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Window Installation Methods Test Results

Task 3.3 Report

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for

California Energy Commission

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Executive Summary

Water spray test procedures for flanged vinyl window installation methods evaluated the ability of the water-resistive barriers (WRB's) 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, interior 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.

Performance evaluations focused on flanged vinyl windows (not recessed) and related installation practices and materials recommended in ASTM E 2112-01 "Standard Practice for Installation of Exterior Windows, Doors, and Skylights", 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 E 2112 guidance.

Experimental protocols were designed to allow exploration of a number of hypotheses regarding WRB options related to window installation methods, including:

- Caulked stucco provides an excellent seal around windows when new.
- Stucco joint cracks, penetrations, WRB installation problems, and window frame cracks each can result in leakage to interior wall cavities.
- All WRB alternatives, if properly installed, provide acceptable resistance to liquid water penetration unless the window frame (with no sill pan) is breached.
- EIFS with drainage mats (not barrier EIFS) provide acceptable resistance to liquid water penetration behind cladding unless the window frame (with no sill pan) is breached.
- WRB's behave differently when subjected to bulk water rather than incidental water that penetrates behind cladding.
- Holes from WRB or lath fastener penetrations can result in leakage into interior wall cavities.
- Sill pan flashings with outlet to exterior side of WRB are effective at managing water penetration behind a leaking window frame.
- Interior foam sealant is effective at stopping water intrusion behind leaking window frames, but does not ensure that such water intrusions will drain outdoors.

Each window was installed according to construction details described in the method under test (e.g., ASTM E 2112-01, Method A). Clear and dyed water spray simulated wind-driven rain on the vertical surface of the 24" x 36" flanged vinyl sliding windows installed in wood frame wall assemblies with 3-coat stucco, 1-coat stucco, or EIFS cladding. Each window assembly was sprayed before and after stucco application 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. To simulate a minor leak due to a cracked window flange, ⅛" holes were drilled at 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.

Only 1 of 15 assemblies (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 ⅛" 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 WRB's with any window installation method, with the possible exception of perforated housewrap.

Observations from these tests include the following:

- Stucco moisture shedding and transport mechanisms had a significant impact on WRB drainage capacity and leakage risk during these experiments.
- A full face seal (stucco with caulked window frame) barrier prevented liquid water penetration at the window/wall interface for all window installation methods tested.
- The reverse shingle-lapped WRB didn't leak with a full face seal.
- Liquid water and capillary moisture flow behind stucco leaked onto OSB sheathing away from window/wall interface through perforated housewrap.
- Pan joint sealant did not fully adhere to field-cut three-piece pliable plastic sill pan flashing lapped joints without supplemental pressure due to differential flexure or inadvertent movement of pan sections during installation.
- Moldable self-adhering sill flashing over backer rod (to create a backdam) did not provide a full length water-tight seal to the window frame, resulting in leakage onto the sill through creases in flashing.
- Low pressure expanding foam sealant applied to interior reveals contained leaks on the sill whenever it achieved a full length seal.
- Marvin instructions for installing self-adhering flexible sill flashing (intended to be functionally similar to ASTM E 2112-01R Draft) did not provide a method to create a back dam with this technology. Without the backdam, sill leakage occurred similar to ASTM E 2112-01 instructions. Foam sealant was successful in stopping the leak in this case.

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 E 2112-01R may reduce the risk of consequential water intrusion into wall cavities in as-built construction. Peer-reviewed field data on performance of different WRB options and failure mechanisms of as-built window/wall assemblies for California new construction 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, project test results are considered informative, but not authoritative. Nonetheless, results were sufficiently compelling to warrant further research and strongly support the need for field data collection on causes and consequences of water intrusion into wall cavities. Results also provided technical support for recommending properly designed and installed WRB's with or without sill pan flashing to reduce the risk of bulk water intrusion.

Research recommendations focus on two major initiatives:

1. Develop and evaluate performance test methods for window installation methods as applied to wall assemblies; and
2. Collect and analyze laboratory and field data on root causes and consequences of building envelope failures to identify and evaluate alternative mold risk reduction strategies for window/wall interfaces.

Task 3.3 – Window Installation Method Test Results

Background

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

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

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

Goal

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

The goal of Task 3.3 was to evaluate conventional and innovative construction practices (i.e., the way individual components and building assemblies are installed in the field) identified in Task 2.4 in accordance with the Laboratory Test Plan developed in Task 3.1. To meet this goal, the project team performed a series of experiments in a controlled environmental setting at GTI's laboratory facilities. Experiments focused on moisture loading and climatic cycling action on assembled systems representing targeted building construction practices. These tests provide empirical data using existing and newly developed test protocols that should permit replication by other testing organizations and provide a technical basis for demonstration home design recommendations in Tasks 3 and 4 and builder guidelines in Tasks 3 and 5.

Scope

Laboratory evaluations under Task 3.3 addressed the following construction practices:

1. Evaluate performance of WRB design alternatives around conventional vinyl windows in stucco wall construction; and
2. Measure moisture content over time of concrete floor slabs and footings with targeted vapor retarder locations and fill materials in the drying period after the slab was poured and when the slab fill materials were subjected to subsequent water intrusion events.

This task report focuses on performance evaluation of WRB design alternatives around windows. A separate Task 3.3 report discusses concrete floor slab tests.

Approach

Water spray test procedures for flanged vinyl window installation methods evaluated the ability of the WRB's 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, interior 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.

Wall assemblies included 3-coat stucco cladding (Figure 1), 1-coat stucco cladding with exterior insulation (Figure 2), and Exterior Insulation Finish System (EIFS) cladding with drainage mat (Figure 3). Structural framing options included open-frame construction and oriented strand board (OSB) sheathing. WRB's included asphalt saturated building paper, perforated housewrap, and non-perforated housewrap. Flashing alternatives included mechanically fastened and self-adhering flashing.

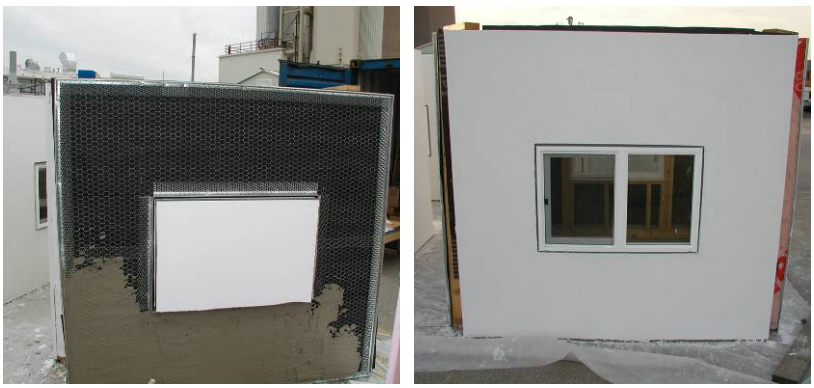
Performance evaluations focused on flanged vinyl windows (not recessed) and related installation practices and materials recommended in ASTM E 2112-01 "Standard Practice for Installation of Exterior Windows, Doors, and Skylights", as well as draft revisions to the standard recommending sill pan flashing. The evaluation also included selected manufacturer installation methods to compare material, installation, and performance issues with ASTM E 2112 guidance. Table 1 lists window installation methods included in the tests. Table 2 describes stucco wall installation procedures.

