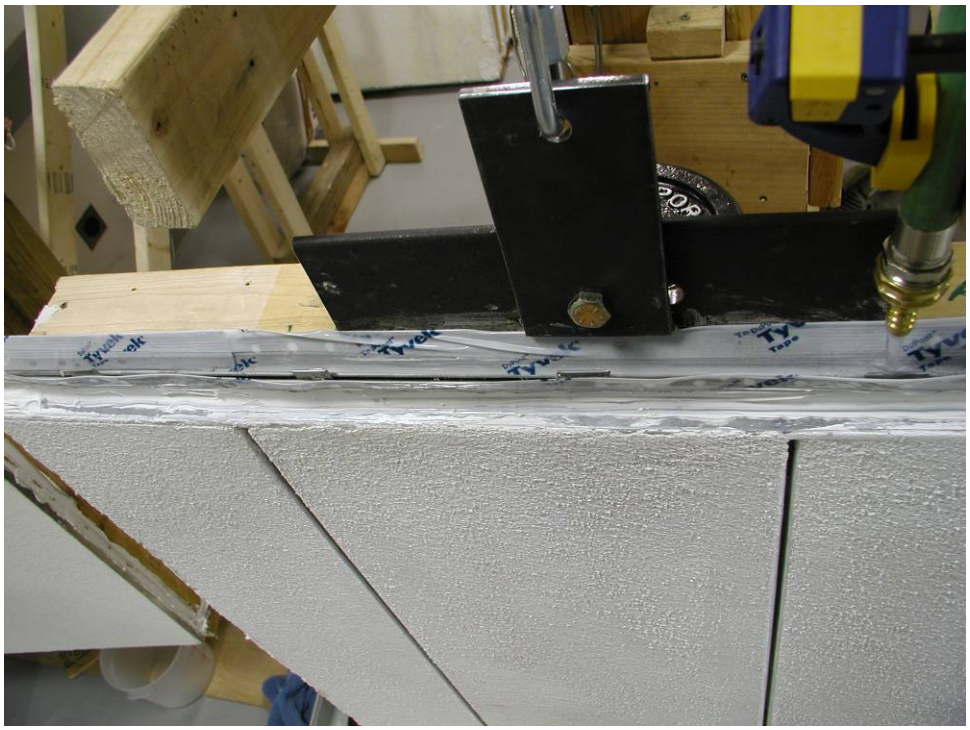


Figure 83 Slitted Trough Between Cladding and WRB for Drainage Capacity Experiments

Figure 84 Caulked and Sealed Wood Studs for Drainage Capacity Experiments

Figure 85 Wall Hanging Apparatus for Drainage Capacity Experiments

a) Water Flow Meter

b) Flow Nozzle

Figure 86 Water Meter and Flow Nozzle for Drainage Capacity Experiments

Figure 87 Rain Simulation Nozzles for Drainage Capacity Experiments

Table 4 Wall Assembly Equilibrium Flow Rates into Trough

Building Assembly	Equilibrium Flow Rate into Trough (gpm)
Three-Coat Stucco, Two Layers Building Paper, OSB Sheathing	0.10
Three-Coat Stucco, Higher Perm Housewrap/Building Paper, OSB Sheathing	0.15
Three-Coat Stucco, High Drainage Housewrap/Building Paper, OSB Sheathing	0.15
Three-Coat Stucco, One Layer Building Paper, Open Frame (no OSB)	0.20
One-Coat Stucco (Exterior Insulation), Two Layers Building Paper, OSB Sheathing	0.20
Three-Coat Stucco, Drainage Channels, Two Layers Building Paper, OSB Sheathing	0.30
Cracked Three-Coat Stucco, Two Layers Building Paper, OSB Sheathing	>1.3
Exterior Insulated Finish System, Two Layers Building Paper, OSB Sheathing	>1.3

.

a) Trickle Drainage at Weep Screed b) Dominant Capillary Flow Through Stucco Face

Figure 88 Drainage Profile, 3-Coat Stucco, 2 Layers Building Paper, OSB

a) Trickle Drainage at Weep Screed b) Dominant Capillary Flow Through Stucco Face

