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Durability and Waterproofing Investigations of the Building Envelope

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Durability and Waterproofing Investigations of the Building Envelope

by

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Thesis

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Dedication

To my loving parents, Stan and Dalene; my brothers, Brett and Alex; and my sisters, Erin and Amie

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Abstract

Durability and Waterproofing Investigations of the Building Envelope

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Durability of the building envelope is an important characteristic to monitor and test on a structure to ensure it does not fail prematurely from water penetration. Due to the building envelop failures existing today, the described testing herein aims to evaluate different building components in an effort to express deficiencies in testing or products so as to better influence the building envelope product market and lessen the possibility of future failures.

This thesis describes the background and protocol for testing water resistive barrier full-scale mockups for long-term durability. An auxiliary study of the product nail sealability testing was also conducted, providing supporting visibility into inconsistencies between manufacturer and test results.

Elastomeric sealants were also tested according to a new standard, ASTM C1589, which evaluates products for the long term based on both movement and weathering—a much needed standardized testing scenario. Initial results show the need for primed, silicone, and SWR Institute validated products.

The water penetration characteristics of concrete masonry units were also analyzed using both ASTM C90 and RILEM tube testing. The results emphasized the need for redundancy in water repellents for porous units and the significant leniency of ASTM C90.

Lastly, masonry veneer anchor guidelines were discussed, and it was found that the prescriptive nature of the MSJC code does not provide adequate guidance on installation of anchors for unique architectural or structural details. Suggestions for placement in these instances are given.

Much of the testing described in this thesis represents best practice suggestions and initial product evaluation. Since this testing has been developed as long-term experiments, the next few years will provide the needed information on failure mechanisms and methods to prevent these failures.

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Chapter 1: Introduction

1.1 Background

The durability of building envelopes is one of the most important characteristics of a structure, but it is often one of the most overlooked due to greater concern for building aesthetics. This results in a wide range of building failures, most of which cause water infiltration and damage. Building durability is focused not only on individual component durability, but the durability of all components that work together as a whole.

Durability revolves around three main concepts. The first is building design life, or the length of time a certain type of building is useful. The second is component design life, and it is usually comparable in design life to that of the structure on which the component is being placed. Next is service life, which is the actual length of time that a component will last. This service life is dependent on a plethora of characteristics: quality, design, installation, maintenance, and exposure. Ideally, the service life will be as long as the design life; however, failure to acknowledge the aforementioned characteristics makes it very common for the service life to be much shorter than the design life, resulting in durability failures.

Durability failures can be avoided—or at least subdued—by taking initial precautionary measures. Products should be designed to perform well in the conditions in which they will be placed, and they should be truthfully marketed. Secondly, the product needs to be assigned and used in the manner for which it was intended. Lastly, proper and educated installation is key so that the product can perform as successfully as possible. If all three are done in a methodical manner without skipping steps, then building durability failures will be far less common.

In order to understand failures and the subsequent need for manufacturers, designers, and installers to critically and truthfully develop, design, and incorporate products, especially given the conditions that construction sites and buildings face upon completion of a project, building envelope components need to be tested in real-world applications over the long term.

1.2 Scope of Project

This research project consists of analyzing different components of the building envelope and how they work together as a whole. Therefore, various subprojects have been completed in terms of understanding long-term durability and waterproofing. Most of these projects involve a significant amount of research regarding the topic followed by testing, which in most cases involves continuous and qualitative monitoring and measurements.

Although some of the research and testing described below is in accordance with ASTM standards, this research project has developed new and innovative test methods to observe how products perform in real world applications, especially in terms of natural, outdoor weathering.

Of the projects described, each is independent of the other, but they all revolve around the same theme of building durability and waterproofing. Much of the testing in this document is in its infancy, so the test set-up, procedure, and initial results are discussed, while it will take years before significant results and failure mechanisms can be conclusively identified.

As Pihlajavaara stated, "durability of a material is its ability to resist changes of its state or, in other words, of its properties" (6). That is exactly what this research project strives to test and better understand.

1.3 Content

This thesis is divided into four separate chapters, each discussing the testing and/or research performed and how it relates to durability of the building envelope and methods to improve performance of the product.

Chapter 2 focuses on the test development and research for water resistive barriers in real-world application mockups to observe their durability upon being placed on outdoor exposure racks. Initial observations regarding their preparation and installation as well as preliminary performance observations are discussed.

Chapter 3 discusses the testing of nearly 200 sealant specimens for their weathering and movement performance in accordance with ASTM C1589.

Chapter 4 addresses the water absorption characteristics of concrete masonry unit single-wythe walls through RILEM tube, ASTM C90, and ASTM C140 testing. Methods for improving these structures are discussed.

Chapter 5 describes research on brick masonry anchors. Suggestions for detailing intricate aspects of a building that are not defined in the code are discussed in order to prevent premature veneer failure.

Lastly, Chapter 6 provides conclusions on the testing and recommendations for future research.

Chapter 2: Durability of Water Resistive Barriers[1]

2.1 INTRODUCTION

Water resistive barriers (WRBs) are an integral part of the building envelope and their placement on the sheathing of a building is imperative in preventing water infiltration if or when moisture penetrates the cladding. Many WRBs also function as air barriers to prevent excess air movement in and out of the building; they can serve as vapor barriers as well which prevent the transmission of water vapor through the membrane and into the structure. These WRBs come in several different forms, such as self-adhered membranes, fluid-applied membranes, felts, house wraps, building paper, and even WRBs integral to the sheathing. WRBs began their early use and testing in the 1930s, but it was not until the 1980s when air, water, and vapor infiltration was introduced into building codes ("History"). They had not gained much popularity until the last few decades, where now many manufacturers are engineering new products. With a plethora of different products in the marketplace, and many more in development, it becomes incredibly difficult to know which WRB is the best in order to satisfactorily protect a building.

2.1.1 WRB Testing

The building codes provide some guidance for WRBs. The 2012 *International Building Code* (IBC) states that "a minimum of one layer of No. 15 asphalt felt, complying with ASTM D226, *Standard Specification for Asphalt-saturated Organic Felt Used in Roofing and Waterproofing*, for Type 1 felt or other approved materials, shall be attached to the studs or sheathing…." The *International Residential Code* (IRC) mimics

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[1] Feero, Beth Anne and David H. Nicastro. "Durability of Water-resistive Barriers." *The Construction Specifier* Feb. 2015: 56-64. Print.
Some or all of text written in this chapter was previously published in the source shown above. All authors contributed equally.

this guideline. For WRBs used in stucco or masonry applications, the wood sheathing must “include a water-resistive vapor-permeable barrier with a performance at least equivalent to two layers of Grade D paper.” These guidelines are appropriate, but with so many different WRBs other than felt and Grade D paper available, it is difficult to know how and if these materials perform as well as the code minimum.

Difficulty in knowing how WRBs perform is due to the fact that there are very few standards which are used solely for building membrane performance. This is partially because all of the WRBs on the market are so different in chemistry and make-up, so finding a suitable test that can work for all types is rather difficult. Despite the lack of standardized testing, it is common to test WRBs with ASTM standards that are typically defined for roofing membranes and horizontal surfaces (Wissink et al. 191) or for paper and textiles (Bomberg et al. 175, Weston et al. 4). If borrowed standards are not implemented, researchers utilize a wide array of different and self-formulated test methods, making it difficult to compare WRBs when no two are tested alike.

Testing of felts, papers, and wraps have historically been done with protocols such as ASTM D779 “Dry Indicator Method”, AATCC-127 “Hydrostatic Pressure Test”, and CCMC 07102 “Ponding Test” to observe how much water and long it takes for water to transport through a small sampling of the membrane (Bomberg et al. 175, Butt 21-23, Weston et al. 4-5). ASTM D779 has since been withdrawn as a standard, since many researchers questioned its inadequate boundary conditions and whether or not it is more applicable for water or vapor transmission characterization. Due to test inadequacies, researchers have proposed various different test methods to better quantify WRB performance. These include the Modified Inverted Cup Test, in response to the existing test method in ASTM E96, the Liquid Penetration Test, and the Modified Flux Test (whose processes can be read in Bomberg et al.). Others have suggested AATCC-35 as an acceptable alternative as well (Weston et al. 6). Bomberg et al. and Weston et al. recognized the importance of testing WRBs for their water and vapor resistance characteristics in relation to applications in the field. Thus, testing was performed when surfactants such as wood chips and soap were added into the water, nail and staple penetrations were introduced to the membrane, and natural short-term weathering was induced on the WRB (Bomberg et al. 177). Weston et al. observed ultraviolet (UV) exposure, abrasion (according to ASTM D3511), and cyclic wetting and drying (10-15).

Testing of fluid-applied WRBs is lacking, especially because they are much newer to the marketplace in comparison to felt, paper, and other wraps. Wissink et al. have done initial testing on fluid-applied WRBs characteristics for adhesion, elongation, and water absorption using ASTM D4541, ASTM D412, and ASTM D471, respectively. The study also included observing long-term durability of these products based on performance in terms of UV light, accelerated aging, water, and freezing temperatures which were achieved through mechanical means.

Weston et al. points out the importance for a more uniform standardized way of testing to be created so that all WRBs on the market can be tested according to it (17). Similarly, Bomberg et al made it a point to note that a defined test method needs to be created to observe the long-term and harsh durability of products (179). Butt also comments that "there is no test information in the literature about comparative water resistance of WRBs after prolonged exposure to water, ultraviolet light, or to wet and dry cycling.", also describing the need for long-term durability testing (25).

As shown in the previous testing, many authors have been able to extract various initial water resistive characteristics of WRBs in terms of small scale testing on unexposed specimens. Some testing has observed the effects of short-term outdoor weathering before testing the durability of the WRB, while others incorporate durability testing through mechanical and artificial means. Given that most of the existing testing to date has been to observe initial characteristics of the WRB before service by use of different test methods and standards, there is a need for a test method to evaluate all types of WRBs after long-term exposure. It will be useful to gain information on the durability of the newer products on the market because real-world, outdoor, long-term exposure of the WRB system has not been tested. The current study aims to observe the long-term durability of various WRBs. A thorough explanation of the testing is presented with some initial results from the first one and a half years of exposure.

2.1.2 WRB Detailing

Although waterproofing the building envelope has gained popularity in the last number of years and many manufacturers have come up with a wide range of different products, WRB detailing remains a very significant issue. One of the biggest issues in regard to improperly detailed WRBs is due to an uneducated installer workforce because of a lack in industry trade specification in waterproofing buildings. Without a designated and educated trade, there is a high probability that the WRB will be installed either improperly or insufficiently. Additionally, the absence of accurate detail drawings of how to install the WRB at penetrations, windows, seams, corners, edges, and other commonly encountered characteristics on a building are rarely depicted in a satisfactory manner (Bateman 85). Without these well depicted drawings, there is a strong likelihood that the WRB will be placed on the sheathing improperly because the installer did not have the proper guidelines to follow.

To address these issues and try to remediate them, it would behoove the manufacturer to create larger, 3-dimentional details with step-by-step sequencing to install the WRB. These improved detailing methods along with meetings between the trades and the contractors can help create a more durable building envelope (Bateman 90, 94).

The research shown within this study reinforces the inadequacies of manufacturer detailing and suggests further methods for which to better improve detailing and protocol from the manufacturer.

2.1.3 Nail Sealability

The ability for nails to seal around fasteners is one of the more important durability characteristics for WRBs. Since there exist no standards to properly test WRBs, there are also no standards to evaluate the nail sealability of WRBs. Bomberg et al. and Weston et al. both tested WRB characteristics when fasteners were penetrated into the membrane and for the most part found the products performed worse than if there were no penetrations, thus showing the need to further explore the nail sealability characteristic of WRBs.

The existing test method to test WRBs for nail sealability is through the use of ASTM D1970, *Standard Specification for Self-Adhering Polymer Modified Bituminous Sheet Materials Used as Steep Roofing Underlayment for Ice Dam Protection*. Another commonly utilized test for water penetration at fasteners is ASTM E331, *Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference* where water penetration is observed after a test specimen is subjected to a water-spray system.

Judging by the popularity of ASTM D1970, which is the standard to which most manufacturers test products, it was used in the test conducted on the WRBs analyzed in this study. This testing was conducted both to observe first-hand how WRBs perform with fasteners and to also see if the results from this testing match those which the manufacturers claim. The original standard was adopted in 1990 to be used for self-adhered roofing membranes; however, this is the predominant test method used for WRBs of all chemistries.

Halfway through the testing phase using ASTM D1970, the standard and corresponding nail sealability testing underwent a revision. Slightly over half of the specimens had been tested by the old standard by the time the newer one was published. Therefore, the remaining specimens were tested to the newer standard, which ended up being slightly less severe.

The testing of WRB nail sealability sheds light on both the need for additional, exclusive, and standardized testing for WRBs as well as for manufacturers to be more thorough and factual in their ASTM standard testing.

2.2 Initial Observations

Building diagnostic engineering firms observe a wide variety of failures due to water infiltration and leakage. Many building envelope failures are due to both poor construction and inadequate products. Thus, this study of various WRBs sought to observe installation instructions, actual observed install characteristics, and UV exposure rating in conjunction with the long-term durability in a natural, outdoor exposure site installed in a real-world system application.

2.2.1 Manufacturer's Instructions

Before the WRB test specimens were constructed, the installation instructions for all of the membranes were researched in order to ensure that the specimens were installed correctly. After the research was underway, many issues were encountered, similar to those described by Bateman. The mockups contain typical penetrations and characteristics of a common wall section, but a significant amount of the product literature did not have the necessary descriptions and detailed drawings required to properly install the WRB. Additionally, some of the manufacturers had a handful of different choices for detailing, whose application was not clearly defined. Therefore, it was necessary to contact the manufacturer in order to learn what the proper detailing was. Interestingly enough, sometimes when the manufacturer was contacted, the representative contradicted what was in the product literature as well as statements by other representatives from the company whom were contacted. This illustrates that many inconsistencies occur within manufacturers' detailing. Although it is always beneficial to contact manufacturers regarding any questions or clarification, it should not be a necessity in order to install the product correctly.

Where there was a proper detailing regimen specified, some of the instructions were significantly unrealistic, mostly in relation to special detailing around a masonry anchor (brick tie). Some products require sealant to be placed underneath or on top of the brick tie, and others require an auxiliary membrane material to be installed before the brick tie is fastened. These detailing characteristics are unrealistic because the WRB installer and the brick tie installer come to the job site on separate days, so coordination is unlikely. If the WRB requires detailing prior to the brick tie, the installation of this detailing is not likely to occur because it is unknown where the brick ties will be placed. If the WRB requires detailing afterward, the WRB installer is very unlikely to return to the job site to just install detailing over the brick tie.

2.2.2 Installation Characteristics

A specialty contractor was hired to construct the specimens in order to have the WRB installed by a professional in an attempt to reduce error. During each application, the installer noted observations and made comments regarding the installation process. From these notes, the installers generally wanted a WRB which was quick and easy to install with few products, fast drying times, and simple sequencing. For the most part, this meant that installers liked the products which had the field membrane plus only one other detailing product that could be used on all penetrations, seams, and edges. It was preferable if the order in which the materials were applied did not matter. Those that required two additional detailing products seemed cumbersome for the installer.

This testing has already shown that the industry is in need of easily installed products whose chemistry or fastening characteristics are interchangeable. That way, even an unskilled installer can place the membrane without significant error.

2.2.3 UV Light Exposure Rating

All WRBs state a UV exposure limit before the product needs to be clad. Of the products tested in this study, these times ranged from one month to an indefinite amount of time. It is interesting that most manufacturers state a specific exposure time, because the amount of UV light will vary from month to month. Therefore, exposure beyond what the material can withstand is a potential risk, depending on the month and location in which the WRB was installed.

Contractors seem to prefer products which have a higher UV rating to allow for more flexibility in exposure and time before cladding has to be installed. After discussions with WRB manufacturers, it is not uncommon for their marketing team to increase the UV rating without altering the product of chemistry, simply to appear more desirable to architects, contractors, and owners.

2.3 Experimental Procedure

The full-scale mockup procedure to test these WRB products was developed with the goal that it become a standardized test for all WRBs for long-term durability with common penetrations and detailing. The test for nail sealability is one of the auxiliary tests to observe additional characteristics that could not be as critically monitored on the full-scale mockups.

2.3.1 WRB Mockups

The preliminary investigations have shown the inadequacy of manufacturers' instructions and issues that lie within installation characteristics and UV exposure. In order to compare these preliminary investigations to determine if further issues exist for long-term durability of these products, the following testing protocol was created.

With the wide variety of WRBs on the market, there are many membranes from which to choose. Many of the products are commonly used in multi-family applications, which is where the bulk of construction is today. The chosen test specimens were selected based on the probability of the product to be around in five to ten years to make sure that once the specimen had yielded sufficient results on the exposure site, which could take a number of years, the product would still be in use so the results can be shared with manufacturers and those who are going to be utilizing the product. From field experience as well as conversations with the manufacturers, 17 different products were chosen to be tested. Most of the first twelve products were installed in December 2013, and the remaining five products were placed on the exposure racks in April 2014.

In order to test the long-term durability of WRBs as a complete structural system, mockups of these 17 different products were constructed and placed on an outside weathering rack for observation (Figure 1).

Figure 1: Full-scale Test Mockups

Each specimen is a 3-ft. by 2-ft. simulated wood stud wall section with the WRB placed over the plywood sheathing, with the exception of one product whose WRB is integral with the sheathing. Rigid plastic was adhered to the back of the specimen with silicone sealant in order to observe moisture penetration. Metal coping was installed on the top to protect the specimen, but it was not made water-tight at the WRB; thus, water may enter the specimen behind the cladding, which is what would happen for any typical WRB. Within the specimen are various details and common characteristics found on a typical wall section that a WRB would encounter (Figure 2):

- 1/8 in. sheathing joint at center
- Outside corner at bottom and left edges
- Window jamb at right edge
- Electrical junction box penetration

- Large diameter pipe penetration
- Small diameter pipe penetration
- Masonry anchor

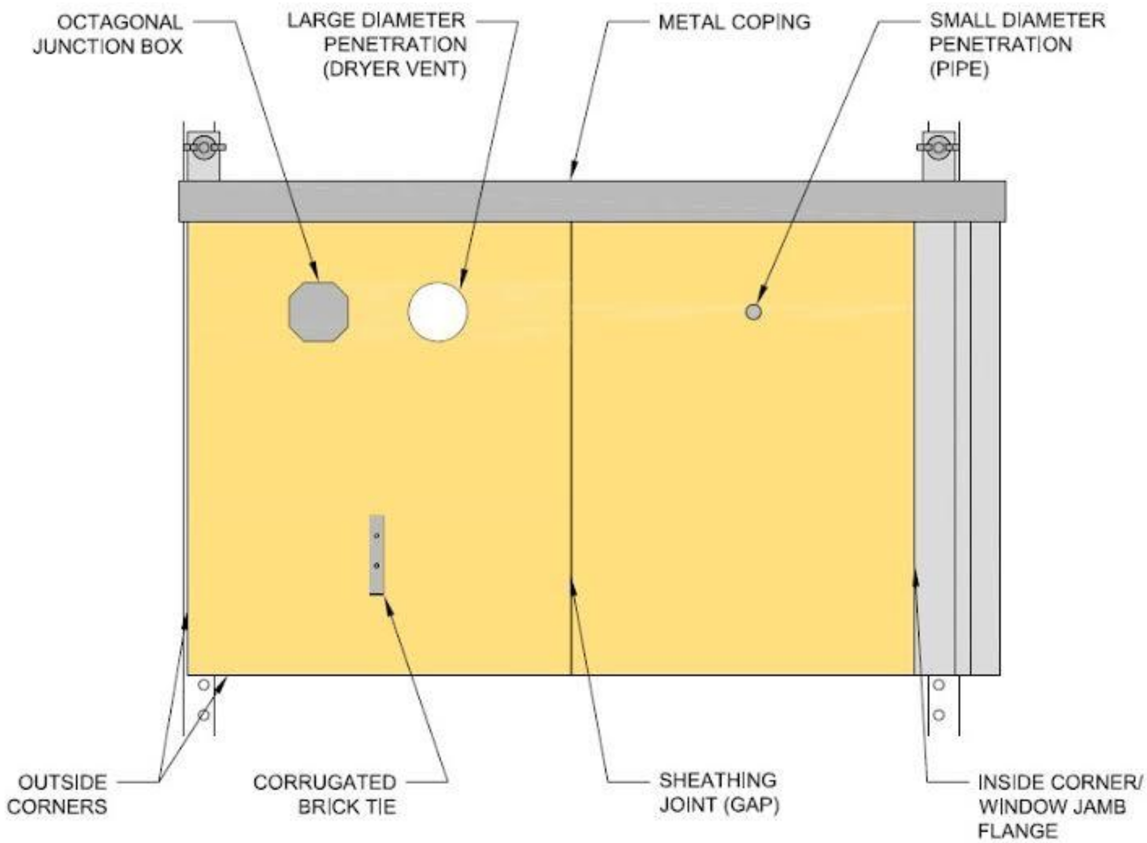

Figure 2: Rendering of WRB Mockup (Feero et al.)

Each of these components was detailed based on the manufacturer's recommendations as shown in their product literature or based on conversations with the manufacturer's representative. Despite common shortcomings and lack of proper detailing commonly observed in the field, the mockups were constructed in accordance with the understanding of the manufacturer's recommendations, as opposed to what is commonly found on a project site.

The specimens were then placed on the metal racks, which face solar south in order to be subjected to the maximum amount of solar radiation. To accelerate weathering even more, the specimens could have been placed at an angle of 30° from horizontal, which is the latitude angle of the testing site, but the effect that gravity has on WRBs is also a very significant factor. Thus, the specimens were oriented vertically to maximize this effect.

As previously described, each WRB has a specific UV exposure limit before the specimen has be clad. To observe how well each product performs up until its UV rating, as well as months and years after its exposure limit, cladding was placed over the top half of the specimen (Figure 3). Therefore, the top half was covered in order to monitor the membrane durability until its UV exposure limit, and the bottom half was left exposed in order to determine how the WRB performs over a longer period of time. When desired, the installed cladding may be removed so that observations of the WRB can be made.

Figure 3: WRB Specimen DRP1009-07 Clad on Top Half

2.3.2 Nail Sealability

Testing of the nail sealability characteristics of WRBs was performed on all of the products that were installed on the exposure racks. In the product literature for all of the products, there were some that did not mention that the product was tested according to ASTM D1970. Even though these products were not tested to the standard, this study sought to examine the performance.

As was mentioned, a little more than halfway through the testing, ASTM D1970 underwent a revision that slightly altered the test method, and it now references the procedure found in ASTM D7349, *Standard Test Method for Determining the Capability of Roofing and Waterproofing Materials to Seal around Fasteners*. The old test method procedure outlined in Section 7.9, "Self Sealability (Head of Water Test)" is as follows:

1. Place the desired membrane on a 12-in. by 12-in. sheet of 3/8-in. APA grade, Exposure 1 plywood at room temperature (73.4 ± 3.6 °F) by peeling the paper or film off the membrane and placing it on the plywood just enough to keep it from lifting off. At least two specimens for each membrane should be tested; select sample rolls according to ASTM D228.
2. Drive two 1.25-in. galvanized roofing nails into the center of the specimen 1 to 2 in. apart, with two pieces of lumber placed underneath for support, until the heads are flush with the membrane.
3. Tap the ends of the nails to raise the head of the nail 0.25 in. above the membrane (Figure 4).
4. Cut the bottom out of a 1-gal. can and place it on the membrane around the nails. Apply 0.25 in. of silicone sealant around the outside of the can to seal it to the membrane.

5. Wait two hours and then apply a second bead of sealant around the inner rim of the can.
6. Let the sealant cure for 24 hours at ambient temperature.
7. Place this assembly on top of another 1-gal can whose bottom is still intact (Figure 5).
8. Fill the top can with 5 in. of distilled or deionized water.
9. Put the entire assembly in an environmental chamber for three days at 40 ± 5 °F.
10. After the test is completed, analyze the specimen for failure if there is water
    a. In the bottom can
    b. On the shanks of the nails
    c. On the underside of the plywood
    d. On the underside of the membrane (pour the water out from the top can, remove the sealed can from the membrane, blot the membrane dry, and peel back the sheet)
11. Mark the product as a failure if there is water in any of the aforementioned locations.

Figure 4: Nails Tapped Up ¼ in. on Nail Sealability Specimen DRP1009-05-B

Figure 5: Fully Prepped Nail Sealability Specimen DRP1009-05-B

In August 2014, the standard was revised and a few changes were made to the procedure now entitled in Section 7.9 as "Capability to Seal Around Nail (Head of Water Test)." These notable changes are as follows and can be seen in Figure 6:

1. Reference to Protocol 4 in ASTM D7349, but two samples are still required and are collected according to ASTM D228 and have fasteners driven in at 1 to 2 in. apart.
2. Plywood is now to be 15/32 in. thick and 10 in. by 10 in.

