

THESIS

INVESTIGATING THE SUITABILITY OF EXISTING COMMERCIAL HYDROPHOBIC
COATINGS FOR SOILING MITIGATION IN THE PHOTOVOLTAIC INDUSTRY

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In partial fulfillment of the requirements

For the Degree of Master of Science

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Spring 2019

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ABSTRACT

INVESTIGATION OF THE SUITABILITY OF EXISTING COMMERCIAL HYDROPHOBIC COATINGS FOR SOILING MITIGATION IN THE PHOTOVOLTAIC INDUSTRY

The global production of solar power has been increasing approximately 40% per year for the last two decades, making solar one of the quickest growing renewable energy technologies. Estimated to increase 14-fold by the year 2040, solar photovoltaic (PV) power will become a major source of electricity. Soiling, the build-up of dust and debris on the surface of a solar module, is the third largest contributor to losses in solar power output. Decreases in solar module energy production of 20-30% have been observed in arid-desert climates, regions where sunlight is most intense and abundant. Current soiling mitigation techniques involve some type of mechanical cleaning process, either manual or automated, which can be highly water, time, and cost intensive. A potentially beneficial option to reducing PV soiling involves the use of anti-soiling coatings. A number of studies have previously examined the anti-soiling properties of various hydrophobic (water-fearing) and hydrophilic (water-loving) coatings. Though studies are ongoing, research generally shows hydrophobic coatings have an advantage over hydrophilic coatings due to lower dust adhesion forces and water-repellency properties. However, existing research efforts have not conclusively shown that hydrophobic coatings can survive the harsh environmental conditions experienced by a solar module during its lifetime. Anti-soiling research on existing commercial hydrophobic coatings is also minimal. Therefore, this research aims to understand the viability of using existing hydrophobic coatings to mitigate soiling losses seen in the PV industry. A group of hydrophobic coatings were obtained from various sectors of

industry, including surface refinement, electronics, ophthalmic, and automotive. An initial screening procedure, designed to characterize the hydrophobic properties of the obtained coatings, was then implemented to identify a group of candidate coatings for this study. An accelerated durability testing procedure, designed specifically for hydrophobic coatings on solar cover glass, was used to identify degradation mechanisms of the candidate coatings in the presence of environmental stressors. Utilizing a custom-built soiling chamber and various dust removal apparatuses, a testing methodology was developed to understand the anti-soiling properties of the coatings. Finally, using an outdoor solar test array, comparative tracking of coated and uncoated modules was performed over an extended period of time. Through durability and anti-soiling experimentation, results from this work led to the identification of a single commercially available hydrophobic coating that demonstrates strong potential for anti-soiling applications in PV.

ACKNOWLEDGEMENTS

I would like to thank Dr. Kurt Barth for his continued support and large contribution of knowledge, as well as being an amazing adviser to my research project. Dr. Barth taught me so much, not only in an engineering/scientific standpoint, but in the project management and business aspects as well. Next, I would like to thank Professor John Walls and his coatings research team Fabiana Lisco, Kenan Isbilir, Farwah Bukhari, Gerald Womack, and Gizelle Oehler for their large contributions, collaboration, and support on this research project. Without them, much of the testing would not have been possible. I would also like to give my gratitude to Dr. Tushar Shimpi for his support and genuine interest in my research activities over the past year. I would like to thank Larry Maple for the many informative discussion we had during my time here as a graduate researcher. His knowledge on various aspects of engineering problem solving, systems engineering, part designing, and manufacturing, helped in part make my project the success that it was. I would also like to thank Larry for his dedication of time in helping me with some of my project builds. I would like to thank Dr. Walajabad Sampath and Dr. Jim Sites for being a part of my graduate committee and providing their time, support, and guidance as needed. I would like to thank Matt Martinez for his expertise and assistance on the electrical components within my research. I give gratitude to Kevin Cameron for his hard work and dedication in keeping this laboratory running smoothly. I would also like to thank him for giving me the opportunity to work in the lab as an undergraduate student; I wouldn't be here otherwise. I must also thank my fellow researchers for their continued support and friendship.

I'd like to give special thanks to my wonderful fiancé Abby Gomer. She has been extremely supportive throughout the pursuit of my graduate degree. This experience would not

have been nearly as amazing without her by my side, during both the good and challenging times. I love you Abby! I'd also like to give appreciation to my mother, Linda Strauss, for her support in all of my endeavors and undertakings. I would not be the man I am today without her.

Love you mom!

During this research I was supported by CSU's Mechanical Engineering Department and NREL's DuraMat program (UGA-0-41027-00, task # ST6P.3311) and DOE Solar Energy Technologies Office (DE-EE0008161).

