

**A NEW SENSING SYSTEM TO DETECT LIQUID WATER  
PENETRATION THROUGH WATER RESISTIVE BARRIERS**

by

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Bachelor of Engineering, University of Victoria, 2019

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER OF APPLIED SCIENCE

in the Department of Mechanical Engineering

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University of Victoria

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# **SUPERVISORY COMMITTEE**

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### **Supervisory Committee**

Dr. Caterina Valeo, (Department of Mechanical Engineering)

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# ABSTRACT

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The current test methods that evaluate the liquid water resistance performance of a water resistive barrier (WRB) have various drawbacks. A Hydrostatic Pressure Test Apparatus (HPTA) provided by SMT Research Ltd. was used to develop a unique test method to detect liquid water penetration through WRBs. The sensor used in HPTA has 42 channels and each channel reads an individual electric resistance. Lower electric resistance indicates more liquid water penetrates the sensor, vice versa. The measurement system of the device was studied and tested. The results showed the measurement system works properly to detect amount change of the liquid water applied to the sensor while there is no proportional relationship between the amount of liquid water and electrical resistance. The change between two adjacent electrical readings was evaluated by a factor called Normalized Difference Vegetation Index (*NDMI*). The *NDMI* factor was determined to be a better measurement than the value of electrical resistance. Preliminary tests using HPTA with Membrane D and Membrane F were done and the apparatus was found to have water leaking through the joint. The clamping method of HPTA was then modified to solve the problem and further WRBs were tested using the modified device. Six WRB materials, Membrane A, Membrane B, Membrane C, Membrane D, Membrane E and Membrane F were tested and 83 tests were conducted in total. A colormap method was used to evaluate the water resistance ability of each material. Among all materials, Membrane E had the highest water resistance ability of long and a water resistance score (WRS) of 337.14. Membrane F had a lower duration of short and a WRS of 78.75. Membrane C and Membrane D have water resistance durations between very short and short and their WRS were 36.5 and 82.71. Membrane A and Membrane B had the lowest water resistance duration of very short and their WRS were 15.15 and 23.19. Plots of Log R vs. Time and *NDMI* vs. Time of the edge sensors and center sensors were plotted in MATLAB. The water movement behaviours in the two groups of sensors varied by materials.

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# CHAPTER 1 INTRODUCTION

Building science is a broad subject that contains knowledge and technologies from different areas, such as structural engineering, geotechnical engineering, environmental engineering, etc. Buildings need to be built using strong engineering fundamentals to ensure the safety and well-being of the occupants. There are many factors which influence the performance of a building such as energy efficiency, moisture management, HVAC system, air leakage and the hygrothermal response of building materials.

## 1.1 MOISTURE MANAGEMENT

In building envelopes, liquid water is one of the most significant performance management issues. The lack of proper moisture management could affect a building in the aspect of structure, appearance, energy, durability and health of the occupants. Detailed problems will be listed in Section 2.1. Figure 1 (a) – (c) shows examples of some moisture related problems.



FIGURE 1 (A) MOLDS GROWTH AND WALL PAINT DETERIORATION (B) WALL COVERING PEELS OFF



(C) MOLDS AND WATER LEAKAGE INSIDE A SHOPPING MALL

Figure 1 (a) is taken in a first-floor apartment in the South East of China built in 2010. The apartment is moist most time. Same mold growth and wall paint fell problems happened in many places in the apartment. Figure 1 (b) shows wall coverings fell over in a hotel room (source: Guangzhou JinWei Trading Co., Ltd). The picture is taken three to four years after wallpapering. Figure 1 (c) is taken in an underground walkway in a shopping mall. The shopping mall was opened in 2010 and is located in the central business district of the city. Many areas in the walkway have the molds and water leakage problems as shown in the above figure.

To solve moisture related problems, correct moisture management strategies aim at three different forms of water should be applied. The ice form of water is not usually considered in moisture management but foundation design. Also, most moisture problems caused by ice will not exit if the liquid and gas forms of water are considered appropriately (Kesik,2016a). A 4Ds principle, deflection, drainage, drying, and durability is used as a water management principle. The drainage principle involves a product called water resistive barrier (WRB), which is the research subject of this work. There are also vapor barriers and air barriers used in the building. Some barriers have more than one function and it is common to use any combination of the three barriers in buildings.

## 1.2 WATER RESISTIVE BARRIERS

Three types of water resistive barriers, felt based, paper based, and polymer based, are stated in ASTM E2556 (2016). There are also other classifications of WRB and they are introduced in Section 2.4.1. The current test methods that test water resistance of a WRB include ASTM D779, the water ponding method from Canadian Construction Materials Center (CCMC), the hydrostatic pressure test from AATCC Test Method 127, ASTM D4869, UU-B-790a and BS EN 1928:2000. Each mentioned test method has one or more drawbacks such as only providing pass/fail results, limited accepted materials, subjective human observation results, not able to distinguish the appearance of liquid water and water vapor, not able to quantify the water resistance performance, or even the description of procedures is not clear.

## 1.3 THESIS OBJECTIVE AND LAYOUT

In this work, a testing method that improves on the above drawbacks is designed using an apparatus provided by SMT Research Ltd. The measurement system of the apparatus is verified,

modification is applied to the device, and six different WRB materials are tested for their water resistance performance.

In Chapter 2, a review of moisture related problems is first given to introduce the critical role of moisture management in building design. Five prerequisites for moisture related issues are then discussed, followed by the 4Ds principle. The WRB is carried out in the drainage principle in the 4Ds. The vapor barrier and air barrier are discussed briefly, with the most focus on their use along with WRBs but not their own properties or detailed usage. Two different layouts of wall assemblies that contain the three types of barriers are also included.

The detail of WRBs is then given. This includes the different classification and comparison of WRB types, the current standards that test liquid water resistance, results from previous tests done by other researchers, and the information of the available WRB materials for this research. In the review of current standards, the content in the material requirement, test method, measurement and report are concluded from the corresponding literature while the comments on problems and limits for each standard are personal ideas. The gaps and research objectives are given at the end of this chapter.

Chapter 3 consists of investigating the measurement system and testing the sensor performance only and testing with the application of WRBs. The measurement system includes the sensor, the signal modification system and the indicator and recorder. Three different tests are done to evaluate the sensor performance, the fully covered water test, the sensor test in groups, and the water droplet test. After verifying the functionality of the sensor, preliminary tests are done using two WRB materials. The HPTA apparatus is then found to have unexpected water leakage problems. The problem is then addressed by clamping method modification. The last part of this section is testing six WRBs with the modified device. It contains the reasons for material selection, a test information table that shows test summaries of all 83 tests, criteria to determine water penetration, procedures of the test, and data processing method.

The results of the sensor tests and WRB membrane tests are given in Chapter 4. This Results section includes plots and descriptive analysis for sensor tests. When analyzing and presenting the results of each of the six WRBs, a colormap is generated by a python script for each test. A column chart and pie chart are then plotted based on this colourmap. Each material is evaluated by a water resistance duration and a water resistance score respectively. The microscope image is

included for each material to discuss the fabric structure. Also, the Log R and *NDMI* data are plotted in each test in two groups of sensors and they are discussed in the Discussion section. This section also includes the discussion of erratic reading, water level drop and water addition method and suggested future work.

## **CHAPTER 2 LITERATURE REVIEW**

### **2.1 ROLE OF MOISTURE MANAGEMENT IN BUILDING ENCLOSURE DESIGN**

Kesik (2016a) stated that moisture management is the most critical consideration in building design. The moisture related problems are illustrated in a bunch of different aspects. The chart below in Figure 2 summarizes the problems from three articles (Straube 2002, EPA 2013, and Kesik 2016a). Moisture can adversely affect occupants' health, structure stability, appearance, energy efficiency, and durability.

There are three essential control functions in enclosure design, heat, air, and moisture. Managing moisture is the primary task because of the consequent griefs mentioned above. Generally, if moisture is appropriately managed in a building, most of the heat and air issues would be resolved. Also, if all the essential control functions are regulated, the building will have additional performance such as good energy efficiency and thermal conform.

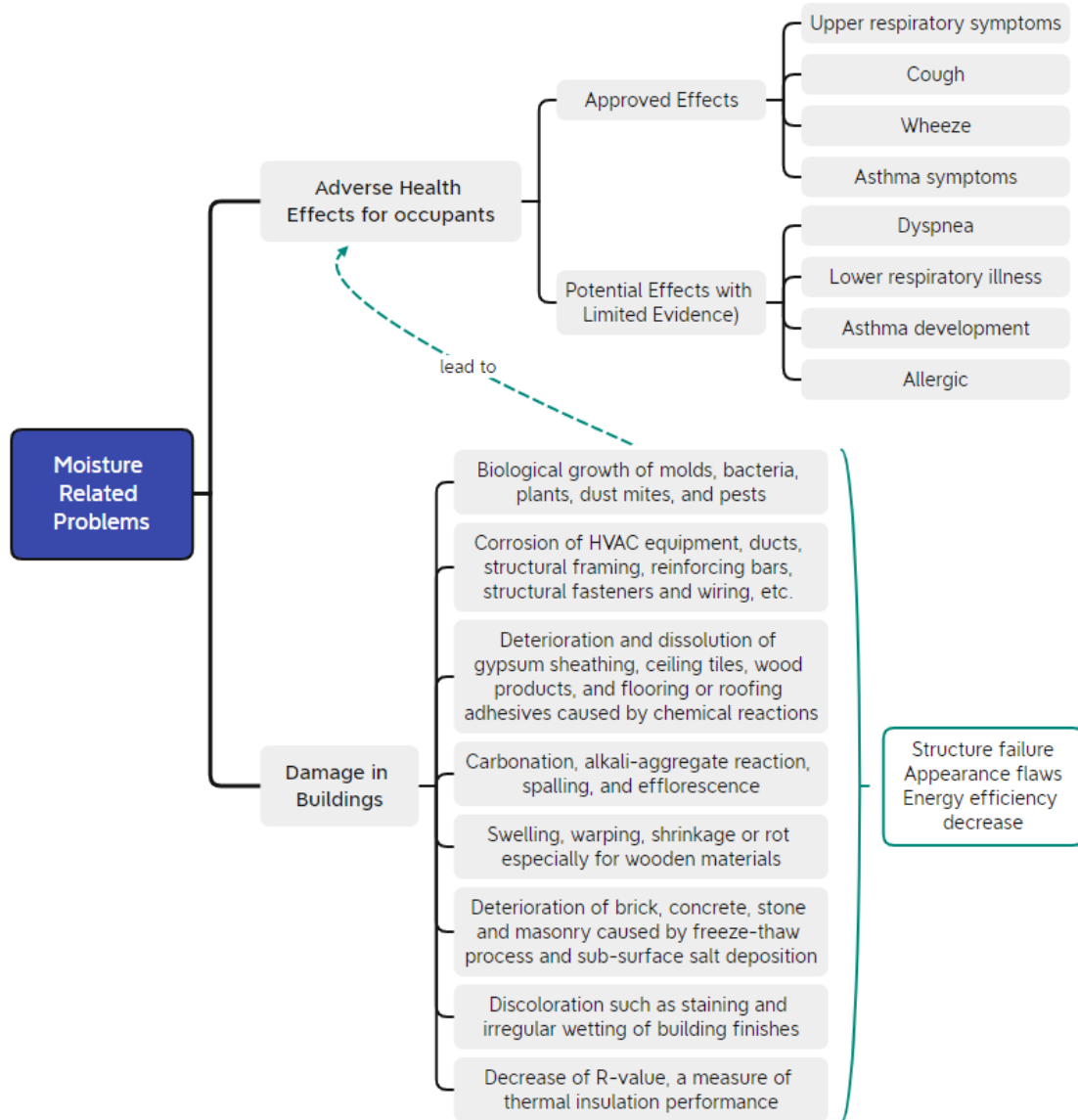


FIGURE 2 MOISTURE RELATED PROBLEMS

## 2.2 MOISTURE MANAGEMENT STRATEGIES

There are five prerequisites for moisture related problems to occur. The first condition that needs to be satisfied is a moisture source. Then the moisture must have a route to travel. The third one is there must be a driving force for the moisture to move. The rest two conditions are the relevant materials need to be vulnerable to moisture damage, and the moisture content must exceed the materials' safe moisture content for a long time (Kesik, 2016a).

For the first condition, the moisture sources could be three physical states of water, solid, liquid and gas forms. All of them can cause moisture related problems in buildings. The solid form, which is usually ice, is not normally considered in moisture management but considered in foundation design. Also, if the other two forms of water are properly managed, most problems caused by ice will be conquered automatically (Kesik,2016a).

The liquid state bulk water comes from precipitation, plumbing leaks, snowmelt, flooding, groundwater, and condensation of water vapor. The gas state water vapor comes from the outside environment and occupants' activities inside the building (Kesik,2016a). The transportation of these moisture sources has a hierarchy, from the most powerful to the least are liquid gravity flow, liquid water capillary, vapor convection and vapor diffusion (Straube,2002).

The second, fourth and fifth prerequisites are about the inherent of the building, such as the wall and joint design and the material selections. The third condition includes gravity, capillary force, air movement, etc. All five conditions need to be fulfilled for a moisture related problem to occur. In reality, a designer can not block all moisture sources, make perfect selections for all building components and materials, or eliminate all driving forces. Typically, successfully managing two or more conditions would be sufficient to avoid moisture problems (Kesik, 2016a). Here a 4Ds principle is used to provide an elementary guideline for water management.

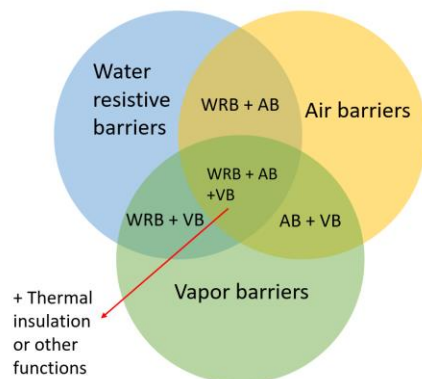
The 4Ds principle includes deflection, drainage, drying and durability. Deflection mainly avoids rain and snow from the exterior wall enclosure, thus minimizing wetting exposure. It is always achieved by increasing roof slope or extending eaves overhangs. Drainage is to drain away from the water that has already penetrated the exterior cladding, and a drainage plane, known as a water resistive barrier is always employed. Drying is to provide adequate ventilation to dry any residual water. Durability is about material selection, where a designer should choose water safe materials as possible (Kesik, 2016b). This research mainly focused on WRBs and because WRBs are always used in combination with vapor barriers and air barriers, a general description of the three barriers will be given in the next section but only WRBs and their codes and standards will be introduced in detail.

## 2.3 THREE DIFFERENT TYPES OF BARRIERS

Code revisions and innovations in sustainable buildings have led to a rising trend in building science research involving air, water, and vapor barriers. Implementing these three types of barriers helps to reduce energy usage in buildings and more importantly, increases the safety level and lifetime of buildings by reducing moisture related problems. The rapid growth of new research provides a great deal of information on each barrier and their combined usages. However, it also brings confusion for choosing the correct barriers for a specific building assembly. Another problem is that occasionally, the designs are unintentionally based on outdated information (Arsenault, 2015).

Arsenault (2015) believes the International Building Code (IBC) is more reliable than other codes' requirements since IBC considers the applications in various situations. The 2012 IBC was the latest version when the article was written. It provided revised definitions of exterior walls, vapor barriers, and water resistive barriers, which helped clarify some existing confusions. The 2012 International Energy Conservation Code (IECC), which was prepared by the International Code Council (ICC), also addressed energy use in buildings and stated detailed requirements for air barriers.

All three types of water resistive barriers, air barriers, and vapor barriers are readily available on the market. Different materials can act as single function or multi function barriers based on their properties. Some materials can serve as water resistive barriers, vapor barriers and air barriers, as well as apply thermal insulation. As shown in Figure 3 below, most materials can provide two or more functions (Butt, n.d.).



**FIGURE 3 FUNCTIONS OF VARIOUS TYPES OF MATERIALS**

The three barriers and other wall components build a common wall assembly. It is not necessary to use all three types of barriers because some of them can work as two or three. Also, although a WRB is usually used outside the building under exterior covering, the air and vapor barrier installation positions are not certain. An air barrier can be used anywhere in the building to stop air movement entering or exiting the building. A vapor barrier should be installed on the warm side of the insulation layer to prevent moisture buildup. Therefore, the installation position for both vapor barriers and air barriers could be in either the exterior or interior based on the specific structure and local climate. Straube (2010) includes “The Perfect Wall” approach as shown in Figure 4. It has thermal control layer beneath the cladding. The rainwater control layer, air control layer, and vapor control layer are all placed on the outside of the building below the thermal control layer. Figure 5 shows another common wall assembly in the North American climate. It has the air barrier and water barrier on the exterior above the exterior sheathing and the vapor barrier on the indoor side.

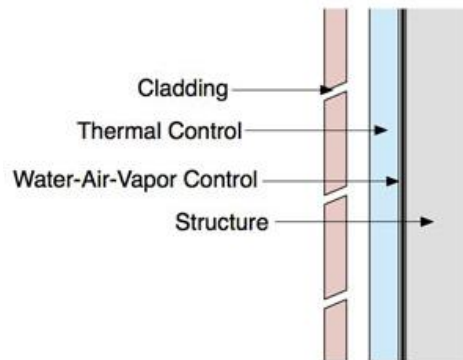


FIGURE 4 THE PERFECT WALL, FROM STRAUBE (2010)

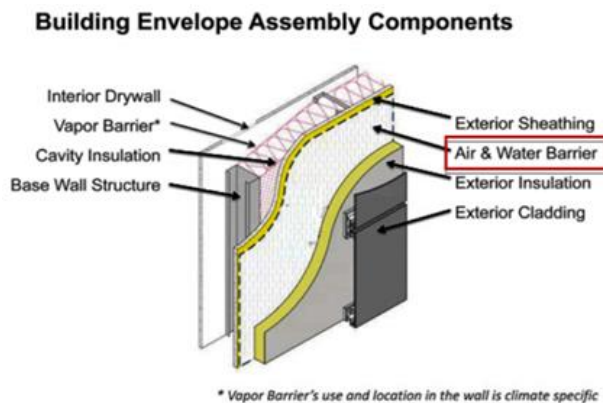


FIGURE 5 BUILDING ENVELOPE ASSEMBLY, IMAGE COURTESY OF DUPONT BUILDING INNOVATIONS

Understanding a material's functionality is essential for designers, particularly if a material can or cannot provide more than one function. This information allows the designer to determine whether a design with a chosen material requires additional functionality that the material cannot offer (Butt, n.d.). The three barriers are defined and explained in several documents and standards, with similarities and differences. The details will be given in the following sections.

## 2.4 WATER RESISTIVE BARRIERS

### 2.4.1 GENERAL INFORMATION ABOUT WATER RESISTIVE BARRIERS

The 2012 IECC defines a WRB as: "A material behind an exterior wall covering that is intended to resist liquid water that has penetrated behind the exterior covering from further intruding into the exterior wall assembly". The 2012 IBC and 2012 International Residential Codes (IRC) have the same definition.

Arsenault (2015) notes that in 2012 IBC, two water resistive barrier materials are mentioned. The first type is noted as a single layer of No.15 asphalt felt at minimum (IBC 1404.2), which follows the requirement for Type 1 felt in ASTM D226. Asphalt felt material is used commonly for thermal function in walls and roofs, but other modern materials seem to be better alternatives for water resistive needs. The second type of accepted water resistive barrier materials does not include a specific material type or a list of different materials; instead, it is expressed as materials that are "acceptable to the building official or authority having jurisdiction" (IBC 202). Arsenault (2015) also stated that the self-adhered sheet membrane was a common material for roof and below-grade walls and they are popular for water resistive barrier use.

When used as a WRB, there are two problems with the self-adhered sheet membrane. The first problem is that some products do not work well for above-grade walls. The second one is that the vapor permeability of some self-adhered sheet membranes could be too close to a vapor barrier. In the requirement of IBC, for cold climates, vapor barriers should be installed on the inside of framed walls in most cases, but WRBs should be installed on the outside. Therefore, a membrane with extremely low vapor permeability will not be a good water resistive material for some climates since it could prevent trapped water vapor from leaving the building, thus causing damage. A class III vapor permeable WRB allows moisture to escape from the building easily. Although the mechanical attachment method could affect the performance, the mechanically

attached flexible sheets made by non-woven materials with higher vapor permeability and sometimes with high airtightness would be more ideal WRBs (Arsenault, 2015).

The U.S. Department of Energy (2000) uses the term “weather resistive barriers” instead of “water resistive barriers”. It defines weather resistive barriers as: “A part of exterior wall systems that protect building materials from exterior water penetration”. Also, when weather resistive barriers prevent liquid water from entering the interior of the building, they should allow water vapor to pass. The U.S. Department of Energy (2000) categorized weather resistive barriers into two materials: building paper and housewrap. Building paper is a traditional paper sheet and felt material that is asphalt coated or impregnated. Housewrap is made of spun-plastic sheet material and it can usually be used as an air barrier at the same time. The fact sheet indicates that building papers can only resist water penetration over short periods while housewraps are able to eliminate water penetration and absorption, thus withstanding repeated wetting. In terms of durability, most building papers have low UV-resistant performances but different housewraps can have distinct UV-resistance, and in addition, housewraps have much better tear resistance compared to building papers.

The above category is considered to be inappropriate in ASTM Standard E2556-10 (2016), *Standard Specification for Vapor Permeable Flexible Sheet Water-Resistive Barriers Intended for Mechanical Attachment*. This standard clearly states three different types of WRBs, felt-based, paper-based, and polymer-based. Confusion exists between felt-based and paper-based WRBs and many people treat them as the same material and refer both of them to the terms such as “building paper”, “tarpaper”, and “felt”. Although papermaking and felting seem to have similar production processes, the final products are very different. The first use of felt in building constructions in the U.S. was in 1844. A pine-tar impregnated paper and wood pitch is used for roofing, which is migrated from ship construction method. It then develops from roofing paper to “rag” felt and then “organic felt”, as the present day felt-based barriers are usually asphalt-saturated organic felts. Building paper falls in the second category of paper-based WRBs. The asphalt-saturated kraft paper is basically made with sulfate pulp fibers. It was first manufactured in the 1950s and its performance seems to be much better than felt-based WRBs in the practice of the past 50 years (ASTM Standard E2556-10, 2016).

ASTM Standard E2556-10 (2016) mentions that the polymer sheets first came out in the 1970s, as “housewrap” for energy saving purposes due to the energy crisis at that time. They are usually thin, lightweight plastic sheet materials that allow water vapor to diffuse and are qualified for air barrier application. Butt presents similar information in his review articles (2005 & n.d.) about the general information of WRBs and classification but with his own additions.

Butt (2005) states that weather resistive barriers are usually used under stucco (cement plaster), wood and wood derived products, vinyl, or masonry veneer claddings of exterior walls. They are designed to prevent water from passing through the outer cladding. For most WRBs, the air passage is rejected but water vapor can pass through. Asphalt-saturated felts and papers were the traditional WRB materials and the polymeric sheets are leading the new trend. Besides, there are also trowel-applied WRBs and rigid board WRBs. Butt (2005) notes that the available information on WRBs, their properties and selection criteria are insufficient. The properties that should be considered when using a WRB include water resistance, water vapor permeance, air resistance, durability, compatibility with other materials, cost, installation challenges, and more.

Butt (n.d.) classifies the three WRB types in ASTM Standard E2556-10 (2016) as sheet materials. Except for sheet materials type WRB, he also introduced liquid applied WRBs, rigid board WRBs, and the relevant standards. When building paper first came out, it was made of an asphalt kraft paper developed based on organic roofing felt. To make the material sturdier, a thin layer of asphalt is laminated between two layers of kraft paper and it is called Grade A building paper. There is also Grade B building paper reinforced by fiberglass or other material.

The dissimilar part is about the appearance of polymer-based WRBs and the alternation from “weather resistive barrier” to “water resistive barrier”. Butt (n.d.) declares that the building codes used the term “weather resistive barrier” because it effectively provides air and water resistance at the same time. However, in the 1980s, the moisture impacts of air infiltration were reconsidered. Polymeric housewraps came out and had high air resistance. The building paper no longer needed to provide air resistance and the codes then revised the term “weather resistive barrier” to “water resistive barrier” (Butt, n.d.).

Selecting the most suitable WRBs need comprehensive considerations. The advantages and disadvantages of each of the three sheet materials WRBs listed by Butt (n.d.), is modified and summarized in Table 1. The information that is not discussed in the article is filled with a slash.

**TABLE 1 COMPARISON OF THREE TYPES OF WRBs**

	Asphalt-Saturated Felt	Asphalt-Saturated Kraft paper	Polymer Sheets
Product history	Longest	Long	Comparatively short
Available performance test data for use as WRBs	Minimal	More than felt	/
Material cost	Low	Low	Relatively expensive
Durability	Longer than paper	/	/
Permeance*	Comparatively high	Lower than felt $\checkmark$	/
Resistance to tearing and breaking	Low	Low	High
Resistance to bending	Low	Better than felt	/
Deterioration caused by exposure to water, combined with exposure to air or U.V.	Vulnerable	Highly vulnerable	No effect with water only
Effect of exposure to surfactants	Decrease water resistance	/	Decrease water resistance
Joints	/	/	Minimized
Air barrier functionality	/	/	Yes
Water vapor permeance	/	/	High

\* The article does not mention if the “permeance” means air permeance or vapor permeance but high permeance is described as a disadvantage since it could lead to wall cavity condensation.

#### *2.4.2 MEASURING LIQUID WATER PENETRATION OF WATER RESISTIVE BARRIERS*

ASTM Standard E2556-10 (2016) categorizes WRBs into three types, felt-based barrier composed of asphalt-saturated organic felts, paper-based barrier mainly composed of sulfate pulp fibers, and polymer-based barrier made of plastic sheet materials and two groups. The standard also sets two groups of WRBs: Type I WRB with base-level water resistance and Type II WRB with enhanced water resistance. The standard does not describe “base-level” and “enhanced” while the minimum performance requirements of each type are listed according to three test methods as shown in Table 2. The three methods, the boat test in ASTM Standard D779, the water ponding method from the Canadian Construction Materials Center (CCMC) and the

hydrostatic pressure test from AATCC Test Method 127, are generally used in the U.S to test water resistance.

**TABLE 2 REQUIREMENT FOR WATER RESISTIVE BARRIERS, EXCERPTED FROM ASTM E2556, TABLE 1**

Test Requirement	Test Method	Minimum Performance Requirements	
		Type I	Type II
Water Resistance Test	Test Method D779	10 min minimum	60 min minimum
	Ponding Test (A1.1)	No water shall penetrate through the membrane in 120 mins	not applicable
	AATCC Test Method 127	not applicable	No leakage is permitted to the underside of any specimen in 5 h

Other standards of testing liquid water passing through WRBs include ASTM Standard D4869 to measure felt-based WRBs, Federal Specification UU-B-790a to measure paper-based WRBs, and AC38 to measure polymer-based WRBs. Another standard British Standard BS EN 1928 measures bitumen, plastic and rubber sheet materials and the terminology used is watertightness. These standards are reviewed below, but the contents of aging such as U.C. exposure and cyclic drying/wetting are not included.

Although felt material is one type of WRB, it is more applied to the roof construction instead of used for a wall assembly. The asphalt-saturated organic felt tests in this test method are declared to be used as an underlayment with steep slope roofing. ASTM Standard D226, Standard Specification for Asphalt-Saturated Organic Felt Used in Roofing and Waterproofing, described the fundamental physical properties of asphalt-saturated organic felt. This specification covers felts that are perforated and not, whereas only the felt without perforation is considered a valid WRB. Although there is no water relevant test in ASTM Standard D226, it is discussed before ASTM Standard D4869 to compare their classification difference.

#### **2.4.2.1 ASTM Standard D779-16**

**Material requirement:** This test method is designated for WRBs, flexible flashings, and other construction materials. Not appropriate if the materials contain large amounts of water-soluble components.

**Test method:** The standard introduces two apparatus, a float arrangement and a boat.

**Float arrangement:** Make a thin-walled aluminum pan that has a diameter of approximately 5 in. and a height of 1 in. with a hole of 2 in. cut in the bottom. A watch glass is clamped above the specimen by a “wire-frame clamp”. The earlier version of this standard, ASTM Standard D779-03, contains content that when there is no float available, the material can be supported by a hollow cylinder and a figure is included (Figure 6).



FIG. 1 Cross Section of Float

FIGURE 6 CROSS SECTION OF FLOAT, ASTM STANDARD D779-03

In the 2016 version, the mentioned content is moved to the boat section as an alternative for materials that have difficulty flowing independently, and the figure is deleted. The description of the float arrangement and the hollow cylinder is not clear even when there was a figure.

**The boat:** Form a boat by folding the edges of the sheathing membrane and float it on top of distilled or demineralized water. The dry indicator powder should be sprinkled on the top surface of the boat. The test can be conducted either with a watch glass covering the boat to stop moisture from escaping or not. Figure 7 below shows the test setups (Dunlap and Flock, 2019).

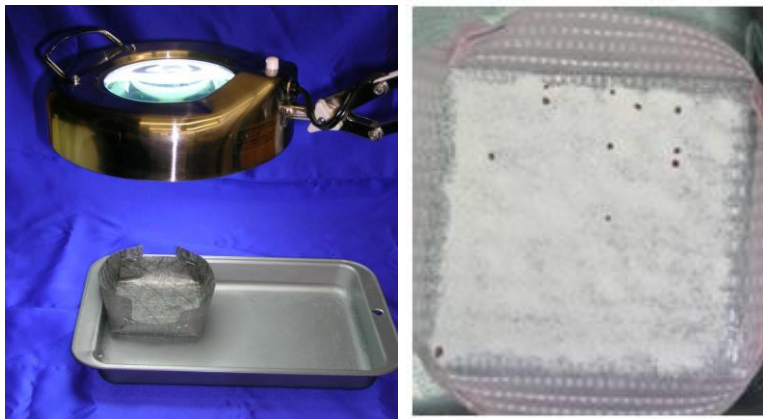


FIGURE 7 THE BOAT TEST (DUNLAP AND FLOCK, 2019)

**Measurement and report:** Five tests on each side of the specimen unless the material has a specified side to get in contact with water. The distilled or demineralized water used for the test should be  $23 \pm 0.5^{\circ}\text{C}$ . The test measures time required for water vapor to pass through the membrane, which is indicated by the color change of the indicator powder. The two averages of five tests on each side need to be reported respectively unless only one side is used for testing. Whether the test used a watch glass or not needs to be recorded.

**Problems and limits:** In ASTM Standard D779-03, the name was “Standard Test Method for Water Resistance of Paper, Paperboard, and Other Sheet Materials by the Dry Indicator Method”, and its scope was about finding the time for water to pass through a specimen. The 2003 version was withdrawn in 2011 and reissued in 2016. In the 2016 version, the standard name is changed to “Standard Test Method for Determining the Water Vapor Resistance of Sheet Materials in Contact with Liquid Water by the Dry Indicator Method” and the scope is also changed to the time required for water vapor to pass through a sheet membrane. ASTM Standard D779-03 indicated that in the first 30 seconds of the test, liquid transudation is dominant but after 30 seconds, when the vapor-transmission rate increases its influence, the measurement of liquid water resistance is not valid. The 2016 version deleted this statement and eliminated all liquid water measurement parts. Therefore, the current version of this standard is no longer a standard to measure liquid water penetration but a standard that measures water vapor.

Another problem is the expression of the float arrangement is still awkward and hard to be understood. No literature that includes the float arrangement is found. All researchers only talk about the boat test when referring to ASTM Standard D779. It is not very meaningful to introduce two apparatus setups when only one of them is understood and used by researchers.

If focusing on the experiment process, the test is subjective and lacks accuracy. The test procedure uses descriptions like “sprinkle the indicator on the specimen by gently tapping the inverted shaker until a thin, even layer is formed...” and mentions either too little or too large amount of powders will affect the test results. It does not quantitatively define “thin” and have to be found out by practice. Because the sprinkle is done with human hands, the powder layer could be different for every test or not evenly distributed in some tests. It says “handle the test specimen with care once the powder is applied for jarring or excessive tipping may cause rearrangement of the powder particles”. At the same time, it requires the researcher to cover the

boat with a watch glass and seal it with paraffin wax to prevent moisture from escaping. There must be excessive tipping when covering the boat and sealing it. Consequently, the results could be affected. If not using a watch glass, the moisture could escape and the result is affected as well. A good test design should consider reducing the procedures that need the researcher to be extra skillful, avoid non-quantifiable or repeatable steps, and all procedures should be designed reasonably so they will not affect other procedures.

#### **2.4.2.2 Water Resistance Ponding Test**

This test is first explicated in CCMC *Technical Guide for Sheathing, Membrane, Breather-Type*, Section 6.4.5 according to Butt (2005). The original file is not found but is included in ASTM E2556, Section A1.1. Because the CCMC file can not be found, the review of the water ponding test in this work will be based on ASTM Standard E2556/E2556M-10 (2016).

**Material Requirement:** This standard evaluates vapor permeable flexible sheet materials. The material needs to be Type I WRB. The performance requirements of Type I WRB are given in Table 2 at the beginning of this section.

**Test method:** The specimen should be placed between two 200-mm diameter aluminum rings and the ring on the top side should be able to hold distilled water of 25 mm in depth. 16000 mm<sup>2</sup> of the specimen should be exposed to 25 mm of water and frequent inspection of water passage through the membrane is required in two hours. A sheet of plain kraft paper should be placed beneath the specimen to help monitor water passage and the ring should be raised 250 mm above the kraft paper.

The “water ponding test” usually refers to the waterproof test of bathroom floors in daily life. Only two testing photos of water ponding tests to test liquid water penetration of WRBs are found (Figure 8). It is obvious that both devices have some modifications from the above description but their descriptions of apparatus setup are not available



FIGURE 8 WATER PONDING TESTS (A) DUNLAP AND FLOCK,2019 (B) FINCH, 2018B

**Measurement and report:** For one WRB material, five specimens should be used. The specimens should be maintained at a temperature of  $23 \pm 2^{\circ}\text{C}$  and R.H. of  $50 \pm 5\%$ . The test gives a pass/fail result for each specimen if there is water passage through the membrane in two hours. The material type and the side used, the sampling procedure, and any modification applied should be recorded as well.

**Problems and limits:** The test method's expression is vague and not precise. It is hard to design an apparatus based on the description. The original expression for the test method is “a ring shall be constructed with a sample of the membrane fastened between two 200-mm [8-in.] diameter aluminum rings using a rubber-type gasket. The membrane shall be placed between the rings and cupped to permit a depth of 25 mm [1 in.] of water to be exposed to  $16000 \text{ mm}^2$  [ $25 \text{ in.}^2$ ] of its surface”. It only declares one 200-mm diameter of the aluminum rings, which is the outer diameter. The inner diameter is not given directly. It needs to be speculated from the area of the specimen exposed surface of  $16000 \text{ mm}^2$ . The test method does not recommend how to clamp the two rings and how to get a cupped shape to hold the 25 mm of water. In Figure 8 (a), the black membrane is clamped by six bolts, where two foam like sheets are placed between the rings and the two sides of the membrane specimen. They help with sealing and cushioning to a limited extent and if the bolts are not properly tightened, water will leak. The test method also includes “the ring shall be raised by 250 mm [9.8 in.] above a sheet of plain kraft paper placed underneath the membrane to aid in monitoring any passage of water”. It does not mention how to raise the ring by 250mm and the place of the plain kraft paper causes ambiguity. Based on the description, it could mean the paper is placed under the bottom ring at a distance of 250mm or the paper is placed just under the membrane specimen and both the paper and membrane specimen are clamped by the two rings. A more precise guide should be provided so the researchers can build similar devices to obtain repeatable and comparable results.

Other than the ambiguous expression, the test result is hard to observe and not accurate. When a test is running, one should regularly check the underside of the membrane specimen to see if water penetrated. Firstly, the bottom ring has to be supported by some mechanism to lift it from the workspace and allow people to observe water passage. In Figure 8 (a), Even if it is raised by 250mm, the researcher will still need to bend his head at a strange angle to look inside the bottom ring. In Figure 8 (b), the device does not seem to be able to get supported and lifted from the table in a simple way. Adding a light source and a mirror or digital camera under the device could help, but frequently checking is still required. If two researchers generate very similar devices and test on the same material, but one checks the result every five minutes and another decides to check every ten minutes, their results could be different. If the material starts to have water passage through at 4 minutes, the first researcher will get an error of one minute and the other one will get an error of 6 minutes. This error is unavoidable unless the researcher keeps staring at the bottom of the ring until water leakage happens in the two hours, and it is not feasible. Even with a five-minute observation, the researcher still needs to check up to 24 times in the two-hour period, which is a lot of manual effort. Improvement that can make some progress to be automatic would help a lot.

Last but not least, this method tests very limited types of WRBs and only gives pass/fail results instead of quantifiable factors. It can check if one material meets the requirement, but it is impossible to compare two materials with pass results. Thus, researchers cannot test a variety of WRB materials and rank their water resistance performance by conducting the Water Ponding Test.

#### **2.4.2.3 AATCC Test Method 127**

**Material Requirement:** This test method tests all types of fabric.

**Test method:** AATCC Test Method 127-2008 introduces the Hydrostatic Tester that measures a fabric's resistance to the penetration of water under constantly increasing hydrostatic pressure. Two apparatus options are given to finish the measurement.

Hydrostatic Pressure Tester (Suter): The apparatus consists of an inverted conical well with a coaxial ring clamp and the specimen is fastened under the well bottom. During the experiment, the overflow device should be set at 10 mm/s. Record the hydrostatic

pressure after three valid droplets penetrate the specimen. Water droplets within 3mm of the clamping edge should not be counted.

This Suter apparatus is not available for sale anymore. Another available Hydrostatic Pressure Tester on the market is shown in Figure 9 below.



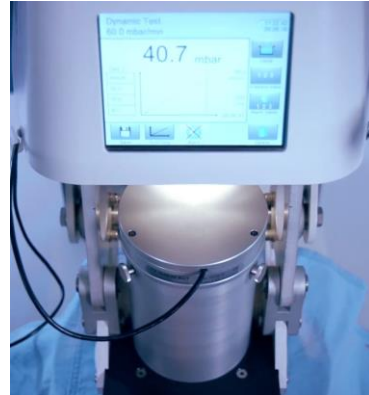
**FIGURE 9 HYDROSTATIC PRESSURE TESTER FROM TESTEX**

Textest FX3000 Hydrostatic Head Tester: An electronically controlled pump is used to apply 60 mbar/min adjustable hydrostatic pressure to the specimen. A circular reservoir with an area of  $100 \pm 5 \text{ cm}^2$  holds distilled or deionized water. The specimen is placed above the reservoir with a coaxial clamp and viewing lamps are equipped for better observation. Record the hydrostatic pressure after three valid droplets penetrate the specimen. Water droplets within 3mm of the clamping edge should not be counted.

The newest FX3000 is on its fourth generation, called FX 3000 Hydro Tester IV, as shown in Figure 10 (a). A cylindrical automatic drop detector can be equipped to detect the droplets that appear on top of the specimen, as shown in Figure 10 (b). Figure 11 (a) is a view on top of the specimen with three water droplets appearing on the specimen surface. The automatic drop detector detects these droplets and their exact positions are shown on the machine screen in Figure 11 (b).



FIGURE 10 (A) FX 3000 HYDRO TESTER IV



(B) AUTOMATIC DROP DETECTOR

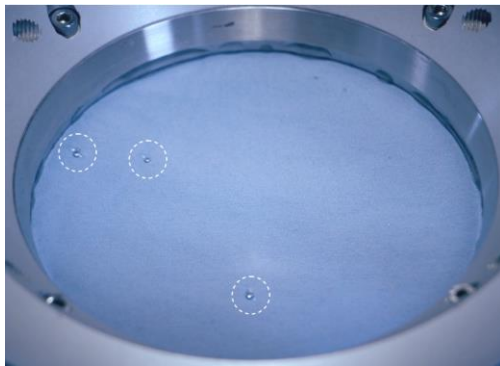


FIGURE 11 (A) WATER DROPLETS ON FABRIC SURFACE



(B) AUTOMATIC DROP DETECTOR OUTPUT

**Measurement and report:** At least three specimens from the same fabric should be tested. The specimens should be kept in an environment of  $21 \pm 2$  °C in temperature and  $65 \pm 2\%$  in R.H. for at least four hours before the test starts. The result to be recorded is the hydrostatic pressure when water droplets penetrate the fabric in three spots. The average hydrostatic pressure for each sample should be calculated. The side used of the specimen needs to be specified. The rate of increasing water pressure, the tester option and modification to the method should be recorded.

**Problems and limits:** AATCC Test Method 127 tests water resistance of all types of fibers and it is not specifically designed to test WRBs used in building constructions. It is generally used for testing water resistance of protective clothing, tent and waterproof jackets under hydrostatic pressure. These materials usually have direct contact with the environment and could experience heavy wind driving rain in their uses so different levels of hydrostatic pressure need to be applied based on the application of each material. However, a WRB is installed behind cladding and in most cases, only water that penetrates the exterior covering will get in contact with the WRB.

For WRBs, the primary consideration is not the pressure but the amount of water getting through the cladding and the time that the WRB remains wet. Therefore, hydrostatic pressure is not the most appropriate measurement for WRBs water resistance.

#### 2.4.2.4 ASTM Standard D226 and ASTM Standard D4869

Although felt material is one type of WRB, it is applied more on the roof construction than wall assemblies. Both ASTM Standard D226 and ASTM Standard D4869 target asphalt-saturated organic felts. ASTM D226 mentioned the felts could be perforated or not but in IBC, only the non-perforated felt is referenced as a WRB. The asphalt-saturated organic felt tests in ASTM D4869 are declared to be used beneath steep slope roofing. This research focuses on WRBs commonly used to construct a wall assembly; thus, the different classifications of felt material in the two standards will not be discussed in detail while the water exposure test determines the resistance to liquid water transmission in ASTM D4869 is included.

**Test method:** The apparatus is shown in Figure 12. A shower head is mounted above the sink to provide a heavy shower. Each single thickness sheet specimen should be mounted on a plywood board. The board is then placed in the sink with an incline of  $14^\circ$  and the center of the board is directly below the shower head of 460mm. Open the shower head, regulate the flow between 42 to 44  $\text{cm}^3/\text{s}$  and run for four hours. After four hours, check if the back side of any test specimen has any sign of wetness or deterioration.

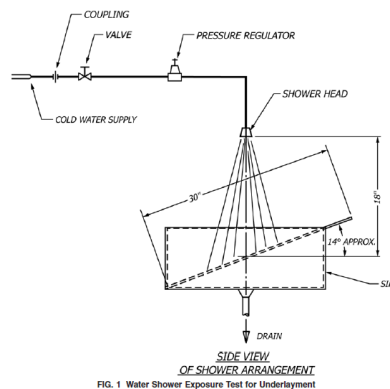


FIGURE 12 WATER SHOWER EXPOSURE TEST (ASTM D4869/D4869M-16A (2021))

**Measurement and report:** The board should be conditioned at 21 – 27 °C and 30 – 55% R.H. for 24 hours before the test. Two specimens should be tested from each roll of product. If the back side of the specimen or the contact surface of the plywood board does not have a sign of

wetness and no visible deterioration is found on any specimen, the test is recorded as a pass. Otherwise a fail should be recorded.

**Problems and limits:** This test method tests limited types of WRB materials as it is designed only for felt materials. The compliance with the test is evaluated by eye observation to see if there is a sign of wetness or deterioration of the specimen, which is subjective and lack of accuracy. The result only gives a pass or fail result and lacks a parameter that can qualify the water resistance of the specimen.

#### 2.4.2.5 Federal Specification UU-B-790a

**Material Requirement:** This specification tests building papers composed of sulphate pulp fibers.

**Classification:** UU-B-790a gives a complex classification of building papers into four types, and each type has subdivisions of types and styles. The types, grades, and water resistance requirements for each grade is included in Table 3. Styles are omitted because they are too specific.