3. An intervening material is specified as a 3-in. by 3-in. single-thickness piece of D3462-labeled asphalt shingle or other applicable roof covers (This testing omitted the intervening material).
4. The fastener is specifically defined as an ASTM F1667 smooth shank steel roofing nail that is 1.25 in. long, has a shank diameter of 0.12 in., has a head diameter of 0.375 in., and has a zinc coating and is hot dipped galvanized.
5. Drive the nails perpendicular to the specimen using a hammer until the fastener is flush with the membrane. Do not back out.
6. Water depth is 5 ± 0.25 in.
7. Test temperature is 39.2 ± 3.6 °F.
8. Test period is 72 ± 0.25 hours.
9. All tests must be reported.

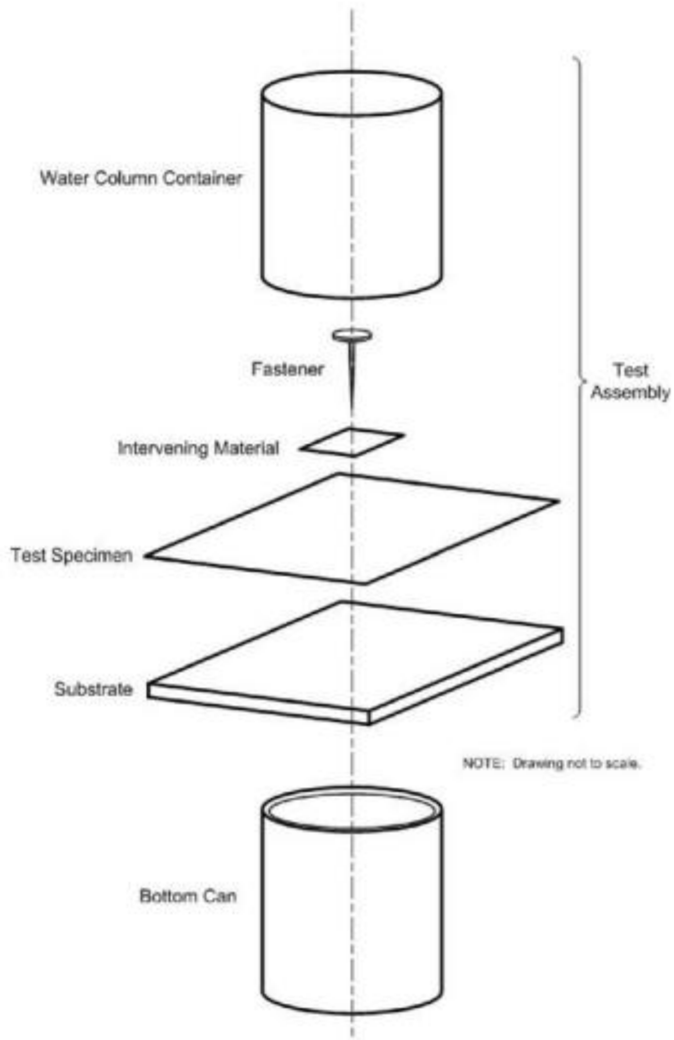

Figure 6: Test Arrangement for Nail Sealability Testing (ASTM D7349)

2.4 Preliminary Results

As is the nature of long-term durability testing, substantial results regarding the performance of many of these WRB mockups will take time to develop. Even though the specimens have only been exposed for a little over a year, some significant results have been observed in this short amount of time, but it will be a number of years before conclusive data on their durability will be available. Nail sealability test results were completed for the set of specimens that were made, and they are described below.

2.4.1 WRB Mockups

Inspection of the specimens occurs every two to three weeks. During these inspections, purely qualitative data are assessed. First, the front of the specimen is assessed, with primary attention paid to the penetrations and fasteners, corners and edges, and the window flange and flashing. When the back of the specimen is assessed, the location of penetrations and fasteners are the main focus. Then, any fishmouthing or gaps in the material, rips or tears, warping of the material, moisture penetration through cladding and staining, and discoloration are all noted. Appendix A contains a complete tabular description of the observations made for each of the 17 specimens.

Some of the failures—both aesthetic and performance—already observed in some of the WRBs are listed, described, and photographed below:

- Dirtiness:

Nearly all of the WRBs are susceptible to dirtiness. It has been observed that most of the specimens with a significant accumulation of dirt, sand, or pollen, are liquid applied membranes. This accumulation can be seen after just a few months and has continued over the life of the product, as shown in Figures 7 and 8.

Figure 7: Dirtiness of Specimen DRP1009-11 After 4 Months (left) and After 1 Year and 3 Months (right)

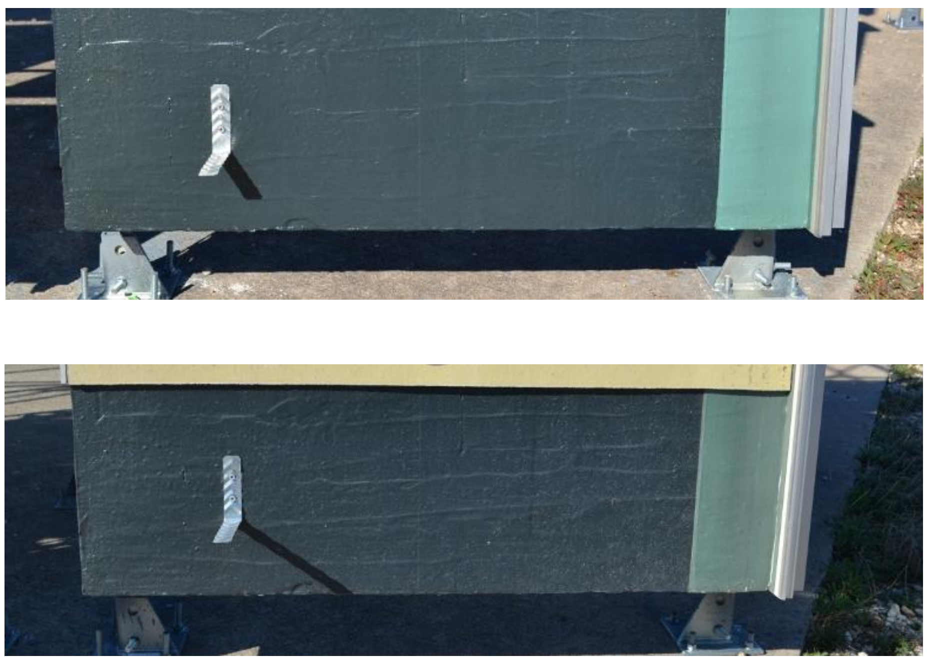

Figure 8: Dirtiness of Specimen DRP1009-07 at Installation (top) and After 1 Year and 3 Months (bottom)

- Discoloration:

The discoloration of some liquid applied WRBs has begun to occur. This chemical reaction occurred before and after the UV exposure limit for various WRBs.

However, since the cladding has not been removed on the top portion for any of the WRBs, it is unknown if discoloration has happened in those regions.

Just three months after being clad, the WRB in Figure 9 exhibited significant discoloration at the left edge, center joint, flashing at window flange, and miscellaneous locations throughout the field of the specimen. Some of the darker discoloration may be due to moisture intake, but the mechanism for the remaining discoloration is unknown.

Figure 9: Specimen DRP1009-03 with Significant Discoloration 3 Months After Cladding

Figure 10 depicts the first trial mockup that was constructed. As can be seen, the layout of penetrations was later altered to better test the products. Due to being a trial specimen, during the first few months it was not facing directly south until the racks were completely assembled, but it has still provided useful observations. The photo on the left is the specimen right at its UV exposure limit, and the photo next to it is the same specimen after a year. It can be seen that the beginning of discoloration of the flashing product was starting at its cladding date, and it has since progressed significantly over the course of one year. By the nature of the discoloration, it seems that the field product is reacting with the flashing product, resulting in the flashing product becoming the lighter pink color of the WRB. Further investigations and testing as the product is exposed further may be able to shed light on the mechanism of this reaction.

Figure 10: Specimen DRP1009-13 Comparison of Discoloration at 6 Months (left) and 1.5 Years (right)

- Fishmouthing:

Fishmouthing of tape products is a large culprit for water infiltration in buildings. Although some fishmouthing can be incredibly small, any imperfection without proper redundancy can cause failures.

For most of these cases, as can be seen in Figures 11 to 14, with the exception of Figure 13, the fishmouthing occurred for each product before it had reached its UV exposure rating. Whether the resultant failure was due to slightly imperfect craftsmanship or simply deterioration of the product and adhesion, issues like these pose a large threat to buildings and can cause potential water intrusion failures. Although this testing has not proceeded sufficiently long enough to observe any significant damage as a result of these failures, it will be interesting to see how the products fare as the years progress.

Figure 11: Fishmouthing of Specimen DRP1009-10 Tape at Sheathing Joint After 2 Months—4 Months Before Required Cladding

Figure 12: Delamination of Specimen DRP1009-02 Detailing at Large Pipe Penetration After 4 Months—Just Prior to Cladding

Figure 13: Fishmouthing of Specimen DRP1009-02 Tape at Joint After 6 Months—2 Months After Required Cladding

Figure 14: Fishmouthing, Delamination, and Cracking of Specimen DRP1009-05 at Flashing Edge After 10 Months—2 Months Before Required Cladding

- Pinholes:

This phenomenon only occurs in liquid applied products. These imperfections have become present at installation, before the UV exposure limit, or after the UV exposure limit for nearly all of the liquid applied products. Sometimes these pinholes appear to be small divots in the field of the membrane as simple popped air bubbles after application, while others appear to have the potential to go all the way through the WRB and act as holes to allow water penetration (Figures 15 to 18).

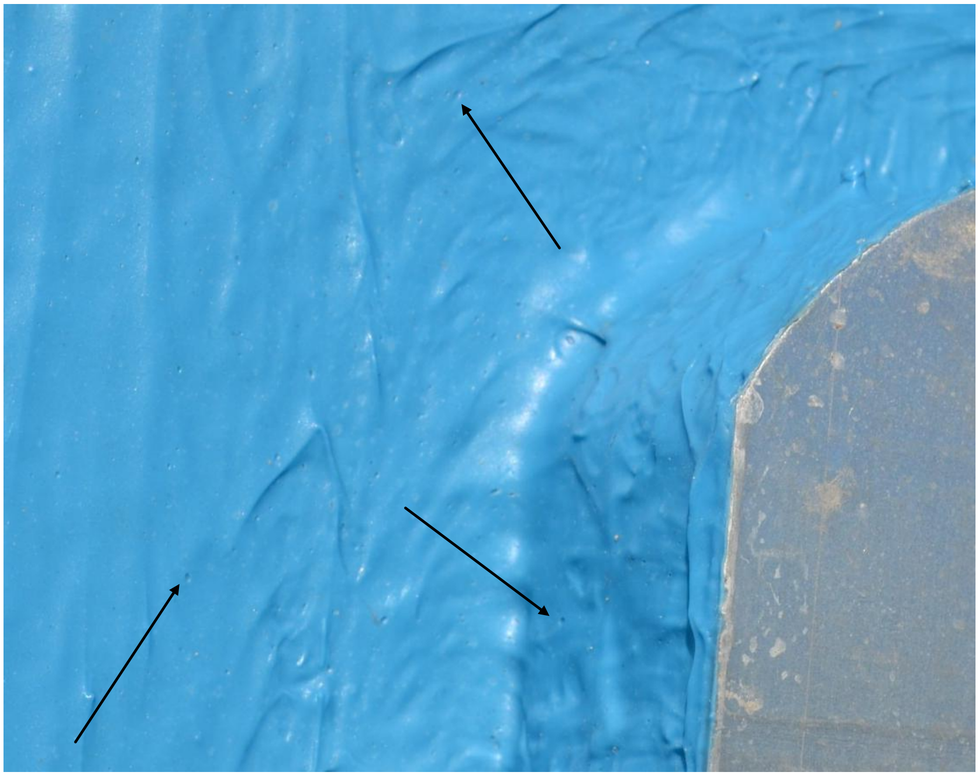

Figure 15: Pinholes in Specimen DRP1009-08 Immediately After Installation on Racks

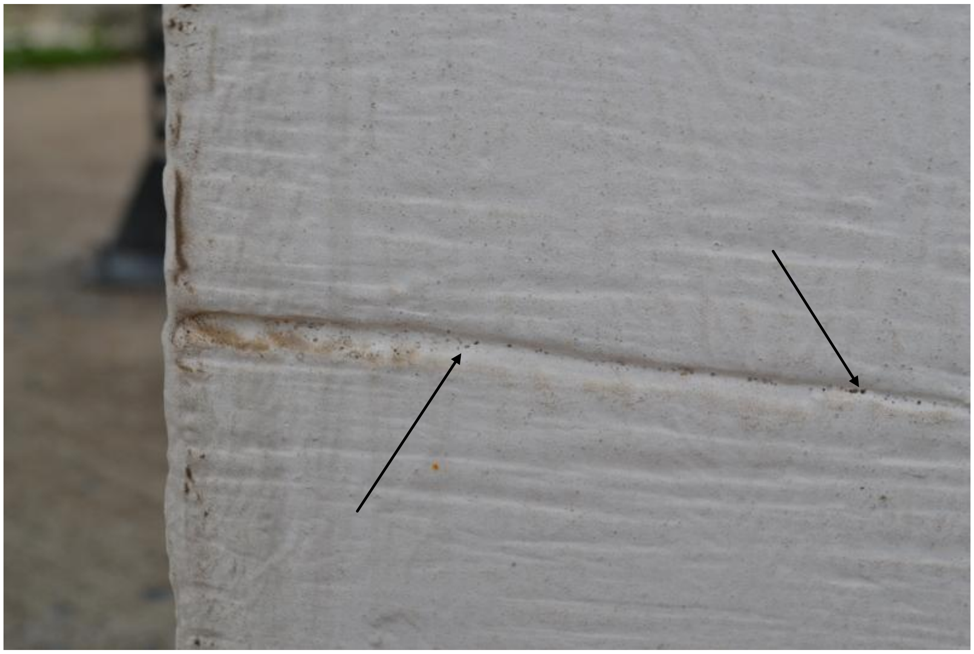

Figure 16: Pinholes in Deep Wood Grain of Specimen DRP1009-11 After 1 Year and 2 Months

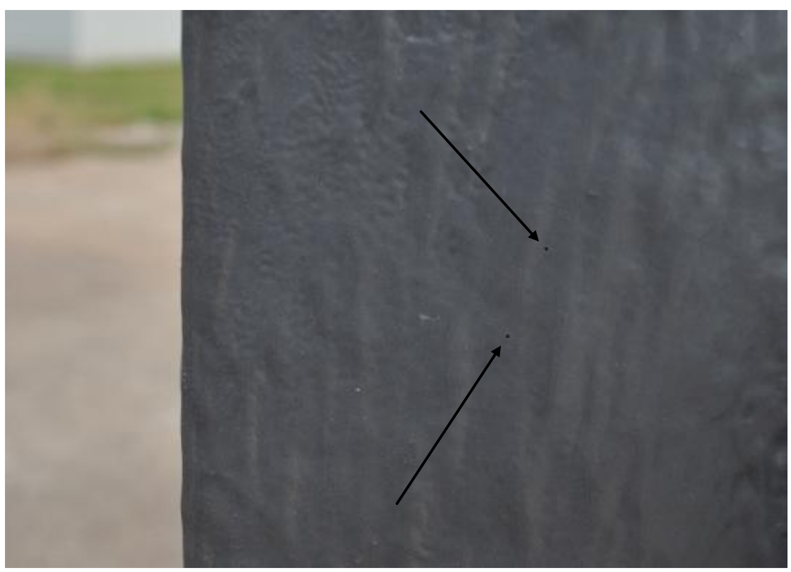

Figure 17: Pinholes in Specimen DRP1009-14 After 5 Months of Exposure

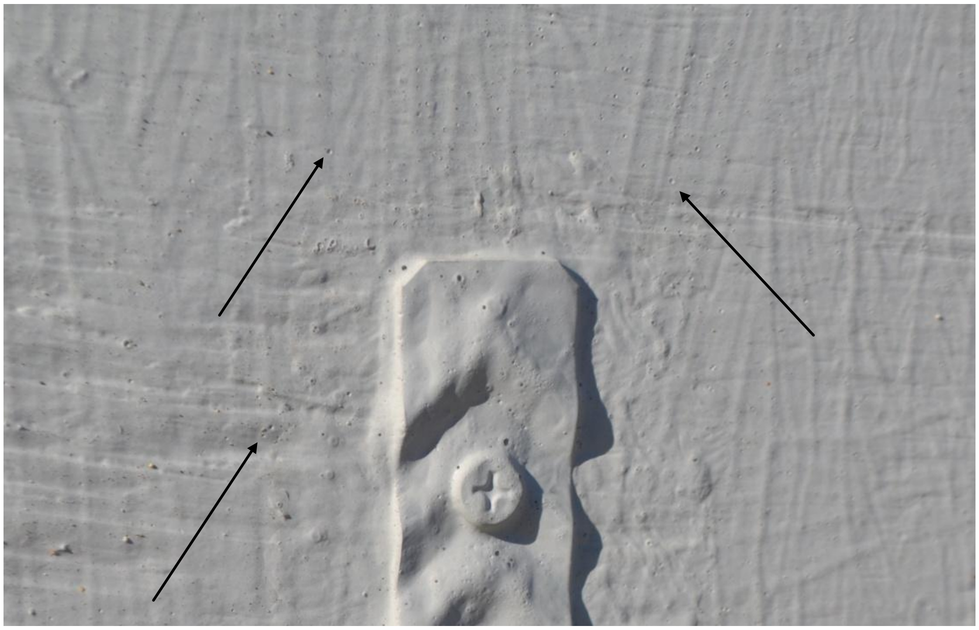

Figure 18: Pinholes Throughout Specimen DRP1009-05 After 1 Year and 3 Months—3 Months After Required Cladding

As can be seen in the above photos, many of the fluid applied products have small pinholes that may or may not penetrate through the thickness of the membrane. Over time there may be some consequences of this characteristic found in these WRBs, but the early stage of this project makes any decisive conclusions difficult.

- Cracking:

Some of the liquid applied products or accessories of felt products have been susceptible to significant cracking. Figures 19 to 23 show that some of the cracking of these products began before the product UV exposure limit, and others have occurred after the limit. Similar to all other observations thus far, the consequences of these failures have not developed yet, since durability issues may take years to fully manifest.

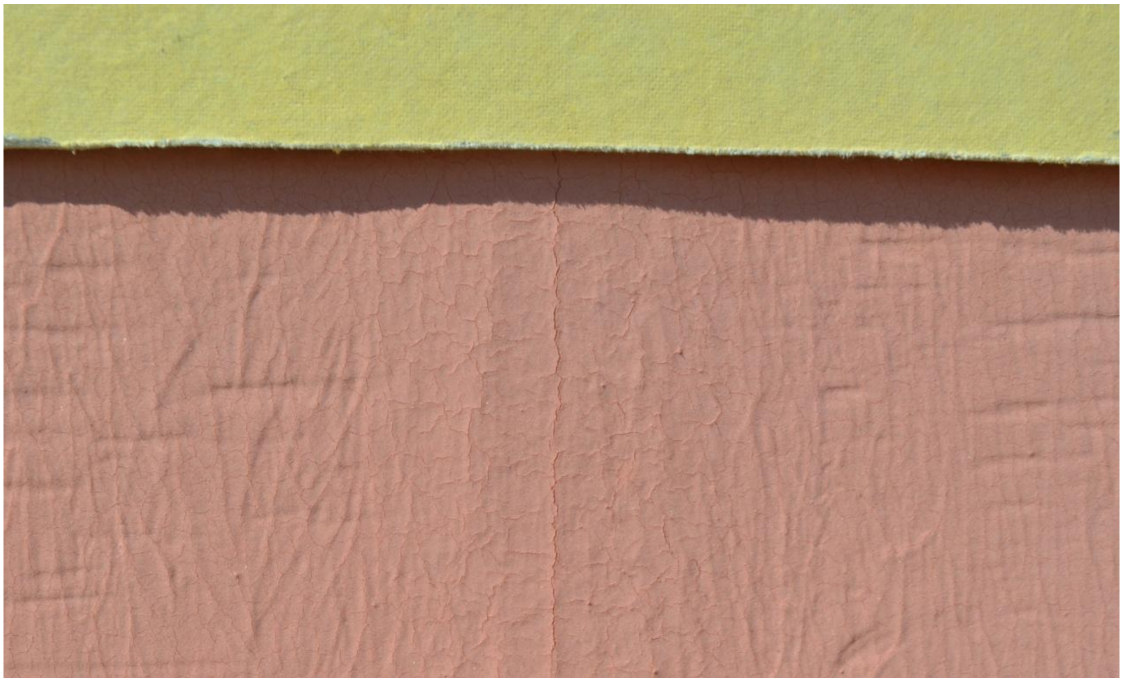

Figure 19: Crazing and Vertical Cracking at Center Joint of Specimen DRP1009-13 After 1 Year of Exposure

Figure 19 shows a cracking failure of a specimen after one year, but there had already been evidence of crazing and cracking along this center seam and around one of the penetrations before cladding was installed per the product UV rating. This illustrates how penetrations and joints in the building envelope are the most susceptible to movement and failures, so careful detailing is necessary.

Figure 20 below shows the cracking of the auxiliary building cement product used to detail around the penetration on a felt WRB specimen. Cracking and failure of this product was noticeable after little exposure outside.

Figure 20: Specimen DRP1009-12 Flashing and Penetration Cracking After 2 Months Exposure

Figure 21: Specimen DRP1009-04 Edge Cracking After 3 Months Exposure

The cracking observed in Figure 21 began propagating just one month after it was placed on the exposure racks. After having been exposed for nearly a year and a half, the cracking has propagated almost along the entire length of the bottom edge of the specimen. As a result, there has been an increased amount of condensation accumulation on the rigid plastic backing, but no visible damage to the studs or sheathing has been observed yet. The manufacturers of this product stated that they have not seen a failure like this before, and they believe that it may be due to the imperfection on the right of the cracking. During installation, the specimen was still drying and accidentally touched another surface, causing the WRB to be pulled off.

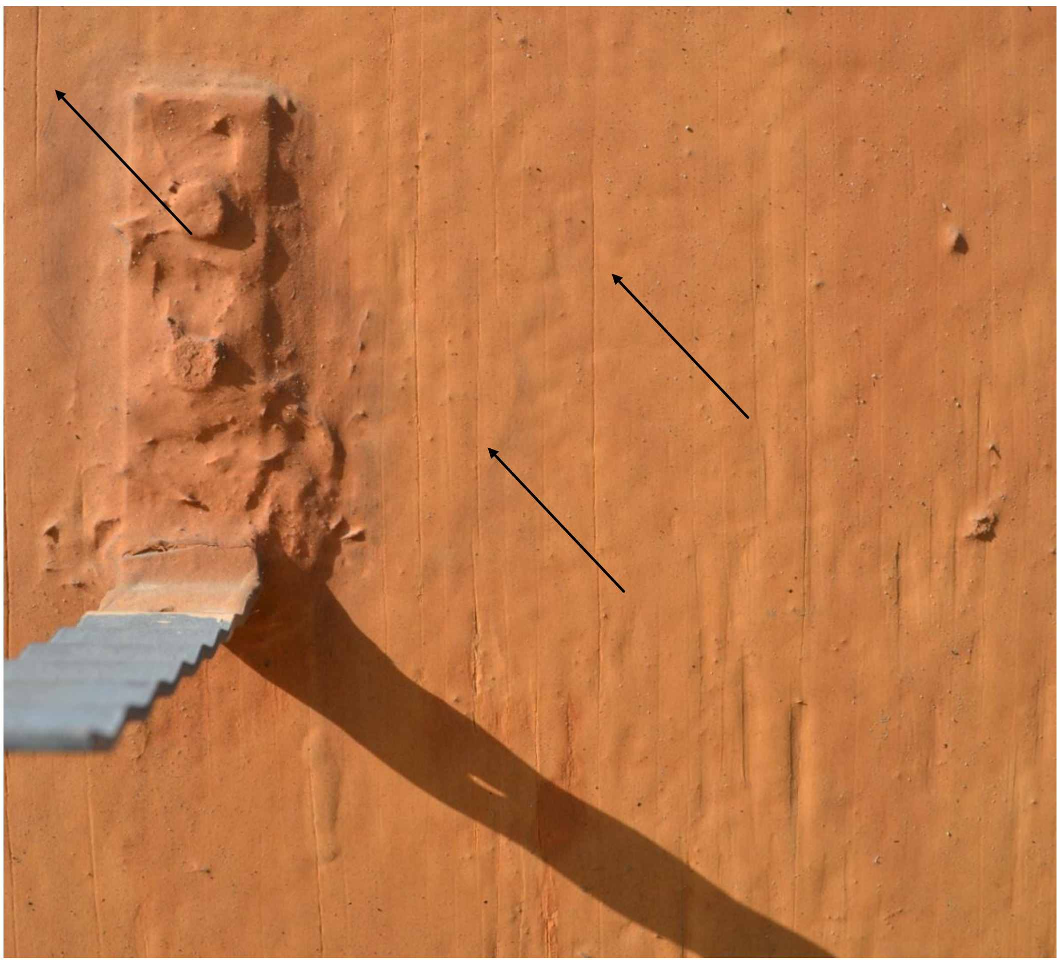

Figure 22: Specimen DRP1009-03 Vertical Cracking After 1 Year, Just Before Exposure Limit

In Figure 22, the vertical cracking had begun to propagate just one month after installation. Now this cracking has spread throughout the specimen, and is most severe on the left side near the electrical and large pipe penetrations and the brick tie. The manufacturers of the product have been notified of this cracking, and they are unfamiliar with such a failure before, and propose that it may be due to simply a bad batch of the material.