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LIST OF NOMENCLATURE

WCA	Water Contact Angle
RoA	Roll-Off Angle
CAH	Contact Angle Hysteresis
PV	Photovoltaic
RH	Relative Humidity
MENA	Middle Eastern and North Africa
VDW	Van der Waals
OH	Hydroxyl
AR	Anti-Reflective
CAG	Contact Angle Goniometer
AM 1.5	Air Mass Standard Spectrum
RI	Refractive Index
SEM	Scanning Electron Microscopy
XPS	X-ray Photoelectron Spectroscopy
DH	Damp Heat
UV	Ultra-Violet
IPA	Isopropyl Alcohol
DI	De-Ionized

CHAPTER 1. INTRODUCTION

1.1 Solar Photovoltaic Power

Roughly 5% of modern electricity generated world-wide comes from solar and wind technology. The global power demand will continue to rise 2% per year, and is expected to grow an astonishing 58% by the year 2040 [1]. With an alarming amount of evidence on the climate-changing effects of rising atmospheric CO₂ levels caused by the consumption of fossil fuels, a shift towards renewable energy production has become paramount. One of the quickest growing renewable energy technologies is photovoltaic (PV) solar power, having a global growth rate approximately of 40% per year over the last 20 years [2]. As shown in Figure 1, the cumulative utility-scale PV production in the U.S. has increased exponentially since 2010, reaching around 25 GW (DC) power production in 2016. The demand for PV installation in 2017 is estimated to be around 79 GW[3].

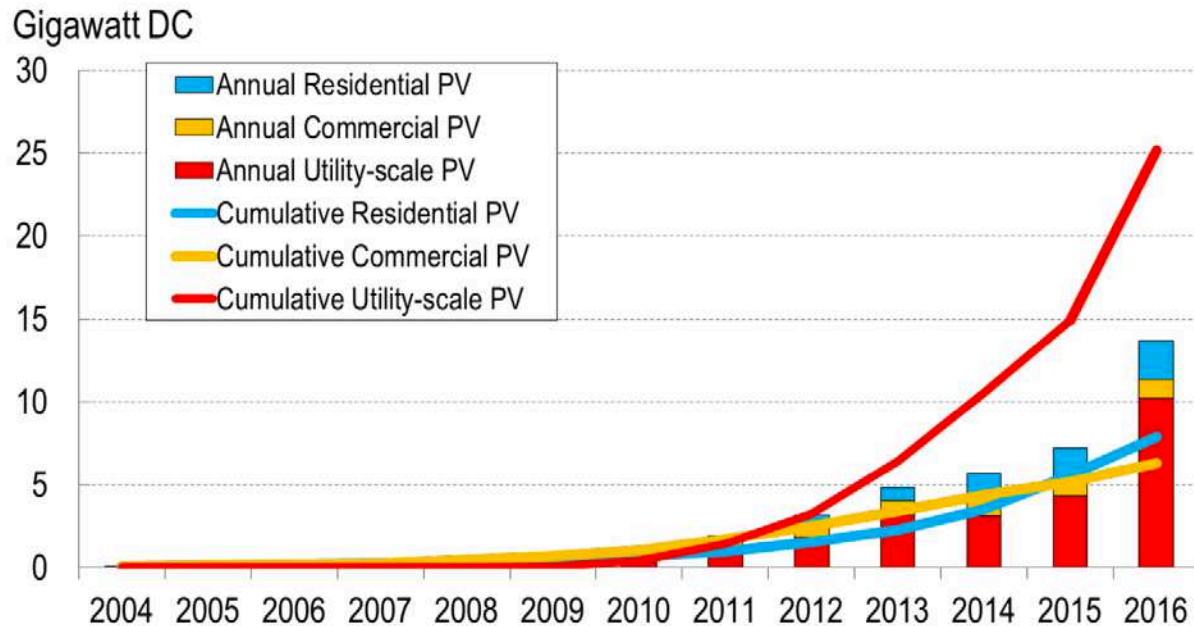


Figure 1. U.S. PV market growth, 2004 - 20016, in GW dc capacity. Adopted from [2].

First Solar, a major producer of thin-film CdTe solar cells, have reached a record low cost of \$0.05/kWh [3] on the utility-scale with their modules, making thin-film PV the cheapest energy technology available, as shown in Figure 2. The steep drop in solar-produced electricity prices stem from a few primary sources: inexpensive modules, cheaper inverters, and most effectively, an increase in the efficiency of the solar cell. According to California's Net Energy Metering, the efficiency of commercial solar modules has increased 3.7% since 2010, reaching a record efficiency of 17.5% in 2016.