**TABLE 3 BUILDING PAPER TYPES AND REQUIREMENTS OF WATER RESISTANCE IN HOURS**

Type	Grade	Requirements of water resistance (h)
Type I - Barrier paper	Grade A - High water-vapor resistance	24
	Grade B - Moderate water-vapor resistance	16
	Grade C - Water resistant	8
	Grade D - Water-vapor permeable	1/6
Type II - Concrete-curing paper	Grade E - Moisture retentive	-
Type III - Fire-resistant paper	Grade F - Water repellent	-
Type IV - Insulation tape paper	Grade G - High tensile strength - water resistant	24

In this specification, concrete-curing paper, fire-resistant paper, and insulation tape paper are included in barrier paper, but they are not usually WRBs. The Grade D barrier paper needs to

withstand the water test for at least 10 minutes and it is the minimum water resistance requirement of WRBs.

**Testing method:** Federal Specification UU-B-790a refers to a water resistance test in UU-P-31 Method number 181. The method is called dry-indicator method and it tests the time of penetration of water through papers and paperboards. The boat test in ASTM Standard D779 came from this test method. Same as in ASTM Standard D779, the specimens are placed in a water bath with their edges turned up or dipped with wax. The indicator reagent is sprinkled on top of the membrane specimen with care. A watch glass seals over the indicator powder is required for better observation of the indicator reagent color change.

**Measurement and report:** Water temperature should be maintained at 23°C +- 0.5°C. The water announced in this test is tap water. For one material, five tests are required for each side. The time of color change in the indicator should be recorded and the result will be the average of the recorded time in minutes or hours.

**Problems and limits:** The standard is regarded as obsolete by ASTM Standard E2556-10. The boat test in ASTM Standard D779 is derived from this test. It is already updated that this method tests water vapor permeability of the specimens instead of their resistance to liquid water. The other limits are the same as the limits listed in ASTM D779.

#### **2.4.2.6 AC38 Acceptance Criteria for Weather Resistive Barriers - 2004**

This standard does not have its own test method of water resistance. Instead, it listed the three types of WRBs same as in ASTM E2556, paper-based barrier, felt-based barrier and polymeric-based barrier, and the codes they should comply with. Section 4 illustrates the specimen preparation of Weathering Tests for polymeric-based WRBs where three samples are needed, one is the control specimen and the other two samples need aging treatment. The test is then conducted based on AATCC 127 with the hydrostatic head to be 55 cm for five hours.

Dunlap and Flock (2019) include cited some paragraphs of AC38 but the standard version is not stated. Section 3.3.2 is the same as in AC38 (2004) while Section 4.2 has a Water Ponding Test same as Water Resistance Ponding Test in ASTM Standard E2556/E2556M-10 (2016) Section A1.1, except the room shall be kept at 20 +- 2° and 65 +- 3% R.H.



**Method B:** This method is intended for high pressure applications such as special roofs, tunnelling and tanking. The device is shown in Figure 14 (a) and the required dimension of the slotted plate is shown in Figure 14 (b). The test specimen (3) has the same diameter as the external diameter of the slotted plate (6) around 130 mm. During the test, the device is filled with water until overflowing. The specimen (3) is placed with its upper side downwards and the slotted plate (6) is placed on top of it. One of the slots (1) should be parallel with the longitudinal direction of the specimen. A cover is applied on top of the plate and the specimen should be tightened properly. Required hydrostatic pressure (4) is applied progressively.

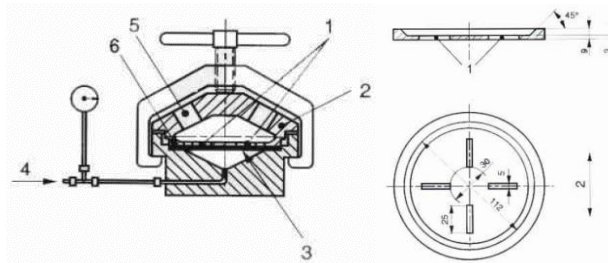


FIGURE 14 (A) SLOT PRESSURE TESTING APPARATUS (B) SLOTTED PLATE, BS EN 1928:2000

**Measurement and report:** The measurement should be conducted at  $23 \pm 5$  °C. There should be at least three test specimens for each test. Both test methods should maintain the pressure for  $24 \pm 1$  hours. For method A, when no discoloration is found on the upper filter paper for all specimens, the sheet passes the test and is considered to be watertight. For method B, if there is no sudden pressure drop or water observed on the dry side of all specimens, the sheet material passes the test and is considered to be watertight.

**Problems and limits:** This test method has a long history since 1928. Although it is specified for roofing materials, it can be used for other waterproofing areas, such as WRBs used for exterior walls. Also, some WRB manufacturers use this test method for their water resistance rating. This standard provides two test methods for low and high pressure applications. The low pressure one uses moisture indicating mixture to identify liquid water passing through, similar to ASTM Standard D779. Thus, it has problem with distinguishing liquid water and water vapor same as ASTM Standard D779. Although the apparatus for both methods have comparatively complex mechanisms, their test results still need to be observed by human eyes and only provide a pass/fail result.

### 2.4.3 PREVIOUS TESTS HAVE BEEN DONE

Williams (2004) studies the water resistance performance of three types of WRBs, Typar and Tyvek, which are polymer-based WRBs, and No. 15 building felt, which is a felt-based WRB. Rainwater, a cedar extractive/rainwater solution, and a powerwash/water solution are used as bulk moisture source respectively. Three different installation scenarios, no contact with oriented strand board (OSB) sheathing, contact with OSB sheathing, and contact with OSB sheathing with staple installed, are applied. The test method is based on the CMCC Water Ponding Test. The tests use rainwater as a moisture source and when there is no contact with OSB use one specimen for each material. No liquid pass-through is found for all specimens but the No.15 building felt has 0.9g weight gain after the two hour test period. The material with other installation scenarios have different results but they are not discussed here.

In Williams (2010), he studied the water resistance performance of five different WRBs using Water Ponding Test. The five materials are non-adhesive, adhesive, and drainage quilted housewrap, three-dimensional surface formed sheet, and creped housewrap. When only the WRB is installed, all five materials passed the test with 1 in. water head for two hours.

Butt (2005) compares water resistance performance results of three materials based on AATCC Test Method 127 using single and double layer of material, ASTM Standard D779, and CCMC Water Ponding Test. The tests results are summarized below in Table 4. In the test based on AATCC Test Method 127, when pressure is a factor, asphalt-saturated kraft paper resists higher pressure than felt material and polymer housewrap resists three times pressure of kraft paper. In the test based on ASTM Standard D779, asphalt-saturated felt has better performance than asphalt-saturated kraft paper and polymer housewrap has the worst performance. The tighter matrix in kraft paper helps it perform better under pressure while more asphalt in felt helps it resist migration of water for a longer period when pressure is low.

**TABLE 4 WATER RESISTANCE OF THREE WRB MATERIALS, SUMMARIZED FROM BUTT (2005), TABLE 2**

Test Method	AATCC Test Method 127-1998 (single layer)		AATCC Test Method 127-1998 (double layer)		ASTM D779	CCMC Water Ponding Test
	Water Head (cm)	Pressure (Pa)	Water Head (cm)	Pressure (Pa)	Water Penetration Time	Pass/Fail

ASTM D226 # 15 Felt (Type I)	60.9	5998	106.8	10480	6h 13min 10s	Pass
60-min, Asphalt- Saturated Kraft Paper	90.9	8894	130.9	12824	1h 3min 20s	Pass
Polymer Housewrap	249.2	24476	375	36818	9min 33s	Pass

Weston et al. (2006) report the water transudation time results from ASTM Standard D779 for four spun-bonded polyolefin (SBPO) housewraps and the hydrostatic water head of several WRBs tested in AATCC-127. The ASTM D779 test results are shown in Table 5, where the transudation time is an average of ten measurements while the hydrostatic head and vapor permeability are from the manufacturer’s literature. The transudation time varies a lot between different SBPOs and there is no apparent relationship between them and the hydrostatic head or vapor permeability. Also, for one type of SBPO, the result can be very different. **Error! Reference source not found.** shows the distribution of measurements on SBPO #4. The histogram is not in normal distribution and the transudation time ranges from 141 to more than 480 minutes. The hydrostatic head results from AATCC-127 of several WRBs are given in Table 6.

TABLE 5 ASTM D779 RESULTS, FROM WESTON ET AL. (2016), TABLE 2

	SBPO #1	SBPO #2	SBPO #3	SBPO #4
ASTM D779 (minutes)	19.6	23.8	149	304
Hydrostatic head (cm)	>210	>210	>210	>280
Vapor permeability	58	50	26	28

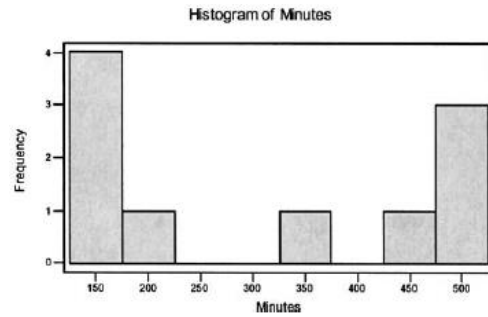


FIGURE 15 DISTRIBUTION OF ASTM D779 MEASUREMENTS ON SBPO #4, WESTON ET AL. (2016)

TABLE 6 HYDROSTATIC HEAD OF SEVERAL WRBs, WESTON ET AL. (2016)

WRBs	Hydrostatic head (cm)
Perforated polymer-based	10 to 27
Nonperforated polymer-based (SBPO)	>210 to >280
Nonperforated polymer-based (film laminate)	130 to >180
Paper-based (10 Min Grade D)	65 to 99
Paper-based (60 Min Grade D)	67 to 103
Felt-based	59 to 80

#### 2.4.4 SOME AVAILABLE WRBs IN CANADA

A total of 10 membrane materials were purchased from online and local retailers in 2019. All materials were sold as WRBs by the retailers. Research on their product specification was done after receiving the materials. The product names to be used in this work and the corresponding material compositions are given in Table 7. Available information on the water resistance rating, water vapor permeance and air permeance of the materials are included in Table 8. The product datasheets used to create the two tables are available in the Thesis Repository.

TABLE 7 PRODUCT NAME AND MATERIAL COMPOSITION

#	Membrane Name	Material
1	Membrane A	3-layered; microporous functional layer, reinforced on both sides with P.P. nonwoven
2	Membrane B	100% flash spunbonded high density polyethylene fibers
3	Membrane C	Protective and covering fleece: Polypropylene microfiber Membrane: monolithic TEEE

4	Membrane D	Spunbonded polypropylene weather membrane with a microporous coating, nonwoven, nonperforated
5	Membrane E	Textured top anti-slip surface along with a superior backside coating using a uniquely engineered polyolefin blend
6	Membrane F	Asphalt-saturated kraft paper
7	Membrane G	Covers: Polypropylene microfiber fleece Membrane: vapour-variable polyethylene copolymer
8	Membrane H	An engineered film and a patented, permeable adhesive technology with split-back poly-release film
9	Membrane I	An engineered film and a patented, permeable adhesive technology with split-back poly-release film
10	Membrane J	Backing: Multilayer Elastomeric Film, Adhesive: Acrylic, Liner: Polycoated Kraft

**TABLE 8 WATER RESISTANCE RATING, WATER VAPOUR PERMEANCE AND AIR PERMEANCE**

#	Name	Water Resistance Rating	Water Vapour Permeance	Air permeance
1	Membrane A	AATCC 127 11 inch	ASTM E96 Method A 54 US Perms Method B 68 US Perms	ASTM E2178 0.0002 cfm/ft <sup>2</sup> @ 1.57 psf (0.0008 L/m <sup>2</sup> .s @ 75 Pa)
2	Membrane B	AATCC 127 280cm	ASTM E96-00 Method A 23 perms* Method B 28 perms	ASTM E2178 0.001 cfm/ft <sup>2</sup> @1.57 psf; ASTM E1677 Type 1
3	Membrane C	AATCC 127 > 2,500 mm	ASTM E96 38 US perms	Passed ASTM E2178<0.004cfm/ft <sup>2</sup>
4	Membrane D	ASTM D779 ASTM E2556, Type II Water- Resistive Barrier	ASTM E96-90 Method A 9-15 perms	ASTM E1677 Type I Air Barrier Material; Aie-Ins (Air leakage Test) ASTM E283 <0.02L/S*M <sup>2</sup> @ 75 PA
5	Membrane E	N/A	N/A	N/A
6	Membrane F	UUB-790a, (1-ply) 30-45 minutes (2-ply) >2.0 Hours	ASTM E96-90 4.8 metric Perms	@ 100 pa: 0.175L/m <sup>2</sup> , sec.
7	Membrane G	N/A	ASTM E96 0.17 perm in winter, 6 perm in summer	ASTM E2178 <0.00005 cfm/ft <sup>2</sup>

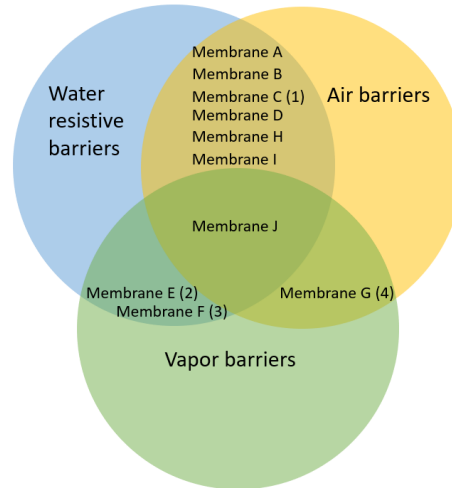
8	Membrane H	ICC - ES AC38, PASS	ASTM E96 Method A 33 perms	ASTM E 2178 maximum 0.02 L/m <sup>2</sup> @75PA, PASS (typo, should be L/s.m <sup>2</sup> )
9	Membrane I	ICC - ES AC38, PASS	ASTM E96 Method A 29 perms	ASTM E 2178 maximum 0.02 L/s.m <sup>2</sup> @75PA, PASS
10	Membrane J	AATCC127 (deviated): 55 cm (21.6 inches) of water for 5 hours, No leakage	ASTM E96 Method A 0.14 US perm Method B 0.26 US perm	ASTM E2178 @ 75 Pa < 0.0002 L/s.m <sup>2</sup> (<0.00005 cfm/ft <sup>2</sup> )

\*According to ASTM E96, the unit perm should be U.S. perm instead of metric perm.

Some materials are defined by their manufacturers as an air barrier or a vapor barrier and some materials are not defined as a WRB in their datasheets. Most materials provide test results of water resistance, vapor permeance and air permeance but some material such as Membrane E, is defined as a water resistive vapor retarder without any test result provided. There are also some materials have a conflict between their definition and test results according to code requirements.

The requirements for sheet materials to be WRBs are given in Section 2.4.2. For an air barrier, ASTM PCR (2017) states an air barrier material should have air permeance  $\leq 0.02\text{L}/(\text{s}\cdot\text{m}^2)$  at a pressure difference of 75 Pa (0.004 cfm/ft<sup>2</sup> at a pressure difference of 1.56 lb/ft<sup>2</sup>) when tested by ASTM Standard E2178. Whether a material is a vapor barrier or not is determined by its vapor permeance. Vapor retarders should have vapor permeance not greater than 10 perms determined by ASTM Standard E96, Procedure B (water method). 2012 IBC defines that a vapor permeable membrane should have a vapor permeance rating equal to or more than 10 perms ( $5.7 \times 10^{-10} \text{kg}/\text{Pa}\cdot\text{s}\cdot\text{m}^2$ ) when tested by ASTM Standard E96, Procedure A (desiccant method). Vapor retarder class is defined by the desiccant method as well. Class I vapor retarder has vapor permeance of 0.1 perm or less, class II has vapor permeance greater than 0.1 perm and less than 1 perm, and Class III has vapor permeance greater than 1 perm and less than 10 perms.

Figure 16 classifies the 10 materials into WRB, air barrier, vapor barrier or any combination of them based on their manufacturer definition and the given property values. When there is a conflict between the definition and property value, the property value is prioritized with details listed below.



**FIGURE 16 MATERIAL CLASSIFICATION**

(1) The datasheet of Membrane C was updated in March 2021. The old datasheet was downloaded online at the same year when the material was obtained. The material was described as an airtight weather resistant barrier in the old datasheet while in the new datasheet, it is defined as a reinforced roof underlay. In the latest datasheet, the water vapor permeance is changed from 38 U.S. perms to 65 U.S. perms and the regulation used for the water column test is also changed. There could be a product update in 2021. The old datasheet was used for reference because the material was obtained in 2019.

(2) Membrane E is defined as a water resistive vapor retarder in its brochure but there is no test result of water resistant, vapor permeance or air permeance included.

(3) Membrane F is characterized as having good “water resistance”, good “water vapour permeability” and good “air barrier properties” by its manufacturer. However, the same document shows it has water vapour permeability (wrong expression, should be permeance) of 4.8 metric perms, which is around 3.16 US perm. Membrane F should be a class III vapor retarder based on this value according to the 2012 IBC. The air barrier rating at 100 Pa is 0.175 L/m<sup>2</sup>, sec. The test method used to obtain this value is not given. The unit is the same as the air permeance unit used in ASTM E2178 but the pressure is 25 Pa higher than the requirement in ASTM International (2017) and 0.175 L/(s\*m<sup>2</sup>) is way larger than 0.02 L/(s\*m<sup>2</sup>) so this material is not qualified for an air barrier. It should be considered as a WRB and vapor barrier.

(4) Membrane G is an air barrier membrane and smart vapor retarder and can be used as a temporary WRB according to its specification sheet but there is no water resistant test mentioned in the file. Also, based on the product website, this product is supposed to be used in the interior of the building. Therefore, it is considered as an air barrier and a vapor barrier but not a WRB here.

## 2.5 GAPS IN KNOWLEDGE AND RESEARCH OBJECTIVES

There is not a perfect standard to test liquid water resistance of WRBs. ASTM Standard D779 measures the time required for the WRB to be penetrated but the result is dominated by water vapor so it should not be used for liquid water resistance evaluation. The Water Ponding Test, ASTM Standard D4869, and British Standard BS: EN:1928 provide pass/fail results after human observation so the results could be subjective and not precise. They lack a quantitative factor to describe the water resistance performance of WRBs. The Water Ponding Test and ASTM Standard D4869 have strict requirements for the tested materials so they cannot be applied to most WRBs. The test method descriptions of ASTM Standard D779 and Water Ponding Test are not clear thus it could cause ambiguities during testing. Compared to other test specifications, AATCC Test Method 127 has a clear manner of description, can be applied for a wide range of WRBs, and provides a result of hydrostatic pressure when water penetration occurs. The newest version of the test apparatus can detect the water drop automatically and record the hydrostatic pressure result in the program file. However, this standard was not specifically designed for WRBs but for waterproof materials like tents or jackets that could experience very high hydrostatic pressure. Hydrostatic pressure is not the most crucial factor for evaluating water resistance of WRBs due to the application environment. A better measurement is the time that a WRB can resist liquid water under constant pressure.

The research objectives of this work are:

1. Complete laboratory verification and apply any necessary improvement for the hydrostatic pressure test apparatus (HPTA) developed by SMT Research Ltd. The device has a sensor that measures electrical resistance. It is supposed to be able to differentiate between water vapor and liquid water. Its design has drawn experience from AATCC 127. The first objective is to verify the accuracy and repeatability of the measuring system as well as fix any design flaw. The

original HPTA device has a water leakage problem through its screw mechanism and impactful improvement is made to the clamping method.

2. Conduct tests using different WRB materials and evaluate the liquid water resistance performance by ranking the time that each WRB gets penetrated by liquid water. Six WRBs are selected for membrane test using the modified device. Although the HPTA apparatus is developed based on AATCC Test Method 127, the final membrane test method in this work has changed a lot and can be considered as a totally different new test method.

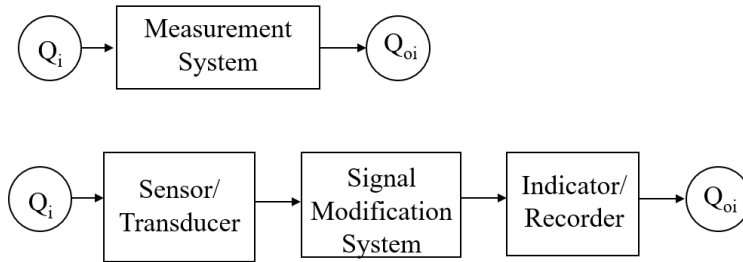
## CHAPTER 3 METHODOLOGY

This section explains the components of the measurement system, including the measurand, the sensor, the signal modification system and the indicator or recorder. The testing methods for the apparatus and the modifications that followed are also detailed in this section. Three different sensor tests are introduced with error analysis and validation.

Two testing devices are discussed in this work. The first device is the Hydrostatic Pressure Test Apparatus (HPTA) provided by SMT Research Ltd. The main difference between HPTA and the other testing methods discussed above is that instead of using the human eye to observe the presence of liquid water, HPTA has an integrated sensor platter that measures electrical resistance to detect and recognize the penetrated liquid water. Therefore, this measurement system is tested to determine if it could measure the liquid water amount penetrating the membrane as a quantifiable, digital value. When stepping into WRB tests, the device is found to have water leakage problem through the joints. Several modifications are applied to solve the problem but the results are not ideal. The mechanical parts of the device to hold the sensor is redesigned and replaced while all electrical components remain unchanged. The design process is given in Section 3.3.

### 3.1 THE MEASUREMENT SYSTEM

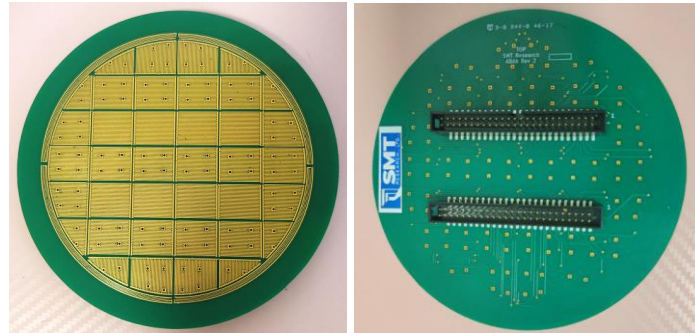
By using a measurement system, the measured variable can be quantified (Figliola and Beasley, 2011). Figure 17 shows the components of a simple measurement system. The dynamic variable  $Q_i$  is the true value of variable  $Q$  at time  $i$ , and  $Q_{oi}$  is the observed value of  $Q_i$ . In this research, the measurand is moisture, more specifically, the liquid water that has penetrated through water resistive barriers ( $\text{ml}/\text{cm}^2$ ). As the Figure indicates, the measurement system is comprised of a sensor (also known as a transducer), a signal modification system (SMS) that affects the sensor's output, which is then forwarded to an indicator or recorder that provides the direct value of  $Q_{oi}$ . The difference between HPTA and the modified HPTA is the method to hold the sensor in place while they share the same electrical elements. Therefore, the two devices have exactly the same sensing element, the SMS, as well as the indicator or recorder.



**FIGURE 17 COMPONENTS OF A MEASUREMENT SYSTEM, MODIFIED FROM WHEELER AND GANJI, 2010**

### *3.1.1 THE SENSOR*

The sensor is a replaceable gold-plated copper sensor platter with 0.17mm mesh separation as shown in Figure 18. The copper sensor has excellent electrical conductivity, so it is sensitive enough to detect very slight changes in the measurand. It is coated with a thin layer of gold with outstanding corrosion resistance to withstand long test times without functional decay. It can be seen that the entire sensor is divided into 42 sections referred to as pads: 38 in the middle and four on the edge. Each pad works as an individual sensor that reads values that are output separately.



**FIGURE 18 HPTA SENSOR**

The pads are numbered alphabetically row by row, A1 to A4, B1 to B6, C1 to C6, D1 to D6, E1 to E6, F1 to F6, G1 to G4, and Edge Sensor 1 to Edge Sensor 4, as shown in Figure 19, (a). It is worth mentioning that the value reading sequence is based on the channel input but not the zone label. The channel input sequence is shown in Figure 19, (b) and the channel to sensor table is given in Appendix A. This will be explained further when explaining the circuit connection of connectors on the back of the sensor.

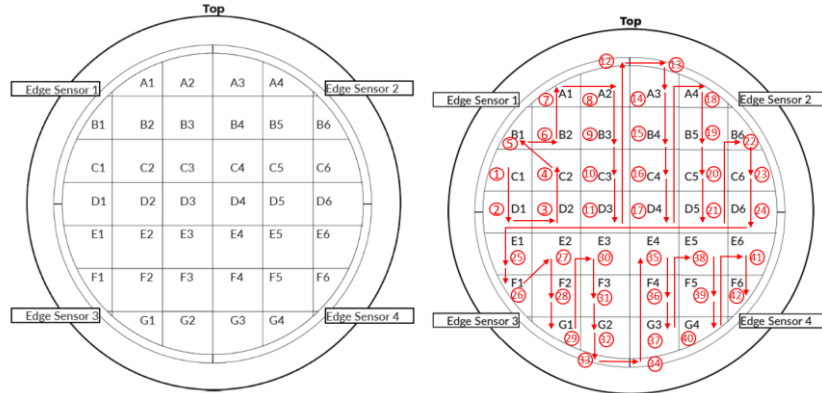


FIGURE 19 (A) SENSOR PLATTER LAYOUT (B) CHANNEL INPUT SEQUENCE

Figure 20, (a) gives a closer look of a rectangular pad in the middle of the sensor platter, its mesh pattern is simply two intersected combs. The composition can be seen clearer in the simplified sketch, Figure 20, (b). One thick line on the side is the positive pole and the other thick line on the other side is the negative pole. The thick lines are called the bus of the comb teeth, and the comb teeth are called branches.

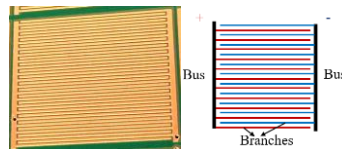


FIGURE 20 (A) POLAR COMB (B) SIMPLIFIED SKETCH

Figure 18 shows there are several different shapes of the pads, and except C2 to C5 and E2 to E5 are imperforated, all other pads have two or four holes on them. Some different shape of pads with four holes are given in Figure 21. The pattern is a little bit more complex than the imperforated pad since the holes cut the way of branches. The holes are bored for balancing the hydrostatic pressure of water applied on top of the sensor. They should not affect any sensor reading. Experiment discussed in later section validated this. The mesh patterns on different shape of pads are different but the composition of two polar combs remain unchanged for all shapes of pads and they should work in the same way.

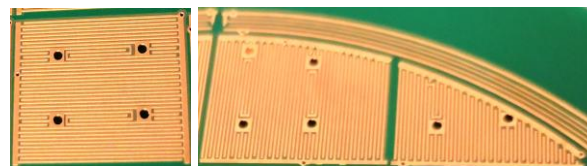


FIGURE 21 DIFFERENT SHAPES OF IMPERFORATED PADS

On the back of the sensor as shown in Figure 22, two 2.54mm pitch 2x25 50-pin PCB mount male flat ribbon cable connectors are used for flat cable-to-board connection. All 50 pins are soldered with the board but only 42 pins have the etched copper tracks connected with the 42 pads. The pins should be counted from right to left. Figure 6 labels the solder joints of positive and negative poles for all 42 pads, where row A and row G used T and B to express top and bottom and the other rows use L and R to express left and right.

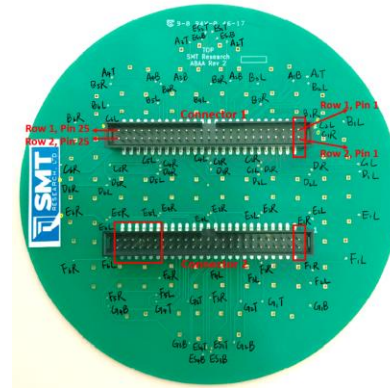


FIGURE 22 LABELS OF POLES

Figure 23 shows the copper track connections from channel 1 to channel 12 in different colors and the corresponding front view. It can be seen that the solder joints of the positive and negative poles of each pad are connected to one column of pins. For example, the first channel C1 (colored in orange) has its left solder joint connected to the second pin of row 2 and its right solder joint connected to the second pin of row 1. The corresponding relations from channel 1 to channel 12 are summarized in Table 9 below. Unused pins are circled in red in Figure 22, they are pin 1 of both connectors and pin 20 to pin 25 of connector 2.

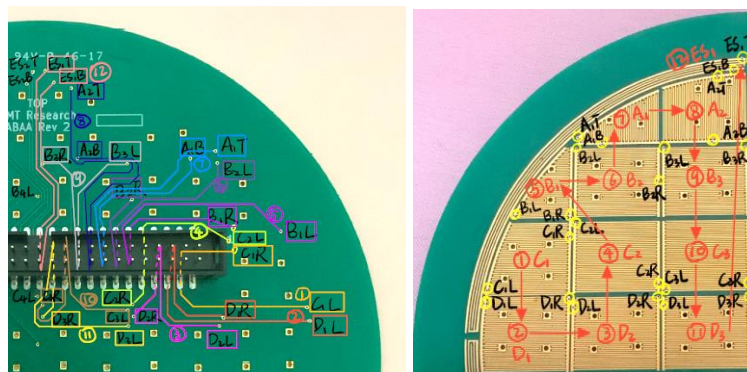


FIGURE 23 CIRCUIT CONNECTION OF CHANNEL 1 TO CHANNEL 12

**TABLE 9 PART OF SOLDER JOINTS AND THEIR CHANNEL NUMBER AND PIN NUMBER**

Channel #	12	11	10	9	8	7	6	5	4	3	2	1	Null
Pin #, Row 1	13	12	11	10	9	8	7	6	5	4	3	2	1
Solder Joint	ES1T	D3L	C3L	B3L	A2B	A1B	B2L	B1R	C2L	D2L	D1R	C1R	Null
Pin #, Row 2	13	12	11	10	9	8	7	6	5	4	3	2	1
Solder Joint	ES1B	D3R	C3R	B3R	A2T	A1T	B2R	B1L	C2R	D2R	D1L	C1L	Null

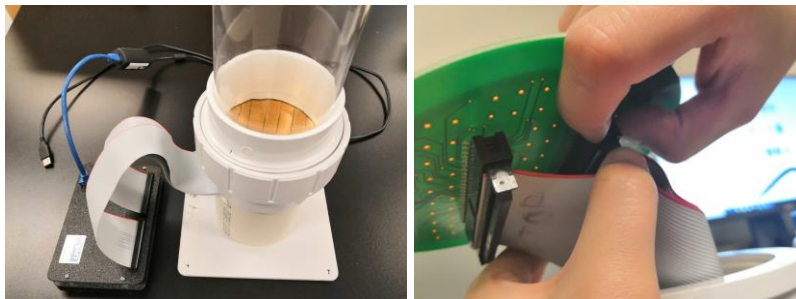
### 3.1.2 THE SIGNAL MODIFICATION SYSTEM

The signal modification system (SMS) modifies the output from sensing element to a more appropriate form (Wheeler& Ganji, 2010). The SMS of both HPTA is the black control box and the ribbon cable connects the control box and the sensor platter on the left of Figure 24, (a). The control box is called MultiScan™ 48R, which is a 48-channel data acquisition controller. The controller has two female connectors on it that can be connected with two ribbon cables that have male connectors on one side. The other sides of the two ribbon cables have female connectors that can connect with the connector 1 and connector 2 on the back of the sensor respectively, as shown in Figure 24, (b). The cable labeled with top should be connect to the upper terminal, vice versa. The output signals from the sensing element are voltage and current. In this SMS, Ohm’s law is used to obtain electrical resistance values.

$$V = IR, R = \frac{V}{I}, \quad (\text{eq 1})$$

Where  $V$  = voltage,  $I$  = current,  $R$  = resistance.

The input voltage is 6 to 12V D.C. and the highest output electrical resistance is 1GΩ. A schematic of ohm’s law in this system is draw in Figure 25.



**FIGURE 24 (A) CONTROL BOX AND RIBBON CABLE (B) CONNECTING RIBBON CABLE TO CONNECTORS**

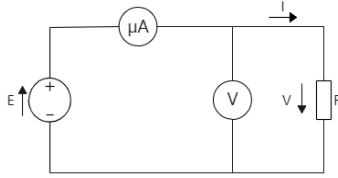


FIGURE 25 OHM'S LAW

### 3.1.3 THE INDICATOR AND RECORDER

The output value from SMS goes to either an indicator or recorder. An indicator can only display values, but the recorder can also save values (Wheeler& Ganji, 2010). During experiments, the controller needs to be connected to a personal computer via a CANKey to provide power as well as transfer data as shown in Figure 26. A CANKey is a CAN USB adaptor that has a CAN speed of 10kBits/s. A software Building Intelligence Gateway© (BiG) need to be used to collect the transferred data. The electrical resistance values from SMS are read and recorded in BiG's database. BiG also allows data exportation and data cloud sync as shown in Figure 27. The readings are completed in a time sequence from one pad to another according to the channel input order (see Figure 19 (b)). Here the BiG software is the indicator and recorder. The output signal of the measurement system is electrical resistance measured in Ohms.

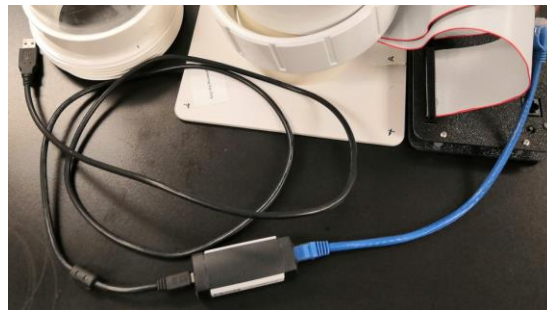


FIGURE 26 CANKEY

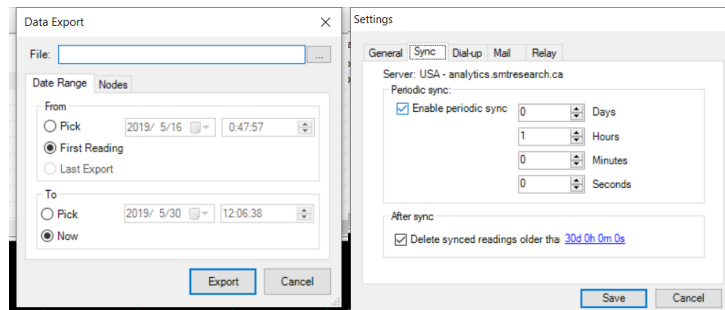


FIGURE 27 DATA EXPORTATION AND SYNCHRONIZATION SETTINGS

The values of electrical resistance indicate if each pad is dry or wet. The original value of a completely dry pad is  $1G\Omega$ . As the pad gets wetter, that is, as liquid water penetrates the WRB specimen, the electrical resistance decreases. An alarm can be set in the software; for example, a threshold value of a WRB specimen is perhaps set to  $2E+6\Omega$  such that any reading below this value will trigger the Alarm. The interface of the software is shown in Figure 28. When values drop below  $2E+6\Omega$ , the green light turns red and the alarm will be triggered. Figure 29 shows the triggered alarm as displayed in BiG.

Name	Node	Input	Type	Last Reading	Reading Date
C1	2517	1		4,060,645.00	19/03/29-18:05:22
D1	2517	2		3,287,312.00	19/03/29-18:05:23
D2	2517	3		318,991.00	19/03/29-18:05:25
C2	2517	4		299,854.00	19/03/29-18:05:26
B1	2517	5		9,032,904.00	19/03/29-18:05:27
B2	2517	6		663,379.00	19/03/29-18:05:29
A1	2517	7		3,154,445.00	19/03/29-18:05:30
A2	2517	8		514,409.00	19/03/29-18:05:31

FIGURE 28 BiG INTERFACE

Time Set	Time Cleared	Alarm	Sensor	Node	Input	Condition	Manually Cleared
19-05-08-10:54:05	--	Moisture	C6	2517	23	LessThan 2000000	
19-05-08-10:51:18	--	Moisture	Edge Sensor 1	2517	12	LessThan 2000000	
19-05-08-10:51:11	--	Moisture	A1	2517	7	LessThan 2000000	
19-05-08-10:51:10	--	Moisture	B2	2517	6	LessThan 2000000	
19-05-08-10:51:08	--	Moisture	B1	2517	5	LessThan 2000000	
19-05-08-10:50:42	--	Moisture	F6	2517	42	LessThan 2000000	
19-05-08-10:50:31	--	Moisture	Edge Sensor 4	2517	34	LessThan 2000000	
19-05-08-10:50:30	--	Moisture	Edge Sensor 3	2517	33	LessThan 2000000	
19-05-08-10:50:21	--	Moisture	F1	2517	26	LessThan 2000000	

FIGURE 29 BiG ALARM FUNCTION

Figure 30 below is modified from Figure 17. It summarized all measurement system components of HPTA.

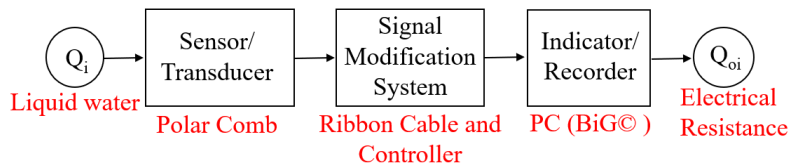


FIGURE 30 MEASUREMENT SYSTEM OF HPTA

In all current test methods for testing liquid water penetrating through water resistive barriers, the amount of liquid water passing through the membrane is not measured. HPTA monitors and outputs the real time electrical resistance of each pad. Observing the value changes makes it

possible to build a quantitative relationship between the electrical resistance in ohms and the amount of penetrated water in ml/cm<sup>2</sup>. With further development, the water penetration rate of each WRB material being tested could be determined.

### 3.2 SENSOR SENSITIVITY AND VALIDATION TESTING

In this section, the accuracy, repeatability, limits, and sensitivity of the HPTA sensor are tested by adding very specific amounts of water to each sensor pad directly and comparing the readings. In mechanical measurements, accuracy is defined as the bias error or systematic error in the instrument. This is obtained by calibrating the device against known values, with the known values being precise quantities of water applied to the sensor with the initial conditions being a completely dry sensor and electrical resistance reading of 1GΩ. Repeatability is a random error arises from the output variation given the same input. This is determined in a test of random error or repeated tests with one known value. Limits are defined as the functional operating range of the device that is exhibited during lab testing; specifically of the electrical resistance. This is determined in the calibration test that provides accuracy. Sensitivity is defined as the change in output, given a change in input. The static sensitivity,  $K$ , is expressed as:

$$K = \frac{d(output)}{d(input)} \approx \frac{\Delta output}{\Delta input}, \quad (\text{eq 2.1, Wheeler and Ganji, 2010}) \quad (\text{eq 2})$$

Sensitivity in this test would be the change in the electrical resistance read by the system per μL of water amount change. Without the application of WRBs, the relationship between the amount of distilled water applied and the corresponding electrical resistance will be more intuitive.

Three sets of tests are done to validate the performance of the device. The first test is to pour a large amount of water into the water column so the data is collected when the entire sensor platter is covered by water. The second group of tests is to apply different volume of water drops on different pads. It is a preliminary test to find the overall performance of different pads so further tests could be carried out. The third group of tests is to apply a same volume of water drops on each pad and repeat the test for different volumes. The result of the third test is evaluated use a factor called *NDMI*. *NDMI* is modified from the term Normalized Difference Vegetation Index (*NDVI*), where the vegetation is changed to moisture. *NDVI* comes from remote sensing approaches. It can be a ratio between any two spectral bands, such as the ratio of the red and near-infrared bands, the equation is:

$$NDVI = \frac{NIR-R}{NIR+R}, \quad (\text{Pettorelli, 2013}) \quad (\text{eq 3})$$

Where  $R$  is the red band and  $NIR$  is the near-infrared band.

Here in the moisture measurement, the  $NDMI$  is the ratio between two adjacent electrical resistance, as shown in eq 4:

$$NDMI = \left| \frac{R1-R2}{R1+R2} \right|, \quad (\text{eq 4})$$

Because after the experiment starts, the sequential reading change is small, only the  $NDMI$  of the first reading should be calculated. For the first reading of each pad in each test,  $R1 = 1G\Omega$ , which is the initial electrical resistance of the dry pad, and  $R2$  is the first reading taken from the experiment.

### 3.2.1 FULLY COVERED WATER TEST

In this test, the water column is installed as shown below in Figure 31 and the controller is connected to a personal computer properly. Before water is added, the readings for all pads in BiG are  $1G\Omega$ . 1 liter of distilled water is poured into the water column immediately after one round of data is collected so when the next round of data starts to collect, it collects data with the sensor fully covered by water. Water leaks through the holes on the sensor quickly and for safety concerns, power is cut off after collecting one round of data. The same test is repeated for three times as shown in Table 10.

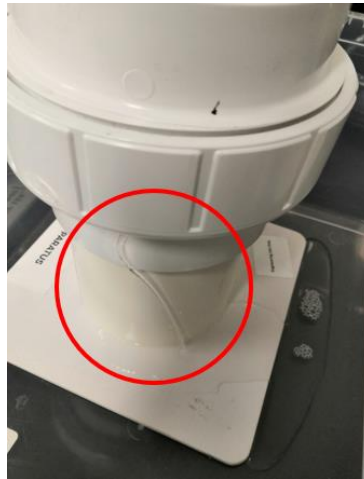


FIGURE 31 FULLY COVERED WATER TEST SETUP

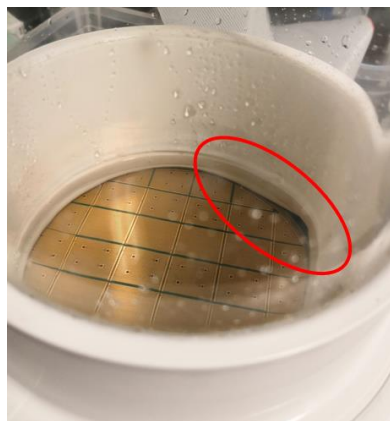
**TABLE 10 FULLY COVERED WATER TEST**

Test #	Experiment Date	Water Added
Test 1	2019-01-15	1 L
Test 2	2019-01-22	1 L
Test 3	2019-01-29	1 L

It is observed that most distilled water leaked through the holes on the sensor immediately as expected but there is also obvious water leakage through the screw edge (circled in red) simultaneously as shown in Figure 32. Figure 33 shows the weather strip on top of the leakage position has twisted (figure 17).



**FIGURE 32 WATER TEST OF HPTA DEVICE**



**FIGURE 33 WEATHER STRIP MOVED**

### 3.2.2 SENSOR TEST IN GROUPS

In this test, the tested sensors are divided into three groups. The first group is row A and row G, marked in red rectangles in Figure 34. The two rows are on the edge of the sensor platter. By comparing the output of these two rows of sensors, the performance of sensor pad that closes to the edge can be studied. The second group is C2 to C5 and E2 to E5. This group represents the central pads that are not adjacent to any edge sensors, marked in yellow rectangles. The third group studies the four edge sensors. The position of each water drop is illustrated by the blue dots.

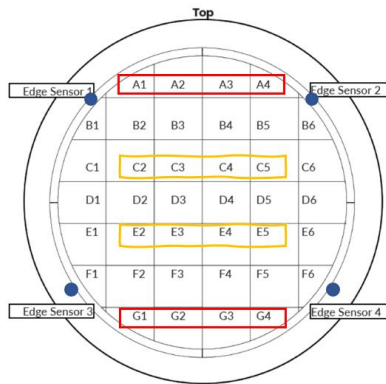


FIGURE 34 SENSITIVITY TEST

Different amounts of water drops are applied for the three groups of pads as shown in Table 11. Before the test started, the sensor platter is carefully cleaned with Isopropyl Alcohol and all readings are at  $1G\Omega$ .

