Evaluation of Water-Resistive Barrier Performance in Stucco Walls

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ABSTRACT

This paper describes the results of a detailed laboratory evaluation and field demonstration of innovative residential building assemblies and construction practices intended to reduce the risk of moisture penetration and mold growth in walls with stucco cladding. Laboratory experiments and field demonstrations of water-resistive barrier (WRB) options in stucco walls are reviewed, with special focus on window installation methods and insulated wall assemblies subjected to moisture loading conditions. Additional laboratory evaluations, as well as consensus performance and prescriptive standards supported by field data and validated models, are recommended.

INTRODUCTION

Mold can grow almost anywhere and requires only air, water, a food source, and moderate temperatures to thrive. Under the correct conditions, new mold growth can occur in as little as 48 hours. When water intrudes into envelope cavities in a sustained manner or does not dry quickly, mold may propagate due to trapped moisture. Damp conditions in envelope cavities and resulting mold growth compromise building envelope energy efficiency, damage building materials, and affect the health and productivity of occupants. Once mold growth occurs, it is costly to remove and can result in expensive litigation. By understanding the building construction parameters affecting mold growth from bulk water intrusion, it may be possible to mitigate or prevent mold growth, thereby limiting heating and cooling energy losses, reducing building remediation costs, and avoiding human exposure.

The Energy Efficient Mold-Resistant Building Assemblies for California Homes program was a 30-month project funded by the California Energy Commission and Gas Research Institute to conduct a detailed investigation of residential building construction practices and innovative building assemblies that are resistant to mold formation and growth. The project team included six research organizations, two California builders, eighteen participating manufacturers, and a Project Advisory Committee (PAC) comprising product manufacturers, building scientists, participating utilities, participating builders, and state agencies. Based on input from Commission staff, the project team, PAC members, and building industry experts, the highest value areas for this project to address with laboratory testing and field demonstrations 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. Components, subsystems, and assemblies have been modeled and tested for mold growth and impact of moisture by building scientists, universities, and manufacturers (Treschel 1994, 2001; TenWolde et al. 1998; Karigiozis 2001, 2006; Morris and Hazelton 2001; Straube 2002; Boone et al. 2004; Rousseau et al. 2004; Teasdale-St-Hilaire et al. 2004; and Rose 2005). The laboratory investigations complemented that testing to provide a better understanding of the behavior of the entire assembly and to collect unique data on the performance of wall cavities and materials as a part of a complete assembly. These tests provided empirical data using existing and newly developed test protocols that were intended to permit replica-

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tion by other testing organizations as well as to provide a technical basis for builder design recommendations.

The project included laboratory and field studies of building assemblies that are important for keeping building materials dry and therefore free of mold growth (Leslie 2006a). This paper summarizes results of laboratory evaluations of WRB design alternatives in stucco wall construction (Leslie 2006b, 2006c, 2007) and a field demonstration of selected WRB materials and installation methods in energy-efficient production homes in California (Leslie 2006d).

OBJECTIVES

The objective of the laboratory studies was to perform a systematic laboratory evaluation of conventional and innovative residential building materials, assemblies, and construction practices identified in a literature review and expert interviews. 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. Laboratory evaluations focused on window installation methods, wall drying rates, and propensity for mold growth in wall cavities.

The objective of the demonstration homes effort was to perform a demonstration of mold-resistant assemblies and construction practices by building production homes containing recommended building components, assemblies, and construction techniques.

APPROACH

Specific laboratory tests and protocols were developed in conjunction with project team members, builders, PAC members, sponsors, and industry consultants, and were summarized in a laboratory evaluation test plan (Leslie 2004). The test plan provided the initial framework for laboratory evaluations of baseline and innovative wall assemblies. Based on experience gained during the performance of laboratory evaluations, the project team updated test goals, protocols, facilities, and test matrices to maximize the value of each experiment.

Wall assemblies included three-coat stucco cladding, one-coat stucco cladding with exterior insulation, and exterior insulation and finish system (EIFS) cladding with drainage mat. Three-coat stucco includes a scratch coat, brown coat, and finish coat, with a total thickness of approximately 0.875 in. (22 mm) including the finish coat. One-coat stucco combines the scratch coat and brown coat into a single base coat of 0.375 in. (10 mm) with a total thickness of approximately 0.5 in. (13 mm) including finish coat. EIFSs (also called *synthetic stucco*) are typically proprietary formulations that include a polymer and cement base coat with a total thickness of approximately 0.25 in (6 mm) including finish coat. All wall assemblies with stucco cladding included metal weep screeds at the bottom. The weep screed for the EIFS wall assembly was a plastic weep screed compatible with the other elements of the EIFS cladding.

Window Installation Methods Laboratory Evaluation

Table 1 describes stucco wall installation procedures for window installation methods tests. Structural framing options included open-frame (wood-frame with no exterior sheathing) construction and wood frame construction with oriented strand board (OSB) sheathing. WRBs included asphalt saturated building paper, perforated housewrap, and nonperforated housewrap. Flashing alternatives included mechanically fastened and self-adhering flashing. Windows were flush-mounted horizontal sliding vinyl windows with integral vinyl flanges. A total of 15 wall assembly/window installation method combinations were evaluated.

