Moisture Performance Comparison of Typical Residential Wall Assemblies

Prepared for

The Brick Industry Association

Prepared by

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Disclaimer

Table of Contents

List of Tables

List of Figures

APPENDICES

EXECUTIVE SUMMARY

This year-long field moisture study, which appends previous research conducted in 2008, examined the moisture performance of a brick wall assembly relative to seven other common wall assemblies. While the study focuses on the performance of the brick wall system, graphical results are included for all 8 wall assemblies and comparative results are presented as appropriate.

The brick veneer wall assembly was the driest of the eight wall types. On an annual basis, sheathing and 2x4 wood studs in the brick veneer wall had the lowest moisture content in both the north and south orientations. The dark color and thermal mass of the brick veneer wall contributed to higher wall cavity temperatures which resulted in drying of the studs and sheathing. The one inch air space is also believed to contribute to the removal of moisture from the brick veneer wall assembly.

The primary findings reported in this paper are: Under normal weather exposure, the studs and sheathing in all walls investigated remained well below 19 percent moisture content. South-facing walls with direct solar exposure consistently resulted in dryer sheathing. The non-absorptive vinyl sided wall had the second lowest sheathing moisture content recorded in the study. Solar gains on darker south-facing walls such as the manufactured stone and brick veneer walls contributed to the drying capability of the wall assemblies.

Controlled injections of water behind the cladding indicated that some walls were less able to drain (or otherwise dissipate) the injected water than were others. Stucco-clad walls with only one layer of water-resistive barrier (WRB) showed the least ability to dissipate injected water. Walls with manufactured stone cladding (which incorporated two layers of WRB) showed lesser ability to dissipate injected water than walls with most of the other cladding systems, but greater ability than stucco-clad walls with a single layer of WRB.

Computer simulations using WUFI predicted moisture levels that differed from actual results, both in magnitude and seasonal phase, which may warrant further investigation of the WUFI assumptions.

INTRODUCTION

The increase in moisture-related problems in new residential homes, combined with the increasing popularity of absorptive claddings in moist climates led to a 2008 field study of the moisture performance of wall assemblies in the mixed-humid climate. The study examined eight wall assemblies that were sheathed with OSB or plywood, clad with stucco, manufactured stone, brick veneer, or vinyl siding, and had three types of WRBs (single-ply felt, double-ply felt, or spun-bonded polyolefin).

The study examines the hygrothermal performance of wall assemblies in an attempt to determine what types of assemblies perform best in a mixed-humid climate, which factors affect their performance, and how lessons can be applied to wall design in order to enhance the durability of energy efficient wall assemblies.

Moisture issues have become a growing concern in residential construction, particularly as building envelopes have become tighter. In recent years, excessive moisture in the exterior walls of residential buildings has garnered a great deal of attention, especially in walls with exterior claddings capable of absorbing moisture including rainwater and interior vapor diffused through the wall assembly. As a result of both increased energy codes and growing consumer demand for comfortable and energy-efficient homes, modern construction practice includes walls that are highly insulated and sealed against air infiltration. Walls in older, leakier homes were more able to sustain repeated wetting and drying without moisture accumulation, whereas the walls of newly constructed homes allow less opportunity for natural drying. Therefore, to enhance the durability and sustainability of energy-efficient buildings, it is important to understand the moisture dynamics within different types of wall assemblies.

Every climate has its own unique characteristics that must be considered when designing a wall system. The mixed-humid climate is defined as a region that receives more than 20 inches of precipitation and has less than 5,400 heating degree days (base 65°F) annually, and in which the average monthly winter temperature is below 45°F. This combination of conditions creates a situation where moisture typically migrates from the inside of a structure out during the winter and from the outside in during the summer. These dynamic hygrothermic conditions can be problematic for certain wall assemblies.

Before determining which wall assemblies work better than others in a given climate, it is important to understand the threshold at which the moisture content of wood can begin to cause problems of decay and compromised performance. Wood building materials and assemblies constructed of wood and wood-based products perform best when they remain in a dry condition. Prominent organizations in the wood industry have generally defined a dry condition as moisture content (MC)[1] for engineered wood

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[1] National Design Specification for Wood Construction 2005 Edition, C9.3.3 Page 219

products[2] (EWP) of less than 16 percent, and MC for solid wood[3] of less than 19 percent. When wood products are used in conditions where moisture contents exceed these levels, Wet Service Factors must be applied for structural considerations. This results in reduced material strength and stiffness design properties that engineers apply to wood designs when they expect that in-service moisture conditions will exceed these thresholds (16% for EWP; 19%for wood). The primary reason the threshold moisture content is lower for engineered wood products than for solid wood is that engineered wood products have lower equilibrium moisture contents than solid wood at equivalent relative humidity conditions[4].

The dry design threshold conditions are essentially equivalent to equilibrium moisture conditions with room temperature air and a relative humidity just below 90 percent. This also corresponds with a moisture level just below the long-recognized 20 percent moisture-content threshold for wood, which will prevent propagation of decay, even in wood previously infected with decay fungi[5]. In fresh, un-infected wood and wood products, decay is only likely to be established when moisture content exceeds the fiber saturation point (average 30% MC in lumber) at temperatures between 50 and 95°F[6]. The long-recognized 20 percent threshold provides a margin of safety with regard to preventing decay propagation.

While ensuring the prevention of decay propagation, the 20 percent wood MC threshold will not guarantee prevention of all moisture-related problems in light-frame construction. The risk of wood infestation by insects (primarily carpenter ants and termites) is related to moisture content; this risk decreases over the 30 to 20 percent MC range, and continues to decline as moisture levels drop below 20 percent MC. Corrosion of fasteners embedded in wood is also related to moisture content. The moisture condition below which corrosion of carbon steel fasteners in (untreated) wood is essentially prevented ranges from roughly 10 to 14 percent MC[7]. The mold growth prevention criteria outlined in ASHRAE Standard 160 consists of three time/temperature/surface relative humidity criteria. The criterion with the longest time duration element (30 days) specifies that surface relative humidity not exceed 80 percent; this corresponds with a wood moisture content of 16 percent (and an OSB moisture content of 13%[8]) at room temperature.

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[2] Engineered wood products include wood structural panels, structural glued laminated timber (glulam), structural composite lumber (SCL) and I-joists .

[3] *National Design Specification for Wood Construction* 2005 Edition, C4.1.4 Page 193

[4] APA Engineered Wood Handbook (ISBN 0-07-136029-8) 2002.

[5] Carll, C. and T. Highley, *Decay of wood and wood-based products above ground in buildings.* ASTM Journal of Testing and Evaluation 27(2):150-158 (March 1999)

[6] *Wood Handbook - Wood as an Engineering Material* 1999 Page 13-4

[7] Cole, I., G. Trinidad, and W.Chan. *Prediction of the impact of the environment on timber components: a GIS-based approach.* Proceedings Durability of Building Materials and Components-8, National Research Council Canada (ISBN 0-660-17737-4 (Vol. 1) 1999.

[8] Table 2 in Chapter 4 of ASTM MNL18-2 *Moisture Control in Buildings: The Key Factor in Mold prevention 2nd Edition.* (ISBN 978-0-8031-7004-9) 2009.

Study Objective

The objective of this research is to quantify the field moisture performance of typical residential wall assemblies. Performance was based on in-situ moisture content of the wood-based sheathing and the wood framing as well as the relative humidity within the wall cavity during a one-year monitoring period.

The experiment was designed to identify wall systems that are capable of maintaining acceptably dry conditions within wall cavities in a mixed-humid climate, to determine the moisture performance of different cladding and drainage systems, and identify how well wall assemblies dry once wetting occurs.

Technical Approach

The brick veneer wall assembly was constructed in a test structure with two other wall sections and parallel to an existing test structure containing five wall sections having similar orientation and solar exposure based on a solar site survey. All eight wall sections were selected based in part on their computer-simulated moisture performance, and in part on their prevalence in new construction. Computer-based moisture modeling was first used to identify wall assemblies that would be expected to exhibit a range of performance characteristics in the mixed-humid climate. Final selection of the wall sections was made by industry professionals on the basis of their common use and practical constructability.

A pair of walls for each of the eight sections was installed in two test structures constructed on the NAHB Research Center campus. The interior of each test structure was climate-controlled to simulate indoor conditions, while the exterior cladding was exposed to ambient conditions. Detailed measurements of indoor and outdoor environmental conditions and the moisture content of studs and sheathing were used to determine hygrothermal performance of each wall assembly.

Methodology

The design of the study attempted to address the primary drivers for moisture accumulation in wall assemblies: vapor diffusion through the wall layer(s); vapor movement entrained in air movement; and bulk water (rain) leakage past the cladding system and the water-resistive barrier (WRB). It uses a three-pronged approach to assess the moisture performance of a selected set of absorptive claddings.

1) Computer simulations to determine the expected range of performance of a variety of possible wall assemblies.
2) Long-term monitoring of a full-scale test structure.
3) Short-term monitoring of bulk moisture injections. Concurrent with exposure of instrumented wall sections, moisture injections were performed to understand the ability of each wall system to dry.

Moisture Simulations

Computer simulations were performed during an early phase of the study to determine the range of expected performance for each of the cladding systems. Various wall systems were modeled and the expected performance was used, to some degree, to guide the selection of cladding systems used in the field research.

The simulation software program selected for this study was WUFI® Pro version 4.2, which calculates one-dimensional transient heat and moisture transport in multilayer building assemblies. Moisture content predictions from the computer simulations, along with field measurements, can be found in Appendix D.

Preliminary simulations predicted that moisture levels in the sheathing would fall between 6 and 20 percent, with higher moisture levels predicted on north-facing walls. The highest sheathing moisture level (20%) was predicted to occur in February in the north-facing wall with manufactured stone cladding. In south-facing walls, no sheathing moisture readings were expected to exceed 11 percent in any of the eight walls.

Test Structure Construction

Two test structures were placed on the grounds of the NAHB Research Center in Upper Marlboro, Maryland, approximately 20 miles east of Washington, D.C. The first structure, commissioned in January 2008, is a post-and-beam design with a nominal footprint of 8’x48’ (Figure 1). The design of the test structure allowed for five pairs of 8’x9’ wall test panels to be installed as exterior wall sections, with one panel of each pair having southern exposure and the other having northern exposure. The second structure was prefabricated, trucked on-site, and commissioned in November 2008. It was designed with the same 8’x48’ footprint and also able to hold five pairs of 8’x9’ walls. Prior to placing the structure on site, a solar site analysis confirmed that the walls in both test structures would have nearly identical solar exposure. In both test structures, wall panels can be removed and replaced for subsequent testing.

The 8’x9’ test panels were framed with nominal 2”x4” wood studs, sheathed with OSB or plywood, and clad with various siding and drainage strategies (see Table 1). A window is located on the west end of the test structure and an entrance door is located on the east. The interior of both test structures was finished with ½-inch drywall and wall cavities were insulated with R-13 Kraft-faced fiberglass batts. The perimeter of each wall section was caulked to eliminate extraneous air infiltration. Each wall pair incorporated two penetrations of modest size: a dryer vent, which fully penetrated the wall, and an electrical outlet, which penetrated only the wall’s interior finish (drywall) and the Kraft facing of the batt insulation. Caulk was applied at the perimeters of each of these penetrations to prevent air infiltration.

Floors of both test structures were raised approximately two feet from the ground and insulated with R-19 fiberglass batt insulation; roofs were shingled on 4/12 pitch trusses and insulated to R-30 at the attic ceiling interface.

Figure 1: South-facing walls of test structures (building 1 right, building 2 left)

Roof overhang was limited to the four-inch gutter and, therefore, test panel exteriors had appreciable exposure to the elements. Gable end walls were clad with horizontal lap vinyl siding over a WRB and OSB. All products were installed in accordance with manufacturer recommendations or, if recommendations were unavailable, in accordance with the prevailing building code.

Two portable air conditioners limited the maximum interior summer temperature to 78°F and resistance heat maintained wintertime indoor temperature at 70°F. There were occasions in the summer when the air conditioners could not maintain 78°F, but both units deviated similarly from the temperature at which each was set. A humidifier maintained indoor relative humidity between 25 and 30 percent in the winter months.

Wall Panel Assemblies

The eight wall panel sections evaluated in the study are outlined in Table 1.

Table 1: Test Wall Configurations

Panel #	Test Structure	Sheathing	WRB	Exterior Finish
1	1	7/16" OSB	Spun bonded polyolefin WRB	Vinyl siding
2	1	7/16" OSB	1 layer No. 15 felt	Stucco
3	1	7/16" OSB	2 layers No. 15 felt	Stucco
4	1	7/16" OSB	WRB 3/8" air gap No. 15 felt	Stucco
5	1	7/16" OSB	2 layers No. 15 felt	Manufactured stone
6	2	7/16" OSB	Spun bonded polyolefin WRB	Fiber Cement Siding
7	2	½" Plywood	2 layers No. 15 felt	Stucco
8	2	7/16" OSB	Spun bonded polyolefin WRB	Brick with 1" air space

To reduce unintentional variability, wall panels 1 through 5 were constructed in the first test structure and similar materials came from a common lot. The brick panel and panels 6 and 7 were in the second test structure and were constructed about 10 months later with similar materials from the same supplier, but from a different lot from the first building. Walls were framed using nominal 2”x4” wood studs spaced at 16-inches on-center with single bottom and double top plates, ½-inch drywall with two rolled-applied coats of latex paint, R-13 face-stapled Kraft-faced batt insulation, and 7/16-inch OSB structural sheathing.

Viewed from the test structure’s interior, the right half of each 8’x 9’ panel was 4-feet wide and consists of three stud bays. The right half of each panel was without penetrations. In this half, the left and right bays functioned as buffer zones to minimize the influence of adjoining wall sections, while the middle stud bay provided the data for the diffusion analysis. On the left half of each panel, the three stud bays had wall cavity penetrations typical of residential construction. The left-most stud bay had a 4-inch dryer vent penetration, and the center stud bay had framing for a sill plate supported by cripple studs.

The center stud bay was designed to simulate a window opening. Because leakage of installed windows varies, windows were not installed. Instead, two ¼-inch dosing tubes were installed to allow controlled injection of water to simulate leaks. As reported previously, water leakage events were simulated on four occasions during the later months of the monitoring period. The first three leakage events were independent one-day injections that resulted in no increase in moisture content of the sheathing. The fourth leakage event was performed over five consecutive days.

Figure 2: Interior face of one wall showing dosing tubes, and dryer vent penetration

Panel 1: Vinyl Sided Wall

The vinyl sided panel (unbacked) was constructed with vinyl siding over a single layer of spun-bonded polyolefin WRB (Tyvek® HomeWrap®) installed in compliance with provisions in Table R703.4 of the 2006 IRC. Vinyl siding was chosen as the baseline for comparison because it is the most frequently installed cladding on new houses[9] and, due to its non-absorptive properties, its performance was expected to contrast the absorptive cladding systems on the other seven wall panel pairs.

Panels 2 through 4: Stucco Clad Walls

Each of the three stucco walls was constructed with an exterior cladding of Portland cement-based material that is designed to serve as a scratch and finish coat material. Stucco was applied over ASTM D226 compliant No. 15 felt to a final thickness of between ½- and ⅝-inches. The felt was stapled to the sheathing or furring strips with ⅜-inch length and 1-inch crown staples and the wire lath was stapled using with ½-inch crown and ¾-inch length staples at 16-inches on-center.

Panel 2: Stucco Clad Wall—One Layer of Felt

Although the 2006 IRC no longer permits stucco cladding over a single layer WRB, this system was tested because it was constructed with some regularity prior to the adoption of the 2006 IRC and some jurisdictions at the time of construction still accept a single layer WRB (including the county in which the NAHB Research Center is located).

Panel 3: Stucco Clad Wall—Two Layers of Felt

The second stucco-clad wall assembly included two layers of building paper but, instead of using two layers of Grade D paper as outlined in Section R703.6.3 of the 2006 IRC, it included two layers of ASTM D-226 Type 1 felt (e.g., No. 15 felt paper) which is the predominant practice in the region. With this construction, the inner layer WRB functions as the drainage plane while the outer WRB bonds to the scratch coat and thus is unable to function effectively as a drainage plane.