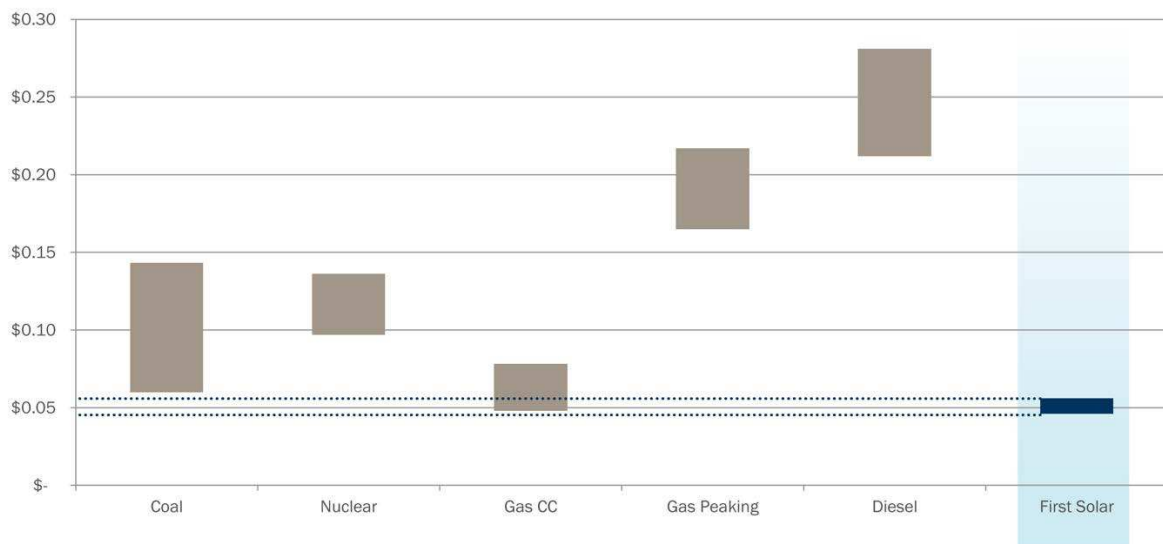


Figure 2. \$/kWh electricity price from First Solar's module vs. common fossil fuel technologies. Adopted from [3].

While the growth of PV is impressive and leads to a promising outlook for the future of energy production, it is not without challenges. Current research efforts are focused on improving the performance of PV technology. Many researchers are striving to achieve fractional increases in cell efficiency in order to boost power output, while others are focused on increasing the durability and lifetime of the solar module itself. Beyond these efforts, three

environmental factors ultimately determine the performance of a solar module in the field, including (1) solar irradiance levels, (2) ambient temperatures, and (3) soiling. Of these three factors, soiling is possibly the most overlooked, yet highly impact stimulus, and is the focus of the current work.

1.2 Soiling Impact and Related Studies

Soiling is the build-up of contaminants on the surface of solar module cover glass, which hinders performance by decreasing the amount of sunlight reaching the solar cell underneath. These contaminants include sand, dust particulates, pollen, pollutants, salts, calcium deposits, and even bird droppings. As the solar market continues expanding into the sunbelt and desert regions world-wide, a desire to understand and mitigate the effects of soiling has become a priority. A number of studies have been executed to investigate the effects of soiling on PV modules. For example, a study in South Central Valley, California, examined the performance of First Solar modules by monitoring the short-circuit current output [4]. As shown in Figure 3, the soil level, measured as a percent decrease in total energy production, reached a high of 8.6% during periods with limited rainfall.