Table 1. Stucco Wall Construction Sequence

Stucco Type	Construction Steps
Three-coat stucco	Staple lath to frame members (open frame) or sheathing (0.5 in. [12 mm] oriented strand board) Apply in. (10 mm) scratch coat; cure for two days Apply in. (10 mm) brown coat; cure for five days Apply in. (3 mm) finish coat; cure for five days Apply backer rod and caulk around window frame
One-coat stucco	Install 1 in. polystyrene insulation with taped seams over WRB Staple lath to frame members (open frame) or 0.5 in. (13 mm) OSB sheathing Apply in. (10 mm) base coat; cure for two days Apply in. (3 mm) finish coat; cure for five days Apply backer rod and caulk around window frame
Exterior insulation finish system (EIFS)	Install backwrap and edgewrap mesh over WRB, folded Install 1 in. (25 mm) polystyrene insulation with taped seams over WRB Fold mesh over insulation and mechanically fasten to sheathing Apply in. (3 mm) base coat over insulation and mesh; cure for two days Apply in. (3 mm) finish coat; cure for two days Apply backer rod and caulk around window frame

Window installation performance evaluations focused on installation practices and materials recommended in ASTM E2112-01, *Standard Practice for Installation of Exterior Windows, Doors, and Skylights* (ASTM 2001), as well as draft revisions to the standard recommending sill pan flashing. The evaluation also included selected manufacturer installation methods to compare material, installation, and performance issues with ASTM E2112-01 guidance. Protocols relied on ASTM standards, such as ASTM E331-00, *Standard Test Method for Water Penetration of Exterior Windows, Doors, Skylights, and CUrtain Walls by Uniform Static Air Pressure Difference* (ASTM 2000a), and ASTM E1105-00, *Standard Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform or Cyclic Static Air Pressure Difference* (ASTM 2000b), and supplemented those methods with new protocols tailored to meet project goals.

Water spray test procedures for window installation methods evaluated the ability of the WRBs associated with each installation method to drain all water successfully to the exterior side of the window/wall assembly. The control parameters were window installation methods, cladding, WRB, flashing methods and materials, foam sealant, and window frame leak. The evaluations identified conditions under which observable liquid water leaked into the interior side of the WRB when the window/wall assembly was subjected to simulated rain and leakage events.

Facilities for the water spray tests included an unconditioned enclosed chamber; test stand for window assemblies; pumped, recirculated, dyed water spray rigs with sump below test stands; and access areas for visual inspection of assemblies during tests.

Each window was installed according to construction details described in the method under test (e.g., ASTM E2112-01, Method A). Clear and dyed water was sprayed on the vertical surface of the 24 × 36 in. (610 × 910 mm) vinyl sliding windows installed in wood-frame wall assemblies with three-coat stucco, one-coat stucco, or EIFS cladding. Spray nozzle flow rate, duration, and configuration were designed to provide acceptable droplet size, total water load, and wall coverage for test purposes, based on parameters described in ASTM E331-00 and ASTM E1105-00 (ASTM 2000a, 2000b), but without application of an air pressure differential. Each window assembly was sprayed before and after stucco application (Figure 2) for a specified period of time to simulate desired rainfall patterns and to explore the ability of the WRB options to shed bulk water intrusions as well as incidental water.

Wall and window construction adhered to relevant installation instructions. A professional stucco contractor installed metal lath, constructed all stucco wall assemblies, and applied caulk around window frames in accordance with their typical installation procedures for each type of cladding. Research staff installed all WRBs, windows, and foam sealant at interior reveals in accordance with selected window installation methods. Minor flaws that occurred during construction (e.g., over-application of foam sealant, lath staples missing framing members, etc.) were noted, but not corrected. Any flaws deemed functionally significant were repaired using sealant, tape, or re-application.

Fourteen of the 15 window/wall assemblies used a single layer WRB. The 15th assembly used double-layer construction specified in the installation instructions. California code requires a second layer of building paper over wood sheathing. However, to meet project objectives and allow reasonably equivalent comparisons, a single layer was used for both open frame and OSB sheathing assemblies.

Sill pan flashing included two types: three piece plastic pans with 0.5 in. (13 mm) backdam (a side and rear lip to keep water in the pan from draining to the interior), and moldable flexible self-adhering flashing. The center sections of the plastic pans were field cut to fit the exact window rough opening width and connected to the side sections using compatible adhesive caulk or plastic cement. For these experiments, 4 in. (100 mm) wide sill pans were used to allow observation of collected water in the pans and to permit supplemental experiments requiring poured water into pan. Moldable flexible self-adhering flashing did not have a backdam design. Half-inch foam backer rod was used underneath the flashing to slope the flashing toward the outside.

Recent surveys have identified window frame leaks as risk factors both in new construction and as the home ages (Criterium Engineers 2003; Lstiburek 2004). Typical homes have between 20 and 30 windows, so the probability of having at least one of those windows leak either right away or as the window ages is very high, though it will be impossible to know beforehand which window(s) will leak. To simulate a minor leak due to a cracked window flange, 0.125 in. (3.2 mm) holes were drilled through the welded seams in the lower two corners of each window after initial tests of the finished stucco walls. To simulate a more significant leak and provide head pressure through the holes, drainage weep holes in the window frames were then plugged.