TABLE 11 SENSOR TEST IN GROUPS

Group #	Pad Name	1 <sup>st</sup> Application ( $\mu$ L)	2 <sup>nd</sup> Application ( $\mu$ L)	
1	G1-G4	5	N/A	
	A1-A4	5	5	
2	C2-C5	5	5	
	E2-E5	E2	5	N/A
		E3	5	5
		E4	5	10
		E5	5	15
3	ES1-ES4	ES1-ES2	5 (middle)	N/A
		ES3-ES4	5 (edge)	N/A

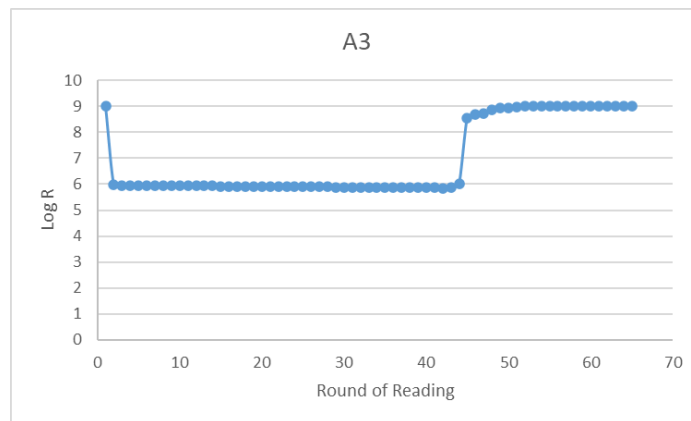
### 3.2.3 WATER DROPLET TEST

In the water droplet test, a fixed volume of water drop is added to every pad using a pipette according to the channel reading order. Two tests are done for 0.5 $\mu$ L, one test is done for 2.5 $\mu$ L and three tests are done for 5 $\mu$ L of distilled water. Table 12 below summarizes the information of the six tests.

**TABLE 12 WATER DROPLET TEST INFORMATION**

Test #	Water Added ( $\mu$ L)	Date
Test 1	0.5	2020-03-04
Test 2	0.5	2020-03-04
Test 3	2.5	2020-03-17
Test 4	5	2020-02-25
Test 5	5	2020-02-25
Test 6	5	2020-03-04

The raw data for each test exported from BiG contains too much information. For example, Figure 35 shows the log of electrical resistance for all readings of pad A3 in Test 5. There are 65 readings for each pad in this test. The four edge sensors are examined to be not stable, so the other 38 sensors are analyzed. It will be time consuming to handle the 65 X 38 data point in excel, so the datasheet is imported to MATLAB to extract the descending data, calculate mean and *NDMI* for each of the 38 sensor pads, same as the datasheets for other tests. processed data are then output to SPSS and excel for descriptive analysis and histogram generation.



**FIGURE 35 LOG R PLOT EXAMPLE**

### 3.3 PRELIMINARY TEST WITH WRBs

After validating the performance of the measurement system, several tests with the application of Membrane D and Membrane F are done to ensure the given device is working properly. Membrane D and Membrane F (Figure 36) are selected for the preliminary test because they are two very different materials. Membrane D is the softest material in all obtained WRBs and it is polymer-based. Membrane F is the hardest material in all obtained materials and it is paper-based. By comparing the test results of the two materials, the performance of the device can be deduced preliminarily.

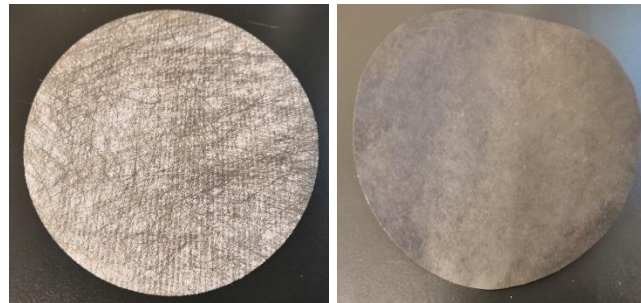


FIGURE 36 (A) MEMBRANE D (B) MEMBRANE F

Figure 37 shows all device components in different views. The steps to conduct tests using HPTA is given below.

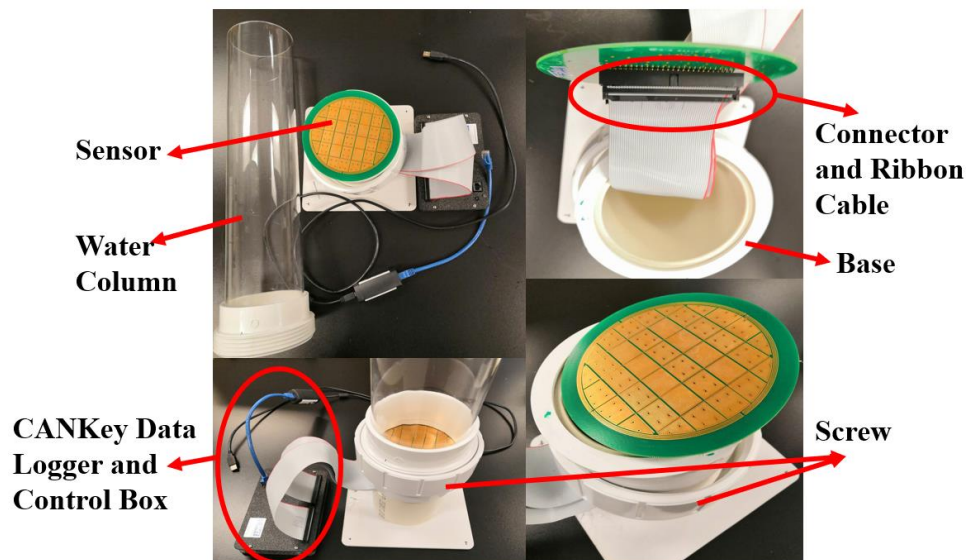


FIGURE 37 HPTA COMPONENTS

1. Check if the sensor is connected with the ribbon cable properly and if the other side of the ribbon cable passes through the base slot and connects with the control box.
2. clean the sensor surface using Delicate Task Wipers and 100% isopropyl alcohol.

3. Place the specimen to be tested on top of the sensor.
4. Place the water column on top of the sensor and screw it with the base screw.
5. Connect the CANKey Data Logger with the control box and connect its USB side to a personal computer.
6. Open BiG on the PC and check if all sensor pads read  $1G\Omega$ . If not, go back to step 2 and dry the sensor platter using a blower.
7. Pour distilled water into the water column and wait.

If the specimen is penetrated by liquid water, decreases in readings will be observed on BiG and water will leak through the holes on the sensor platter to the base chamber. If side leakage is observed, it means the device is not clamped appropriately and the test result will lack accuracy. In the fully covered water test in Section 3.2, side leakage caused by the twisted weather strip is observed. Therefore, before each test starts, the water column is screwed carefully to ensure the weather strip is in the correct position. If misalignment happens, the water column should be unscrewed and screwed again until the weather strip is in position.

Three tests are done for both materials, and every test starts with a new sample as shown in Table 13. Water leakage happens to five out of the six tests, thus leading to inaccurate and unrepeatable results.

**TABLE 13 PRELIMINARY TEST WITH WRBS**

Test #	Material	Sample #	Water Leakage
1	Membrane D	1	Yes
2		2	Yes
3		3	Yes
4	Membrane F	1	Yes
5		2	No
6		3	Yes

Both the preliminary test using two WRBs and the fully covered water test without WRBs indicate the present sealing method is not stable since water escapes from the side instead of only goes through the specimen. Therefore, a consistent sealing method should be developed before conducting further tests.

### 3.3.1 CHALLENGES TO BE ADDRESSED

From the observation and investigation of the device, the clamping failure is caused by four main reasons.

#### 3.3.1.1 Weather Strip

The weather strip sealing method is the most obvious problem. Weather strip is used by the design because it is easy to apply (Figure 38) and provides adequate sealing. However, after several tests, the strip itself could be damaged by dirt and screwing behavior, especially for this soft weather strip. Also, the soft strip could twist while screwing with the base. Then it is not able to create a perfect sealing environment.



FIGURE 38 WEATHER STRIP SEALING, FROM SMT REPORT

#### 3.3.1.2 Aligning

It can be seen that there is a margin (red circled in Figure 39) between the sensor and the screw. It can not be fixed by adjusting the position of the sensor. Because of the threads on the screw, the sensor can never align on the base properly. More liquid water can pass through the margin than other sides of the sensor.

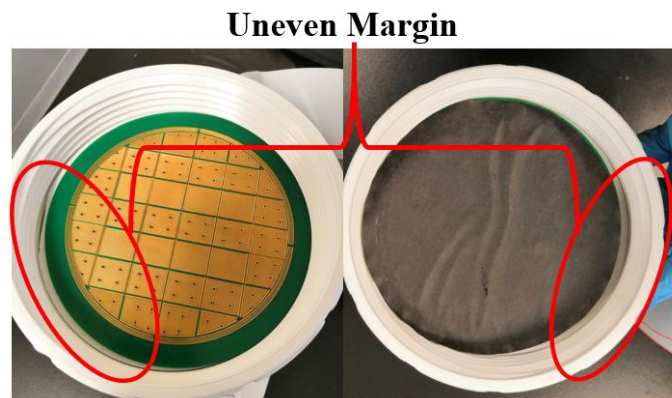


FIGURE 39 UNEVEN MARGIN

### 3.3.1.3 Screw Design

Other than the aligning problem, the screw mechanism itself (Figure 40) is very hard to be tightened. Also, the diameters of the water column and the base are too large to use a tightening tool properly, such as a rubber strap wrench. It requires two persons to hold each part of the device and tight them together. Even doing this, it can still be not tight enough. Also, the o-ring and the membrane material can be displaced or twisted while tightening.



FIGURE 40 SCREW MECHANISM

### 3.3.1.4 Material Edge Wicking

In Figure 41, it can be seen that there is a wicking problem around the edge of the material. When water wicks through the edge, the water can pass to the sensor from the back side of the material without penetration. This will give incorrect results for the test.

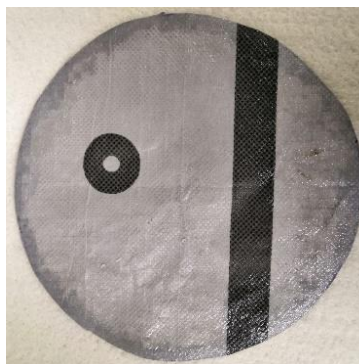


FIGURE 41 MATERIAL WICKING

### 3.3.2 TRAILS TO FIX THE PROBLEMS

To solve the sealing problem, three minor changes, attaching a harder weather strip at the inside of the column, applying water resistive glue all over the bottom surface, and using only the O-

Ring, are shown in Figure 42. All three changes are not able to solve the problem but the second one results in the largest amount of leaking and the third one had the least leakage amount. Based on that observation, the modified method eliminated the use of weather strip and replaced the O-ring with an X-ring (See Figure 43). One restriction is that the test procedures (Figure 43 to Figure 48) need to be followed strictly to gain the best results.



FIGURE 42 (A) WEATHER STRIP INSIDE COLUMN (B) WATER RESISTIVE GLUE (C) O-RING ONLY



FIGURE 43 COMPARISON BETWEEN O-RING AND X-RING

Step 1: Cut the membrane material based on the 4.775” acrylic round plate.

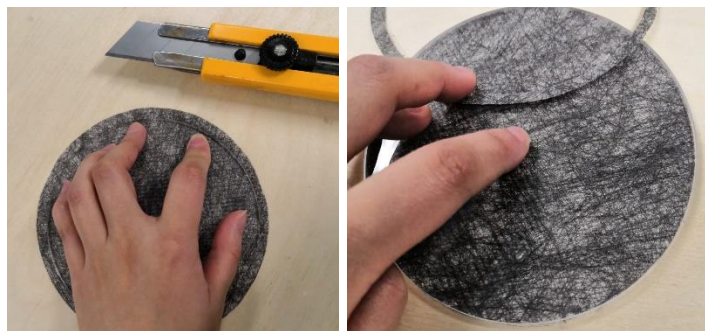


FIGURE 44 CUT THE MATERIAL TO THE SPECIFIED SIZE

Step 2: Clip both sides of the material with two 4.5” acrylic round plates. Apply sneaker waterproof protector spray on the edges of the material on both sides.



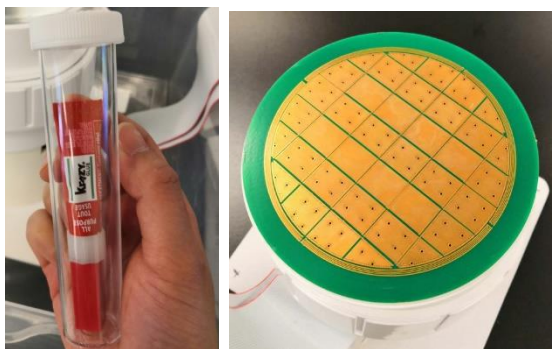
**FIGURE 45 APPLY WATER RESISTIVE SPRAY**

Step 3: Place the membrane on top of the X-Ring surface; make sure the material edge is between two edges of the X-Ring.



**FIGURE 46 LOCATE THE MEMBRANE**

Step 4: Apply a small amount of Krazy Glue on the base to fix the sensor with the base.



**FIGURE 47 FIX THE SENSOR WITH BASE**

Step 5: Place the base and sensor on top of the water column. Screw tight.



FIGURE 48 TIGHT THE DEVICE

Six tests are done after the modification using Membrane F and Membrane D. One test out of three trials of Membrane F is successful and all three tests of Membrane D fail. Therefore, a new attach method is proposed for stable and accurate results.

### *3.3.3 DESIGN PROCESS OF THE NEW CLAMPING METHOD*

The objective of this design is to upgrade the current apparatus so that it can have better accuracy and repeatability. It directly influences the experiment results to evaluate water penetration rate of WRB materials. In this stage, the most important design factor is to solve the leakage problem. The need and goal statements are listed below.

**Need Statement:** The current device is having problems with properly clamping the membrane materials and it is therefore not able to complete experiments on most materials.

**Goal Statement:** To improve the clamping method so that it can work more accurate and give repeatable results.

#### **3.3.3.1 User requirements and Design specifications**

The user requirement is mostly generated from the previous testing trials along with the communication with SMT Research Ltd. To meet the goals of this design project and requirements, a client requirement matrix is generated to evaluate concept designs, as shown in Table 14. The priority of each requirement is divided into three different levels. Level 1 denotes the must achieve requirements to keep the system functioning correctly, level 2 is the goal of the

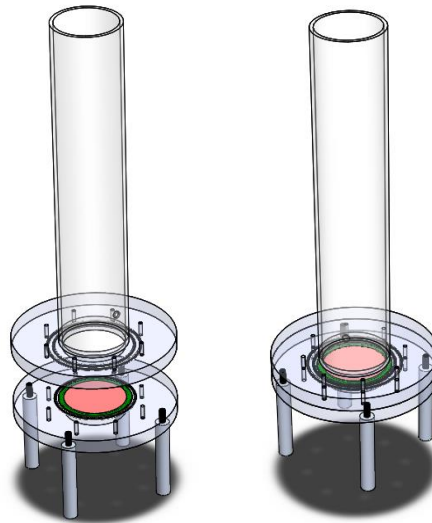
project to accomplish and level 3 is the better to have features. The corresponding design specifications are given in the next column.

**TABLE 14 USER REQUIREMENTS AND DESIGN SPECIFICATIONS**

Priority Level	User Requirements	Design Specification	Value and Unit
1	The prototype must not leak.	Times of test	9/10 tests
1	The testing should be able to conduct with the specific pressure applied.	Pressure	Atmosphere pressure
1	The results should be repeatable.	Times of test	9/10 same results
2	The size of the sensor should keep unchanged or very little change	Inch	<5.3''
3	The device should keep a simple mechanism	User's satisfaction	N/A
3	The sensor condition should be visible	User's satisfaction	N/A

### 3.3.3.2 Preliminary Design Concepts

The CAD model generated in SolidWorks is shown in Figure 49. The original device has its water column screws with the base while the new design simply uses bolts to connect two acrylic plates together so they can be clamped tight. At the same time, the transparency of acrylic plates allows easy observation of the specimen.



**FIGURE 49 CAD MODEL**

For better sealing, four O-Ring are used in this design. They are in three sizes, one large, two intermediate and one small. The layout and serial number are shown in Figure 50. Figures showing other machined parts in detail will be given in the Results section.

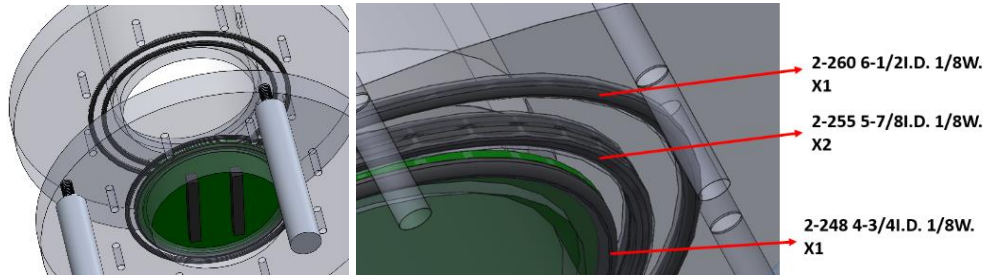


FIGURE 50 O-RING SPECIFICATION

### 3.4 TEST WITH WRBS USING MODIFIED DEVICE

#### 3.4.1 MATERIAL SELECTION

There are 10 membrane materials involved in this work as described in Section 2.4.4. Their appearances are shown in Figure 51. The materials are divided into three groups: materials with two different sides, materials with identical sides and materials with one adhesive side as shown in Figure 52 to Figure 54.

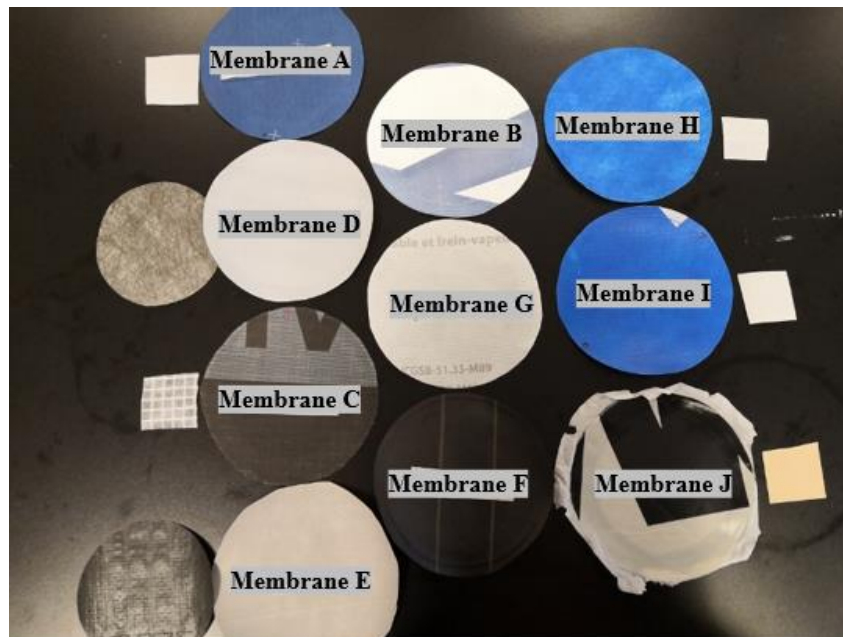


FIGURE 51 ALL MATERIALS

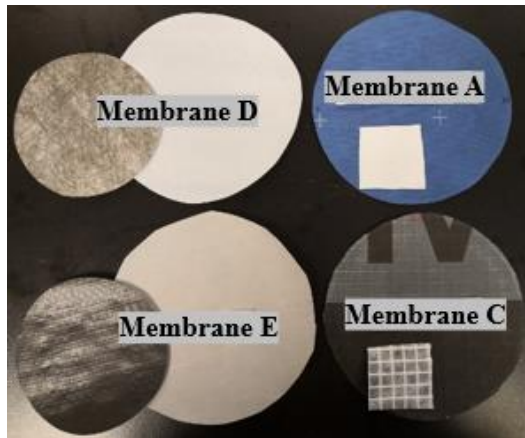


FIGURE 52 GROUP A: TWO SIDES WITH DIFFERENT MATERIALS



FIGURE 53 GROUP B: TWO SIDES WITH SAME MATERIALS



FIGURE 54 GROUP C: ONE SIDE ADHESIVE

Although the local retailer sold Membrane G as a WRB, it is not defined as an WRB in its product information and no available water test information is available. Inner barriers are out of the scope of this work so Membrane G is not going to be tested.

When testing the WRBs with one adhesive side, Membrane H, Membrane I and Membrane J, a piece of Delicate Task Wipers that is fully water penetrable is used to separate the sensor and the membrane in case the WRB sticks on the sensor platter. However, for all three WRBs, the adhesive additive starts to dissolve after one test. The adhesive is left on the entire sensor platter and is difficult to clean. The surface is cleaned using Delicate Task Wipers and isopropyl alcohol but there is a concern of possible residue and the hard cleaning behavior could damage the sensor, so no further tests are done for these materials. In the one test done for each material, Membrane J does not penetrate for five hours and the test is extended to 48 hours and still, no water leakage occurred. Membrane H has three points of water penetration within two minutes and all sensor pads are penetrated within five minutes. Membrane I lasts 53 minutes before three points are penetrated and at 55 minutes, all sensor pads detect liquid water. Membrane J seems to have very high water resistivity and Membrane I has better performance than Membrane H. However, there is only one test result for each material and it is not enough to represent the water resistance performance of a WRB material so the WRBs with one adhesive side are eliminated from further analysis. This apparatus is found to be not suitable for testing adhesive WRBs and further modification should be applied in future work.

### *3.4.2 TEST INFORMATION*

Except for Membrane G and the three adhesive materials, all other materials are tested for at least three times. Table 15 below summarizes the tested materials, the date of tests, their duration and the corresponding figure numbers. For each test, a colormap is generated using a python script and four plots are produced in MATLAB. The figure numbers column lists the figure number of the colormap of each test. If the MATLAB plots of one test are given in the Results section, they are also listed. All the plots are uploaded to the data repository folder although not all of them are included in this work. The file names are the test numbers followed by LogR or *NDMI* and Edge Group or Interior Group. For example, the file names of the four MATLAB plots for Test 1 are Test1 LogR Edge Group, Test 1 LogR Interior Group, Test1 *NDMI* Edge Group, and Test1 *NDMI* Interior Group. They can be accessed with permissions from the owner Wenqin Qi, Caterina Valeo and Phalguni Mukhopadhyaya.

**TABLE 15 TEST SUMMARY**

Test#	Membrane Type	Test Date	Duration (Hour)	Duration (Min)	Figure #
Test 1	Membrane A	2019/08/15	17.7	1059	101,144,151
Test 2	Membrane A	2019/08/18	8.2	489	101
Test 3	Membrane A	2019/08/20	20.7	1239	101
Test 4	Membrane A	2019/09/09	4.1	244	101
Test 5	Membrane A	2019/09/10	4.7	279	101
Test 6	Membrane A	2019/09/11	6.1	363	101
Test 7	Membrane A	2019/09/12	6.0	361	102
Test 8	Membrane A	2019/09/13	4.2	254	102
Test 9	Membrane A	2019/09/16	6.3	380	102
Test 10	Membrane A	2019/09/17	6.0	360	102
Test 11	Membrane A	2019/09/18	7.7	460	102
Test 12	Membrane A	2020/10/29	23.9	1432	102
Test 13	Membrane A	2020/11/02	23.7	1419	103
Test 14	Membrane A	2020/11/06	8.2	489	103
Test 15	Membrane A	2020/11/09	7.9	474	103
Test 16	Membrane A	2020/11/10	8.0	481	103
Test 17	Membrane A	2020/11/13	8.0	478	103
Test 18	Membrane B	2019/09/19	6.8	406	107
Test 19	Membrane B	2019/09/20	5.1	306	107
Test 20	Membrane B	2019/09/23	3.8	225	107, 145
Test 21	Membrane B	2019/09/24	4.6	275	107
Test 22	Membrane B	2019/09/25	6.2	373	107, 153
Test 23	Membrane B	2019/09/26	9.0	539	107
Test 24	Membrane B	2019/09/27	4.3	260	108
Test 25	Membrane B	2019/09/30	4.8	287	108
Test 26	Membrane B	2020/09/28	3.8	225	108
Test 27	Membrane B	2020/09/29	1.8	106	108
Test 28	Membrane B	2020/09/30	2.6	154	108
Test 29	Membrane B	2020/10/01	3.3	199	108
Test 30	Membrane B	2020/10/02	3.9	232	109
Test 31	Membrane B	2020/10/05	24.6	1476	109
Test 32	Membrane B	2020/10/07	11.8	706	109
Test 33	Membrane B	2020/10/13	10.5	629	109
Test 34	Membrane B	2020/10/15	24.4	1462	109
Test 35	Membrane B	2020/10/20	8.0	481	109
Test 36	Membrane B	2020/10/21	7.6	456	110
Test 37	Membrane B	2020/10/26	7.8	470	110
Test 38	Membrane B	2020/10/27	8.3	497	110

Test 39	Membrane B	2020/10/28	7.9	472	110
Test 40	Membrane C	2019/10/01	4.9	291	114, 152
Test 41	Membrane C	2019/10/02	6.1	364	114
Test 42	Membrane C	2019/10/03	4.6	275	114
Test 43	Membrane C	2019/10/04	3.8	230	114
Test 44	Membrane C	2019/10/07	5.7	342	114
Test 45	Membrane C	2020/12/21	8.0	479	114
Test 46	Membrane C	2020/12/22	8.0	479	115
Test 47	Membrane C	2020/12/23	5.8	349	115
Test 48	Membrane D	2019/10/08	4.8	289	119, 154
Test 49	Membrane D	2019/10/09	5.5	330	119
Test 50	Membrane D	2019/10/10	5.6	336	119
Test 51	Membrane D	2019/10/11	13.0	782	119
Test 52	Membrane D	2019/10/15	10.7	644	119
Test 53	Membrane D	2019/10/29	23.9	1434	119
Test 54	Membrane D	2019/10/31	8.0	478	120
Test 55	Membrane D	2019/11/01	6.8	406	120
Test 56	Membrane D	2019/11/04	6.9	412	120
Test 57	Membrane D	2020/11/16	8.0	477	120
Test 58	Membrane D	2020/11/17	13.0	779	120
Test 59	Membrane D	2020/12/02	24.0	1438	120
Test 60	Membrane D	2020/12/06	8.0	477	121, 146
Test 61	Membrane D	2020/12/08	8.0	479	121
Test 62	Membrane D	2020/12/09	24.2	1450	121
Test 63	Membrane D	2020/12/11	8.0	479	121
Test 64	Membrane D	2020/12/13	8.0	479	121, 147
Test 65	Membrane E	2019/11/08	13.3	795	125, 127
Test 66	Membrane E	2019/11/08	86.7	5199	125, 128
Test 67	Membrane E	2019/11/12	31.6	1894	125, 129
Test 68	Membrane E	2019/11/14	26.6	1598	125
Test 69	Membrane E	2020/11/20	26.3	1576	125, 130
Test 70	Membrane E	2020/11/23	23.7	1420	125, 131, 132
Test 71	Membrane E	2020/11/25	8.0	480	126, 133, 148
Test 72	Membrane E	2020/11/26	7.9	474	126
Test 73	Membrane E	2020/11/27	24.0	1437	126
Test 74	Membrane E	2020/11/30	11.1	663	126, 155
Test 75	Membrane E	2020/12/1	8.0	479	126, 134, 149
Test 76	Membrane F	2019/11/18	21.6	1298	138, 150
Test 77	Membrane F	2019/11/20	6.8	408	138
Test 78	Membrane F	2019/11/21	13.4	805	138
Test 79	Membrane F	2019/11/25	5.4	326	138

Test 80	Membrane F	2019/11/26	3.5	207	138
Test 81	Membrane F	2020/12/16	8.0	478	138
Test 82	Membrane F	2020/12/17	11.0	659	139, 143
Test 83	Membrane F	2020/12/18	4.8	288	139

### 3.4.3 CRITERIA TO DETERMINE IF WATER PENETRATION HAPPENS

In the current standards, ASTM Standard D779 measures the time that water vapor passes the specimen, the Water Ponding Test gives a pass result if no water passes through the specimen in two hours, AATCC Test Method 127 measures the hydrostatic pressure at the time when three points are penetrated by liquid water, ASTM Standard D4869 gives a pass result if the back side of any test specimen has no sign of wetness or deterioration, and British Standard BS:EN:1928 gives a pass result if there is no presence of water in 24 hours. In the requirement of ASTM Standard E2556, Type I WRBs that with base-level water resistance should withstand water for at least 10 minutes when using test method in ASTM Standard D779 and 120 minutes when conducting Water Ponding Test. Type II WRBs with enhanced water resistance should resist liquid water for at least 60 minutes when using test method in ASTM Standard D779 and 5 hours when using test method AATCC Test Method 127. The Weathering Test in AC38 requires the weathered specimen to withstand 55cm water head for five hours. It can be seen that there is not a uniform provision of the time that a WRB needs to resist liquid water and the required time ranges widely from 10 minutes to 24 hours.

After consideration, setting a time threshold such as saying a WRB is water resistive if no water penetrates the material within a specific time is improper since there is not enough information to deduce a proper time threshold. All standards listed above do not give any reason of why the time is picked, no matter the picked time is 10 minutes or 24 hours. A better solution will be to set different water duration levels of water resistance to include a wide time range. Then WRB materials can be ranked based on their water duration level and building designer can choose materials based on their demand.

Before water is poured into the water column, all sensor pads should read the original dry value of  $1G\Omega$ . After the test started, if the dry value decreased, it means liquid water has passed through the specimen and had contact with the sensor surface. After three sensor pads detect liquid water, the specimen is considered to be penetrated and the time used will be the

penetration time for this test. For now, the water resistance is ranked by penetration time as shown in Table 16 below. The water resistance of each WRB can be further ranked by fraction scores, which will be introduced in Section 3.4.5.

**TABLE 16 WATER RESISTANCE DURATION TABLE**

Water Resistance duration	Penetration Time (min)
Very short	< 1
Short	1~20
Moderate	20~180
Long	180~480
Very long	>480

To rank WRBs based on Table 16, all tests should be conducted for more than eight hours. From Table 15, it can be seen that many tests are shorter than eight hours and some tests are way longer than eight hours. This is caused by the way that the experimenter runs the test. The experimenter usually sets up the test in the lab in the morning and come back to end the test in the afternoon or the evening. Sometimes the experimenter comes back earlier and if the specimen is penetrated by liquid water already, the test is ended. Some tests have a very long duration because the experimenter has a tight schedule and cannot go to the lab to end the test.

It is found that after each test, no matter the test lasts for several hours or days, the sensor pad needs at least one night to get dry. Suppose the experimenter wants to start another test immediately. In that case, even if the surface of the sensor is wiped and dried using a blower, there is a high possibility that some sensor pads cannot read the  $1G\Omega$  original dry value. Thus, although the device cannot continuously conduct different tests, it allows the experimenter to run tests based on their own schedule. Compared to the existing test methods, using HPTA does not require the researcher to observe if water passes through the membrane by human eyes. Once water penetration happens and liquid water gets in contact with the sensor surface, the electrical resistance reading in BiG will drop and the alarm will be triggered. BiG records all electrical resistance reading in its database and syncs it once a while depending on user setting. This means the researcher does not need to stay in the lab for several hours and check the device frequently.

### 3.4.4 TEST PROCEDURE

The steps to run a test are listed below:

1. Place the bottom plate on the table, and check if the O-rings are in position and completely dry.

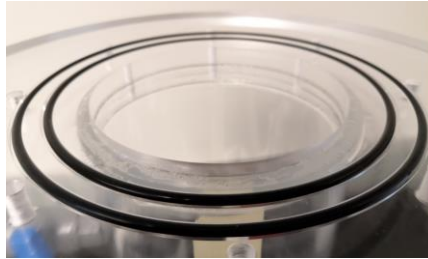


FIGURE 55 O-RINGS ON THE BOTTOM PLATE

2. Connect the male connectors on the ribbon cable to the connectors on the back of the sensor platter. Make sure the ribbon cable labeled with “TOP” is on the same side with the printed label on the back of the sensor and the “TOP” label on the acrylic plate.

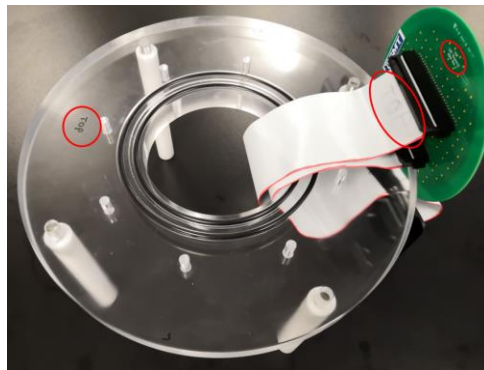


FIGURE 56 RIBBON CABLE AND SENSOR PLATTER CONNECTION

3. Place the sensor in the cut slot. Make sure the sensor platter is settled well and the top surface of the sensor is at the same level as the top surface of the bottom plate.

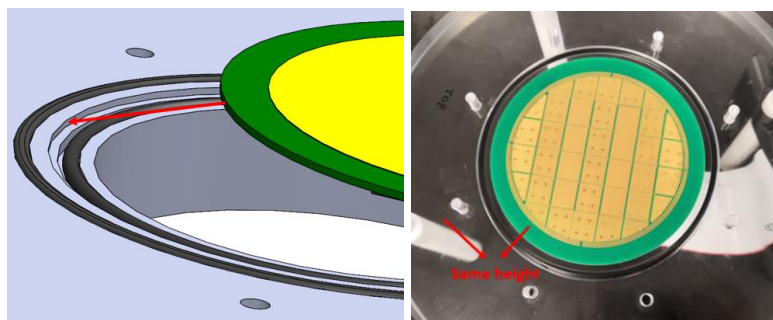
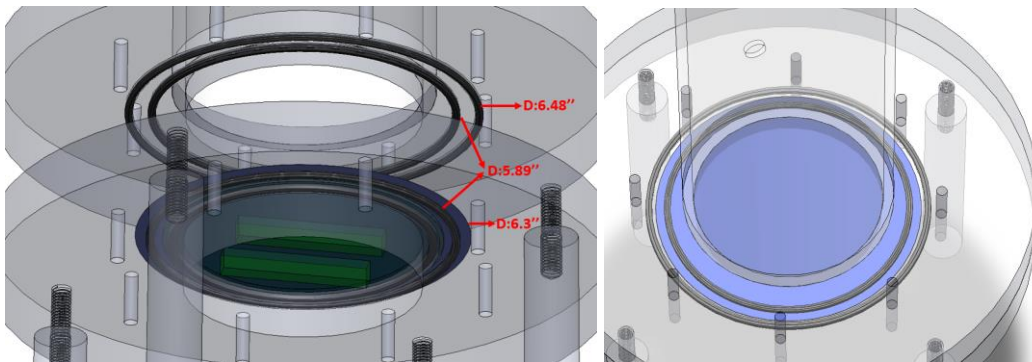


FIGURE 57 SENSOR PLACEMENT

4. Clean the sensor surface using Delicate Task Wipers and 100% isopropyl alcohol. This step helps to eliminate any dust or impurities on the surface. As the sensor is very sensitive, any impurities on the surface could prevent the sensor from reading the original dry value of  $1G\Omega$  when the sensor is actually dry.
5. Connect the CANKey Data Logger with the control box and connect its USB side to a personal computer.
6. Open BiG on the PC and check if all sensor pads read  $1G\Omega$ . If not, go back to step 4 and dry the sensor platter using a compressed gas duster. If the readings are still changing, use a hair dryer. Sometimes the sensor is cleaned multiple times and already blowed for a long time, but some pads' readings still fluctuate. If the amount of sensor pads that do not read the dry value is less than or equal to three, continue the test. Otherwise, leave the sensor for 12 hours before further steps.
7. Place the testing sheet material on a wood board. Press an acrylic plate with 6.3 inch diameter on the sheet material and cut through the edge using a utility knife to get the specimen to be tested. 6.3 inch diameter allows the specimen to cover the outer O-ring on the bottom plate but still in the range of the outer O-ring on the top plate.



**FIGURE 58 PREPARE AND PLACE THE WRB SPECIMEN**

8. Place the top plate on the bottom plate. Make sure the specimen is concentric with the O-rings.
9. Clamping the top and bottom plate by installing the eight pairs of hex bolts, washers and nuts. The experimenter should use both hands to install the fasteners because when tightening the nut, the bolt head should be clamped by a slip-joint plier. Both installation directions in figure x below are tested to be able to clamp the two plates tight enough without water leakage but when the nut is on the top, there is more space to spin the wrench so this direction is preferred.



FIGURE 59 BOLT AND NUT DIRECTION

10. Put the entire device in a large plastic box so if any water penetrates the specimen, it will be kept inside the box instead of damaging the workspace.

11. Make sure the water valve is perpendicular to the pipe so it is closed. Check the time on BiG and record the time. At the beginning of a round of data collection, pour distilled water into the water column immediately until it reaches the 55 cm mark. The water column has a diameter of 4.5 inch. The water needs to be added is  $V = \pi * (4.5 \text{ in} * 2.54)^2 * 55 \text{ cm} = 22562.37 \text{ cm}^3 = 22.56 \text{ L}$ . The water tank used to store distilled water is about 15L so about one tank and a half of distilled water need to be filled. Each round of data collecting takes around 1 minute 20 seconds and pouring water needs to be finished within this time so at the beginning of the next round of data collection, the sensor platter is submerged with a 55cm water head and data analysis should start at that time.

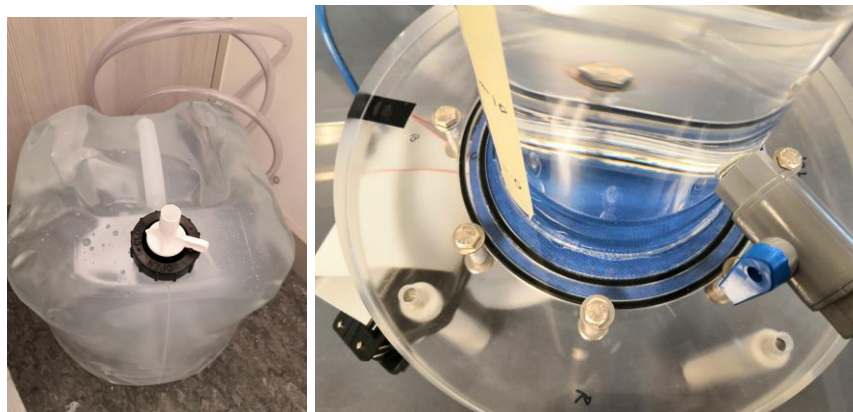
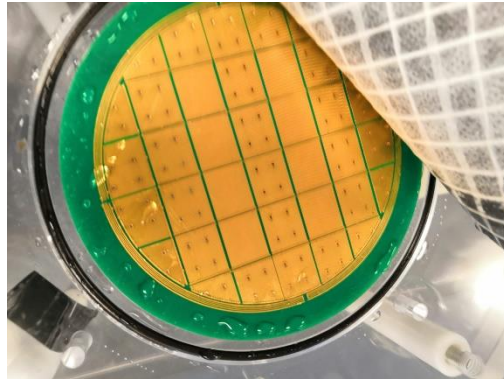


FIGURE 60 DISTILLED WATER ADDITION

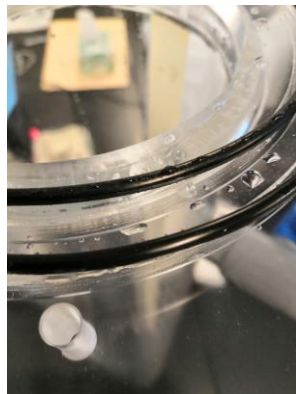
12. After 5 hours or the specimen is penetrated by liquid water, record the time on BiG and disconnect the data logger from PC. Open the water valve and use a water bucket to collect the water exits from the water pipe. Hold the device and tilt it to empty the residue water.

13. Disattach the top plate and bottom plate. Remove the specimen and gently wipe the sensor surface with the Delicate Task Wipers. Disconnect the connector on the ribbon cable with the sensor connectors to allow the pins to get dry.



**FIGURE 61 DISASSEMBLY OF THE DEVICE**

14. Take out the O-rings on both plates. Dry the O-rings and re-lubricate is necessary. Leave the device for at least 12 hours before the next test.



**FIGURE 62 WATER RESIDUE IN AND AROUND THE O-RING SLOTS**

### ***3.4.5 DATA PROCESSING METHOD***

There are 83 tests in total and each test contains 38 sensors to be analyzed. According to the timestamp record in BiG, it takes around 55s to read all 42 electrical resistance values and stop for 21s before the next round of data collection. If a test lasts for eight hours, there will be about 15,000 rows of data generated and there are some tests last longer than eight hours. Therefore,

finding the best way to analyze the collected data is one of the most important things in this research.

When testing the WRBs to withstand liquid water penetration, the most critical factor should be when the sensor pads first get wet. Thus, a figure showing all sensor pads and painting them in different colors according to the time each sensor first gets wet would be sufficient and clear. But when considering performance factors other than time, a problem needs to be answered first is although the four edge sensors are eliminated from the analysis, there are still 38 sensor pads that read separate values. Should the analysis treat the entire sensor as a whole or should the analysis be able to express the performance of each sensor pad?

To answer this question, the initial design idea of this sensor should be considered. When SMT designed this sensor, they hope the electrical resistance can help qualify the amount of liquid water that passes through the WRBs materials. When doing this analysis, the sensor could be treated as a whole by summarizing all data and providing descriptive analysis such as average, median or standard deviation for each material. However, according to the sensor sensitivity and validation tests, the value of electrical resistance does not have a linear relationship with the amount of water that has contact with the sensor pad so this analysis will not be done in the WRBs test.

If treat each sensor pad separately, the  $\log R$  and corresponding *NDMI* factors can be calculated for each pad. The *NDMI* factor indicates the change between two adjacent electrical resistance values, which could be useful for evaluating the water resistance performance of WRBs. But analyzing 38 sets of data of *NDMI* is too time consuming and complicated. Given the sensor was designed to read the values of all pads separately so it can tell which part of the sensor is first penetrated by liquid water. By making use of this feature, the 38 pads can be separated into different groups. It is meaningless to separate the circle into quadrants or more small pieces because the position will always change according to the material orientation and installation process. One grouping method that will not be affected is the interior and exterior of the sensor no matter how it rotates. Therefore, the answer to the question is neither. The sensor will be treated as two areas, an interior area and an edge area.

### **3.4.5.1 Data Preprocessing**

The data for each test is stored in BiG database. It can be exported as an excel file directly from BiG but the file contains massive data that is hard to process in Excel. Also, the exported excel file contains some random mistakes such as reads value of 1 for some sensor or missed readings of some sensor. It is found that many mistakes happen at the time when BiG is syncing data to its online database. Fortunately, the data on the online database is usually correct. A python script is used to pull data from the online database using an API provided by the company. The data is stored as a db file that can be opened using DB Browser for SQLite. The DB Browser can sort and filter a large amount of data at a comparatively high processing speed. This helps to excerpt the required data range so it can be imported to MATLAB for further analysis.

In the db file, the data should be excerpted between the first C1 after the recorded start time in the 11<sup>th</sup> step of test procedures and the last F6 before the end time recorded in the 12<sup>th</sup> step so that the data will be a multiple of 42, and can be imported to MATLAB to run the script attached in Appendix B. In the sensor sensitivity and validation test, it is concluded that the four edge sensors read unreliable results so they should be eliminated in further tests. This is done in the MATLAB script.

For overnight tests, any data collect between 23:59:59 and 0:00 will not be collected successfully. In this situation, if all sensors already detect liquid water, in other words, the specimen is fully penetrated by liquid water, cut the data at the last F6 before the missing data. If there are still dry sensor pads, the missing data must be filled manually so the MATLAB script can function properly. To do this, for example, if the missed data is D4 at 23:59:59, the previous reading and next reading of D4 should be found. If both readings are  $1G\Omega$ , add  $1G\Omega$  for the missing D4. If the two readings are different, take the average and use the average as the missing D4. This approximation is made because the electrical resistance drops when time passes by in most situations.