A recent survey (cited by Thomas Butt in 2004) of over 3,500 vinyl windows that were less than two years old found that 20 percent had already begun to leak. Typical homes have between 20 and 30 windows, so the probability of having at least one of those windows leak is very high – though it will be impossible to know beforehand which window(s) will leak. Figure 4 shows a common leak site for vinyl windows at a sill flange corner weld. The current revision to ASTM E 2112-01 recognizes this issue and consequently recommends sill pan flashings under all windows and doors. Field data collected by SureSill from its installed base of pan flashings in the Southeast US (Table 3) indicates a high incidence of field issues that may be resolved by proper installation of sill pan flashing. Test protocols were designed to evaluate the performance of sill pan flashing technologies installed in open frame and sheathed window/wall assemblies.

ASTM E 2112 is currently a prescriptive standard. The cognizant committee is exploring appropriate approaches to performance testing methods so materials, practices, and applications not explicitly covered by the prescriptive practices can be evaluated. The approach and protocols used in this project were intended to assist those efforts by establishing reasonable performance test methods based on current standards for related wall components. Protocols relied on ASTM standards such as ASTM E 331 and ASTM E 1105 and supplemented those methods with new protocols tailored to meet project goals.

a) ⅜” Scratch Coat b) ⅜” Brown Coat c) ⅛” Finish Coat

Figure 1 Three-Coat Stucco Wall Assembly



a) ⅜” Base Coat b) ⅛” Finish Coat

Figure 2 One-Coat Insulated Stucco Wall Assembly

a) Insulation Over WRB b) Lath and Roughed Insulation c) ⅛” Synthetic Stucco Coat

Figure 3 Exterior Insulation Finish System (EIFS) Wall Assembly

Table 1 Window Installation Method Construction Sequence

Window Installation Method	Construction Sequence
ASTM E2112-01 Method A (Typically Used with Building Paper)	Install Sill Flashing; Caulk Window Flanges All 4 Sides; Install Window; Caulk Exterior Side of Jamb Flanges; Install Jamb Flashing; Caulk Exterior Side of Head Flange; Install Head Flashing; Shingle-lap WRB (Under Sill Flashing, Over Jamb and Head Flashing); Apply Foam Sealant at Interior Reveals, All 4 Sides
ASTM E2112-01 Method B (Typically Used with Building Paper)	Install Sill Flashing; Install Jamb Flashing; Caulk Window Flanges All 4 Sides; Install Window; Caulk Exterior Side of Head Flange; Install Head Flashing; Shingle-lap WRB (Under Sill Flashing, Over Jamb and Head Flashing); Apply Foam Sealant at Interior Reveals, All 4 Sides
ASTM E2112-01 Method A1 (Typically Used with Housewrap)	Install WRB with Head Flashing Flap and Window Opening Cuts; Install Sill Flashing; Caulk Window Flanges All 4 Sides; Install Window; Caulk Exterior Side of Jamb Flanges; Install Jamb Flashing; Caulk Exterior Side of Head Flange; Install Head Flashing; Tape WRB Flap Shingle-lapped to Head Flashing; Apply Foam Sealant at Interior Reveals, All 4 Sides
ASTM E2112-01 Method B1 (Typically Used with Housewrap)	Install WRB with Head Flashing Flap and Window Opening Cuts; Install Sill Flashing; Caulk Jamb Flanges; Install Jamb Flashing; Caulk Window Flanges All 4 Sides; Install Window; Caulk Exterior Side of Head Flange; Install Head Flashing; Tape WRB Flap Shingle-lapped to Head Flashing; Apply Foam Sealant at Interior Reveals, All 4 Sides
ASTM E2121-01R Draft Method A (Typically Used with Building Paper)	Install Sill Flashing; Install Pan Flashing (Note: Access to Adjust Shims Impeded by Back Dam With This Method); Caulk Window Flanges Except Sill; Install Window; Caulk Exterior Side of Jamb Flanges; Install Jamb Flashing; Caulk Exterior Side of Head Flange; Install Head Flashing; Shingle-lap WRB (Under Sill Flashing, Over Jamb and Head Flashing); Apply Foam Sealant at Interior Reveals, All 4 Sides NOTE: No Sealant Applied at Pan Flashing for Experiments
ASTM E2112-01R Draft Method B (Typically Used with Building Paper)	Install Sill Flashing; Install Pan Flashing (Note: Access to Adjust Shims Impeded by Back Dam With This Method); Install Jamb Flashing; Caulk Window Flanges All 4 Sides; Install Window; Caulk Exterior Side of Head Flange; Install Head Flashing; Shingle-lap WRB (Under Sill Flashing, Over Jamb and Head Flashing); Apply Foam Sealant at Interior Reveals, All 4 Sides NOTE: No Sealant Applied at Pan Flashing for Experiments
ASTM E2112-01R Draft Method A1 (Typically Used with Housewrap)	Install WRB with Head Flashing Flap and Window Opening Cuts; Install Sill Flashing; Install Pan Flashing (Note: Access to Adjust Shims Impeded by Back Dam With This Method); Caulk Window Flanges Except Sill; Install Window; Caulk Exterior Side of Jamb Flanges; Install Jamb Flashing; Caulk Exterior Side of Head Flange; Install Head Flashing; Tape WRB Flap Shingle-lapped to Head Flashing; Apply Foam Sealant at Interior Reveals, All 4 Sides NOTE: No Sealant Applied at Pan Flashing for Experiments

Table 1 Window Installation Method Construction Sequence (Continued)