Window installation methods tested in this project consider low curing pressure door and window foam sealant an air leakage control product and not a part of the WRB. However, it may be effective as a sealant for bulk water under certain circumstances, and it may reduce water head pressure due to wind-driven rain by reducing the air pressure differential. To examine the impact of sealant on leaks with head pressure, foam sealant was then applied to all reveals, except at plastic sill pans. To avoid any issues with inadvertent cuts when trimming, the foam sealant was not trimmed for any tests.

A special experiment was also conducted to evaluate liquid water and capillary drainage patterns in a window/wall assembly with a leak under a plastic sill pan flashing. With a dry stucco wall and without water spray, water was trickled from a hose into the sill pan flashing at a sufficient rate to maintain an equilibrium water level in the sill pan. Water flow rate and drainage patterns on the stucco wall in the vicinity of the leak site were noted.

The measurement parameter for these tests was visual evidence of water penetration behind the WRB. For open frame construction, visual observation did not require dyed water. For walls with OSB sheathing, all experiments were conducted with clear water to examine leaks on the interior side of the sheathing. The final experiment was repeated with dyed water, followed by destructive evaluation of the exterior side of the sheathing. Any water stains were noted and photographed.

Wall Assembly Laboratory Evaluation

All wall assembly evaluations were conducted in a 15 ft (4.6 m) high air-conditioned laboratory in nearly still air controlled at 78°F (25°C). Test apparatus included

- two test stands with load cells for weight differential measurements;
- precision scales for gross wall and insulation weights;
- moisture loading nozzle and flow controller to inject water into wall assemblies;
- moisture content, relative humidity, and temperature sensors;
- infrared camera for surface temperature measurements;
- sensor control and signal conditioning microprocessors; and
- data acquisition system to record and monitor data.

The load cell test stands were designed and constructed at the laboratory to provide precise measurements of wall assembly weight (Figure 1). Each test stand included

- wood posts for pivot bearing, embedded in concrete casing;
- pillow block pivot bearing and metal counterweight bar with counterweights;
- compression load cell attached to wood frame;
- adjustable wall hanging clips for centering and vertically hanging wall assemblies; and
- data acquisition wiring harness and punchdown block for sensor wiring.

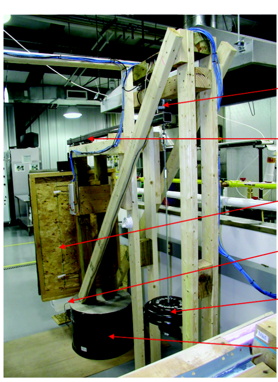

Figure 1 *Wall weight load cell apparatus.*

Wall assemblies were hung from each fixture and counterweights were added to provide approximately 5 lb (2.3 kg) net weight on the compression load cell (20% of full range) when dry.

The automated data acquisition system (DAS) was a signal conditioning microprocessor and datalogger with two 64 channel multiplexers, power supply, battery backup, and Ethernet access. Software programs for signal conditioning and datalogging were written for each test sequence.

Sensors included insulation temperature and relative humidity, wood stud and OSB moisture content and temperature, and room temperature and relative humidity. Temperature and relative humidity sensors were thermistors and thin film capacitance sensors encased in 58 perm water resistant sheathing. Resistance moisture pins and wood temperature thermistors were specially designed and fabricated for this project. Data were collected once a minute, and hourly averages were recorded to the file.

Building assemblies' laboratory evaluations involved three categories of experiments, each with different protocols to achieve task objectives:

- Susceptibility to mold growth
- Moisture content over time
- WRB drainage capacity

Table 2 lists the wall assemblies evaluated in these experiments. Wall assemblies (Figure 2) included three-coat stucco cladding, one-coat stucco cladding with exterior insulation, and EIFS cladding with drainage mat. Structural framing options included open-frame construction and OSB sheathing. WRB's included asphalt saturated building paper and nonperforated higher permeance housewrap.

Initial moisture content and mold growth experiments were conducted in accordance with the Laboratory Evaluation Test Plan. 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.

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 plastic (three layers of shrinkwrap) to maintain high moisture content for an extended period. For wall drying experiments, five of the six sides were encased in plastic taped to the assembly to bias vapor flow toward the WRB side. The revised protocols were more successful in meeting experiment goals, but are considered less representative of actual field conditions than the initial protocols.