### **3.4.5.2 The Colormap and Information Table**

The colormap method provides a visual solution to express the wet situation of all sensor pads. It is generated by a python script to indicate the time that each sensor detects liquid water. To get the colormap, data need to be preprocessed in MATLAB by finding the earliest time that each sensor reads an electrical resistance less than  $1G\Omega$ . The 38 time data are in minutes. They are

exported to an excel file and the excel file is exported to the python script. An interface as shown in Figure 63 is then generated. There is a color bar on top of the page which indicates time in minutes. For example, the first color MidnightBlue indicates the time that the sensor first gets wet is less than one minute and the second color RoyalBlue indicates the time is more than 1 minute but less than five minutes. After running the script, all sensor pads will be colored by its corresponding wet time. In the example in Figure 64 Membrane D Test 1, no pad is colored with MidnightBlue so no sensor gets wet before one minute, 15 sensor pads are colored with RoyalBlue so they get wet between one minute to five minutes..., and so on.

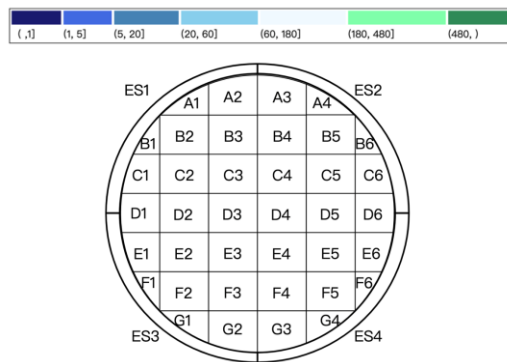


FIGURE 63 COLORMAP DEFAULT INTERFACE

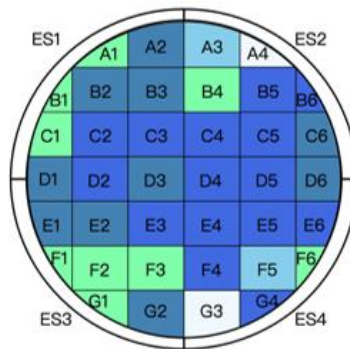


FIGURE 64 COLORMAP EXAMPLE

An information table for each material is then included. Table 17 is a part of the Membrane D table. The table contains the total test number, material test number, the water level drop in centimeter, amount of valid sensor pads in each test, and the number of sensor pads with respect to the time ranges used in the colormap, and a water resistance score. Use Figure 46 as an example again, it is test #48, the first Membrane D test. At the time that the test is stopped, there is no visible water level change inside the water column. All 38 sensor pads in this test have the

expected 1GΩ dry value before water is added. There is 0 sensor pads detects liquid water before one minute, 15 between one to five minutes, ten between five minutes to 20 minutes, two between 20 minutes to 60 minutes, two between 60 minutes and 180 minutes, and nine between 180 minutes and 480 minutes.

**TABLE 17 MEMBRANE D INFORMATION TABLE EXAMPLE**

Test #	Material Test #	Water level drop	Valid Sensors	First Wet time (min)							Score
				0~1	1~5	5~ 20	20~ 60	60~ 180	180~ 480	>480	
Test 48	MD 1	0 cm	38	0	15	10	2	2	9	0	118
Test 49	MD 2	0 cm	38	0	7	4	2	5	20	0	204
Test 50	MD 3	0 cm	38	0	17	8	6	2	5	0	97

The score on the table is water resistance score (WRS) calculated based on the weighting coefficient in Table 18 below:

$$WRS_{MD1} = 0 * 0 + 15 * 1 + 1.5 * 10 + 2 * 3 + 2 * 5 + 9 * 8 + 0 * 10 = 118$$

The final WRS for Membrane D will be the average of WRSs calculated for all Membrane D Tests.

Because different tests using a same material could have very different WRS, the coefficient of variation (COV) is also calculated to show the WRS dispersion of each material. The sample calculation for Membrane D is given below:

$$COV = \frac{\sigma}{\mu} = \frac{53.79}{82.72} = 0.65$$

where  $\sigma$  is standard deviation and  $\mu$  is mean.

**TABLE 18 WEIGHTING COEFFICIENT TABLE**

Time Range (min)	Weighting Coefficient
<1	0
1~5	1
5~20	1.5
20~60	3
60~180	5
180~480	8
>480	10

The water resistance duration in Section 3.4.3 only counts the time right after the third sensor pad gets wet and gives a simple solution for designers to choose WRB materials. While the weighting coefficient considers all sensor pads so it provides an integrative result for researchers to study the performance of the sensor platter. The two ways of ranking WRBs have different purposes but both of them are useful.

### 3.4.5.3 100% Stacked Bar Chart and Pie Chart

After getting the full information table for one material, the total amount of each time range can be calculated. Table 19 is a part of the Membrane C information table. The 100% stacked bar chart can be generated by selecting the bolded cells as shown in Figure 65. The pie chart can be generated by selecting the total row as shown in Figure 66. Both the bar chart and the pie chart use the same color palette as the colormap. These two figures exhibit the dominant wet time of each material.

TABLE 19 MEMBRANE C INFORMATION TABLE EXAMPLE

Valid Sensors	First Wet Time (min)			
	0~1	1~5	5~20	20~60
38	<b>0</b>	<b>33</b>	<b>5</b>	<b>0</b>
38	<b>3</b>	<b>31</b>	<b>4</b>	<b>0</b>
38	<b>2</b>	<b>15</b>	<b>21</b>	<b>0</b>
38	<b>1</b>	<b>28</b>	<b>9</b>	<b>0</b>
38	<b>0</b>	<b>30</b>	<b>8</b>	<b>0</b>
38	<b>5</b>	<b>33</b>	<b>0</b>	<b>0</b>
38	<b>21</b>	<b>17</b>	<b>0</b>	<b>0</b>
38	<b>6</b>	<b>30</b>	<b>1</b>	<b>1</b>
Total:	38	217	48	1

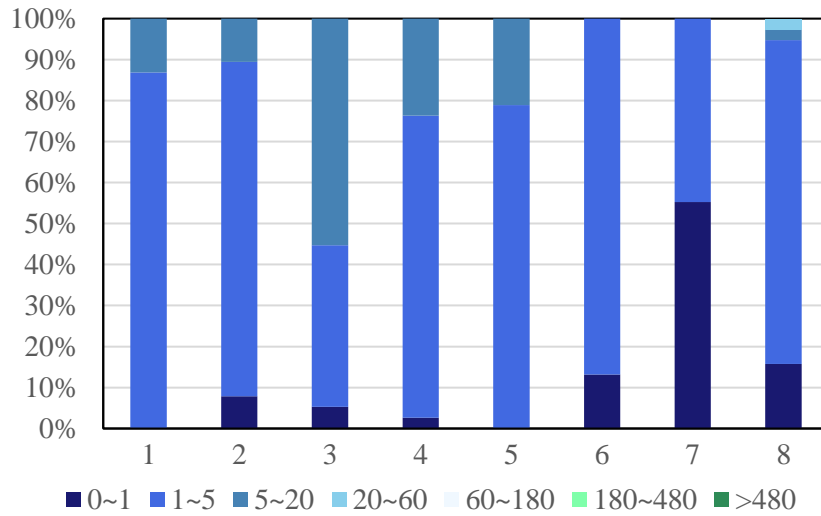


FIGURE 65 100% STACKED BAR CHART EXAMPLE

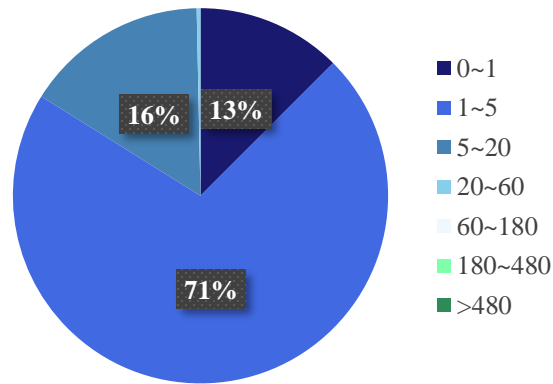


FIGURE 66 PIE CHART EXAMPLE

### 3.4.5.4 The Edge Group and Interior Group

The 38 sensor pads are divided into two groups, an edge group and an interior group as shown in Figure 67 (a). The sensors in the edge group directly connect with the four edge sensors, and all other sensors belong to the interior group. The channel number after eliminating the four edge sensors are given in Figure 67 (b).

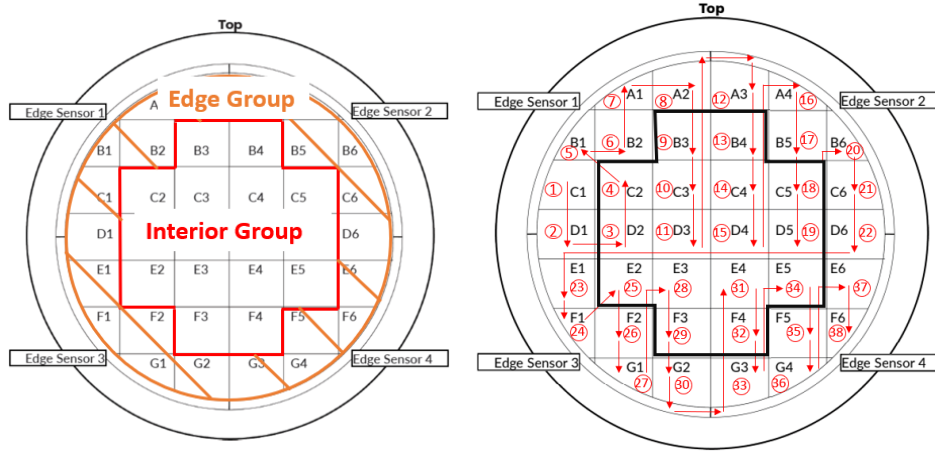


FIGURE 67 (A) EDGE GROUP AND INTERIOR GROUP (B) CHANNEL NUMBER

The MATLAB script generates two plots for each group, one log R plot and one *NDMI* plot. The legend information for the edge group and the interior group are given in Figure 68 (a) and (b). There are 22 datasets in the edge group and 16 datasets in the interior group. The colors and line styles are generated by MATLAB automatically. The dataset number, its corresponding channel number, sensor name and legend style are listed in Table 20. The plots for test 12 are given as an example in Figure 69. Due to the comparatively large number of datasets for both groups, it is not easy to tell which line is plotted by which dataset instantly. Therefore, all plots are available in the data repository of this thesis and the readers can ask for access to explore details of any interested plots.

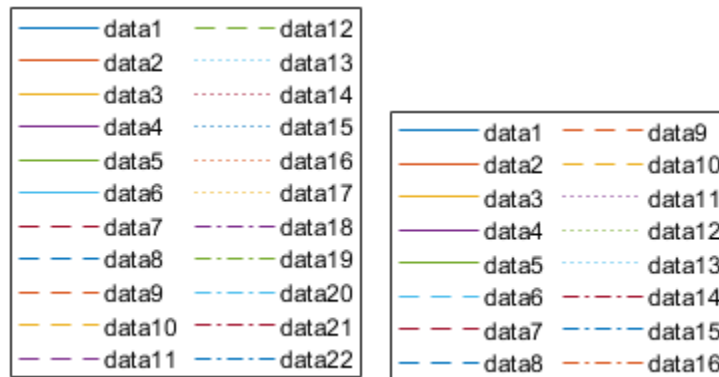


FIGURE 68 LEGEND INFORMATION (A) EDGE GROUP (B) INTERIOR GROUP

TABLE 20 EDGE GROUP AND INTERIOR GROUP LEGEND STYLE

Edge Group				Interior Group			
Dataset #	Channel #	Sensor Name	Legend Style	Dataset #	Channel #	Sensor Name	Legend Style
data1	1	C1	Dark Blue Solid Line	data1	3	D2	Dark Blue Solid Line
data2	2	D1	Orange Solid Line	data2	4	C2	Orange Solid Line
data3	5	B1	Yellow Solid Line	data3	9	B3	Yellow Solid Line
data4	6	B2	Purple Solid Line	data4	10	C3	Purple Solid Line
data5	7	A1	Green Solid Line	data5	11	D3	Green Solid Line
data6	8	A2	Light Blue Solid Line	data6	13	B4	Light Blue Dashed Line
data7	12	A3	Red Dashed Line	data7	14	C4	Red Dashed Line
data8	16	A4	Dark Blue Dashed Line	data8	15	D4	Dark Blue Dashed Line
data9	17	B5	Orange Dashed Line	data9	18	C5	Orange Dashed Line
data10	20	B6	Yellow Dashed Line	data10	19	D5	Yellow Dashed Line
data11	21	C6	Purple Dashed Line	data11	25	E2	Purple Dotted Line
data12	22	D6	Green Dashed Line	data12	28	E3	Green Dotted Line
data13	23	E1	Light Blue Dotted Line	data13	29	F3	Light Blue Dotted Line
data14	34	F1	Red Dotted Line	data14	31	E4	Red Dash-dotted
data15	26	F2	Dark Blue Dotted Line	data15	32	F4	Dark Blue Dash-dotted
data16	27	G1	Orange Dotted Line	data16	34	E5	Orange Dash-dotted
data17	30	G2	Yellow Dotted Line				
data18	33	G3	Purple Dash-dotted				
data19	35	F5	Green Dash-dotted				
data20	36	G4	Light Blue Dash-dotted				
data21	37	E6	Red Dash-dotted				
data22	38	F6	Dark Blue Dash-dotted				

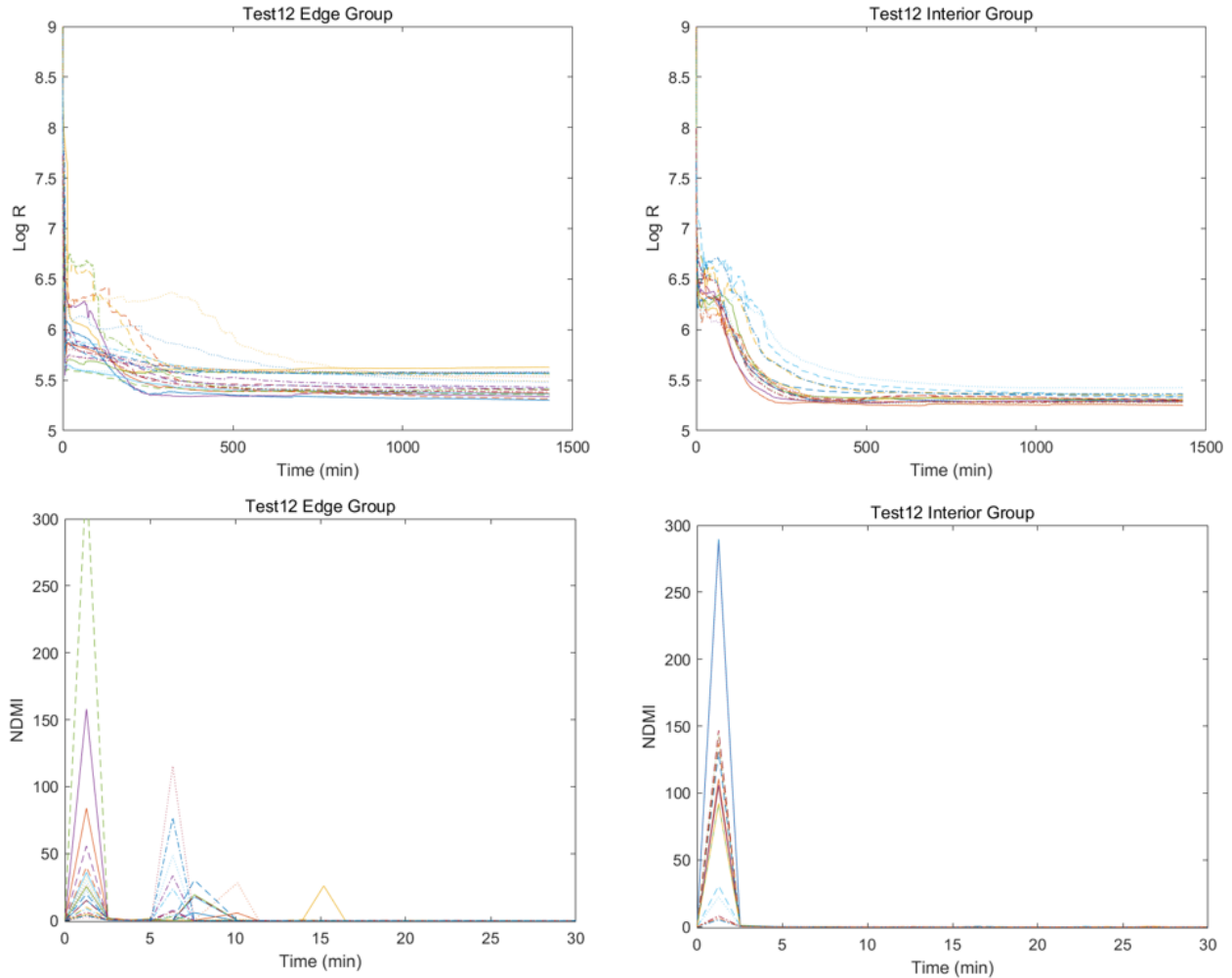


FIGURE 69 MATLAB PLOTS EXAMPLE

In the Results section, only some representative plots will be included like in Figure 69 and most other plots will be left for further study in the future. The log R plots give an overview of when the sensor pads detect liquid water and the the behavior of the two groups of sensors during the test. In this test, most Log R curves have a large drop at the beginning, followed with a short time increase trend and drop again and all curves reach around 5.3 until the test is ended. Compared to the log R plots, the *NDMI* plots better express the post-first instance of liquid water entry characteristics. The x axis that shows time is cut to a shorter range based on each material so the *NDMI* values can be seen clearer.

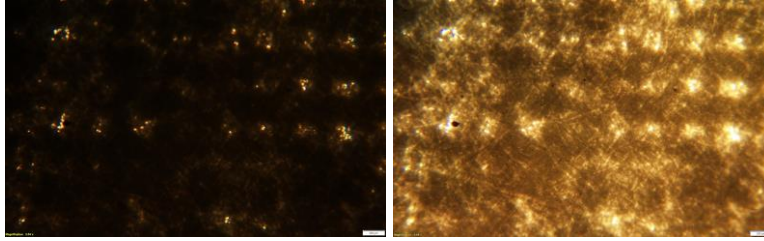
### 3.4.5.5 Microscope observation

The textile structures of all six materials are examined using an electrical microscope. Porosities of each material are calculated by a MATLAB script that was originally used to calculate the porosity of pavement surfaces. The adaptive threshold with a sensitivity of 0.8 is first changed to 0.5 and then deleted while converting the image to a binary image using “imbinarize” function as shown in Figure 70. Figure 71 shows two microscope images of Membrane B taken from the same spot with the same magnification. The only difference between them is the time of exposure for the left one is 1/1099s and for the right one is 1/115s. The results use the sensitivity factor of 0.8 and 0.5 are given in Figure 72 and Figure 73. Figure 74 shows the results without an adaptive threshold.

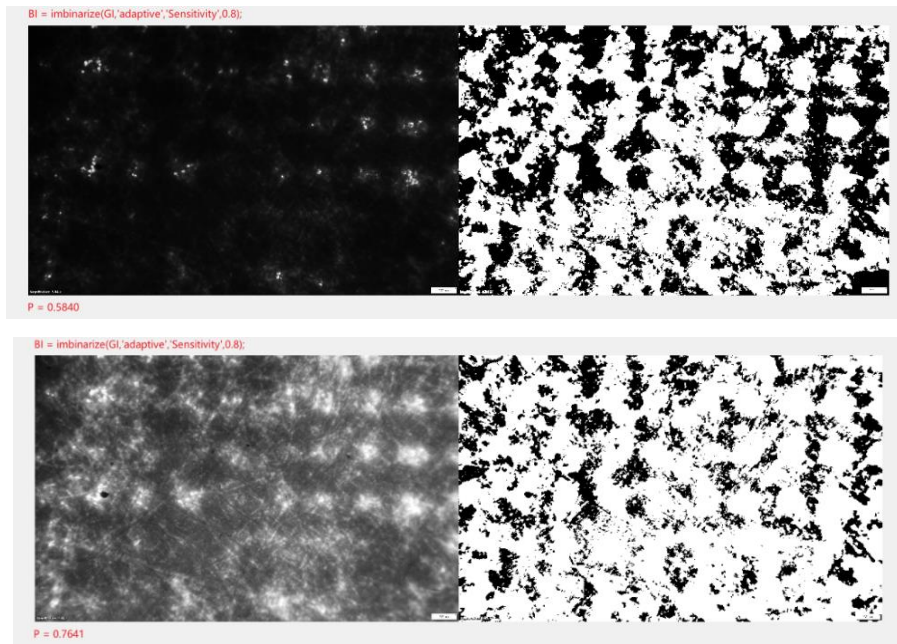
It can be seen that with the 0.8 sensitivity in Figure 72 (a), the originally very dark image is brightened too much and the percentage of voids is obviously high. Same as Figure 72 (a), Figure 72 (b) is also overexposed and many spots that are supposed to be dark are treated as voids. The percentage of voids is very different from 0.5840 to 0.7641. When the sensitivity is 0.5, Figure 73 (a) is still overexposed. Although some dark areas are treated as voids, almost all voids that are hard to observe from the original figure is now identified. Figure 73 (b) expressed the voids properly with this sensitivity factor. The P values are 0.2271 and 0.2682, which is more accurate. This means by adjusting the sensitivity factor, the hiding details in the revealed but the sensitivity factor needs to be selected carefully. In this example, 0.5 has a better effect than 0.8 but it is probably not the best sensitivity factor. Also, the best sensitivity factor could be different for each figure. In Figure 74 (a), it is obvious that all unclear features are eliminated and only the brightness parts are kept as voids with a P of 0.0066. While Figure 74 (b) has enough lightness in the original image so all features are binarized properly and P is 0.273, which is very close to Figure 73 (b).

```
BI = imbinarize(GI,'adaptive','Sensitivity',0.8); BI = imbinarize(GI,'adaptive','Sensitivity',0.5); BI = imbinarize(GI);
% Show grayscale and binary side by side % Show grayscale and binary side by side % Show grayscale and binary side by side
imshowpair(GI,BI,'montage') imshowpair(GI,BI,'montage') imshowpair(GI,BI,'montage')
% Display the percentage of voids % Display the percentage of voids % Display the percentage of voids
N = numel(BI); N = numel(BI); N = numel(BI);
NT = sum(BI(:)); NT = sum(BI(:)); NT = sum(BI(:));
P = (NT/N); P = (NT/N); P = (NT/N);
display(P); display(P); display(P);
```

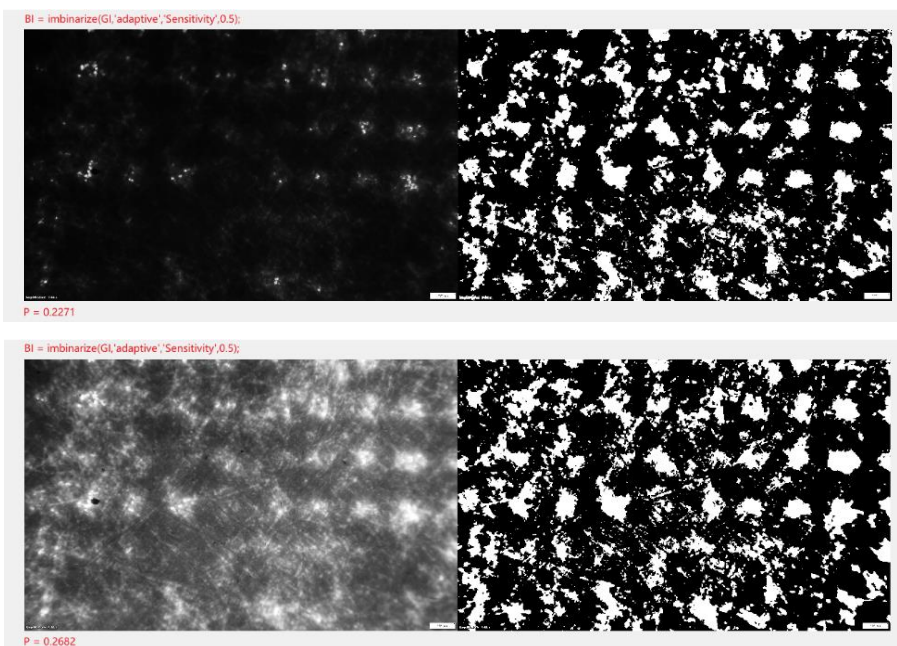
FIGURE 70 MATLAB SCRIPT OF POROSITY



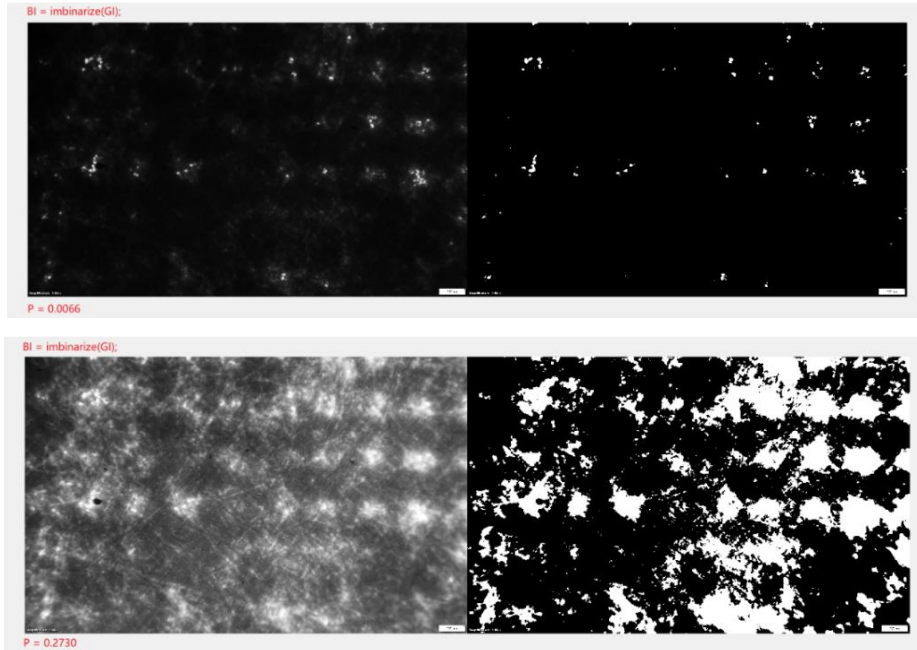
**FIGURE 71 MICROSCOPE IMAGES OF MEMBRANE B**



**FIGURE 72 SENSITIVITY OF 0.8 (A) AND (B)**

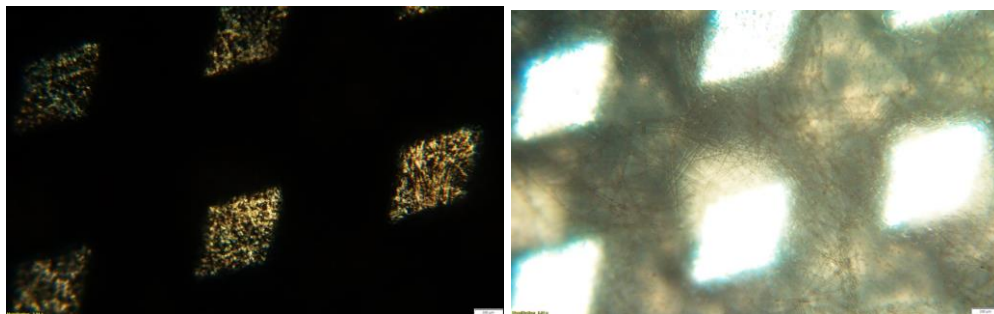


**FIGURE 73 SENSITIVITY OF 0.5 (A) AND (B)**



**FIGURE 74 RESULTS WITH NO ADAPTIVE THRESHOLD (A) AND (B)**

Therefore, adaptive thresholding could be disabled for images with enough brightness to obtain the best result. For images that do not have adequate brightness, attempts to adjust the sensitivity factors are necessary. Some materials are very dark and thick and an external light source is used for a clearer view when taking microscope images. Distance also needs to be adjusted because almost all WRB materials are composed of several layers and the zoom button knob needs to be turned frequently to view different layer. A tiny adjustment can lead to very different views thus very different porosity values as shown in Figure 75. Hence, this porosity script is not suitable for evaluating the porosity of WRBs using the microscope images. Another approach could be developed to examine the porosity of WRBs in the future. In this stage, the microscope images of each material will be described based on their pattern shape and arrangement.



**FIGURE 75 LAYER DIFFERENCE**

# CHAPTER 4 RESULTS

## 4.1 SENSOR PLATTER VALIDATION TEST

To test the accuracy, repeatability, limits, and sensitivity of the measurement system, the fully covered water test, the preliminary test and the water droplet test are done. A detailed analysis of their results is given in the following sections.

### 4.1.1 FULLY COVERED WATER TEST RESULTS

The results of fully covered water tests are given in Figure 76. It can be seen that the readings of channels 12, 13, 33, and 34 in all three tests are very different from other pads. The four channels correspond to the four edge sensor pads. It can be concluded that the readings of edge sensors varied a lot compared to the central sensors. Also, when repeating the same test, the readings of each edge sensor also varied. Therefore, the edge sensors are not able to provide steady and meaningful results. The results of edge sensors could be ignored in membrane tests.

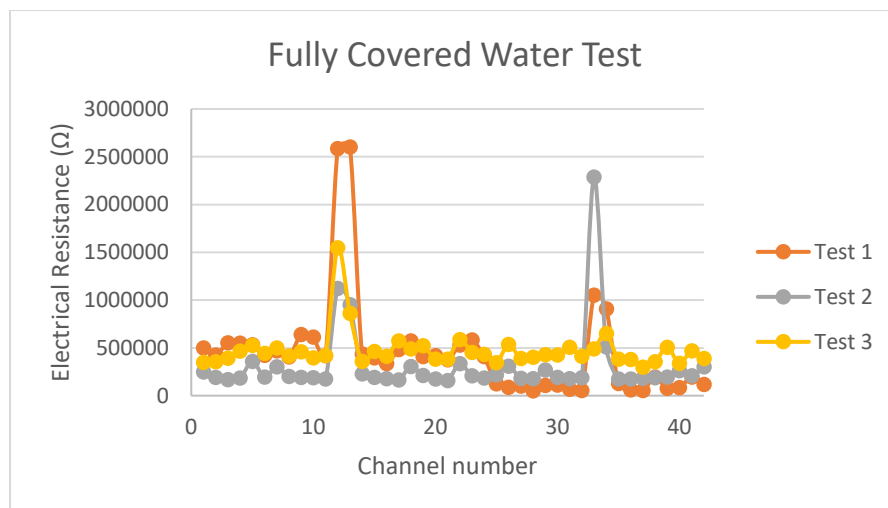


FIGURE 76 FULLY COVERED WATER TEST RESULT 1

Figure 77 eliminated the readings of the edge sensors and changed the readings to log values as well. Except for the second half of Test 1, the results seem consistent and all readings are around  $5.2\Omega$  towards  $5.8\Omega$ . Compared to the dry value of  $9\Omega$ , the changes are very small. The sudden drop happened in the 25<sup>th</sup> reading of Test 1 and it could be caused by liquid water spreading to the solder joint tails and then leading to a system error. Because there is no membrane applied in this test, water went through the holes on the sensor very quickly. It can be seen in Figure 78 that

the solder tails are all exposed and if water touches the tails, the circuit will be shorted and this could be the reason for the sudden drop in readings.

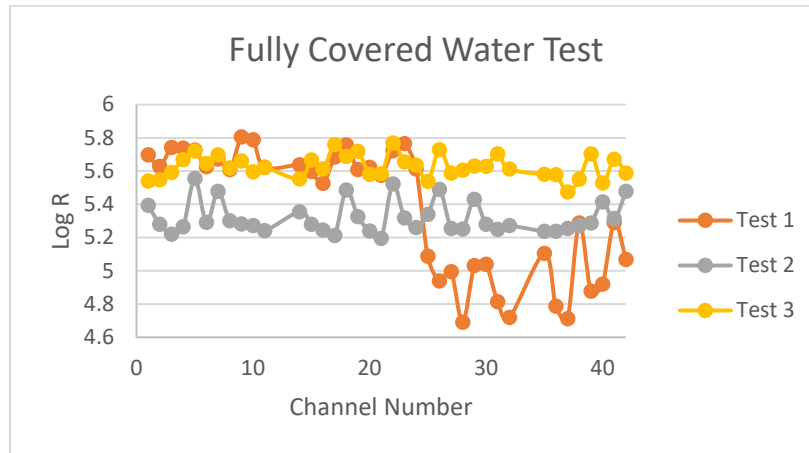


FIGURE 77 FULLY COVER WATER TEST RESULT 2

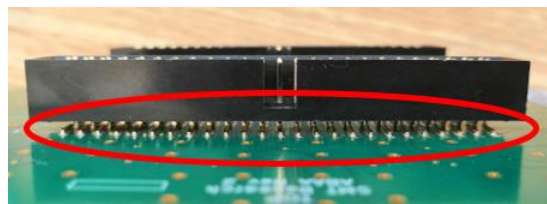


FIGURE 78 EXPOSED SOLDER TAILS

A descriptive analysis result of the first 25 readings of the three tests is given in Table 21. Test 1 and Test 3 had very close mean values of 5.62 and 5.64. The mean of Test 2 is 5.33, which is a little lower but still not far away from the other two tests.

TABLE 21 FULLY COVER WATER TEST DESCRIPTIVE STATISTICS

Descriptive Statistics						
	N	Range	Minimum	Maximum	Mean	Std. Deviation
Test1	24	0.87	4.94	5.80	5.62	0.20
Test2	24	0.36	5.19	5.55	5.33	0.11
Test3	24	0.23	5.54	5.77	5.64	0.07
Valid N (listwise)	24					

#### 4.1.2 SENSOR TEST IN GROUPS RESULTS

The highest reading in the preliminary test is  $1\text{G}\Omega$  and the lowest is  $625058\Omega$ . The readings are generally large so the log scale is used to replace the original readings. The  $1\text{G}\Omega$  is the reading when there is no liquid water detected. It equals to 9 on the log scale. Figure 79 includes the Log results for the first test group.

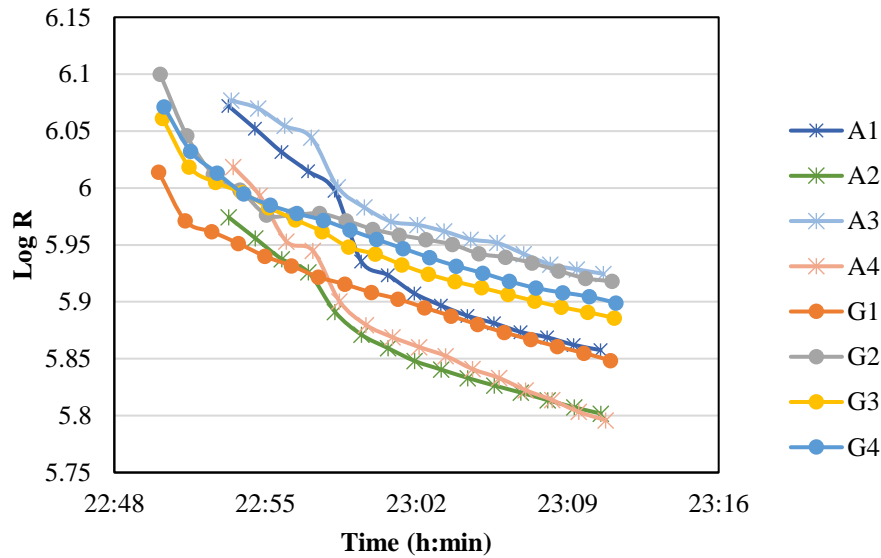


FIGURE 79 SENSOR TEST RESULTS OF A1-A4 & G1-G4

According to Table 11, at the beginning of the test,  $5\ \mu\text{L}$  water is added to each of G1 to G4 and A1 to A4 but the second application of  $5\ \mu\text{L}$  water is only given to A1 to A4. This reflects in Figure 79. The curves of G1 to G4 decreased smoothly except G2 has a low data at its fourth reading. The one low reading could be ignored since the rest readings are smoothly decreasing again. For A1 to A4, the second applications of  $5\ \mu\text{L}$  water are supposed to be added after the fifth readings, and the curve should have sharp drops at their sixth readings. However, the second drops for pads A2, A3 and A4 are added before their fifth readings due to misoperation. The drops on these three curves occur at their fifth readings. These results show the device is able to sense the addition of water droplets but with the same amount of water applied, the readings range from 5.97 to 6.08 for the beginning point and 5.79 to 5.92 for the ending point. Although the changes are tiny compared to the dry value of 9, no exact linear relationship could be computed between the water amount applied and the resulting electrical resistance.

Same as pad A1 to A4, the second application of 5  $\mu\text{L}$  water is added to C2 to C5 after their fifth readings, and their sixth readings have an obvious decrease, especially C3 and C5 as shown in Figure 80. E2 only has one time application of 5  $\mu\text{L}$  water and it has a nice slowly decreasing curve like G1 to G4. E3, E4 and E5 have a second application of 5  $\mu\text{L}$  water, 10  $\mu\text{L}$  water, and 15  $\mu\text{L}$  water respectively. The curve of E4 and E5 have lower readings than E3 but they look very similar. Therefore, same as what is concluded in the previous figure, the sensor can respond to water amount changes, and there is an inverse relationship between the input water amount and output electrical resistance, but it cannot precisely determine how many changes are made.

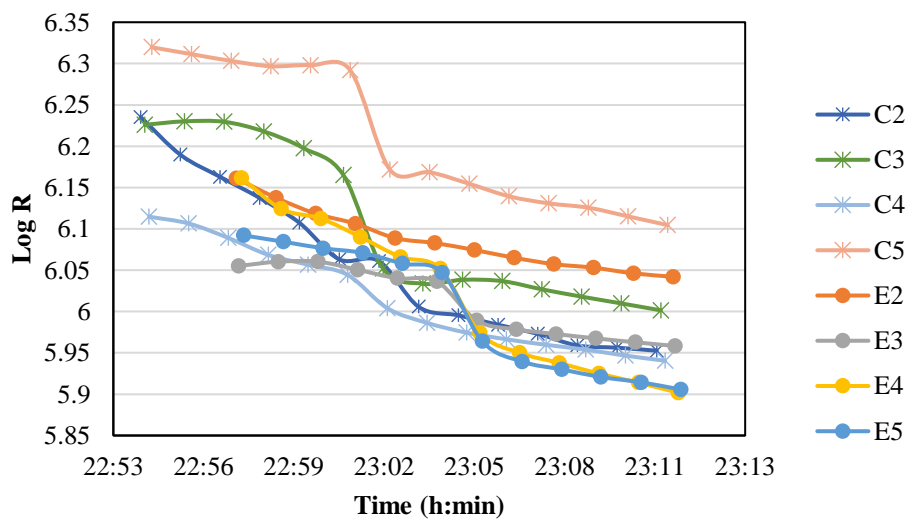


FIGURE 80 SENSOR TEST RESULTS OF C2-C5 & E2-E5

A 5  $\mu\text{L}$  water drop is added to each of the four edge sensors. The water drops on edge sensor 3 and edge sensor 4 barely touch the sensors with their most parts on the green PCB board, and all readings of the two sensors remain at the 1 G $\Omega$  dry value. Figure 81 shows the readings of edge sensor 1 and 2. The water drops are placed in the center of the two edge sensors, and there is no follow up addition. The readings do not give a smoothly decreasing curve like G1 to G4. Edge sensor 1 has its third reading going up and the fifth reading going down quickly. Edge sensor 2 has its third reading going up and the seventh reading going down. Same as what is concluded from the fully covered water test, this indicated the behavior of edge sensors should not be considered during the formal membrane test.

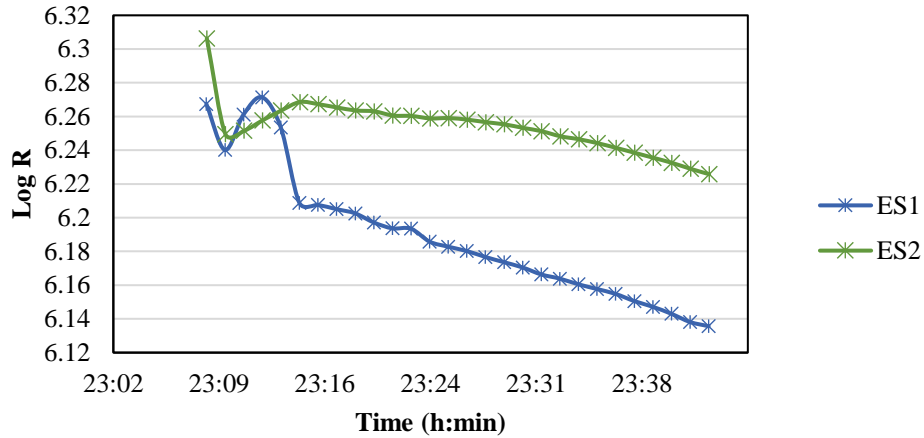


FIGURE 81 SENSOR TEST RESULTS OF ES1 & ES2

#### 4.1.2.1 Sensitivity

In the second test group, pads E2 to E5 had cumulative drops added. Sensitivity could be calculated based on equation 2. A sample calculation of sensitivity of E3 is given below. Table 22 shows the readings of E3, the second application of 5  $\mu$ L happened at 23:05.

TABLE 22 E3 DATA EXAMPLE

sensor_name	time	reading	log
E3	22:59	1148840	6.06026
E3	23:00	1149064	6.060344
E3	23:01	1123575	6.050602
E3	23:02	1097031	6.040219
E3	23:04	1087327	6.03636
<b>E3</b>	<b>23:05</b>	<b>975595</b>	<b>5.98927</b>
E3	23:06	951457	5.978389
E3	23:07	939106	5.972715
E3	23:09	927932	5.967516
E3	23:10	917855	5.962774
E3	23:11	908492	5.958321

$$K_{E3} = \frac{d(\text{output})}{d(\text{input})} \approx \frac{\Delta \text{output}}{\Delta \text{input}} = \frac{(975595\Omega - 1087327\Omega)}{5\mu\text{L}} = -22346.4 (\Omega/\mu\text{L})$$

Table 23 summarized the sensitivity results of the sensor pads that have a second application of water.

**TABLE 23 SENSITIVITY RESULTS**

Pad Name	Water amount Change ( $\mu\text{L}$ )	Sensitivity ( $\Omega/\mu\text{L}$ )
A1	5	-7986.60
A2	5	-12956.80
A3	5	-21193.00
A4	5	-17119.00
C2	5	-1107.80
C3	5	-67105.40
C4	5	-19609.00
C5	5	-94722.20
E3	5	-22346.40
E4	10	-18451.40
E5	15	-12944.73
Average (A1 – E3)	/	-29349.58

The results in Table 23 show although pads A1 to E3 have the same water amount change of 5  $\mu\text{L}$ , their sensitivity varies a lot. The average of their sensitivity is  $-29349.58 \Omega/\mu\text{L}$  while the lowest sensitivity is at  $-1107.8 \Omega/\mu\text{L}$  and the highest sensitivity is at  $-94722.2 \Omega/\mu\text{L}$ . Also, by comparing the sensitivity of E3, E4, and E5, it can be concluded that the sensitivity decreases when the water amount change increases. Therefore, the device is able to sense any change in water amount but it can not predict how much is the change.

#### *4.1.3 WATER DROPLET TEST RESULTS*

##### **4.1.3.1 Accuracy**

The means of all rounds of data for the 38 pads are calculated by MATLAB and given in Table 24 below. The first column denotes the channel number of the 38 pads. The descriptive analysis results for the six tests are summarized in Table 25.