ASTM E2112-01R Draft Method B1 (Typically Used with Housewrap)	Install WRB with Head Flashing Flap and Window Opening Cuts; Install Sill Flashing; Install Pan Flashing (Note: Access to Adjust Shims Impeded by Back Dam With This Method); Install Jamb Flashing; Caulk Window Flanges Except Sill; Install Window; Caulk Exterior Side of Head Flange; Install Head Flashing; Tape WRB Flap Shingle-lapped to Head Flashing; Apply Foam Sealant at Interior Reveals, All 4 Sides NOTE: No Sealant Applied at Pan Flashing for Experiments
Marvin Instructions (Building Paper Used in Experiments)	Install 9" Building Paper at Sill; Install Self-Adhering Flexible Sill Flashing (No Back Dam Approach Specified) to Cover Sill Entirely (Note: Access to Adjust Shims Impeded by Back Dam if Pan Flashing Chosen for This Method); Install 13" Wide Building Paper at Jambs, Overlapped and cut to Cover Rough Opening; Caulk Window Flanges Except Sill; Install Window; Apply Loose Insulation or Foam Sealant at Interior Reveals; Install Drip Cap Caulked on Back Sides; For Housewrap, Install WRB with Head Flashing Flap and Window Opening Cuts; Install Self-Adhering Jamb Flashing; Install Self-Adhering Head Flashing; For Building Paper, Shingle-lap Double Layer Building Paper (Under Sill and Jamb Flashing, Over Head Flashing); For Housewrap, Tape WRB Flap Shingle-lapped to Head Flashing
Pella Southwestern Stucco Instructions (Building Paper Used in Experiments)	Install Mechanically Fastened Sill Flashing; Install Mechanically Fastened Jamb Flashing; Install Self-Adhering Flashing Tape (No Back Dam Approach Specified) to Cover Sill Entirely; Install Window (no caulk); Install Self-Adhering Jamb Flashing Tape; Install Self-Adhering Head Flashing Tape; Install Mechanically Fastened Head Flashing; Shingle-lap WRB (Under Sill Flashing, Over Jamb and Head Flashing); Apply Foam Sealant at Interior Reveals, All 4 Sides
Owens Corning Instructions (Building Paper Used in Experiments)	Install 8" to 12" Felt Paper at Sill with 1" Fold on Sill; Caulk Window Flanges All 4 Sides; Install Window; Pack Insulation at Interior Reveals, All 4 Sides; Install Felt Paper at Jambs; Install Felt Paper at Head; Use Common Sense to Complete Exterior
CertainTeed Instructions (Building Paper Used in Experiments)	Install Mechanically Fastened Sill Flashing (8" Plus Sill Width), Folded and Cut to Cover Entire Sill Plus 9" up Jamb; Caulk Perimeter of Rough Opening Except Sill; Install Window; Install Jamb Flashing; Install Head Flashing; Shingle-lap WRB (Under Sill Flashing, Over Jamb and Head Flashing); Pack Insulation at Interior Reveals, All 4 Sides, Do NOT Use Foam Sealant at Interior Reveals (Note: Foam Sealant Used in Experiments)

Table 2 Stucco Wall Construction Sequence

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

Figure 4 Window Frame Crack in Stucco Wall Assembly

Table 3 Warranty Cost Data on Exterior Door Leaks

Source: SureSill Survey of Southeast US Builders and Distributors

Reported Callbacks for exterior door leaks

11/28/2005

Pre SureSill Callbacks			Callbacks with SureSill			SureSill Incremental Cost		
				Doors		Doors		
Number of homes surveyed	Minimum Callback for Door leaks	Minimum Repair Cost	Number of homes surveyed	SureSill Related Callbacks	Non-SureSill Related Callbacks	Materials, 40" unit for doors	Added Labor for SureSill Pan 5 minutes @ $40/HR	Total
17,000	32%	$451	6,500	0%	1.00%	$15	$3.33	$18

Homes surveyed in Texas, Louisiana, Florida, Alabama, Georgia, South Carolina, North Carolina, Tennessee, and Virginia.

Survey includes 5 distributors, 6 volume builders, 4 custom builders

Protocols

Experimental protocols were designed to allow exploration of a number of hypotheses regarding WRB options related to window installation methods, including:

- Caulked stucco provides an excellent seal around windows when new.
- Stucco joint cracks, penetrations, WRB installation problems, and window frame cracks each can result in leakage to interior wall cavities.
- All WRB alternatives, if properly installed, provide acceptable resistance to liquid water penetration unless the window frame (with no sill pan) is breached.
- EIFS with drainage mats (not barrier EIFS) provide acceptable resistance to liquid water penetration behind cladding unless the window frame (with no sill pan) is breached.
- WRB's behave differently when subjected to bulk water rather than incidental water that penetrates behind cladding.
- Holes from WRB or lath fastener penetrations can result in leakage into interior wall cavities.
- Sill pan flashings with outlet to exterior side of WRB are effective at managing water penetration behind a leaking window frame.
- Interior foam sealant is effective at stopping water intrusion behind leaking window frames, but does not ensure that such water intrusions will drain outdoors.

Each window was installed according to construction details described in the method under test (e.g., ASTM E 2112-01, Method A). Clear and dyed water spray simulated wind-driven rain on the vertical surface of the 24" x 36" flanged vinyl sliding windows installed in wood frame wall assemblies with 3-coat stucco, 1-coat stucco, or EIFS cladding. A 36"W x 24"H ThermaStar by Pella™ Series 10 flanged vinyl window was flush mounted in each 5'-6"H x 6'-2"W stucco wall section (Figures 5 through 8). The window size and type were selected to minimize the overall size and height of the test assemblies while still providing a realistic configuration. Each window assembly was sprayed before and after stucco application 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. GTI staff installed all WRB's, windows, and foam sealant at interior reveals. Minor flaws that occurred during construction (e.g., over-application of foam sealant, lath staples missing framing members) 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.

WRB tests used four spray nozzles spaced to provide reasonably even flow rate across the vertical wall test area (Figure 9). Spray nozzle flow rate, duration, and configuration were designed to provide acceptable droplet size, total rain load, and wall coverage for test purposes, based on parameters described in ASTM E 331-00 and ASTM E 1105-01, but without application of an air pressure differential. Spray nozzles were Bex 1/4S14WSQ at 40 PSI, 32" from the test sample. Dye was Precision Laboratories Super Signal Blue spray pattern indicator (visible blue stain). A recirculating pump with strainer and bypass to sump was sized and configured to provide variable flow rate for the test stand. An 11½" deep by 3' wide by 8' long sump was placed under the test stand to capture runoff and provide water storage for recirculation (Figure 10). The indoor side of the wall assembly was protected from inadvertent overspray by a 6 mil polyethylene sheet.

To simulate a minor leak due to a cracked window flange, ⅛" holes were drilled at the welded seams in the lower two corners of each window after initial tests of the finished stucco walls (Figure 11). To simulate a more significant leak and provide head pressure through the holes, drainage weep holes in the window frames were then plugged (Figure 12).

Sill pan flashing included two types: Three piece plastic pans with ½" backdam, 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" 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.

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 applied to all reveals, except at plastic sill pans (Figures 13 and 14). 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 (Figure 15). With a dry stucco wall and without water spray, water was trickled from a hose into the sill pan flashing (Figure 16) 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.

The spray tests included the following steps on each of the 15 window/wall assemblies evaluated:

1. Construct window/wall assembly in accordance with the window installation method and framing option under test.
2. Perform and replicate 15 minute spray test on assembly prior to application of stucco cladding.
3. Apply stucco cladding and caulk around window perimeter (except as noted in individual tests)
4. Perform and replicate 15 minute spray test on assembly after application of stucco cladding.
5. Drill ⅛" hole in each lower corner of the window flange at compound 45º angle.
6. Perform and replicate 15 minute spray test on assembly with ⅛" holes.
7. Plug both weep holes in window frame.
8. Perform and replicate 15 minute spray test on assembly with ⅛" holes and plugged weep holes.
9. Apply low pressure foam sealant to all interior reveals, except sill pan flashing with backdam.
10. Perform and replicate 15 minute spray test on assembly with ⅛" holes, plugged weep holes, and foam sealant.
11. For walls with OSB sheathing, perform and replicate 15 minute spray test on assembly with ⅛" holes and plugged weep holes using blue dyed water.
12. For walls with OSB sheathing, destructively disassemble walls to identify hidden leakage paths by noting any dye stains behind WRB.
13. For the special experiment to examine the root causes of a leak under sill pan flashing, run water from a hose above the leak site such that an equilibrium level of water is maintained near the leak site. Slope the sill pan flashing using shims such that no water is in the pan away from the leak site. Note the drainage at the weep screed compared to the water inlet flow rate, and note the wetting pattern of the exterior side of the stucco over a 30 minute period.