For mold-resistant gypsum panel experiments, R-19 kraft-faced fiberglass insulation was compressed into the 3.5 in. (89 mm) cavity to increase initial water loading in the

Table 2. Stucco Wall Assembly Components

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, wood studs with kraft-faced R-13 fiberglass batt insulation, 0.5 in. (13 mm) gypsum panel, latex primer and finish coat
High/low drainage openings	Baseline with high/low drainage openings
Housewrap	Baseline with 58 perm housewrap for inner layer
Textured housewrap	Baseline with 50 perm textured housewrap for inner layer
One-coat, insulated sheathing	Baseline with one-coat stucco, insulated sheathing
EIFS	Baseline with EIFS instead of three-coat stucco
Cellulose insulation	Baseline with cellulose instead of fiberglass insulation
Antimicrobial gypsum panel	Baseline with antimicrobial gypsum panels
Fiberglass gypsum panel	Baseline with fiberglass gypsum panels
Mold-resistant sealer	Baseline with mold-resistant sealer

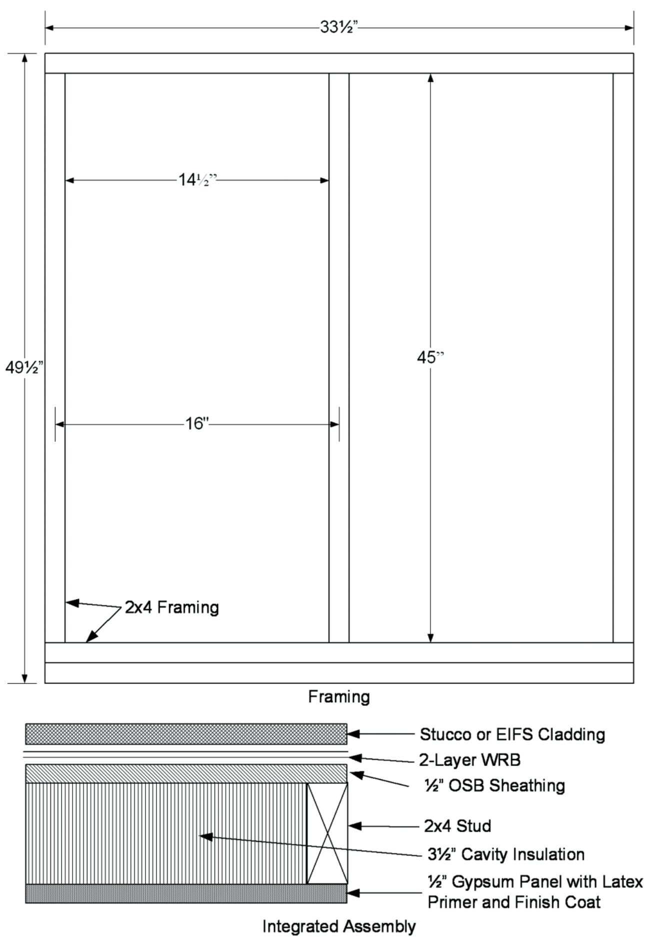

Figure 2 *Stucco wall assembly construction for moisture measurement experiments.*

insulation layer. Each wall assembly had four vertical gypsum panel sections painted with one coat of latex primer and one coat of contractor grade latex paint, with the edges sealed with waterproof tape. Two sections were conventional gypsum panels, and two 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, R-19 kraft-faced fiberglass insulation was compressed into the 3.5 in. (89 mm) cavity to increase initial water loading in the insulation layer. The wall assembly had a conventional 0.5 in. (13 mm) gypsum panel painted with one coat of latex primer and one coat of contractor grade latex paint, with the edges sealed with waterproof tape. The wall cavity was divided into four sections. Two sections were untreated studs and OSB, and two sections were painted with mold-resistant sealer. 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 conventional 0.5 in. (13 mm) gypsum panel painted with one coat of latex primer and one coat of contractorgrade latex paint, with the edges sealed with tape. The wall cavity was divided into two sections. One section had R-13 kraft-faced fiberglass insulation. The other section had loose-fill cellulose insulation applied to the cavity. The two sections provided an interior and exterior stud exposure for each type of insulation.

Exterior edges of the wood frames for all experiments were caulked and sealed with three coats of elastomeric paint to minimize leakage during preconditioning. Wall assemblies were then laid flat, stucco cladding side down. Water collected from a local field was poured into the wall assembly to a depth of 0.25 in. (6 mm) to soak the OSB for a period of three to five 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 panel sections were sprayed with water to wet the back sides only, and installed with screws and washers to allow nondestructive inspection. Edges were sealed with waterproof tape. Wall assemblies were wrapped in plastic and flipped over, with the gypsum panel side now facing the floor. Wall assemblies remained in this configuration for a period of five days to precondition 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.

Monitoring included visual inspections of visible wall assembly surfaces to check the 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 of 85% to 100% percent. Two 250 W heat lamps pointed at the lower half of the assembly were used to heat the cladding and drive moisture toward the interior cavity and gypsum panels. 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 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 preconditioning. Wall assemblies were then disassembled for a complete visual inspection for mold growth. No effort was made to differentiate mold species or to quantify the severity of mold growth.

Preconditioning protocols for wall drying rate experiments were similar to mold growth experiment protocols. Wall assemblies were laid flat with the stucco cladding side down. Water collected from a local field was poured into the wall assembly to a depth of 0.25 in. (6 mm) to soak the OSB for a period of three 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 nondestructive inspection. Edges were sealed with waterproof tape. Wall assemblies were wrapped in shrinkwrap plastic except for the stucco face and flipped over, with the gypsum panel side now facing the floor. Wall assemblies remained in this configuration for a period of five days to precondition the insulation and gypsum panels. The wall assemblies were closed with all sides except the stucco cladding wrapped in plastic, and hung on load cells for the four-week duration of the experiment.