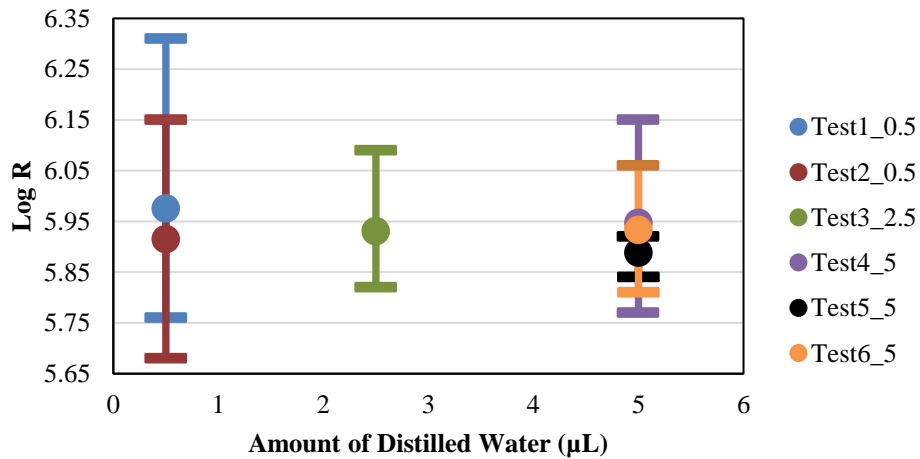
**TABLE 24 MATLAB MEAN OUTPUT TABLE**

Channel #	Test1_0.5	Test2_0.5	Test3_2.5	Test4_5	Test5_5	Test6_5
1	6.09	6.05	6.09	5.84	5.84	6.02
2	5.92	5.96	5.98	5.94	5.89	6.02
3	5.88	5.91	5.83	5.97	5.88	5.81
4	6.14	6.14	6.00	5.97	5.91	5.92
5	6.03	5.84	6.00	5.95	5.9	5.94
6	5.87	5.85	5.87	5.92	5.9	5.82
7	5.86	5.83	5.85	5.93	5.87	5.96
8	5.76	5.68	5.97	5.77	5.88	5.89
9	5.89	5.82	5.92	5.88	5.89	5.89
10	6.02	6.03	5.99	6.06	5.89	6.06
11	5.93	5.94	5.87	5.91	5.89	5.84
12	5.96	5.9	5.91	5.91	5.91	6.04
13	5.89	5.9	5.83	5.87	5.87	5.87
14	6.31	5.94	5.96	5.93	5.9	5.94
15	6.14	5.98	6.03	6.15	5.9	6.06
16	5.82	5.81	5.88	5.89	5.88	6.04
17	5.98	5.92	5.91	5.96	5.84	5.99
18	6.07	6.01	6.00	6.1	5.88	5.98
19	6.07	6.1	5.94	6.02	5.86	5.96
20	5.98	5.91	6.00	6.01	5.86	6.06
21	6.04	5.9	5.96	5.88	5.91	5.99
22	5.97	5.83	5.91	5.86	5.89	5.92
23	5.99	5.95	5.91	5.9	5.9	5.87
24	5.99	6.15	5.89	5.9	5.88	5.88
25	6.14	6.00	6.03	5.9	5.91	6.00
26	6.00	5.94	5.91	6.02	5.9	5.95
27	5.96	5.82	5.85	5.94	5.89	5.83
28	5.86	5.82	5.95	5.92	5.89	5.89
29	5.98	5.91	5.89	6.03	5.89	5.85
30	5.92	5.82	5.86	5.92	5.91	5.83
31	5.95	5.89	6.05	5.95	5.92	5.95
32	6.00	5.87	5.96	5.96	5.9	5.96
33	5.89	5.92	5.95	5.96	5.9	5.89
34	5.97	5.85	5.9	6.06	5.88	5.96
35	6.02	5.85	5.82	5.9	5.89	5.92
36	5.96	5.87	5.91	6.05	5.85	5.84
37	5.92	5.82	5.91	5.94	5.9	5.91
38	5.88	6.01	5.87	5.89	5.85	5.92

**TABLE 25 WATER DROPLET TEST DESCRIPTIVE ANALYSIS RESULTS**

		Statistics					
		Test1_0.5	Test2_0.5	Test3_2.5	Test4_5	Test5_5	Test6_5
N	Valid	38	38	38	38	38	38
	Missing	0	0	0	0	0	0
Mean		5.98	5.91	5.93	5.94	5.89	5.93
Std. Deviation		0.10	0.10	0.07	0.08	0.02	0.07
Range		0.55	0.47	0.27	0.38	0.08	0.25
Minimum		5.76	5.68	5.82	5.77	5.84	5.81
Maximum		6.31	6.15	6.09	6.15	5.92	6.06

It can be seen that the means of all 38 pads are around 5.89 to 5.98, which are very close. The standard deviation between the readings is small as well. Figure 82 is plotted based on the mean, minimum, and maximum.

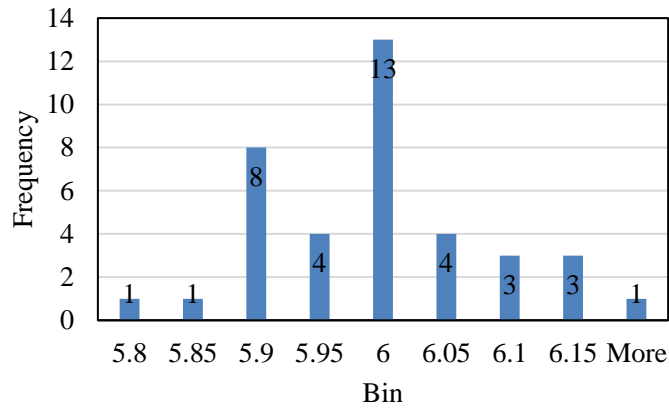


**FIGURE 82 LOG R VS. AMOUNT OF DISTILLED WATER**

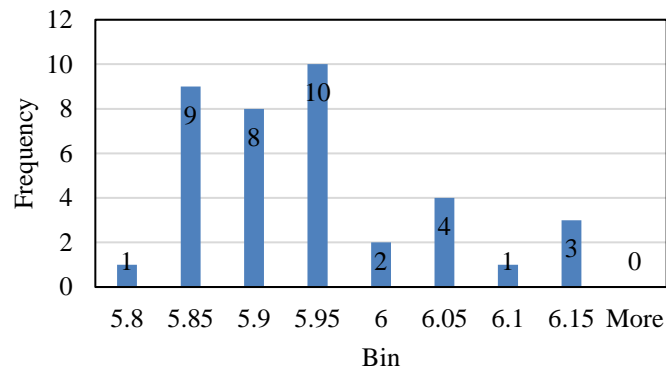
The round markers are the means, and the positive markers and negative markers are the maximum and minimum for each test. Test 1 and Test 2 that use 0.5 µL of water have relatively larger range but their means are still close to the other tests. Table 26 is the frequency table used to generate the histogram. The histograms for the six tests are plotted in Figure 83 to Figure 88.

**TABLE 26 WATER DROPLET TEST FREQUENCY TABLE**

<i>Bin</i>	<i>Frequency</i>					
	Test 1_0.5	Test 2_0.5	Test 3_2.5	Test 4_5	Test 5_5	Test 6_5
5.8	1	1	0	1	0	0
5.85	1	9	4	1	2	7
5.9	8	8	9	7	23	7
5.95	4	10	9	14	13	8
6	13	2	11	6	0	8
6.05	4	4	4	4	0	5
6.1	3	1	1	3	0	3
6.15	3	3	0	1	0	0
More	1	0	0	1	0	0



**FIGURE 83 TEST 1\_0.5μL HISTOGRAM**



**FIGURE 84 TEST 2\_0.5μL HISTOGRAM**

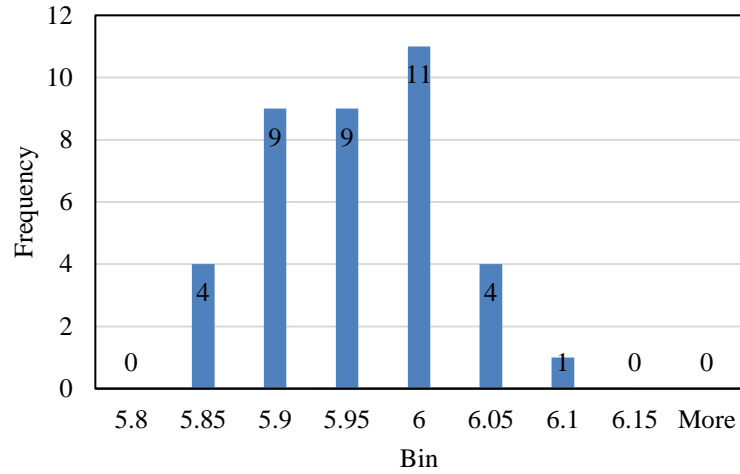


FIGURE 85 TEST 3\_2.5µL HISTOGRAM

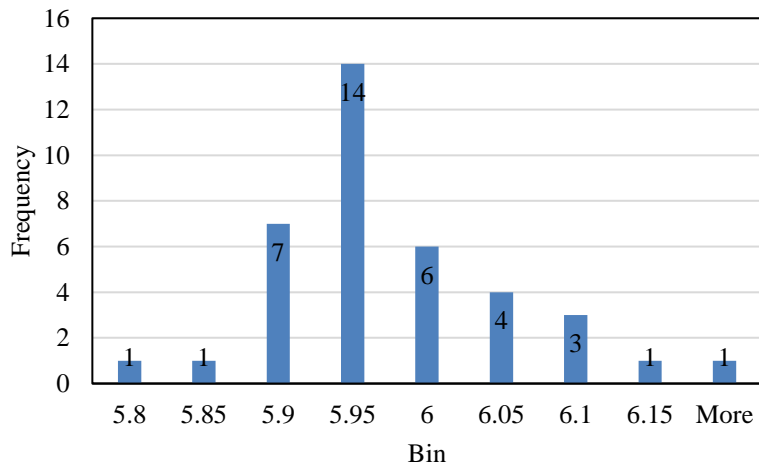


FIGURE 86 TEST 4\_5µL HISTOGRAM

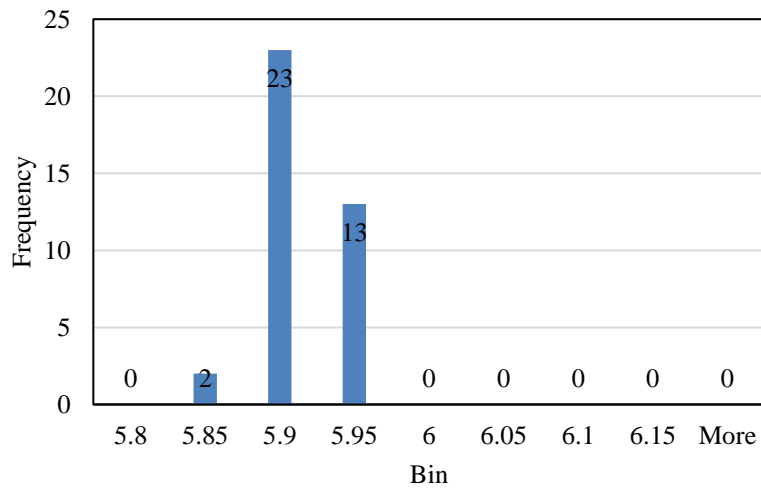
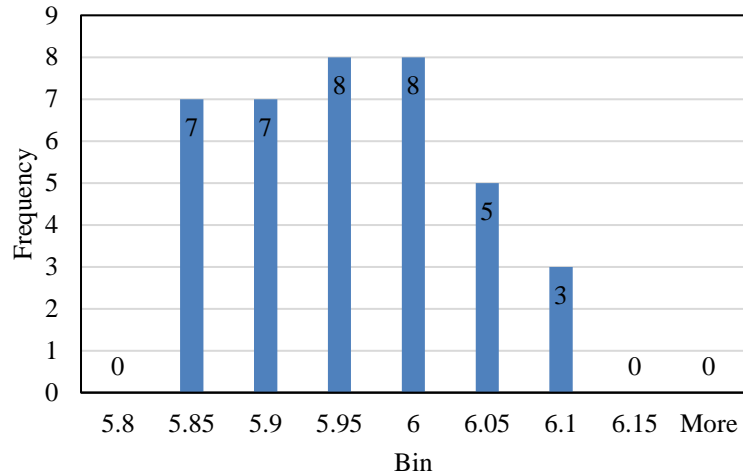


FIGURE 87 TEST 5\_5µL HISTOGRAM



**FIGURE 88 TEST 6\_5 $\mu$ L HISTOGRAM**

It can be seen that the bins have comparative higher frequencies at 5.9, 5.95 and 6.

#### **4.1.3.2 Range**

For the fully covered water test, in all three tests, the largest applied amount is 1 L of water poured on the entire sensor platter, which means all pads are fully covered by water. The highest value can be read is 1G  $\Omega$ , which is read from a dry pad without impurities. The lowest value read for a pad that fully covered by water is 49052  $\Omega$ , which is also the lowest reading in all three types of tests. The range is computed as 999995000  $\Omega$ , technically speaking, but this is meaningless as the device output is really a binary system as a result of the fact that the preliminary and water droplet tests for water volume vs resistance relationships, demonstrate no relationship.

#### **4.1.3.3 NDMI**

The *NDMI* of each pad in every test is calculated by MATLAB shown in Table 27. The first column denotes the channel number of the 38 pads. The descriptive analysis results are summarized in Table 28.

TABLE 27 NDMI DATASHEET

Channel #	Test1_0.5	Test2_0.5	Test3_2.5	Test4_5	Test5_5	Test6_5
1	0.184249	0.193654	0.19044	0.204697	0.19214	0.185863
2	0.196337	0.19662	0.190762	0.195587	0.19585	0.182692
3	0.203589	0.203552	0.202709	0.187681	0.196798	0.202437
4	0.181874	0.185868	0.1934	0.183119	0.196194	0.194723
5	0.188872	0.203248	0.184267	0.191118	0.195943	0.187695
6	0.201296	0.20552	0.200253	0.195247	0.195359	0.197841
7	0.200918	0.206924	0.205575	0.196551	0.196623	0.187053
8	0.210363	0.219992	0.198962	0.207225	0.196826	0.192809
9	0.200432	0.210493	0.19616	0.200639	0.196581	0.196803
10	0.193059	0.19318	0.194456	0.187653	0.195867	0.186176
11	0.199773	0.198827	0.196872	0.196861	0.199134	0.201231
12	0.190184	0.202246	0.19273	0.202597	0.195137	0.181114
13	0.198683	0.19744	0.201154	0.200142	0.197193	0.197757
14	0.169428	0.194221	0.191934	0.198913	0.195071	0.190589
15	0.174552	0.197353	0.182813	0.165749	0.19588	0.179959
16	0.203444	0.209632	0.202801	0.199447	0.194105	0.180986
17	0.193124	0.204224	0.194005	0.191492	0.197042	0.187369
18	0.188768	0.195555	0.193269	0.18211	0.196238	0.182696
19	0.184663	0.182333	0.192243	0.170439	0.197614	0.185985
20	0.190802	0.201426	0.193159	0.17081	0.195936	0.183009
21	0.178911	0.19971	0.191133	0.195009	0.195387	0.181904
22	0.192031	0.208638	0.193476	0.188305	0.19655	0.193928
23	0.192755	0.197021	0.19702	0.201023	0.195249	0.198773
24	0.193525	0.1803	0.196318	0.188093	0.19639	0.193624
25	0.181108	0.195721	0.188828	0.196404	0.194377	0.187766
26	0.190743	0.194359	0.192209	0.180266	0.193238	0.187941
27	0.19272	0.208272	0.202047	0.186112	0.19214	0.198532
28	0.202221	0.211423	0.186796	0.19487	0.195533	0.195656
29	0.19199	0.200904	0.198466	0.175851	0.196423	0.199826
30	0.197928	0.209252	0.203797	0.188041	0.194432	0.202744
31	0.189942	0.20244	0.181686	0.190713	0.193398	0.189298
32	0.188301	0.204321	0.194448	0.177233	0.193912	0.185655
33	0.195366	0.195933	0.196712	0.192543	0.194607	0.195431
34	0.19123	0.203003	0.199426	0.181977	0.196639	0.191515
35	0.18469	0.203568	0.206347	0.190966	0.195942	0.188512
36	0.193195	0.204903	0.195799	0.184319	0.195496	0.197666
37	0.19653	0.210149	0.196105	0.183872	0.196046	0.193233
38	0.197911	0.192964	0.203894	0.18472	0.197743	0.192898

TABLE 28 *NDMI* DESCRIPTIVE ANALYSIS

		Statistics					
		Test1_0.5	Test2_0.5	Test3_2.5	Test4_5	Test5_5	Test6_5
N	Valid	38	38	38	38	38	38
	Missing	0	0	0	0	0	0
Mean		0.19	0.20	0.20	0.19	0.20	0.19
Std. Deviation		0.01	0.01	0.01	0.01	0.00	0.01
Range		0.04	0.04	0.02	0.04	0.01	0.02
Minimum		0.17	0.18	0.18	0.17	0.19	0.18
Maximum		0.21	0.22	0.21	0.21	0.20	0.20

The means for the six tests are around 0.19 to 0.2, which are pretty close and the standard deviation between each reading is very low. An *NDMI* vs. Amount of distilled water plot is given in Figure 89.

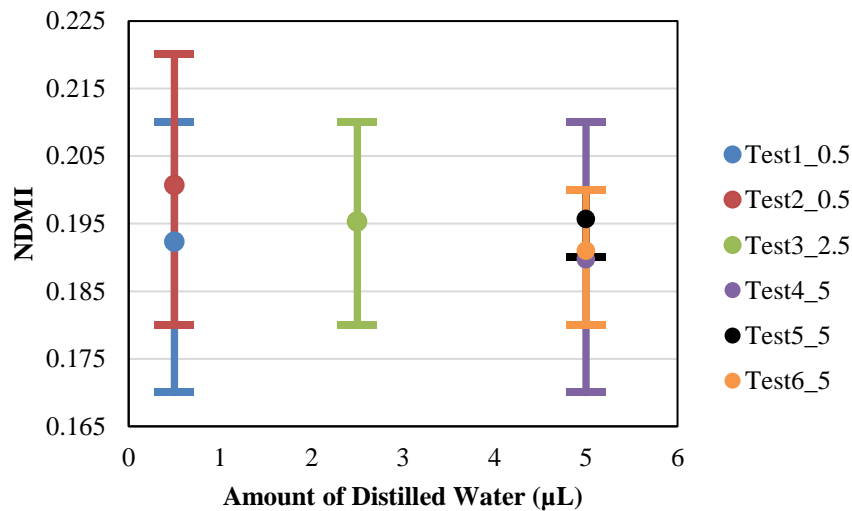
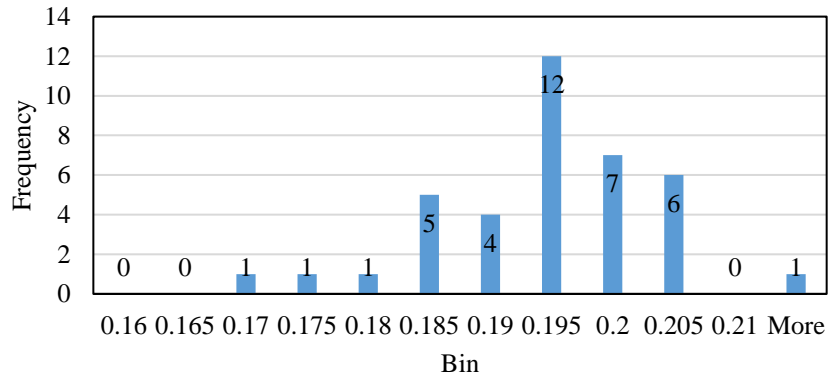


FIGURE 89 *NDMI* VS. AMOUNT OF DISTILLED WATER

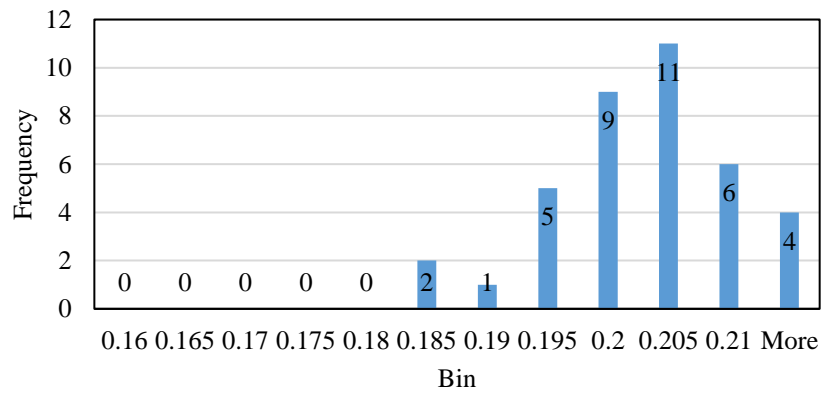
The round markers are the *NDMI* values, and the positive markers and negative markers are the maximum and minimum *NDMI* in each test. Test 1 and Test 2 and Test 4 have a relatively larger range than other tests but their means are still close to the other tests. There is no relationship found between the amount of distilled water applied and the *NDMI*. Table 29 is the frequency table, and the histograms are then plotted in Figure 90 to Figure 95.

**TABLE 29 NDMI FREQUENCY TABLE**

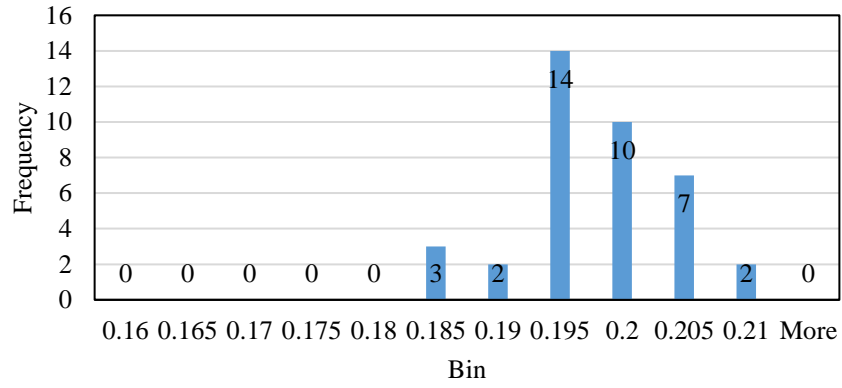
Bin	Frequency					
	Test 1_0.5	Test 2_0.5	Test 3_2.5	Test 4_5	Test 5_5	Test 6_5
0.16	0	0	0	0	0	0
0.165	0	0	0	0	0	0
0.17	1	0	0	1	0	0
0.175	1	0	0	2	0	0
0.18	1	0	0	2	0	1
0.185	5	2	3	7	0	6
0.19	4	1	2	6	0	11
0.195	12	5	14	6	9	8
0.2	7	9	10	8	29	9
0.205	6	11	7	5	0	3
0.21	0	6	2	1	0	0
More	1	4	0	0	0	0



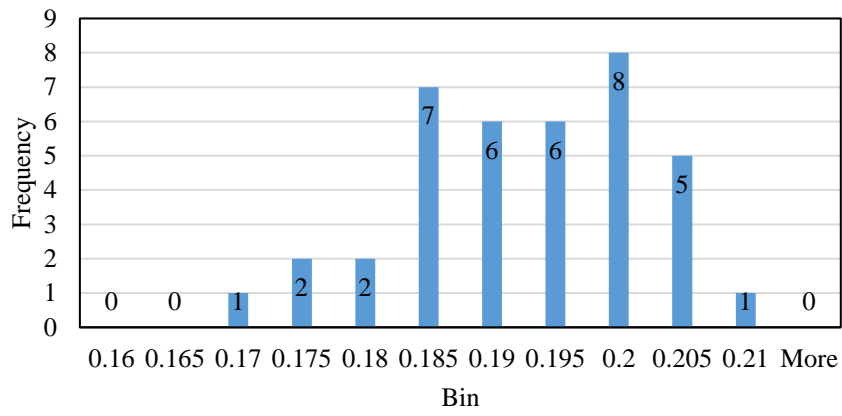
**FIGURE 90 TEST 1\_0.5µL HISTOGRAM**



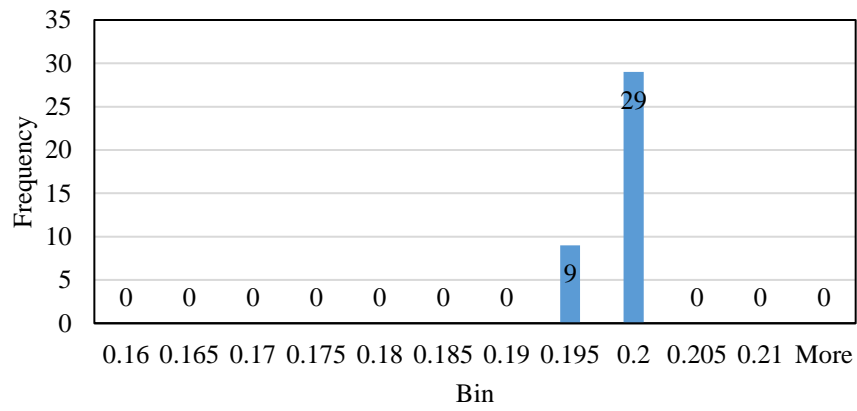
**FIGURE 91 TEST 2\_0.5µL HISTOGRAM**



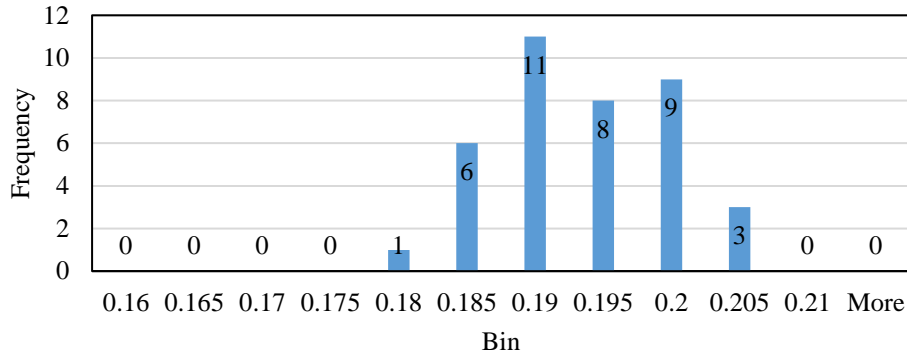
**FIGURE 92 TEST 3\_2.5µL HISTOGRAM**



**FIGURE 93 TEST 4\_5µL HISTOGRAM**



**FIGURE 94 TEST 5\_5µL HISTOGRAM**

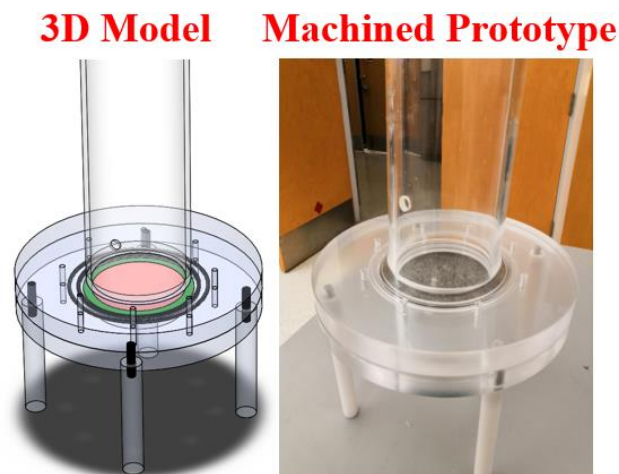


**FIGURE 95 TEST 6\_5µL HISTOGRAM**

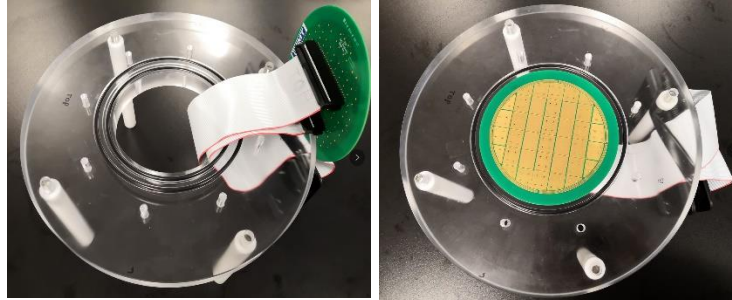
The *NDMI* in Test 5 only spreads in 0.195 and 0.2 and when looking at all six figures, 0.195 and 0.2 have high frequencies. Test 2 has the most values in 0.205 and Test 6 has the most values in 0.19 but 0.205 and 0.19 have lower frequencies in other tests. Overall, the bins 0.185 to 0.205 have most values.

#### 4.2 MODIFIED HPTA DEVICE

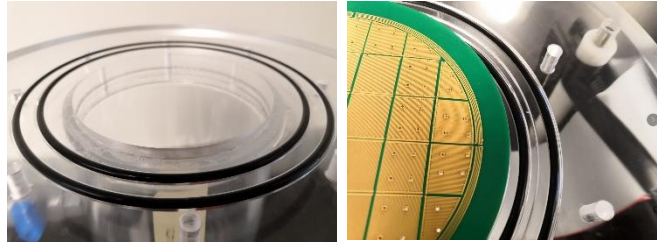
The prototype is built in UVic Machine Shop under the supervise of Mr. Rodney Katz, Senior Scientific Assistant. The prototype is built strictly based on the SolidWorks model as shown in Figure 96. The engineering drawings are attached in Appendix C. Figure 97 to Figure 99 shows the detailed views of the bottom plate, o-ring details, and the top plate. The detailed machining process is attached in Appendix D and a comparison of the original HPTA apparatus and the modified device is given in Figure 100.



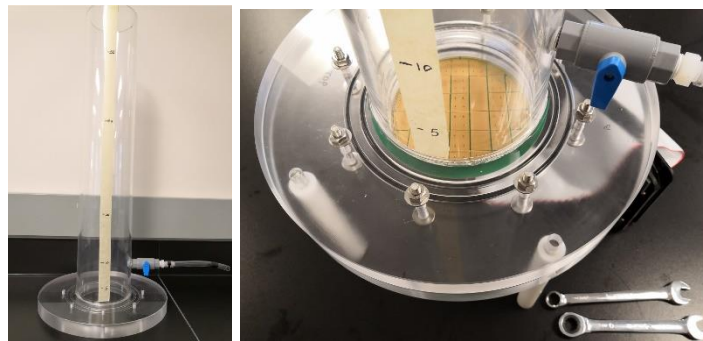
**FIGURE 96 3D MODEL AND MACHINED PROTOTYPE**



**FIGURE 97 BOTTOM PLATE**



**FIGURE 98 O-RING DETAIL**



**FIGURE 99 TOP PLATE**



**FIGURE 100 ORIGINAL DEVICE AND THE MODIFIED DEVICE**

#### *4.2.1 EVALUATION OF THE PROTOTYPE*

The modified HPTA solve the leaking problem properly and it can conduct tests on almost all types of materials. However, there are still some problems that remain unsolved. The first one is the pin of the sensors are not properly sealed as mentioned in Section 4.1.1, Figure 78. Circuit shortage could happen if water touches any pin and the results could be affected. The second problem is the device is even heavier than the original device. It makes it is less portable. Also, the clipping method is working well but not convenient. The user needs to hand tight all 8 bolts which is very time-consuming. The material to be tested could fail in less than 1 minute after water is added but setting up the device or taking the device apart take a much longer time.

#### **4.3 TEST WITH WRBS RESULT**

The colormaps of the six tested materials and their summary tables will be given below. In some tests, there are some sensor pads read erratic initial values before water is added. These sensors are circled in red and should not be counted for analysis. In the test procedure in Section 3.4.4 step 6, if more than three sensors have erratic initial values instead of  $1G\Omega$ , the test should be paused and wait for 12 more hours until the sensors have erratic initial conditions less than or equal to three. Although tests 4, 16, 26 and 62 have more than three erratic initial values, these tests are completed and included for analyzing the possible influence of the unnormal initial values. They should not be counted when analyzing the WRBs water resistance.

#### *4.3.1 MEMBRANE A*

There are 17 tests done for Membrane A and the colormaps are given in Figure 101 to Figure 103. It is the first material to be tested and the researcher is still getting familiar with the testing device. Test 4, Test 9, Test 11, and Test 16 are labeled with \* because the comments made during the experiment indicated the test is invalid for analyzing the water resistance of this material. Test 4 and Test 16 have more than three initial erratic dry readings. The experimenter comments on Test 11 that many sensors can not read the correct dry value. Test 9 started with water trapped inside the top O-ring grooves. The information table is given in Table 30.

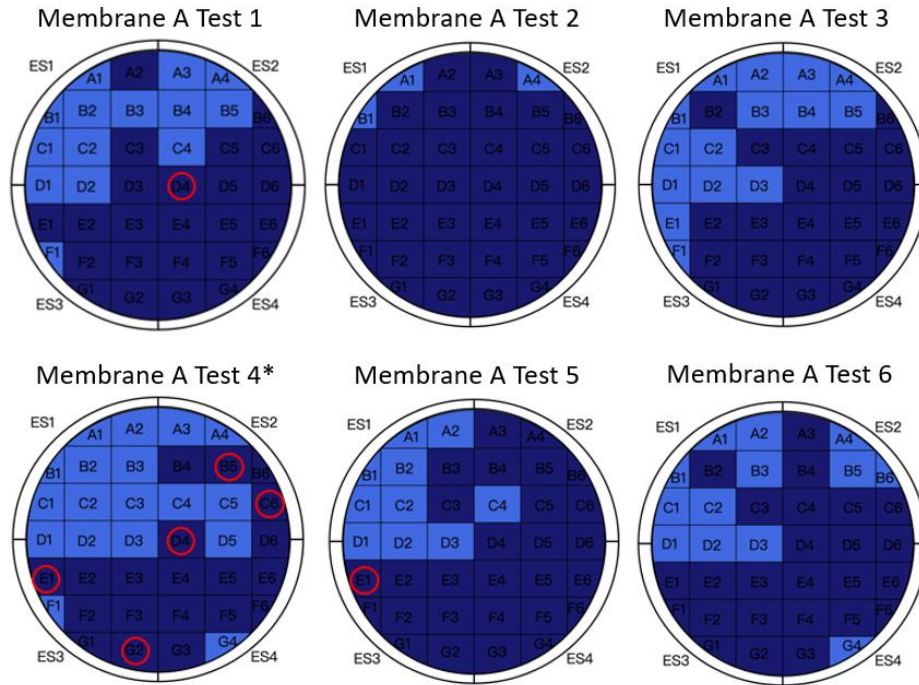


FIGURE 101 MEMBRANE A TEST 1 – 6 COLORMAP

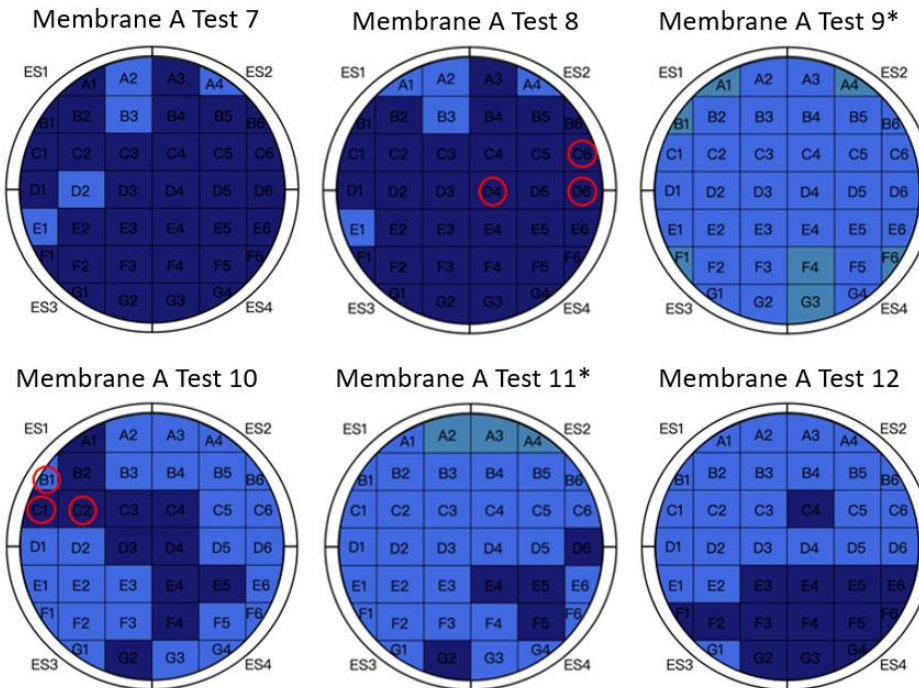


FIGURE 102 MEMBRANE A TEST 7 – 12 COLORMAP

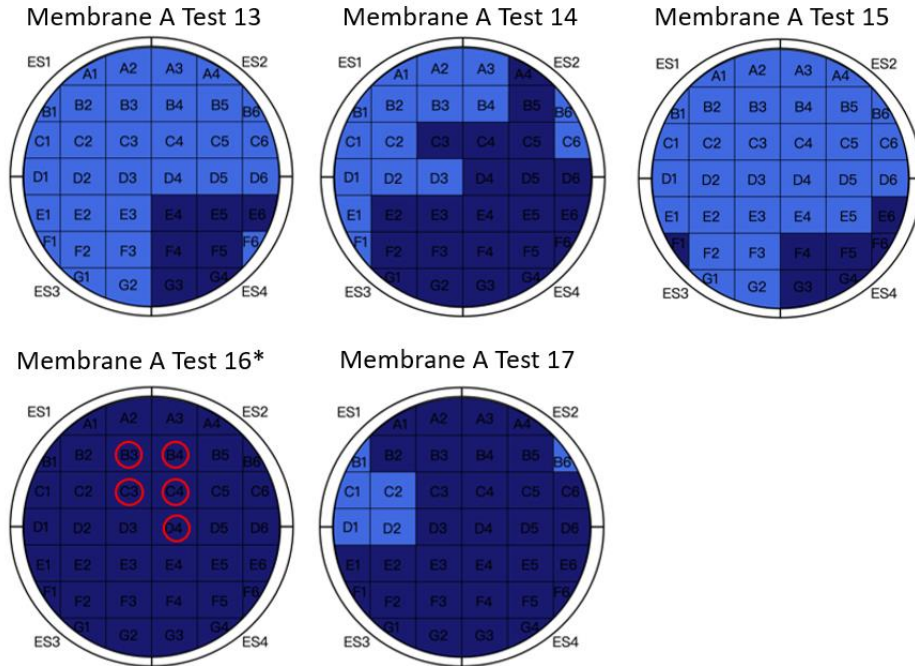


FIGURE 103 MEMBRANE A TEST 13 – 17 COLORMAP

TABLE 30 MEMBRANE A INFORMATION TABLE

Test #	Material Test #	Water level drop	Valid Sensors	First Wet Time (min)							Score
				0~1	1~5	5~20	20~60	60~180	180~480	>480	
Test1	MA 1	0 cm	37	23	14	0	0	0	0	0	14
Test2	MA 2	0 cm	38	35	3	0	0	0	0	0	3
Test3	MA 3	0 cm	38	23	15	0	0	0	0	0	15
Test5	MA 5	4 cm	37	27	10	0	0	0	0	0	10
Test6	MA 6	7 cm	38	25	13	0	0	0	0	0	13
Test7	MA 7	14 cm	38	33	5	0	0	0	0	0	5
Test8	MA 8	15 cm	35	30	5	0	0	0	0	0	5
Test10	MA 10	5 cm	35	10	25	0	0	0	0	0	25
Test12	MA 12	0 cm	38	14	24	0	0	0	0	0	24
Test13	MA 13	12 cm	38	7	31	0	0	0	0	0	31
Test14	MA 14	6 cm	38	23	15	0	0	0	0	0	15
Test15	MA 15	10 cm	38	7	31	0	0	0	0	0	31
Test17	MA 17	5 cm	38	32	6	0	0	0	0	0	6
Total:				289	197	0	0	0	0	0	/
Total Valid Test: 13				Average Score: 15.15				COV of WRS: 0.62			

The colormaps of the 13 valid Membrane A tests indicate all sensor pads detect liquid water before 5 minutes. A 100% stacked column chart and a pie chart with percentage is given in Figure 104 and Figure 105. 59% of sensors detect liquid water before one minute and 41% of

sensors detect liquid water between one to five minutes. All 13 tests have more than three sensor pads detect liquid water before one minute, according to Table 16 in Section 3.4.3, Membrane A has very short water resistance. A WRS of 15.15 is calculated using the weighting coefficient table in Section 3.4.5.4.

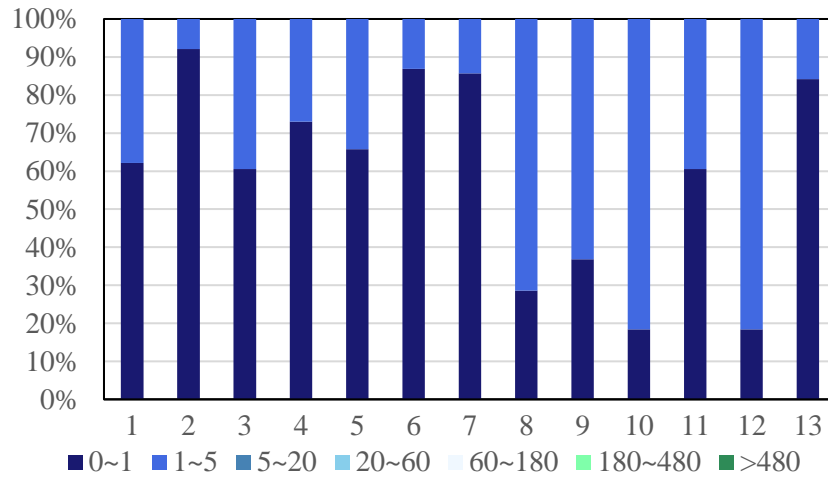


FIGURE 104 MEMBRANE A 100% STACKED COLUMN CHART

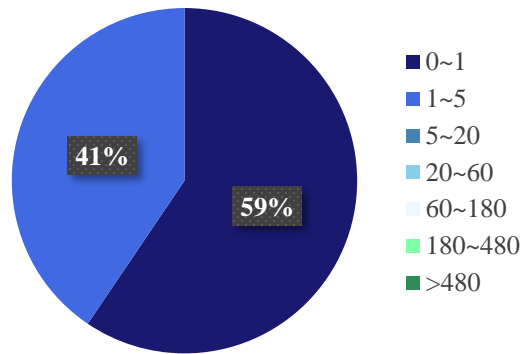


FIGURE 105 MEMBRANE A PIE CHART

Figure 106 shows an image of a Membrane A specimen under the electrical microscope. It can be seen that there are diamond shape holes lined in order and there are lighter square shape shadows at the back. These shadows are the holes line up at the lower layer. There are massive fibers besides the holes and the fibers are not even. Some places have denser fibers but some places have more voids between fibers.

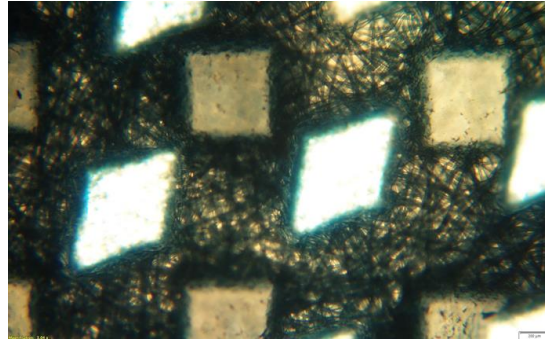


FIGURE 106 MEMBRANE A MICROSCOPE IMAGES

### 4.3.2 MEMBRANE B

There are 22 tests done for Membrane B and the corresponding colormaps are given in Figure 107 to Figure 110. Test 9 has more than three initial erratic dry readings so only 21 tests are valid. The information table is given in Table 31.