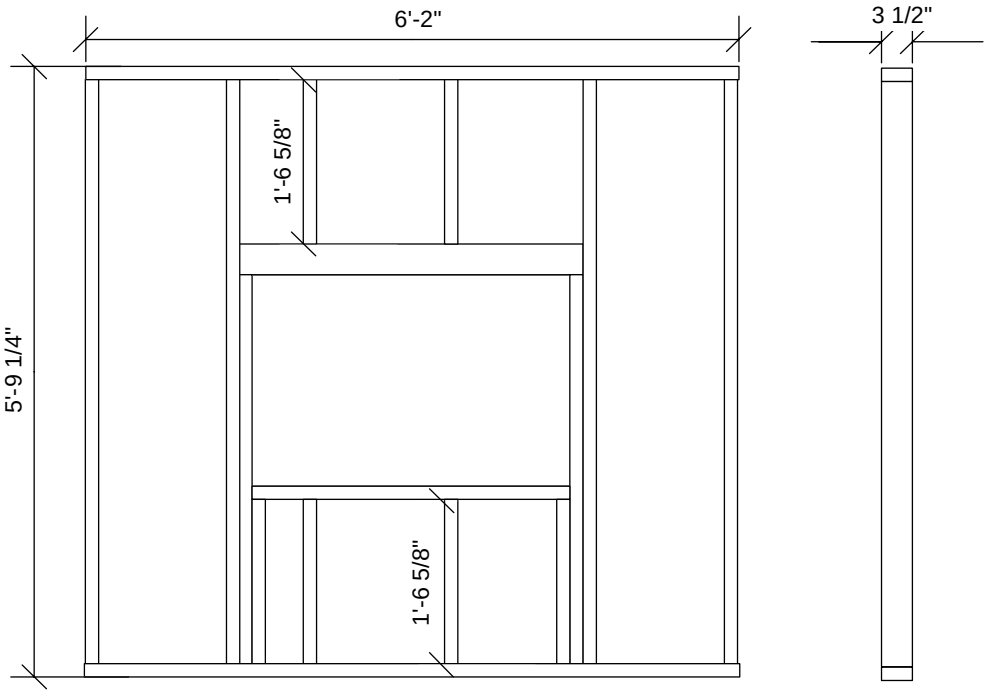


Figure 5 Window Framing in Stucco Wall Assembly

Figure 6 Window/Wall Framing Assembly with Open Frame Construction

Figure 7 Window/Wall Framing Assembly with OSB Sheathing

Figure 8 Window/Wall Framing Assembly with OSB Sheathing and Sill Pan Flashing

Figure 9 Spray Nozzles with Flow Control Valves and Hose Sprayer

Figure 10 Spray Rig Setup with Recirculating Pump and Shielded Water Trough

Figure 11 ⅛" Drilled Holes at Flange Welds to Simulate Cracked Flange

Figure 12 Plugged Weep Holes to Provide Head Pressure and More Significant Window Leak

Figure 13 Foam Sealant Applied to Head, Jamb, and Sill Interior Reveals

Figure 14 Foam Sealant Applied to Interior Reveals, except at Sill Pan Flashing

Figure 15 Leak at Staple Hole under Sill Pan Flashing

Figure 16 Hose Setup for Special Experiment on Stucco Drainage Pattern

Results

Table 4 summarizes test results for each installation method/stucco wall assembly tested. Only 1 of 15 assemblies (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 ⅛" 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 WRB's with any window installation method, with the possible exception of perforated housewrap.

Observations from these tests include the following:

- Stucco moisture shedding and transport mechanisms had a significant impact on WRB drainage capacity and leakage risk during these experiments.
  - Stucco cladding is a complex moisture transport and drainage system that:
    - Acts as a primary barrier to water intrusion,
    - Impacts gravity drainage at the WRB, and
    - Transports moisture through capillary suction (liquid) and diffusion (vapor).
  - Stucco can provide an excellent life-of-home barrier to bulk liquid water penetration, but absorbs and transports moisture to the interior side of the stucco through capillary suction and vapor diffusion.
  - Joints, cracks, holes, capillary suction, and WRB drainage from above are mechanisms for bulk liquid water penetration to the interior side of stucco cladding.
  - Gravity drainage at the WRB behind stucco significantly increases when there are capillary breaks that allow bulk water to flow down and drain out. Capillary breaks may occur due to:
    - Designed gaps (e.g., air spaces with furring strips).
    - WRB de-bonding from stucco as it cures.
    - Cracks in stucco that allow liquid water to flow more freely down and out.
    - Weep screed and control joints de-bonding from stucco as it cures.
  - 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 17).
  - Based on laboratory experiments on stucco walls conducted under Task 3.2 of this project (Figures 18 through 20), 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.
  - Reduced gravity drainage capacity from capillary-dominated moisture transport with no gaps between the WRB and stucco caused leaks from bulk water collected by sill pan flashing.
    - 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 pan/WRB joint or through staple holes (Figures 21 and 22).
    - Bulk water collected by the sill pan did not leak under head pressure when there were no holes in the restricted drainage path.

- A full face seal (stucco with caulked window frame) barrier prevented liquid water penetration at the window/wall interface for all window installation methods tested.
  - Stucco and caulking around window frames provided a full face seal. Without caulking, incomplete stucco coverage beneath the window permitted bulk water intrusion to the WRB and resulted in an observable leak (Figure 23). The breach in the WRB was not visible, but the nature of the leak was similar to another observed leak at a staple hole created during stucco application. The same window/wall assembly had no observable leaks prior to stucco application.

- Incidental water penetration and flow due to capillary suction during 15 minute tests with a full face seal was not sufficient to cause observable leaks through minor tears or staple holes in the WRB.
- Incidental water penetration and flow due to capillary suction was sufficient to cause observable leaks in perforated housewrap away from window/wall interface (Figure 24).

- The reverse shingle-lapped WRB didn't leak with a full face seal.
  - Leaks occurred whenever liquid water drained at the WRB. Water flowed down the WRB and through reverse shingle-laps after stucco application when there was no caulk around window frame (Figure 25), and when the window frame hole/plugged weep holes caused liquid water flow down the flashing and behind the reverse shingle-lap (Figure 26).
  - No leaks occurred when the primary moisture transport mechanism was capillary suction. The full face seal (stucco/caulked window frame) limited bulk liquid water gravity drainage down the WRB across the entire wall. As a result, liquid water never reached the reverse shingle-lap.