For drainage capacity experiments, water was discharged through a hose nozzle at a controlled and metered flow rate into the top of the wall assembly to measure the equilibrium drainage rate, with and without water sprayed on the exterior wall surface. A 1 in. (25 mm) high metal trough with a slotted bottom opening was inserted between the cladding and WRB and taped and caulked to seal all edges. 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. The trough drained the metered water flow into the wall assembly between the WRB and stucco cladding. The water flow rate for each assembly was adjusted as necessary to maintain an approximately 0.5 in. (13 mm) 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.

Exterior edges of the wood frames were caulked and sealed with three coats of elastomeric paint to prevent leakage between the wood frame and cladding. 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.

Each wall assembly was hung from the same load cell to facilitate experiments and to enable moisture weight measurements if desired. City water was fed into the trough through a flowmeter and hose nozzle. 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.

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 collecting 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 flowmeter.

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.

Demonstration Home Construction

One participating builder constructed a total of eight ENERGY STAR® demonstration homes as a part of a development in Chino, California. Two included only modifications to the concrete slabs, and four included only modifications to the wall assemblies and selected interior spaces. Two baseline concrete slab homes were also included to provide data on the impact of concrete slab installation procedures and materials on concrete slab performance and cost.

The other participating builder constructed a single demonstration home as a part of a zero energy home development in Watsonville, California. The home was joist construction on built-up foundation and did not include any concrete slab construction features. It was predominantly open frame construction, and incorporated selected innovative assemblies that were compatible with zero energy home construction materials and practices used by the builder.

For field modifications, participating manufacturers provided technical information and on-site support to ensure a successful installation and to provide incremental installed cost data. Data acquisition system specifications for the concrete slab demonstration homes were developed by the project team in conjunction with cofunding noncontractual participants from the concrete industry.

Innovative materials and installation practices in these homes focused on concrete slab installation methods and vapor retarder materials, WRB options and construction sequence, window installation methods, mold-resistant sealer and interior gypsum panels, construction drying services, ventilation control, and noise reduction strategies.

RESULTS

Window Installation Methods Laboratory Evaluation

Table 3 summarizes test results for each installation method/stucco wall assembly tested. Only one of 15 assemblies (Assembly No. 4, a sill pan flashing method) had no observable leaks under all test conditions. Leaks occurred in 14 of 15 assemblies during the most challenging experiment (drilled holes and plugged weep holes in window frames, no interior sealant). Stucco cladding with caulked windows deflected bulk water effectively. Remaining "incidental" water from capillary suction did not leak through the WRBs with any window installation method, with the possible exception of perforated housewrap.

Results illustrate the complex nature of stucco drainage mechanisms, as well as the impact of penetrations and face leaks on wall assembly performance. Stucco moisture transport mechanisms are complex, comprising barrier, capillary suction, gravity drainage, and vapor diffusion transport. Different mechanisms can dominate depending on design, installation, and maintenance. As a porous material, stucco complicates drainage flows.

Table 3. Window Installation Method Test Results Summary

Assembly	Wood Sill Covered?	Observed Leakage to Interior Side of Wall Assembly				
		No Stucco	With Stucco, Caulked Except as Noted	Caulked, With Drilled Holes	Drilled Holes, Plugged Weep Holes	Plugged Weep Holes, Foam Sealant
1	No	No	No	No	Yes	No
2	No	No	No	No	Yes	No
3	Yes	Yes*	No	No	Yes	Yes
4	Yes	No	No; no caulk	No	No	No
5	Yes	No	No	Yes	Yes	Yes
6	Yes	No	No	Yes	Yes	Yes
7	Yes	No	No	No	Yes	Yes
8	Yes	Yes*	No	No	Yes	Yes*
9	No	No	No	Yes	Yes	Yes
10	Yes	No	No	No	Yes	No
11	Yes	No	Yes; no caulk	Yes	Yes	No
12	No	Yes	No	Yes	Yes	Yes
13	No	Yes	Yes; no caulk	No	Not tested	Yes
14	Yes	No	No	No	Yes	No
15	Yes	Yes	No	No	Yes	No

* Leakage occurred in wall assembly away from window/wall interface.