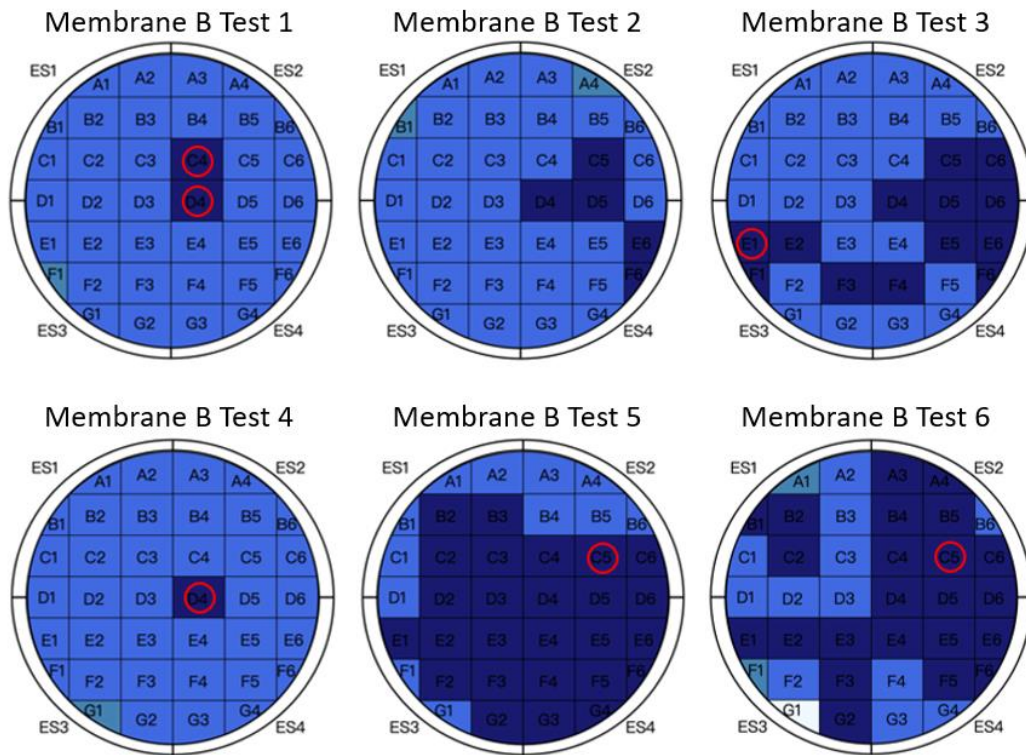


FIGURE 107 MEMBRANE B TEST 1 – 6 COLORMAP

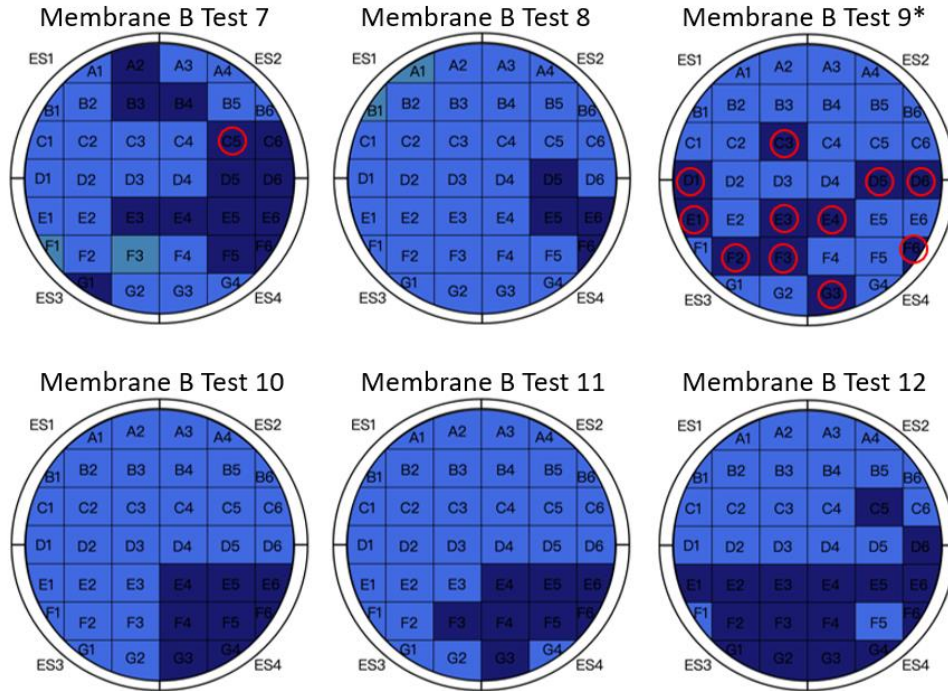


FIGURE 108 MEMBRANE B TEST 7 – 12 COLORMAP

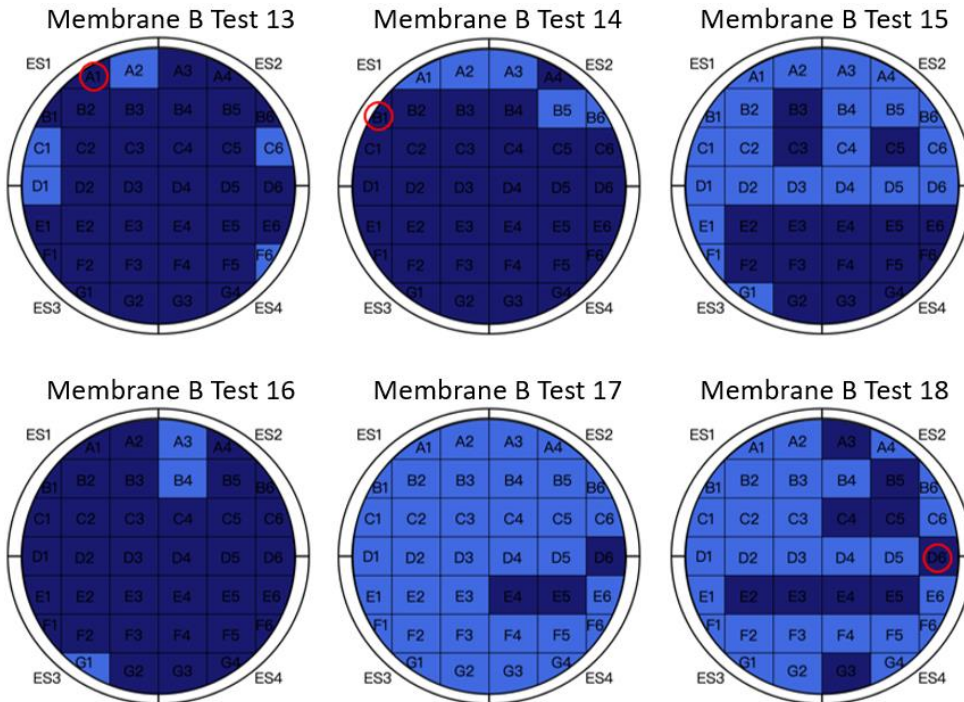


FIGURE 109 MEMBRANE B TEST 13 – 18 COLORMAP

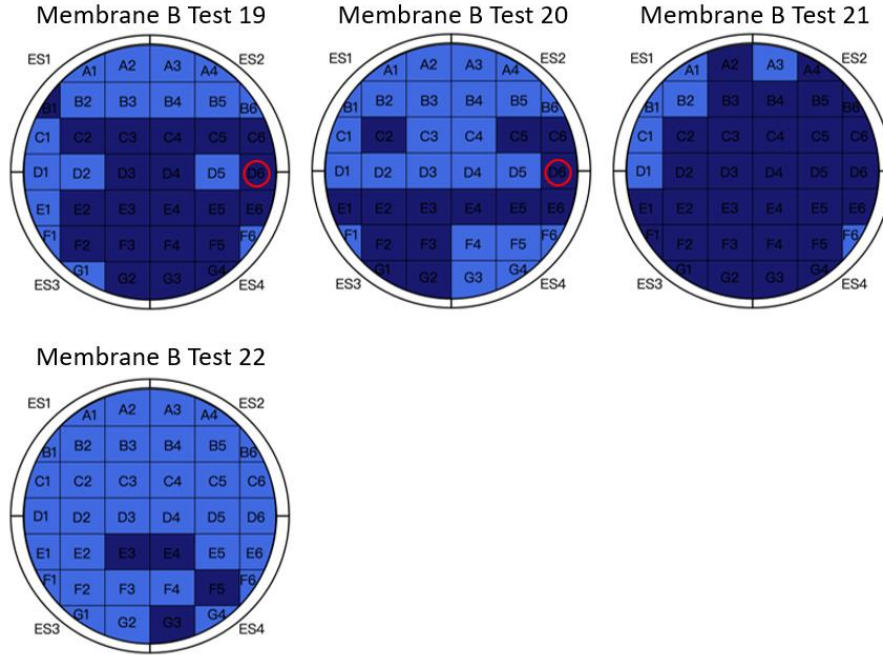


FIGURE 110 MEMBRANE B TEST 19 – 22 COLORMAP

TABLE 31 MEMBRANE B INFORMATION TABLE

Test #	Material Test #	Water level drop	Valid Sensors	First Wet Time (min)							Score
				0~1	1~5	5~20	20~60	60~180	180~480	>480	
Test 18	MB 1	0 cm	36	0	35	1	0	0	0	0	36.5
Test 19	MB 2	0 cm	38	5	31	2	0	0	0	0	34
Test 20	MB 3	0 cm	37	12	25	0	0	0	0	0	25
Test 21	MB 4	0 cm	37	0	36	1	0	0	0	0	37.5
Test 22	MB 5	0 cm	37	25	12	0	0	0	0	0	12
Test 23	MB 6	0 cm	37	22	12	2	0	1	0	0	20
Test 24	MB 7	0 cm	37	13	22	2	0	0	0	0	25
Test 25	MB 8	0 cm	38	4	32	2	0	0	0	0	35
Test 27	MB 10	3 cm	38	8	30	0	0	0	0	0	30
Test 28	MB 11	5 cm	38	8	30	0	0	0	0	0	30
Test 29	MB 12	5 cm	38	16	22	0	0	0	0	0	22
Test 30	MB 13	8 cm	37	32	5	0	0	0	0	0	5
Test 31	MB 14	0 cm	37	32	5	0	0	0	0	0	5
Test 32	MB 15	0 cm	38	16	22	0	0	0	0	0	22
Test 33	MB 16	0 cm	38	35	3	0	0	0	0	0	3
Test 34	MB 17	0 cm	38	3	35	0	0	0	0	0	35
Test 35	MB 18	0 cm	37	9	28	0	0	0	0	0	28
Test 36	MB 19	0 cm	37	20	17	0	0	0	0	0	17
Test 37	MB 20	0 cm	37	13	24	0	0	0	0	0	24

Test 38	MB 21	0 cm	38	31	7	0	0	0	0	0	7	
Test 39	MB 22	0 cm	38	4	34	0	0	0	0	0	34	
Total:				308	467	10	0	1	0	0	/	
Total Valid Test: 21				Average Score: 23.19					COV of WRS: 0.47			

Based on the colormap, most tests have all sensor pads detect liquid water before 5 minutes. Only a few sensors in Tests 1, 2, 4, 6, 7, and 8 get wet between 5 to 20 minutes. The 100% stacked column chart and the pie chart are given in Figure 111 and Figure 112. There are 39% of sensors detect liquid water before 1 minute and 60% of sensors detect liquid water between 1 to 5 minutes. Only 1% of sensors get wet between 5 to 20 minutes. Only two tests have more than three sensor pads that detect liquid water between 1 to 5 minutes while all other tests detect liquid water before 1 minute thus Membrane B is regarded as has very short water resistance duration. The WRS is calculated as 23.19.

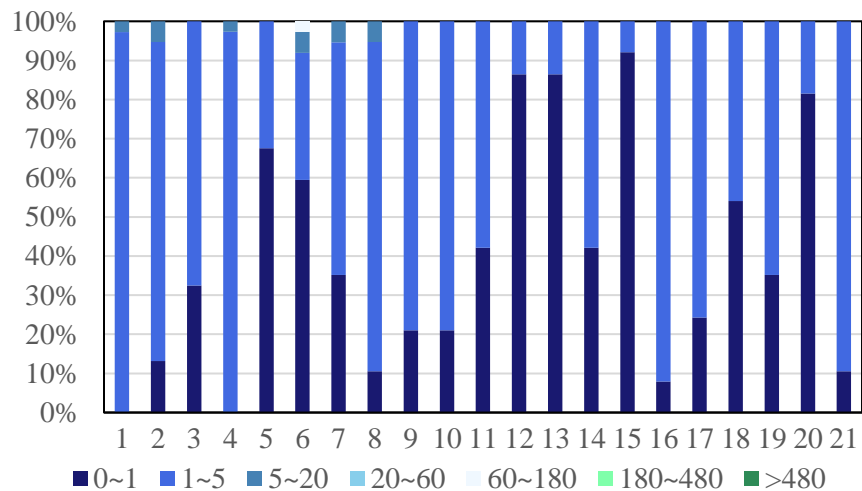


FIGURE 111 MEMBRANE B 100% STACKED COLUMN CHART

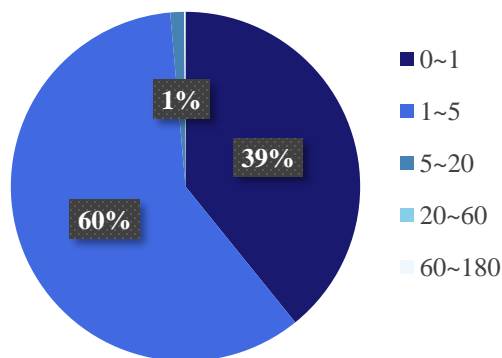


FIGURE 112 MEMBRANE B PIE CHART

Three microscope images are given in Figure 113. On the left image, it can be seen there are holes line on the specimen but the shapes of the holes are not uniform and the distance between the holes also varies. In other words, the distribution of holes is uneven. Some areas are dark spotted and the hole arrangement is in disorder. In the middle image, it can be seen the view is split by two colors so the membrane is not made with one consistent material. According to the datasheet of the manufacturer, Membrane B is made of 100% polyethylene fibers so the different colors could be different polyethylene fibers. The fibers can be barely seen in the middle image but slightly clearer in the right image, but they are still not as clear as in other materials.

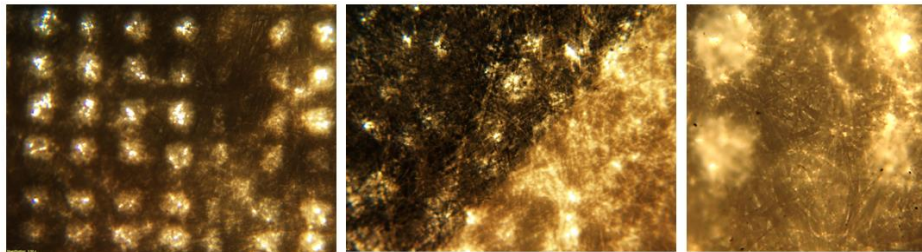


FIGURE 113 MEMBRANE B MICROSCOPE IMAGES

#### 4.3.3 MEMBRANE C

There are eight tests done for Membrane C and the colormaps are given in Figure 114 and Figure 115. In all eight tests, all sensors read the  $1G\Omega$  dry value correctly before the start of the experiment. All the eight tests are valid for further analysis and the information table is given in Table 32.

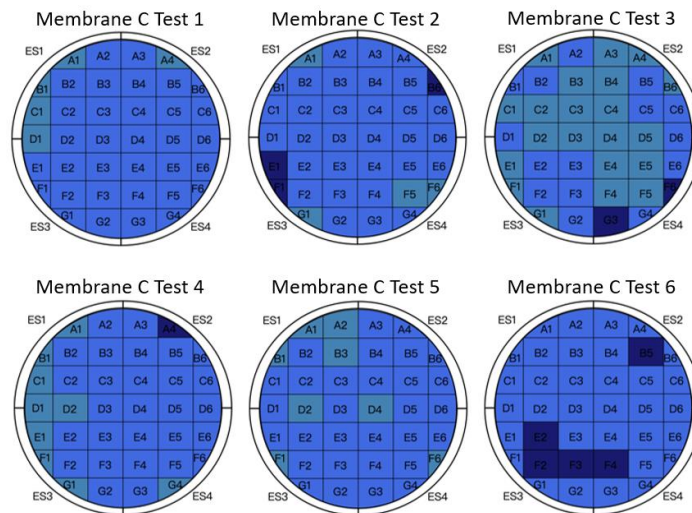


FIGURE 114 MEMBRANE C TEST 1 – 6 COLORMAP

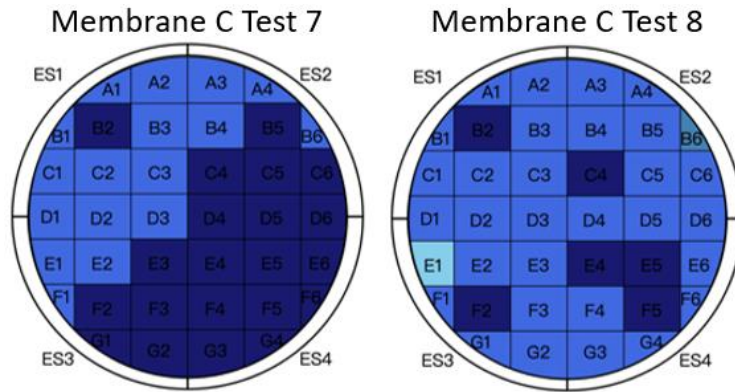


FIGURE 115 MEMBRANE C TEST 7 – 8 COLORMAP

TABLE 32 MEMBRANE C INFORMATION TABLE

Test #	Material Test #	Water level drop	Valid Sensors	First Wet Time (min)							Score
				0~1	1~5	5~20	20~60	60~180	180~480	>480	
Test 40	MC 1	10 cm	38	0	33	5	0	0	0	0	40.5
Test 41	MC 2	30 cm	38	3	31	4	0	0	0	0	37
Test 42	MC 3	34 cm	38	2	15	21	0	0	0	0	46.5
Test 43	MC 4	25 cm	38	1	28	9	0	0	0	0	41.5
Test 44	MC 5	0 cm	38	0	30	8	0	0	0	0	42
Test 45	MC 6	15 cm	38	5	33	0	0	0	0	0	33
Test 46	MC 7	16 cm	38	21	17	0	0	0	0	0	17
Test 47	MC 8	20 cm	38	6	30	1	1	0	0	0	34.5
Total:				38	217	48	1	0	0	0	/
Total Valid Tests: 8				Average Score: 36.5				COV of WRS: 0.23			

Three major time ranges appear on the colormaps, less than 1 minute, 1 to 5 minutes and 5 to 20 minutes. The 100% stacked column chart in Figure 116 shows that most sensors get wet between 1 and 5 minutes. The pie chart in Figure 117 demonstrates that 71% of sensors get wet between 1 to 5 minutes, 16% of sensors get wet between 5 to 20 minutes and 13% of sensors get wet before 1 minute. There is only one reading of 20 to 60 minutes in all tests so it can be ignored. Four tests have more than three sensors that detect water before 1 minute and the rest four tests have more than three sensors detect water between 1 to 5 minutes. According to Table 8, Membrane C lies between very short and short. The WRS is 36.5, which is higher than Membrane B and Membrane A.

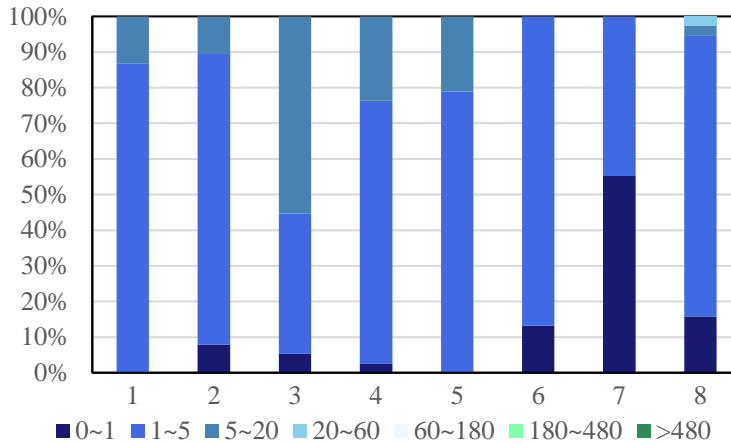


FIGURE 116 MEMBRANE C 100% STACKED COLUMN CHART

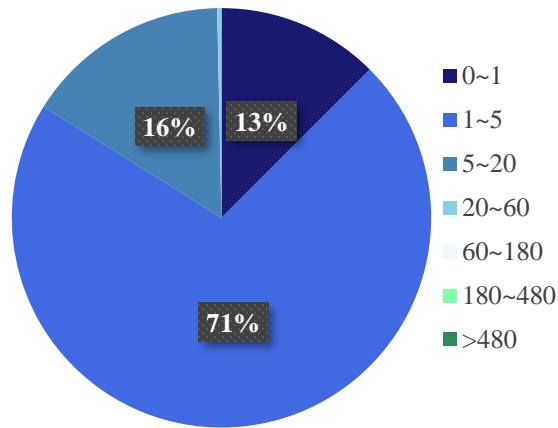


FIGURE 117 MEMBRANE C PIE CHART

Not like Membrane A and Membrane B have light colors, Membrane C has a black color on one side and is comparatively thicker. The image is fully dark without applying an extra light source. Figure 118 shows three microscope images of a Membrane C specimen, all placed under the slide glass with a flashlight. The two images on the left are shot in the same position. The difference between them is a very tiny adjustment of the focus knob. In the top image, the fibers can be seen clearly. The black fibers are out of focus on the bottom image, but the fibers on the back of the oval holes are visible. The fibers are distributed unevenly. The image on the right uses a filter glass to bluish the colour. Under this filter glass, it can be seen that there is a strip in the middle of the image. This could be the grid boundary on the back of the membrane.

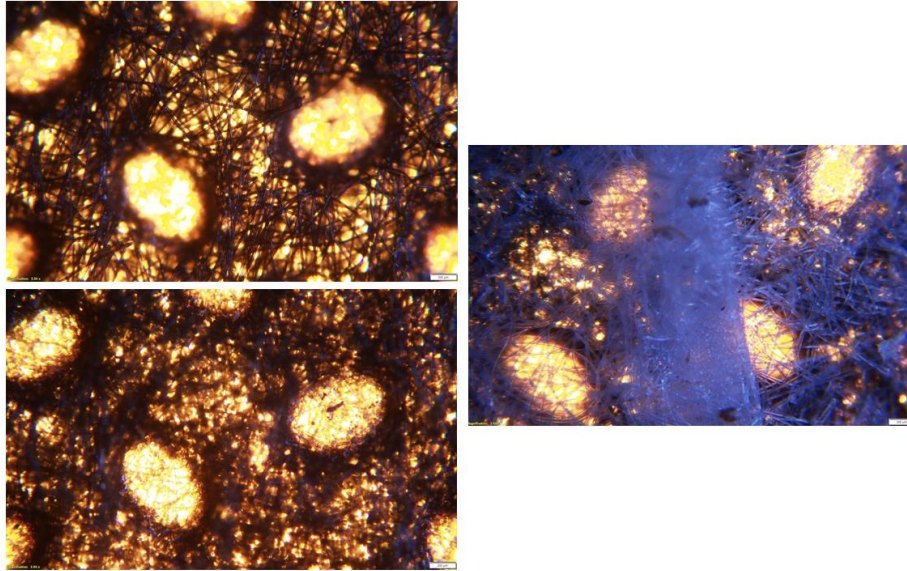


FIGURE 118 MEMBRANE C MICROSCOPE IMAGES

#### 4.3.4 MEMBRANE D

There are 17 tests done for Membrane D and the colormaps are given in Figure 119 to Figure 121. Test 15 has more than three sensor pads that have erratic dry readings so only 16 tests are valid. The information table is given in Table 33.

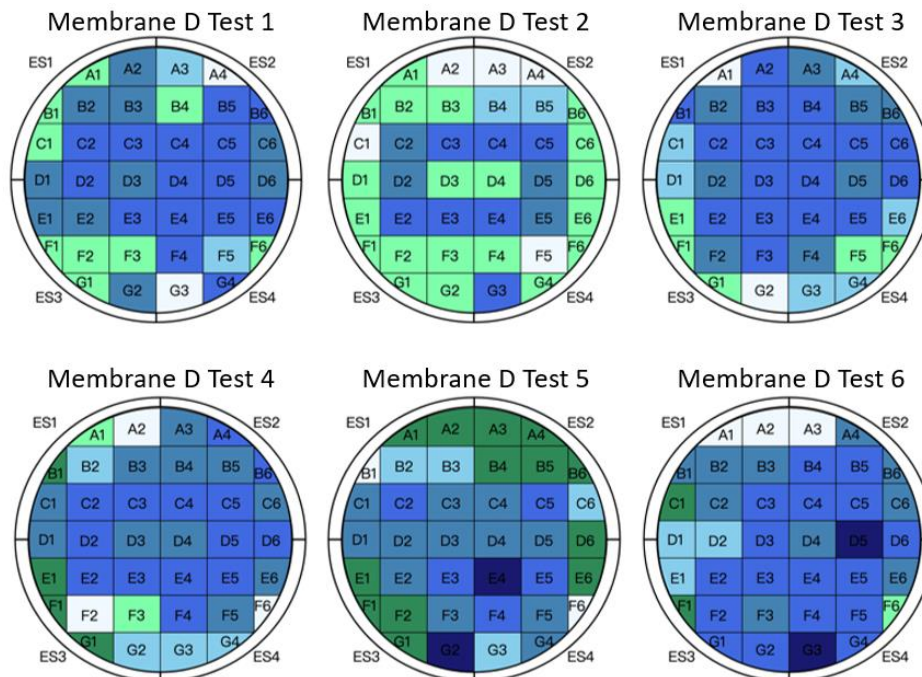


FIGURE 119 MEMBRANE D TEST 1 – 6 COLORMAP

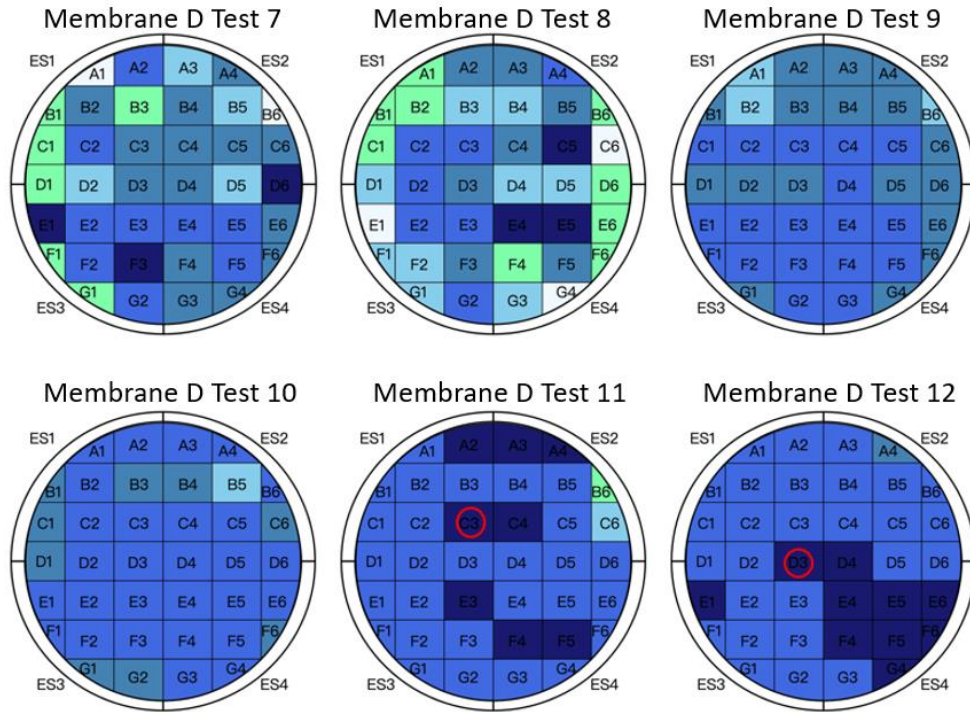


FIGURE 120 MEMBRANE D TEST 7 – 12 COLORMAP

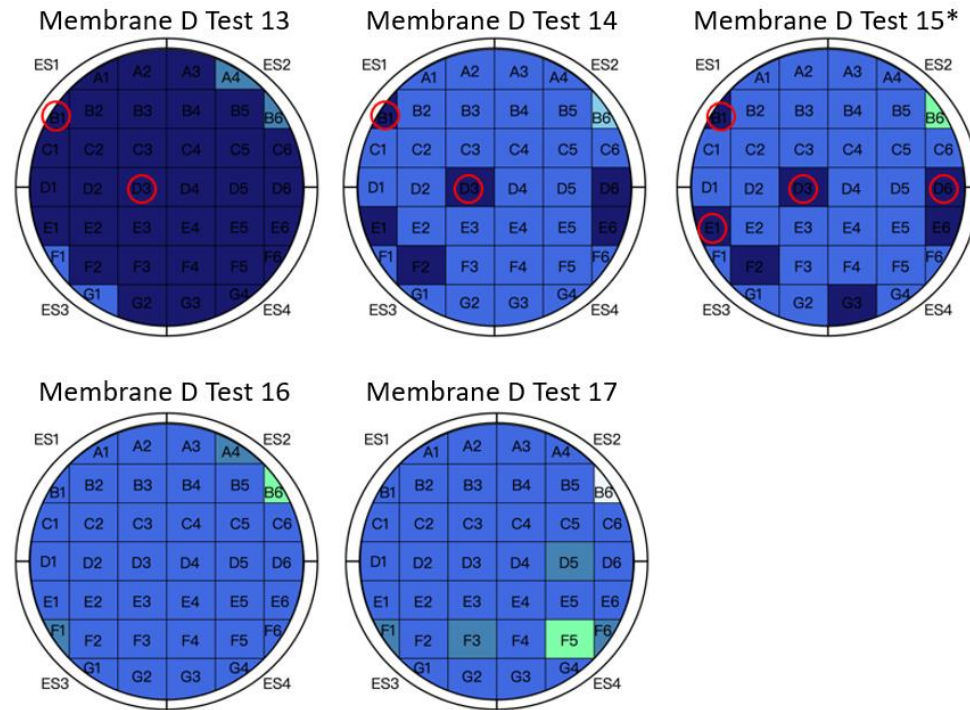


FIGURE 121 MEMBRANE D TEST 13 – 17 COLORMAP

TABLE 33 MEMBRANE D INFORMATION TABLE

Test #	Material Test #	Water level drop	Valid Sensors	First Wet Time (min)							Score
				0~1	1~5	5~20	20~60	60~180	180~480	>480	
Test 48	MD 1	0 cm	38	0	15	10	2	2	9	0	118
Test 49	MD 2	0 cm	38	0	7	4	2	5	20	0	204
Test 50	MD 3	0 cm	38	0	17	8	6	2	5	0	97
Test 51	MD 4	0 cm	38	0	14	11	4	3	2	4	113.5
Test 52	MD 5	0 cm	38	2	5	12	4	2	0	13	175
Test 53	MD 6	0 cm	38	2	17	10	3	3	1	2	84
Test 54	MD 7	0 cm	38	3	9	14	4	2	6	0	100
Test 55	MD 8	0 cm	38	3	7	7	9	3	9	0	131.5
Test 56	MD 9	0 cm	38	0	18	17	3	0	0	0	52.5
Test 57	MD 10	0 cm	38	0	28	9	1	0	0	0	44.5
Test 58	MD 11	0 cm	37	7	28	0	1	0	1	0	39
Test 59	MD 12	0 cm	37	9	27	1	0	0	0	0	28.5
Test 60	MD 13	0 cm	36	32	2	2	0	0	0	0	5
Test 61	MD 14	0 cm	36	4	31	0	1	0	0	0	34
Test 63	MD 16	0 cm	38	0	35	2	0	0	1	0	46
Test 64	MD 17	0 cm	38	0	32	4	0	1	1	0	51
Total:				62	292	111	40	23	55	19	/
Total Valid Tests: 16				Average Score: 82.72				COV of WRS: 0.65			

The colormaps of many tests contain five to six colors, which means the sensors detect liquid water in a variety of time range. The 100% stacked column chart in Figure 122 has seven colors covered in all tests and 1 to 5 minutes has the most readings. According to the pie chart in Figure 123, the 1 to 5 minutes time range occupies 49% of all time ranges, 5 to 20 minutes occupies 18% and less than 1 minute has 10%. Each of 180 to 480 minutes, 20 to 60 minutes, 60 to 180 minutes and more than 480 minutes is less than 10%. Although there are seven different colors shown in the colormaps, ten tests have more than three sensors detect liquid water between 1 to 5 minutes and six tests have more than three sensors detect liquid water before 1 minute. The material is still ranged between very short and short water resistance duration, which is similar to other materials while the water resistance score is 82.72 and is much higher than the previously discussed materials.

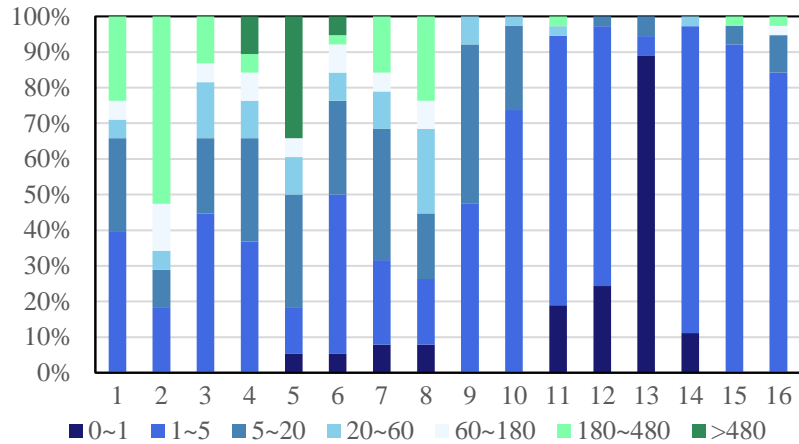


FIGURE 122 MEMBRANE D 100% STACKED COLUMN CHART

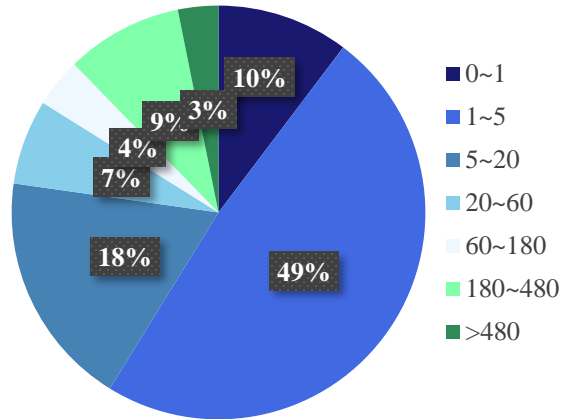


FIGURE 123 MEMBRANE D PIE CHART

Figure 124 shows an image of a Membrane D specimen under the electrical microscope. Obviously, this material is composed of fibers only and the arrangement of fibers is not even. No patterned holes can be seen in this material.

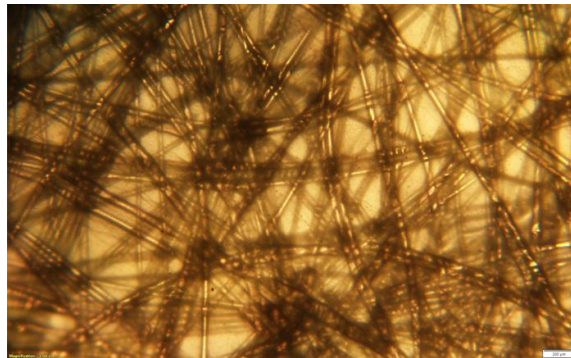


FIGURE 124 MEMBRANE D MICROSCOPE IMAGES

### 4.3.5 MEMBRANE E

There are 11 tests done for Membrane E. The colormaps are included in Figure 125 to Figure 126. Seven tests have erratic dry values but no test has more than three irregular dry values so all eleven tests are valid. All tests are run for at least eight hours except Test 8 only has 7.9 hours. The information table is given in Table 34.

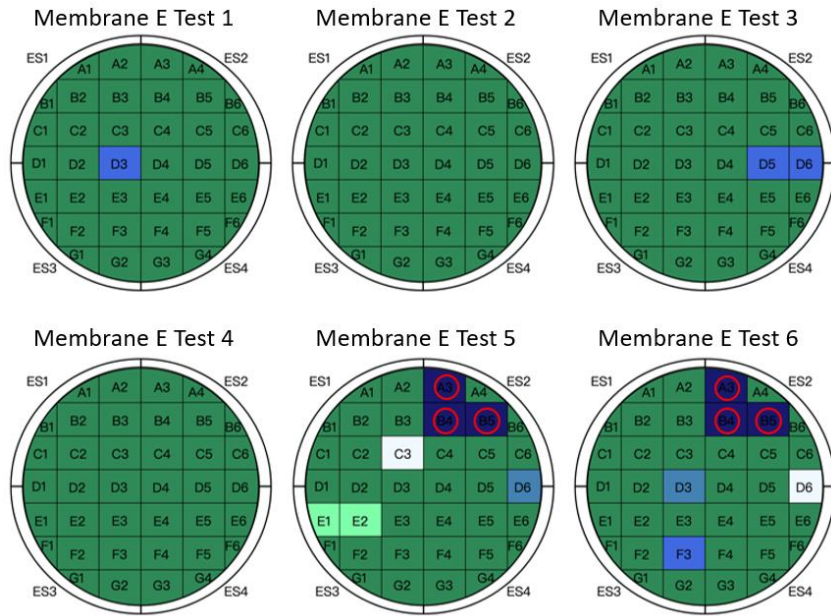


FIGURE 125 MEMBRANE E TEST 1 – 6 COLORMAP

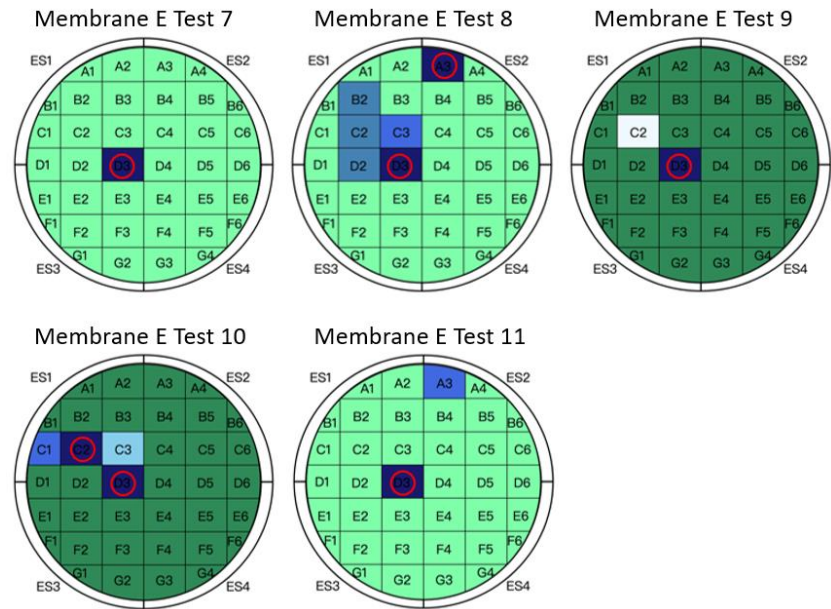


FIGURE 126 MEMBRANE E TEST 7 – 11 COLORMAP

TABLE 34 MEMBRANE E INFORMATION TABLE

Test #	Material Test #	Water level drop	Valid Sensors	First Wet Time (min)							Score
				0~1	1~5	5~20	20~60	60~180	180~480	>480	
Test 65	ME 1	0 cm	38	0	1	0	0	0	0	37	371
Test 66	ME 2	0 cm	38	0	0	0	0	0	0	38	380
Test 67	ME 3	0 cm	38	0	2	0	0	0	0	36	362
Test 68	ME 4	0 cm	38	0	0	0	0	0	0	38	380
Test 69	ME 5	0 cm	35	0	0	1	0	1	2	31	332.5
Test 70	ME 6	6 cm	35	0	1	1	0	1	0	32	327.5
Test 71	ME 7	0 cm	37	0	0	0	0	0	37	0	296
Test 72	ME 8	0 cm	36	0	1	3	0	0	32	0	261.5
Test 73	ME 9	0 cm	37	0	0	0	0	1	0	36	365
Test 74	ME 10	0 cm	36	0	1	0	1	0	0	34	344
Test 75	ME 11	0 cm	37	0	1	0	0	0	36	0	289
Total:				0	7	5	1	3	107	282	/
Total Valid Tests: 11				Average Score: 337.14				COV of WRS: 0.11			

The specimens in Test 2 and Test 4 stay dry for at least eight hours from the colourmaps. It brings an assumption that Membrane E has very long water resistance so the MATLAB plots of other tests need to be evaluated manually to see if the detection of liquid water is caused by material failure or system mistake. In test 1, only D3 detects liquid water. Figure 127 shows D4 only reads an 8.92 at 1.267 minutes and at 2.53 minutes, the reading of D4 goes back to 9.

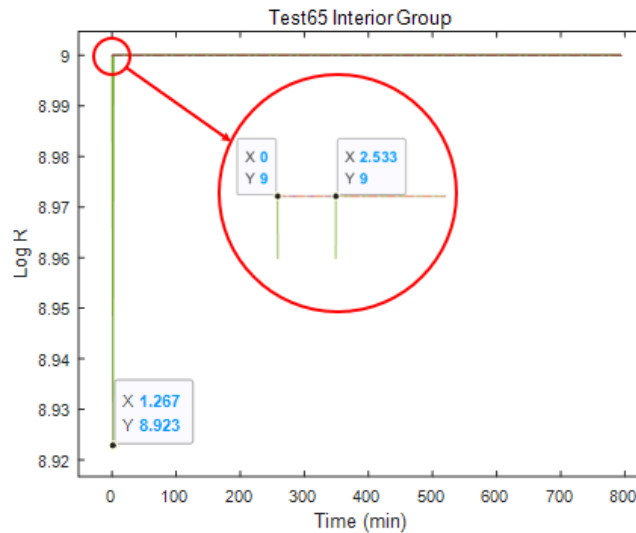


FIGURE 127 MATLAB PLOT MEMBRANE E 1 (TEST 65)

Test 2 gives the most ideal plots for a WRB as shown in Figure 128: there are only straight lines for both the Log R plot and the *NDMI* lot.

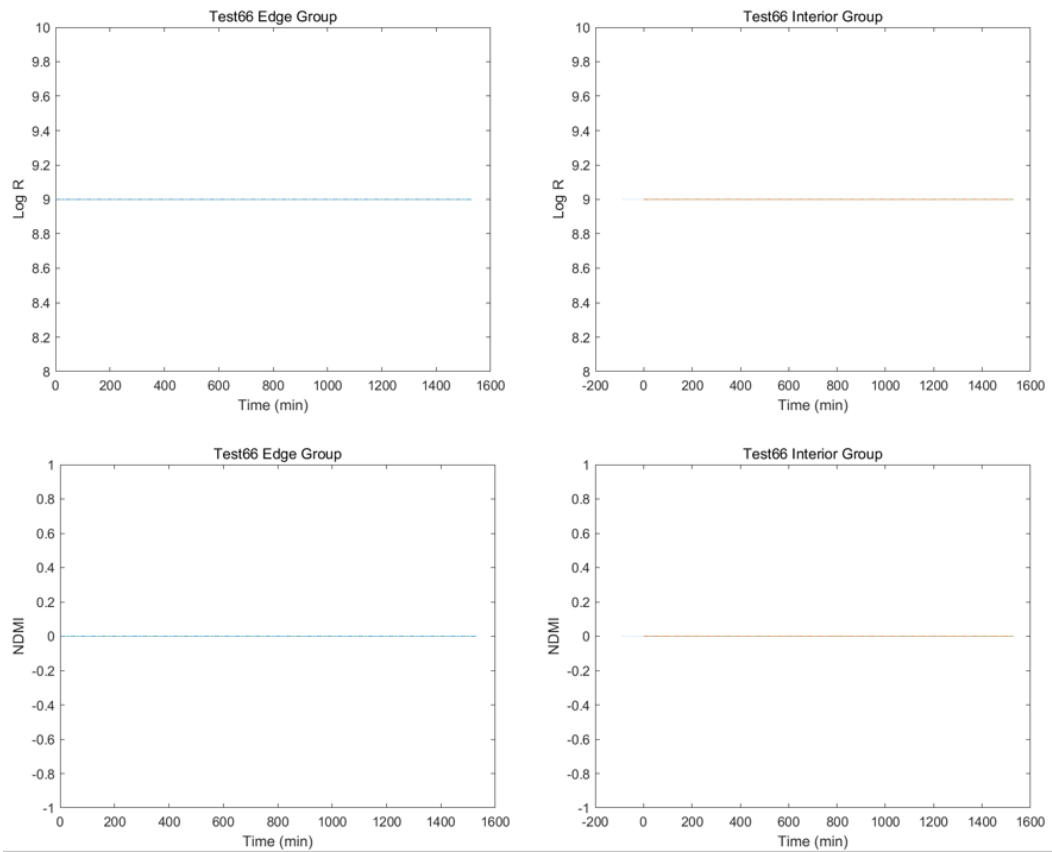


FIGURE 128 MATLAB PLOTS MEMBRANE E 2 (TEST 66)

In Test 3, D5 and D6 have wet readings detected before 5 minutes. In the Log R plot of the interior group in Figure 129, D5 has the same behavior as the D4 in Test 1 while in the plot of the edge group, D6 dropped to around 3.3 and kept this reading until the end of the test.