- Liquid water and capillary moisture flow behind stucco leaked onto OSB sheathing away from window/wall interface through perforated housewrap.
  - Leaks occurred with bulk liquid water impinging directly on perforated housewrap but not nonperforated housewrap or building paper before application of stucco cladding (Figure 27).
  - No observable leaks occurred on interior side of OSB sheathing at window/wall interface.
  - 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 (Figures 28 and 29).

- Pan joint sealant did not fully adhere to field-cut three-piece pliable plastic sill pan flashing lapped joints without supplemental pressure (Figure 30) due to differential flexure or inadvertent movement of pan sections during installation.
  - Field cuts were required to provide exact fit to rough opening. Flexible plastic did not assure a full line seal at joints without pressure.
  - Hard plastic sill pan sections did not flex, but still needed a clamp to ensure proper alignment and fit until cement set.

- Moldable self-adhering sill flashing over backer rod (to create a backdam) did not provide a full length water-tight seal to the window frame without interior sealant, resulting in leakage onto the sill through creases in the flashing (Figure 31).
  - Leakage occurred even with relatively low head pressure without interior foam sealant.
  - Foam sealant applied to interior reveals did not effectively seal all creases in this assembly, and did not contain the leak.

- Low pressure expanding foam sealant applied to interior reveals contained leaks on the sill whenever it achieved a full length seal.
  - Sealant stopped previous leakage under head pressure whenever foam successfully sealed the full length of the reveal, especially the sill reveal. (Figures 32 through 35).
  - Sealant did not stop previous leakage under head pressure when the wood sill not covered by flashing and when foam did not successfully seal the full length of flashing due to misapplication of incompatibility with substrates (Figures 36 through 38). All stakeholders involved in design and installation need to ensure compatibility of materials for intended use
  - Sealant may trap water on the sill surface between the window frame leak and sealant. The effect of this ponded water on sill deterioration over time is unknown.
  - Low pressure foam expanded significantly while curing. The impact of trimming the foam on both sill flashing performance (due to inadvertent cuts) and water resistance (due to trimming off hardened foam skin) was not explored in these tests.

- Marvin instructions for installing self-adhering flexible sill flashing (intended to be functionally similar to ASTM E 2112-01R Draft) did not provide a method to create a back dam with this technology. Without the backdam, sill leakage occurred similar to ASTM E 2112-01 instructions (Figure 39). Foam sealant was successful in stopping the leak in this case.

Table 4 Window Installation Methods Test Results Summary

Assembly	Wood Sill Covered	Observed Leakage				
		No Stucco	With Stucco, Caulked Except as Noted	Caulked, With Drilled 1/8" 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; Not Caulked	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; Not Caulked	Yes	Yes	No
12	No	Yes	No	Yes	Yes	Yes
13	No	Yes	Yes; Not Caulked	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

No Leaks with Full Stucco/Caulk Seal

No Leaks Under All Tests In Only One Case

No Leaks with Most WRB's Without Stucco

Perforated WRB Leaks With/Without Stucco

Leaks Most Often with Most Severe Test

Foam Sealant Contained Leak in Some Cases

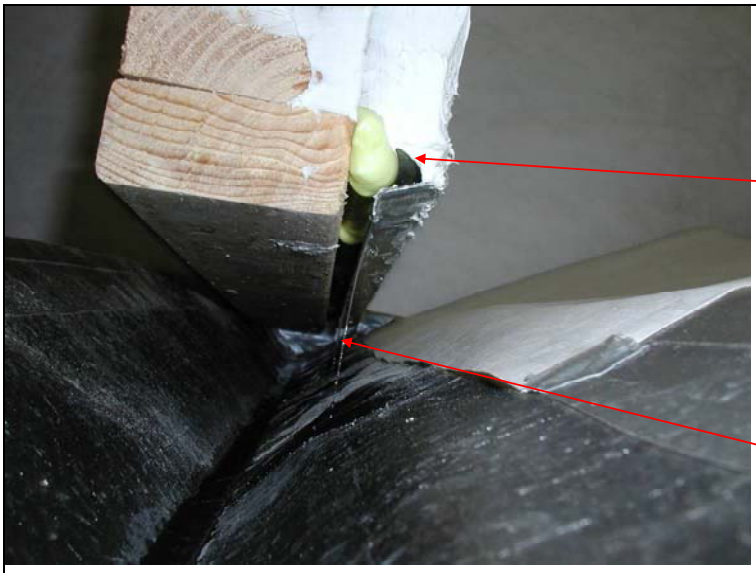
No Leak, Sill Protected

No Observed Leak, Sill not Protected

Observed Leak

Water drained slowly from sill pan, with capillary moisture transport to front of stucco dominating gravity drainage.

Figure 17 Capillary Drainage Pattern from Water Poured into Sill Pan



Stucco Adhering Directly to Weep Screed Severely Restricted Gravity Drainage Rate

Capillary-Dominated Drainage Trickled at Exterior Side of Weep Screed

Capillary-Dominated Drainage Capacity Was an Order of Magnitude Lower Than Effective Gravity Drainage

Figure 18 Capillary-Dominated Drainage with No Gaps and Stucco Bonded to Weep Screed