The difference between Grade D paper and Type 1 felt is primarily in the permeance of the materials. Grade D paper has a permeance in excess of 10, whereas No. 15 felt usually has a permeance of around 5. The felt used in the test, however, had a wet cup permeance of over 13. Some jurisdictions have amended Section R703.6.3 to include No.15 felt as being acceptable under Portland cement exterior claddings.[10]

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[9] http://www.census.gov/const/C25Ann/sftotalexwallmat.pdf

[10] The state of Minnesota has amended section R703.6.3 of the 2006 International Residential Code to also accept 2 layers of #15 felt under plaster wall coverings.

Panel 4: Stucco Clad Wall with Vented Cladding

A rain screen, or vented cladding, system was installed on Panel 4 in accordance with the latest building science recommendations. By creating an air gap between the cladding and the structural wall, a vented cladding system assists in the drying process of the wall assembly. The air gap helps with three mechanisms at work in the drying process: gravity drainage of bulk moisture that gets behind the cladding; removal of water vapor that has diffused out of the wall assembly toward the outside; and removal of water vapor that has diffused through the stucco toward the inside.

Although proprietary systems are available to vent cladding, an airspace was created in the test panel by adding 1½”-wide by ⅜”-thick (10mm) furring strips (cut from plywood) spaced 8-inches on-center over a spun-bonded polyolefin WRB. The venting was designed such that it was open at the bottom and sealed at the top. Lath and stucco were applied over a single layer of No. 15 felt. In order to maintain the ⅜-inch ventilation gap, temporary strips were placed in the ventilation cavities during the application of the stucco scratch coat.

Panel 5: Wall Clad with Manufactured Stone

Manufactured stone products are generally cast concrete, which is composed of portland cement, aggregate, and pigments. They look and feel much like natural stone. They can be installed as a decorative veneer in both interior and exterior locations. The manufactured stone (cast concrete) cladding was installed similarly to the stucco in Panel 3 with two layers of No. 15 felt paper as the WRB. Type S mortar mix was used for the scratch coat and grout. The stone was darker in color than the other four wall claddings and the thickness of the stone varied between 1 and 2-5/8 inches.

Panel 6: Stucco Wall with Plywood Sheathing

Panel 6 is constructed identical to Panel 3 except ½” plywood sheathing is used instead of 7/16” OSB. Plywood is the second-most common sheathing and was expected to perform differently due to its permeability characteristics which differ from OSB.

Panel 7: Fiber Cement Wall

In Panel 7, fiber cement siding was installed over spun bonded polyolefin WRB and OSB sheathing. The wall system was selected to compare the properties of fiber cement, which has gained significant market share for claddings over the last few years with other popular claddings. The siding was painted with cream color exterior latex paint and no caulk was applied at butt joints.

Panel 8: Brick Veneer

The brick veneer wall was constructed with a one inch air space behind the brick. A 1/2 inch slot at the top of the wall allowed the air space to vent into the attic. The nominal 4 inch bed depth brick was laid in Type N masonry cement mortar. Flashing was installed under the first course of brick and open head joint weep holes were installed at 24 inches on center immediately above the flashing.

Bulk Moisture Experiments

Each wall section was subjected to five consecutive days of simulated water intrusion to determine the wall systems' ability to dry after wetting due to a leak. Water intrusion events were simulated by injecting 30 milliliters of water behind the cladding system through each of two, ¼-inch hoses.[11] The hoses terminated on opposite sides of the WRB; one terminated between the WRB and the cladding (or between the WRBs when two WRB layers were present), and the other terminated between the WRB and the sheathing. The moisture sensors in the sheathing detected any accumulation of water in the sheathing; readings over time indicated the wall assemblies' ability to dissipate moisture.

Wall Material Permeability

Each material used in construction of the walls was tested to determine its permeability in order to compare and correct, if necessary, physical properties used in the moisture modeling and also to determine if there were any large deviations from expected results.

Table 2: ASTM E96 Results

Material	Thickness	Density	Permeance (Perms)	
	(in)	(lb/ft^3)	Dry Cup	Wet Cup
Drywall	0.489	37.9	48	44
Painted drywall	0.496	38.6	40	40
OSB	0.448	41.5	4.1	4.5
Plywood	0.475	33.4	0.72	3.3
Stucco	0.758	51.2	4.3	5.5
Manufactured stone (trimmed)	0.767	99.9	2.8	5.1
Spun bonded polyolefin	0.005	35.4	36	35
No. 15 asphalt paper	0.018	68.3	6.9	13.9
Stud (trimmed)	0.699	21.5	0.6	6.1
Kraft paper from batt insulation	0.006	36.2	3.4	3.8
Fiber cement siding	0.314	90.6	3.2	13.2

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[11] Sixty ml of water, were it all to be absorbed uniformly by a rectangular prism of OSB measuring 14.5" by 30" by 7/16", would raise the OSB's moisture content by approximately 2.7% moisture content. Such an increase would be readily detectable by the instrumentation.

Two materials – OSB and painted drywall had notably higher permeability than expected. The OSB was roughly twice the permeability and the painted drywall was over 10 times more permeable than expected based on both manufactures' literature and the ASHRAE Handbook of Fundamentals. The permeability of the remaining materials was as anticipated.

Wall Sensors

Sensor Placement and Data Collection

Forty-four sensors capable of recording temperature, relative humidity, and wood moisture content were installed in each wall section. Each sensor (pictured in Figure 3) includes two, 2-inch stainless steel screws that secure each device to wood framing or OSB sheathing and penetrate ⅜-inch into the substrate to obtain a conductance reading correlated to substrate moisture content. The sensors are capable of measuring moisture content between 7 and 40 percent, temperature between negative 40°F and 185°F, and relative humidity from 0 to 100 percent at programmable time intervals. Data was transmitted wirelessly from the sensors every 30 minutes during the testing period to researchers via the internet. Sensor placement is depicted in Figure 4.

All moisture readings were taken using a conductance meter calibrated to Douglas fir moisture content. Moisture content readings were calibrated for each wood type: studs, OSB, and plywood, and gravimetrically adjusted accordingly.

Figure 2. Wireless temperature, humidity, and wood moisture sensor

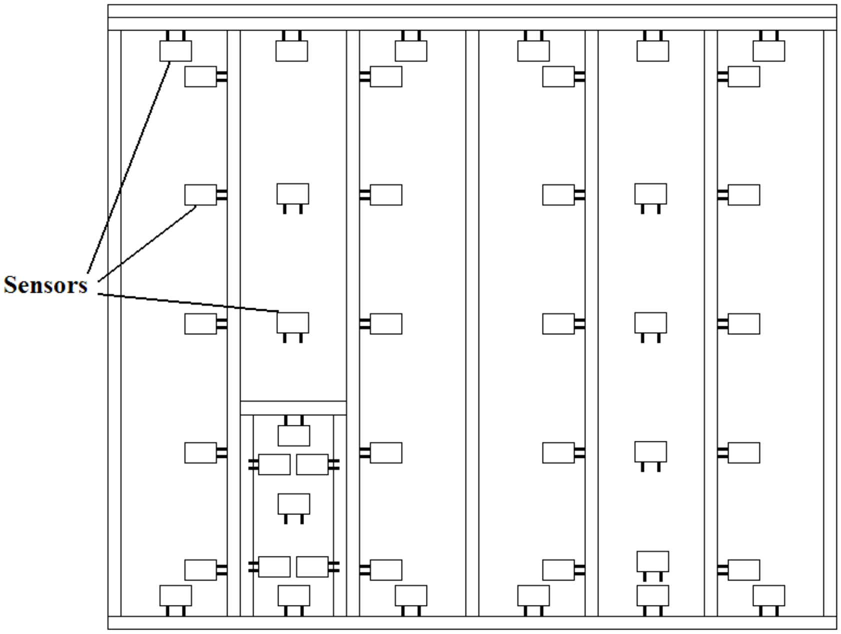


Figure 3. Sensor placement and wall framing

Data Acquisition and Control of Indoor Conditions

In addition to the net-connected wireless sensors installed in the walls, a separate data acquisition system and controller was installed in the test structure to record and control indoor temperature and relative humidity conditions. The datalogger was programmed to read temperature and relative humidity sensors every five seconds, and to average and record data every 30 minutes. Appendix D contains photographs of the indoor instrumentation.

Results and Data Analysis

Data was gathered for all eight wall sections for 12 months between November 1, 2008 and November 1, 2009. The five original walls were monitored an additional 10-months from January 2008 through November 1, 2008. Data was eliminated from 15 of the 704 sensors due to malfunction. Weather conditions during this time were close to 30-year historical average conditions for the region. Summer cooling degree days were about 20% lower than historical average, winter heating degree days were within 1% of average, and rainfall was 5% lower than historical average. Appendix B details the monthly weather data.

Wind Driven Rain

Wind-driven rainfall at the wall surface was measured and found to be approximately 20% greater on the north wall surface than the south wall surface. However, no direct relationship could be established between increased moisture readings and wind driven rain events compared to walls not exposed to wind driven rain. Increased sheathing moisture content did not vary.

Incident Solar Radiation

Figure 4 depicts solar radiation data on a horizontal surface and in the plane of the north- and south-facing walls. The figure shows that, seasonally, the radiation on the south-facing surface is out of phase with the radiation on a horizontal surface. The south-facing surface radiation is at a maximum in the winter as the sun is low in the sky and the surface remains unshaded. The figure also indicates the north-facing walls received only a fraction of the radiation received by the south-facing walls; the north-facing walls receive only diffuse radiation. This information is useful when trying to understand the solar intensity on the north and south walls throughout the year.

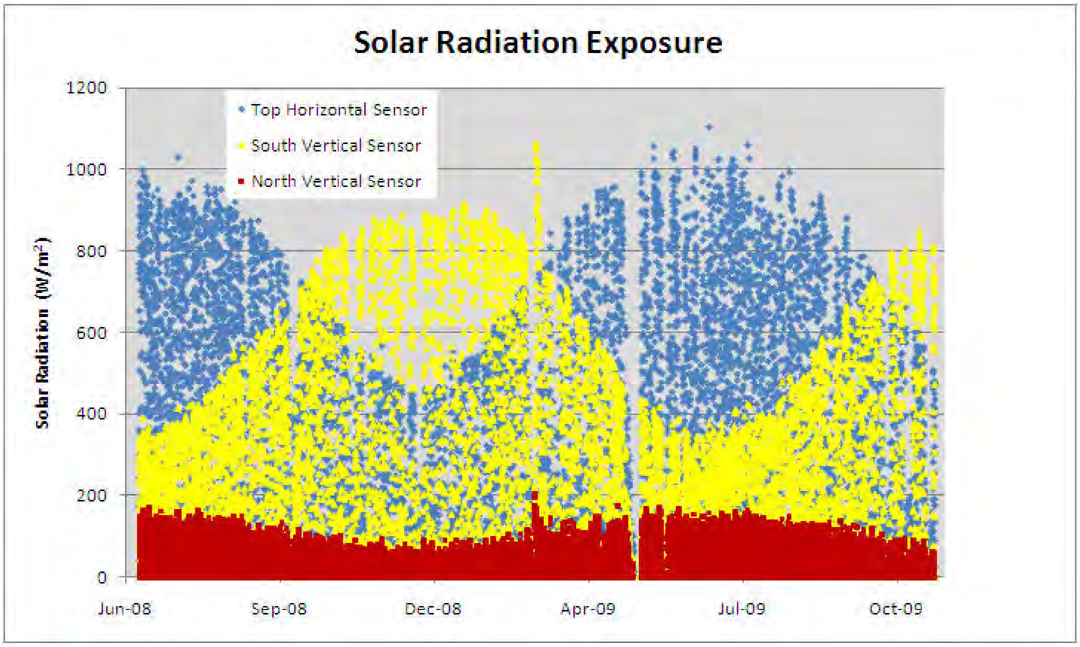


Figure 4. Hourly solar radiation on vertical wall surfaces

Due to the higher levels of radiation, the south-facing walls experienced higher cavity temperatures, lower cavity relative humidity, and lower wood moisture levels than the north-facing walls experienced.

Moisture Content of Studs

Although moisture content of the studs fluctuated somewhat throughout the study, all studs, regardless of panel type, remained below 12 percent moisture content. This is an acceptable level of moisture that would not be conducive to mold or rot. Fluctuation in moisture content was small with all studs falling between 8 and 12 percent moisture content over the duration of the study.

Over the monitoring period, the studs in the brick wall were the driest, both north and south orientations, once the initial drying of the wall assembly occurred (Figures 5 and 6). The north brick wall studs were only slightly drier than the vinyl sided wall studs; however, the south facing brick wall studs were nearly over 0.25%MC (3%) drier than any other wall section and nearly 1.5% MC (16%) drier than the unvented stucco walls during the winter months.