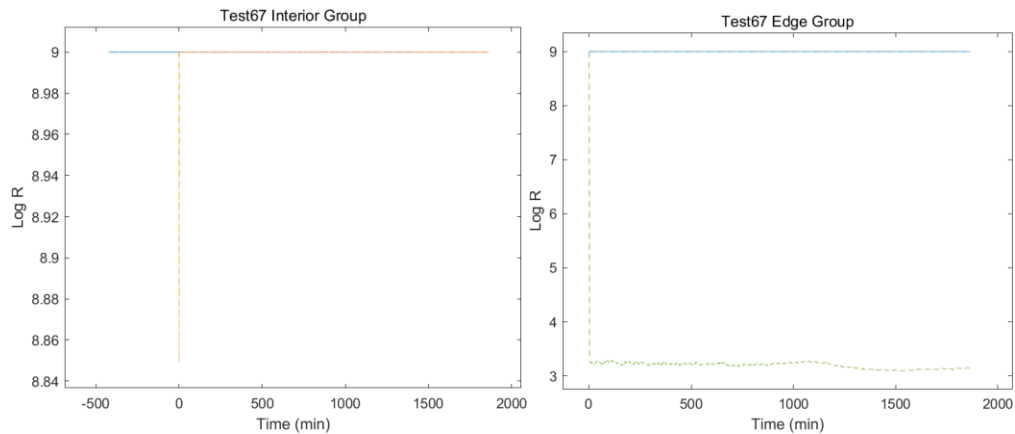


FIGURE 129 MATLAB PLOTS MEMBRANE E 3 (TEST 67)

The plots for Test 5 are given in Figure 130. A3, B4, and B5 are the sensors with erratic readings before water participates in the test. B5 and B4 have a similar checkmark shape that they decrease in a short time and start to increase until the end of test. There are some fluctuations while the curve is rising. Compared to B5 and B4, A3 decreases in a short time and keeps a relatively flat curve until the end of test and the fluctuations are not obvious. Both E1 and E2 have a small drop for one reading and then go back to 9. D6 fluctuates through the entire test while C3 has two separate small drops and a continuous fluctuation for 100 minutes. The curves in this test show more complicated behaviors.

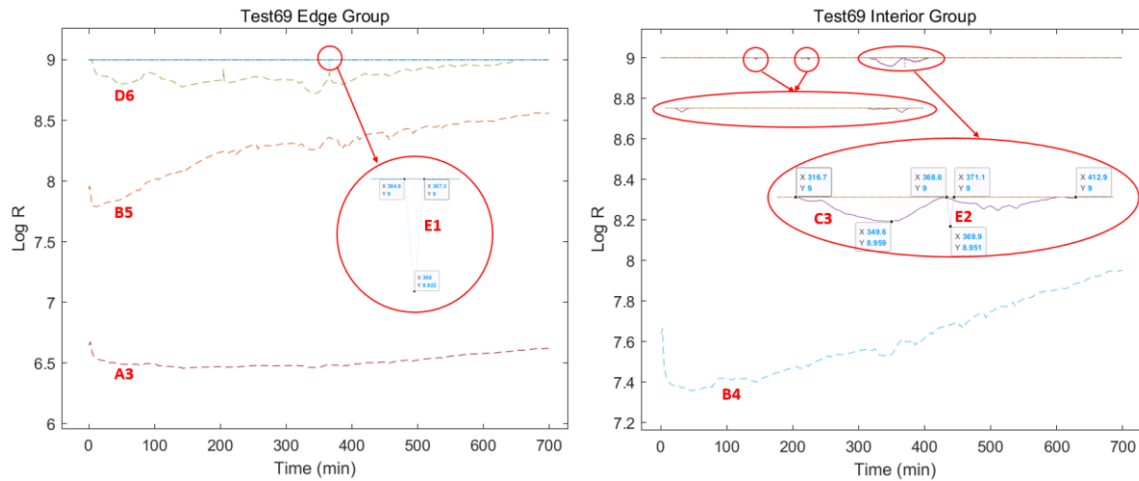


FIGURE 130 MATLAB PLOTS MEMBRANE E 5 (TEST 69)

In Test 6, except A3, all other five sensors that get wet fluctuate dramatically for the entire test time as shown in Figure 131. In this situation, the *NDMI* plots in Figure 132 have a lot of fluctuation as well and negative values hence not readable.

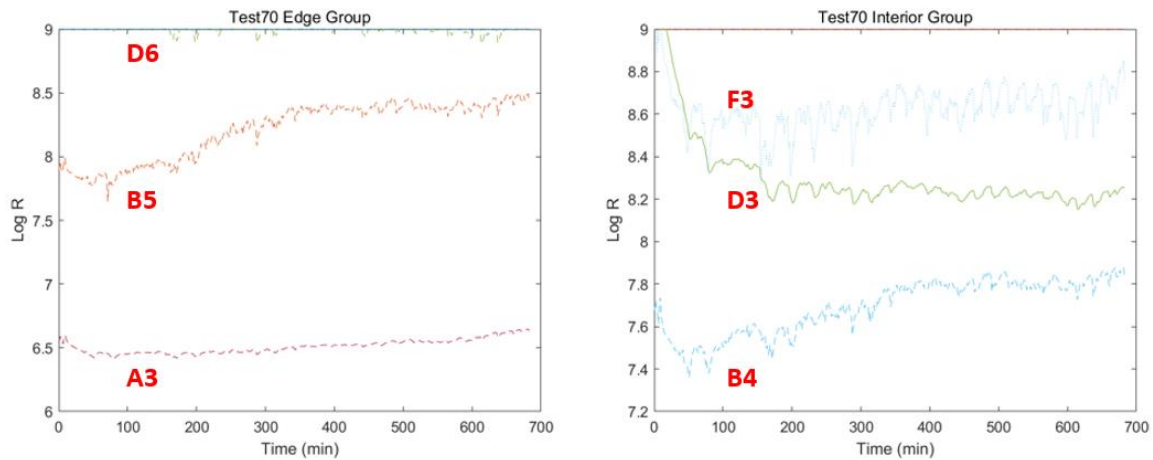
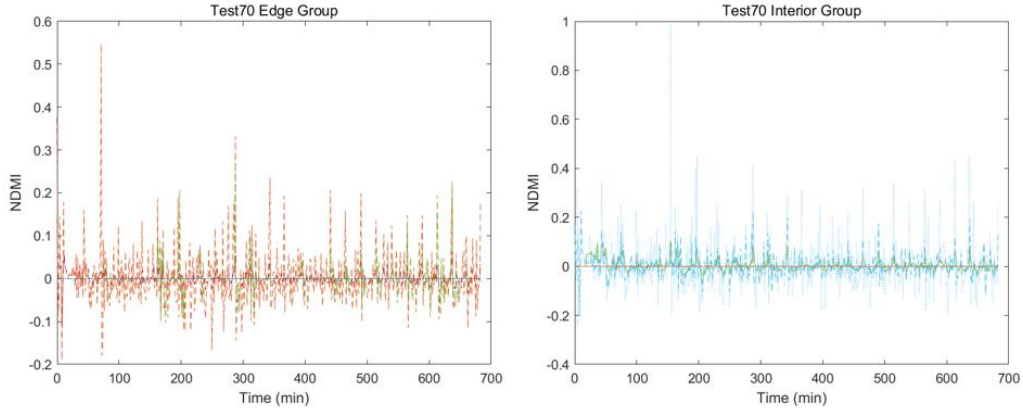
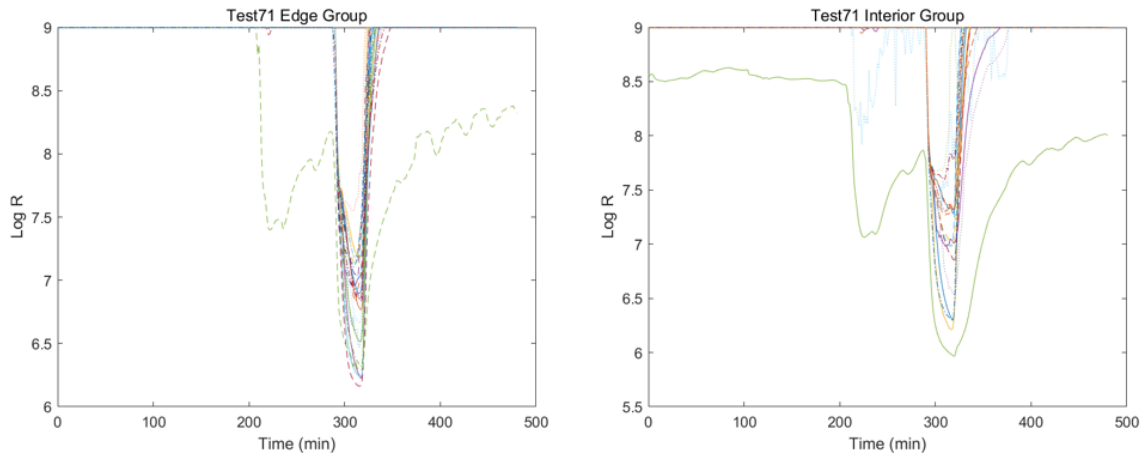


FIGURE 131 MATLAB LOG R PLOTS MEMBRANE E 6 (TEST 70)

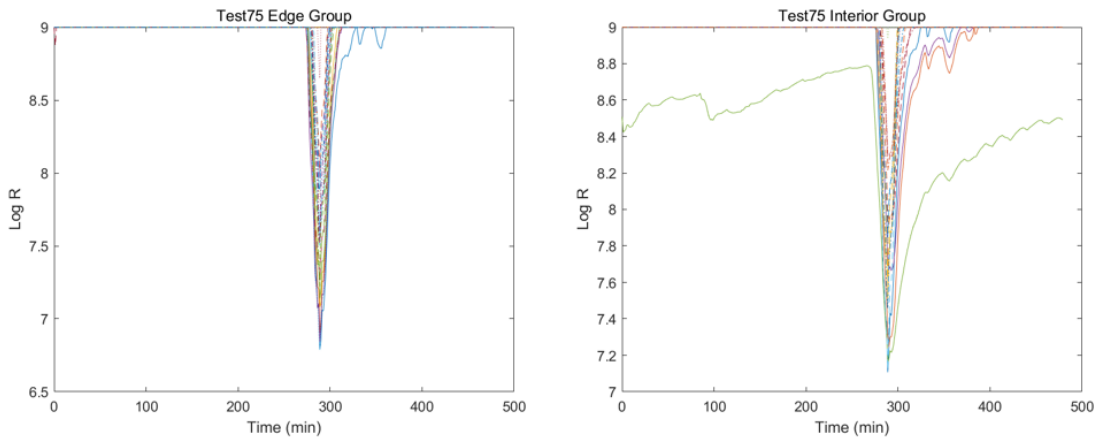


**FIGURE 132 MATLAB NDMI PLOTS MEMBRANE E 6 (TEST 70)**

For Test 7 and 11, the Log R readings generate strange curves as shown in Figure 133 and Figure 134. For both tests, most curves hit the lowest point at the specific time, 317 minutes for Test 7 and 288 minutes for Test 11.



**FIGURE 133 MATLAB PLOTS MEMBRANE E 7 (TEST 71)**



**FIGURE 134 MATLAB PLOTS MEMBRANE E 11 (TEST 75)**

Test 8 has most readings in light green color because the test is 7.9 hours so it is not possible to show dark green anyway but most sensors are dry until the end of the test. In Tests 9 and 10, less than three sensors detect liquid water when not counting the circled sensors.

From the colormaps and above analysis, there are six tests can be identified as having very long water resistance duration, three tests having long duration and two tests having short and moderate water resistance duration respectively. Overall, Membrane E can be considered as having long water resistance duration.

A 100% stacked column chart and a pie chart with percentage is given in Figure 135 and Figure 136. There are 70% of sensors detect liquid water after 480 minutes and 26% of sensors detect liquid water between 180 to 480 minutes. The WRS is 337.14.

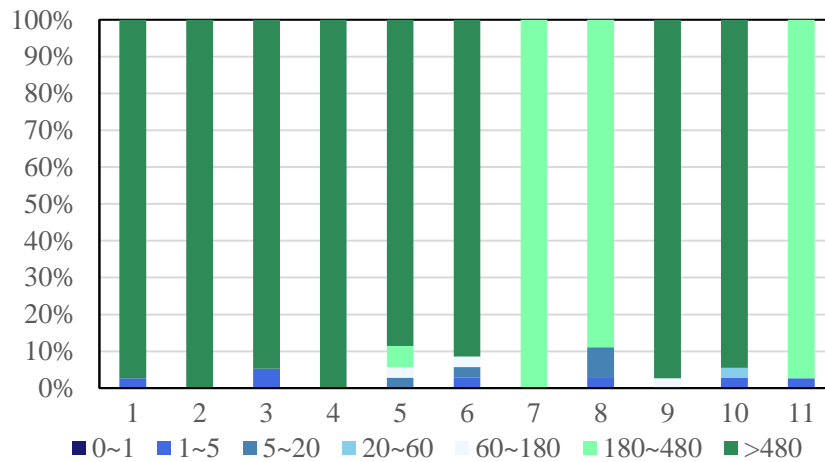


FIGURE 135 MEMBRANE E 100% STACKED COLUMN CHART

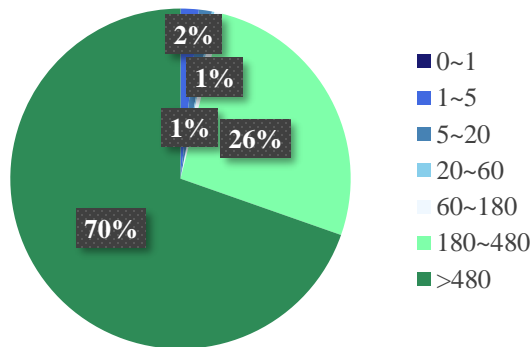


FIGURE 136 MEMBRANE E PIE CHART

Figure 137 shows three images of a Membrane E specimen under the electrical microscope. The two images on the left show the white side of the specimen and the image on the right is taken from the black side. From the left image, the material is full of fibers and there are square shape patterns lying on it while the arrangement is not strict as some squares are in different directions. On the other side of the material, fibers are not visible but an X shape division can be seen. This division can also be seen on the top left image.

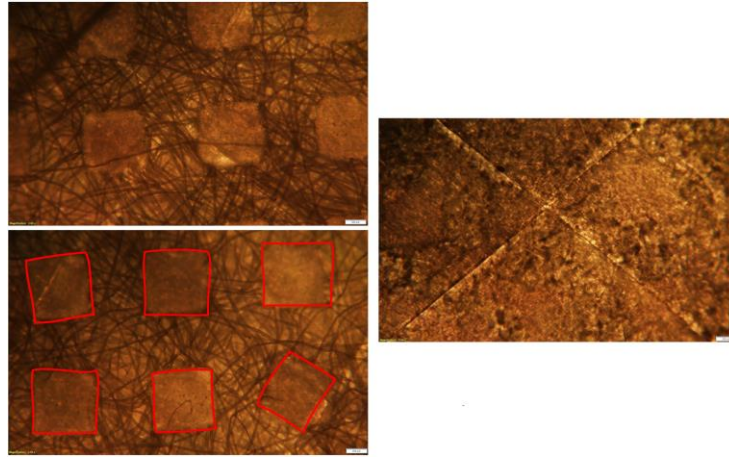


FIGURE 137 MEMBRANE E MICROSCOPE IMAGES

#### 4.3.6 MEMBRANE F

There are eight tests done for Membrane F and the colormaps are given in Figure 138 and Figure 139. All tests are valid. The information table is given in Table 35.

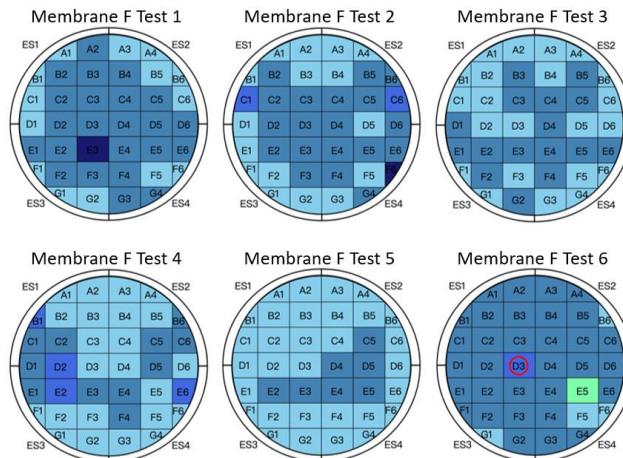


FIGURE 138 MEMBRANE F TEST 1 – 6 COLORMAP

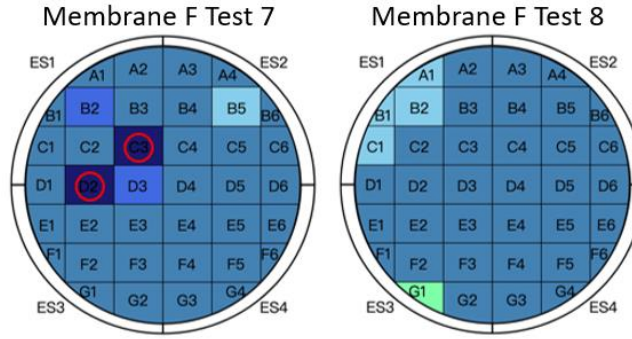


FIGURE 139 MEMBRANE F TEST 7 – 8 COLORMAP

TABLE 35 MEMBRANE F INFORMATION TABLE

Test #	Material Test #	Water level drop	Valid Sensors	First Wet Time (min)							Score
				0~1	1~5	5~20	20~60	60~180	180~480	>480	
Test 76	MF 1	0 cm	38	1	0	23	14	0	0	0	76.5
Test 77	MF 2	0 cm	38	1	2	19	16	0	0	0	78.5
Test 78	MF 3	0 cm	38	0	0	16	22	0	0	0	90
Test 79	MF 4	0 cm	38	0	4	11	23	0	0	0	89.5
Test 80	MF 5	0 cm	38	0	0	7	31	0	0	0	103.5
Test 81	MF 6	0 cm	37	0	0	32	4	0	1	0	68
Test 82	MF 7	0 cm	36	0	2	33	1	0	0	0	54.5
Test 83	MF 8	0 cm	38	0	0	33	4	0	1	0	69.5
Total:				2	8	174	115	0	2	0	/
Total Valid Tests: 8				Average Score: 78.75				COV of WRS: 0.18			

From the colormaps, most sensors get wet before 60 minutes. The 100% stacked column chart in Figure 140 illustrates the time range between 5 to 20 minutes are the most frequent. The pie chart in Figure 141 shows among all time ranges, 5 to 20 minutes occupies 58% and 20 to 60 minutes occupies 38%. All other time ranges have less than 2% each. There are five tests have more than three sensors detect liquid water between 5 to 20 minutes and three tests have more than three sensors detect liquid water before 5 minutes. Hence Membrane F has short water resistance duration. The WRS is calculated as 78.75.

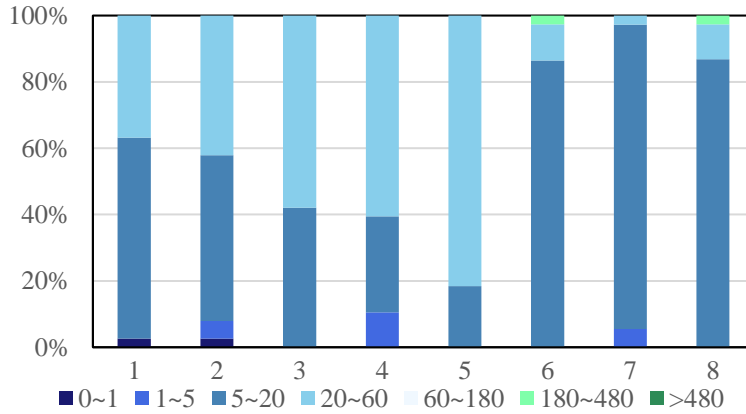


FIGURE 140 MEMBRANE F 100% STACKED COLUMN CHART

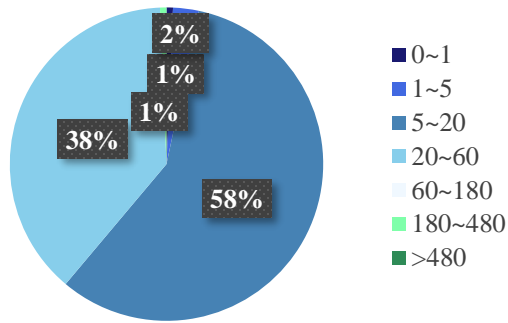


FIGURE 141 MEMBRANE F PIE CHART

Membrane F is not a polymer-based WRB but an asphalt-saturated kraft paper. It is the thickest in all six WRB materials and a flashlight is needed to provide enough brightness for imaging. An electrical microscope image is given in Figure 142. Not like other materials, no fibers can be seen in the image. There are black strips and red color voids in the image. On the right side of the image, there is a layer of lighter black stripes in pieces. This material has no patterned holes, and the voids are not evenly distributed.

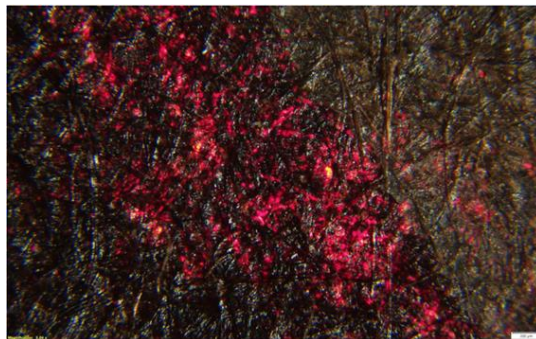


FIGURE 142 MEMBRANE F MICROSCOPE IMAGES

#### 4.3.7 MATERIAL RANKING

Table 36 summarizes the water resistance duration and water resistance score of the six materials. Water resistance duration is ranked based on the time that the first three sensors get wet while water resistance is calculated by the wet time of all 38 sensors. Membrane E has the best water resistance duration and outstanding water resistance score among all six materials. Membrane A and Membrane B have very short duration and their scores do not vary a lot so the performance of the two materials is similar. Both Membrane C and Membrane D are ranked between very short and short water resistance durations but Membrane D has a much higher water resistance score. Although Membrane D has three points that get penetrated soon, other areas can resist liquid water longer than Membrane C. Membrane F is ranked as short so the time it started to get penetrated is later than Membrane C and Membrane D. When comparing the scores, Membrane F has its other areas that get wet later than Membrane C but is similar to Membrane D. There is no moderate or very long water resistance duration found in this research. The coefficient of variation shows Membrane D has the most variant WRS in all its tests and the WRS of Membrane F tests are the closest.

TABLE 36 SUMMARY OF WATER RESISTANCE DURATION AND WATER RESISTANCE SCORE

Material	Water Resistance Duration	Water Resistance Score	COV of WRS
Membrane A	Very short	15.15	0.62
Membrane B	Very short	23.19	0.47
Membrane C	Very short/Short	36.5	0.23
Membrane D	Very short/Short	82.72	0.65
Membrane F	Short	78.75	0.11
Membrane E	Long	337.14	0.18

## 4.4 DISCUSSION AND FUTURE WORK

### 4.4.1 LOG R PLOTS

The Log R plots show the electrical resistance change in the Log scale during each test. The 38 sensors are divided into two groups, the edge group and the interior group for plotting. Figure 143 shows a test with comparatively ideal plots where the curves drop after the corresponding sensor detects liquid water and stays flat and smooth to the end of the test. However, more tests

have strange, unexpected behaviors. The reasons leading to the strange curves are not examined yet. Some examples are given in Figure 144 to Figure 150.

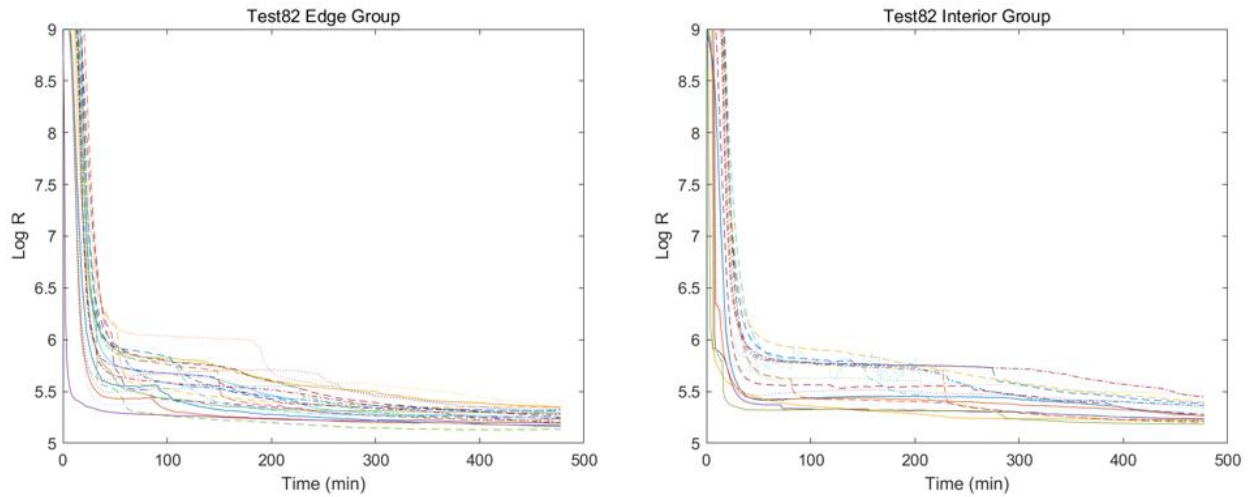


FIGURE 143 COMPARATIVELY IDEAL PLOTS (TEST 82)

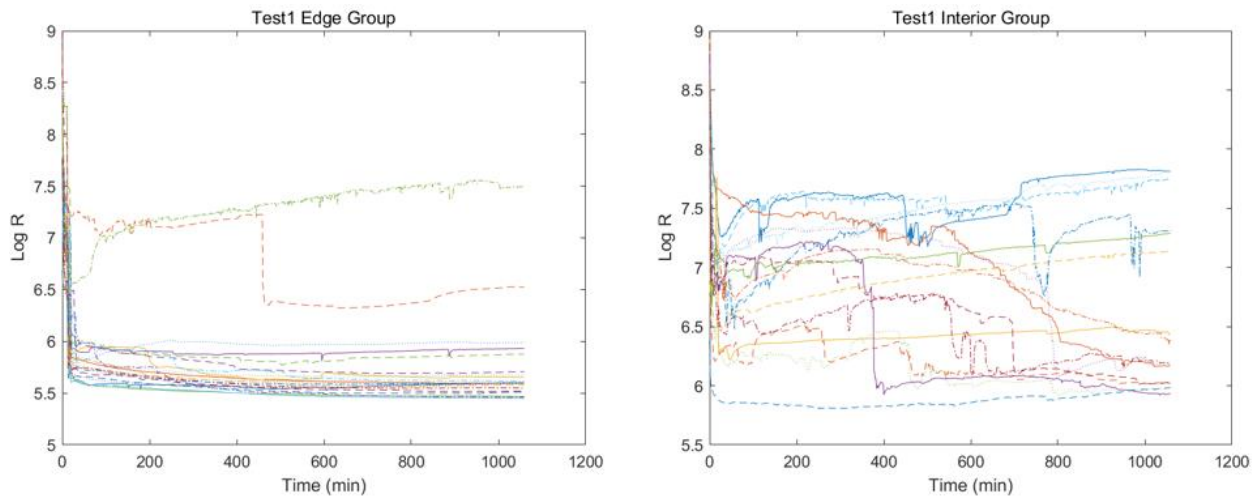
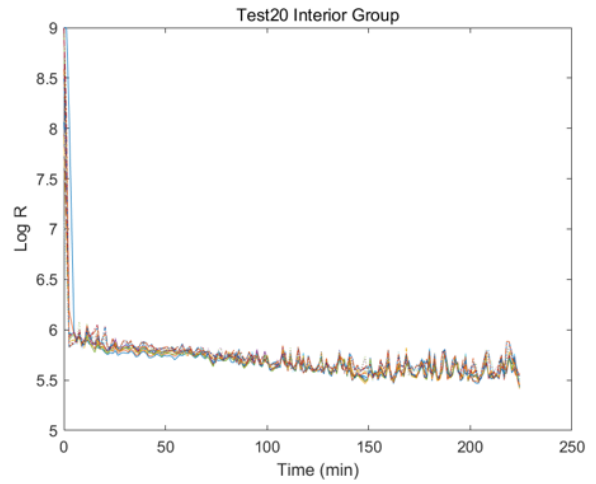
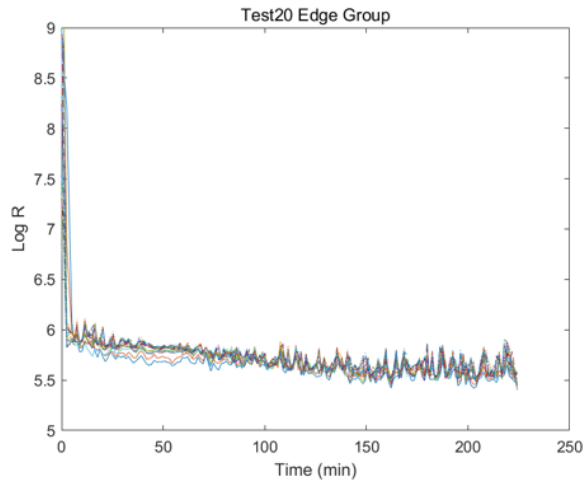
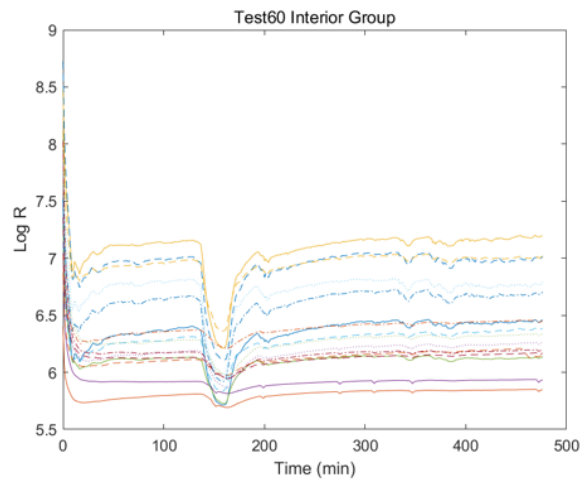
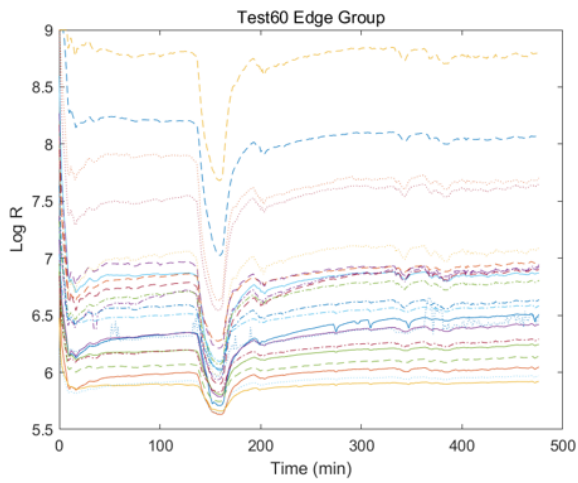


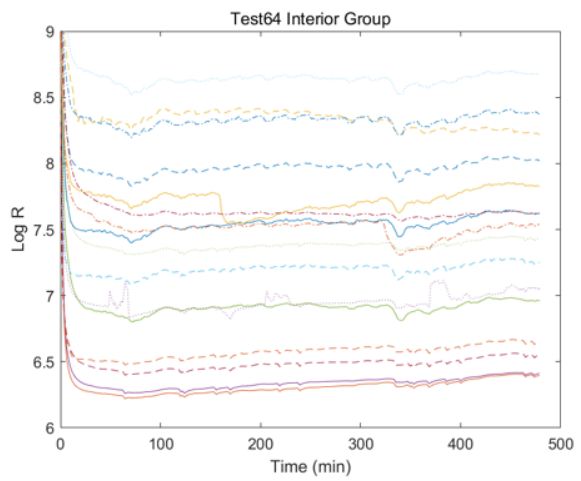
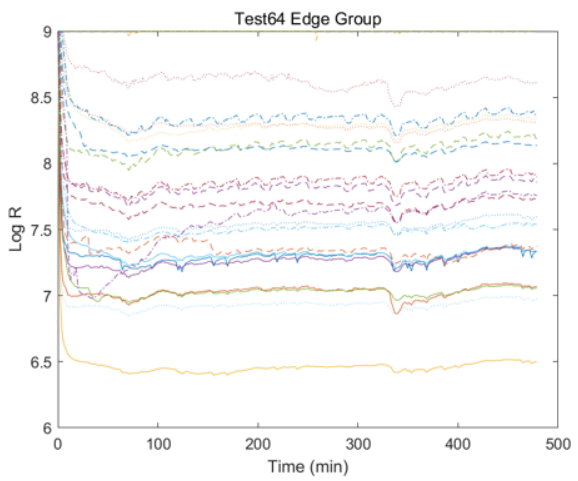
FIGURE 144 UNEXPECTED OUTLIERS EXAMPLE (TEST 1)



**FIGURE 145 UNEXPECTED OUTLIERS EXAMPLE (TEST 20)**



**FIGURE 146 UNEXPECTED OUTLIERS EXAMPLE (TEST 60)**



**FIGURE 147 UNEXPECTED OUTLIERS EXAMPLE (TEST 64)**

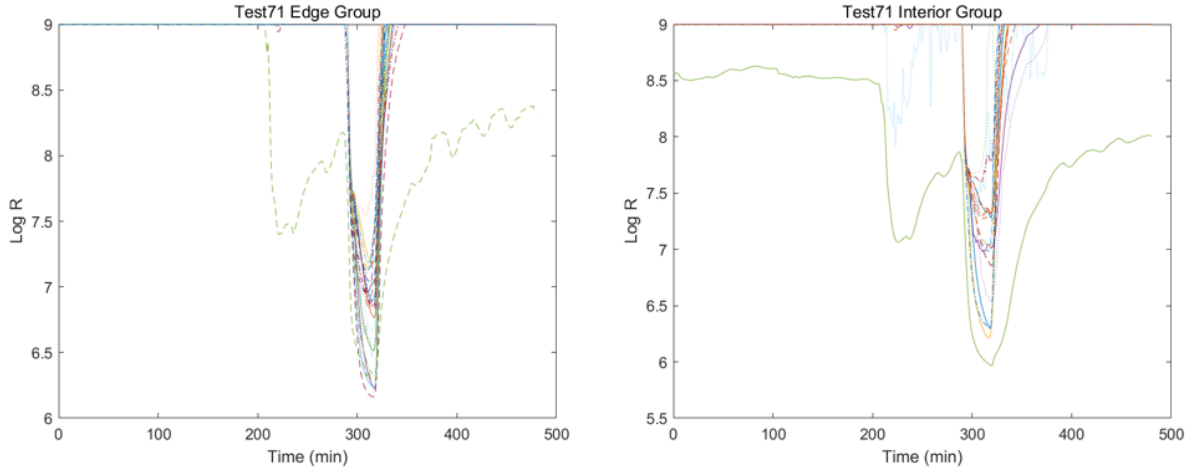


FIGURE 148 UNEXPECTED OUTLIERS EXAMPLE (TEST 71)

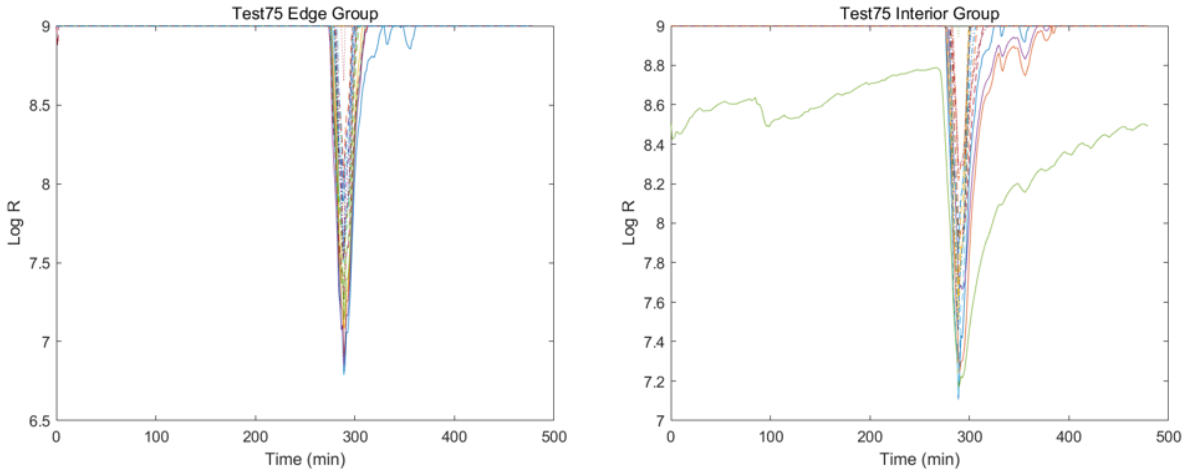


FIGURE 149 UNEXPECTED OUTLIERS EXAMPLE (TEST 75)

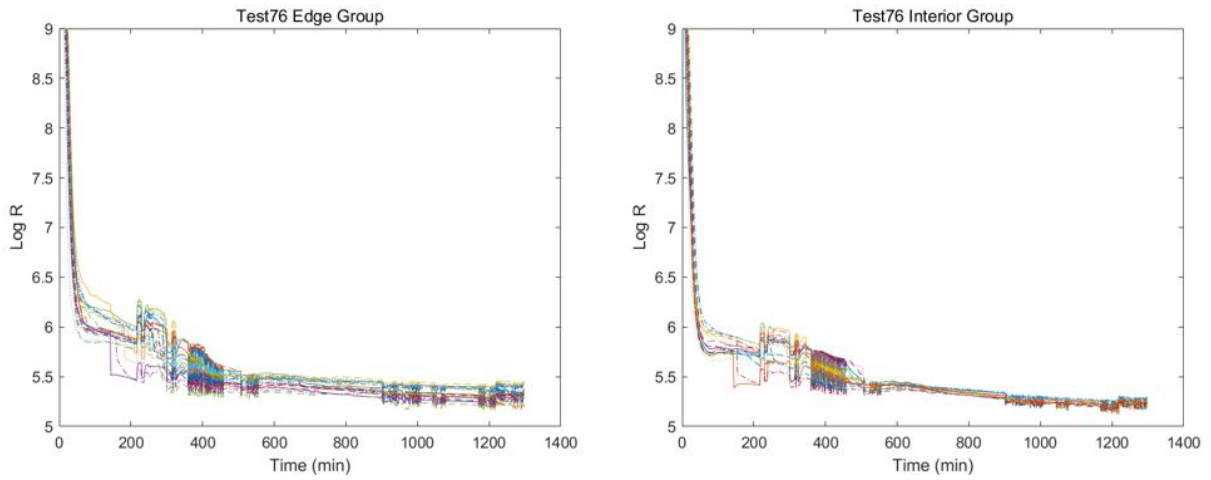


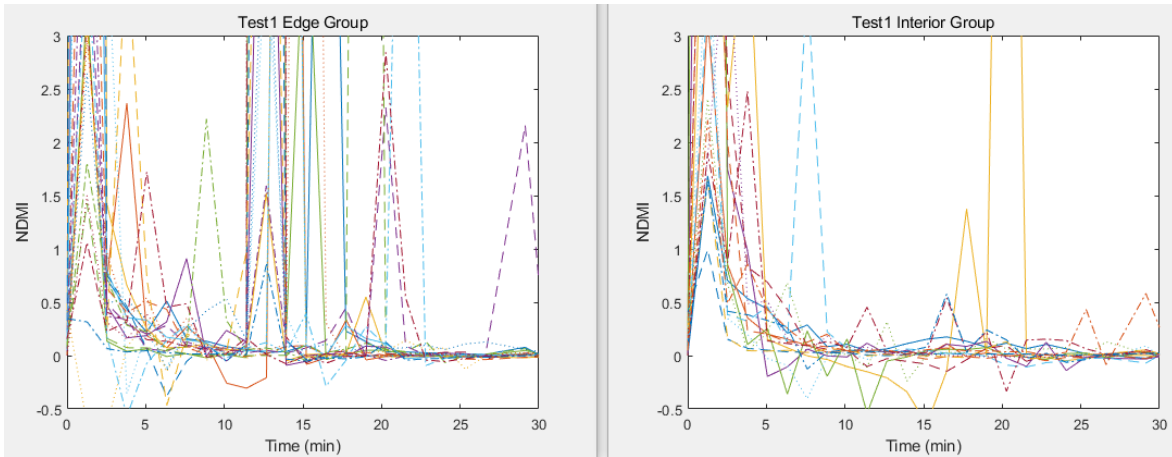
FIGURE 150 UNEXPECTED OUTLIERS EXAMPLE (TEST 76)

There are some assumptions such as liquid water is moving around in Figure 54 or vibration from the environment could affect the readings of all sensors in Figure 56 but there is not enough evidence to prove them. Additional tests are necessary for further study. It could be helpful if the test can be conducted along with a digital camera installed below the sensor to record the appearance of liquid water. This allows the researcher to compare the video with the plots and determine any possible relationship between them. A predictable limit is there is a delay in the video because it takes time for water to travel from the upper side to the lower side of the sensor. This should be taken into consideration if the video aid will be used.

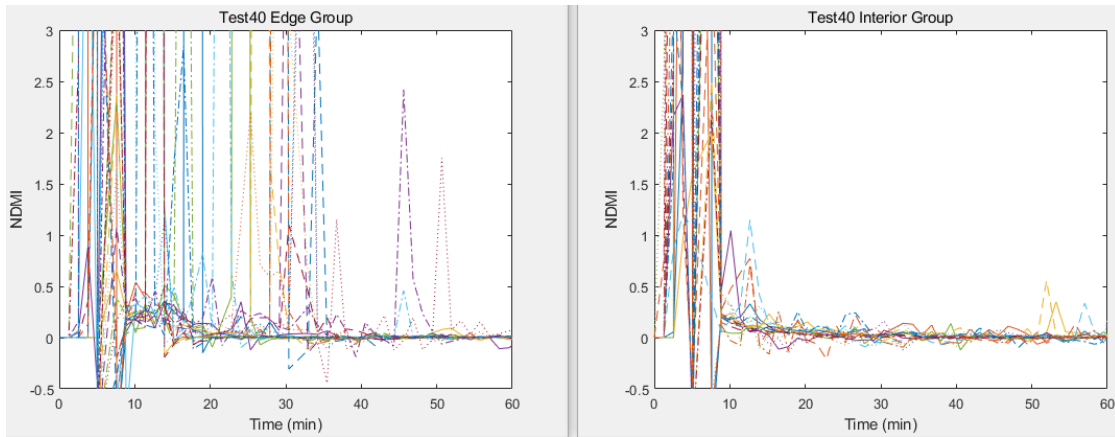
#### *4.4.2 POST SECONDARY BEHAVIOUR – NDMI PLOTS*

The *NDMI* plots help the researcher to understand the post secondary behaviour of each sensor. The y axis range is set to -0.5 to 3 to show the most valuable results. The x axis range is different for different materials. Membrane A and Membrane B have their x axes from 0 to 30 minutes as they have short water resistance duration. Membrane C and Membrane D have x axes set to 0 to 60 minutes because their water resistance duration is between very short and short. Membrane F has the x axis from 0 to 120 minutes and Membrane E has its x axis from 0 to 480 because they have short and long water resistance duration respectively. It is assumed that setting the x axis time range based on water resistance duration ensures the plots display enough data most straightforwardly. This is true for most materials except Membrane D. The exception will be explained later.