Figure 89 Drainage Profile, 3-Coat Stucco, Housewrap/Building Paper, OSB

a) Trickle Drainage at Weep Screed b) Dominant Capillary Flow Through Stucco Face

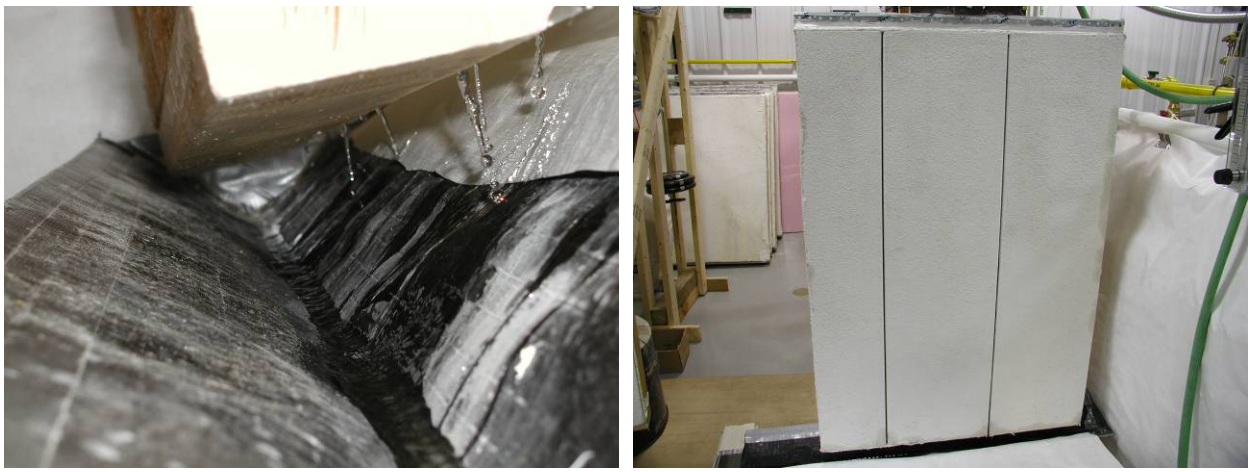
Figure 90 Drainage Profile, 3-Coat Stucco, High Drain Housewrap/Building Paper, OSB

a) Trickle Drainage and Leak Flow at Weep Screed b) Little Capillary Flow Through Stucco Face

Figure 91 Drainage Profile, 3-Coat Stucco, 1 Layer Building Paper, Open Frame

a) Trickle Drainage at Weep Screed b) Dominant Capillary Flow Through Stucco Face

Figure 92 Drainage Profile, 1-Coat Stucco, Insulation, 2 Layers Building Paper, OSB



a) Increased Drainage at Channels Only b) Limited Capillary Flow Through Stucco Face

Figure 93 Drainage Profile, 3-Coat Stucco with Drainage Channels

a) High Gravity Drainage at Weep Screed b) High Capillary Flow Through Stucco Face