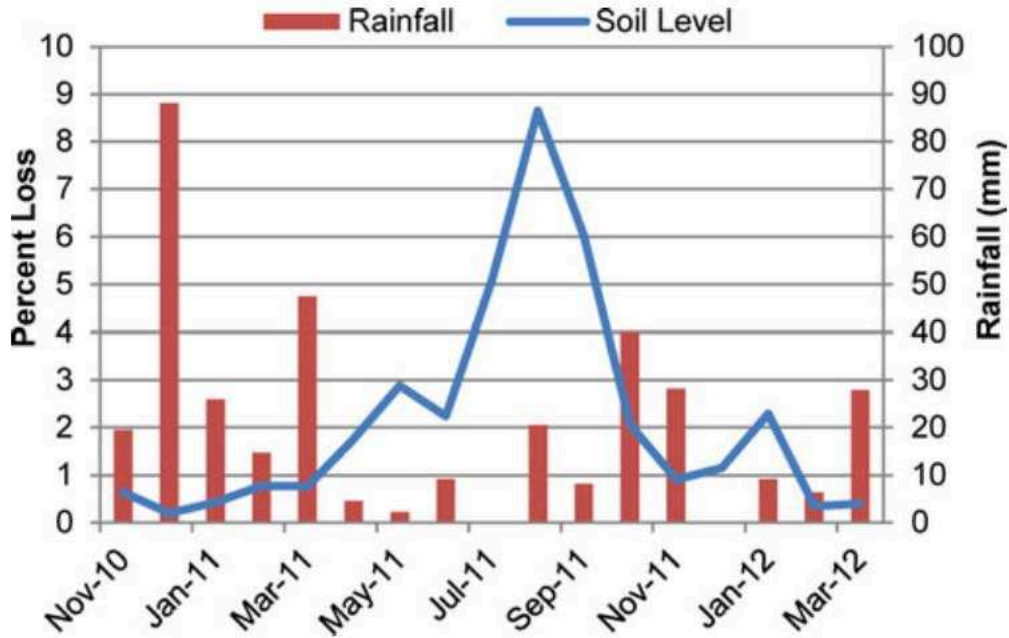


Figure 3. Southern Central Valley, California soil level and rainfall from November 2010 to March 2012. Adopted from [4].

The amount of power loss depends on five key variables: dust composition, dust density, relative humidity (RH), particle size, and shape [5]. The composition of dust can vary greatly depending on the geological location. Dust from dry agricultural areas tend to be organic compounds, while dust near urban areas tend to consist of pollutants (e.g. as hydrocarbons), and dust in desert regions are mainly composed of silica. Some locations experience a larger reduction in power production due to region-specific climates and weather patterns. For example, a study performed in Algeria [6] showed a 16.2% reduction in power output, while a rooftop solar array in Spain [5], experienced a 20% power reduction during prolonged dry periods. *AlbBusairi* and *Moller* demonstrated soiling losses of 20-30% in Kuwait due to a high average RH and dusty rain events [7]. Staggering power output losses of up to 70-80% can also result from a single dust storm in the Middle East and North Africa (MENA) region [8]. This amount of soiling is enough to effectively terminate the power production from a given PV plant.

Globally, the average annual power production losses due to soiling range from 1-6% [9],[10],[4]. Because of the large impact of soiling on PV performance, the PV research community is interested in methods to reduce its effects. A common approach is through the use of anti-soiling coatings. Understanding the mechanisms by which dust interacts with the cover-glass of a solar module strongly influences the research efforts towards PV soiling mitigation.

1.3 Mechanisms of Soiling

Dust, defined as a particulate having a diameter less than 500 μm [11],[12], interacts with the surface of a solar module through a combination of Van der Waals (VDW) forces, cementation, and electrostatic forces (negatively or positively charged particles and module surfaces). Of these, cementation is one of the strongest binding mechanisms [13]. Cementation occurs when a dust particle containing water-soluble salts forms salt droplets when exposed to an environment with high RH, dew formation, or a wetting event (light rain). Upon drying, these salt droplets can form a cement that adheres the dust particle to the surface, making it extremely difficult to remove. The cementation process is illustrated in Figure 4. In a dry environment, VDW forces dominate the dust-surface interaction [14]; lowering the surface energy (anti-soiling coatings) and roughening the surface will reduce these forces. Kazmerski et. al [11] found that dust adhesion forces decreased eight-fold in the presence of surfaces coated with various types of hydrophobic anti-soiling coatings. These coatings alter the interfacial forces between the module cover-glass, the dust particles, and/or water molecules, all in order to reduce the negative effects of soiling.