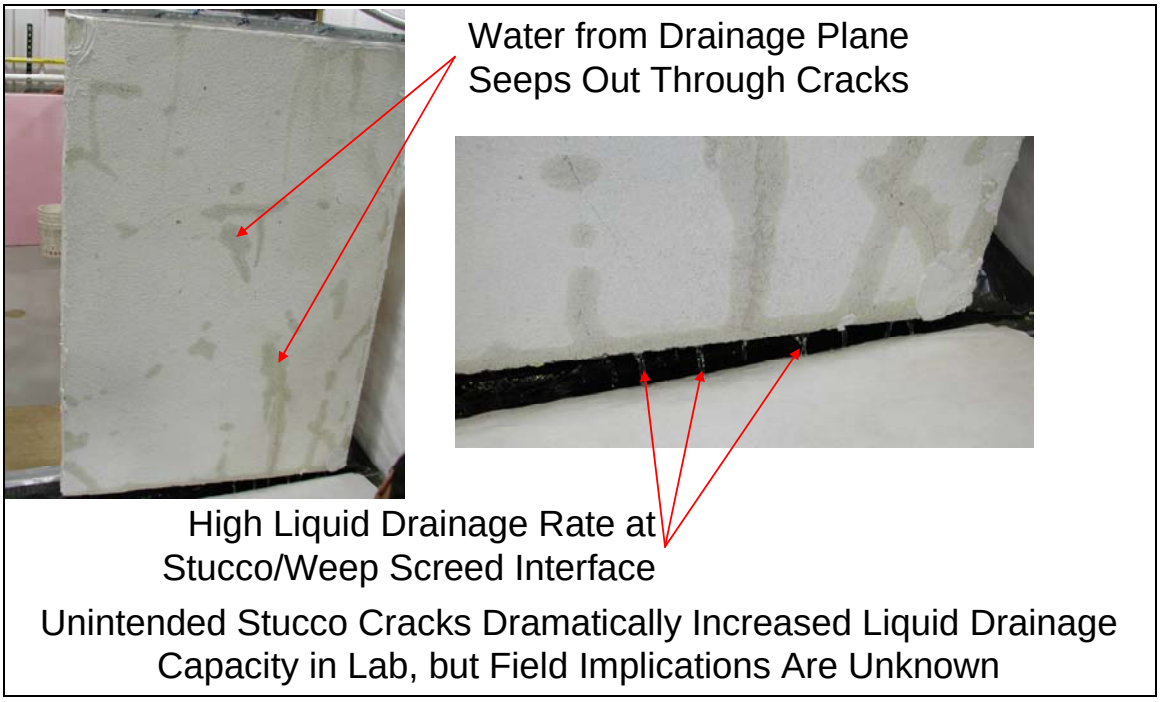


Figure 19 Gravity-Dominated Drainage with De-Bonded Stucco from Cracked Wall

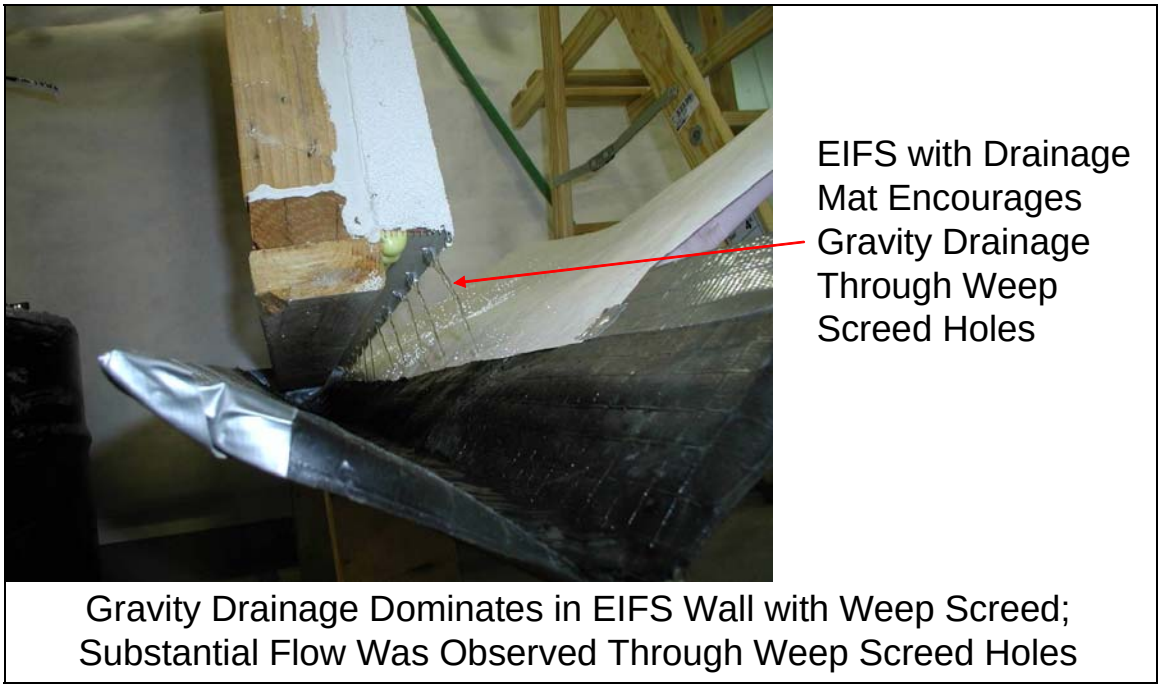


Figure 20 EIFS Wall with Designed Weep Screed and Drainage Mat with Gap

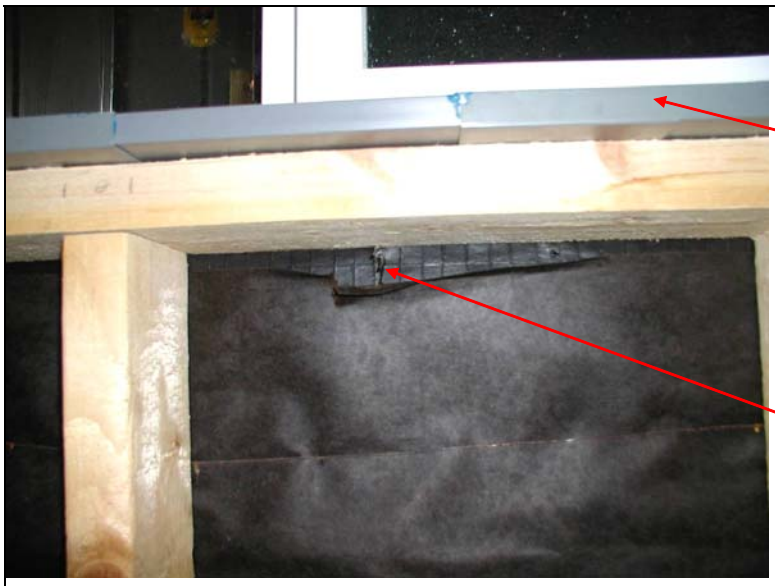


Figure 21 Leakage at Staple Hole Due to Capillary-Dominated Drainage of Water from Sill Pan

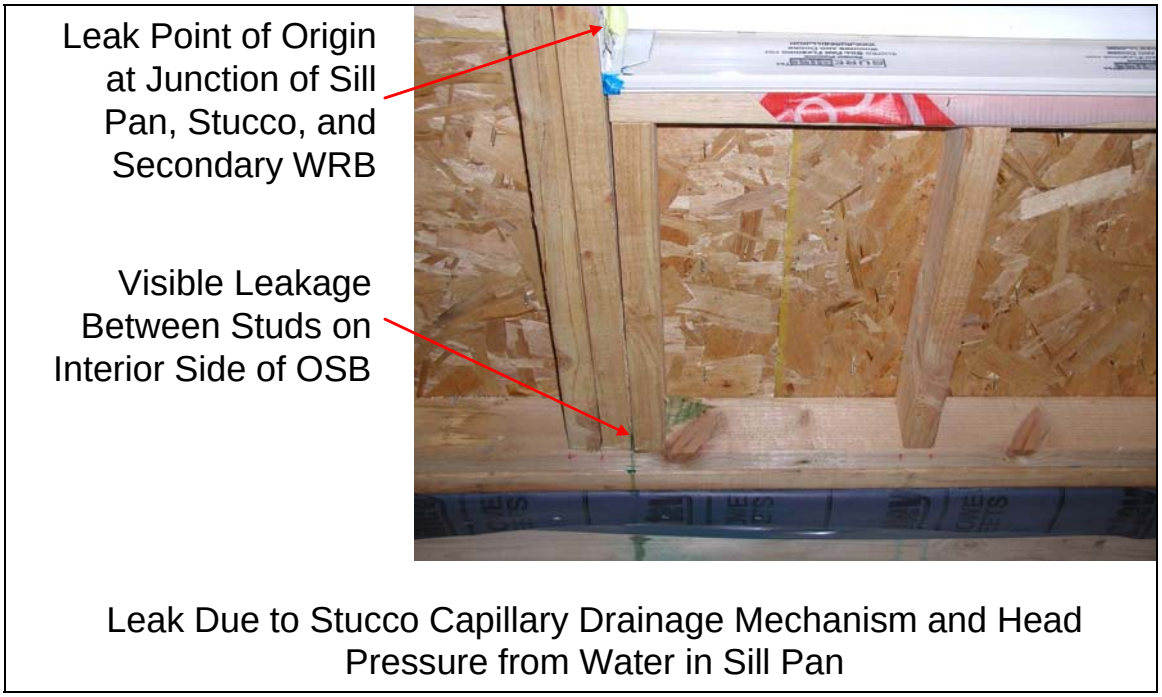


Figure 22 Leakage at Jack Stud Due to Capillary-Dominated Drainage of Water from Sill Pan