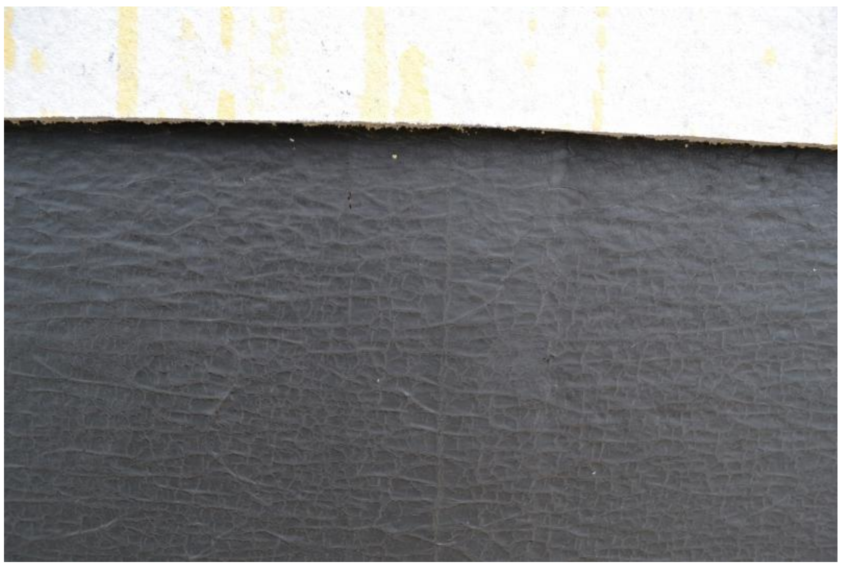

Figure 23: Specimen DRP1009-09 Crazing After 1 Year Exposure

As seen in Figure 23, this liquid applied WRB has experienced significant crazing over the course of one year. This product began experiencing this effect after about nine months of exposure, and it has propagated further ever since. It should be noted, however, that this product has a UV exposure rating of 1 month (with potential approval from the manufacturer representative of up to 6 months, depending on application). In the future it will be telling to see if the cladded half of the specimen will experience the type of cracking that is seen here. This product is also the only WRB so far that has experienced blistering as well, which is described below.

- Blistering:

Blistering of products is a result of trapped water vapor behind the membrane and has only occurred on one tested specimen so far; it seemed to result after field crazing. This blistering began in the product after about 10 months, or one month after the substrate began to experience crazing (Figure 24).

Figure 24: Specimen DRP1009-09 Blistering After 1 Year and 3 Months Exposure

Overall, there have been a handful of various product failures over the course of just one and a half years. As these failures continue to be weathered, it will be very interesting for future researchers to analyze the repercussions of these failures that result from this exposure.

2.4.2 Nail Sealability

The nail sealability test is a very severe test and was performed on all of the products which have been placed at the exposure site. Of the 16 products (there are 17 specimens, but two are the same WRB field product with different detailing products) present at the site, six of them were not tested for this standard by the manufacturer. However, all of the products were tested in this experiment regardless of what was found in the product literature. The results from this experimentation resulted in some significant findings about the WRB industry.

It is first important to note that the fluid applied products are not completely applicable to the ASTM D1970 method, since one of the requirements is to lift the sheet up to observe any water penetration underneath. Usually the manufacturers will modify the test, such as putting fluorescent dye in the water and then cutting through the substrate after the test and visually observing the moisture penetration with a black light. But, many times, these modifications will not be known.

Before testing to the new method, nine of the 16 products had already been tested according to the old standard. Of these nine products, each with three replicates, only two of the 27 total passed; one of these specimens manufacturer's literature did not state that it was tested in accordance with the ASTM D1970 standard. All of the remaining specimens failed. Water was observed on the nail shanks, on the underside of the plywood, underneath the membrane, in the can below, and sometimes outside of the test setup and in the environmental chamber (Figures 25 to 29).

Figure 25: Visible Moisture Droplets on Nail Shanks of Specimen DRP1009-08-A

Figure 26: Significantly Saturated Underside of Plywood of Specimen DRP1009-03-A

Figure 27: Significant Water Penetration Underneath Specimen DRP1009-06-B, a Self-adhered Membrane

Figure 28: Water in Bottom Can of Specimen DRP1009-07-C

Figure 29: Water Leaking Out Corners of Specimen DRP1009-02-A and -B, Which are Wrap WRBs, Within Minutes of Placement in Environmental Chamber

In Figures 25 to 29, the products that have been reported by the manufacturers to pass the test are those found in Figures 25, 26, and 28. Figures 27 and 29 were products for which it has not been stated whether or not the WRB passed the test.

Due to the wide range of failures, this testing was halted temporarily to discuss the cause of failure with many of the manufacturers. After speaking with them, some interesting information on how they performed the test came to light.

Some manufacturers were testing their product until they had two passing results; these were the only results that were reported. So, in actuality, a manufacturer could test the specimen until the desired results were achieved. However, with the revised standard, all tests have to be reported. Therefore, there is no longer the ability for manufacturers to test their product until it passes, without also reporting the failures.

When testing the remaining seven products to the new ASTM standard, the results were remarkably different. Some of the specimens failed, and some passed, which makes the standard much more useful in terms of product comparison. A complete list of the pass and failed products for both the old and new test methods can be found in Appendix B. The biggest difference was the elimination of the requirement for the nails to be tapped back up. Many times, this caused the membrane to be ripped apart, as seen in Figure 30, making it very easy for water to penetrate.

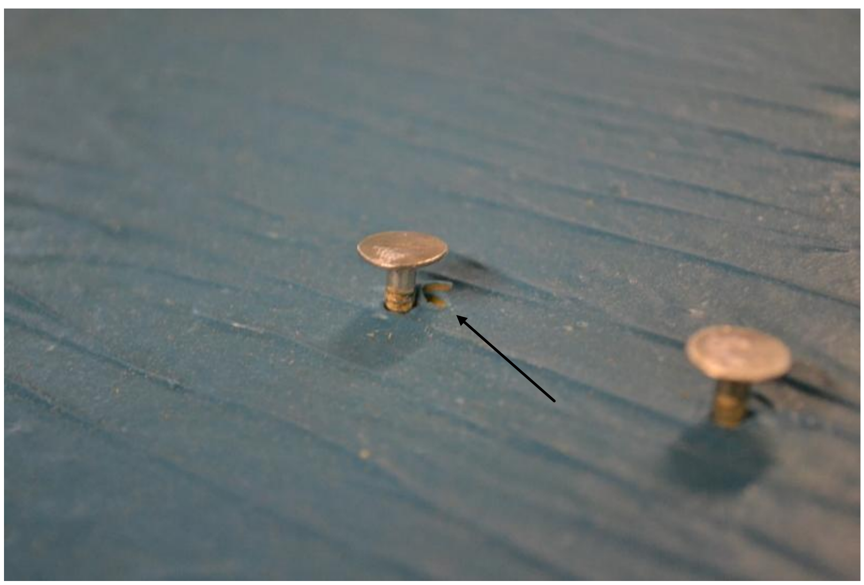

Figure 30: Clear Distress of Specimen DRP1009-08-C After Nail Backed Out 0.25 in., According to Old ASTM D1970 Standard

2.5 Discussion

Durability of products, especially WRBs, requires long-term monitoring due to weathering. This testing analyzes the WRB service life and how long it will actually last, versus how long it is supposedly designed to last. Due to all of the failures already observed including dirtiness, discoloration, fishmouthing, cracking, and blistering, it further reinforces the fact that closer examination of these products' performance is necessary before being placed on a project.

The initial research aspect of the project, even before the WRBs were placed on the exposure racks has also lead to some interesting observations. It shows that manufacturers need to improve their product literature to make sure it is much more clear. Additionally, it would be best if the WRB could consist of just a few products in order to fully install the system no matter what penetrations or intricacies that may be found.

One of the main reasons why many of these WRBs are failing to perform as needed is due to the lack of an industry standard for testing products for durability and weathering characteristics, especially as a system. The tests being performed today are not able to encompass all aspects of WRB behavior, especially in regard to durability and water penetration, which is the cause of most failures. The testing described here could be an appropriate starting point from which to develop a standardized test method. Its greatest benefit is that it tests *long-term* durability in a realistic setting (with slight modifications to accelerate the testing results).

Although the durability results from this study are not completely conclusive simply because the products have not been exposed for very long, over the next several years, the distress and failures already observed will likely propagate further. As a result, the testing will help to explain a lot about common durability failures, the mechanisms behind them, and potential impacts.

In terms of further testing, there is additional space on the existing racks for three more specimens. As new products arise and look to be strong market contenders, they will be installed on the racks for continuous monitoring. Additionally, later on the top cladding of these specimens will be removed so that observations of cladded WRB performance can be made.

The nail sealability observations also have introduced some interesting insight. Although the original version of the standard was very severe, it does not take away the fact that virtually all of the specimens failed, rendering the standard useless. While the product literature claims otherwise, this shows that published information is not always reliable, and manufacturers should work diligently to ensure that their literature is truthful about the performance of their products.

Since not all of the products were tested to the new ASTM D1970 standard, new specimens in accordance with the revised standard are planned on being made to further examine the behavior of all of the tested WRBs on the exposure racks.

The nail sealability characteristic is just one of a few auxiliary and smaller scale test methods regarding WRB performance. A testing protocol to monitor and observe the durability of the tapes and adhesives used on these products is underway. Additionally, examination of the crack bridging characteristics of these WRB products is beginning as well. Neither of these tests is in accordance with any ASTM standard; they are being developed with the goal of understanding the durability of a WRB and all of its accompanying characteristics.

Chapter 3: Durability of Elastomeric Sealants[2]

3.1 INTRODUCTION

Structural sealants are used on the exterior of nearly all constructed buildings as a method for which to seal and adhere joints and gaps in facilities to prevent air, water, and dirt infiltration. Durability of these sealants are what allows them to perform as they are intended, and the environment in which a sealant is placed largely dictates its performance. Indeed, designers, manufacturers, and installers all need to take part in ensuring that sealant products are durable to both movement and weathering. The research described is in its early stage; therefore, much of what is presented will be an in-depth description of the test methodology and initial results, in order to project how these might affect long term research results.

Satisfactory performance comes from three participants whose input is imperative for success of sealant performance. First, the designer must specify products whose performance will ensure that any potential movement, exposure, or contact with different substrates will not cause an adverse effect on the durability of the sealant to perform its duty. Eventually as the sealant begins to degrade, the designer should make sure that there is a secondary defense to protect the structure from any intrusion of air, water, or debris. Secondly, the manufacturer has an important role in creating a sealant product that is not only durable, but one that has proper, accurate, and accessible product information that correctly describes the product capabilities. Lastly, the contractor should ensure that the product is installed correctly. Without correctly applying a product, no amount of design or manufacturing can help to keep this product performing well. These three

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[2] Nicastro, David H. and Beth Anne Feero. "Durability of Elastomeric Sealants." *The Construction Specifier* Mar. 2015: 50-59. Print.
Some or all of text written in this chapter was previously published in the source shown above. All authors contributed equally.

components: designing, manufacturing, and installing are all important characteristics of sealants and their application in order to assist in positive performance.

3.1.1 Sealant Degradation

Sealant testing has been actively addressed since the 1970s, so there is a long history of testing. UV light is one the largest culprits for the disintegration of organic, elastic sealants causing degradation of the binder, and it results in failures associated with chain scission and crosslinking causing softness and brittleness, respectively, over time. UV and natural sunlight can also cause damages such as discoloration, crazing, and chalking (Wolf, "Ageing" 67). Contrastingly, inorganic sealants are not subject to these same disintegrations (Wolf, "Ageing" 70). Thermal loading, or the accumulation of radiation energy from sunlight, will cause sealants to expand and contract as solar radiation varies throughout the day, which adds additional strain to the product (Wolf, "Ageing" 72). Additionally, the effect of heat can cause additional crosslinking, or "post cure" in most types of sealants from evaporation of plasticizers (Wolf, "Ageing" 74). Similarly, when subjected to colder temperatures, sealants become brittle. (Wolf, "Ageing" 76).

The effect of moisture and water also has a significant effect on the durability of sealants. Water diffuses into the sealant causing it to swell. Upon drying, the sealant endures tensile stresses, which can initiate cracking. This phenomenon is also particularly harmful for water-borne acrylic sealants and evaporation-cure sealants, since the intrusion of water can cause the binder to break down or cause leaching of important components of the sealant chemistry, such as fillers, plasticizers, and pigments. Continual exposure to water, especially during the curing process can have permanent effects on the sealant, preventing adhesive bonds from forming and resulting in a failure to adhere to the sealant substrate. Coupled with high temperatures, sealants may have difficulty adhering to substrates (Wolf, “Ageing” 78-79).

When observing sealant adhesion to glass specifically, organic sealants have very poor adhesion unless silane is either added to the formulation or a primer is placed on the substrate prior to sealant installation (Wolf, “Ageing” 72). Although failures may still result from these sealants even with the added silane, it is usually an interphasal adhesive failure rather than a complete adhesive failure.

Other degradations have been attributed to oxygen and ozone, pollutants, and micro- and macrobiological influences. (Wolf, “Ageing” 80-84). However, these have not knowingly yielded significant degradation in this research thus far, and will not be discussed in detail.

These environmental effects can have a large impact on the performance of sealants, especially when coupled with movement. Thus, it is important to address the two characteristics through testing.

3.1.2 Sealant Test Methods

ASTM C920, *Standard Specification for Elastomeric Joint Sealants* is the existing standard with which nearly all specifications require compliance. It has requirements for rheological properties, extrusion rate, application life, hardness, heat aging, tack-free time, stain and color change, adhesion, accelerated weathering, and immersion in liquids. These requirements reference procedures taken from several other ASTM standards.

A second commonly used standard to test the durability of sealants is ASTM C719, *Adhesion and Cohesion of Elastomeric Joint Sealants Under Cyclic Movement (Hockman Cycle)*, which is a Sealant, Waterproofing, and Restoration (SWR) Institute validated standard. This standard provides a test for sealants in compression and extension at hot and cold temperatures. It examines sealant durability when subjected to movement, but it fails to test the products for weathering as well. The SWR Institute is a non-profit, independent corporation that looks to test various products to ensure that they perform satisfactorily and as the manufacturers claim they should.

Testing sealants for accelerated weathering due to UV light, heat, and liquid exposure is commonly investigated and expresses the more successful performance of silicone sealants over urethanes (Bridgewater et al.). Others have performed accelerated weathering but incorporated cyclic movement into the testing regimen (Beasley et al.). Natural weathering, instead of accelerated weathering, combined with cyclic movement is testing that has been investigated in some additional research (Hurley). The sealants are put outside on racks for natural weathering, and they are placed in vises, which are manually operated versus an automatic strain cycling exposure rack. Karpati, who was heavily involved in developing these racks and hand-crank vises, performed testing to naturally weather specimens and show comparable results between strain-cycling racks and her simple hand-crank vises (Karpati, Lacasse).

However, there still exists little knowledge in terms of the long-term durability and aging of sealants when undergoing movement, and until recent years, there has been a lack of a standard to test for this characteristic (Lacasse).

3.2 Experimental Procedure

Fortunately, a newer ASTM Standard has been approved that tests for both movement and weathering. ASTM C1589, *Standard Practice for Outdoor Weathering of*

Construction Seals and Sealants, has several alternative procedures that test for weather exposure as well as extension and compression of the material.

This study utilizes Procedure C, "Outdoor Weathering of Building Joint Sealants with Periodic Manual Extension and Compression", which is a user-friendly method. This allows for homeowners, contractors, or architects to test products before they commit to a sealant based solely on manufacturers' claims. The procedure is as follows:

1. Consult ASTM C719 for test specimen dimensions, cure, and substrates (concrete, aluminum, or steel).
2. Any suitable clamping device can be used to hold the specimens, such as the one in Figure 31, which has 4.5-in. aluminum (or steel) bars with drilled holes at the ends in order to thread 4-in. bolts and nuts to secure the device together so that the specimen can be compressed and extended.
3. Mark all specimens clearly with an identification number or symbol.
4. Create at least three specimens of each product being tested.
5. Retain one file specimen of each in 73.4 ± 3.6 °F temperature conditions and 50 ± 20% relative humidity.
6. Record the initial appearance of the specimen.
7. Attach the specimens to an exposure rack, which has no backing and is positioned at 45°.
8. Movement cycle can vary depending on desired results. Potential methods are as follows:
    a. After specimen cure, place the specimens in compression in the summer, neutral in the fall, extension in the winter, and neutral in the spring.

b. Change the specimen in compression or extension at the end of every week, two weeks, or every month for accelerated damage.

9. Do not compress or extend specimens faster than 0.118 in. per minute.
10. After each cycle, examine the specimen for cracks, crazing, tears, adhesive or cohesive failures, or other failure mechanisms.
11. Following the specimen examination, the modulus of the unstressed specimen can be tested using ASTM C1135.

Figure 31: Example of Clamping Device

3.2.1 Product Selection

Thirty-two different sealant products were tested in this study. The products were specifically chosen based on those products with the largest market share and that perform well historically. Silicones, urethanes, and hybrids were tested in this experiment, and most were placed on both concrete and aluminum substrates (with a few exceptions) in order to model the common placement of sealants on building façades. All of the products claimed to pass ASTM C719, which is referenced in ASTM C920 and are able to withstand strains of ±25%.

3.2.2 Specimens

For each of the 32 products, seven specimens were made for 24 of the products, and the remaining eight had only three specimens (one product had four), which means that a total of 193 specimens were tested. Those that were exposed can be seen in Figure 32. Most of the sealants were colored white in order not to induce aging due to pigment, while nine specimens were clear. Of the products with seven specimens, the first four were primed and the last three were unprimed. The fourth primed specimen was left as a file specimen and placed inside with no weathering.

Figure 32: All Specimens on Rack

One of the additional goals from this testing is to observe the effect of primers with sealants. Experts suggest primer assists with adhesion, but it is important to test the success of primed products in long-term weathering and movement. Primers not only allow for the sealant to adhere more successfully to the substrate, as mentioned in Wolf, but they emulsify laitance and condition the surface to encourage adhesion (“Ageing” 72). Despite primer benefits, it is common for manufacturers to refrain from requiring this product in an attempt to appeal to more contractors and installers by removing the need for an extra step (time) and cost in the overall construction.

The actual specimens themselves were dimensioned according to ASTM C719 “Hockman” dimensions, which means that the sealant has dimensions of 0.5 in. by 0.5 in. by 2 in. as shown in Figure 33. This shape has been used in sealant testing dating back to the 1970s, so there is reason to mimic these dimensions in order to obtain results which can be compared more easily. This is important to remember, especially because in real service applications, an hourglass shape will be utilized with use of a backer rod and tooling. The sealants were left to cure in ambient temperature for around 28 days, slightly longer than what is suggested in the standard. However, this was done based on other research which suggests that some products are not fully cured after 21 days (Klosowski, "Summary" 89).

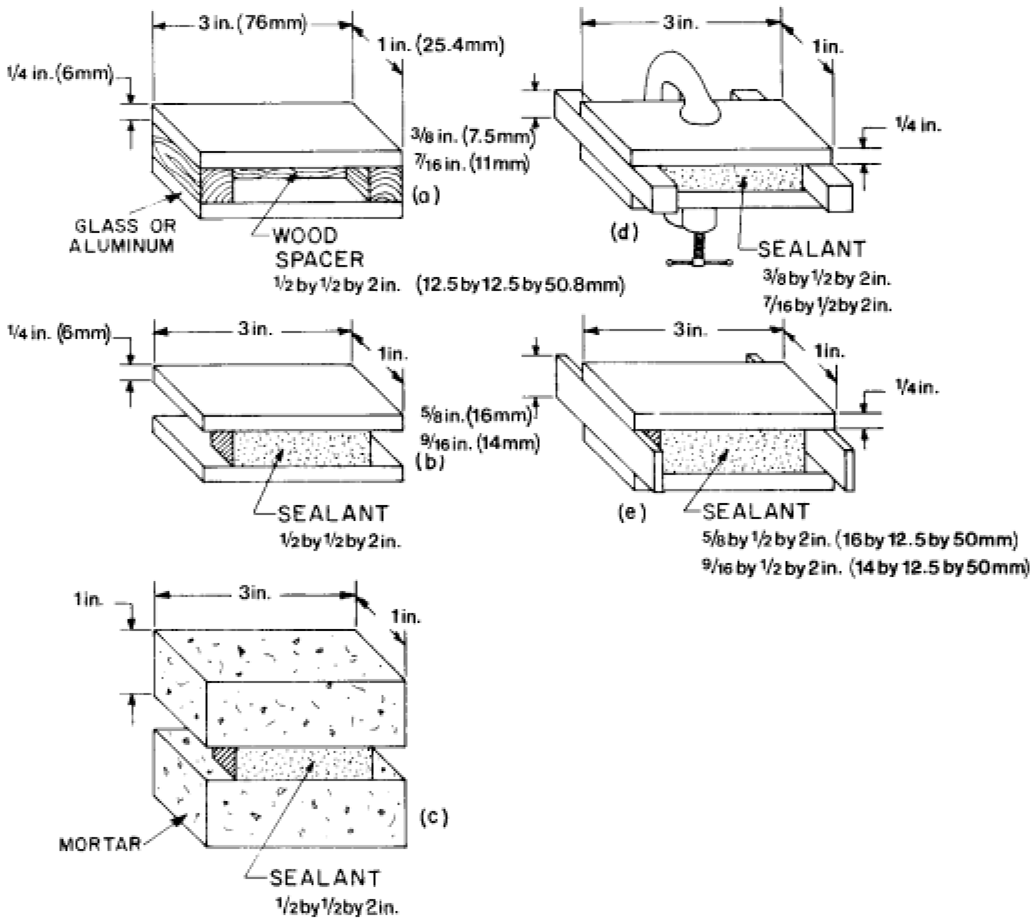

Figure 33. Hockman Cycle Dimensions as Seen in Drawings (b) and (c)

3.2.3 Specimen Racks

The racks used for testing were constructed out of metal tubing with wire mesh as the backing so as not to create additional thermal effects on the specimens, which greatly influence sealant behavior. Because of the large number of specimens on this rack, metal bars were placed behind in order to prevent sag and help the specimens maintain uniform positions. Guy wires and tensioners were attached to the rack in order to stabilize it from high winds that frequent the testing area. Zip ties were used to attach the specimens to the mesh backing.

In order to maximize solar radiation, the rack was positioned to face solar south and tilted to 45° as specified in the standard. Given the location of the test set up, had the rack been tilted to an angle of 30° from horizontal, which is representative of the latitude of the town, the witnessed weathering due to radiation would have been 33% faster.

3.2.4 Testing Cycle

ASTM C1589 calls for the specimens to be tested at ±25% elongation, but gives the researcher liberty on when to induce this effect. All of the specimens in this testing were installed on the racks after the spring equinox, in May and June 2014. Upon their installation, the specimens were already compressed to 3/8 in. from the ½-in. neutral state. It was chosen to compress the specimens first, instead of extending them, for two reasons. In-service sealants naturally compress in the summer months and extend in the winter (Wolf "Experimental" 123, O'Connor 12). Additionally, compressed sealants do not recover well due to compression set which may be a result of permanent reorientation of polymer chains or additional crosslinking (Margeson et al. 100). After the fall equinox, in December 2014, the specimens were extended to 5/8 in. Those that did not fail this first round of testing were installed back onto the exposure rack to be compressed back to 3/8 in. at the next spring equinox.

3.2.5 Methodology

To test the specimens for extension, they were removed from the racks and then slowly taken out of their metal clamps. After this, the specimens were placed in a hand crank vise whose jaws are fabricated with C-shaped clamps that could easily hold the specimen, as seen in Figure 34. Prior to any tension placed on the specimen, calipers were used to measure the widths of the sealant prior to testing in order to obtain the compression set for the sealant. Ensuring that the turning rate was not greater than 0.118 in. per minute, they were extended to the 5/8-in. value unless the product failed.

Figure 34: Specimen DRP1014-A4P in Metal Clamps of Vise Before Extension

After the testing, each specimen was assigned as having a "pass" rating, where no visible distress was observed, a "distress" rating if it had some tearing or crazing, "failing" if the sealant was becoming significantly distressed and nearing failure, and then the product was designated as 'fail' if the two substrates were separate and the product no longer adhered the substrates together.

Among international experts, it has been concluded that specimens which exhibit slight tears—no more than 3 mm. long—at the corner are considered to have "no failure," due to the potential of this type of flaw during specimen fabrication. If it is a real failure, it will propagate further with continuous extension and compression (Klosowski, "Re: Sealant").

Shortly after the testing was complete and the un-failed specimens were on the rack, continual monitoring every three weeks was completed in order to describe any more deleterious effects that would manifest over time.

3.3 Preliminary Results

The results from this testing have already yielded some interesting trends in terms of their durability. However, as this testing is still in early stages, it will be interesting to observe the results as they continue to be weathered and compressed and extended.