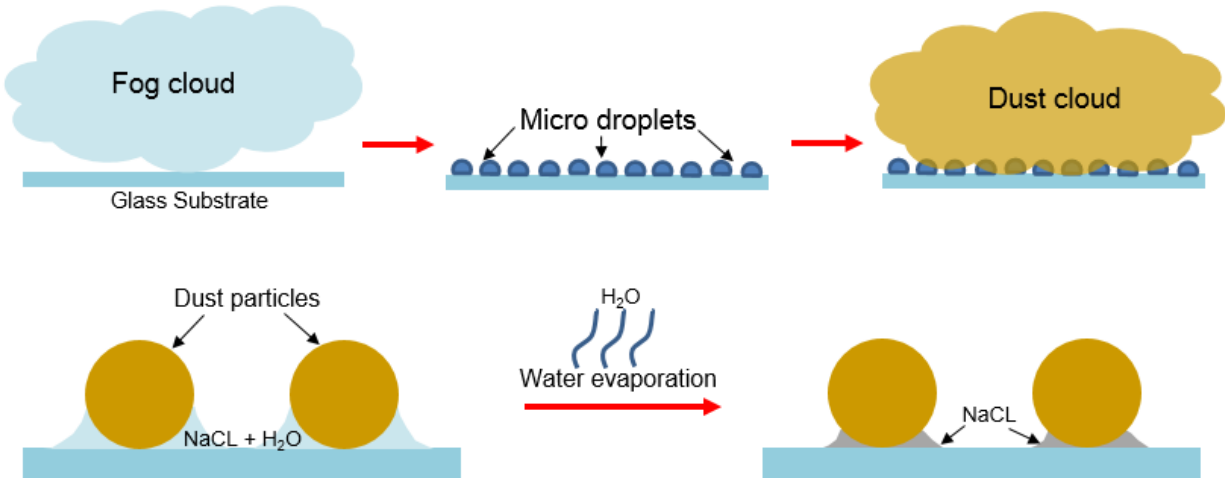


Figure 4. Illustration of the dust cementation process.

1.4 Hydrophobic and Hydrophilic Coatings

Anti-soiling coatings generally fall into two main categories, those with hydrophobic (water-repellent) properties and those with hydrophilic (water-attractant) properties. Each coating interacts with a given surface through differing mechanisms. Consider a soda-lime glass substrate. Dangling oxygen bonds on the surface of the glass interact with water vapor in the air, forming hydroxyl (OH) functional groups. These functional groups are highly polar and act to attract the polar water molecules. A hydrophobic coating occupies the OH groups through various bonding mechanisms, rendering the surface non-polar (i.e. water-repelling). Hydrophilic coatings on the other hand, increase the number of OH groups on the surface, creating more anchoring points for water molecules (i.e. water-attracting).

Numerous research investments have been dedicated to discovering various techniques in developing both (super)hydrophobic and (super)hydrophilic engineered surfaces. Hydrophobic and hydrophilic coatings are defined by their liquid contact angle. The water contact angle (WCA) θ is illustrated in Figure 5a, and is defined by Young's equation for a smooth surface

$$\cos(\theta) = (\gamma_{SV} - \gamma_{SL})/\gamma_{LV} \quad (1)$$

where γ_{SV} , γ_{SL} , and γ_{LV} , are the solid-vapor, solid-liquid, and liquid-vapor interfacial energies, respectively. A surface with a WCA less than 90° is termed hydrophilic, while a WCA less than 30° defines superhydrophilic surfaces. Likewise, a WCA above 90° results in a hydrophobic surface, and a WCA above 130° results in superhydrophobicity. The maximum theoretical WCA for a smooth surface is around 120° [15], and in order to achieve a higher WCA, the surface roughness must be increased. One approach to superhydrophobicity involves roughening a naturally low-surface energy (hydrophobic) surface, while a second approach involves roughening a hydrophilic surface and modifying this surface with low-surface energy materials. Both approaches aim to decrease the overall solid-liquid contact area, leading to reduced interfacial forces between the liquid and solid surface. In the case of hydrophilicity, the surfaces and materials have a high-surface energy and roughening the surface acts to increase the overall surface area of the solid. Many methods, such as laser and plasma etching, mechanical roughening, and lithography techniques, are used to roughen surfaces on a nanometer-scale level.

Water will naturally take on one of two states when in contact with a (super)hydrophobic surface. The Wenzel state, Figure 5b, is defined by the equation

$$\cos(\theta') = \frac{r(\gamma_{SV} - \gamma_{SL})}{\gamma_{LV}} = r \cos(\theta) \quad (2)$$

where r is the roughness factor, or the fraction of actual to projected surface area. As the roughness of a surface increases, the roughness factor increases, and the apparent WCA θ' increases. In the Wenzel state, the water penetrates the nano-features, completely wetting the surface. While the Wenzel state may result in high, possibly superhydrophobic-level contact angles, line-pinning can occur between the droplet and surface, holding the droplet in place [16],[17],[18]. Line-pinning is an undesirable trait for a self-cleaning surface, where the shedding

of water at a shallow tilt-angle is required. The alternative state, defined as the Cassie-Baxter state, involves the water droplet resting on the top of the nano-scale surface features, leaving air pockets trapped between the features and underneath the droplet. The apparent WCA in this state is defined by

$$\cos(\theta') = f\cos(\theta) + (f - 1) \cos(180) = f\cos(\theta) + f - 1 \quad (3)$$

where f is the fractional area of the solid-liquid interface. The Cassie-Baxter state is preferred for self-cleaning properties due to the minimal contact between the water droplet and solid surface. This reduced contact allows the water droplet to roll off the substrate at very shallow angles. While the two wetting states were discussed as separate occurrences, it is often the case that a hybrid state exists [16]. This leads to the conclusion that superhydrophobic surfaces are often metastable and may not be the best fit for PV applications.