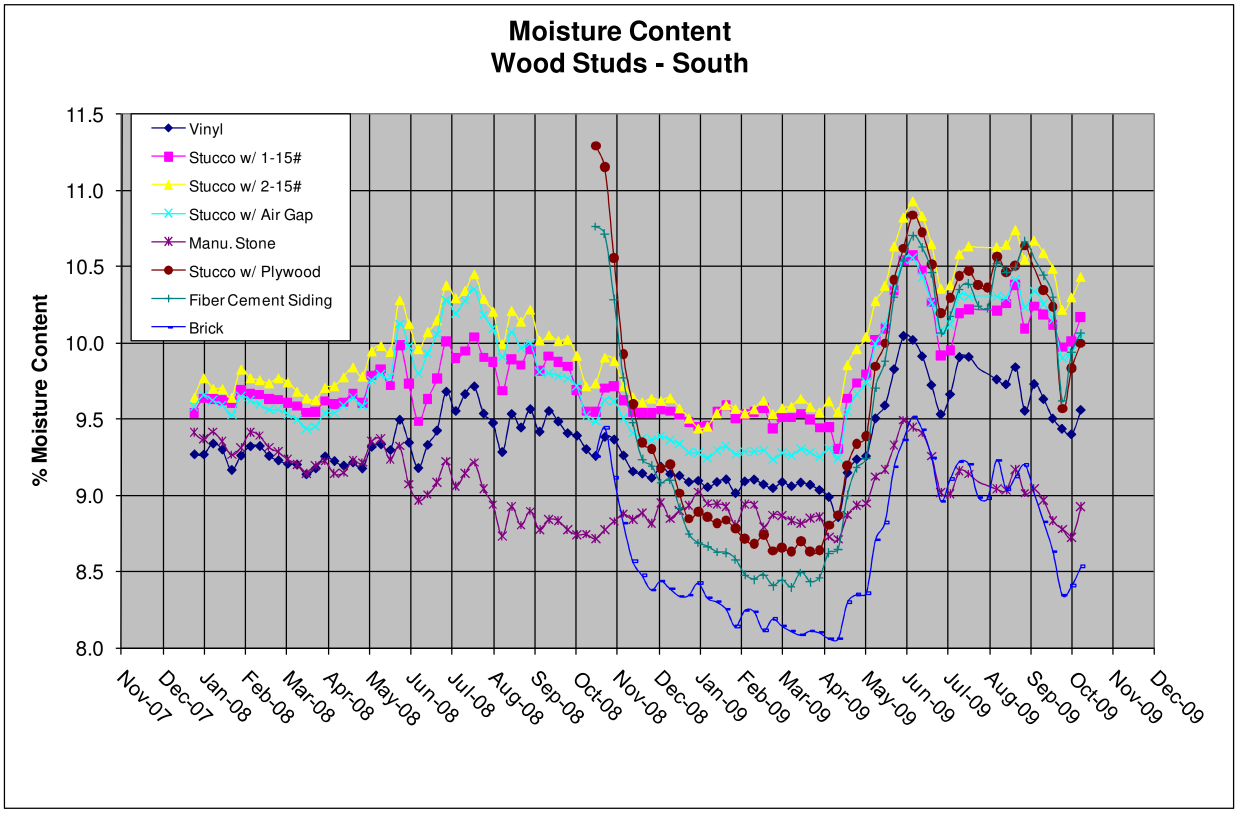


Figure 5. Monthly average stud moisture content, southern exposure

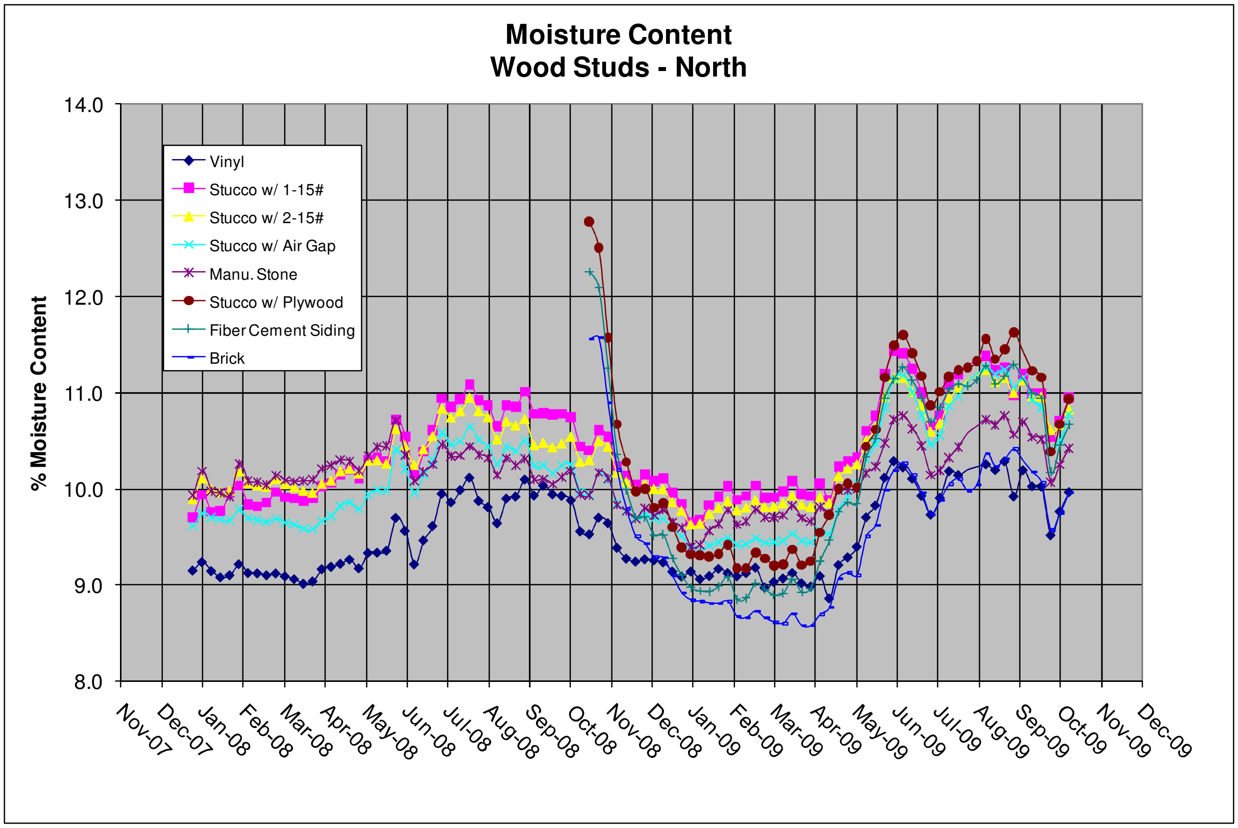


Figure 6. Monthly average stud moisture content, northern exposure

Moisture Content of Sheathing

The south facing brick veneer wall had the driest sheathing of all the wall configurations. The next driest south facing sheathing was in the manufactured stone wall. These two walls had two distinct differences that may have contributed to the lower moisture content of the sheathing- the darker color of the wall increased the thermal absorptance of the solar radiation and the thermal mass of these two walls was signficantly higher than those of the other assemblies. So not only do these two claddings more readily absorb the sun's heat, they also have more heat capacity allowing them to store and release more heat and thereby maintain a higher temperature and a lower equilibrium moisture content in the sheathing.

After the initial moisture conditions of the wall assembly equilibrated to ambient conditions, the sheathing in the south facing brick veneer wall was consistently drier than in any other wall section. The north wall sheathing moisture content readings for the brick veneer and vinyl siding walls were very similar.

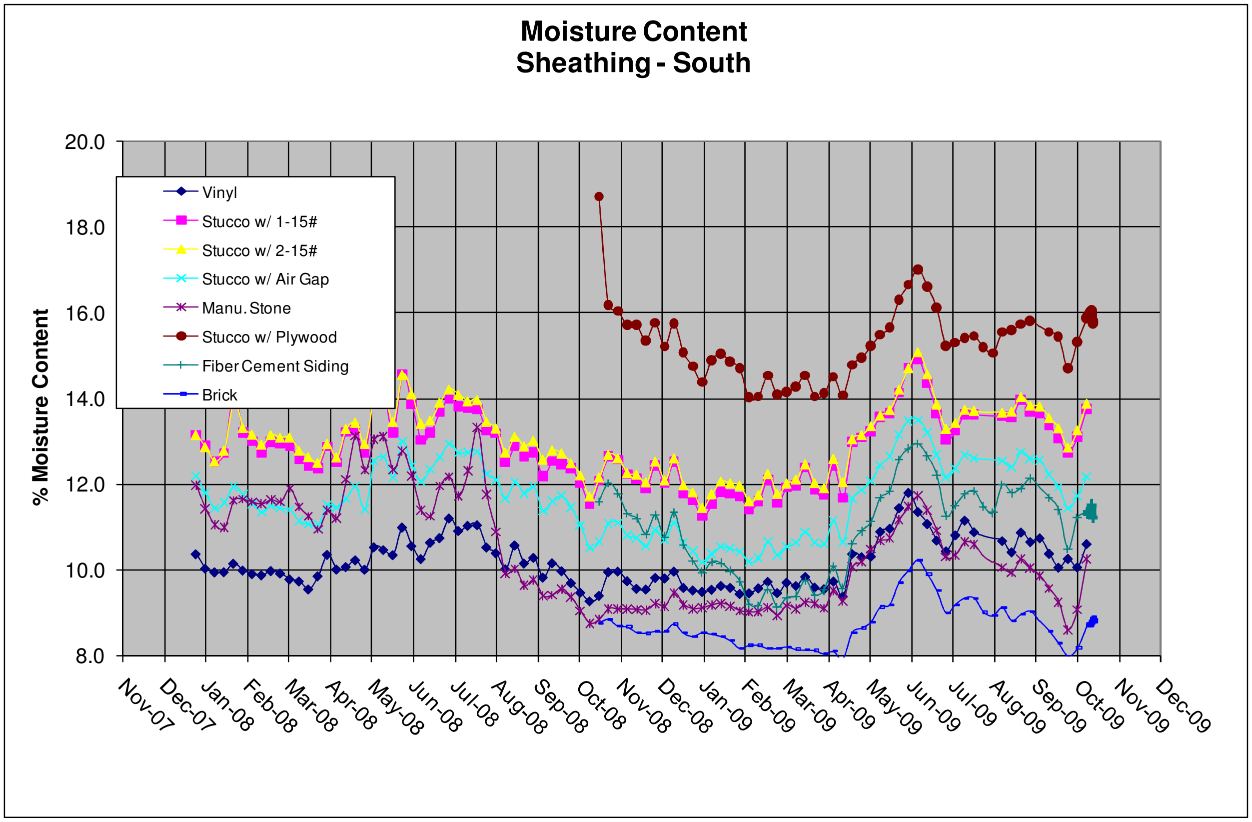


Figure 7. Weekly average sheathing moisture content on south-facing wall

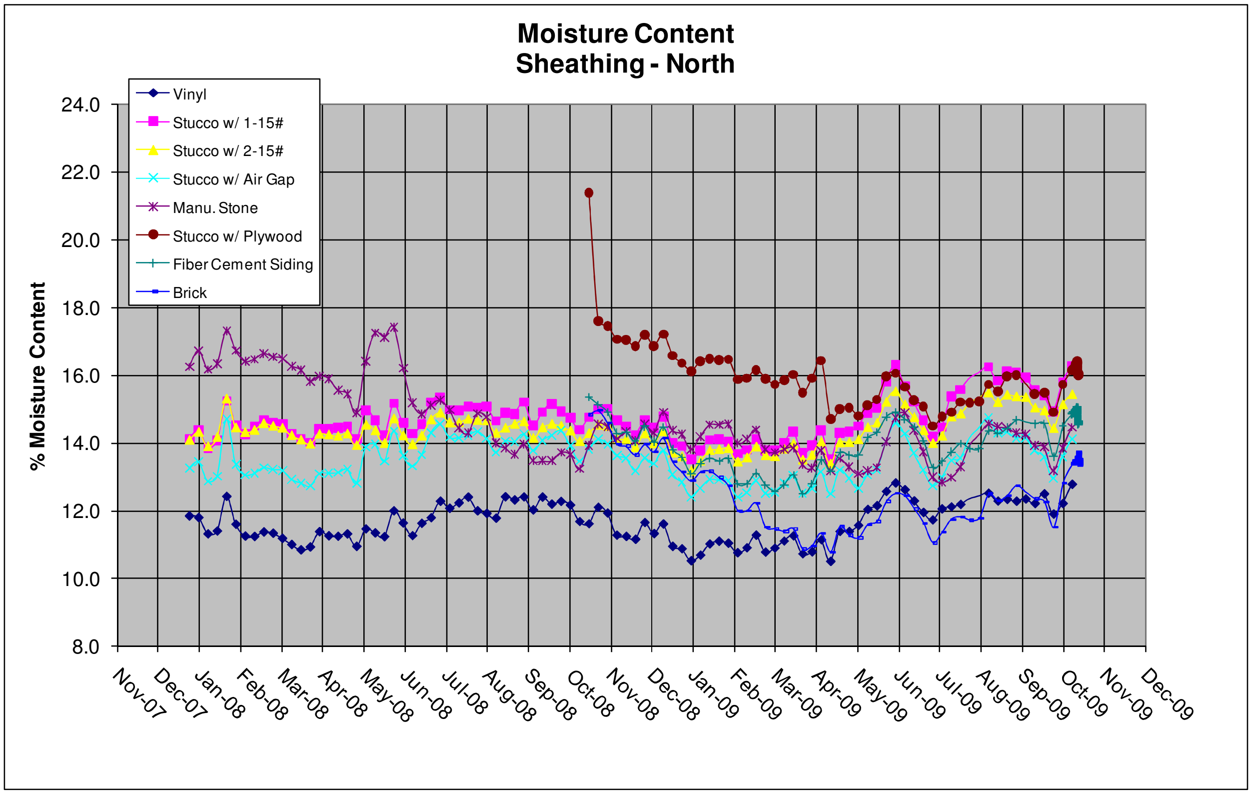


Figure 8. Weekly average sheathing moisture content on north-facing wall

Wall Cavity Temperature

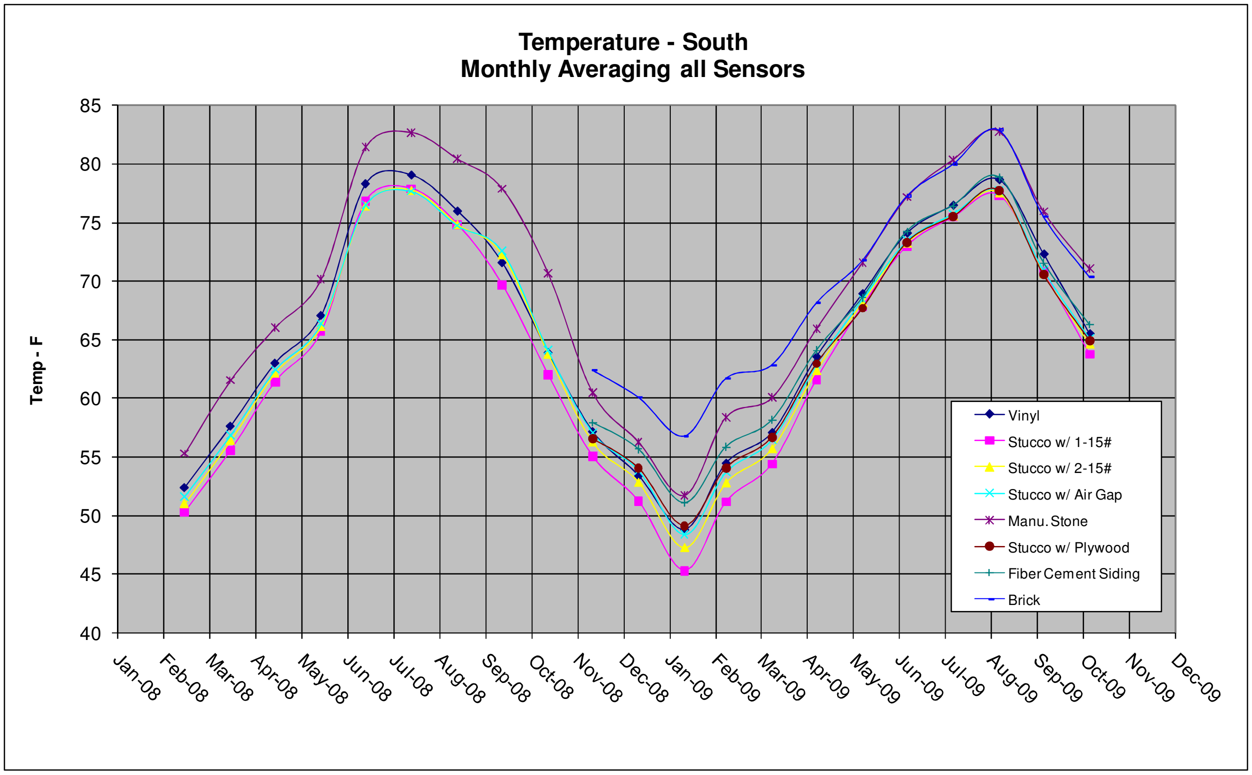


Figure 9. Monthly averaging all sensors temperature south

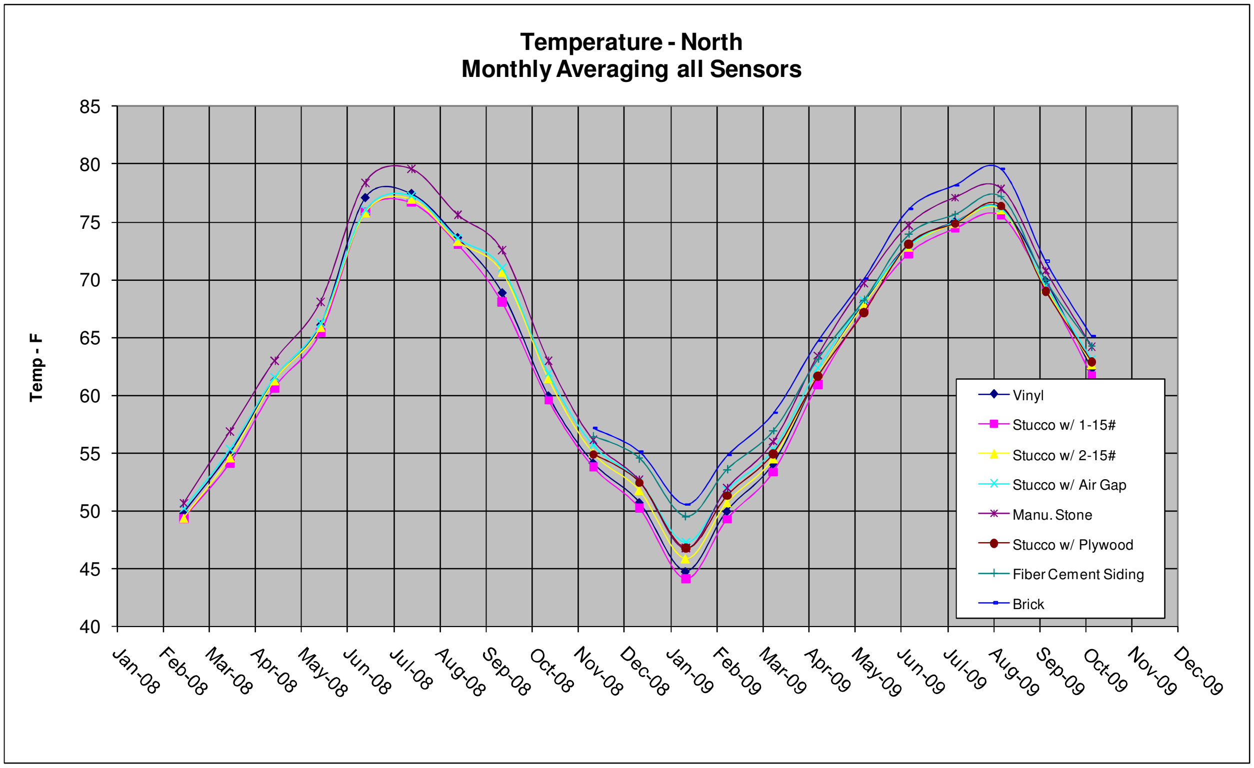


Figure 10. Monthly average stud bay temperatures

Stud cavity temperature readings were similar among the wall systems, with north-facing walls varying by less than 5°F and south-facing cavities by less than 7°F with the exception of the brick veneer wall where the January wall cavity temperature was 11°F warmer than the coldest wall. Of the north-facing assemblies, the brick veneer wall had the highest stud cavity temperature year-round, presumably because it was the darkest wall with the most thermal mass providing the ability to absorb more solar radiation (primarely diffuse radiation on north side) than the other wall systems. In addition, the insulating air space would also increase the wintertime wall cavity temperature. In the winter, the northern fiber cement (without direct solar exposure) wall was appreciably warmer than the all but the brick wall, perhaps because the lapped siding created and airspace with a limited amount of air circulation behind the cladding providing some insulative value.