Given that only nine specimens were clear, the results and trends described here are only for those which are white. Appendix C has the table that contains all of the sealant data and performance.

After the first round of extension was completed, the specimens that had not failed were returned back to the racks for the next round of weathering. If the specimens were completely failed, then they were not placed on the racks, and the clamps will be used again for additional testing later. Every three weeks, observations of the sealant performance were documented, and those results four months after extension are described here. Over that time, more failures and distress has occurred and can be seen in

Table 1. Those entries with an asterisk (*) mean that the corresponding cells do not contain the file specimens.

Table 1: Sealant Performance After Weathering and First Round Extension

Specimen Description		Number of Specimens	Number Failing and Failed	% Failing and Failed
Silicone	**Primed***	51	20	39
	Unprimed*	45	29	64
	File Specimens	15	5	33
	Total	111	54	49
Urethane	**Primed***	30	16	53
	Unprimed*	24	20	83
	File Specimens	8	4	50
	Total	62	40	65
Hybrid	**Total**	11	7	64
SWRI Validated Products*		117	57	49
Non-Validated Products*		42	34	81
All Specimens		184	101	55

The results are rather telling, even though this is just the first round of movement after weathering. Of the 184 specimens shown, only 37—or 20%--of them have no visible signs of distress and were considered to have passed the first extension. The hybrids did not perform very well, but due to the fact that only 11 hybrid specimens were tested, their performance was not broken down into characteristics due to potential implication of false results. One of the more notable results is that 55% of all of the specimens failed or are in the process of failing, with silicones performing better than urethanes, and primed specimens performing better than unprimed specimens in most cases. Another fascinating trend that can be noticed is how the SWR Institute sealants performed far better than those that were not validated. In fact, of the exposed specimens that passed, all of them were validated; none of them were non-validated. Figures 35-42 show some specimens immediately after extension and/or at four months later.

Figure 35 shows the effect of having an unprimed, urethane product that is not validated by SWR Institute. Although not all failed this drastically, it shows the potential magnitude of failure when having these characteristics. Figure 36 contains the same characteristics as the sealant in Figure 35, but immediately after the extension, the product looked immaculate. However, after four months outside the product lost all adhesion to the concrete substrate. Contrastingly, the sealant in Figure 37 has performed well after extension and through the weathering it has endured for four months. The stark contrast between this specimen and that from Figures 35 and 36 is that it is a SRW Institute validated, primed, silicone sealant.

Figures 38 and 39 show specimens from the same product, while one is primed and the other is not. This simple comparison is able to show how much of a difference primer can do to promote adhesion to a substrate.

The last three Figures, 40 to 42, show other failures observed beyond the most common adhesive failure. Crazing affected DRP1014-F, -G, and –V, while chain scission has only affected DRP1014-R. Cohesive failures were uncommon and only affected a few of the clear products.

The results after extension resulted in predominantly adhesive failures, with some cohesive failures, crazing, chain scission. As the specimens weather longer and are subjected to more rounds of extension and compression, it will be interesting to see how these failure mechanisms will continue to propagate and what other failures will result.

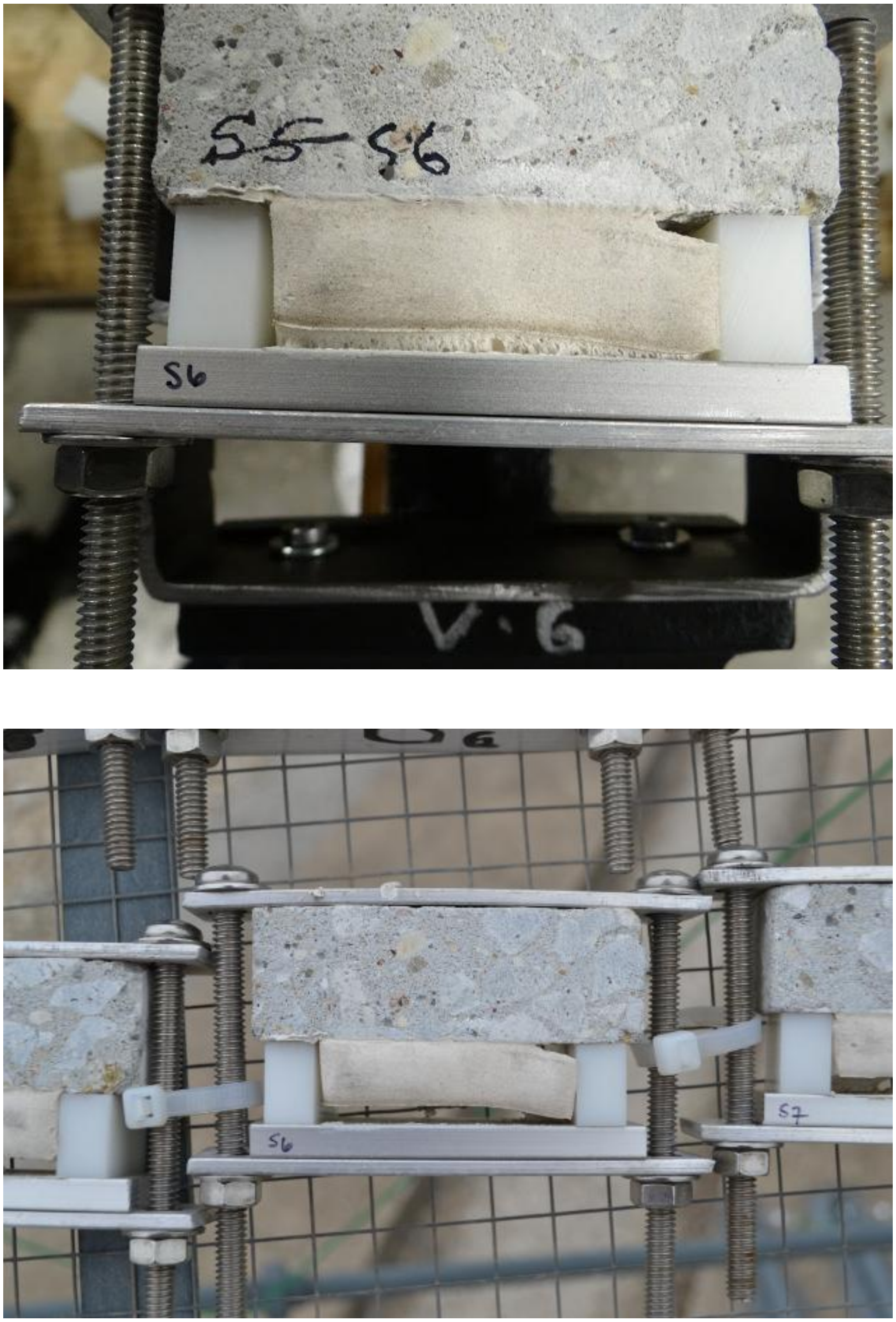

Figure 35: Sealant Specimen DRP1014-S6 (Urethane, Non-SWRI validated, Unprimed) Immediately After (top) and 4 Months in Extension (bottom)

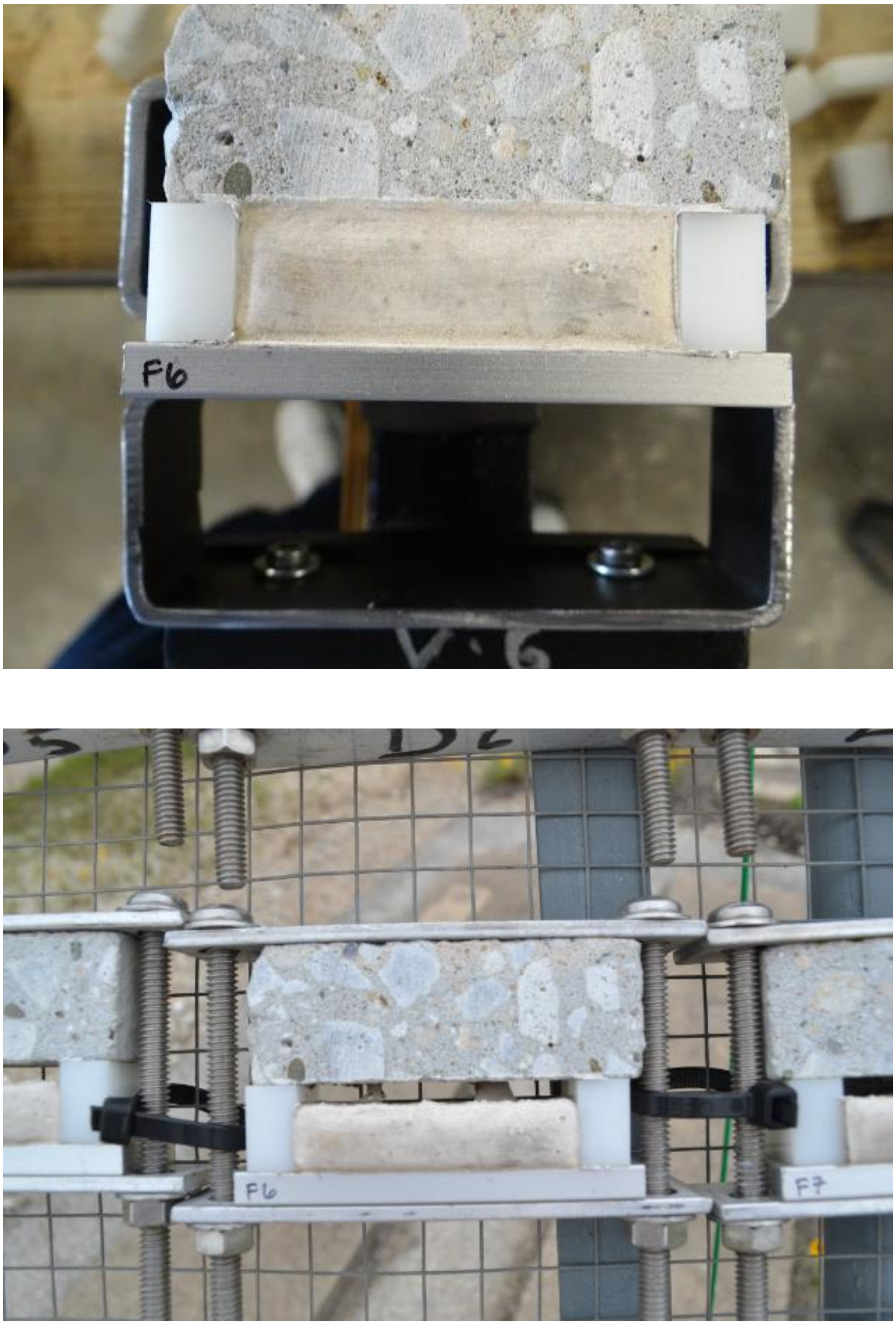

Figure 36: Sealant Specimen DRP1014-F6 (Urethane, Non-SWRI Validated, Unprimed) Immediately After (top) and Four 4 Months in Extension (bottom)

Figure 37: Sealant Specimen DRP1014-T2P (Silicone, SWRI Validated, Primed)
Immediately After (top) and 4 Months in Extension (bottom)

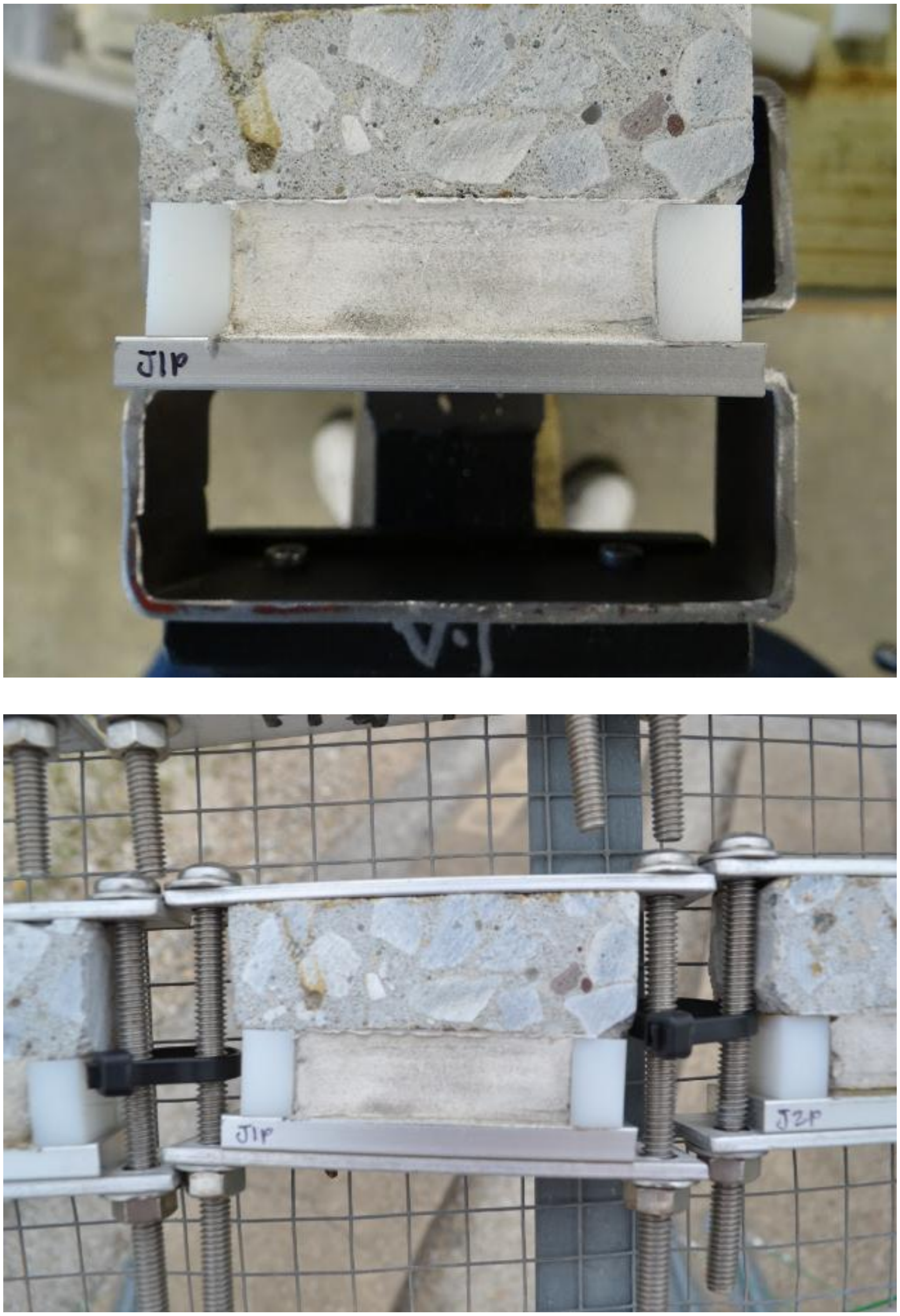

Figure 38: Sealant Specimen DRP1014-J1P (Urethane, SWRI Validated, Primed) Immediately After (top) and 4 Months in Extension (bottom)

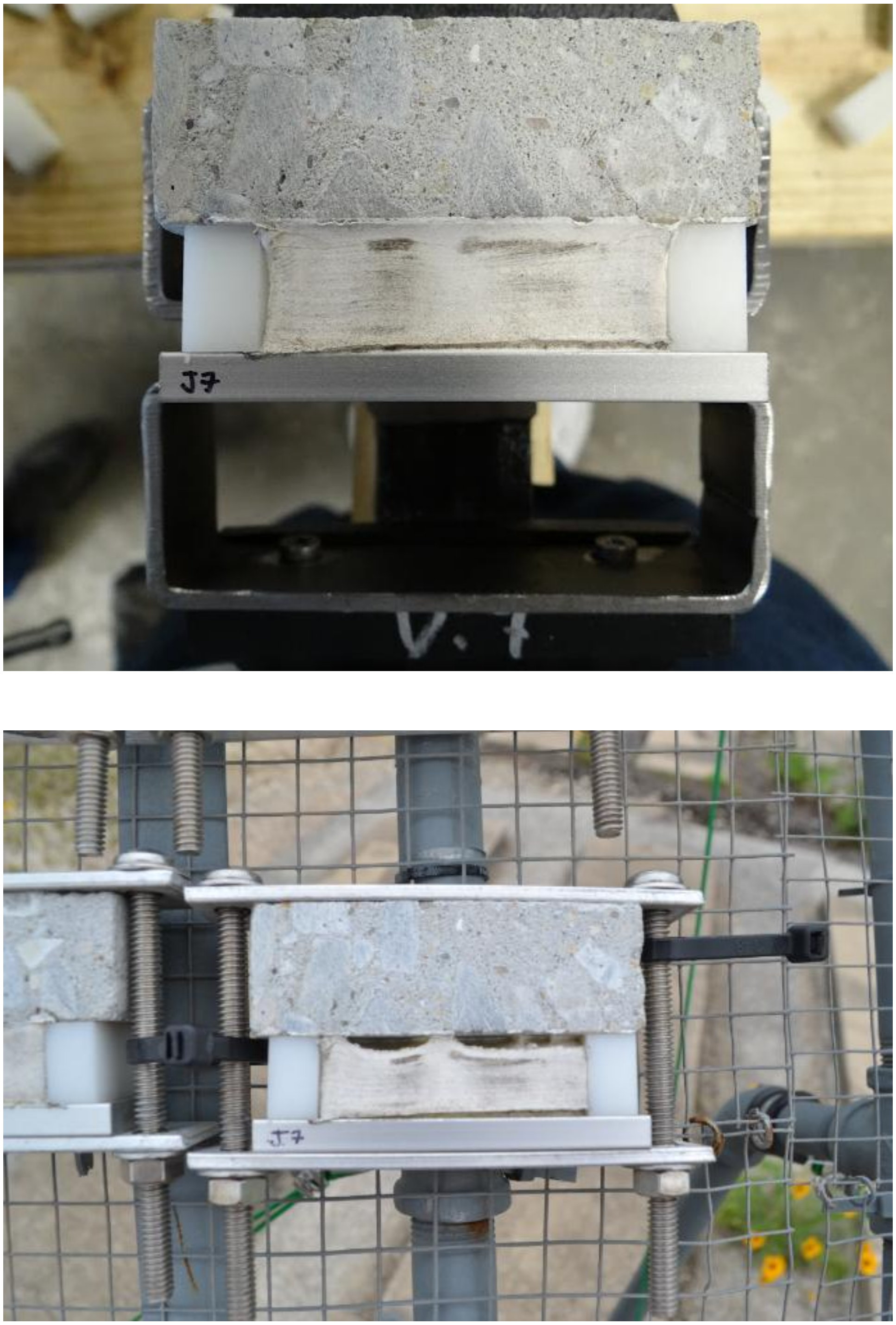

Figure 39: Sealant Specimen DRP1014-J7 (Urethane, SWRI Validated, Unprimed) Immediately After (top) and 4 Months in Extension (bottom)

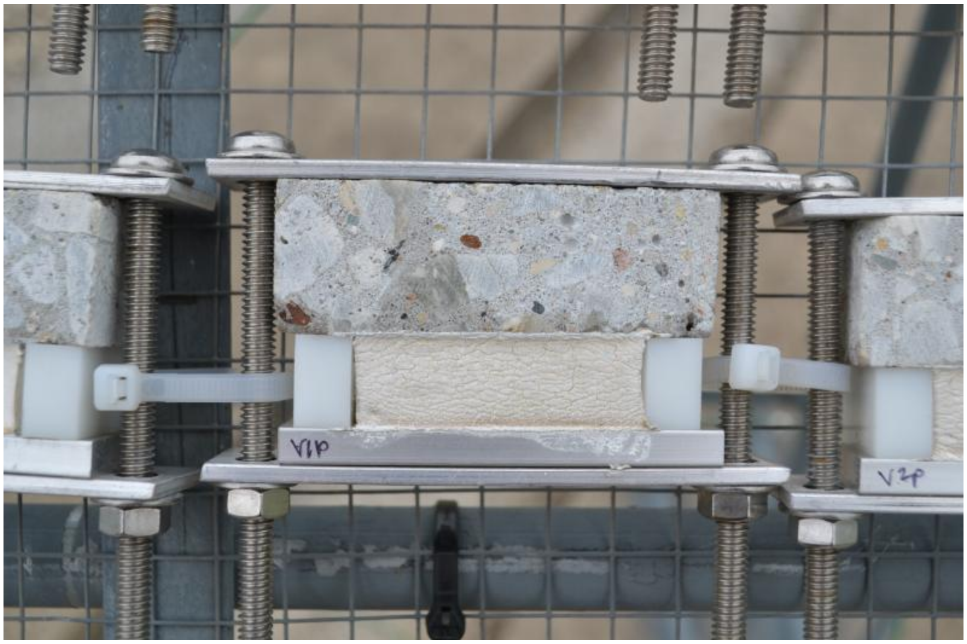

Figure 40: Specimen DRP1014-V1P Crazing After 4 Months in Extension

Figure 41: Specimen DRP1014-EE2P Partial Cohesive Failure After 4 Months in Extension

Figure 42. Specimen DRP1014-R7 Chain Scission After 4 Months in Extension

3.4 DISCUSSION

Sealant durability due to both movement and weathering is an incredibly important characteristic and is necessary to help ensure that the building envelope stay free from external forces such as air and water. Testing simply for weathering is not enough, and simply testing only for movement is not enough. The two are interrelated, since a building is naturally exposed to weather and movement, so long-term testing should simulate that combination of effects.

Not only this, but durability is also dependent upon the manufacturer and the installer, along with the designer. It is the responsibility of all facets of the construction industry to ensure that these products are made, designed, and placed properly.

Initial suggestions from this testing are as follows, and there is no doubt that further suggestions on sealant durability will arise as the products continue to weather and be extended and compressed.

The results show that those products which were independently certified by the SWR Institute performed better. Manufacturers should strive to engineer products which can withstand the testing put forth by this agency. Designers should be sure to utilize these validated products in their design protocol.

Next, it is suggested that silicone sealants be used in place of hybrids or urethanes because of their inorganic chemistry and ability to perform satisfactorily when weathered. There are some cases in which other sealant chemistries are needed due to surface incompatibilities, in which case the appropriate sealant should be utilized.

Be sure to prime all substrates, even if the manufacturing literature lists priming as an option. This first round of testing already expresses the benefits of having a primed surface before the sealant is applied. Although the upfront cost is greater, it will save from additional costs in the future if the sealant has failed and needs to be completely replaced.

In order to ensure that the sealants are not overstressed throughout their lifetime, designers should work toward insuring that the joint size is large enough to make sure that the sealants are not strained more than half of their maximum potential movement. This will help in preventing failure along with distress.

Overall, this research of sealants and the observed initial performance according to ASTM C1589 has shown that it is incredibly important to test these products for combined movement and weathering over the long term. Many existing trends of best practice, such as priming, using silicone (when applicable), and using SWR Institute validated products, have been confirmed through this test method. Those studies which test one or the other, such as the existing ASTM C920 which many sealants are tested under, can greatly overestimate the durability of these products. It will be interesting to see how the remaining products will fair over time, but it is reasonable to hypothesize that these existing trends will continue to manifest over the next few years.

Chapter 4: Water Penetration of Concrete Masonry Units[3]

4.1 Introduction

Concrete Masonry Units (CMUs) are a common building material due to their low cost, ease of installation, fire resistance, and ability to combine both structural support and cladding in one element. Unfortunately, one of the biggest drawbacks for CMUs is the susceptibility to water intrusion. CMUs are constructed with the same components found in typical concrete: aggregate, water, and cement. Lightweight CMUs are made with porous, lightweight aggregate, with absorption around 12%, which makes it easier to handle manually but renders it inherently prone to water penetration (Bajare et al.). The mineralogy from which the aggregate is extracted will also play a role in the aggregate absorption and permeability; therefore prescriptive methods for CMU design cannot be applied universally. If the CMU is placed in the formwork and not properly compacted, interconnected pores may still exist, allowing for water ingress.

Water can also enter the masonry unit from shrinkage cracking, especially when the water absorption of the CMU increases. This amount of shrinkage is also a function of the curing regimen for the unit (Grimm, "Masonry" 260). The effect of creep in CMUs can cause net tensile stress in the unit if it is not properly recognized that it can occur, and this can result in cracking (Badger 35). Water can enter the CMU through capillary suction from the pressure of wind-driven rain at crack widths as little as 0.004 in. (Birkeland et al. 4-5). This in turn can lead to deterioration in terms of "corrosion, decay, efflorescence, free-thaw spalling or splitting, heat transmission, condensation, deterioration of interior finishes and building contents…" (Grimm, "Water" 179). The

[3] Chamra, Robert M. and Beth Anne Feero. "Durable Waterproofing for Concrete Masonry Walls: Redundancy Required." *The Construction Specifier* July 2014: 34-46. Print.
Some or all of text written in this chapter was previously published in the source shown above. All authors contributed equally.

mortar joints can also undergo shrinkage cracks from moisture loss when curing and cracking due to creep from sustained loading—at a rate nearly 5 times that of concrete due to lack of stiffness (Nicastro 80).

Ways to compensate for this characteristic are to install brick veneer, allowing for a cavity wall to be formed as a method for water drainage, which can be a larger cost, or waterproofing components can be added to the CMU.