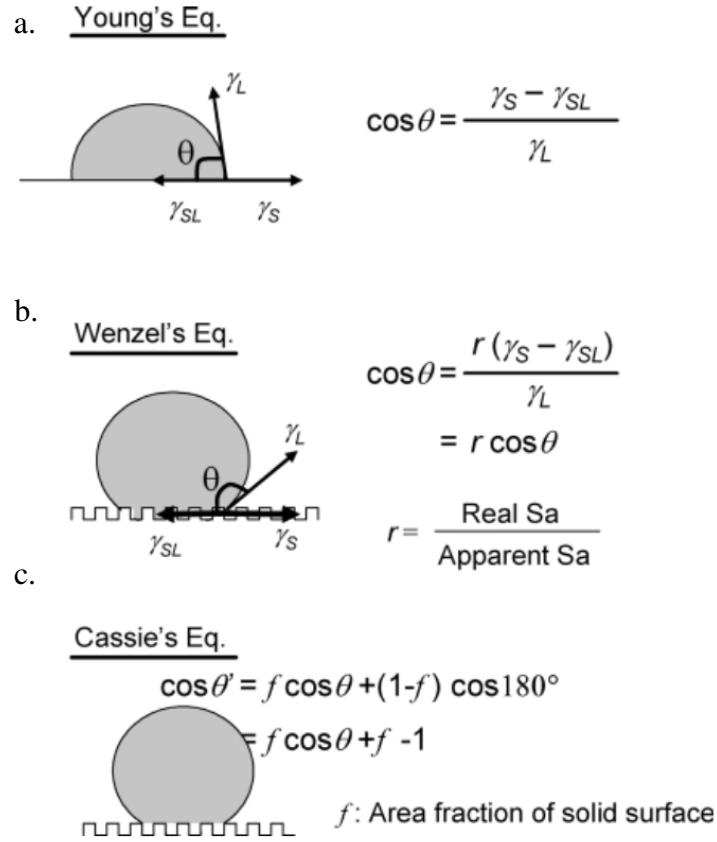


Figure 5. Schematic illustration of a.) Young, b.) Wenzel, and c.) Cassie's models for water contact angle. Adopted from [17].

Most real surfaces exhibit either textural heterogeneity (roughness) or chemical heterogeneity (surface energy gradients). In this case, Young's contact angle alone can no longer accurately describe the hydrophobicity of the surface. One must either report the apparent (static) WCA or measure the advancing and receding WCA's (Figure 6). The measure of a surface's "stickiness" can be represented by the contact angle hysteresis (CAH), defined as the difference between the advancing (θ_a) and receding (θ_r) contact angles. Looking at Figure 6, one can imagine the CAH increasing in value for a sticky surface compared to a slippery surface as the tilt (α) is larger in the first case. In other words, there is more droplet distortion if the droplet were to remain pinned to the surface. For most real surfaces, the apparent contact angle (the

angle measured under static conditions) lies somewhere in between θ_a and θ_r . Therefore, the WCA's discussed in this work are the apparent, or static, contact angles of a given hydrophobic surface.

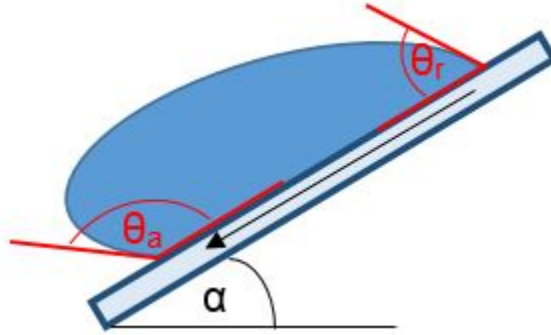


Figure 6. Advancing (θ_a) and receding (θ_r) contact angles on a droplet in motion under a surface tilt of α . θ_a defines the WCA on the leading edge of the droplet, while θ_r defines the WCA on the trailing edge.

1.5 Current Anti-Soiling Coating Investigation Efforts

Hydrophilic and hydrophobic coatings are being investigated to mitigate PV module soiling losses. While these coatings have self-cleaning properties, the mechanisms in which they remove or prevent debris build-up differ. Hydrophilic surfaces, especially surfaces with a very low WCA, spread individual water droplets out until complete wetting occurs. With sufficient water present, a film of water is formed that suspends the dust particulates and carries them off the surface. Hydrophobic coatings, due to their low-surface energy, form sphere-like water droplets on the surface. These droplets then roll off the surface and pick up any dust along the path of travel. The ability of a coating to shed water droplets under a surface tilt is called the roll-off angle (RoA). The RoA is defined as the angle with respect to the horizontal at which a droplet begins to roll from the surface. Figure 6 illustrates the concept of a droplet moving under

a given surface tilt, α . There are advantages and disadvantages to both types of anti-soiling coating technologies.