Wall Cavity Relative Humidity

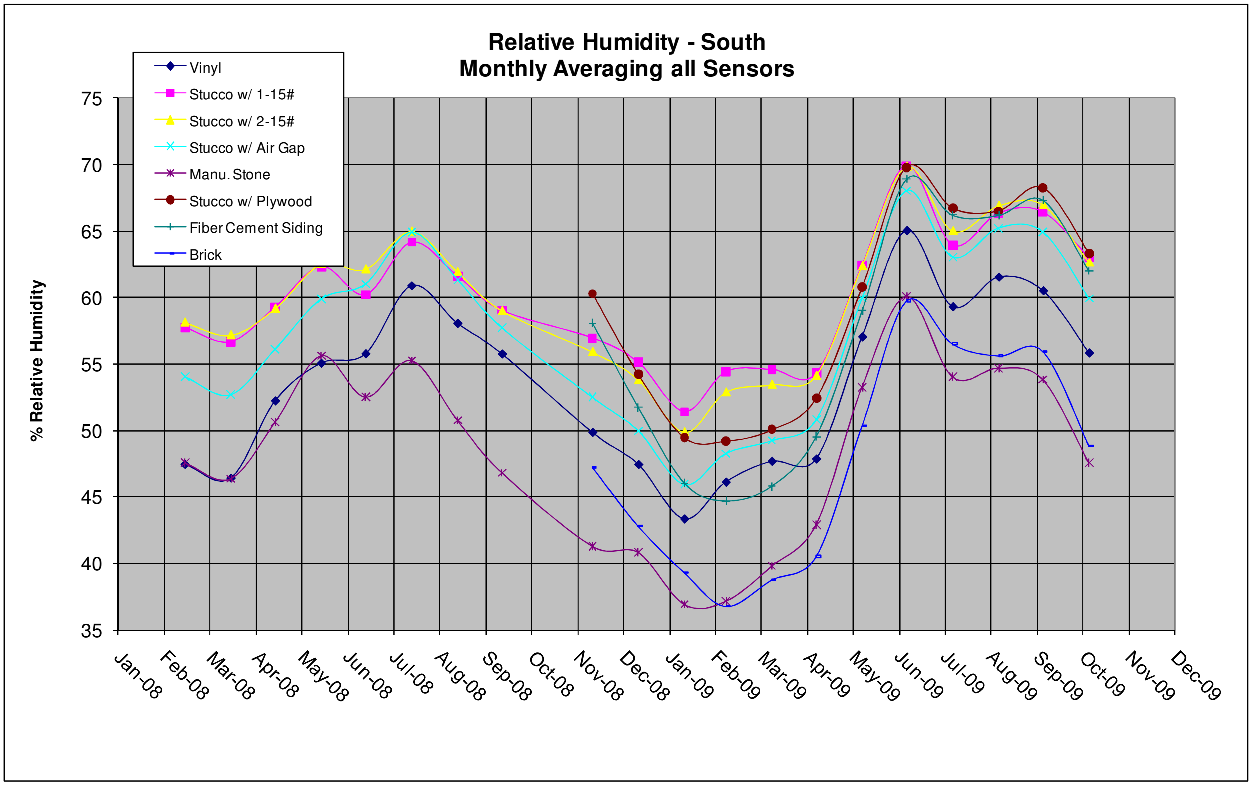


Figure 11. Relative Humidity south monthly averaging all sensors

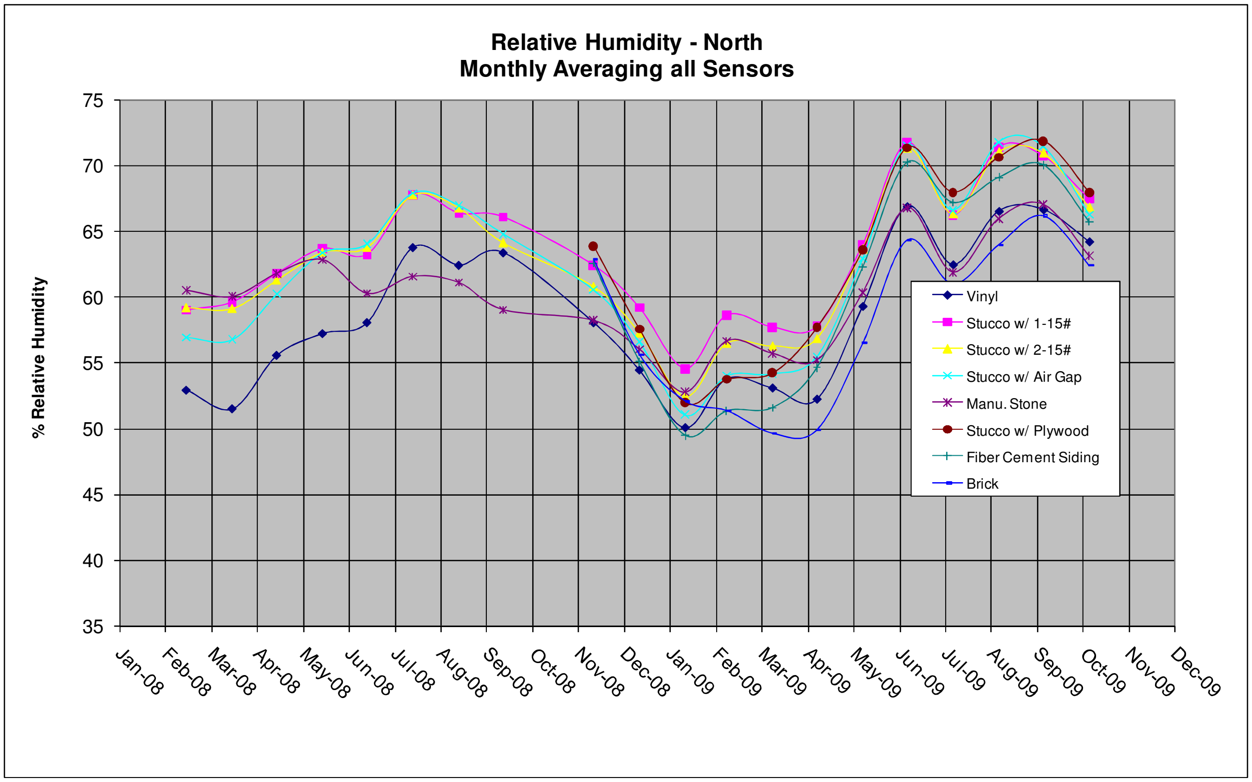


Figure 12. Monthly Average Stud Bay Relative Humidity

The relative humidity readings in the stud bays are reasonably well correlated with sheathing moisture content readings. The brick veneer wall (once dried after construction) consistently maintained the lowest or second lowest cavity relative humidity.

Simulated versus Actual Results

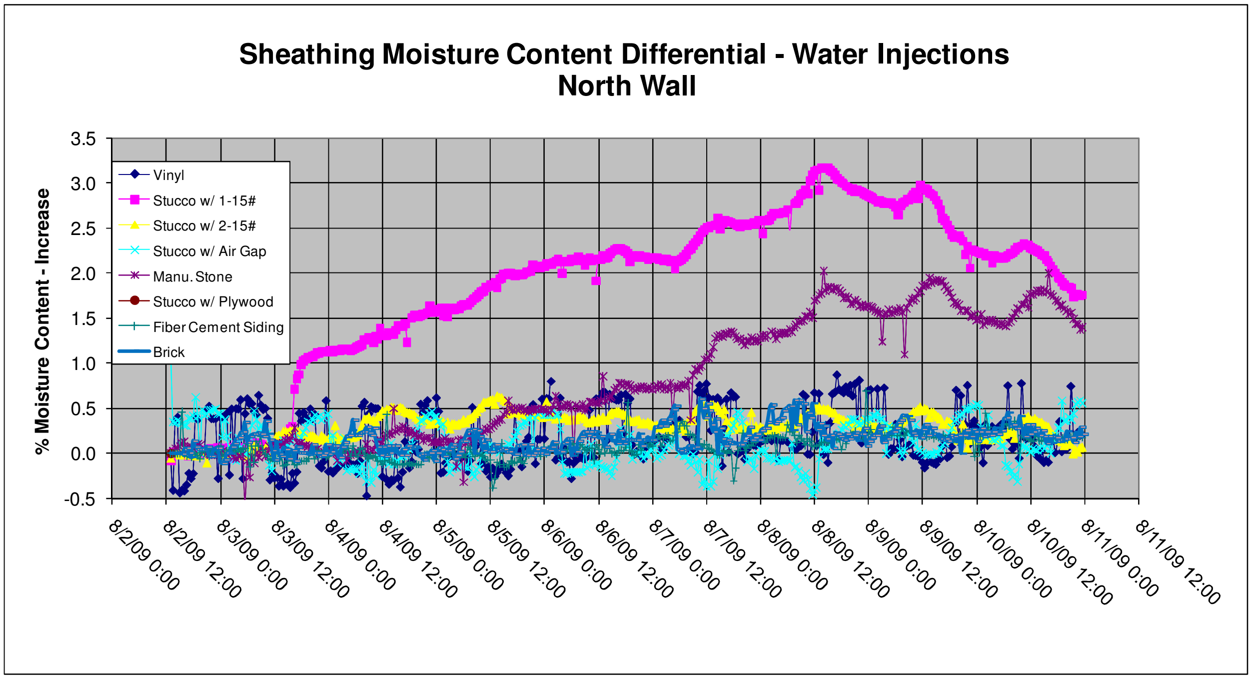
Comparing predicted moisture content (using a historically-based TMY3 weather file) to actual moisture content reveals a few trends. Most wall assemblies showed results which were seasonally out of phase with the measured moisture content—with measured readings peaking in summer and modeled moisture content peaking in winter (see Appendix A for graphs).

Some of the difference between predicted and measured results may be explained by the difference in weather data between the historical weather file used in modeling and the actual conditions in the field test. However, the discrepancy between simulations and field measurements—especially with regard to the phase shift—may warrant further investigation.

Bulk Moisture Injections

To understand the moisture response of wall sections after water gets behind the cladding (for example, due to a leaking window), 60 ml of water—30 ml on each side of the primary WRB—was injected into each of the wall sections once each day for five consecutive days, starting August 3rd around noon, with the moisture content change reflected in Figures 14 and 15. These readings were compared to moisture content readings from an area unaffected by the injections. The response indicated the degree to which the moisture was absorbed into the sheathing and the ability of the wall assembly to dry after wetting.

With the exception of a ten hour short moisture spike, the brick veneer walls were mostly unaffected by the moisture injections. It is apparent that a one inch air space with the ability to exhaust moisture laden air that may be present is effective in keeping the wall assembly dry.



Note: Stucco wall with plywood readings were determined to be unreliable, thus were not reported on this graph

Figure 13. North wall moisture response, August 2009 bulk water injections

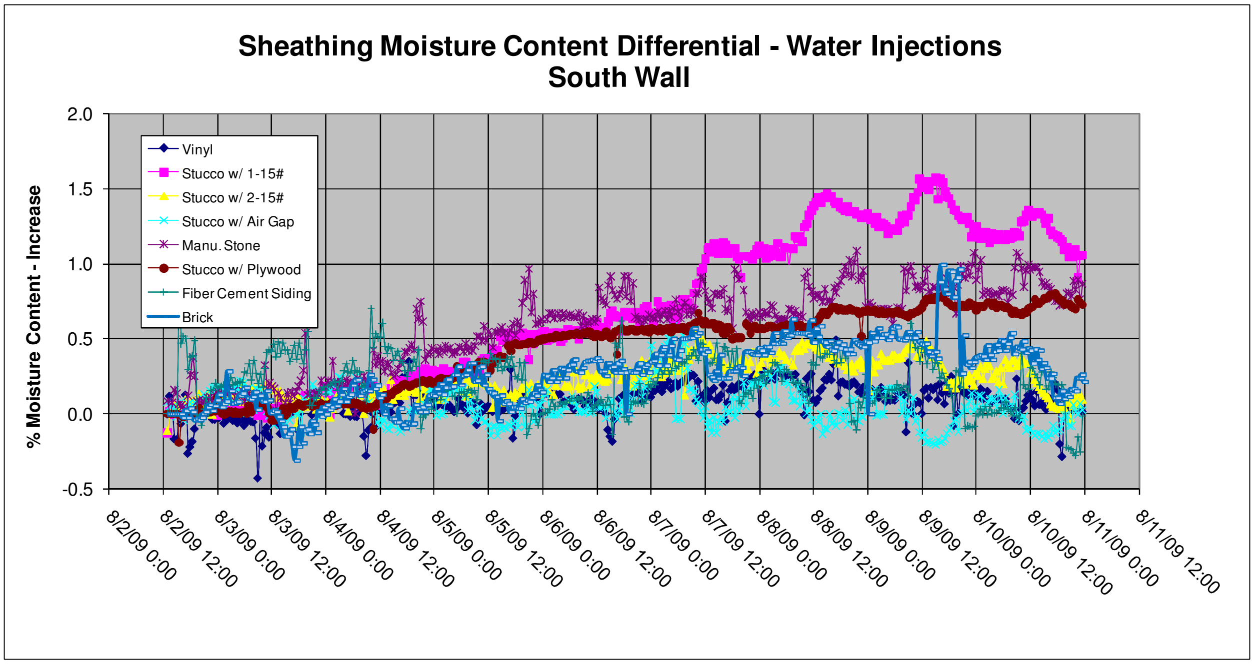


Figure 14. South wall moisture response, August 2009 bulk water injections

Dryer Vent Penetrated Wall versus Wall with No Penetrations

Data was compiled to compare moisture response of a wall with no penetrations versus that of a penetrated wall of the same type. However, there was very little difference between the moisture content of the walls with no penetrations and the dryer-vent penetrated walls. This indicates that generally, the effects of a wall penetration will not change the moisture performance of the wall. Exceptions to this might include: a bulk moisture leak at the penetration or a pressurized (or depressurized) building that constantly draws moisture into the wall cavity.

Conclusions

Over the monitoring period, sheathing in all of the eight pairs of walls (16 walls) evaluated in this study generally remained below the industry-recognized moisture content threshold level of 16 percent, although there were some exceptions. Two of the wall pairs (four walls) did not incorporate wet-placed cladding materials; in these walls, and in walls with brick veneer cladding, there was little indication of construction moisture, and the sheathing in these walls remained substantially below 16 percent MC throughout the monitoring period. North-facing walls clad with manufactured stone and stucco-clad walls with plywood sheathing (facing either north or south) had the highest initial moisture contents and were the slowest to dry. In stucco-clad walls with plywood sheathing and in the north-facing stucco-clad wall with a single layer of #15 felt, there were periods, after dissipation of construction moisture, when sheathing moisture contents briefly exceeded 16 percent.