a) Stucco Missing Beneath Window Frame b) Resulting Leak Through WRB

Figure 23 Stucco Flaw Resulting in Leak Through WRB

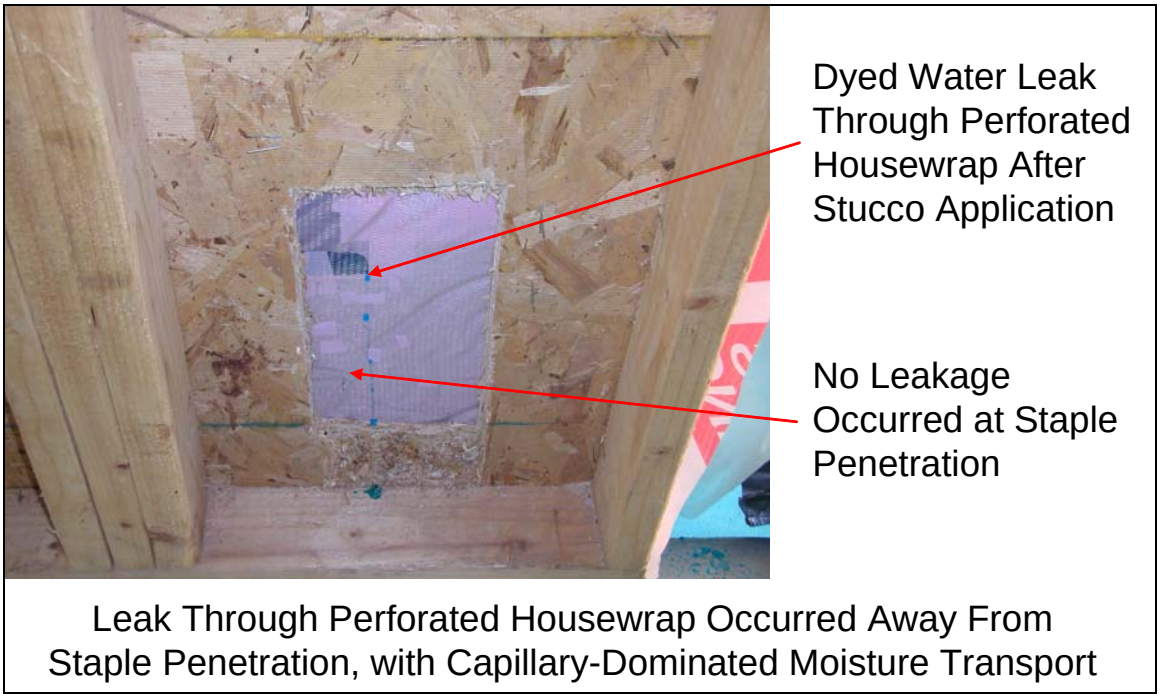


Figure 24 Leak Through Perforated Housewrap During 15 Minute Blue Dye Spray Test

Figure 25 Leaks Through Reverse Shingle-lap After Stucco Application, Uncaulked Window Frame

a) Leak Behind Reverse Sill Flashing

b) Leak on Sill Under Foam Sealant

Figure 26 Leaks During Reverse Shingle-lap Test with ⅛" Hole and Weep Holes Plugged