4.1.1 NCMA Recommendations

The National Concrete Masonry Association (NCMA) outlines best practice considerations in terms of concrete masonry installation in order to prevent water infiltration into the building envelope. TEK 19-2B is the article which outlines useful waterproofing characteristics, such as surface water repellent, integral water repellant (IWR), and proper drainage through the wall cavity.

Clear surface water repellents, which are typically silicones, silanes, siloxanes, or acrylics, are what prevent water entrance and slow vapor from penetrating the unit. These resins are classified as either films or penetrant repellents, meaning that films simply form a layer on the unit, while penetrants go into the pores of the CMU and create a lining. Application is administered by either a roller or sprayer after the mortar has been able to fully cure. The benefit of allowing vapor to transmit through the unit is that if water gets behind the unit, it will allow for the envelope to breathe and let out the infiltrated water. Surface repellents can also provide other benefits, such as keeping the unit clean and free from dirt that can migrate into the unit and stain (TEK 19-1).

IWRs are incorporated as an admixture while the CMU is being produced and also added into the mortar mix on site to ensure that all components of the envelope have sufficient repellency. Bond strength of the mortar is not compromised with the incorporation of an integral water repellent, as bond strength is achieved by mechanical means (TEK 19-1). It is also important to understand that just because a mortar has an incredibly high strength, it does not mean that it will prevent or lower the amount of cracking. A mortar is far more durable if strength, bond, workability, and weatherability are balanced ("Section"). If the mortar was to be stiffer and higher in strength, any movement of the structure or thermal changes would cause cracking, allowing the potential for water infiltration.

Installation of the mortar and proper tooling of the joints should not be taken lightly. Concave and V-joints are the most desirable because they press the mortar to the surface of the masonry, facilitating bond and reducing the potential for water infiltration. Other joints as shown in Figure 43 depict that they are not tooled to ensure adhesion to the masonry or to drive water away from that point of entry (TEK 19-2B).

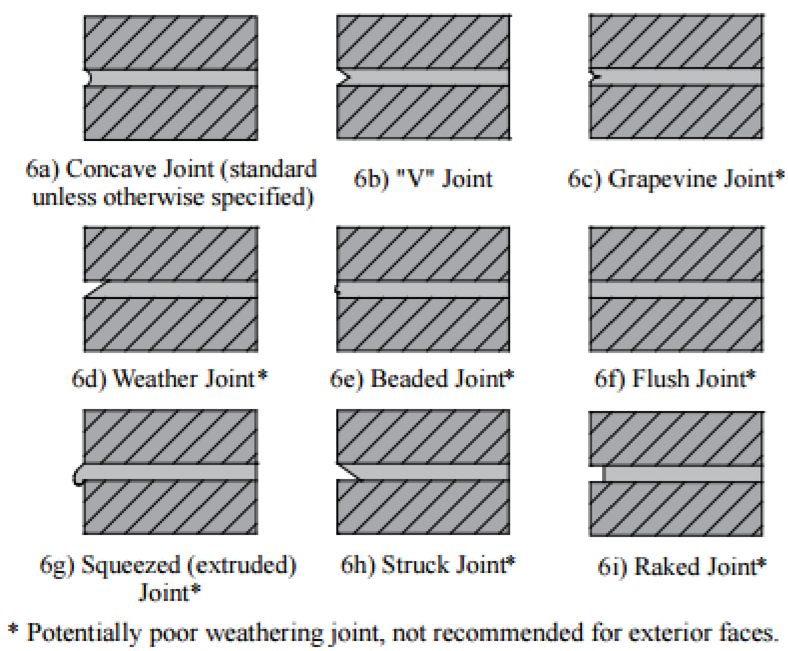

Figure 43: Mortar Joints (TEK 19-2B)

NCMA provides other recommendations in relation to proper drainage techniques and was beyond the scope of this research project, for the CMU itself was of interest.

4.1.2 CMU Permeability Testing

Testing for water permeability of CMUs can be done in a handful of different ways. Beyond those which this study addressed, other completed studies by researchers include ASTM E 514, *Standard test Method for Water Penetration and Leakage Through Masonry,* which consists of a masonry wall section subject to modeled wind driven rain for four hours. Testing by Suave et al. describes how their wall mockups with CMUs with no water repellent, integral water repellent, and a patented "water leakage controlling" CMU (with integral water repellent, durable mix design, chamfered edges, and grooves on the face to force proper drainage off the unit) performed just as expected. The "water leakage controlling" CMU let in the least amount of water, followed by the integral water repellent mockup and lastly the CMU wall with no water repellents at all (192).

NCMA also provides other tests to use in order to evaluate water permeability of CMUs, which include the water stream/water droplet test, the spray bar test, and the water uptake test. The water stream test requires a water stream dispenser to spray water for a fixed length of time on the unit and then record the absorption. The water droplet test requires the user to apply five groups of small water puddles on the CMU and describe the absorption after three time intervals. The spray bar test is completed by having a constant stream of water run down the face of the CMU while monitoring for the appearance of water on all surfaces other than that being sprayed; the CMU is weighed before and after to examine amount of water absorption. The last described test is the water uptake test which simply requires the unit to be placed in 1/8 in. of water; the unit is weighed before and during the test at varying time intervals to measure the amount of water absorption. These tests are all meant to be relatively simple and easy for the everyday user to complete (TEK 19-7).

4.2 EXPERIMENTAL PROCEDURE

In order to observe the absorbency and permeability of CMUs, two different tests were employed on CMUs: ASTM C140 and RILEM tube testing.

4.2.1 ASTM C140

Due to experience with CMU issues with regard to water absorption, this study investigated what can be the root of the problem and how to fix it. The ASTM standard procedure which governs characteristics of CMUs is ASTM C90, *Standard Specification for Loadbearing Concrete Masonry Units*. This standard lists requirements for light-, medium-, and normal-weight CMUs in terms of dimensions, absorption, density, and compressive strength. For water absorption, the standard references ASTM C140, *Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units* as the standard by which to test this characteristic.

To see if CMUs actually comply with the standard, 24 lightweight and smooth-faced units were tested for their absorption characteristics, where half of them had integral water repellent, and half of them did not. There was one unit with surface applied water repellent for informal comparison purposes, but the results for that testing are not reported here. The procedure is as follows:

1. Submerge the test specimen in 60 to 80 °F water for 24 hours with 6 in. or more of head above, and at least 0.125 inches of water below.
2. While in the water, weigh the immersed specimen to yield W_i.

3. Remove the specimen from the water, drain for one minute, dry off excess water, and weigh the saturated specimen to yield W_s.
4. Place the specimen in an environmental chamber at 230 ± 9 °F for at least 24 hours and weigh to obtain the oven-dry weight, W_d.
5. Ensure that the two "successive weighings" between two hours for W_d do not yield a weight difference of more than 0.2%.
6. Calculate the absorption and density using the following calculations outlined in the standard:

$$Absorption, \frac{lb}{ft^3} = \left[\frac{W_s - W_d}{W_s - W_i}\right] * 62.4$$

$$Density, \frac{lb}{ft^3} = \left[\frac{W_d}{W_s - W_i}\right] * 62.4$$

4.2.2 RILEM Tube Testing

The second round of testing completed on these CMUs was Réunion Internationale des Laboratoires et Experts des Matériaux, systèmes de construction et ouvrafes (RILEM) tube testing. This test originated in the 1980s as a way to observe water absorption. This test consists of attaching a plastic tube, which mimics the effect of wind driven rain, with impermeable putty to the desired vertical substrate. There are two sizes of RILEM tubes: a short and tall tube which correlate to 60 mph at 2 mL and 98 mph at 5 mL, respectively (Figure 44). There also exist horizontal RILEM tubes for testing horizontal surfaces, but was not implemented in this study. The procedure for this test of vertical RILEM tubes is as follows:

1. Observe the testing substrate and ensure that it is clean and free of debris.

2. Place the RILEM tube on the substrate with the adherence from the impermeable putty. Ensure the putty is placed so that only the 1-in. circular contact area is free to receive water absorption.
3. Fill the tube with water using a squeeze bottle, ensuring that the water stream hits the side of the tube and trickles down to the bottom. This will help reduce air bubbles which forces the test to be redone.
4. From the moment the water reaches the 0-mL mark (or any other desired height), begin the timer. Record the water level at 5-, 10-, 20, 30- and 60-minutes time intervals. The substrate can be considered to have "passed" if there is no water loss and "failed" if there is water loss.

It is common to infer that if there is no water loss after 20 minutes, there will be no loss after 60 minutes. This characteristic was seen in the testing completed in this study; so the results are merely listed as a pass or fail, meaning that the CMU passed the test of it retained all the water, and it failed the test if there was water loss. Additionally, the RILEM tube test is not necessarily a one-time test; it can be used to observe trends in water penetration of a substrate over time.

Figure 44: Tall RILEM tube (left) and Short RILEM Tube (right) (Chamra et al.)

4.4 RESULTS

The results from this study shed some very interesting light on the absorption of CMUs from both the ASTM C140 testing as well as the RILEM tube testing. The results from this testing can be found in Table 2.

When this testing began, 12 CMUs (which passed ASTM C90) were purchased from a general home improvement store for water repellent examination. Upon the initial testing, it was found that these particular units were not going to be suitable for the testing. Absorption testing and confirmation of compliance with ASTM C140 was completed for these units, but the results are not included here because the units were unable to perform satisfactorily with the RILEM tube testing. These units failed drastically with both the short and the tall RILEM tube, indicating their incredibly porous nature and bringing up an interesting phenomenon: although units may pass the ASTM C90 standard, it does not mean that the products can prevent water penetration.

Thus, to further test CMU performance, 24 units (whose results are reported here) were donated from a local stone distributor. Twelve of the units contained IWR and the others did not. Upon delivery, it was unclear as to which CMUs had the IWR and which did not, but by completing the RILEM tube testing, the results showed which units had the IWR. Although all 24 blocks failed the RILEM tube test with the tall, 5-mL tube, there were significant differences in the short tube tests. Those that passed with no water loss after 20 minutes had IWR, and those that failed with lost water almost instantly did not have IWR (Figure 45).

Figure 45: Failed Short RILEM Tube Test on CMU without IWR

Table 2: Summary of Absorption Testing With ASTM C140 and the RILEM Tube Test

Specimen #	Immersed Weight of Specimen, W_i (lb)	Saturated Weight of Specimen, W_s (kg)	Oven-dry Weight of Specimen, W_d (lb)	Absorption (lb/ft^3)	Density (lb/ft^3)	RILEM Tube Test
DRP1004-28	13.4	30.3	29.5	2.8	108.9	Pass
DRP1004-29	13.2	30.0	27.4	9.4	101.9	Pass
DRP1004-30	13.3	30.0	27.7	8.7	103.6	Pass
DRP1004-31	13.3	30.0	29.7	1.2	111.1	Pass
DRP1004-32	13.3	29.9	27.9	7.5	105.0	Fail
DRP1004-33	14.8	31.5	27.6	14.8	102.6	Fail
DRP1004-34	14.3	31.5	27.1	16.0	98.5	Fail
DRP1004-35	14.4	31.5	27.0	16.5	98.4	Fail
DRP1004-36	12.9	29.2	25.2	15.2	96.4	Fail
DRP1004-37	14.9	32.2	28.3	14.0	102.5	Fail
DRP1004-38	14.9	32.4	29.5	10.2	105.3	Pass
DRP1004-39	15.0	32.4	30.0	8.7	107.5	Pass
DRP1004-40	14.9	32.4	29.7	9.8	105.5	Pass
DRP1004-41	14.9	32.4	29.8	9.4	106.0	Pass
DRP1004-42	13.4	30.4	27.4	10.9	100.6	Pass
DRP1004-43	14.7	31.3	27.9	12.8	104.6	Fail
DRP1004-44	14.8	31.7	28.2	13.0	104.0	Fail
DRP1004-45	14.1	31.3	27.6	13.6	100.2	Fail
DRP1004-46	13.8	31.4	27.2	14.8	96.4	Fail
DRP1004-47	14.7	31.6	27.4	15.4	100.9	Fail
DRP1004-48	14.8	32.1	27.7	15.9	100.1	Fail
DRP1004-49	15.6	32.7	30.0	10.0	109.0	Pass
DRP1004-50	14.7	31.7	28.1	13.3	102.7	Pass
DRP1004-51	15.3	32.4	30.0	8.9	109.5	Pass

When testing for absorption and density as defined in ASTM C140, those results for each specimen can be found in Table 2. Comparing the average of these results for the specimens with IWR and without IWR can be seen in Table 3. It was found that the absorption of CMUs both with and without IWR were significantly below the requirement set in ASTM C90 for lightweight units—47% and 19%, respectively. However, when observing the density, the values for the CMUs with and without IWR were very similar to the requirement, with the average CMU density for the units with IWR being slightly higher than what is suggested. This slight over exceedance may be due to the somewhat vague directions in ASTM C140 describing how to obtain the saturated weight and how much to dry off when "removing visible surface water" prior to measuring the weight.

Table 3: Comparison Results from ASTM C140 and the Requirements in ASTM C90 for Lightweight CMUs

CMU Type	**Average Absorption (lb/ft^3)**	**Absorption Relative Change from ASTM C90 (%)**	**Average Density (lb/ft^3)**	**Density Relative Change from ASTM C90 (%)**
ASTM C90	18	N/A	105	N/A
With IWR	10	47	106	1
Without IWR	15	19	101	4

4.5 DISCUSSION

The results from this testing have yielded some useful insight on the CMU industry and its governing ASTM standard. The RILEM tube testing, even though the results were recorded for the short 2-mL tube, can be enlightening on CMU construction. It is clear that CMUs need to have waterproofing components to prevent serious water infiltration and damage, which was shown by the successful performance of CMUs with IWR. However, it should be noted that medium- and normal-weight CMUs would perform better in this testing, due to their higher density and therefore higher efficiency with water repellants.

The results also show that CMUs have a far lower absorption than the maximum allowable, which raises questions about the ASTM C90 standard. When testing the units for the RILEM test, neither of the units was able to pass using the tall tube, and water was able to be seen passing through the front face of the unit. This shows that the CMUs can be excellent performers in absorption, but not as much for water penetration. Thus, this visual susceptibility for significant water ingress poses serious concerns as to the usefulness of ASTM C90 standard and if the requirements are strict enough. If all units can pass all three requirements of density, absorption, and compressive strength, but are unable to pass even a small RILEM tube test, the standard may need to be addressed again in terms of its applicability.

Therefore, it is important that the architect, designer, and contractor carefully design and install the CMUs while additionally waterproofing the building by heeding the recommendations that the NCMA suggests, especially if using lightweight CMUs. However, on top of these resources, it is important to employ redundancy in CMU single-wythe wall systems. Because of the likelihood for cracks, imperfection, issues at the mortar joint and tooling, and ease of water penetrability into these units, redundancy in the waterproofing components is crucial. Depending on location of the structure, the design should be tailored specifically to that location. It is possible that even ensuring that the units have IWR as well as a surface applied water repellent, along with good construction practice, will not prevent water penetration. Other methods such as elastomeric wall coatings to bridge cracks can assist in creating closer to a waterproof single-wythe CMU wall.

Chapter 5: Durability of Masonry Anchors[4]

5.1 Introduction

Masonry anchors (commonly referred to as brick ties) are a crucial element of the building envelope when a structure has a veneer finish. Masonry anchors are installed so as to ensure the masonry is tied into the main structure to prevent collapse of the veneer element or water and debris from penetrating the structure due to initial cracks and failures of the system. However, case studies have shown that brick veneer failures are surprisingly common in the building industry (French, Nelson, Bates). There is a need for attention to be drawn to this topic so that proper good practice techniques of somewhat complicated structural components can be properly detailed for masonry anchors in order to reduce the potential for failure of these veneer systems.

These failures can be due to a handful of different mechanisms: fastener pull-out, mortar-anchor bond, poor anchor embedment, fastener or anchor corrosion, and poor mortar quality. As it is with many building envelope failures, there is generally no one person assigned to the task of masonry anchor specification and layout, so it is common for failures to occur simply because of the lack of designation of tasks. Ultimately, the manufacturer, designer, and installer are all parties that need to pay attention to masonry anchor detailing in order to create a seamless veneer envelope.

Due to an increase in modern architectural design and computer modeling in structural engineering, buildings are becoming more and more complex. The one disadvantage to such an advancing field is that some characteristics, such as masonry anchor layout, become increasingly difficult and forgotten. The building code is able to

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[4] Fagan, Brett T., Nickie N. Ramm, and Beth Anne Feero. "Durability of Brick Veneer." *The Construction Specifier* Jan. 2014: 50-58. Print.
Some or all of text written in this chapter was previously published in the source shown above. All authors contributed equally.

provide provisions for prescriptive brick tie spacing, which is indeed useful. However, complex structures can easily deviate from the prescriptive design and are faced with new and challenging architectural features that are not clearly specified in the code. Therefore, the research presented here is a discussion of proper masonry anchor detailing at challenging architectural detailing and how to remediate this based on code definitions and expert opinion; no physical testing was conducted.

5.1.1 MSJC Code Specifications

Masonry anchor installation guidelines are specified in the *Building Code Requirements and Specification for Masonry Structures and Related Commentaries*, which is more commonly known as the *Masonry Standards Joint Committee* (*MSJC*). Most of the requirements are found in Chapter 6 of the 2011 edition, and Chapter 12 of the 2013 edition. The requirements are the same for both editions.

The MSJC provides prescriptive requirements for common, vertical veneer applications in terms of spacing, installation, and anchor dimension requirements. Although veneer encompasses a wide range of types of stones and bricks, this research is geared toward unit masonry, such as bricks, which are easily placed by hand. When looking to discuss masonry anchorage for large, irregular stones or CMUs, the requirements and types of anchors will vary much more and will most likely have to be designed by a structural engineer.

General sizing provisions within the code are as follows. When using corrugated sheet-metal anchors, wire anchors, or adjustable anchors, the maximum wall area spacing is 2.67 ft^2, with a maximum possible horizontal spacing of 32 in. and a maximum vertical spacing of 25 in. For all other anchors besides those listed above, the maximum wall area spacing in 3.5 ft^2 per anchor. It is important to keep in mind that spacing anchors at 32 in.

horizontally and 25 in. vertically, will result in 5.56 ft^2, which far exceeds both area requirements. For residential applications, wood studs are typically spaced at 16 in. on center (o. c.); therefore, the anchors would be spaced every 16 in. horizontally and 24 in. vertically. The spacing would be reversed for advanced framing buildings whose studs are at 24 in. o. c. For multi-family construction with typical 12 in. o. c. stud spacing, the vertical spacing would be at 32 in.

However, this seemingly seamless spacing matrix becomes very challenging when common but irregularly spaced design elements are introduced in the design. These irregularities deserve specific guidance so that veneer failures can be minimized.

5.2 Design Challenges and Suggestions for Remediation

The code provides excellent guidance for the general, maximum spacing requirements that are required of anchors; however, this leaves the precise spacing decisions to be made by the installer.

5.2.1 Floor Lines and Expansion Joints

Many structures are designed such that they have expansion joints that are aligned with a stud because of being along a window jamb, or they have wood trusses at floor lines that disturb the uniform spacing of masonry anchors. This provides difficulty in ensuring that the 2.67 ft^2 spacing area not be exceeded. In instances such as these, the installer and designer need to define specific guidelines for proper support for the veneer. An example of a potential remediation can be found in Figures 46 and 47 below for a building with studs at 16 in. o. c. facing an expansion joint and a floor truss. The horizontal spacing at the joint is enlarged to 32 in. o. c., while the vertical spacing is reduced to 12 in. oc in order to have a wall area of 2.67 ft^2. The installer has to be sure not to compromise the floor truss by placing the anchors on the webs of the joist, unless there is no other option in terms of proper spacing. Not placing fasteners in the joist web keeps symmetry and regularity to the anchor spacing, and it also ensures that the sheathing is not blindly nailed many times as the installer is looking for the web. Inputting additional nails in the wall assembly runs the risk that they will be removed, which is makes that hole a prime suspect for water intrusion. If this is the case, it is best to leave the abandoned fasteners in place.

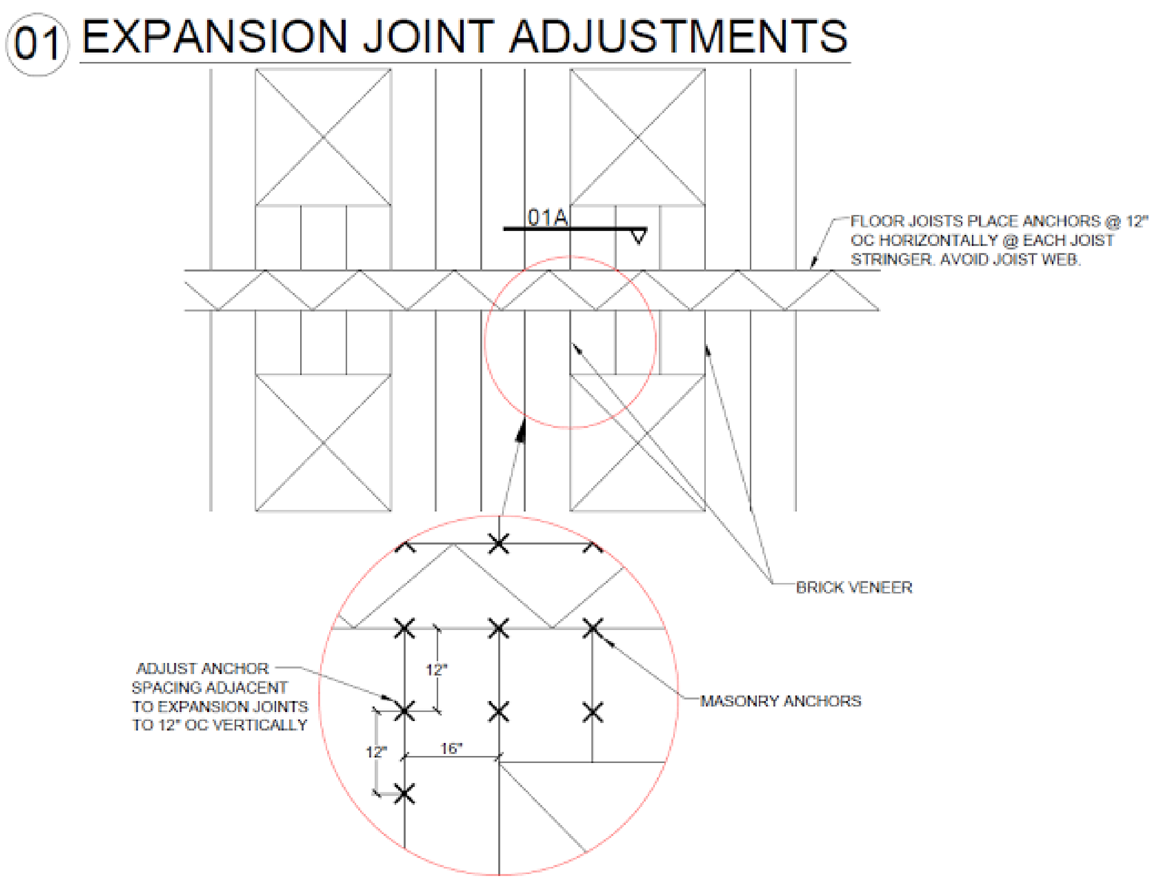

Figure 46: Elevation View of Suggested Masonry Anchor Placement with Floor Trusses and Expansion Joints (Fagan et al.)

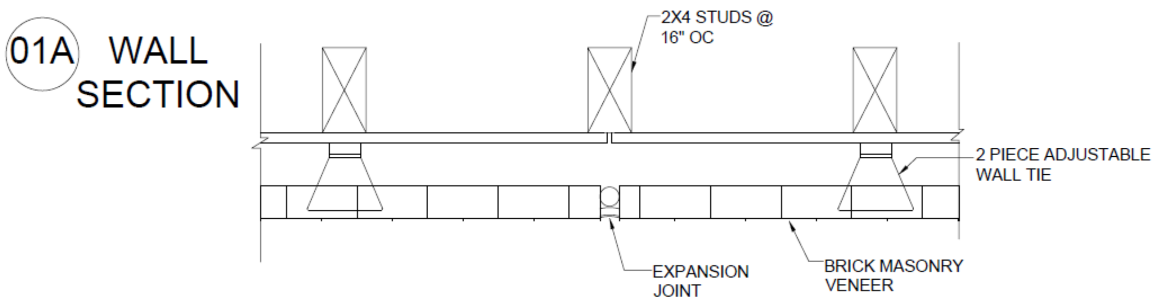

Figure 47. Section View of Masonry Anchor Detailing with Expansion Joint (Fagan et al.)

5.2.2 Framing Spacing Changes

Some multiple story structures alter the spacing of the framing throughout the building, meaning that some buildings will have the stud spacing on the bottom few floors at only 12 in. o. c., but 16 in. o. c. at the top few floors for reduced loading. This provides a challenging detailing regimen. As a useful suggestion, the installer should place masonry anchors at 24 in. o. c. in the horizontal direction and 16 in. in the vertical direction on the first few floors, but then transition to 16 in. o. c. in the horizontal direction and 24 in. in the vertical direction.