There were two primary mechanisms that acted to lower the moisture content of the wood based sheathings: air circulation and wall temperature. Air circulation behind the cladding contributed to the drying capability of the vinyl siding, brick, vented stucco, and to a lesser extent fiber cement siding. Higher wall cavity temperatures generally correlated with lower sheathing moisture contents. This was especially true with darker claddings with southern solar exposure such as brick and manufactured stone.

The 30-day mold-growth minimizing criterion outlined in ASHRAE Standard 160 (a running average surface RH below 80 percent RH) effectively specifies lower sheathing moisture contents than the 16 percent “wet service factor” threshold value. As indicated previously, an 80 percent surface RH value corresponds with approximately 13 percent MC for OSB and 14 percent MC for plywood. The ASHRAE Standard 160 criterion also has a temperature component; the surface RH criterion applies when the 30-day running average temperature exceeds 41°F (5°C). The ASHRAE Standard 160 criterion was not exceeded in five of the eight south-facing walls. The three south-facing walls in which the criterion was exceeded were stucco-clad, with and without an air gap. In contrast, the criterion was exceeded in six of the nine north-facing walls. The only north-facing walls where the criterion was not exceeded were the walls clad with vinyl siding, and brick veneer. It is important to note that the mold-growth inhibition criteria outlined in ASHRAE Standard 160 are termed “Conditions Necessary to Minimize Mold Growth.” If the ASHRAE Standard 160 criteria are exceeded there is some risk of mold growth, but mold growth will not necessarily occur. ASHRAE Standard 160 contains an acknowledgment that criteria for inhibition of mold are typically more restrictive than other moisture limitation criteria applicable to buildings, thus this criterion was not considered determinate on the performance of the wall assemblies. In addition, core samples of the sheathing were examined at the conclusion of the study period and no evidence of mold growth was observed on either side of the sheathing.

Additional observations, based on sheathing moisture content readings, were as follows:

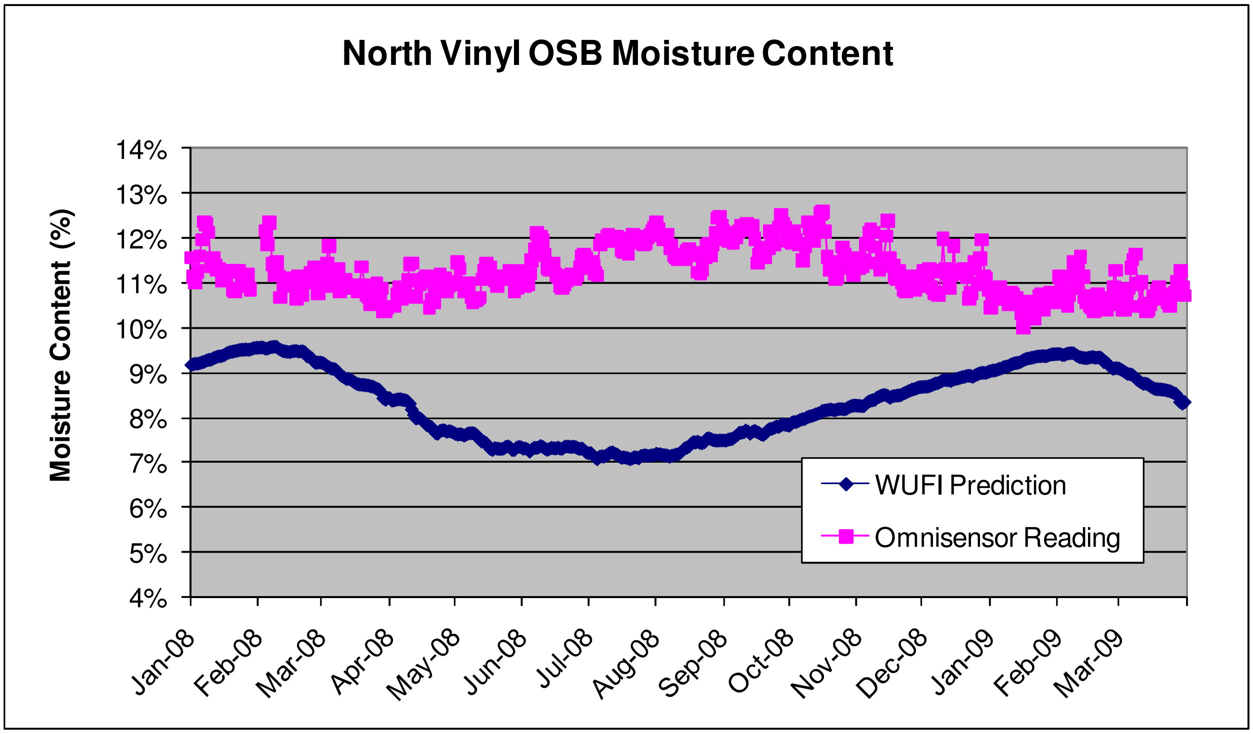
- Orientation and solar exposure is an important factor in wall performance. All north-facing walls experienced higher moisture and cavity humidity readings than the corresponding south-facing wall of the same construction.
- The wall pair with vented stucco cladding performed better than any other wall clad with stucco. The performance of this pair was similar to that of the wall pair with the fiber cement lap siding.
- The two walls with dark claddings performed quite differently on the south than the north. South-facing walls with brick (dark red) and manufactured stone (dark earth tones) had relatively high cavity temperatures throughout the monitoring period.
- The wall pair clad with brick veneer was the driest of all the walls evaluated in this report. The one-inch air gap along with the increased absorptance (darker color) is attributed in providing the increased drying capability.
- Manufactured stone had the greatest sensitivity to orientation. Sheathing moisture content was reduced by nearly a third in the south-facing wall with manufactured stone cladding (14 percent north, 10 percent south). This was attributed to higher wall cavity temperatures because of increased radiant gains on the darker colored stone on its southern exposure.
- Vinyl siding generally provided for consistently dry sheathing conditions. The loose fit of the siding allowed the wall to dry from the inside toward the outside, while the siding also shed bulk moisture.
- A second layer WRB becomes critical for stucco applications when bulk moisture gets behind the cladding. Stucco-clad walls with one and two WRB layers performed comparably under normal exposure; however, when moisture was injected, the sheathing in the wall with two layers of WRB had virtually no increase in moisture content while the sheathing in both the north- and south-facing stucco-clad walls with a single layer of WRB saw moisture increases of up to 3.5 percent MC over the five-day injection period.
- The north-facing wall with manufactured stone cladding, which had two WRB layers, did not perform as well as the north-facing stucco-clad wall with two WRB layers and the same sheathing material (OSB).
- Wall assemblies with an air gap (fiber cement, vinyl, vented stucco, and brick veneer), saw no sustained increase in sheathing moisture content during moisture injections.

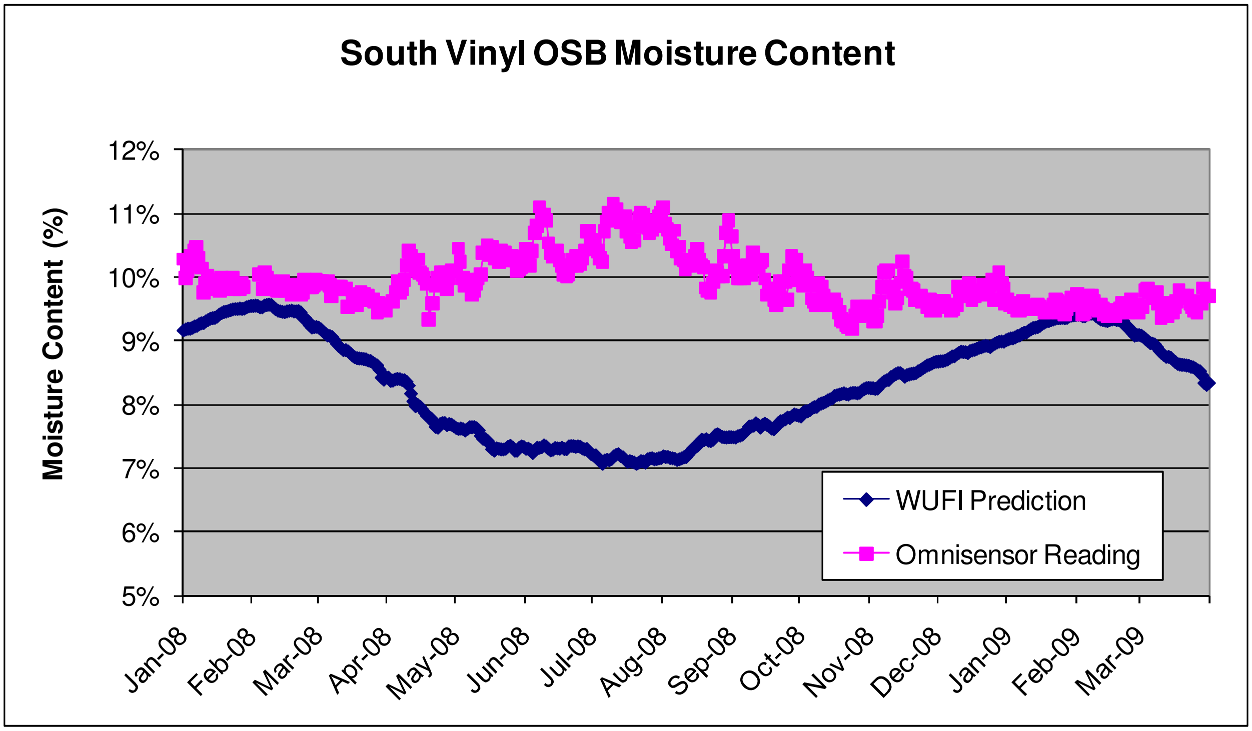
WUFI® moisture modeling when using TMY3 weather, generally predicted the trend of accumulation and dissipation of moisture in the sheathing for the brick veneer wall assembly- unlike most of the other walls; however, the WUFI modeling generally under-predicted the level of moisture in the walls with the exception of the manufactured stone clad wall. Further investigation is warranted to determine if actual weather conditions, which were reasonably close to historical, would change the phase and level of the predicted curves.

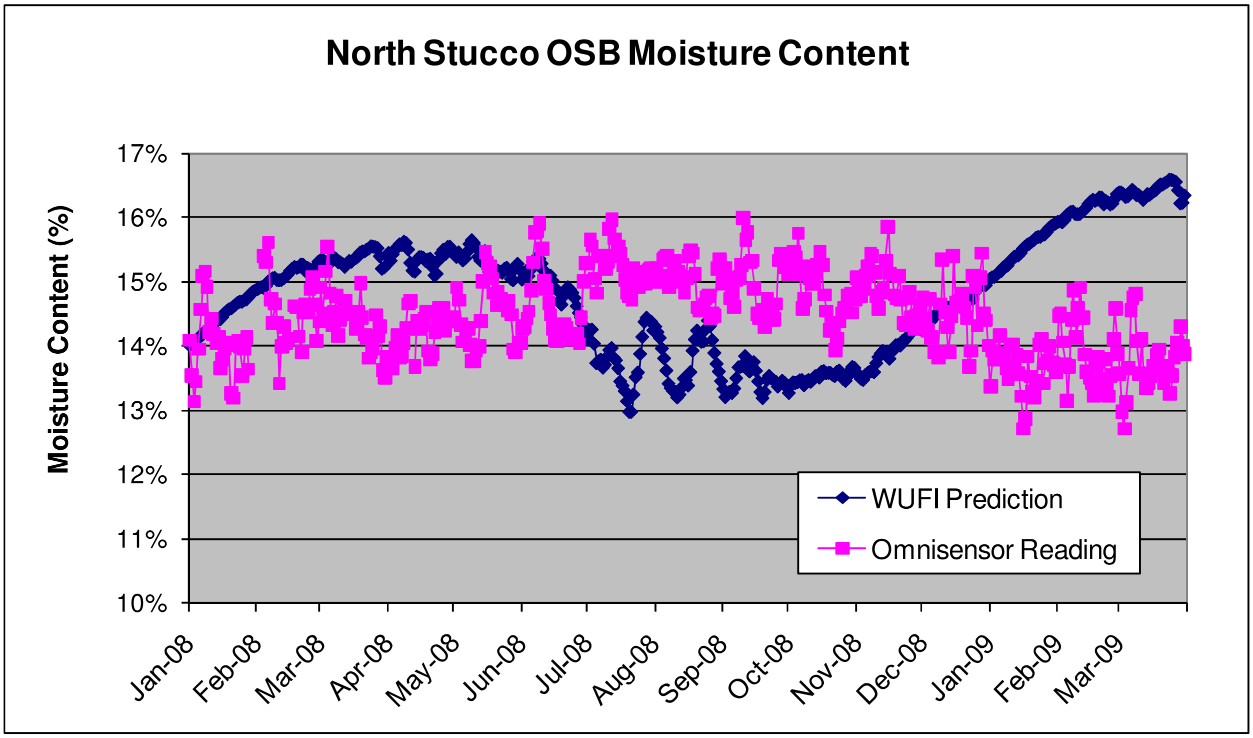
Although the instrumentation indicated that acceptable moisture levels were maintained for all cladding systems over the duration of the monitoring period, the interior and exterior conditions may not have been as challenging as would be found in other residential structures. For example, the test structure was a single-story in height, the roof eave was guttered, and the gutter remained functional over the monitoring period; the walls were not exposed to as much wind-driven rain as might be expected on second-story walls, and the walls were effectively protected from splash wetting. Furthermore, interior relative humidity was held within the range of 25 to 30 percent during the winter months. Higher indoor relative humidity settings would increase relative humidity within the wall cavity, as well as moisture content levels in the studs and sheathing. Additional research to investigate the impact of indoor humidity settings on wall performance would be beneficial to aid in the understanding of wood moisture content under a variety of indoor environmental conditions.

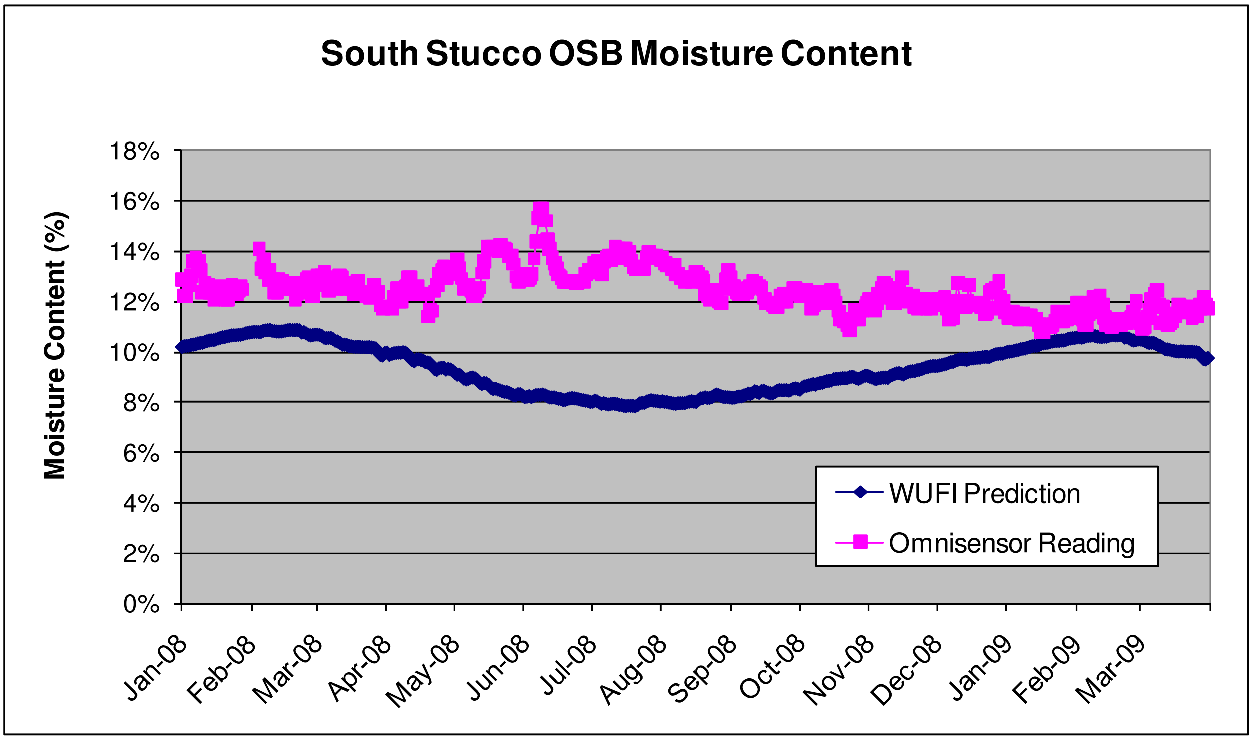
Although moisture problems and building failures related to moisture have been seen in the field on absorptive claddings, extended high moisture levels were not observed in this study. The problems that have been experienced on residences could be due to a variety of factors: material selection; workmanship problems; elevated interior humidity conditions; increased weather exposure and/or lack of design considerations. A more thorough effort is necessary to adequately understand moisture-related wall failures.