Figure 94 Drainage Profile, Cracked 3-Coat Stucco, 2 Layers Building Paper, OSB

a) Full Gravity Drainage at Weep Screed b) No Capillary Flow Through EIFS Face

Figure 95 Drainage Profile, EIFS, 2 Layers Building Paper, OSB

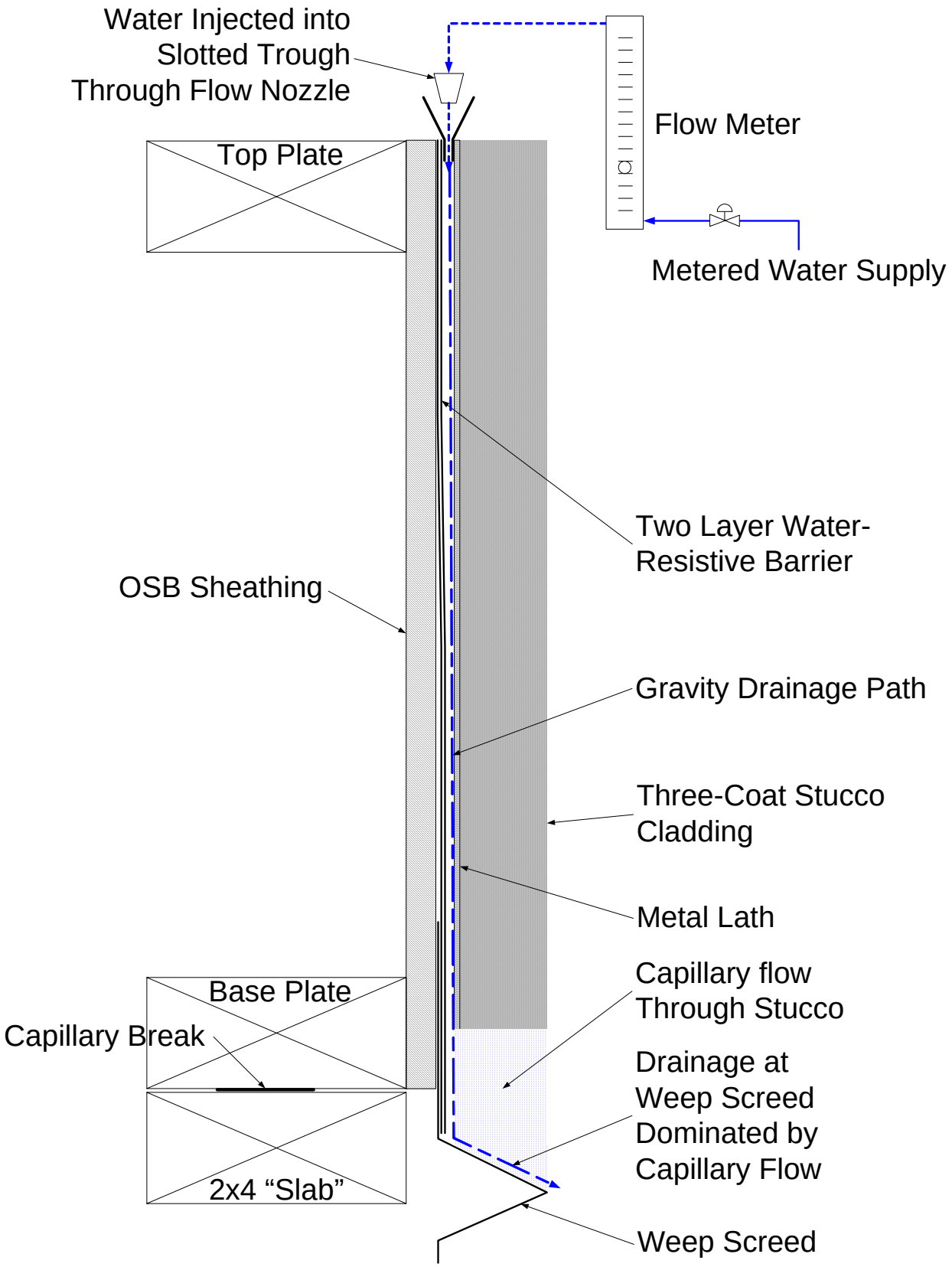


Figure 96 Capillary Flow at Weep Screed with Water Injected at WRB Interface

Figure 97 Leakage Through OSB Sheathing with Drainage Dominated by Capillary Flow

Figure 98 Leakage Through Staple in OSB with Drainage Dominated by Capillary Flow