5.2.3 Large Openings

According to the MSJC, additional anchors are required on openings (windows, doors, and balconies) whose size is larger than 16 in. They should not be spaced more than 3 ft. o. c. around the opening, and they should be within 12 in. of the opening. For example, for a 3-ft. by 5-ft. window, the extra anchors would be located all around the opening. Two anchors would be needed on either side of the window, and one at the top and bottom of the window would be needed as well. These would all be placed in addition to the existing field anchors.

5.2.4 Fasteners

The code requires certain types of fasteners to be used with certain anchors and substrates. When attaching to a wood stud, a corrosion-resistant 8d common nail, or another fastener with equivalent pullout strength, is required. For an 8d common nail, its pullout strength is 128 lb (Appendix D shows the calculation). When anchors are installed on steel stud framing, No. 10 corrosion-resistant screws or larger are required.

According to the MSJC, only one fastener is required for each anchor (even if there are two nail holes in the anchor). However, it is recommended that two fasteners be used so as not to encourage veneer pullout from the wall due to the slack in the anchor. Installers should take caution in that this requirement does not mean that two nails of lower strength that add up to the strength of one 8d common nail can be used. This requirement is based on nail behavior at pullout. Although both fasteners will take an equal amount of the load, the entire assembly will fail when the first nail fails.

5.2.5 Sheathing and Substrate

The MSJC does not provide much input on what fasteners can be used on what thickness of sheathing. The standard interpretation is for ½-in. sheathing for the 8d common nail at wood studs. But if two layers of sheathing are desired, the fastener will have to be larger due decreased depth of stud penetration and the need to maintain the same pullout strength with single sheet sheathing. The Federal Emergency Management Agency (FEMA) recommends that the nail should penetrate at least 2 in. into the stud as well as being a ring shank nail instead of a smooth shank nail ("Attachment").

Often times on multifamily buildings the structure will be faced with four different backings: wood studs at the residences, CMUs at infill walls, steel framing for retail, and a concrete perimeter beam at the podium slab. With so many different substrates and changes, it makes detailing very difficult. Thorough written instructions for proper detailing need to be included so that the veneer is sufficiently supported. However, often times job sites are only equipped with the means to install one type of anchor, but these different substrates cannot work with the same anchoring systems, especially due to cavity widths that change with substrate. Therefore, anchors on certain incompatible substrates are omitted, with the best of intensions of returning again to the site to complete proper anchorage. Contractors need to ensure that the anchor installers are equipped with all proper materials for adequate installation in order to prevent the potential for failure.

5.2.6 Architectural Details

Many architectural details on the building envelope also present interesting challenges. It is common for architects to specify stack-bonded CMUs as an accent or around openings. This masonry requires horizontal joint reinforcement, which is 9 gage wire at 18 in. o. c. due to a pattern other than running bond. Rowlock and soldier courses also require horizontal reinforcement above and below these details.

Bump-outs and recesses in the field of the building are common accents incorporated in an architect's design. These aspects of the building are quite challenging, mostly in regard to cavity space. With an architectural bump-out, the cavities are often greater than 3 in. (which is still acceptable by code), but this poses difficulties an terms of choosing a proper masonry anchor that will maintain adequate mortar embedment. Usually, higher strength anchors are used in this situation to span the large cavity. It is important that the design strictly outline specific instructions for these types of details in order to preserve the integrity of the masonry wall.

5.3 Discussion

The different scenarios described above illustrate that there are a fair number of intricacies on the building envelope, in terms of veneer construction, that are not well specified in codebooks. Designers can help increase safety and durability of a veneer wall by incorporating some important techniques.

The designer should specify each type of anchor that is needed for the job, depending on the substrate backing and framing. To make the general field anchor installation more straightforward for the installer, the designer can specify the placement based on brick courses that will be installed, versus based on stud spacing. Designers should pay particular attention to cavity spacing and define higher strength masonry anchors as needed. Additionally, proper anchor installation around openings is important, and the implementation of additional anchors in these instances is crucial due to lack of support from surrounding masonry at that location. Although seismic detailing was beyond the scope of this research, it is important to consider such effects in seismically active regions and reinforce as needed.

Chapter 6: Conclusions

Durability of the building envelope has an incredibly wide scope of topics. The research included a limited number of necessary test methods to observe long-term durability and waterproofing of building envelope materials. Some of the most important results and discoveries from this study so far show the need for proper manufacturing, design, and installation. It is imperative that the manufacturers develop a high performing product that can be durable for years. Equally so, the product literature needs to be thorough, accurate, and clear for the average reader. The designer must be highly educated on the products in the market in order to assign a certain product that is used in the correct manner. Additionally, the installer needs to be knowledgeable about the product information so that proper installation is achievable.

With the WRB testing, the results expressed the need for long-term durability of these products due to market saturation. The testing will help installers know the best products to use. Complete results on product durability based on this research will not be achievable for a few years, but the current mock-up testing already shows promise as a potential standardized test method for WRB durability. This testing also shed light on nail sealability characteristics of WRBs. The results from the old standard show the need for WRBs to have their own standard for nail sealability which tests the products vertically, versus horizontally, and uses screws for the fasteners. These are characteristics that are more consistent with real-world WRB application. As such, more manufacturers would be likely to test according to that standard. The old standard also illustrated how product literature may not always be reliable since the results from this study did not always match up with what the manufacturers said.

The sealant testing, also in an early stage, has already provided significant useful information. The recommendation to use silicones, primers, and SWR Institute products was clearly shown in this testing, and these results will probably become more apparent as the testing continues. The results are enlightening in terms of showing the need for a test method that accounts for both movement and weathering of sealants, since in-service sealants are subject to both of those characteristics.

The testing of CMUs again showed possible inadequacies in current governing ASTM standards that may be too lenient. But it more importantly showed the need for redundant waterproofing of the CMU in the form of IWR, surface applied water repellent, and even an elastomeric coating over top if needed.

Lastly, the research on brick tie placement illustrated the holes that exist in the current building code for masonry. Although the prescriptive based approach is able to address the main characteristics of a structure, it does not work quite as well with the increase in difficult architectural design that introduces challenging building aspects.

This durability testing has sparked the need for further research on additional building envelope components. In addition to testing WRBs for crack bridging as well as the different tapes and adhesives used with these products, further research can branch out in other directions. Early stages of research are being conducted by the author on different water repellents, the absorption characteristics of different building sheathings, a full-scale stucco wall model to monitor the effect of different control joints, as well as continuous insulation constructability and detailing. Along with the continual testing of WRB and sealant durability, the testing for durability and waterproofing has a bright future ahead of it in hopes of bettering the engineering and architectural communities by showing how products fail and what needs to be done to mitigate that failure.

This research has also been able to show how many failures exist in various building envelope components and how there is a great need for buildings to be constructed better in order to avoid water infiltration failures and the ramifications which stem from that failure. Addressing this issue takes diligence from all parties. Many materials today have a very short service life before replacement has to occur. Instead of creating products cheaply with no intention of it lasting a long time, products need to have a higher standard of performance. Additionally, owners and contractors should be striving toward investing funds at construction with a durable product that gets installed correctly and can last for many years, rather than a cheaper product that lasts a few years and needs constant maintenance and replacement. Although it is common not to think far into the future, it is necessary in order to both lower costs and preserve the durability of the structure. It is a hope that the research being performed here will not only shed light on the susceptibility for failure, but will encourage others to formulate, design, and construct more durable buildings.

Appendix A – WRB Specimen Observations

Table A1: Specimen DRP1009-01 Observations

DRP1009-01	Install	3 months	6 months	9 months	1 year	1 year 3 months
Edges	- Material applied evenly against edges - Slight abrasion at bottom left	-	-	-	-	- Abrasion and cracking more prominent
Window Flange	- Flashing applied evenly at window - Brought tightly against window frame - Can see small gap at top right at coping	- Indentation of window flange and fasteners in the flashing - Slight hole at bottom left of flange; does not seem to penetrate	-	-	-	-
Electrical Penetration	- Thick coating all around, applied well and thoroughly - No apparent gaps	-	- Electrical box slightly visible through top right of penetration	-	-	-
3" Pipe	- Thick coating all around, applied well and thoroughly - No apparent gaps	-	-	-	-	-
1" Pipe	- Thick coating all around, applied well and thoroughly - No apparent gaps	-	-	-	-	-
Brick Tie	- Secured tightly against WRB - No additional coating placed on top; not imbedded in additional coating	- Imbedded in additional coating (at 1 month)	-	-	-	-

DRP1009-01	Install	3 months	6 months	9 months	1 year	1 year 3 months
Sheathing Joint	- Reinforcement and coating applied thoroughly	-	-	- Joint becoming more prominent and can see mesh reinforcement	-	-
Back Side	- No condensation	- No condensation	No condensation	- No condensation	- No condensation	- Slight condensation at one reading - Rigid plastic is cracked
General Comments	- Air bubbles visible throughout; some are popped and some are not - Slight mass accumulation of WRB at top left underneath coping - Two vertical slits (1/2" in length) visible at center of specimen just left of the center joint	- Slight dirtiness of membrane - Dark, black spot at bottom, right side of specimen	- Increased dirtiness - Outline of wood grain visible through WRB - Small pinholes visible throughout - Mass accumulation is becoming more squished - More of initial air bubbles are popped	- Cladding applied (at 9 months) - Increased dirtiness - Outline of wood grain more visible through WRB - Two vertical slits becoming more prominent	-	-

Table A2: Specimen DRP1009-02 Observations

DRP1009-02	Install	3 months	6 months	9 months	1 year	1 year 3 months
Edges	- Material wrapped tightly and smoothly around corners	-	-	-	-	-
Window Flange	- Slight waviness at edge - Top layer may be delaminating from bottom layer in two, small locations - Pressed firmly against window frame	- Termination sealant applied - Significant increase in waviness - Gaps and delamination between layers are beginning to form at middle and bottom	- Gapping and fishmouthing of flashing without termination sealant	-	-	- Gapping at flashing becoming slightly larger
Electrical Penetration	- Membrane secured tightly and smoothly against penetration - No apparent gaps	- Delamination beginning to form at bottom left	- Slight increase in delamination	-	-	-
3" Pipe	- Membrane secured tightly and smoothly against penetration - No apparent gaps	- Delamination is becoming noticeable at bottom, left side - Delamination at top, left side - Slight delamination slowly progressing to nearly all around penetration	-	-	-	-
1" Pipe	- Membrane secured tightly and smoothly against penetration - No apparent gaps	- Slight delamination at left side	-	-	-	-

DRP1009-02	Install	3 months	6 months	9 months	1 year	1 year 3 months
Brick Tie	- Secured tightly against membrane - No additional detailing placed on top or behind	- Additional detailing placed behind (at 1 month)	- Slight delamination at top of detailing	-	-	- Slight delamination at top left side
Sheathing Joint	- Tape applied well over joint - Some locations of gaps at edges of tape	- Fishmouthing and slight gaps in tape at the two fasteners	- Fishmouthing propagating further	-	-	-
Back Side	- No condensation	- No condensation	- No condensation	- No condensation	- No condensation	- Slight condensation at one reading
General Comments	-	- Bottom is bulging at window flange - Membrane is more wavy/loose - Logos are becoming sun bleached - Roughness at bottom, right of the brick tie detailing	- Cladding applied (at 4 months) - Slight increase in waviness of wrap	- Bulge is becoming slightly larger and more wavy (making it not as rounded as before) - Fibers on wrap are beginning to come up off sheet significantly	-	- Unique red mark at bottom of flashing on the bulging area

Table A3: Specimen DRP1009-03 Observations

DRP1009-03	Install	3 months	6 months	9 months	1 year	1 year 3 months
Edges	- Material applied evenly and smoothly against edges - Small chip at bottom, left corner exposing pink layer underneath - Cracking at the bottom, right side	- Chips and cracks along right side of bottom	- Chips and cracks at all edges - Can see wood through chips at corner	-	-	- Left corner is looking more abraded, especially right on the front face
Window Flange	- Flashing applied evenly at window - Brought tightly against window frame - Slight black color at flashing along the bottom right next to window flange	- Sealant applied at top, right next to flange where apparent gap existed - Slight whitening of preexisting black mark	- Complete whitening of black mark	-	-	-
Electrical Penetration	- Thick coating all around, applied well and thoroughly - No apparent gaps	-	-	-	-	-
3" Pipe	- Thick coating all around, applied well and thoroughly - No apparent gaps	-	-	-	-	-
1" Pipe	- Thick coating all around, applied well and thoroughly - No apparent gaps - Rust beginning to form on pipe	- Gradual complete rusting of pipe - Surrounding edge of WRB turning a rust color	-	-	-	-

DRP1009-03	Install	3 months	6 months	9 months	1 year	1 year 3 months
Brick Tie	- Covered in a thick layer of material - Horizontal crack at the 90° bend in tie	-	-	- Can see pink layer showing through at the top of the bottom fastener	-	-
Sheathing Joint	- Thick coating applied over joint - Can see slight indentation of joint detailing	- Joint is becoming very noticeable underneath WRB	- Joint seems very prominent	-	-	- Joint is darkened more than the rest of the WRB
Back Side	- Heavy condensation	- Slight condensation at one reading - Sealant applied over cracks in rigid plastic	- No condensation - New rigid plastic installed (at 6 months)	- No condensation	- No condensation	- Slight condensation at one reading
General Comments	- Dirt/debris stuck to WRB	- Thin, vertical indented lines present throughout WRB, most significantly on left side - Beginnings of cracking along right wide of WRB as well as between electrical and large pipe penetration	- Discoloration and light spots prominent on WRB - Vertical indented lines are more prominent throughout, especially at bottom left near the brick tie - Two small indented/chipped spots on bottom side of specimen at center - Two additional scratches, revealing a pink layer underneath, on the underside of the specimen on the left side	- Discoloration and dirtiness increase - Vertical cracking all around WRB continues propagating - Further propagation of cracking and abrasion at electrical and large pipe penetrations; wood sheathing underneath clearly showing through	- Cladding applied (at 1 year) - Continual increase in discoloration, which looks like it follows the grain of the wood - Vertical cracks throughout continue propagating and can be found about every 1/8"-1/4" - Cracks to the right and bottom of the brick tie are more abraded and show the wood sheathing underneath	- Continual increase in discoloration and cracks, especially around the brick tie - Left side of front surface is more abraded and more wood can be seen underneath - New vertical crack has begun to propagate on bottom, left side

Table A4: Specimen DRP1009-04 Observations

DRP1009-04	Install	3 months	6 months	9 months	1 year	1 year 3 months
Edges	- Material applied evenly and smoothly against edges for the most part - Bottom back left corner is chipped and exposed - Other areas of chipped material along edges apparent	- Cracking along left edge near bottom as well as the bottom edge on the left side - Cracking beginning to propagate toward the center along the bottom	- Cracking along bottom has propagated all the way to the center of the specimen. - Cracking beginning to form intermittently along right bottom edge	- Cracking along right bottom edge is propagating further so that almost the entire length of the specimen is fully cracked	-	-
Window Flange	- Flashing applied evenly at window - Brought tightly against window frame	-	-	-	-	- Slight lightening and discoloration of flashing - Slight cracking beginning to form all over flashing
Electrical Penetration	- Thick coating all around; applied well and thoroughly - No apparent gaps	-	- Pinholes visible around right side of penetration	-	-	-
3" Pipe	- Thick coating all around; applied well and thoroughly - No apparent gaps	- Slight indication of hairline cracks at top of penetration	- Hairline cracks visible at top of penetration	-	-	-
1" Pipe	- Thick coating all around; applied well and thoroughly - No apparent gaps	-	- Small gaps around penetration at bottom and top right	-	-	-

DRP1009-04	Install	3 months	6 months	9 months	1 year	1 year 3 months
Brick Tie	- Secured tightly against WRB - No additional coating placed on top; not imbedded in additional coating	- Additional coating placed overtop (at 1 month)	-	-	-	- Slight discoloration of coating placed on top
Sheathing Joint	- Thick coating applied over joint	-	- Joint is a little more noticeable	-	-	- Slight map cracking at joint
Back Side	- Very slight condensation	- Significant condensation at one reading	- Slight condensation and heavy condensation at two separate readings	- Heavy condensation at one reading	- Heavy condensation and slight condensation at two separate readings	- Significant condensation
General Comments	- On bottom of specimen, chipping of only the top layer visible underneath. It is a section of about 5"x2" in size on the left-hand side, as well as a 1/2"x2" portion on right side - Other abrasion and cracking at WRB-flashing interface is noticeable	- On the large, exposed section, some of the WRB is peeling further off and hanging - Slight dirtiness	- Cladding applied (at 6 months) - Indentation of nail heads all along bottom of specimen - Cracks beginning to form perpendicularly to the WRB-flashing interface on bottom of specimen - Piece of WRB hanging off specimen at right side exposed section - Other intermittent cracks (parallel to the face) have begun initiation on bottom of specimen	- Small pinholes visible throughout WRB - Large portion of WRB is peeling off at WRB-flashing interface - New crack at 1/2" in length has formed at the center of the bottom half of the left side.	- Perpendicular cracks on the bottom of the specimen are becoming more prominent	- New crack on left side of specimen beginning to propagate further

Table A5: Specimen DRP1009-05 Observations

DRP1009-05	Install	3 months	6 months	9 months	1 year	1 year 3 months
Edges	- Top left edge is squished from the coping - Gap at bottom left edge - Some of WRB was peeled/scratched off on left hand side during transportation and is about 4"x0.125" wide, except for half of it, which is 0.5" wide - Slight bit of WRB peeled off at bottom edge in the center of sheathing joint	-	-	-	-	- Left edge is almost entirely black, as it appears that the WRB has rubbed off slightly just at the edge
Window Flange	- Flashing pressed evenly at window and brought tightly against window frame	- Termination sealant applied - More waviness and very slight fishmouthing at top, left side of flashing	- Fishmouthing has propagated further - Entire left edge peeling up, especially at bottom	- Increase in fishmouthing and peeling up of flashing	- Increase in fishmouthing and peeling up of flashing	- Continued fishmouthing and cracking of flashing - Termination sealant is cracking most prominently at the top - Flashing is becoming slightly lighter and more discolored
Electrical Penetration	- Detailing secured tightly and smoothly against penetration and covered with WRB - No apparent gaps	-	- Flashing is just a bit more bumpy and indented	-	-	-
3" Pipe	- Detailing secured tightly and smoothly against penetration and covered with WRB - No apparent gaps	-	- Flashing is just a bit more bumpy and indented - Slight peeling up of flashing around top of penetration	- High accumulation of pinholes at top of penetration and surrounding flashing	-	-

DRP1009-05	Install	3 months	6 months	9 months	1 year	1 year 3 months
1" Pipe	- Detailing secured tightly and smoothly against penetration and covered with WRB - No apparent gaps	- Edge of flashing is rough along penetration	- Flashing is just a bit more bumpy and indented - Slight peeling up of flashing around top of penetration	-	-	-
Brick Tie	- Secured tightly against membrane - No additional coating placed on top; not imbedded in additional coating	- Additional coating placed overtop (at 1 month)	-	-	-	-
Sheathing Joint	- Detailing secured tightly and smoothly over joint and covered with WRB - Slight bulging in a vertical line over the nail heads - No apparent gaps	-	-	-	-	- Slight increase in bubbliness over top nails
Back Side	- Slight condensation	- Slight condensation at two readings - New rigid plastic installed (at 2 months)	- No condensation	- No condensation	- Slight condensation at one reading	- Slight condensation witnessed at one time
General Comments	- Slight bit of WRB is chipped off at bottom of center joint detailing - Sporadic chipping off of WRB all along bottom underneath - Protrusions of fasteners at center joint are visible - Slight number of pinholes present in WRB	- Slight dirtiness of WRB - Additional chipping WRB seen on underneath side	- Significant number of pinholes - Increased dirtiness - Outline of wood grain visible through WRB	- Increase in small pinholes on WRB surface - Significant indentation at nail heads	- Cladding applied (at 1 year) - Significant indentation at nail heads	- Small pin head sized holes visible in indented grain of the sheathing on left side

Table A6: Specimen DRP1009-06 Observations

DRP1009-06	Install	3 months	6 months	9 months	1 year	1 year 3 months
Edges	- Product tightly applied - Slight creases visible	-	-	-	-	-
Window Flange	- Flashing pressed firmly against membrane - Applied securely against window frame - At top, right of flashing near coping, a portion of the WRB is bunched up	- Termination sealant applied	- Slight delamination at left edge	- Yellowing of termination sealant at WRB-flange transition	-	- Slight fishmouthing at flashing at center overlap
Electrical Penetration	- Membrane secured tightly and smoothly against penetration - No apparent gaps	-	-	-	-	-
3" Pipe	- Membrane secured tightly and smoothly against penetration - No apparent gaps	-	- Flashing delaminating at top - Flashing around penetration is bubbled	- More noticeable bubbling all around penetration	-	-
1" Pipe	- Membrane secured tightly and smoothly against penetration - No apparent gaps	-	-	- Slight delamination at top, left edge	-	-
Brick Tie	- Secured tightly against membrane - No additional detailing placed on top or behind	-	-	-	-	-

DRP1009-06	Install	3 months	6 months	9 months	1 year	1 year 3 months
Sheathing Joint	- Membrane applied tightly and smoothly over joint	-	- Raised bumps from nails at joint are more visible	-	-	-
Back Side	- No condensation	- No condensation - New rigid plastic installed (at 2 months)	- No condensation	- No condensation	- No condensation	- Slight condensation at one reading
General Comments	- Slight indentation of WRB at the center, right below the top layer of WRB	- Sealant applied at top of window flange where apparent gap is visible	-	-	-	-

Table A7: Specimen DRP1009-07 Observations

DRP1009-07	Install	3 months	6 months	9 months	1 year	1 year 3 months
Edges	- Material applied evenly and smoothly against edges - Small chipped area at bottom left side edge; can see light green underneath	-	-	-	-	-
Window Flange	- Flashing applied evenly at window - There is a slight bit of coverage at the top, right that is bunched up at the corner	- Protrusion of window flange underneath membrane is more prominent - Bunched up corner at top covered up with a sealant - Lightness in coating visible at corner between specimen and window flange	-	- Small cracking of flashing at bottom left edge - Looks like vertical cracking may be forming along left edge of flashing, about 1/8" inside its outer edge	-	- Vertical cracking at flashing now fully formed - Cracking is mostly at top part of bottom half - White discoloration at flashing-flange interface
Electrical Penetration	- Thick coating all around; applied well and thoroughly - No apparent gaps	-	-	-	-	-

DRP1009-07	Install	3 months	6 months	9 months	1 year	1 year 3 months
3" Pipe	- Thick coating all around; applied well and thoroughly - No apparent gaps	- Incredibly slight cracking appearing to form around top and right side of penetration	- Top crack seems to have widened slightly - Perpendicular cracks (mostly on top and about 1/8" long) have begun to form off of the existing crack, creating crazing - Edge of the crack is curling upward - Side crack doesn't appear to have propagated further	-	-	-
1" Pipe	- Thick coating all around; applied well and thoroughly - No apparent gaps	- Slight gap around penetration at bottom and top	- Horizontal cracks visible on penetration at the top	-	-	-
Brick Tie	- Secured tightly against WRB - No additional coating placed on top; not imbedded in additional coating	-	-	- Bubbliness has gotten more noticeable around brick tie	-	-
Sheathing Joint	- Thick coating applied over joint	-	-	-	-	-
Back Side	- Heavy condensation	- Heavy condensation at two readings	- No condensation	- Moderate condensation at one reading	- Significant condensation at one reading	- Slight and severe condensation at two readings

DRP1009-07	Install	3 months	6 months	9 months	1 year	1 year 3 months
General Comments	- Pea size bubbles present throughout WRB	-	- Cladding applied (at 6 months) - Bubbles seem to be more noticeable - Increase in dirtiness	-Bubbliness has increased - Spider web like cracking has begun to form on surface - Increase in dirtiness	-	- Cracking of WRB looks more like scarred lines now - Bubbles on surface now form lines

Table A8: Specimen DRP1009-08 Observations

DRP1009-08	Install	3 months	6 months	9 months	1 year	1 year 3 months
Edges	- Material applied evenly against edges - A conglomerate of small pinholes: 2" x 1/2" on the bottom, left edge of the specimen	-	- Small, pin-sized holes present at left side corner; there are about 6 of them	- During readings noticed that holes change shape reading after reading--shows movement of specimen	-	- Can see wood sheathing through pin-sized holes on left side
Window Flange	- Flashing applied evenly at window - Brought tightly against window frame	-	- Can begin to see indentation of window flange in flashing	-	-	- Can see outline of meshing used for flashing
Electrical Penetration	- Thick coating all around; applied well and thoroughly - No apparent gaps	-	-	-	-	-
3" Pipe	- Thick coating all around; applied well and thoroughly - No apparent gaps	-	-	-	-	-
1" Pipe	- Thick coating all around; applied well and thoroughly - No apparent gaps	- Small gap between membrane and bottom of pipe has formed	-	-	-	-
Brick Tie	- Secured tightly against WRB - No additional coating placed on top; not imbedded in additional coating	-	-	-	-	-
Sheathing Joint	- Thick coating applied over joint	-	-	-	-	-