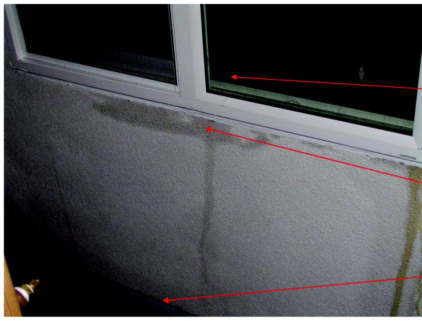

Figure 3 *Capillary-dominated drainage with water poured into sill pan.*

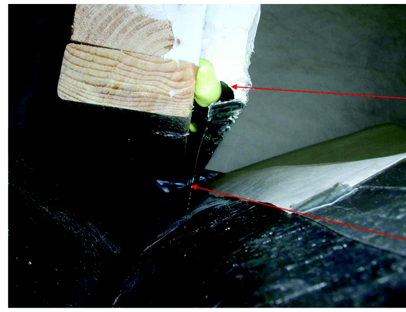

Figure 4 *Drainage channel at weep screed for three-coat stucco wall.*

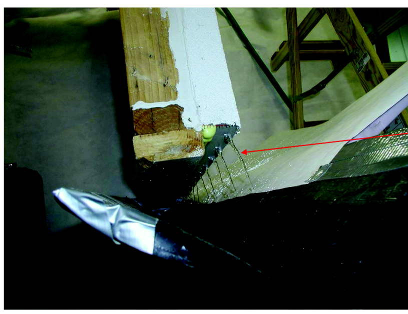

Figure 5 *EIFS drainage through screed.*

Figure 6 *Leakage with sill pan and OSB sheathing.*

Stucco drainage mechanisms impacted WRB drainage capacity and leak risk. Capillary moisture transport (liquid wicking/soaking) provided relatively slow drainage at the interface between stucco and the WRB and transported liquid water to both sides of the stucco cladding as well (Figure 3).

Based on related laboratory experiments on stucco walls (Figures 4 and 5), capillary-dominated drainage of liquid water poured into the top of the interface of the WRB and interior side of stucco was at least an order of magnitude slower than gravity drainage when there were designed or unintentional gaps between the stucco and the WRB that provided a capillary break (Leslie 2006c).

Reduced gravity drainage capacity from capillary-dominated moisture transport caused leaks from bulk water collected by sill pan flashing. Sill pans effectively collected water leaking through window frames. However, bulk water under head pressure (due to height between the sill pan and leak site with restricted drainage) leaked through small holes in the WRB at sill pans/WRB joints or through staple holes (Figure 6). Bulk water collected by the sill pan did not leak under head pressure when there were no holes in the restricted drainage path.

Stucco with a freshly caulked window frame prevented liquid water penetration at window/wall interface, even with reverse shingle-lap. Stucco cladding with caulk provided a face seal and stopped bulk water flow. Capillary suction transported moisture to the interior side of stucco, with little or no liquid drainage at the WRB.

Low pressure expanding foam sealant (an air barrier) improved WRB performance at the sill in some cases (Figure 7). The sealant contained leaks when a full seal was achieved. The sealant did not contain leaks when misapplied or incompatible with its substrate.

Perforated housewrap leaked through perforations with and without stucco cladding. No observable leaks occurred on the interior side of OSB sheathing at window/wall interface. However, leaks occurred when the moisture drainage mechanism was either liquid water or possibly capillary moisture flow after application of stucco cladding based on destructive disassembly (Figure 8).

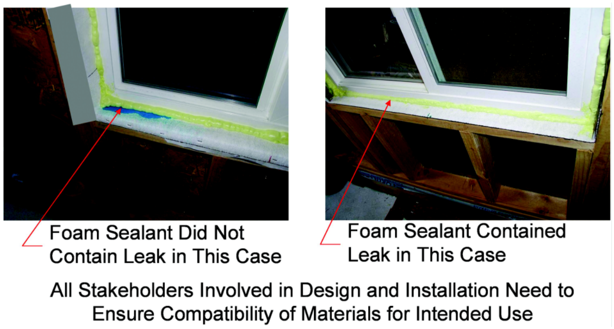

Figure 7 *Leak with foam sealant due to misapplication/incompatibility.*

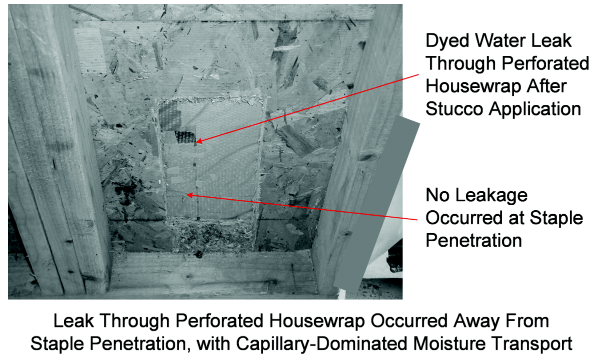

Figure 8 *Leak through perforated housewrap during 15-minute blue dye spray test.*

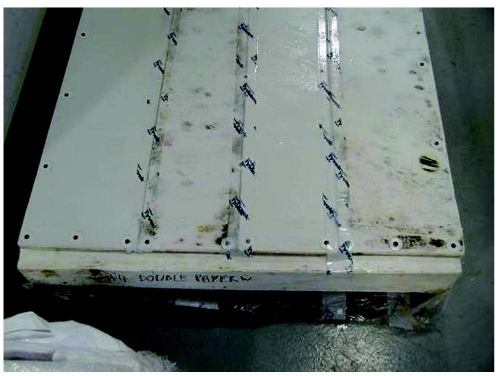

Figure 9 *Mold-resistant panels vs. conventional gypsum panels.*

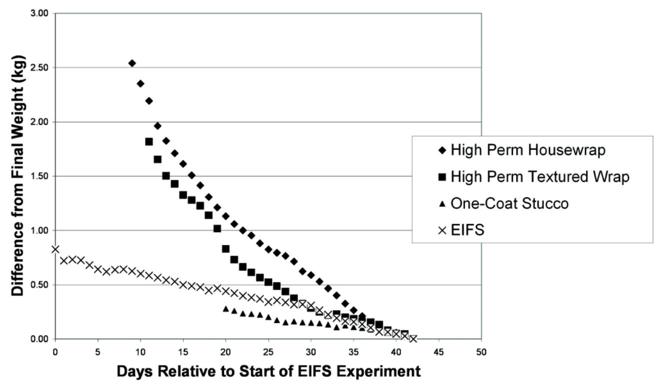

Figure 10 *Wall weight profiles normalized to end date.*

Wall Assembly Laboratory Evaluation

All of the wall assemblies in the mold resistance 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 significantly affected mold formation and growth. 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. Little visible mold growth occurred elsewhere, including the OSB, higher up in the wall, fiberglass insulation, and gypsum panels.