A number of studies have tested the effectiveness of various hydrophobic and hydrophilic coatings for PV use. A study from Fraunhofer Institute for Solar Energy Systems [19] performed a series of artificial dust-deposition tests and transmission tests to examine the anti-soiling benefits of commercial hydrophilic coatings. Their results estimated an average annual energy yield increase of 3% versus uncoated modules. First Solar also investigated the hydrophilic anti-soiling effects of their anti-reflective (AR) coating in a number of climatic regions in North and South America [20]. A soiling measurement system was developed using coated versus uncoated modules, revealing the anti-soiling effects of their hydrophilic AR-coating. Monitoring periods, spanning approximately one year, resulted in an average 60% decrease in the rate of soil build-up. Two additional studies [14],[6], investigated transmission reductions of hydrophobically coated versus uncoated sample glass after dust deposition tests. Using a commercial hydrophobic coating. Fathi et al. developed a dust deposition test simulating conditions in the MENA region [6]. Their findings reported an average of 8.53% difference in transmission reduction between the coated and uncoated glass sample after lab dusting. Quan and Zhang developed a transparent hydrophobic coating composed of silica dioxide nanoparticles and silica sol, and used three varying dust removal techniques to test its anti-soiling abilities [14]. Following a carefully controlled deposition of dust, the samples were subjected to either mechanical vibration, dry-air blowing, or moist-air blowing to observe levels of dust removal. In all three cases, the hydrophobically coated glass slides experienced less transmittance reduction after dust removal. For the air-blowing tests, a difference of around 19.6% between the coated and uncoated samples

were observed. The results from the previous studies show the strong anti-soiling effects of hydrophobic and hydrophilic coatings.

According to research conducted by Ed Cuddihy at Sandia National Laboratory [21], there are benefits to using hydrophobic over hydrophilic coatings. Among the various properties an optimal anti-soiling surface should exhibit, hydrophobicity is one of them. This claim is due to the low-surface energy and repellency of water. Lowering the surface energy will decrease the forces associated with dust adhesion, while water repellency prevents surface contamination due to drying stains like calcium/salt build-up. Hydrophilic coatings on the other hand, tend to degrade quicker due to surface contamination from the entrapment of water in nano-scale surface features [21]. In addition, hydrophilic coatings increase dust adhesion forces due to an innate higher surface energy. Nevertheless, durability is an issue for both hydrophilic and hydrophobic coatings, and research in this area remains sparse.

1.6 Remaining Gaps in Anti-Soiling Research

While there are several studies examining the potential of hydrophobic coatings as a solution to soiling in PV, coating durability and the effects of environmental exposure are not fully understood. Previous research has not fully studied the ability of a hydrophobic coating to survive the environmental conditions experienced by a solar module during an over 20-year lifetime. Table 1 qualitatively compares the anti-soiling properties of hydrophilic and hydrophobic coating technologies.

Table 1. Qualitative summary of anti-soiling property strengths for hydrophobic and hydrophilic coatings, ranked on a scale of (---) to (+++). [Table generated with information from NREL, 12].

	Cost Low Medium High	Application Ease	Effectiveness (dry)	Effectiveness (wet)	Durability	PID Potential	Automation Potential
(Super) hydrophobic	L/M	+	+	+++	?	?	?
(Super) hydrophilic	L/M	+	+	+	?	--	?

From Table 1, the durability, potential induced degradation (PID), and automation potential of PV adopted hydrophobic coatings, are generally unknown in the research community. In addition, the investigation of commercially available hydrophobic coating for use in the PV industry is non-existent. Therefore, this knowledge gap provides a large opportunity for novel research to determine the suitability of utilizing existing hydrophobic coatings for soiling mitigation.

1.7 Objectives

The objective of this research is to investigate the suitability of available hydrophobic coatings for use as anti-soiling coatings for PV applications. Specifically, this work investigates the overall performance, durability and anti-soiling properties of coatings using existing (commercially available) coatings. The outcome of this work is the quantification of different coatings' capabilities, fundamental understanding of the performance and degradation behaviors, and specific recommendations for improvement to enable subsequent development for commercial application.