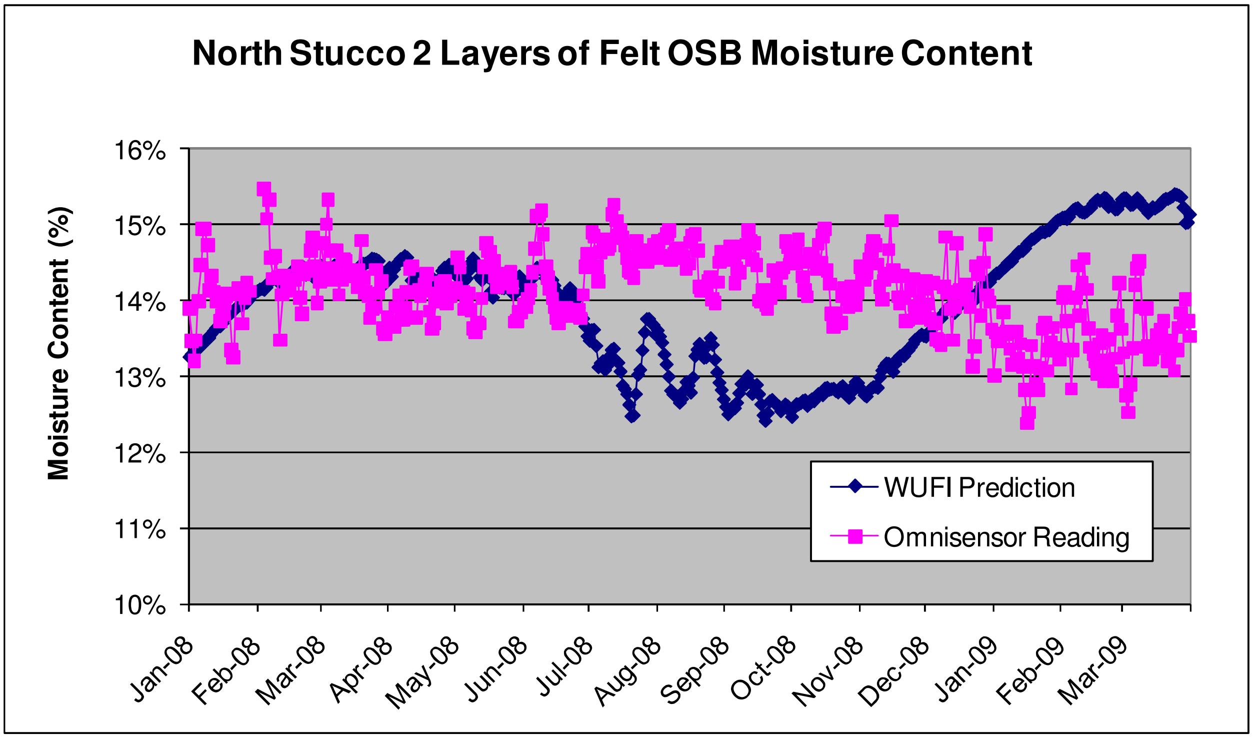
Appendix A- WUFI vs Actual Graphs

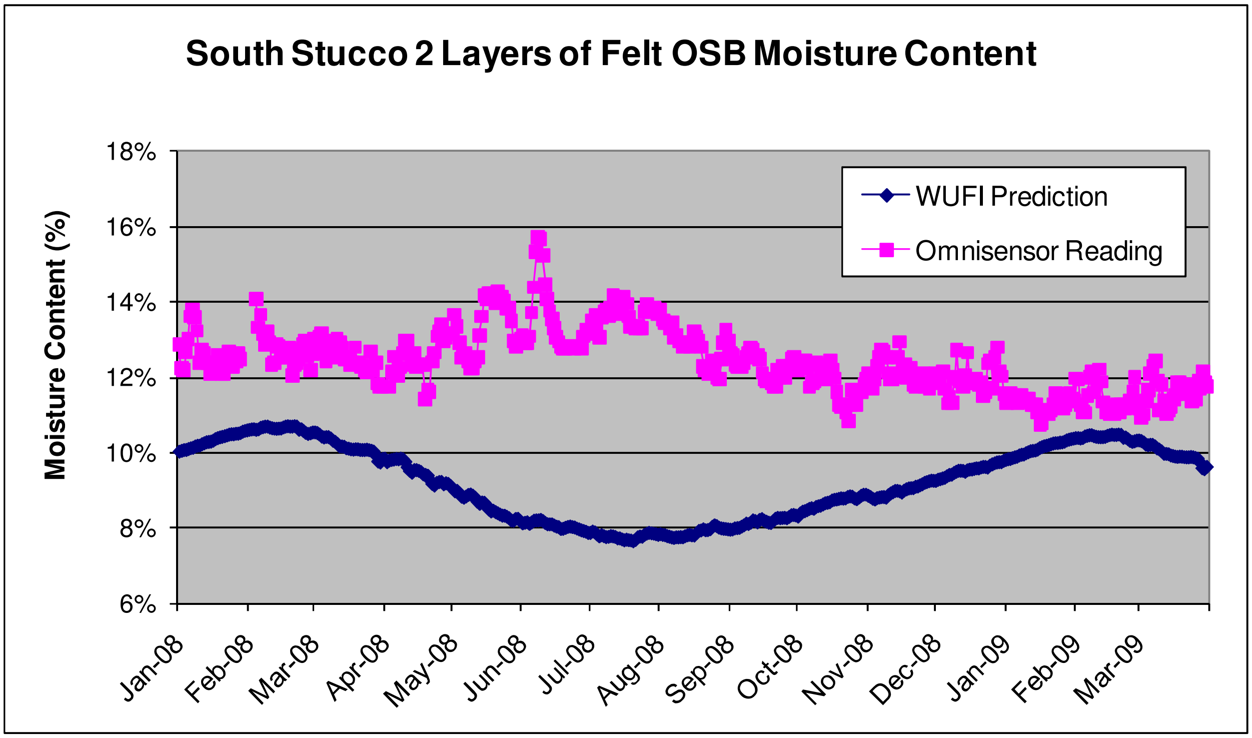


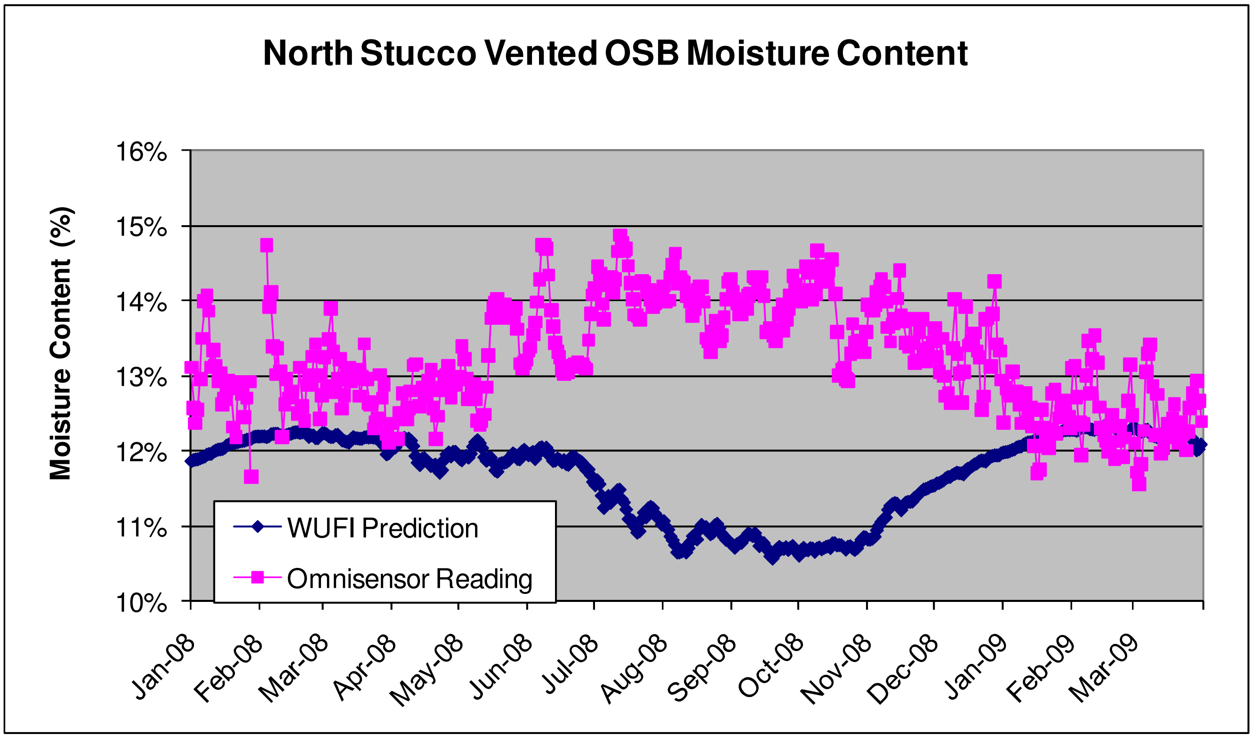


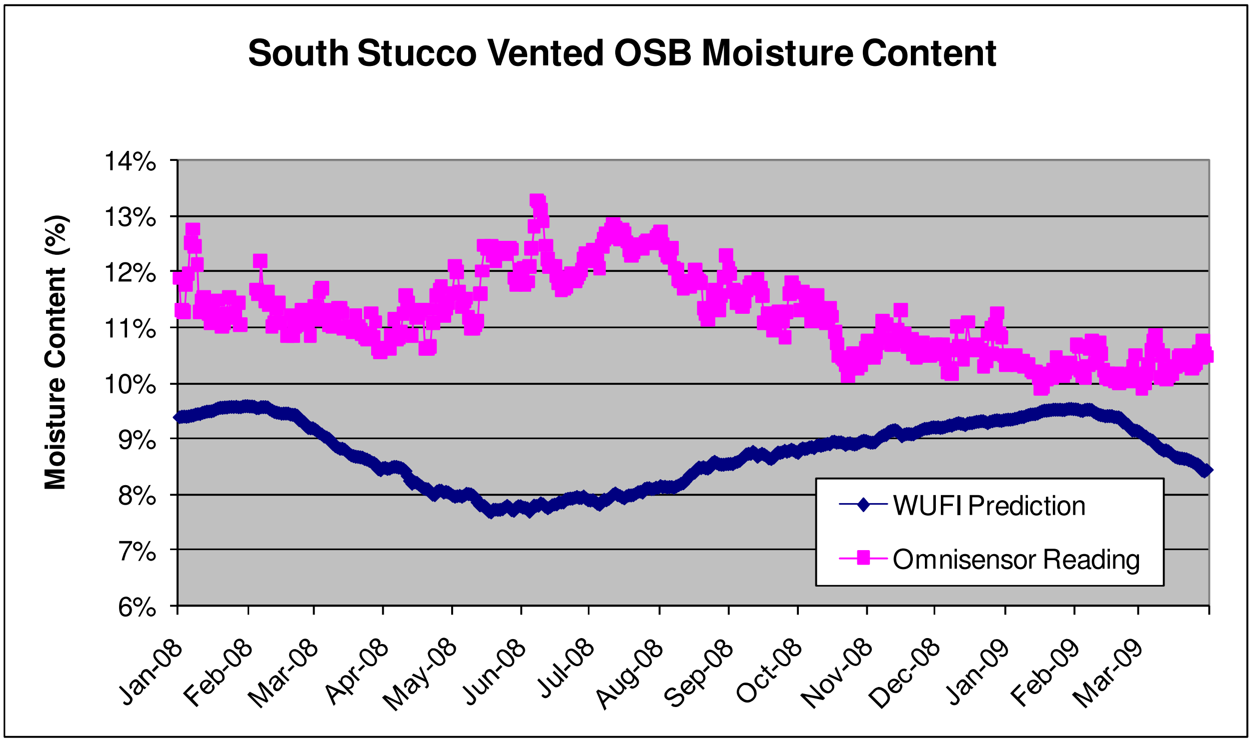

North Stucco OSB Moisture Content
Moisture Content (%)
17%
16%
15%
14%
13%
12%
11%
10%
Jan-08
Feb-08
Mar-08
Apr-08
May-08
Jun-08
Jul-08
Aug-08
Sep-08
Oct-08
Nov-08
Dec-08
Jan-09
Feb-09
Mar-09
WUFI Prediction
Omnisensor Reading

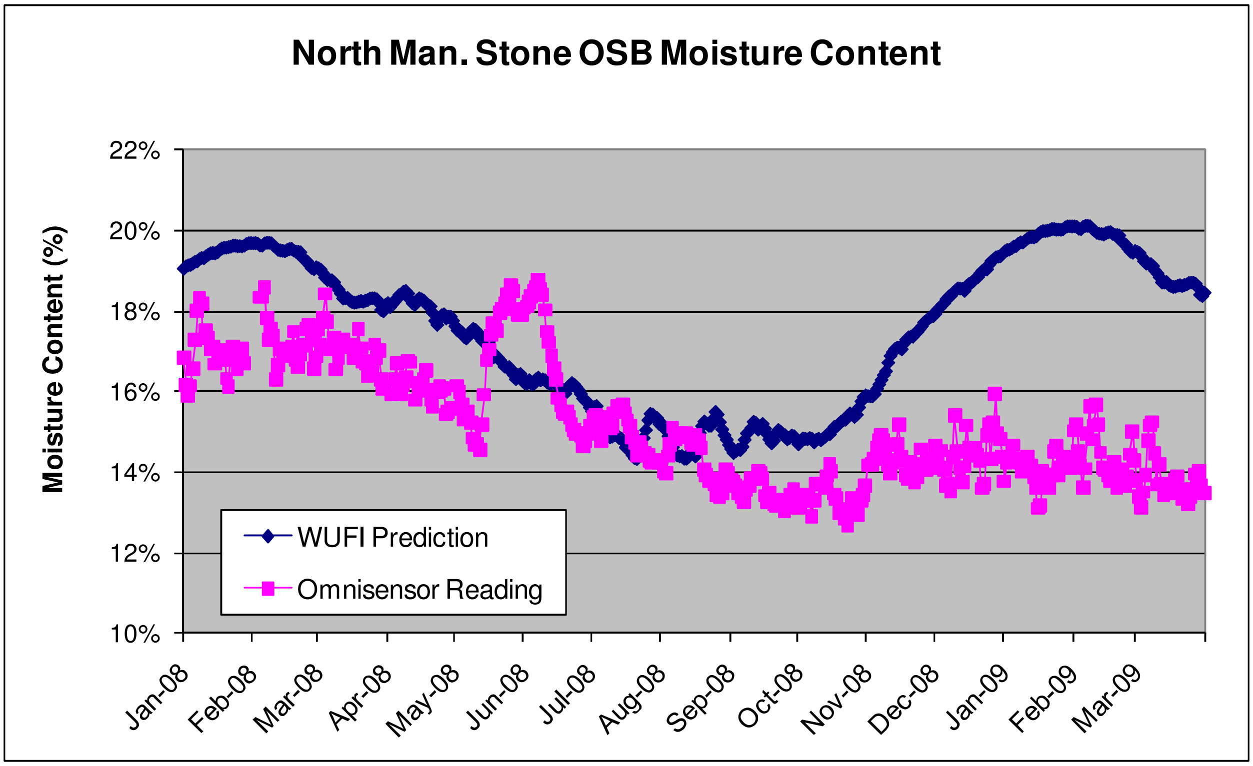

South Stucco OSB Moisture Content
Moisture Content (%)
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
Jan-08
Feb-08
Mar-08
Apr-08
May-08
Jun-08
Jul-08
Aug-08
Sep-08
Oct-08
Nov-08
Dec-08
Jan-09
Feb-09
Mar-09
WUFI Prediction
Omnisensor Reading