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.

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 (Figure 9). The remainder of the wall assembly experienced significant mold growth.

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.

For drying rate experiments, 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 non-perforated spunbonded polyolefin housewrap (flat and textured) 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-

Table 4. Wall Assembly Drainage Rates

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

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.

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 (Figure 10). Heating the gypsum pane with infrared lights slightly increased the drying rate of each wall.

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

Table 4 lists equilibrium drainage flow rates for each wall assembly without rain simulation. Rain simulation did not impact drainage capacity for any of the wall assemblies but did impact leakage through the open frame wall assembly. Drainage capacities of 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. The open frame wall assembly behaved differently than the other four stucco walls. 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 drainage capacity significantly compared to capillary-dominated drainage. 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.

The other high drainage wall assembly was the EIFS with designed drainage mat and weep screed. In this case, the increased gravity drainage capacity was a function of the narrow gap designed 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. 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, 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 leakage at the exterior side of OSB sheathing, since that surface was not visible. None of the high drainage capacity walls experienced any visible leaks.

Demonstration Home Construction

Demonstration homes were production homes built over a nine-month period using commercially available products. All demonstration homes were sold to consumers. Innovative assemblies and practices incorporated into demonstration homes included several WRB options and related construction sequence, self-adhering flashing options, ASTM E2112-01R window installation methods (Figure 11), mold-resistant

Figure 11 *Window installation, ASTM E 2112-01R Method A1.*

Figure 12 *Application of mold-resistant sealer.*

sealer (Figure 12), mold-resistant interior gypsum panels, and bath ventilation control.

Demonstration homes required the builders to make several changes in materials and construction sequences. The selected housewrap construction sequence is rarely used in California home construction with stucco cladding, although it is preferred by manufacturers and building scientists for optimum air barrier and WRB performance. Integrating this method with building paper increased the risk of reverse shingle-laps at penetrations flashed by other trades unfamiliar with the required flashing sequence. Successful widespread application will require improved trade coordination and education for construction sequence modifications. There was also incremental labor content compared to two-ply building paper that is applied in one step. There is also a risk of leaks at taped butt joints (e.g., holes, tears, v-cut for head flashing) and an increased number of staple holes.

Application of other options went smoothly. Consideration for future implementation will be based on perceived cost/benefit. Based on their experience, the builders and installing contractors prefer to continue using two-ply building paper for stucco at this time. The builder is considering several options for future homes, including:

- Self-adhering flashing
- Sill pans under windows
- Concrete slab seats under doors
- High-performance concrete slab vapor retarders
- Low noise energy-efficient bath exhaust fan/lights
- Mold resistant sealer on selected OSB and studs
- Quality inspection service

CONCLUSIONS

Laboratory evaluations of the window/wall interface and WRBs support the following conclusions:

- Capillary break between stucco and WRB is required for optimal gravity drainage. Additionally, a double-layer WRB is preferred for stucco walls. The interior layer provides space for gravity drainage, and the outer layer provides a bond break. Sill pans should drain to the interior layer (the functional WRB).
- When windows leak, additional design elements are necessary. Unpredictable amount and location of leaks complicates risk mitigation strategies. A panned sill drainage system is essential to mitigate this risk, and a full air barrier is required at all reveals.

Demonstration homes met established goals. Voluntary builder, contractor, and manufacturer commitment and input were critical for success. Builder and manufacturer feedback indicates mutually beneficial value from participation. Based on results, builders and manufacturers are willing to participate in suitable future demonstrations. Demonstration home results also corroborated research needs previously identified.

Laboratory data collected during this research project provided some support for the hypothesis that placing a sill pan flashing beneath vinyl windows as recommended by ASTM E2112-01R may reduce the risk of consequential water intrusion into wall cavities in as-built construction. Data collected under wall assembly experiments provided evidence of the beneficial impact of mold-resistant materials on mold formation and growth but only on the materials themselves. Results provided technical support for recommending properly designed and installed WRBs to reduce the risk of bulk water intrusion and mold growth. 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.

Peer-reviewed field data on performance of different WRB options and failure mechanisms of as-built window/wall assemblies for new construction in California could not be found during this project. Anecdotal data and forensic evaluations provided helpful information but did not establish authoritative links between various designs and long-term field performance as implemented. The protocols and targeted installation methods included in this project were intended to simulate bulk water intrusion on as-built construction realistically and to evaluate both design and construction factors related to bulk water drainage. However, there is no way to judge the true relevance of this work without field performance data and associated methods of test. As a result, test results presented in this paper are considered informative, but not authoritative. Nonetheless, results, if credible, were sufficiently compelling to warrant further research and strongly support the need for field data collection.