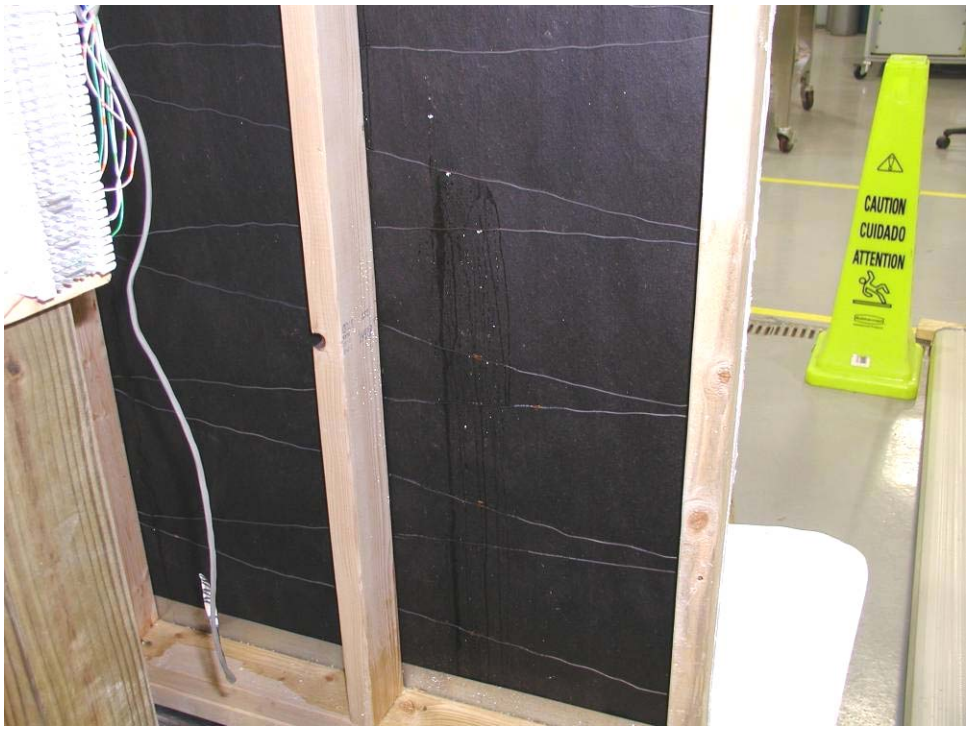


Figure 99 Leakage Through One-Layer Building Paper with Open Frame Construction

Figure 100 Leakage at Top Plate with Open Frame and Rain Simulation

5.0 Conclusions and Research Recommendations

5.1 Conclusions

Data collected under Task 3.2 provided evidence of the beneficial impact of mold-resistant materials on mold formation and growth, but only on the materials themselves. The experiments also provided information on drying rates and impact of thermal loading on wall cavity moisture profiles. Finally, drainage capacity experiments demonstrated the importance of providing adequate space for gravity drainage. A capillary break between the stucco cladding and WRB is required for optimal gravity drainage. Additionally, a double layer WRB is essential for stucco walls, with a sacrificial exterior layer for bond break and an interior layer for gravity drainage.

All of the test protocols used in this task were tailored to meet project goals and did not use consensus methods such as ASTM standards. Consequently, all project results are considered informative, but not authoritative. Nonetheless, many of the project results were sufficiently compelling to warrant further research.

5.2 Research Recommendations

Research recommendations based on Task 3.2 laboratory evaluations focus on three major initiatives::

1. Collect and analyze laboratory and field data on root causes and consequences of building envelope failures to identify and evaluate alternative mold risk reduction strategies for homes with stucco cladding.
2. Develop and evaluate laboratory and field performance test methods for integrated cladding and wall assemblies. The test methods should be realistic and relevant, supported by field data and validated models.
3. Perform laboratory and field moisture content and drying rate measurements of new and innovative building assemblies using consensus test methods to provide additional data to validate hygrothermal models.

The root cause field data collection and analysis program comprises a data collection effort involving laboratory experiments, laboratory house data collection and analysis, and targeted new homes representing a full cross section of California construction and climate zones. The overall goal is to link moisture parameters with appropriate home construction parameters to enable authoritative root cause analysis of moisture and mold problems. Only by understanding these relationships can the building community move from the current status of experience-based "building art" to data-based "building science" and provide robust solutions to important problems.

Development of the integrated assembly performance test methods should focus on voluntary standards development processes such as ASTM. As inputs to that process, the research community should conduct additional research using reasonable test methods developed by industry experts.

Moisture and drying rate measurement should be conducted by research organizations such as universities using protocols developed in conjunction with hygrothermal model developers to ensure that the measured data is of adequate quality and in a format that is useful for model validation.