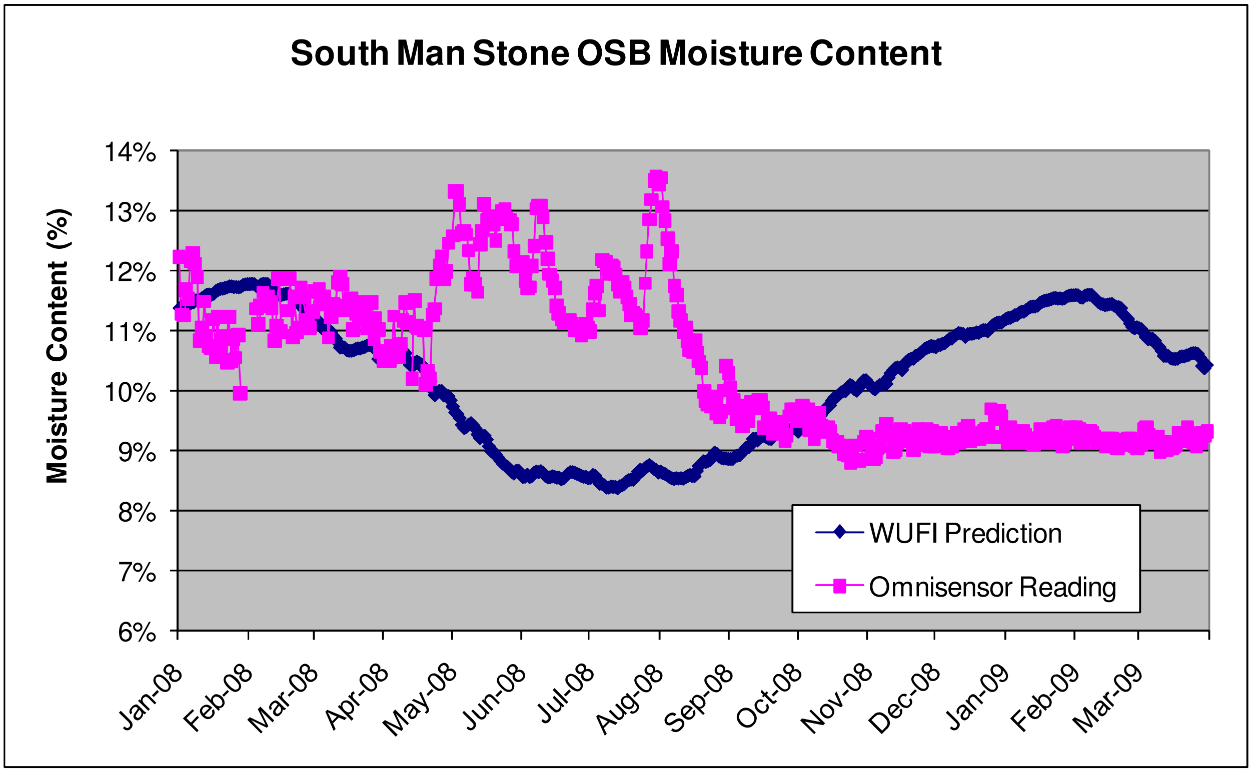

North Stucco 2 Layers of Felt OSB Moisture Content
Moisture Content (%)
16%
15%
14%
13%
12%
11%
10%
Jan-08
Feb-08
Mar-08
Apr-08
May-08
Jun-08
Jul-08
Aug-08
Sep-08
Oct-08
Nov-08
Dec-08
Jan-09
Feb-09
Mar-09
WUFI Prediction
Omnisensor Reading

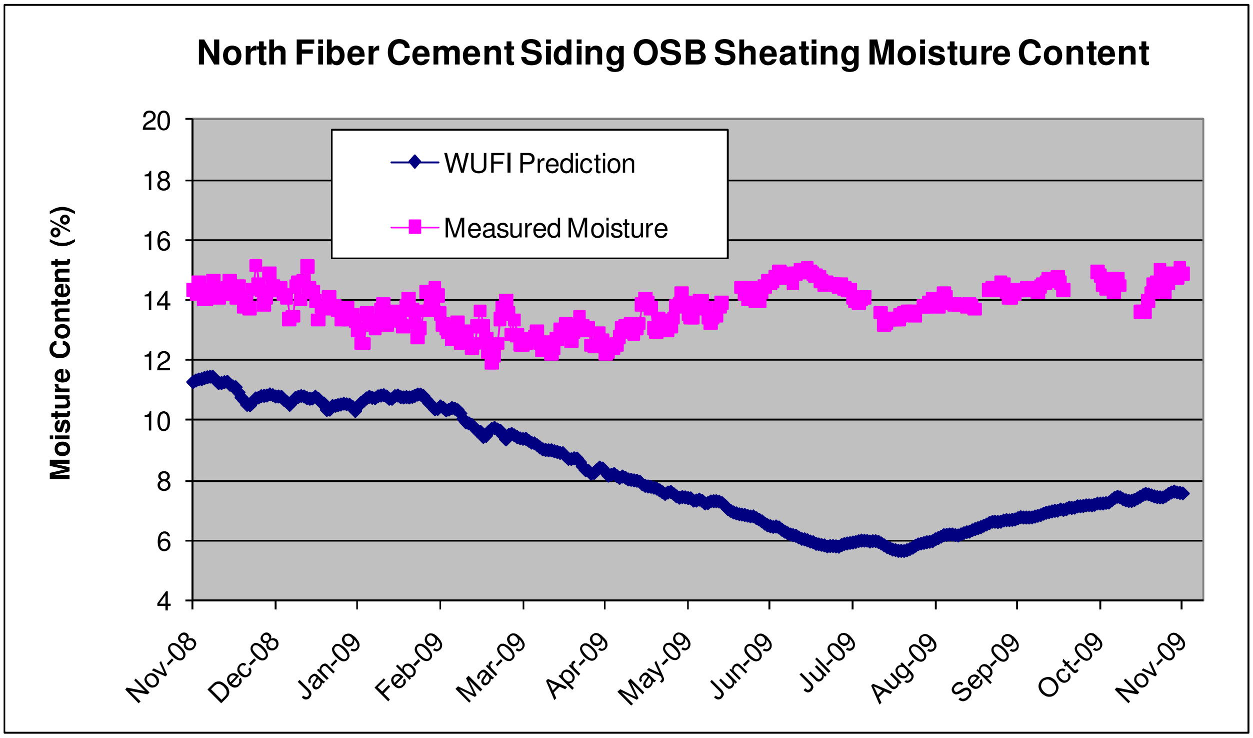

South Stucco 2 Layers of Felt OSB Moisture Content
Moisture Content (%)
18%
16%
14%
12%
10%
8%
6%
Jan-08
Feb-08
Mar-08
Apr-08
May-08
Jun-08
Jul-08
Aug-08
Sep-08
Oct-08
Nov-08
Dec-08
Jan-09
Feb-09
Mar-09
WUFI Prediction
Omnisensor Reading

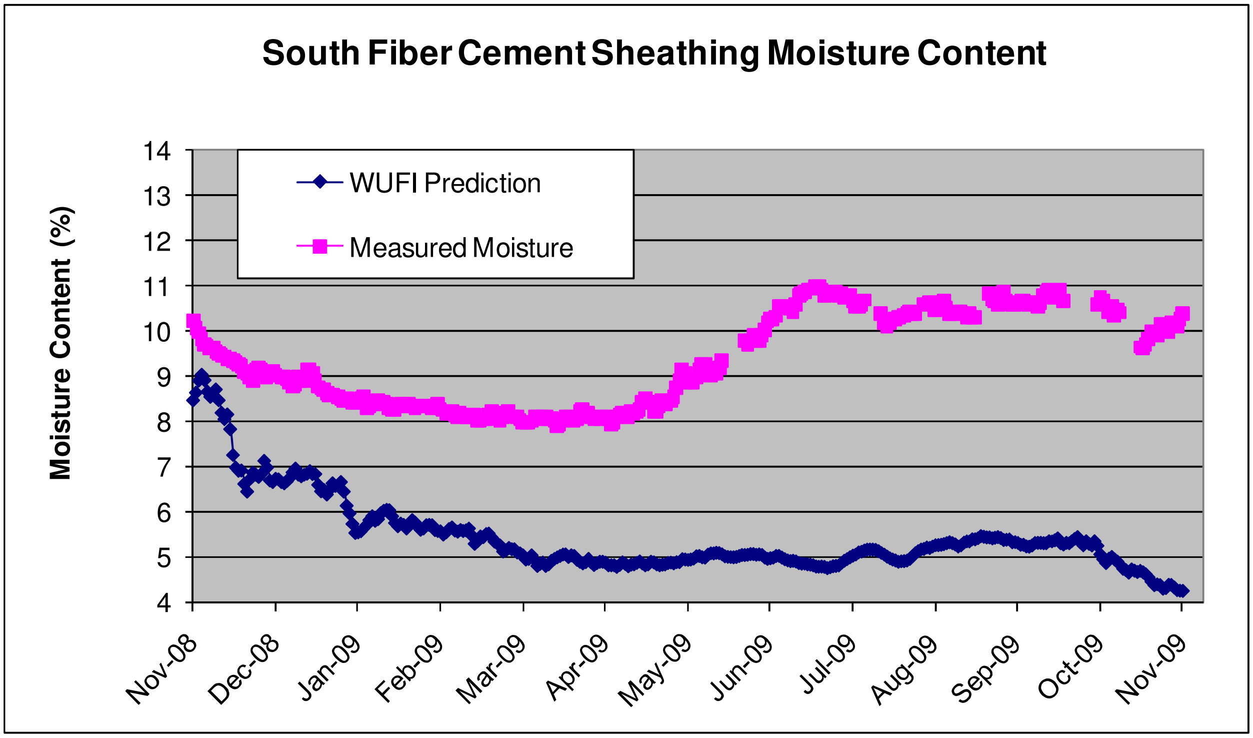

North Stucco Vented OSB Moisture Content
Moisture Content (%)
16%
15%
14%
13%
12%
11%
10%
WUFI Prediction
Omnisensor Reading
Jan-08
Feb-08
Mar-08
Apr-08
May-08
Jun-08
Jul-08
Aug-08
Sep-08
Oct-08
Nov-08
Dec-08
Jan-09
Feb-09
Mar-09

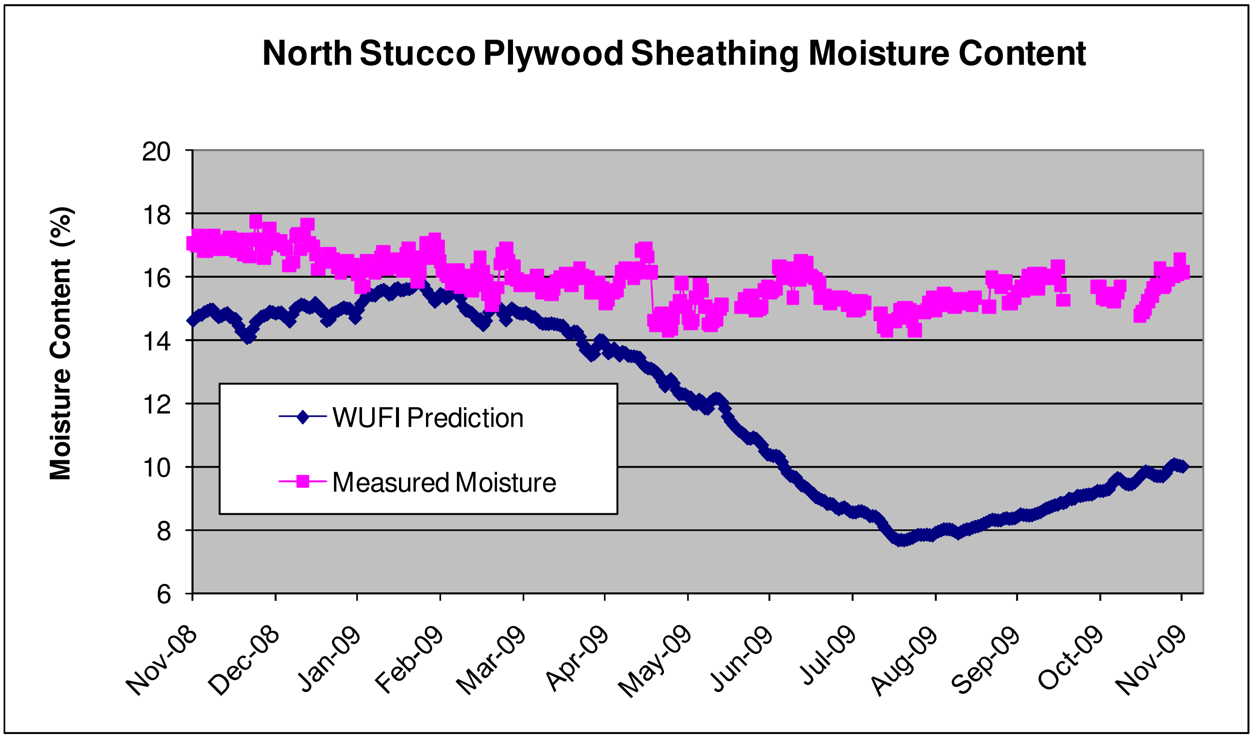

South Stucco Vented OSB Moisture Content
Moisture Content (%)
14%
13%
12%
11%
10%
9%
8%
7%
6%
WUFI Prediction
Omnisensor Reading
Jan-08
Feb-08
Mar-08
Apr-08
May-08
Jun-08
Jul-08
Aug-08
Sep-08
Oct-08
Nov-08
Dec-08
Jan-09
Feb-09
Mar-09

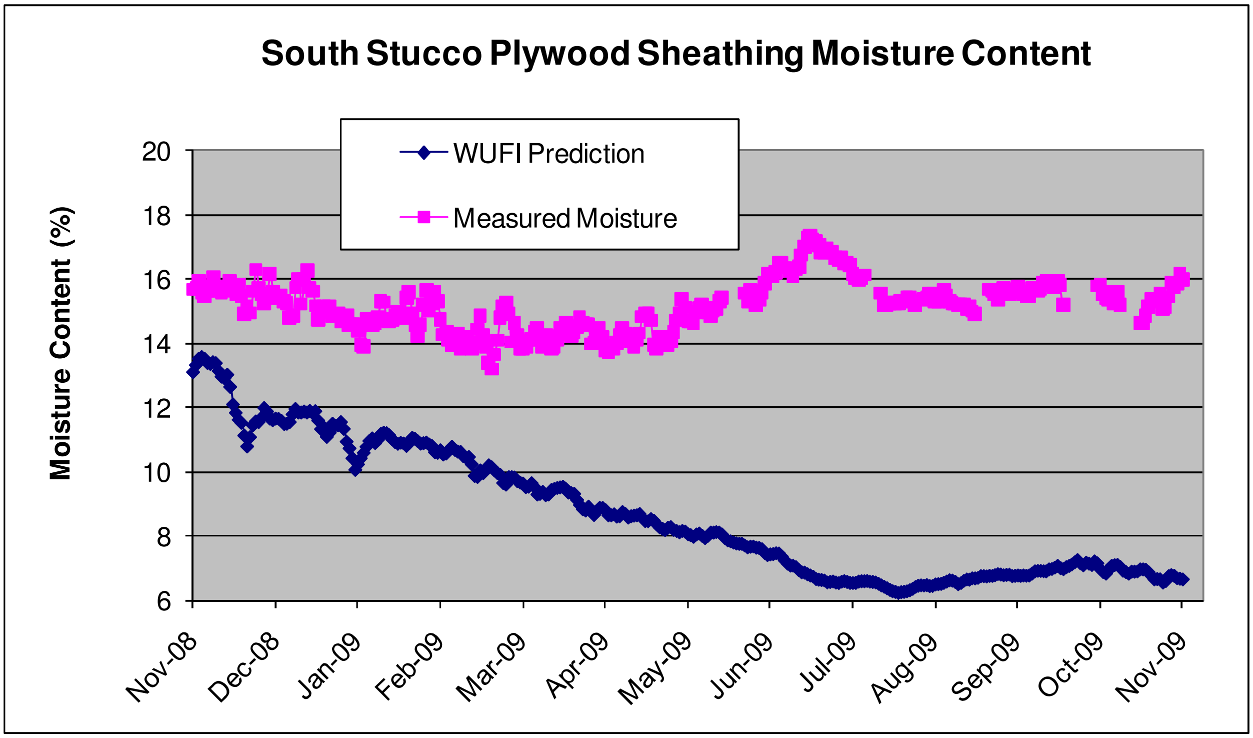

North Man. Stone OSB Moisture Content
Moisture Content (%)
22%
20%
18%
16%
14%
12%
10%
WUFI Prediction
Omnisensor Reading
Jan-08
Feb-08
Mar-08
Apr-08
May-08
Jun-08
Jul-08
Aug-08
Sep-08
Oct-08
Nov-08
Dec-08
Jan-09
Feb-09
Mar-09