After comparing the *NDMI* plots for the edge group and the interior group, it is found that the curves in 16 out of 17 tests using Membrane A and 8 out of 8 tests using Membrane C have more fluctuation in the edge group than the interior group. Examples of comparison plots for the two materials are given in Figure 151 and Figure 152. This reveals the water movement near the clamping edge is definitely more active than the center area for these two materials.

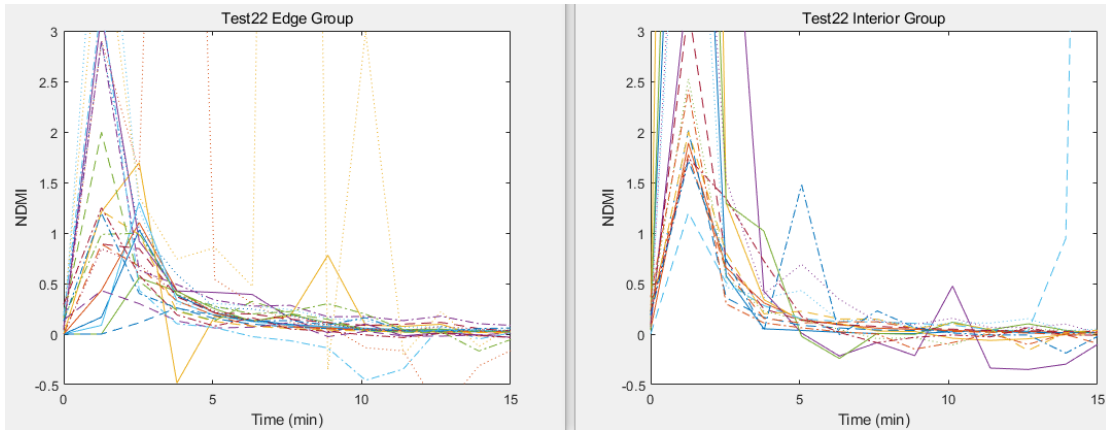


**FIGURE 151 MATLAB NDMI PLOTS (TEST 1)**



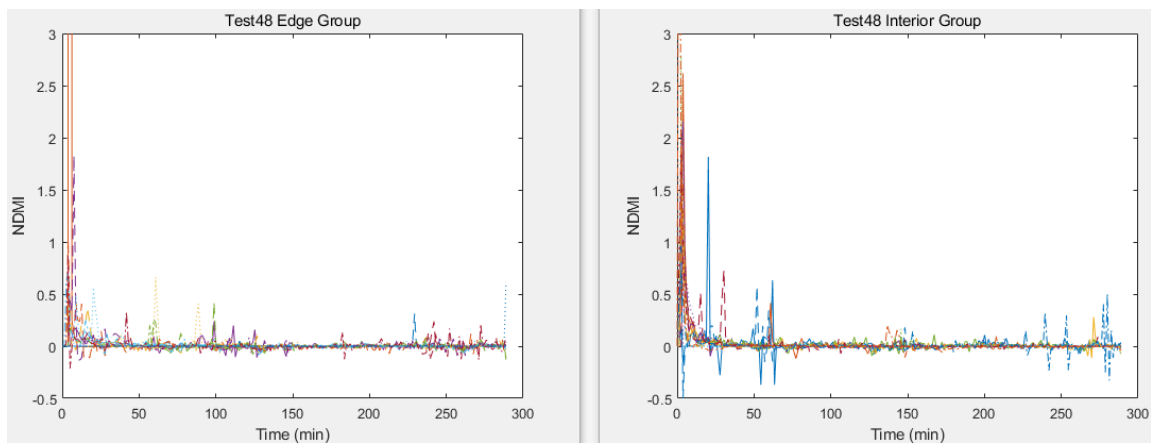
**FIGURE 152 MATLAB NDMI PLOTS (TEST 40)**

12 out of 22 tests using Membrane B have the same observation. The rest ten tests are not in the opposite situation that the interior group curves are more fluctuating but the two groups have similar fluctuations. An example is given in Figure 154. In a situation like this, it is hard to tell which plot contains more fluctuations.



**FIGURE 153 MATLAB NDMI PLOTS (TEST 22)**

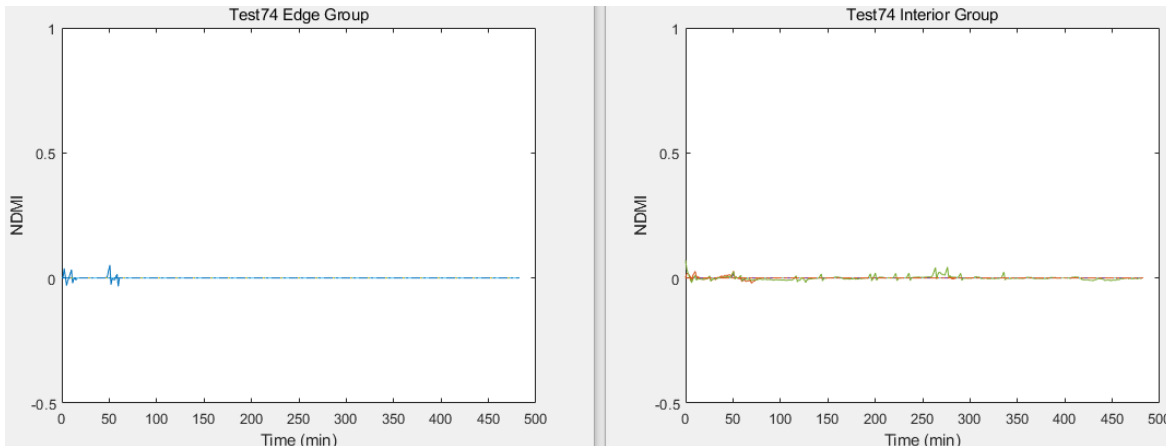
When setting the x axis of Membrane D tests to 0 to 60 minutes, it is found that the curves can not show enough information since although the time for the first three sensors to get wet is short in most tests but the time for all sensors to get wet are quite different from less than 1 minute to more than 480 minutes. Therefore, the range should be set to 0 to 480 minutes to prevent misjudgment. It is then found that for all tests, the fluctuation continues for the entire test as shown in Figure 154 and only three tests show more fluctuation in their edge group plots. All other plots do not have a big difference between the edge group and interior group. This indicates for Membrane D, the water movement near the clamping edge and the center are both vigorous and the movements last for the entire test.



**FIGURE 154 MATLAB NDMI PLOTS (TEST 48)**

For Membrane E, there are five tests do not have curves because there is no water penetration or only a second of water penetration detected. Test 71 and Test 75 (Membrane E 7 and 11) in Figure 148 and Figure 149 above have the strange Log R plots and the *NDMI* plots are strange as

well. All other tests only have a few sensors to detect liquid water. An example is given in Figure 155. No conclusion can be drawn for Membrane E. For Membrane F, the curve difference between the edge group and interior group is not obvious. The water movement behavior around the edge and the center are similar.



**FIGURE 155 MEMBRANE E NDMI PLOTS (TEST 74)**

It is sure that more information can be studied from the *NDMI* plot, but before that, the MATLAB script needs modification to obtain plots that are more readable. In this stage, there are too many curves in one plot and it is not easy to distinguish which curve belongs to which dataset. For now, it is not possible to only look into one curve and see which is its first peak, which is the second, or the third one. Improvements should be made to this. Also, the sensor pads that have erratic readings are not eliminated from the plots. The script should add the function of eliminating any input dataset based on user choice.

#### 4.4.3 ERRATIC READINGS OF THE DRY PAD VALUE

In 32 tests, there are sensors that have erratic readings before any water is added while the expected reading is  $1\text{G}\Omega$  at that time. Sometimes one test and its following test have the same sensors that have this problem but it is not always like that. If tests are conducted frequently, Table 37 summarizes the amount of all appeared erratic readings of the 38 sensors. D3, D4, D6, E1, B1, C3, B5, and B4 read erratic values for more than three times but the other seven sensors in the table only read erratic values once. The sensor pads that not shown on the table always read the correct  $1\text{G}\Omega$  value. Further investigation should be done to determine what factors affect the dry reading.

TABLE 37 COUNTS OF THE SENSORS THAT READ ERRATIC DRY VALUES

D3	10	G2	1
D4	6	C1	1
D6	6	B3	1
E1	5	D1	1
B1	5	D5	1
C3	4	E3	1
B5	3	E4	1
B4	3	F2	1
C5	3	F3	1
A3	3	F6	1
C6	2	G3	1
C2	2	A1	1
C4	2	D2	1
Total: 67			

#### 4.4.4 WATER LEVEL DROP

The water is always added to 55cm in all tests. The after test water level is recorded so the water level drop can be calculated and they are given in the information tables for each test. For Membrane A, there are four tests that do not have water level change while the other nine tests change from 4cm to up to 15cm. For Membrane B, there are 17 tests do not have a water level decrease and four tests change from 3cm to 8cm. For Membrane C, only one test does not have water level drop while other tests have water level decrease up to 34 cm. All tests using Membrane D and Membrane F do not have water level change and there is only one test using Membrane E has a decrease of 6cm. Except for Membrane E tests, all sensors detected liquid water in all other tests but even with the same material, some tests have huge water level changes some tests have no change at all. It seems that no relationship can be found between the amount of water level decrease and the readings of the sensor. Further study should be carried out to investigate the reason causes water level drop.

#### 4.4.5 POSSIBLE IMPROVEMENT FOR WATER ADDITION METHOD

Sometimes the distilled water is poured right onto the material instead of flowing through the water column wall. The two ways of pouring water could lead to different readings because the pressure when the membrane first gets in contact with water is different. The ideal situation

would be the distilled water added to the water column always flowing through the water column wall evenly without direct contact with the membrane. However, it is hard to control the way that water flows into the water column with the current device because the researcher needs to raise a very heavy water tank to add water. Figure 156 below is an example of a possible modification of the device. The water pipe has four outlets, each is 90° apart from another, and is connected with an electrical pump. By setting the electrical pump to a calculated pressure, four streams of water will be sprayed to four points on the water column wall that have the same height. In this way, distilled water can be added to the water column smoothly and evenly for any test and the researcher does not need to raise the heavy water tanks.

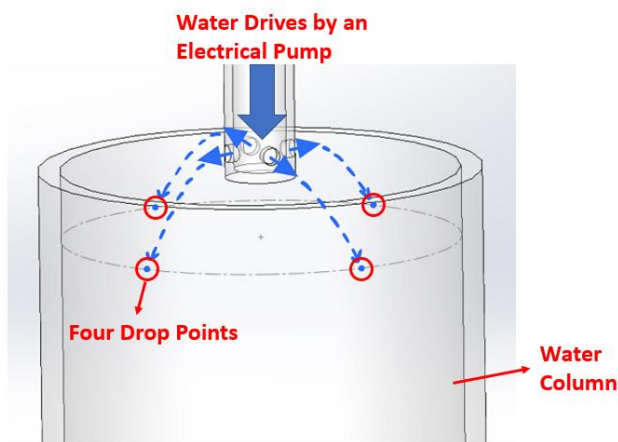


FIGURE 156 WATER ADDITION MODIFICATION

#### 4.4.6 INFLUENCE OF THE ENVIRONMENT

In the tests of Membrane C and Membrane D, the results obtained in 2019 and 2020 are apparently different. One assumption is both materials have their tests in 2019 in October and 2020 in December. There was no air conditioning or humidifier in the lab at that time. Therefore, the temperature and relative humidity mainly depend on the outdoor environment. The weather in October 2019 was very different from the weather in December 2020 so this difference could be an influencing factor that brings diverged test results of the same material. Also, the distilled water used in some tests is obtained from UVIC distilled water facilities while some tests use distilled water purchased from Walmart. To eliminate the possible effect from the environment and the distilled water, it is ideal to conduct tests at a fixed temperature and relative humidity as well as always use distilled water from the same place.

## CHAPTER 5 CONCLUSION

Moisture management is one of the major considerations in building design. A water resistive barrier (WRB) that is usually installed beneath the exterior covering helps the exterior wall of the building resist liquid water effectively. However, all current testing methods that test the ability of a WRB to resist liquid water have limitations. Each existing method has one or more problems:

1. Only gives a pass/fail result thus it is not possible to compare two materials with the same result.
2. Only suitable for a few types of WRBs.
3. Not able to distinguish the appearance of liquid water and water vapor.
4. The results are obtained from subjective human observation and the observation is hard due to the rough design of the device, which leads to a lack of accuracy.
5. The experimenter must stay beside the testing apparatus and observe it frequently for hours.
6. The test method is not designed for WRBs but other materials that are applied in very different environments. The resulting parameter is unfit for describing water resistance of WRBs.

In this work, a better method to test liquid penetration of WRBs is developed using a hydrostatic pressure test apparatus (HPTA) provided by SMT Research Ltd., which includes a sensor platter that reads electrical resistance values and stores the values in PC and online database. The sensor has 42 channels and each channel reads a separate value. This feature enables the device to tell which positions on the sensor are getting wet. A value of  $1G\Omega$  indicates the sensor pad is completely dry and any decrease in the value is a sign of the appearance of liquid water.

HPTA perfectly solves the first, fourth, fifth, and sixth problems listed above. The device is suitable for most WRBs but does not work well with self-adhesive materials. It was designed to sense liquid water only but there is no evidence to prove if it also senses water vapor arising from condensation.

The device was designed to quantify the amount of liquid water penetrates a WRB membrane. The validation tests of the measurement system proves that the sensor is able to sense water

droplets as little as 0.5 $\mu$ L and when more water is added, the electrical resistance will decrease. However, there is not a linear relationship between the amount of liquid water added and the resulting electrical resistance. It is realized that the influential factor is not the electrical resistance value but the change between two adjacent values. A factor called Normalized Difference Moisture Index (*NDMI*), modified from Normalized Difference Vegetation Index (*NDVI*), is then used to study the sequential reading change. The *NDMI* histograms in the water droplet test does not give much useful information so still, when analyzing *NDMI*, the important factor is not the value but the change. The *NDMI* analysis is used for analyzing the post-secondary wet entrance in WRB tests. The sensor tests also find the four edge sensor pads have unstable and unreliable readings so they should be eliminated in further tests.

In the WRB tests, six WRB materials, Membrane A to Membrane F are used and a total of 83 tests are conducted. A colormap is generated for each test showing the time that every sensor pad first gets wet using a python script. After obtaining the colormaps, a 100% stacked column chart and a pie chart for each material can be plotted to rank the water resistance duration and water resistance score (WRS) of this material. Provided that the quantitation of WRB water resistance using electrical resistance failed, the WRS is a proper factor to describe and rank WRB materials in the current stage. The water resistance duration contains very short, short, moderate, long and very long and the corresponding time ranges are less than 1 minute, 1 to 5 minutes, 5 to 20 minutes, 20 to 180 minutes, and 180 to 480 minutes. It gives the designer a preliminary idea about the water resistance ability of one WRB.

Among the six tested materials, Membrane E has the highest water resistance duration of long and the highest WRS of 337.14. Membrane F is ranked as short with 78.75 WRS. Membrane C and Membrane D are ranked between very short and short water resistance durations while their WRS are quite different at 36.5 and 82.72. The variation implies although Membrane C and Membrane D have the first three spots detect liquid water at a similar time, but it takes more time for the entire specimen of Membrane D to get wet. Membrane A and Membrane B both lie at the very short duration level and their WRS are similar at 15.15 and 23.19.

A MATLAB script is used to generate datasheet used for creating the colormap. More than that, the 38 channels use in this research is divided into an edge group and an interior group. The MATLAB script plots Log R value and *NDMI* for both groups. The problem is there are too

many datasets in one plot so the plot is hard to read. Also, the sensors with erratic dry readings before water is added are not eliminated from the plots. For now, it can be concluded that for Membrane A and Membrane C, the water near the edge has more active movement than water in the center. Around a half of tests in Membrane B show a similar trend but the other half does not. The water under Membrane D in all areas moves more vigorous than other materials and Membrane E has no liquid water or very limited liquid water penetrated through the specimen so it is excluded from this comparison. For Membrane F, there is no obvious curve difference between the edge group and interior group and its water movement behaviors around the edge and the center are similar.

Overall, the new sensing system to detect liquid water penetration through WRBs is useful and solves most problems of current test methods. Six WRB materials are ranked by their water resistance performance. The WRS quantitatively describes the ability of a WRB to resist liquid water. Further study is recommended on the reasons for the strange reading in Log R plots, the post secondary wetting behavior analysis based on the *NDMI* plots, the reasons for the erratic dry readings, and the reasons for different water level drop in the water column.

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# APPENDICES

## APPENDIX A CHANNEL NUMBER AND ZONE LABEL

Channel Input*	Zone Label	Database #
1	C1	290379
2	D1	290380
3	D2	290381
4	C2	290382
5	B1	290383
6	B2	290384
7	A1	290385
8	A2	290386
9	B3	290387
10	C3	290388
11	D3	290389
12	A3	290392
13	B4	290393
14	C4	290394
15	D4	290395
16	A4	290396
17	B5	290397
18	C5	290398
19	D5	290399
20	B6	290400
21	C6	290401
22	D6	290402
23	E1	290403
24	F1	290404
25	E2	290405
26	F2	290406
27	G1	290407
28	E3	290408
29	F3	290409
30	G2	290410
31	E4	290413
32	F4	290414
33	G3	290415
34	E5	290416
35	F5	290417
36	G4	290418
37	E6	290419
38	F6	290420

\* The channel input does not contain the four edge sensors.

## APPENDIX B MATLAB SCRIPT

```
for idx_readingfile = 48:64 % run multiple files one after another, 1:10

    clearvars -EXCEPT idx_readingfile;
    close all
    clc
    %test_n = 1;
    test_n = idx_readingfile;
    test_name = "Test"+test_n + ".csv";

    %% import csv file and delete the first id column
    import_RawDataa = readtable (test_name, 'PreserveVariableNames', true);
    import_RawDataa(:,1)=[];
    import_RawDataa(:,4:5)=[];

    %% global variable
    NumOfR = size(import_RawDataa,1); % get number of rows
    N = NumOfR/42; % get amount of data groups

    %% delete edge sensor
    import_RawData = import_RawDataa;
    import_RawData((N*11)+1:(N*13), :) = [];
    import_RawData((N*30)+1:(N*32), :) = [];

    %% create Map
    import_SensorId2Name =
containers.Map({290379,290380,290381,290382,290383,290384,290385,290386,29038
7,290388,290389,290392,290393,290394,290395,290396,290397,290398,290399,29040
0,290401,290402,290403,290404,290405,290406,290407,290408,290409,290410,29041
3,290414,290415,290416,290417,290418,290419,290420},{ 'C1', 'D1', 'D2', 'C2', 'B1'
, 'B2', 'A1', 'A2', 'B3', 'C3', 'D3', 'A3', 'B4', 'C4', 'D4', 'A4', 'B5', 'C5', 'D5', 'B6', '
C6', 'D6', 'E1', 'F1', 'E2', 'F2', 'G1', 'E3', 'F3', 'G2', 'E4', 'F4', 'G3', 'E5', 'F5', 'G4
', 'E6', 'F6'});
    NumOfRow = size(import_RawData,1); % get number of row
    import_SensorId = import_RawData(:,1); % get sensor id
    import_MappedRow = string(zeros(1, NumOfRow)); %inicialize a new string
to store mapped value

    for idx_maploop = 1:NumOfRow % for loop to get mapped values and store in
MappedRow
        import_MappedRow(idx_maploop) =
import_SensorId2Name(table2array(import_SensorId(idx_maploop,1)));
    end

    import_SensorName = num2cell(import_MappedRow'); % get transpose of
MappedRow, change it to cell type

    %% combine MappedRow and the initial table
    Table_full = cat(2, import_SensorName, import_RawData);
    Table_full.Properties.VariableNames{1}='sensor_name';

    %% add column log_R
```

```

GetLog = num2cell(log10(Table_full.reading));
Table_full = cat(2,Table_full,GetLog);
Table_full.Properties.VariableNames{5}='log_R';

%% area weighted
pad_area = [1.86 2.06 2.16 2.27 0.79 2.11 0.99 1.96 2.08 2.24 2.14 1.96
2.08 2.24 2.14 0.99 2.11 2.27 2.16 0.79 1.86 2.06 1.86 0.79 2.27 2.11 0.99
2.24 2.08 1.96 2.24 2.08 1.96 2.27 2.11 0.99 1.86 0.79];
Aweighted = array2table(zeros(N,2));
Aweighted.Properties.VariableNames{1} = 'LogR_ave';
Aweighted.Properties.VariableNames{2} = 'NDMI_ave';

%% find C1 - G4
NumOfRow = NumOfR-N*4;
%wet_threshold = log10(2*10^6); not using the wet threshold anymore
FirstWetValueNDMI = array2table(zeros(38,3));
FirstWetValueNDMI.Var1(1:38) = -1;
%FirstWetValueWT = array2table(zeros(38,2));
Sensor_seperate =
{'C1","D1","D2","C2","B1","B2","A1","A2","B3","C3","D3","A3","B4","C4","D4","
A4","B5","C5","D5","B6","C6","D6","E1","F1","E2","F2","G1","E3","F3","G2","E4
","F4","G3","E5","F5","G4","E6","F6"}';

for a = 1:38
    Sensor_seperate{a} = Table_full((N*(a-1))+1:(N*a),:);
    [Sensor_seperate{a}] = convertTime(Sensor_seperate{a},N);

    %Wet threshold method
    % [s,t] = getWetInfoWT(Sensor_seperate{a}, N,wet_threshold);
    % FirstWetValueWT(a,1) = array2table(s);
    % FirstWetValueWT(a,2) = array2table(t);

    %NDMI method
    [c, r,Sensor_seperate{a}] = getWetInfoNDMI(Sensor_seperate{a}, N);
    for idx_ndmichange = 1:N
        if Sensor_seperate{a}.NDMI(idx_ndmichange)>0
            p = Sensor_seperate{a}.NDMI(idx_ndmichange);
            q = Sensor_seperate{a}.minute(idx_ndmichange);
            r = Sensor_seperate{a}.log_R(idx_ndmichange);

            break
        else
            p = 0;
            q = Sensor_seperate{a}.minute(idx_ndmichange);
            r = Sensor_seperate{a}.log_R(idx_ndmichange);
        end
    end
    % [p,q] = max(Sensor_seperate{a}.NDMI);
    FirstWetValueNDMI(a,1) = array2table(q);
    FirstWetValueNDMI(a,2) = array2table(p);
    FirstWetValueNDMI(a,3) = array2table(r);
end
NDMI_Map_Output = FirstWetValueNDMI.Var1(1:38)';

%% find area weighted logR and NDMI

```

```

Sorted_Table_full = sortrows(Table_full, 'timestamp', 'ascend');
for d = 1:38
    for b = 1:N
        Aweighted.LogR_ave(b) =
(pad_area(1)*Sorted_Table_full.log_R(d*(b-
1)+1)+pad_area(2)*Sorted_Table_full.log_R(d*(b-
1)+2)+pad_area(3)*Sorted_Table_full.log_R(d*(b-
1)+3)+pad_area(4)*Sorted_Table_full.log_R(d*(b-
1)+4)+pad_area(5)*Sorted_Table_full.log_R(d*(b-
1)+5)+pad_area(6)*Sorted_Table_full.log_R(d*(b-
1)+6)+pad_area(7)*Sorted_Table_full.log_R(d*(b-
1)+7)+pad_area(8)*Sorted_Table_full.log_R(d*(b-
1)+8)+pad_area(9)*Sorted_Table_full.log_R(d*(b-
1)+9)+pad_area(10)*Sorted_Table_full.log_R(d*(b-
1)+10)+pad_area(11)*Sorted_Table_full.log_R(d*(b-
1)+11)+pad_area(12)*Sorted_Table_full.log_R(d*(b-
1)+12)+pad_area(13)*Sorted_Table_full.log_R(d*(b-
1)+13)+pad_area(14)*Sorted_Table_full.log_R(d*(b-
1)+14)+pad_area(15)*Sorted_Table_full.log_R(d*(b-
1)+15)+pad_area(16)*Sorted_Table_full.log_R(d*(b-
1)+16)+pad_area(17)*Sorted_Table_full.log_R(d*(b-
1)+17)+pad_area(18)*Sorted_Table_full.log_R(d*(b-
1)+18)+pad_area(19)*Sorted_Table_full.log_R(d*(b-
1)+19)+pad_area(20)*Sorted_Table_full.log_R(d*(b-
1)+20)+pad_area(21)*Sorted_Table_full.log_R(d*(b-
1)+21)+pad_area(22)*Sorted_Table_full.log_R(d*(b-
1)+22)+pad_area(23)*Sorted_Table_full.log_R(d*(b-
1)+23)+pad_area(24)*Sorted_Table_full.log_R(d*(b-
1)+24)+pad_area(25)*Sorted_Table_full.log_R(d*(b-
1)+25)+pad_area(26)*Sorted_Table_full.log_R(d*(b-
1)+26)+pad_area(27)*Sorted_Table_full.log_R(d*(b-
1)+27)+pad_area(28)*Sorted_Table_full.log_R(d*(b-
1)+28)+pad_area(29)*Sorted_Table_full.log_R(d*(b-
1)+29)+pad_area(30)*Sorted_Table_full.log_R(d*(b-
1)+30)+pad_area(31)*Sorted_Table_full.log_R(d*(b-
1)+31)+pad_area(32)*Sorted_Table_full.log_R(d*(b-
1)+32)+pad_area(33)*Sorted_Table_full.log_R(d*(b-
1)+33)+pad_area(34)*Sorted_Table_full.log_R(d*(b-
1)+34)+pad_area(35)*Sorted_Table_full.log_R(d*(b-
1)+35)+pad_area(36)*Sorted_Table_full.log_R(d*(b-
1)+36)+pad_area(37)*Sorted_Table_full.log_R(d*(b-
1)+37)+pad_area(38)*Sorted_Table_full.log_R(d*(b-1)+38))/(sum(pad_area));
        end
    end

    %% Create wet table
    Sensor_name =
array2table(["C1", "D1", "D2", "C2", "B1", "B2", "A1", "A2", "B3", "C3", "D3", "A3", "B4"
, "C4", "D4", "A4", "B5", "C5", "D5", "B6", "C6", "D6", "E1", "F1", "E2", "F2", "G1", "E3", "
F3", "G2", "E4", "F4", "G3", "E5", "F5", "G4", "E6", "F6"]);
    Sensor_name.Properties.VariableNames = {'Var4'};
    Sensor_number = array2table(1:38);
    Sensor_number.Properties.VariableNames = {'Var5'};

% FirstWetValueWT = cat(2,FirstWetValueWT,Sensor_name);
% FirstWetValueWT = cat(2,FirstWetValueWT,Sensor_number);

```

```

FirstWetValueNDMI = cat(2,FirstWetValueNDMI,Sensor_name);
FirstWetValueNDMI = cat(2,FirstWetValueNDMI,Sensor_number);

%Wet threshold method
% SortedWetValueWT = sortrows(FirstWetValueWT,1);
% k = 1;
% noZerosWT = nonzeros(SortedWetValueWT.Var2);
% noZerosSizeWT = size(noZerosWT,1);
% while k < noZerosSizeWT
%     FirstW = noZerosWT(1);
%     if noZerosWT(k) == FirstW
%         WetTableWT(k) = SortedWetValueWT.Var5(k+(38-
noZerosSizeWT));
%         k = k+1;
%     elseif size(WetTableWT,2) <3
%         FirstW = noZerosWT(size(WetTableWT,2)+1);
%         WetTableWT(k) = SortedWetValueWT.Var5(k+(38-
noZerosSizeWT));
%         k = k+1;
%     else
%         break
%     end
% end

%NDMI method
SortedWetValueNDMI = sortrows(FirstWetValueNDMI,1);
k = 1;
noZerosNDMI = nonzeros(SortedWetValueNDMI.Var2);
noZerosSizeNDMI = size(noZerosNDMI,1);
if noZerosSizeNDMI ~= 0
    while k <= noZerosSizeNDMI
        FirstW = noZerosNDMI(1);
        if noZerosNDMI(k) == FirstW
            WetTableNDMI(k) = SortedWetValueNDMI.Var5(k+(38-
noZerosSizeNDMI));
            k = k+1;
        elseif size(WetTableNDMI,2) <3
            FirstW = noZerosNDMI(size(WetTableNDMI,2)+1);
            WetTableNDMI(k) = SortedWetValueNDMI.Var5(k+(38-
noZerosSizeNDMI));
            k = k+1;
        else
            break
        end
    end
else
    WetTableNDMI = 0;
    disp 'All NDMIs are zero.'
end

%% determin group
group1 = [7,8,12,16,5,6,17,20,1,21,2,22,23,37,24,26,35,38,27,30,33,36];
group2 = [9,13,4,10,14,18,3,11,15,19,25,28,31,34,29,32];

%Wet threshold method

```

```

%     j = 1;
%     temptableWT = array2table(zeros(38,2));
%     temptableWT = cat(2, Sensor_number, temptableWT);
%     while j <= size(WetTableWT,2)
%         isGroup2 = 0;
%         for m = 1:16
%             if WetTableWT(j) == group2(m)
%                 isGroup2 = 1;
%                 disp(WetTableWT(j) + ": Group2 "
+SortedWetValueWT.Var2(j+(38-noZerosSizeWT)))
%                 temptableWT.Var1(WetTableWT(j)) = 2;
%                 temptableWT.Var2(WetTableWT(j)) = -
SortedWetValueWT.Var2(j+(38-noZerosSizeWT));
%                 break
%             end
%         end
%         if isGroup2 == 0
%             disp(WetTableWT(j) + ": Group1 " +SortedWetValueWT.Var2(j+(38-
noZerosSizeWT)))
%             temptableWT.Var1(WetTableWT(j)) = 1;
%             temptableWT.Var2(WetTableWT(j)) = SortedWetValueWT.Var2(j+(38-
noZerosSizeWT));
%         end
%         j = j+1;
%     end

%NDMI method
j = 1;
temptableNDMI = array2table(zeros(38,2));
temptableNDMI = cat(2, Sensor_number, temptableNDMI);
if WetTableNDMI ~= 0
    while j <= size(WetTableNDMI,2)
        isGroup2 = 0;
        for m = 1:16
            if WetTableNDMI(j) == group2(m)
                isGroup2 = 1;
                disp(WetTableNDMI(j) + ": Group2 "
+SortedWetValueNDMI.Var2(j+(38-noZerosSizeNDMI)))
                temptableNDMI.Var1(WetTableNDMI(j)) = 2;
                temptableNDMI.Var2(WetTableNDMI(j)) = -
SortedWetValueNDMI.Var2(j+(38-noZerosSizeNDMI));
                break
            end
        end
        if isGroup2 == 0
            disp(WetTableNDMI(j) + ": Group1 "
+SortedWetValueNDMI.Var2(j+(38-noZerosSizeNDMI)))
            temptableNDMI.Var1(WetTableNDMI(j)) = 1;
            temptableNDMI.Var2(WetTableNDMI(j)) =
SortedWetValueNDMI.Var2(j+(38-noZerosSizeNDMI));
        end
        j = j+1;
    end
end

%% export NDMI as csv files with experiment date
%name_ExperimentDate = yyyyymmdd(Table_full.timestamp(1,1));

```

```

%name_WT = [num2str(name_ExperimentDate),'wt','.csv'];
%WTmapOutput = temptableWT.Var2';
%writematrix(WTmapOutput,name_WT);

%name_NDMI = [num2str(name_ExperimentDate),'ndmi','.csv'];
name_NDMI = ['Test',num2str(test_n),'_NDMI_Map','.csv'];
%NDMImapOutput = temptableNDMI.Var2';
writematrix(NDMI_Map_Output,name_NDMI);

%% plot
group1_1 = [1,2,5,6,7,8];
group1_2 = [12,16,17,20,21,22];
group1_3 = [23,24,26,27,30];
group1_4 = [33,35,36,37,38];

group2_1 = [3,4,9,10,11];
group2_2 = [13,14,15,18,19];
group2_3 = [25,28,29];
group2_4 = [31,32,34];

figure('name','Edge Group NDMI');
for idx_plotGroup1 = group1_1

plot(Sensor_seperate{idx_plotGroup1,1}.minute,Sensor_seperate{idx_plotGroup1,
1}.NDMI,'-');
    hold on
end
for idx_plotGroup1 = group1_2

plot(Sensor_seperate{idx_plotGroup1,1}.minute,Sensor_seperate{idx_plotGroup1,
1}.NDMI,'--');
    hold on
end
for idx_plotGroup1 = group1_3

plot(Sensor_seperate{idx_plotGroup1,1}.minute,Sensor_seperate{idx_plotGroup1,
1}.NDMI,':');
    hold on
end
for idx_plotGroup1 = group1_4

plot(Sensor_seperate{idx_plotGroup1,1}.minute,Sensor_seperate{idx_plotGroup1,
1}.NDMI,'-.');
    hold on
end
xle = xlim;
if xle(2)>480
    xlim([0 480])
end
%xlim([0 120]);
ylim([-0.5 3]);%y axis range
xlabel('Time (min)');
ylabel('NDMI');
title(['Test',num2str(test_n),' Edge Group']);
name_plot1 = ['Test',num2str(test_n),' NDMI Edge Group'];

```

```

    saveas(gcf,['D:\A SMT Project - Moisture Sensor\Writing\Methodology and
Results\membrane results\Matlab_NDMI_test\plot\',name_plot1, '.fig']);
    hold off

    figure('name','Interior Group NDMI');
    for idx_plotGroup2 = group2_1

plot(Sensor_seperate{idx_plotGroup2,1}.minute,Sensor_seperate{idx_plotGroup2,
1}.NDMI);
        hold on
        end
        for idx_plotGroup2 = group2_2

plot(Sensor_seperate{idx_plotGroup2,1}.minute,Sensor_seperate{idx_plotGroup2,
1}.NDMI, '--');
        hold on
        end
        for idx_plotGroup2 = group2_3

plot(Sensor_seperate{idx_plotGroup2,1}.minute,Sensor_seperate{idx_plotGroup2,
1}.NDMI, ':');
        hold on
        end
        for idx_plotGroup2 = group2_4

plot(Sensor_seperate{idx_plotGroup2,1}.minute,Sensor_seperate{idx_plotGroup2,
1}.NDMI, '-. ');
        hold on
        end
        xle = xlim;
        if xle(2)>480
            xlim([0 480])
        end
        %xlim([0 120]);
        ylim([-0.5 3]);% y axis range
        xlabel('Time (min)');
        ylabel('NDMI');
        title(['Test',num2str(test_n), ' Interior Group']);
        name_plot2 = ['Test',num2str(test_n), ' NDMI Interior group'];
        saveas(gcf,['D:\A SMT Project - Moisture Sensor\Writing\Methodology and
Results\membrane results\Matlab_NDMI_test\plot\',name_plot2, '.fig']);
        hold off

    figure('name','Edge Group LogR');
    for idx_plotGroup1 = group1_1

plot(Sensor_seperate{idx_plotGroup1,1}.minute,Sensor_seperate{idx_plotGroup1,
1}.log_R, '-');
        hold on
        end
        for idx_plotGroup1 = group1_2

plot(Sensor_seperate{idx_plotGroup1,1}.minute,Sensor_seperate{idx_plotGroup1,
1}.log_R, '--');
        hold on
        end

```

```

    for idx_plotGroup1 = group1_3

plot(Sensor_seperate{idx_plotGroup1,1}.minute,Sensor_seperate{idx_plotGroup1,
1}.log_R, ':');
    hold on
    end
    for idx_plotGroup1 = group1_4

plot(Sensor_seperate{idx_plotGroup1,1}.minute,Sensor_seperate{idx_plotGroup1,
1}.log_R, '-. ');
    hold on
    end
    xlabel('Time (min) ');
    ylabel('Log R');
    title(['Test',num2str(test_n), ' Edge Group']);
    name_plot3 = ['Test',num2str(test_n), ' LogR Edge Group'];
    saveas(gcf,['D:\A SMT Project - Moisture Sensor\Writing\Methodology and
Results\membrane results\Matlab_NDMI_test\plot\' ,name_plot3, '.fig']);
    hold off

    figure('name','Interior Group LogR');
    for idx_plotGroup2 = group2_1

plot(Sensor_seperate{idx_plotGroup2,1}.minute,Sensor_seperate{idx_plotGroup2,
1}.log_R);
    hold on
    end
    for idx_plotGroup2 = group2_2

plot(Sensor_seperate{idx_plotGroup2,1}.minute,Sensor_seperate{idx_plotGroup2,
1}.log_R, '--');
    hold on
    end
    for idx_plotGroup2 = group2_3

plot(Sensor_seperate{idx_plotGroup2,1}.minute,Sensor_seperate{idx_plotGroup2,
1}.log_R, ':');
    hold on
    end
    for idx_plotGroup2 = group2_4

plot(Sensor_seperate{idx_plotGroup2,1}.minute,Sensor_seperate{idx_plotGroup2,
1}.log_R, '-. ');
    hold on
    end
    xlabel('Time (min) ');
    ylabel('Log R');
    title(['Test',num2str(test_n), ' Interior Group']);
    name_plot4 = ['Test',num2str(test_n), ' LogR Interior Group'];

    saveas(gcf,['D:\A SMT Project - Moisture Sensor\Writing\Methodology and
Results\membrane results\Matlab_NDMI_test\plot\' ,name_plot4, '.fig']);
    hold off

end

```

```

%% ----- function
-----

function [reading_table] = convertTime(reading_table,N)
    for i = 2:N
        reading_table.second(1) = 0;
        reading_table.second(i) =
round(datenum(reading_table.timestamp(i))*24*60*60-
datenum(reading_table.timestamp(1))*24*60*60);
        reading_table.minute(1) = 0;
        reading_table.minute(i) = datenum(reading_table.timestamp(i))*24*60-
datenum(reading_table.timestamp(1))*24*60;
        reading_table.timediffsec(1) = 0;
        reading_table.timediffsec(i) =
round(datenum(reading_table.timestamp(i))*24*60*60-
datenum(reading_table.timestamp(i-1))*24*60*60);
    end
end

function [counter, reading] = getWetInfoWT(reading_table,N, wet_threshold)
    i = 1;
    while i < N
        if reading_table.log_R(i) > wet_threshold
            i=i+1;
            counter = 1;
            reading = 0;
        else
            reading = reading_table.log_R(i);
            counter = i;
            break
        end
    end
end

function [counter, reading,reading_table] = getWetInfoNDMI(reading_table,N)

    reading_table.NDMI=zeros(1,N)';
    %if reading_table.log_R(1) >7
        %reading_table.NDMI(1) = 0;
    %else
        reading_table.NDMI(1) = (9 -
reading_table.log_R(1))/reading_table.log_R(1);
    %end

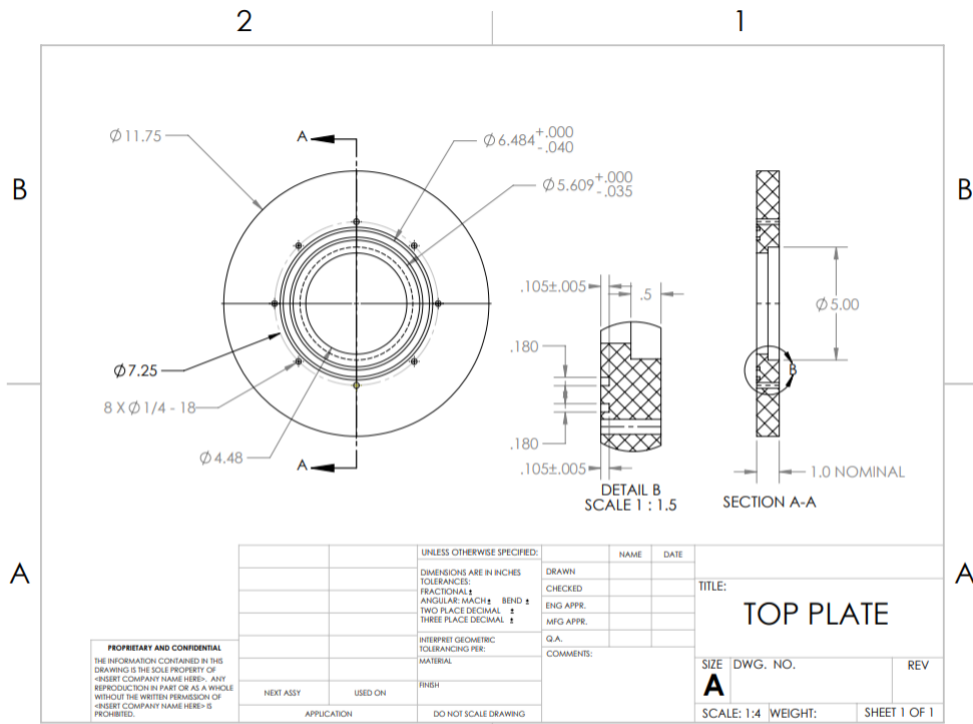
    i = 2;
    while i <= N
        %if reading_table.log_R(i) > 7
            %counter = "null";
            %reading = "null";
            %i=i+1;
        %else
            %for idx_ndmi = 1:(N-1)

                %reading_table.NDMI(i) = (reading_table.log_R(i-1) -
reading_table.log_R(i))/(reading_table.log_R(i)); change the equation
            end
        end
    end
end

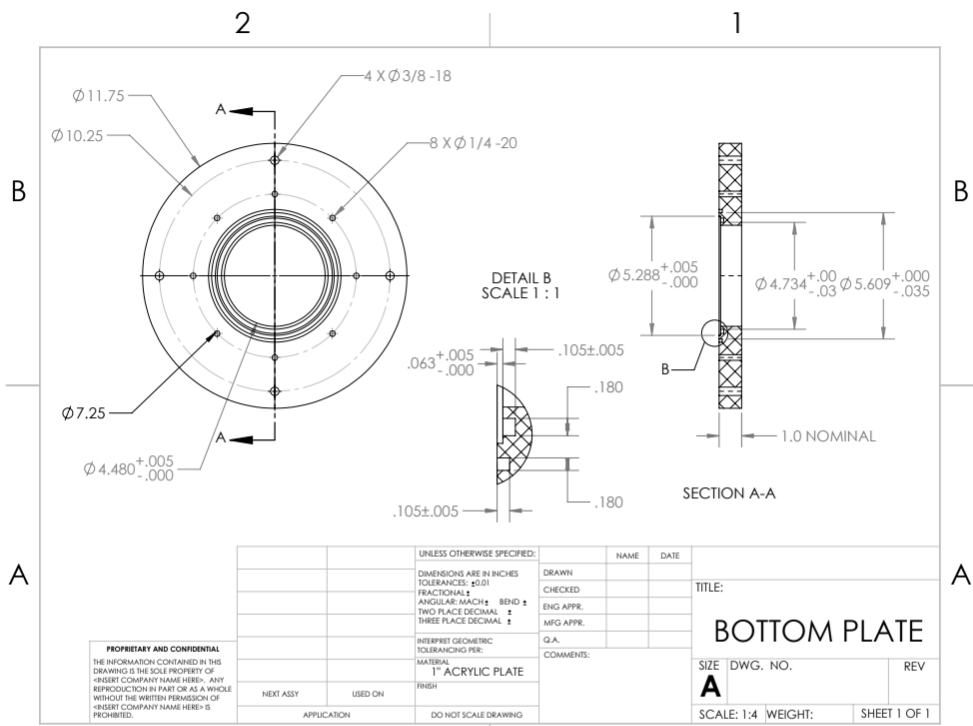
```

```
        reading_table.NDMI(i) = (reading_table.reading(i-1) -  
reading_table.reading(i))/(reading_table.reading(i));  
        %end  
        reading = reading_table.log_R(i);  
        counter = i;  
        i = i+1;  
    %end  
end  
end
```

# APPENDIX C ENGINEERING DRAWING OF THE MODIFIED DEVICE



SOLIDWORKS Educational Product. For Instructional Use Only.



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APPENDIX D MACHINING PROCESS