DRP1009-08	Install	3 months	6 months	9 months	1 year	1 year 3 months
Back Side	- Significant condensation	- Severe condensation at two readings - New rigid plastic installed (at 2 months)	- No condensation	- Slight condensation at one reading	- No condensation	- Severe condensation each reading
General Comments	- Pinholes present throughout WRB, while bigger ones are around the penetrations	- Indent from nails at outer left and bottom edges around perimeter is visible	- Cladding applied (at 6 months) - Increased dirtiness	-	-	- Increased dirtiness at raised portion of WRB

Table A9: Specimen DRP1009-09 Observations

DRP1009-09	Install	3 months	6 months	9 months	1 year	1 year 3 months
Edges	- Material applied evenly against edges	-	- Cracking and peeling up of material at bottom center edge of WRB	- Cracking and peeling has gotten worse all along bottom edge	- Continued peeling and cracking along bottom edge	- Blistering at edge and can see the wood sheathing underneath
Window Flange	- Flashing applied evenly at window - Brought tightly against window frame - Slight lack of application over window flange at bottom	- Can begin to see discoloration of flashing that is applied on sheathing vs. applied on window flange	- Flashing is not cracking like main surface - Pinholes have formed - Window flange appears not to be adhered anymore--it is beginning to bulge out	-	- Window flange has peeled up and is causing cracking and tearing of flashing	- Can see the black color of the WRB through the grey colored flashing
Electrical Penetration	- Thick coating all around; applied well and thoroughly - No apparent gaps	-	-	-	-	-
3" Pipe	- Thick coating all around; applied well and thoroughly - No apparent gaps	-	-	-	-	-
1" Pipe	- Thick coating all around; applied well and thoroughly - No apparent gaps	-	-	-	-	-
Brick Tie	- Secured tightly against WRB - No additional coating placed on top; not embedded in additional coating	- Increase in dirtiness	-	-	-	-

DRP1009-09	Install	3 months	6 months	9 months	1 year	1 year 3 months
Sheathing Joint	- Thick coating applied over joint - Material protecting center point protrudes out of surface	- Additional coating placed over top (at 1 month)	- Vertical crack beginning to form at joint	-	-	-
Back Side	- Significant condensation	- Slight condensation at two instances	- Some condensation at one reading	- Some condensation at one reading	-	- Some condensation at two readings; severe condensation at one reading
General Comments	-	- Cladding applied (at 1 month) - Increase in dirtiness	-	- The entire surface has map cracking and is beginning to fill with dirt.	- On bottom portion of WRB, blisters have formed and peeling of WRB is visible - The map cracking continues to worsen	- Continued cracking and blistering - Map cracking seems to be scarring over

Table A10: Specimen DRP1009-10 Observations

DRP1009-10	Install	3 months	6 months	9 months	1 year	1 year 3 months
Edges	- Tape applied very evenly and smoothly - Two slight locations of creases/gaps in the tape	-	- Bubbling along left edge beginning to form	-	-	-
Window Flange	- Tape applied very evenly and smoothly - A few slight locations of creases/fishmouthing in the tape near top and center, but it remains securely attached to board	- Termination sealant applied	-	- Very slight fishmouthing of tape at flange that sits on top of the bottom edge tape - Window flange is coming loose and bubbling up the flashing tape	-	-
Electrical Penetration	- Tape applied smoothly against penetration - No apparent gaps or significant creases in tape	- Crease in tape is becoming larger, especially at top left - No delamination at edges	-	-	-	-
3" Pipe	- Tape applied smoothly against penetration - No apparent gaps or significant creases in tape	-	- Slight fishmouthing at top of penetration	-	-	-
1" Pipe	- Tape applied smoothly against penetration - No apparent gaps or significant creases in tape.	-	-	-	-	-
Brick Tie	- Secured tightly against WRB - No tape applied over or behind	-	-	-	-	-

DRP1009-10	Install	3 months	6 months	9 months	1 year	1 year 3 months
Sheathing Joint	- Tape applied smoothly over joint - Slight fishmouthing/crease in tape exists on top half of specimen - Backlapping of tape at bottom edge	-	-	-	-	-
Back Side	- Significant condensation	- Slight condensation at two readings	- No condensation	- No condensation	- Slight condensation at one reading	- Slight condensation at one reading
General Comments	-	-	- Cladding applied (at 6 months) - Tape is becoming more dirty - Grain of the wood is becoming more prominent - Cracking of tape on underside of specimen on the right side; 3-4 locations about 1" in length propagating perpendicular to face	-	-	- Beginning to see surface cracks all over exposed portion, revealing the wood backing; measure only 1/2" in length

Table A11: Specimen DRP1009-11 Observations

DRP1009-11	Install	3 months	6 months	9 months	1 year	1 year 3 months
Edges	- Material applied evenly and smoothly against edges	- Chip about 1/2" wide found at top half of edge - Another chip 1/4" wide found near bottom of edge (may be after plastic reinstallation)	-	-	-	-
Window Flange	- Flashing applied evenly at window - Brought tightly against window flange	- Sealant applied at top right corner of flashing next to coping to close up the gap	- Visible indentation at nail heads	Applied sealant at the top right corner of the flashing next to the coping is beginning to crack	-	-
Electrical Penetration	- Thick coating all around; applied well and thoroughly - No apparent gaps	-	-	-	-	-
3" Pipe	- Thick coating all around; applied well and thoroughly - No apparent gaps	-	-	-	-	-
1" Pipe	- Thick coating all around; applied well and thoroughly - No apparent gaps	-	-	-	-	-
Brick Tie	- Secured tightly against WRB - No additional coating placed on top; not imbedded in additional coating	-	-	-	-	- Horizontal crack formed just to left of brick tie; only 1/2" long
Sheathing Joint	- Thick coating applied over joint	-	- Joint is indented and more noticeable	-	-	-

DRP1009-11	Install	3 months	6 months	9 months	1 year	1 year 3 months
Back Side	- No condensation	- No condensation - New rigid plastic installed (at 2 months)	- No condensation	- No condensation	- No condensation	- Severe condensation at one reading
General Comments	- Few dimples on WRB	- Increased dirtiness of WRB, especially at penetrations - Significantly more dimples all over WRB	- Increased dirtiness	- Increased dirtiness	-	- Increased dirtiness - Grain indentation has a lot of pinholes in it

Table A12: Specimen DRP1009-12 Observations

DRP1009-12	Install	3 months	6 months	9 months	1 year	1 year 3 months
Edges	- Felt attached securely to specimen.	- Gapping seen at corner edge	- Gapping at corner edge becoming larger and more wavy	- Small hole in bottom left-hand corner; can see wood underneath	-	-
Window Flange	- Flashing applied securely - Looks to be two separate layers, judging by the bulging, but no breaks in flashing are visible - Flange is slightly exposed at bottom edge, and there is a slight chip just to the left of the flange - Some of flashing is slightly peeled up at bottom of flange	- Discoloration (brown/black in center, gray at edges) is forming - Cracking/splitting near bottom is beginning to noticeably form in two different locations along the layered overlap - Cracking at horizontal center overlap and the two rightmost nail gaskets is beginning to form - Indentations from nails are visible - Vertical splitting on top half is beginning to form	- Increase in discoloration, where the flashing is almost entirely gray - Increase in cracking and splitting in all locations - Cracking beginning to propagate up from pre-existing peeling up of flashing at flange - Vertical splitting at center of flashing is beginning to propagate all the way up the specimen. - Vertical cracking at inside corner of flashing and window flange near the center (can see white underneath)	- Increase in cracking and splitting in all locations - Water stains along right side of exposed flashing as well as center - Cracking at inside corner of flashing and window flange is becoming more prominent	- Many micro cracks in flashing along with existing larger cracks	- Flashing is becoming lighter as a whole - Increase in cracking
Electrical Penetration	- Thick, consistent coating applied - No apparent gaps	- Discoloration (lightening to brown) and significant cracking noticeable	- Cracking seems to be disappearing, and the flashing reforming and closing the cracks. - Flashing is turning a more dark color.	-	-	-

DRP1009-12	Install	3 months	6 months	9 months	1 year	1 year 3 months
3" Pipe	- Thick, consistent coating applied - No apparent gaps	- Discoloration (lightening to brown) and significant cracking noticeable	- Cracking seems to be disappearing, and the flashing material seems to be reforming and closing the cracks. - Flashing is turning a more dark color.	-	-	-
1" Pipe	- Thick, consistent coating applied - No apparent gaps	- Discoloration (lightening to brown) and significant cracking noticeable	- Cracking seems to be disappearing, and the flashing material seems to be reforming and closing the cracks. - Flashing is turning a more dark color.	-	-	-
Brick Tie	- Secured tightly against WRB. - No additional coating placed on top; not imbedded in additional coating	- Additional coating placed over top (at 1 month) - Slight cracking and discoloration - Slight lightness discoloration at bottom - Cracking seems to be healing itself	- Slight lightness at outer edges	- Increased lightness at edges, darker at center - Cracking within middle portion of detailing is beginning to reform and become more significant (larger cracks in the center, smaller ones on the outside)	- Increased lightness and visibility of cracks	- Detailing almost completely lightened - Increase in cracks
Sheathing Joint	- Felt attached securely over joint	- Overlap becoming more gapped and wavy	- Overlap becoming more gapped and wavy	-	-	-
Back Side	- Significant condensation	- Slight condensation at two instances	- No condensation	- No condensation	- No condensation	- Slight condensation at one instance

DRP1009-12	Install	3 months	6 months	9 months	1 year	1 year 3 months
General Comments	- Slight gaps in overlap visible - Slight ripping and discoloration underneath near window flange	- Overlaps of membrane are becoming more noticeably gapped. - Slight ripping underneath a bit worse than before - Overall lightness in color	- Cladding applied (at 6 months) - Overlaps are more wavy and loose	-	-	-

Table A13: Specimen DRP1009-13 Observations

DRP1009-13	6 months	9 months	1 year	1 year 3 months	1 year 6 months
Edges	- Abraded area slightly above center of left side edge - Chip mark at center of bottom edge	-	-	-	- Water stain all along left side near the edge
Window Flange	- Leftmost edge of flashing is the same color as the WRB - Can see indentation of the window flange in the flashing	- Indentations from nails in window flange are visible	-	-	- Lightness discoloration of flashing
Electrical Box	- No cracking along edges of box, but cracking begins at the 90° corner of the WRB to the box - Some of WRB is squished up on the top due to metal coping	- Cracking at top left edge seems to have propagated further	-	-	
3" Pipe	- Slight chip in flashing at top left side - Cracking only apparent between flashing transition from pipe to WRB face	- Circular water mark around penetration - Cracking from WRB is beginning to propagate around penetration	- Crazing all around penetration - Cracking of detailing around penetration at the bottom is noticed	-	- Water stain around penetration - Some detailing appears to have chipped off at the top
Brick Tie	- N/A	- N/A - Brick tie installed (at 9 months)	-	-	
Sheathing Joint	- Can see bulging from joint detailing	-	- Crack down center of joint is very prominent	-	- Darkened at crack at center joint due to potential water accumulation
Back Side	- Metal backing	- Metal Backing - Clear rigid plastic installed (at 9 months)	- Heavy condensation at one instance	- Heavy condensation at one instance	- Moderate to heavy condensation at all instances

DRP1009-13	6 months	9 months	1 year	1 year 3 months	1.5 years
General Comments	- White discoloration all along the left side at the interface between the darker red and pink WRB coatings - Slight crazing of WRB visible	- Cladding applied (at 9 months) - Crazing seems to be propagating further - Water stain at bottom right and top left - Indentation from wood grain is visible	- Horizontal water line all along the bottom about 2" up the specimen - Crazing appears to be more significant	- A few prominent water stains at center of specimen and near the brick tie	- Lightness discoloration (similar to flashing) of the darker red coating on the left side

Table A14: Specimen DRP1009-14 Observations

DRP1009-14	Install	3 months	6 months	9 months	1 year
Edges	- Material applied evenly and smoothly against edges	-	-	-	-
Window Flange	- Flashing applied evenly at window - Brought tightly against window frame	-	-	-	-
Electrical Penetration	- Thick coating all around; applied well and thoroughly - No apparent gaps	-	-	-	-
3" Pipe	- Thick coating all around; applied well and thoroughly - No apparent gaps	-	-	-	-
1" Pipe	- Thick coating all around; applied well and thoroughly - No apparent gaps	-	-	-	-
Brick Tie	- N/A	- N/A - Brick tie installed (at 2 months)	- Additional coating placed over top (at 4 months)	-	-
Sheathing Joint	- Thick coating applied over joint - Can see indentation of detailing at joint	-	-	-	-
Back Side	- No condensation	- No condensation	- No condensation	- Slight condensation at two instances	- Slight condensation at three instances

DRP1009-14	Install	3 months	6 months	9 months	1 year
General Comments	- Surface is slightly bumpy and "wormy" at places - A few pea sized bubbles are present throughout specimen - Can see indentation of detailing at penetrations	- Slight dirtiness, especially at tops of penetrations - Four slightly discolored yellow spots (about 1" in diameter). One at center, one at bottom left, and two at WRB and flashing interface near the center	- Another yellow spot has become more prominent at left side at mid height - Pinholes visible	- Increase in dirtiness	- Increase in dirtiness - Another discolored yellow spot to the left of small diameter penetration

Table A15: Specimen DRP1009-15 Observations

DRP1009-15	Install	3 months	6 months	9 months	1 year
Edges	- Sheet attached securely to specimen.	-	-	-	-
Window Flange	- Sheet layer and tape applied smoothly and without noticeable fishmouthing - Can see indentation of nails at window flange, and can see indentation of flange edge	- Slight fishmouthing of tape is visible at location of sheet overlap - Horizontal bump in tape at undersheet edge becoming more noticeable	- Window flange appears to be building up as if it is no longer adhered to the substrate	-	- Increase in bubbliness and wrinkles
Electrical Penetration	- Sheet layer and tape applied smoothly and without noticeable fishmouthing	-	- Fishmouthing at bottom, horizontal strip of the outer, squarely applied tape around penetration	-	-
3" Pipe	- Sheet layer and tape applied smoothly and without noticeable fishmouthing	-	- Fishmouthing at bottom, horizontal strip of the outer, squarely applied tape around penetration	-	-
1" Pipe	- Sheet layer and tape applied smoothly and without noticeable fishmouthing	-	-	-	-
Brick Tie	- N/A	- N/A - Brick tie installed (at 2 months)	- Underlayment sheet installed beneath brick tie (at 4 months)	-	- Increase in bubbliness and wrinkles
Sheathing Joint	- Material applied tightly over joint - Indentation of joint detailing - Can see indentation of nail at center joint	-	-	-	-

DRP1009-15	Install	3 months	6 months	9 months	1 year
Back Side	- No condensation	- No condensation	- No condensation	- No condensation	- Slight condensation at two instances
General Comments	- Slight bubbling around all penetrations.	- Sheet is loosening - Tape around all penetrations seems to be more wavy	- Cladding applied (at 4 months) - Increase in bubbling up of sheet	- Increase in bubbling up of sheet	- Increase in bubbling up of sheet

Table A16: Specimen DRP1009-16 Observations

DRP1009-16	Install	3 months	6 months	9 months	1 year
Edges	- Material applied evenly and smoothly against edges	-	-	-	-
Window Flange	- Flashing applied evenly at window - Brought tightly against window frame - Large bubble at bottom of flashing - Can see indentations from nails and flange	- Slight bulging in flashing at the window flange near the top	-	-	-
Electrical Penetration	- Thick coating all around; applied well and thoroughly - No apparent gaps	-	-	-	-
3" Pipe	- Thick coating all around; applied well and thoroughly - No apparent gaps	-	-	-	-
1" Pipe	- Thick coating all around; applied well and thoroughly - No apparent gaps - Slight green discoloration at underside of pipe at detailing edge	-	-	-	-
Brick Tie	- N/A	- Brick tie installed (at 2 months)	- Sealant applied over top brick tie (at 4 months)	-	-
Sheathing Joint	- Thick, even coating applied over joint - Can see crease of the center joint as well as a crease from the detailing around the penetrations	-	-	-	-

DRP1009-16	Install	3 months	6 months	9 months	1 year
Back Side	- No condensation	- No condensation	- No condensation	- No condensation	- Slight condensation at two readings
General Comments	- Large knot in bottom left side of specimen. - A few small, pin-sized dimples in WRB	- Small pin-sized holes more dense throughout - Slight dirtiness of membrane	- Cladding applied (at 6 months)	-	-

Table A17: Specimen DRP1009-17 Observations

DRP1009-17	Install	3 months	6 months	9 months	1 year
Edges	- Material applied somewhat evenly and smoothly against edges - There is a long line of bubbled up material all along the left edge about 1" in on face of WRB	-	-	-	-
Window Flange	- Flashing applied evenly at window - Brought tightly against window frame - Can see indentation from nail head and edge of window flange	-	-	-	-
Electrical Penetration	- Thick coating all around; applied well and thoroughly - Slight peeling at the very edge of the penetration	-	-	-	- Cracking at top right side and right side of penetration (due to early cladding installation)
3" Pipe	- Thick coating all around; applied well and thoroughly - Slight gap is visible at the top right side at end of penetration coverage - Short line of bubbles protruding outward of penetration at a 45° angle from the bottom left side	-	-	-	- Cracking at top of large pipe at edge of detailing (due to early cladding installation)
1" Pipe	- Thick coating all around; applied well and thoroughly - No apparent gaps	-	-	-	-

DRP1009-17	Install	3 months	6 months	9 months	1 year
Brick Tie	- N/A	-	-	-	-
Sheathing Joint	- Thick coating applied over joint - Can see crease of center joint	-	-	-	-
Back Side	- No condensation	- No condensation	- No condensation	- No condensation	- Slight condensation at one instance
General Comments	- Can see crease from the detailing around the penetrations - Few pin-sized dimples present throughout - Outline of wood grain visible through WRB	- Slight dirtiness of membrane - Slight increase in the amount of pinholes	- A lot of pinholes present	-	- Cladding applied (at 1 year) - Surface slightly abraded where cladding was installed too early, especially around nail holes and slightly raised parts of the surface

Appendix B – Nail Sealability Test Data

Table B1: Nail Sealability Test Data

Specimen Number	ASTM D1970 Pass Stated in Literature	Tested to New or Old Standard	Pass/Fail	Failure Mechanisms				
				Water in Bottom Can	Water on Nail Shanks	Water on Underside of Plywood	Water Under Sheet	Water Loss in Top Can
DRP1009-01-A	Y	Old	Fail	N	Y	N	N/A	Slight
DRP1009-01-B	Y	Old	Fail	N	Y	N	N/A	Slight
DRP1009-01-C	Y	Old	Fail	N	Y	N	N/A	Slight
DRP1009-02-A	N	Old	Fail	Y	Y	Y	Y	None left
DRP1009-02-B	N	Old	Fail	Y	Y	Y	Y	None left
DRP1009-02-C	N	Old	Fail	Y	Y	Y	Y	None left
DRP1009-03-A	Y	Old	Fail	Y	Y	Y	N/A	Slight
DRP1009-03-B	Y	Old	Fail	N	Y	Y	N/A	Slight
DRP1009-03-C	Y	Old	Fail	N	Y	Y	N/A	None
DRP1009-04-A	Y	Old	Fail	N	Y	Y	N/A	Slight
DRP1009-04-B	Y	Old	Fail	N	Y	Y	N/A	Slight
DRP1009-04-C	Y	Old	Fail	N	Y	Y	N/A	Slight
DRP1009-05-A	N	Old	Fail	Y	Y	Y	N/A	Slight
DRP1009-05-B	N	Old	Fail	N	Y	Y	N/A	Slight
DRP1009-05-C	N	Old	Fail	N	Y	Y	N/A	Slight
DRP1009-06-A	N	Old	Fail	N	Y	Y	N	Slight
DRP1009-06-B	N	Old	Fail	Y	Y	Y	Y	3/5 left
DRP1009-06-C	N	Old	Fail	Y	Y	Y	Y	Slight
DRP1009-07-A	Y	Old	Pass	N	N	N	N/A	None
DRP1009-07-B	Y	Old	Fail	Y	Y	Y	N/A	Slight
DRP1009-07-C	Y	Old	Fail	Y	Y	Y	N/A	Slight

Specimen Number	ASTM D1970 Pass Stated in Literature	New or Old Standard	Pass/Fail	Failure Mechanisms				
				Water in Bottom Can	Water on Nail Shanks	Water on Underside of Plywood	Water Under Sheet	Water Loss in Top Can
DRP1009-08-A	Y	Old	Fail	N	Y	Y	N/A	Slight
DRP1009-08-B	Y	Old	Fail	N	Y	N	N/A	None
DRP1009-08-C	Y	Old	Fail	Y	Y	Y	N/A	Slight
DRP1009-09-A	N	Old	Pass	N	N	N	N/A	None
DRP1009-09-B	N	Old	Fail	Y	Y	Y	N/A	Slight
DRP1009-09-C	N	Old	Fail	N	Y	Y	N/A	Slight
DRP1009-10-A	N	New	Fail	Y	Y	Y	N/A	½”
DRP1009-10-B	N	New	Fail	Y	Y	Y	N/A	¾”
DRP1009-10-C	N	New	Fail	Y	Y	Y	N/A	½”
DRP1009-11-A	Y	New	Pass	N	N	N	N/A	None
DRP1009-11-B	Y	New	Pass	N	N	N	N/A	None
DRP1009-11-C	Y	New	Pass	N	N	N	N/A	None
DRP1009-12-A	N	New	Pass	N	N	N	N/A	None
DRP1009-12-B	N	New	Pass	N	N	N	N/A	None
DRP1009-12-C	N	New	Pass	N	N	N	N/A	None
DRP1009-13-A	Y	New	Fail	N	Y	Y	N/A	Slight
DRP1009-13-B	Y	New	Pass	N	N	N	N/A	None
DRP1009-13-C	Y	New	Fail	N	Y	Y	N/A	Slight
DRP1009-14-A	Y	New	Pass	N	N	N	N/A	None
DRP1009-14-B	Y	New	Pass	N	N	N	N/A	None
DRP1009-14-C	Y	New	Pass	N	N	N	N/A	None
DRP1009-15-A	Y	New	Fail	N	N	Y	Y	None left

Specimen Number	ASTM D1970 Pass Stated in Literature	New or Old Standard	Pass/Fail	Failure Mechanisms				
				Water in Bottom Can	Water on Nail Shanks	Water on Underside of Plywood	Water Under Sheet	Water Loss in Top Can
DRP1009-15-B	Y	New	Fail	N	N	Y	Y	None left
DRP1009-15-C	Y	New	Fail	N	N	Y	Y	None left
DRP1009-16-A	Y	New	Pass	N	N	N	N/A	None
DRP1009-16-B	Y	New	Pass	N	N	N	N/A	None
DRP1009-16-C	Y	New	Pass	N	N	N	N/A	None

Appendix C – Sealant Specimen Test Data

Table C1: Sealant Specimen Test Data

Specimen Number	Exposed or File Specimen	Color	SWR Institute Validated?	Parts	Type	Start Width (in.)		Average Compression Set (%)	Status (at test)	Status (at 2 months)	Status (at 4 months)
						Left	Right				
DRP1014-A1P	Exposed	White	Yes	1	Silicone	0.405	0.41	18.5	Pass	Pass	Pass
DRP1014-A2P	Exposed	White	Yes	1	Silicone	0.402	0.409	18.9	Distress	Distress	Distress
DRP1014-A3P	Exposed	White	Yes	1	Silicone	0.412	0.395	19.3	Distress	Distress	Distress
DRP1014-A4P	File	White	Yes	1	Silicone	0.405	0.409	18.6	Distress	Distress	Distress
DRP1014-A5	Exposed	White	Yes	1	Silicone	0.408	0.4	19.2	Pass	Pass	Pass
DRP1014-A6	Exposed	White	Yes	1	Silicone	0.412	0.421	16.7	Pass	Pass	Pass
DRP1014-A7	Exposed	White	Yes	1	Silicone	0.423	0.411	16.6	Distress	Distress	Distress
DRP1014-B1P	Exposed	White	Yes	1	Silicone	0.389	0.395	21.6	Distress	Failing	Failing
DRP1014-B2P	Exposed	White	Yes	1	Silicone	0.394	0.395	21.1	Distress	Failing	Failing
DRP1014-B3P	Exposed	White	Yes	1	Silicone	0.406	0.381	21.3	Distress	Failing	Failing
DRP1014-B4P	File	White	Yes	1	Silicone	0.399	0.39	21.1	Distress	Distress	Failing
DRP1014-B5	Exposed	White	Yes	1	Silicone	0.398	0.379	22.3	Distress	Failing	Failing
DRP1014-B6	Exposed	White	Yes	1	Silicone	0.396	0.408	19.6	Distress	Failing	Failing
DRP1014-B7	Exposed	White	Yes	1	Silicone	0.403	0.397	20	Distress	Failing	Failing
DRP1014-C1P	Exposed	White	Yes	1	Silicone	0.389	0.391	22	Distress	Distress	Distress
DRP1014-C2P	Exposed	White	Yes	1	Silicone	0.376	0.389	23.5	Pass	Pass	Pass
DRP1014-C3P	Exposed	White	Yes	1	Silicone	0.415	0.371	21.4	Pass	Pass	Pass
DRP1014-C4P	File	White	Yes	1	Silicone	0.403	0.396	20.1	Pass	Pass	Pass
DRP1014-C5	Exposed	White	Yes	1	Silicone	0.401	0.394	20.5	Distress	Failing	Failing
DRP1014-C6	Exposed	White	Yes	1	Silicone	0.391	0.399	21	Distress	Failing	Failing
DRP1014-C7	Exposed	White	Yes	1	Silicone	0.395	0.39	21.5	Distress	Fail	Fail
DRP1014-D1P	Exposed	White	Yes	1	Silicone	0.366	0.379	25.5	Pass	Pass	Pass