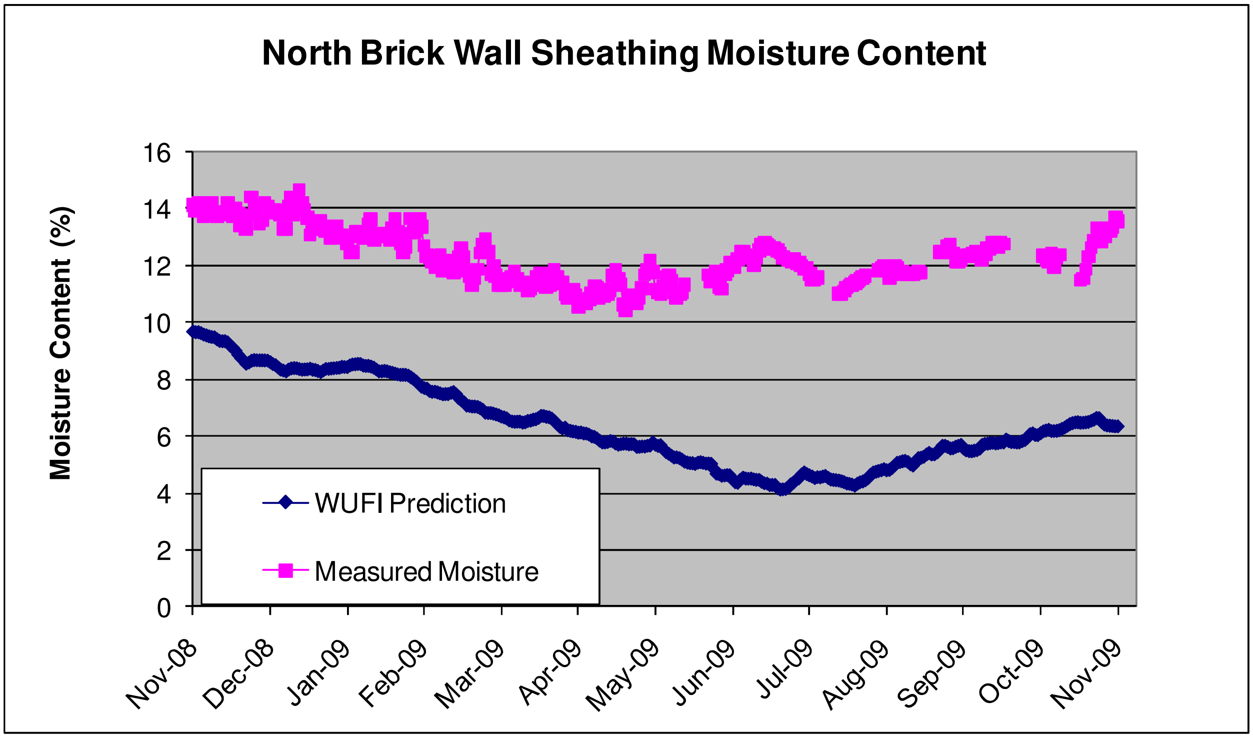

South Man Stone OSB Moisture Content
Moisture Content (%)
14%
13%
12%
11%
10%
9%
8%
7%
6%
WUFI Prediction
Omnisensor Reading
Jan-08
Feb-08
Mar-08
Apr-08
May-08
Jun-08
Jul-08
Aug-08
Sep-08
Oct-08
Nov-08
Dec-08
Jan-09
Feb-09
Mar-09

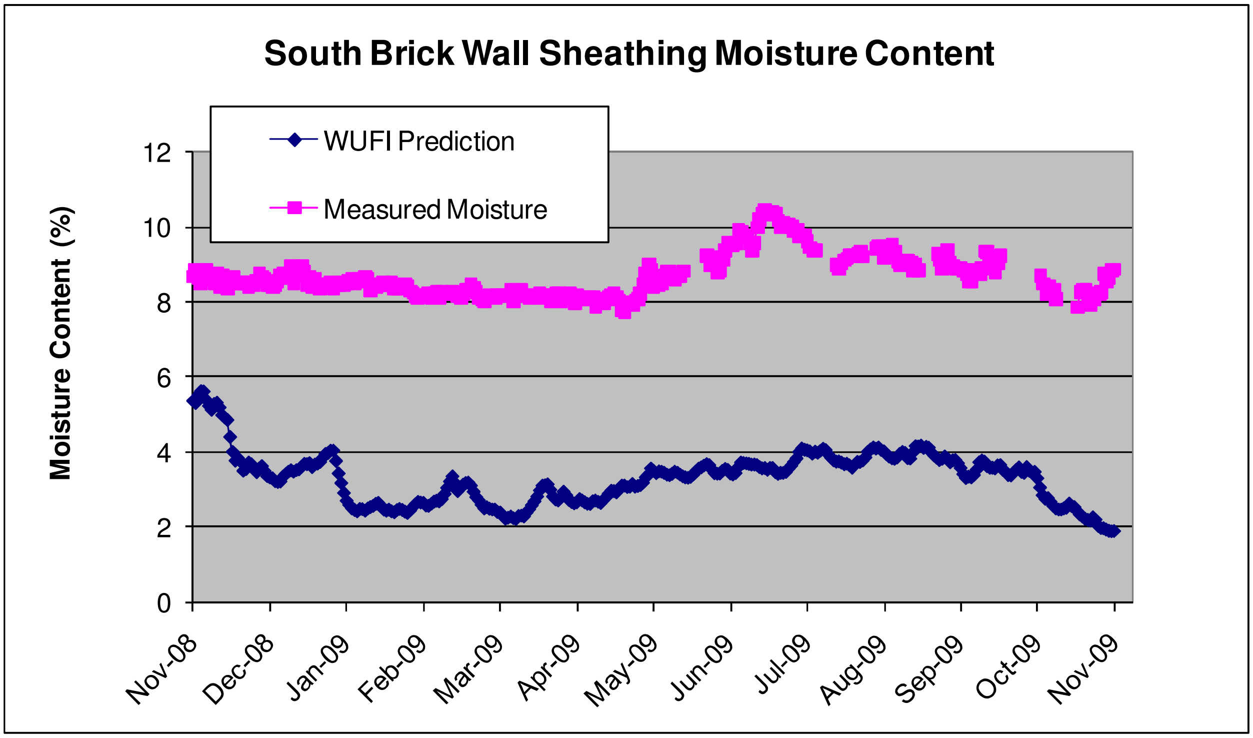

North Fiber Cement Siding OSB Sheating Moisture Content
Moisture Content (%)
20
18
16
14
12
10
8
6
4
WUFI Prediction
Measured Moisture
Nov-08
Dec-08
Jan-09
Feb-09
Mar-09
Apr-09
May-09
Jun-09
Jul-09
Aug-09
Sep-09
Oct-09
Nov-09


South Fiber Cement Sheathing Moisture Content
Moisture Content (%)
14
13
12
11
10
9
8
7
6
5
4
WUFI Prediction
Measured Moisture
Nov-08
Dec-08
Jan-09
Feb-09
Mar-09
Apr-09
May-09
Jun-09
Jul-09
Aug-09
Sep-09
Oct-09
Nov-09


North Stucco Plywood Sheathing Moisture Content
Moisture Content (%)
20
18
16
14
12
10
8
6
WUFI Prediction
Measured Moisture
Nov-08
Dec-08
Jan-09
Feb-09
Mar-09
Apr-09
May-09
Jun-09
Jul-09
Aug-09
Sep-09
Oct-09
Nov-09

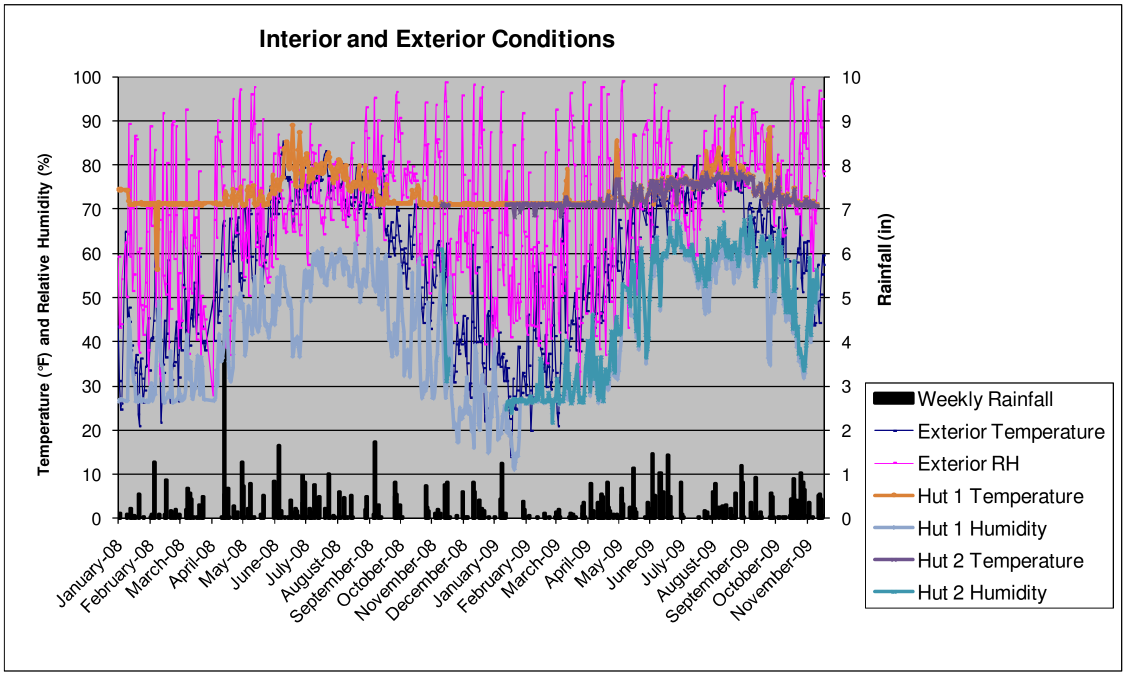

South Stucco Plywood Sheathing Moisture Content
Moisture Content (%)
20
18
16
14
12
10
8
6
WUFI Prediction
Measured Moisture
Nov-08
Dec-08
Jan-09
Feb-09
Mar-09
Apr-09
May-09
Jun-09
Jul-09
Aug-09
Sep-09
Oct-09
Nov-09


North Brick Wall Sheathing Moisture Content
Moisture Content (%)
16
14
12
10
8
6
4
2
0
WUFI Prediction
Measured Moisture
Nov-08
Dec-08
Jan-09
Feb-09
Mar-09
Apr-09
May-09
Jun-09
Jul-09
Aug-09
Sep-09
Oct-09
Nov-09


South Brick Wall Sheathing Moisture Content
Moisture Content (%)
12
10
8
6
4
2
0
WUFI Prediction
Measured Moisture
Nov-08
Dec-08
Jan-09
Feb-09
Mar-09
Apr-09
May-09
Jun-09
Jul-09
Aug-09
Sep-09
Oct-09
Nov-09

Appendix B: 2008 and Typical Meteorological Year Weather data for Andrews AFB, Maryland

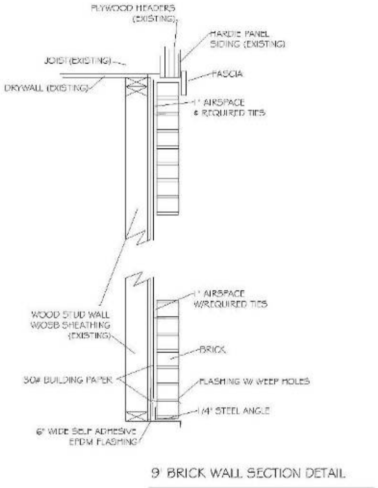
ASHRAE/NOAA Historical Averages					NAHBRC Weather Station Data				
	Average Temp (F)	Ave. Precipitation (in)	Heating Degree Days	Cooling Degree Days		Average Temp (F)	Total Precipitation (in)	Heating Degree Days	Cooling Degree Days
January	34.6	3.5	943	0	Jan-08	36.5	1.1	798	0
February	37.7	3.0	764	0	Feb-08	39.1	2.9	754	2
March	45.1	3.9	622	5	Mar-08	46.0	2.8	476	0
April	54.8	3.0	324	19	Apr-08	56.4	7.1	264	14
May	63.8	3.9	117	79	May-08	62.7	3.4	126	54
June	72.7	3.4	12	242	Jun-08	75.2	5.6	0	305
July	77.7	3.9	1	394	Jul-08	77.1	3.5	0	375
August	75.6	3.7	2	330	Aug-08	73.0	2.3	0	249
September	68.4	4.0	44	145	Sep-08	69.3	4.5	25	154
October	57.3	3.2	263	24	Oct-08	55.5	1.2	311	17
November	48.1	3.1	510	3	Nov-08	46.1	2.7	566	0
December	38.6	3.4	819	0	Dec-08	40.4	2.5	762	0
Year	56.3	41.9	4421.0	1241.0	Year	56.4	39.6	4081	1170
January	34.6	3.5	943	0	Jan-09	30.7	2.6	1062	0
February	37.7	3.0	764	0	Feb-09	39.8	0.3	706	0
March	45.1	3.9	622	5	Mar-09	44.6	1.5	638	4
April	54.8	3.0	324	19	Apr-09	56.6	4.0	305	51
May	63.8	3.9	117	79	May-09	64.1	3.9	83	61
June	72.7	3.4	12	242	Jun-09	72.2	7.9	10	226
July	77.7	3.9	1	394	Jul-09	74.9	1.0	0	306
August	75.6	3.7	2	330	Aug-09	76.5	4.6	0	357
September	68.4	4.0	44	145	Sep-09	66.6	2.8	31	80
October	57.3	3.2	263	24	Oct-09	56.5	6.0	277	14
Jan-Oct	58.8	35.5	3092	1238	Jan-Oct	58.2	34.6	3112	1097


Interior and Exterior Conditions
Temperature (°F) and Relative Humidity (%)
100
90
80
70
60
50
40
30
20
10
0
Rainfall (in)
10
9
8
7
6
5
4
3
2
1
0
January-08
February-08
March-08
April-08
May-08
June-08
July-08
August-08
September-08
October-08
November-08
December-08
January-09
February-09
March-09
April-09
May-09
June-09
July-09
August-09
September-09
October-09
November-09
Weekly Rainfall
Exterior Temperature
Exterior RH
Hut 1 Temperature
Hut 1 Humidity
Hut 2 Temperature
Hut 2 Humidity

Appendix C- Construction Photos

Construction of Test Structure 1

Weep Holes



Brick Veneer Wall Assembly Drawing

nish Coat

Grouting of the Manufactured Stone

Stucco Scratch Coat

Installing Fiber Cement Siding

Completed Structure 1

Completed Structure 2

Appendix D- Instrumentation and Controls

Wireless moisture sensors installed in an OSB stud bay with the dryer vent

Wireless moisture sensors installed in the plywood stud bay with the dryer vent

Wall Cavity before insulation was installed

Datalogger and controller used to record indoor and outdoor conditions and control indoor temperature and humidity

Rain gauge and horizontal solar radiation sensor

Anemometer, temperature humidity sensor

Humidifier

One of five electric resistance heaters

Vertical pyronometer located on wall surface

Wind driven rain sensor

First stage air conditioner with direct vent

Second stage air conditioner