RECOMMENDATIONS

Research recommendations focus on continuing consensus standard development and application currently underway at ASHRAE, ASTM, and other standards organizations. Consensus laboratory and field performance test standards for integrated cladding and wall assemblies are needed, both performance and prescriptive, for materials and installation methods. These should be realistic and supported by field data and validated models. Laboratory and field data are needed on root causes and consequences of building envelope failures to identify and evaluate alternative mold risk reduction strategies for homes with stucco cladding. Laboratory and field moisture content and drying rate measurements of new and innovative building assemblies should be performed using consensus test methods to provide additional data to validate hygrothermal models.

Development of the integrated assembly performance test methods should focus on voluntary standards development processes such as ASHRAE and ASTM. As inputs to that process, the research community should conduct additional research using reasonable test methods developed by industry experts. The ASTM E2112 standard committee recently formed a working group to explore options on fenestration installation performance test methods. Public and private stakeholder involvement in this process is strongly encouraged. Collaborative research efforts to evaluate candidate methods in laboratories and in the field are recommended.

The recommended 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 an authoritative root cause analysis of moisture and mold problems.

Moisture and drying rate measurements should be conducted by research organizations such as universities, using protocols developed in conjunction with hygrothermal model developers (see, for example, Karagiozis [2001]) to ensure that the measured data is of adequate quality and in a format that is useful for model validation.

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REFERENCES

ASTM. 2000a. *ASTM Standard E331-00, Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference*. Philadelphia: American Society for Testing and Materials International. .

ASTM. 2000b. *ASTM Standard E1105-00, Standard Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform or Cyclic Static Air Pressure Difference*. Philadelphia: American Society for Testing and Materials International.

ASTM. 2001. *ASTM Standard E2112-01, Standard Practice for Installation of Exterior Windows, Doors and Skylights*. Philadelphia: American Society for Testing and Materials International.

Boone, K., T. Weston, and X. Pascual. 2004. Wall drying in hot and humid climates. *Proceedings Fourteenth Symposium on Hot and Humid Climates, College Station, TX, Texas A&M University.*

Criterium Engineers. 2003. Construction quality survey. Portland, ME: Criterium Engineers.

Karagiozis, A.N. 2001. Advanced hygrothermal models and design models. The Canadian Conference on Building Energy Simulation, Ottawa, Canada, CANMET Energy Technology Center/Natural Resources Canada, Ministry of Supply & Services M39-79/2001 (ISBN 0-660-61650-5). Ottawa. CANMET.

Karagiozis, A.N. 2006. The hygrothermal performance of exterior wall systems: Key points of the Oak Ridge National Laboratory NET facilities research project January 1, 2005 through March 30, 2006. Morrow, GA: EIFS Industry Members Association.

Leslie, N.P. 2004. Laboratory evaluation test plan. Report to the California Energy Commission, Sacramento.

Leslie, N.P. 2006a. Final report for energy efficient mold resistant materials and construction practices for new California homes. Report to the California Energy Commission, Sacramento.

Leslie, N.P. 2006b. Window installation methods test results. Report to the California Energy Commission, Sacramento.

Leslie, N.P. 2006c. Building assemblies laboratory evaluation results. Report to the California Energy Commission, Sacramento.

Leslie, N.P. 2006d. Demonstration homes summary report. Report to the California Energy Commission, Sacramento.

Leslie, N.P. 2007. Laboratory Evaluation of Residential Window Installation Methods in Stucco Wall Assemblies. AS*HRAE Transactions* 113(1).

Lstiburek, J.W. 2004. *Water Management Guide*. Bloomington, MN: Energy and Environmental Building Association.

Morris, P.I., and D.G. Hazelton. 2001. Evaluation of vapor diffusion ports on drying of wood-frame walls under controlled conditions. Technical Series 02-130, Canada Mortgage and Housing Corporation, Ottawa.

Rose, W.B. 2005. *Water in Buildings: An Architect's Guide to Moisture and Mold*. Hoboken, NJ: John Wiley and Sons.

Rousseau, M.Z., B. Arch, and W.A. Dalgliesh. 2004. Selected findings of an IRC study of the wetting and drying potentials of wood-frame walls exposed to different climates. CIB World Building Congress, May 2–7, Toronto, Canada.

Straube, J.F. 2002. Moisture in buildings. *ASHRAE Journal* 44(1):15–19.

Teasdale-St-Hilaire, A., D. Derome, and P. Fazio. 2004. Behavior of wall assemblies with different wood sheatings wetted by simulated rain infiltration. *Proceedings of Performance of the Exterior Envelopes of Whole Buildings IX International Conference, Atlanta.*

TenWolde, A., C.G. Carll, and V. Malinauskas. 1998. Air pressures in wood frame walls. *Proceedings of the Conference on Thermal Performance of the Exterior Envelopes of Buildings VII, Atlanta.*

Treschel, H.R., ed. 1994. *Moisture Control in Buildings*. Philadelphia: American Society for Testing and Materials.

Treschel, H.R., ed. 2001. *Moisture Analysis and Condensation Control in Building Envelopes*. Philadelphia: American Society for Testing and Materials.