Specimen Number	Exposed or File Specimen	Color	SWR Institute Validated?	Parts	Type	Start Width (in.)		Average Compression Set (%)	Status (at test)	Status (at 2 months)	Status (at 4 months)
						Left	Right				
DRP1014-D2P	Exposed	White	Yes	1	Silicone	0.375	0.387	23.8	Pass	Distress	Distress
DRP1014-D3P	Exposed	White	Yes	1	Silicone	0.397	0.362	24.1	Distress	Distress	Failing
DRP1014-D4P	File	White	Yes	1	Silicone	0.385	0.381	23.4	Pass	Failing	Failing
DRP1014-D5	Exposed	White	Yes	1	Silicone	0.363	0.357	28	Distress	Failing	Failing
DRP1014-D6	Exposed	White	Yes	1	Silicone	0.373	0.385	24.2	Distress	Failing	Failing
DRP1014-D7	Exposed	White	Yes	1	Silicone	0.37	0.371	25.9	Distress	Failing	Failing
DRP1014-E1P	Exposed	White	Yes	1	Urethane	0.46	0.464	7.6	Distress	Failing	Failing
DRP1014-E2P	Exposed	White	Yes	1	Urethane	0.455	0.463	8.2	Pass	Failing	Failing
DRP1014-E3P	Exposed	White	Yes	1	Urethane	0.464	0.445	9.1	Distress	Failing	Failing
DRP1014-E4P	File	White	Yes	1	Urethane	0.487	0.48	3.3	Distress	Failing	Failing
DRP1014-E5	Exposed	White	Yes	1	Urethane	0.452	0.442	10.6	Distress	Failing	Failing
DRP1014-E6	Exposed	White	Yes	1	Urethane	0.431	0.452	11.7	Distress	Failing	Failing
DRP1014-E7	Exposed	White	Yes	1	Urethane	0.463	0.451	8.6	Distress	Failing	Failing
DRP1014-F1P	Exposed	White	No	1	Urethane	0.434	0.438	12.8	Pass	Distress	Distress
DRP1014-F2P	Exposed	White	No	1	Urethane	0.435	0.435	13	Pass	Distress	Failing
DRP1014-F3P	Exposed	White	No	1	Urethane	0.441	0.42	13.9	Pass	Distress	Distress
DRP1014-F4P	File	White	No	1	Urethane	0.449	0.445	10.6	Pass	Distress	Failing
DRP1014-F5	Exposed	White	No	1	Urethane	0.434	0.431	13.5	Pass	Fail	Fail
DRP1014-F6	Exposed	White	No	1	Urethane	0.428	0.446	12.6	Pass	Failing	Failing
DRP1014-F7	Exposed	White	No	1	Urethane	0.442	0.428	13	Pass	Failing	Failing
DRP1014-G1P	Exposed	White	No	2	Urethane	0.41	0.42	17	Pass	Pass	Distress
DRP1014-G2P	Exposed	White	No	2	Urethane	0.406	0.414	18	Distress	Distress	Distress
DRP1014-G3P	Exposed	White	No	2	Urethane	0.424	0.404	17.2	Pass	Distress	Distress

Specimen Number	Exposed or File Specimen	Color	SWR Institute Validated?	Parts	Type	Start Width (in.)		Average Compression Set (%)	Status (at test)	Status (at 2 months)	Status (at 4 months)
						Left	Right				
DRP1014-G4P	File	White	No	2	Urethane	0.47	0.444	8.6	Pass	Pass	Pass
DRP1014-G5	Exposed	White	No	2	Urethane	0.413	0.413	17.4	Distress	Distress	Failing
DRP1014-G6	Exposed	White	No	2	Urethane	0.407	0.422	17.1	Pass	Distress	Failing
DRP1014-G7	Exposed	White	No	2	Urethane	0.41	0.411	17.9	Pass	Distress	Failing
DRP1014-H1P	Exposed	White	Yes	1	Urethane	0.455	0.453	9.2	Distress	Failing	Failing
DRP1014-H2P	Exposed	White	Yes	1	Urethane	0.435	0.448	11.7	Distress	Failing	Failing
DRP1014-H3P	Exposed	White	Yes	1	Urethane	0.477	0.458	6.5	Distress	Failing	Failing
DRP1014-H4P	File	White	Yes	1	Urethane	0.461	0.452	8.7	Pass	Failing	Failing
DRP1014-H5	Exposed	White	Yes	1	Urethane	0.439	0.427	13.4	Distress	Failing	Failing
DRP1014-H6	Exposed	White	Yes	1	Urethane	0.439	0.446	11.5	Distress	Failing	Failing
DRP1014-H7	Exposed	White	Yes	1	Urethane	0.442	0.428	13	Distress	Failing	Failing
DRP1014-I1P	Exposed	White	Yes	1	Hybrid	0.378	0.378	24.4	Distress	Failing	Failing
DRP1014-I2P	Exposed	White	Yes	1	Hybrid	0.37	0.378	25.2	Distress	Failing	Failing
DRP1014-I3P	Exposed	White	Yes	1	Hybrid	0.386	0.374	24	Distress	Failing	Failing
DRP1014-I4P	File	White	Yes	1	Hybrid	0.391	0.373	23.6	Distress	Failing	Failing
DRP1014-I5	Exposed	White	Yes	1	Hybrid	0.389	0.384	22.7	Pass	Pass	Pass
DRP1014-I6	Exposed	White	Yes	1	Hybrid	0.379	0.382	23.9	Pass	Pass	Pass
DRP1014-I7	Exposed	White	Yes	1	Hybrid	0.377	0.374	24.9	Pass	Distress	Distress
DRP1014-J1P	Exposed	White	Yes	1	Urethane	0.431	0.426	14.3	Pass	Pass	Pass
DRP1014-J2P	Exposed	White	Yes	1	Urethane	0.419	0.434	14.7	Distress	Distress	Distress
DRP1014-J3P	Exposed	White	Yes	1	Urethane	0.448	0.423	12.9	Pass	Pass	Distress
DRP1014-J4P	File	White	Yes	1	Urethane	0.466	0.448	8.6	Pass	Pass	Pass
DRP1014-J5	Exposed	White	Yes	1	Urethane	0.446	0.431	12.3	Pass	Distress	Distress

Specimen Number	Exposed or File Specimen	Color	SWR Institute Validated?	Parts	Type	Start Width (in.)		Average Compression Set (%)	Status (at test)	Status (at 2 months)	Status (at 4 months)
						Left	Right				
DRP1014-J6	Exposed	White	Yes	1	Urethane	0.427	0.435	13.8	Pass	Distress	Failing
DRP1014-J7	Exposed	White	Yes	1	Urethane	0.432	0.423	14.5	Distress	Failing	Failing
DRP1014-K1P	Exposed	White	Yes	1	Silicone	0.42	0.422	15.8	Distress	Failing	Failing
DRP1014-K2P	Exposed	White	Yes	1	Silicone	0.422	0.428	15	Pass	Failing	Failing
DRP1014-K3P	Exposed	White	Yes	1	Silicone	0.428	0.407	16.5	Pass	Failing	Failing
DRP1014-L1P	Exposed	White	Yes	1	Silicone	0.397	0.405	19.8	Pass	Distress	Distress
DRP1014-L2P	Exposed	White	Yes	1	Silicone	0.381	0.412	20.7	Pass	Distress	Failing
DRP1014-L3P	Exposed	White	Yes	1	Silicone	0.402	0.397	20.1	Pass	Failing	Failing
DRP1014-L4P	File	White	Yes	1	Silicone	0.383	0.398	21.9	Pass	Distress	Failing
DRP1014-L5	Exposed	White	Yes	1	Silicone	0.41	0.395	19.5	Distress	Failing	Failing
DRP1014-L6	Exposed	White	Yes	1	Silicone	0.398	0.403	19.9	Distress	Failing	Failing
DRP1014-L7	Exposed	White	Yes	1	Silicone	0.403	0.408	18.9	Distress	Failing	Failing
DRP1014-M1P	Exposed	White	Yes	1	Silicone	0.387	0.381	23.2	Pass	Pass	Distress
DRP1014-M2P	Exposed	White	Yes	1	Silicone	0.376	0.387	23.7	Pass	Pass	Pass
DRP1014-M3P	Exposed	White	Yes	1	Silicone	0.405	0.381	21.4	Pass	Pass	Distress
DRP1014-M4P	File	White	Yes	1	Silicone	0.398	0.393	20.9	Pass	Pass	Pass
DRP1014-M5	Exposed	White	Yes	1	Silicone	0.382	0.371	24.7	Distress	Distress	Distress
DRP1014-M6	Exposed	White	Yes	1	Silicone	0.405	0.402	19.3	Distress	Distress	Distress
DRP1014-M7	Exposed	White	Yes	1	Silicone	0.382	0.385	23.3	Distress	Distress	Distress
DRP1014-N1P	Exposed	Clear	No	1	Silicone	0.414	0.412	17.4	Fail	Fail	Fail
DRP1014-N2P	Exposed	Clear	No	1	Silicone	0.414	0.412	17.4	Fail	Fail	Fail
DRP1014-N3P	Exposed	Clear	No	1	Silicone	0.414	0.412	17.4	Fail	Fail	Fail
DRP1014-O1P	Exposed	White	Yes	1	Silicone	0.414	0.412	17.4	Pass	Pass	Pass

Specimen Number	Exposed or File Specimen	Color	SWR Institute Validated?	Parts	Type	Start Width (in.)		Average Compression Set (%)	Status (at test)	Status (at 2 months)	Status (at 4 months)
						Left	Right				
DRP1014-O2P	Exposed	White	Yes	1	Silicone	0.415	0.412	17.3	Pass	Distress	Distress
DRP1014-O3P	Exposed	White	Yes	1	Silicone	0.415	0.412	17.3	Pass	Distress	Distress
DRP1014-O4P	File	White	Yes	1	Silicone	0.415	0.412	17.3	Pass	Pass	Pass
DRP1014-O5	Exposed	White	Yes	1	Silicone	0.415	0.412	17.3	Pass	Pass	Distress
DRP1014-O6	Exposed	White	Yes	1	Silicone	0.415	0.412	17.3	Pass	Distress	Distress
DRP1014-O7	Exposed	White	Yes	1	Silicone	0.415	0.412	17.3	Pass	Distress	Distress
DRP1014-P1P	Exposed	White	No	1	Hybrid	0.415	0.413	17.2	Fail	Fail	Fail
DRP1014-P2P	Exposed	White	No	1	Hybrid	0.415	0.413	17.2	Fail	Fail	Fail
DRP1014-P3P	Exposed	White	No	1	Hybrid	0.415	0.413	17.2	Fail	Fail	Fail
DRP1014-P4P	File	White	No	1	Hybrid	0.415	0.413	17.2	Pass	Pass	Pass
DRP1014-Q1P	Exposed	White	Yes	1	Silicone	0.415	0.413	17.2	Fail	Fail	Fail
DRP1014-Q2P	Exposed	White	Yes	1	Silicone	0.415	0.413	17.2	Fail	Fail	Fail
DRP1014-Q3P	Exposed	White	Yes	1	Silicone	0.415	0.413	17.2	Distress	Failing	Failing
DRP1014-Q4P	File	White	Yes	1	Silicone	0.415	0.413	17.2	Pass	Pass	Pass
DRP1014-Q5	Exposed	White	Yes	1	Silicone	0.415	0.413	17.2	Fail	Fail	Fail
DRP1014-Q6	Exposed	White	Yes	1	Silicone	0.415	0.413	17.2	Fail	Fail	Fail
DRP1014-Q7	Exposed	White	Yes	1	Silicone	0.415	0.413	17.2	Fail	Fail	Fail
DRP1014-R1P	Exposed	White	Yes	2	Urethane	0.415	0.413	17.2	Pass	Distress	Distress
DRP1014-R2P	Exposed	White	Yes	2	Urethane	0.415	0.413	17.2	Pass	Distress	Distress
DRP1014-R3P	Exposed	White	Yes	2	Urethane	0.415	0.413	17.2	Pass	Distress	Distress
DRP1014-R4P	File	White	Yes	2	Urethane	0.415	0.413	17.2	Distress	Distress	Distress
DRP1014-R5	Exposed	White	Yes	2	Urethane	0.415	0.413	17.2	Pass	Distress	Distress
DRP1014-R6	Exposed	White	Yes	2	Urethane	0.415	0.413	17.2	Pass	Distress	Distress

Specimen Number	Exposed or File Specimen	Color	SWR Institute Validated?	Parts	Type	Start Width (in.)		Average Compression Set (%)	Status (at test)	Status (at 2 months)	Status (at 4 months)
						Left	Right				
DRP1014-R7	Exposed	White	Yes	2	Urethane	0.415	0.413	17.2	Pass	Distress	Distress
DRP1014-S1P	Exposed	White	No	2	Urethane	0.415	0.413	17.2	Distress	Failing	Failing
DRP1014-S2P	Exposed	White	No	2	Urethane	0.415	0.413	17.2	Distress	Failing	Failing
DRP1014-S3P	Exposed	White	No	2	Urethane	0.415	0.413	17.2	Distress	Failing	Failing
DRP1014-S4P	File	White	No	2	Urethane	0.415	0.413	17.2	Distress	Failing	Failing
DRP1014-S5	Exposed	White	No	2	Urethane	0.415	0.414	17.1	Fail	Fail	Fail
DRP1014-S6	Exposed	White	No	2	Urethane	0.415	0.414	17.1	Distress	Failing	Failing
DRP1014-S7	Exposed	White	No	2	Urethane	0.415	0.414	17.1	Distress	Failing	Failing
DRP1014-T1P	Exposed	White	Yes	1	Silicone	0.415	0.414	17.1	Pass	Pass	Pass
DRP1014-T2P	Exposed	White	Yes	1	Silicone	0.416	0.414	17	Pass	Pass	Pass
DRP1014-T3P	Exposed	White	Yes	1	Silicone	0.416	0.414	17	Pass	Pass	Pass
DRP1014-T4P	File	White	Yes	1	Silicone	0.416	0.414	17	Distress	Distress	Failing
DRP1014-T5	Exposed	White	Yes	1	Silicone	0.416	0.414	17	Pass	Distress	Distress
DRP1014-T6	Exposed	White	Yes	1	Silicone	0.416	0.414	17	Pass	Pass	Pass
DRP1014-T7	Exposed	White	Yes	1	Silicone	0.416	0.414	17	Pass	Pass	Pass
DRP1014-U1P	Exposed	White	Yes	1	Silicone	0.416	0.414	17	Pass	Pass	Pass
DRP1014-U2P	Exposed	White	Yes	1	Silicone	0.416	0.414	17	Pass	Pass	Pass
DRP1014-U3P	Exposed	White	Yes	1	Silicone	0.416	0.414	17	Pass	Pass	Pass
DRP1014-U4P	File	White	Yes	1	Silicone	0.416	0.414	17	Pass	Pass	Pass
DRP1014-U5	Exposed	White	Yes	1	Silicone	0.416	0.414	17	Pass	Distress	Failing
DRP1014-U6	Exposed	White	Yes	1	Silicone	0.416	0.414	17	Pass	Distress	Failing
DRP1014-U7	Exposed	White	Yes	1	Silicone	0.416	0.414	17	Pass	Pass	Pass
DRP1014-V1P	Exposed	White	Yes	1	Urethane	0.416	0.414	17	Pass	Distress	Distress

Specimen Number	Exposed or File Specimen	Color	SWR Institute Validated?	Parts	Type	Start Width (in.)		Average Compression Set (%)	Status (at test)	Status (at 2 months)	Status (at 4 months)
						Left	Right				
DRP1014-V2P	Exposed	White	Yes	1	Urethane	0.416	0.414	17	Pass	Distress	Distress
DRP1014-V3P	Exposed	White	Yes	1	Urethane	0.416	0.414	17	Pass	Distress	Distress
DRP1014-V4P	File	White	Yes	1	Urethane	0.416	0.414	17	Pass	Pass	Pass
DRP1014-V5	Exposed	White	Yes	1	Urethane	0.416	0.415	16.9	Pass	Failing	Failing
DRP1014-V6	Exposed	White	Yes	1	Urethane	0.416	0.415	16.9	Pass	Failing	Fail
DRP1014-V7	Exposed	White	Yes	1	Urethane	0.416	0.415	16.9	Pass	Fail	Fail
DRP1014-W1P	Exposed	White	Yes	1	Silicone	0.416	0.415	16.9	Pass	Pass	Pass
DRP1014-W2P	Exposed	White	Yes	1	Silicone	0.416	0.415	16.9	Pass	Distress	Distress
DRP1014-W3P	Exposed	White	Yes	1	Silicone	0.416	0.415	16.9	Distress	Distress	Distress
DRP1014-W4P	File	White	Yes	1	Silicone	0.416	0.415	16.9	Distress	Distress	Distress
DRP1014-W5	Exposed	White	Yes	1	Silicone	0.416	0.415	16.9	Pass	Distress	Distress
DRP1014-W6	Exposed	White	Yes	1	Silicone	0.416	0.415	16.9	Distress	Distress	Failing
DRP1014-W7	Exposed	White	Yes	1	Silicone	0.416	0.415	16.9	Pass	Pass	Pass
DRP1014-X1P	Exposed	White	No	1	Silicone	0.416	0.415	16.9	Distress	Distress	Distress
DRP1014-X2P	Exposed	White	No	1	Silicone	0.416	0.415	16.9	Distress	Distress	Distress
DRP1014-X3P	Exposed	White	No	1	Silicone	0.416	0.415	16.9	Distress	Distress	Distress
DRP1014-X4P	File	White	No	1	Silicone	0.416	0.415	16.9	Pass	Pass	Pass
DRP1014-X5	Exposed	White	No	1	Silicone	0.416	0.415	16.9	Distress	Failing	Failing
DRP1014-X6	Exposed	White	No	1	Silicone	0.417	0.415	16.8	Distress	Failing	Failing
DRP1014-X7	Exposed	White	No	1	Silicone	0.417	0.415	16.8	Distress	Failing	Failing
DRP1014-Y1P	Exposed	White	No	1	Urethane	0.417	0.415	16.8	Distress	Failing	Failing
DRP1014-Y2P	Exposed	White	No	1	Urethane	0.417	0.415	16.8	Pass	Fail	Fail
DRP1014-Y3P	Exposed	White	No	1	Urethane	0.417	0.415	16.8	Distress	Failing	Failing

Specimen Number	Exposed or File Specimen	Color	SWR Institute Validated?	Parts	Type	Start Width (in.)		Average Compression Set (%)	Status (at test)	Status (at 2 months)	Status (at 4 months)
						Left	Right				
DRP1014-Z1P	Exposed	White	No	2	Urethane	0.417	0.415	16.8	Distress	Fail	Fail
DRP1014-Z2P	Exposed	White	No	2	Urethane	0.417	0.415	16.8	Distress	Failing	Failing
DRP1014-Z3P	Exposed	White	No	2	Urethane	0.417	0.416	16.7	Distress	Failing	Failing
DRP1014-AA1P	Exposed	White	Yes	1	Silicone	0.417	0.416	16.7	Distress	Distress	Failing
DRP1014-AA2P	Exposed	White	Yes	1	Silicone	0.417	0.416	16.7	Pass	Failing	Failing
DRP1014-AA3P	Exposed	White	Yes	1	Silicone	0.417	0.416	16.7	Pass	Distress	Distress
DRP1014-AA4P	File	White	Yes	1	Silicone	0.417	0.416	16.7	Pass	Pass	Pass
DRP1014-AA5	Exposed	White	Yes	1	Silicone	0.417	0.416	16.7	Fail	Fail	Fail
DRP1014-AA6	Exposed	White	Yes	1	Silicone	0.417	0.416	16.7	Fail	Fail	Fail
DRP1014-AA7	Exposed	White	Yes	1	Silicone	0.417	0.416	16.7	Fail	Fail	Fail
DRP1014-BB1P	Exposed	White	Yes	1	Silicone	0.417	0.416	16.7	Pass	Pass	Pass
DRP1014-BB2P	Exposed	White	Yes	1	Silicone	0.417	0.416	16.7	Pass	Pass	Pass
DRP1014-BB3P	Exposed	White	Yes	1	Silicone	0.417	0.416	16.7	Pass	Pass	Pass
DRP1014-BB4P	File	White	Yes	1	Silicone	0.417	0.416	16.7	Pass	Pass	Pass
DRP1014-BB5	Exposed	White	Yes	1	Silicone	0.417	0.416	16.7	Pass	Failing	Failing
DRP1014-BB6	Exposed	White	Yes	1	Silicone	0.417	0.416	16.7	Pass	Pass	Distress
DRP1014-BB7	Exposed	White	Yes	1	Silicone	0.417	0.416	16.7	Pass	Failing	Failing
DRP1014-CC1P	Exposed	White	No	1	Silicone	0.417	0.416	16.7	Fail	Fail	Fail
DRP1014-CC2P	Exposed	White	No	1	Silicone	0.417	0.416	16.7	Fail	Fail	Fail
DRP1014-CC3P	Exposed	White	No	1	Silicone	0.417	0.416	16.7	Fail	Fail	Fail
DRP1014-CC4P	File	White	No	1	Silicone	0.417	0.416	16.7	Fail	Fail	Fail
DRP1014-CC5	Exposed	White	No	1	Silicone	0.417	0.416	16.7	Fail	Fail	Fail
DRP1014-CC6	Exposed	White	No	1	Silicone	0.417	0.416	16.7	Fail	Fail	Fail

Specimen Number	Exposed or File Specimen	Color	SWR Institute Validated?	Parts	Type	Start Width (in.)		Average Compression Set (%)	Status (at test)	Status (at 2 months)	Status (at 4 months)
						Left	Right				
DRP1014-CC7	Exposed	White	No	1	Silicone	0.417	0.417	16.6	Fail	Fail	Fail
DRP1014-DD1P	Exposed	Clear	No	1	Silicone	0.417	0.417	16.6	Pass	Distress	Failing
DRP1014-DD2P	Exposed	Clear	No	1	Silicone	0.417	0.417	16.6	Pass	Pass	Pass
DRP1014-DD3P	Exposed	Clear	No	1	Silicone	0.417	0.417	16.6	Pass	Distress	Failing
DRP1014-EE1P	Exposed	Clear	Yes	1	Silicone	0.418	0.417	16.5	Distress	Fail	Fail
DRP1014-EE2P	Exposed	Clear	Yes	1	Silicone	0.418	0.417	16.5	Distress	Failing	Failing
DRP1014-EE3P	Exposed	Clear	Yes	1	Silicone	0.418	0.417	16.5	Distress	Failing	Failing
DRP1014-FF1P	Exposed	White	No	2	Silicone	0.418	0.417	16.5	Fail	Fail	Fail
DRP1014-FF2P	Exposed	White	No	2	Silicone	0.418	0.417	16.5	Fail	Fail	Fail
DRP1014-FF3P	Exposed	White	No	2	Silicone	0.418	0.417	16.5	Fail	Fail	Fail

Appendix D – 8d Common Nail Withdrawal Capacity Calculation

$$Given:$$

$$D\ (diameter) =\ 0.131\ in.\ [Table\ L4]$$

$$L\ (length) =\ 2.5\ in.\ [Table\ L4]$$

$$Douglas\ Fir\ Larch, G = 0.50\ [Table\ 11.3.2A]$$

$$sheathing\ thickness = \frac{1}{2}\ in.$$

$$W\ = 32\frac{lb}{in}\ [Table\ 11.2C]$$

$$C_D = 2.0\ [Table\ 2.3.2, assuming\ load\ duration\ was\ short]$$

$$C_M = 1.0\ [Table\ 10.3.3, assuming\ MC\ at\ fabrication\ and\ in\ service \leq 19\%]$$

$$C_t = 1.0\ [Table\ 10.3.4, assuming\ dry\ conditions\ and\ T \leq 100°\text{F}]$$

$$C_{eg} = 1.0\ [Sec. 11.5.2, assuming\ not\ in\ end\ grain]$$

$$C_{tn} = 1.0\ [Sec. 11.5.4, assuming\ no\ toenail\ connection]$$

$$Calculation:$$

$$W' = WC_DC_MC_tC_{eg}C_{tn}$$

$$W' = 32\frac{lb}{in}(2.0)(1.0)(1.0)(1.0)(1.0)$$

$$W' = 64\frac{lb}{in}$$

$$L = W'P$$

$$where\ P = nail\ length - sheathing\ thickness$$

$$P = 2.5\ in. - \frac{1}{2}in. = 2\ in.$$

$$L = 64\frac{lb}{in}(2\ in)$$

$$\boldsymbol{L = 128\ lb}$$

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