Figure 27 Leakage onto OSB Sheathing Through Perforated Housewrap Without Stucco

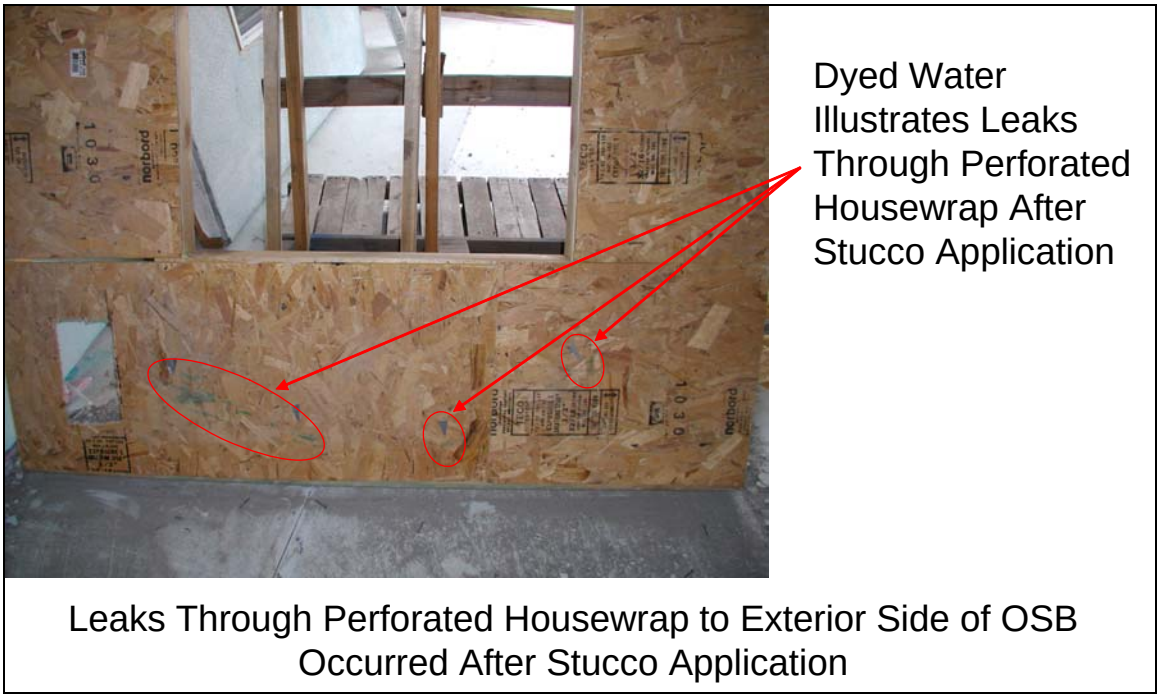


Figure 28 Leaks Through Perforated Housewrap to OSB After Stucco Application

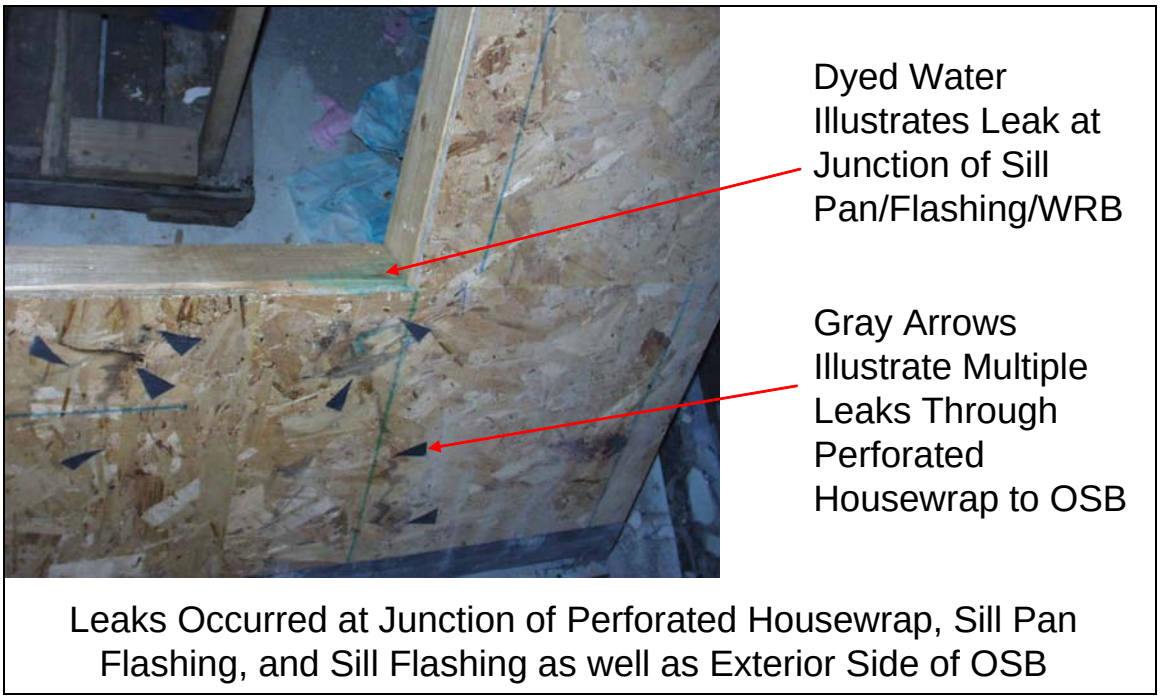


Figure 29 Leaks through Perforated Housewrap with Sill Pan Flashing

Figure 30 Supplemental Pressure Needed to Seal Joints on Pliable 3-Piece Plastic Sill Pans

Figure 31 Leakage through Creases in Moldable Self-Adhering Sill Flashing over Backer Rod

Figure 32 Foam Sealant Stopped Leak; Moldable Self-Adhering Sill Flashing

Figure 33 Foam Sealant Stopped Leak; Self-Adhering Metal Tape Sill Flashing

Figure 34 Foam Sealant Stopped Leak; Bare Wood Sill

Figure 35 Foam Sealant Stopped Leak; Flexible Sill Flashing

Figure 36 Foam Sealant Did Not Stop Leak due to Misapplication

Figure 37 Foam Sealant Did Not Stop Leak; Bare Wood Sill

a) Leakage Site at Left Corner b) Leakage Site at Right Corner c) Leakage after 15 Minutes

Figure 38 Foam Sealant Did Not Stop Leak due to Incompatibility with Flashing

Figure 39 Lack of Backdam Resulted in Leak with ⅛" Hole and Weep Holes Plugged

Conclusions and Research Recommendations

Laboratory evaluations of the window/wall interface and WRB's support the following conclusions:

- Capillary break between stucco and WRB is required for optimal gravity drainage.
    - Double layer provides space, outer layer provides bond break
    - Sill pan drains to interior layer (the functional WRB)
- Windows leak.
    - Unpredictable amount and location
    - Panned sill drainage system is essential
    - Full air barrier is required at all reveals
- Consensus standards are needed.
    - Performance and prescriptive, material and installation
    - Realistic, supported by field data and validated models

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 E 2112-01R may reduce the risk of consequential water intrusion into wall cavities in as-built construction. Peer-reviewed field data on performance of different WRB options and failure mechanisms of as-built window/wall assemblies for California new construction 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, project test results 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 on causes and consequences of water intrusion into wall cavities. Results also provided technical support for recommending properly designed and installed WRB's to reduce the risk of bulk water intrusion and mold growth.

Disposition of laboratory results developed during this project will depend on which of the following scenarios is considered valid:

1. Unacceptable Protocols
    a. The protocols were unacceptable because they did not align with current industry consensus standards and did not use appropriate methods or materials.
    b. Ignore project results, wait for appropriate protocols developed by consensus organizations such as ASTM to address legitimate research questions.
2. Reasonable Protocols, but Poor Quality Implementation
    a. The protocols used reasonable methods and materials in the absence of industry consensus standards, but the implementation in the actual experiments was of poor quality. Better implementation would have shown more credible results.
    b. Ignore project results, and implement similar protocols with qualified staff and facilities to provide credible results.

3. Reasonable Protocols Implemented Well, but with Questionable Relevance
    a. The protocols used reasonable methods and materials in the absence of industry consensus standards and generated credible results, but have questionable relevance to actual field experience. Protocols may be too severe or not targeted to relevant issues, and may contain numerous laboratory artifacts.
    b. Publish results for scientific value, but do not interpret them or make substantive recommendations. Results are likely to be misleading and could result in significant negative unintended consequences in the marketplace. Encourage further research on building science phenomena, and initiate major field data collection effort to identify underlying causes and consequences of moisture and mold problems. Continue development of consensus standards using best available methods and expertise in the absence of corroborating field data. Obtain feedback from relevant market participants regarding major effort to collect field data on targeted parameters based on expert judgments and appropriate field collection methods.
4. Reasonable Protocols; Relevance is Unknown, but May Be Significant
    a. The protocols appear to have used reasonable methods and materials in the absence of industry consensus standards, and may have significant but unknown relevance to actual field experience.
    b. Publish results, provide information on potential market relevance, but avoid speculation as much as possible. Replicate at other laboratories, and validate results with field data. Encourage further research on building science phenomena, and initiate major field data collection effort to identify underlying causes and consequences of moisture and mold problems. Until field data is collected, results remain potentially misleading and could result in significant negative unintended consequences in the marketplace. Obtain feedback from relevant market participants regarding major effort to collect necessary field data on targeted parameters based on expert judgments and appropriate field collection methods.

Based on interactions with project advisors and participating manufacturers throughout the course of this project, Scenario 3 and Scenario 4 are the two most likely scenarios. Accordingly, research recommendations based on project results focus on two major initiatives:

- Develop and evaluate performance test methods for window installation methods as applied to wall assemblies; and
- Collect and analyze laboratory and field data on root causes and consequences of building envelope failures to identify and evaluate alternative mold risk reduction strategies for window/wall interfaces.

The ASTM E 2112 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 authoritative root cause analysis of moisture and mold problems.