Using standardized durability testing procedures [22] developed specifically for hydrophobic coatings on solar cover glass, obtained coating solutions from top manufacturers across the globe are subjected to an accelerated durability experiments. These experiments include damp heat and UV exposure tests, as well as abrasion testing. From this, a prediction of

how specific coatings degrade in the field is obtained. The anti-soiling properties of the candidate coatings are also quantitatively examined through various dust deposition and dust removal experiments. In addition to lab testing, select modules in a nearby solar array are coated and photo-documented in order to qualitatively compare performance differences between coated and uncoated modules in real-world conditions. The analyzed data from this work aims to provide insight to the suitability of utilizing commercially available hydrophobic coatings for soiling mitigation in the PV industry.

CHAPTER 2. INVESTIGATION OF COMMERCIALLY AVAILABLE HYDROPHOBIC COATINGS

2.1 Research and Obtainment of Industrial Hydrophobic Coatings

Insight to problems encountered in research can often be found through related solutions already existent in industry. There are a number of industrial sectors that utilize protective engineered coatings to enhance product performance; the automotive industry, ophthalmic industry (glass lenses), glass manufacturing companies, electronics manufacturers, and a variety of other surface-modification industries use hydrophobic coatings. Therefore, a research program was developed by the research team to identify and study commercially available anti-soiling coatings for PV applications.

Two general criteria were set in place for the initial investigation of existing hydrophobic coatings. The coating needs to be transparent and have a sufficient manufacturer claimed lifetime (in excess of 1 year). With these criteria, extensive research through online resources led to a group of ten hydrophobic coatings. These vendors were then contacted, and samples of the coating formulation were obtained. The coating's chemical technology and industry of focus are summarized in Table 2. A preliminary testing procedure characterizing the coating's transmission, static WCA and RoA was developed and executed to reduce the ten obtained coatings to a group of candidates for subsequent, more in-depth investigations.

Table 2. Summary of the obtained commercial hydrophobic coatings.

Coating	Materials/ Chemicals/Technology	PV Experience	Industry of focus
Coating A	Colloidal sol-gel self assembling monolayer	No	Automotive
Coating B	Silane modified surface	No	Ophthalmetry
Coating C	Perfluoropolyether silane	No	Life-sciences, aerospace, electronics, communications
Coating D	Silane modified silica nanoparticles	No	Supplier
Coating E	Flouroalkylsilane (FAS17)	Yes	Automotive
Coating F	Ethonal with special additives	No	Surface refinement
Coating G	Ethonal with special additives	No	Protective glass coatings
Coating H	Silane Formulation	No	Multi-surface coatings
Coating I	Silane head with fluoro tail group	No	Appliances
Coating J	Covalently bonded nanoparticles	Yes	Solar protection

2.2 Preliminary Water Contact Angle Characterization

2.2.1 Materials and Methods

The first order of business after obtaining the ten commercial hydrophobic coatings was to immediately begin down-selecting to a group of candidate coatings. Using a Kruss DSA10 Drop Shape Analyzer Contact Angle Goniometer (CAG), the static WCA can be measured. The WCA is a good measure of the hydrophobicity, or water repellency, of a coating. With 90° being

the accepted cut-off WCA for hydrophobicity, it was determined that a minimum contact angle of around 110° would result in a selection of coatings that were well within the hydrophobic region. It has also been qualitatively observed by the coatings team at Loughborough University that coatings with a WCA near or above 110° begin exhibiting anti-soiling properties. Excluding Coating B, which was coated by vacuum deposition in-facility, the remaining coating formulations were all coated per the instructions from the manufacturer for wipe-on application. For each coating formulation, two (5x5) cm samples were prepared using Starphire's ultra-low iron content solar cover glass. After a 48-hour cure time at room temperature, the WCA for each sample was measured using the CAG with a 2 μ l droplet volume at three locations on the coated surface (left-side, center, and right-side). An average WCA was then calculated for each sample. Identical WCA measurement methods described above were used throughout the remainder of the research.

2.2.2 Results and Discussion

The results of this screening WCA procedure are displayed in Figure 7. The red dashed line highlights the minimum WCA cut-off criteria for candidate coatings, while the orange dashed line represents a tolerance of minus 5° from 110° . From this, six hydrophobic coating formulations measured within the tolerance or exceeded the critical contact angle of 110° (coatings A, B, E, F, G, and I). After further discussion with the manufacturer of Coating B, it was decided they would no longer be able to participate in the study due to the high cost of their coating. The varying levels of hydrophobicity seen in the obtained coatings relate back to the chemistry and materials used in the coating formulation. A hydrophobic surface with a low surface energy will exhibit a higher WCA due to the relationship defined by the Young's equation (Equation 1). Therefore, assuming a smooth surface, the five available coatings that

satisfied the WCA criteria theoretically have a lower surface energy compared to the remaining coating formulations. This WCA test is the first stage in the screening process, and the selected coatings were further characterized using transmission and roll-off angle (RoA).

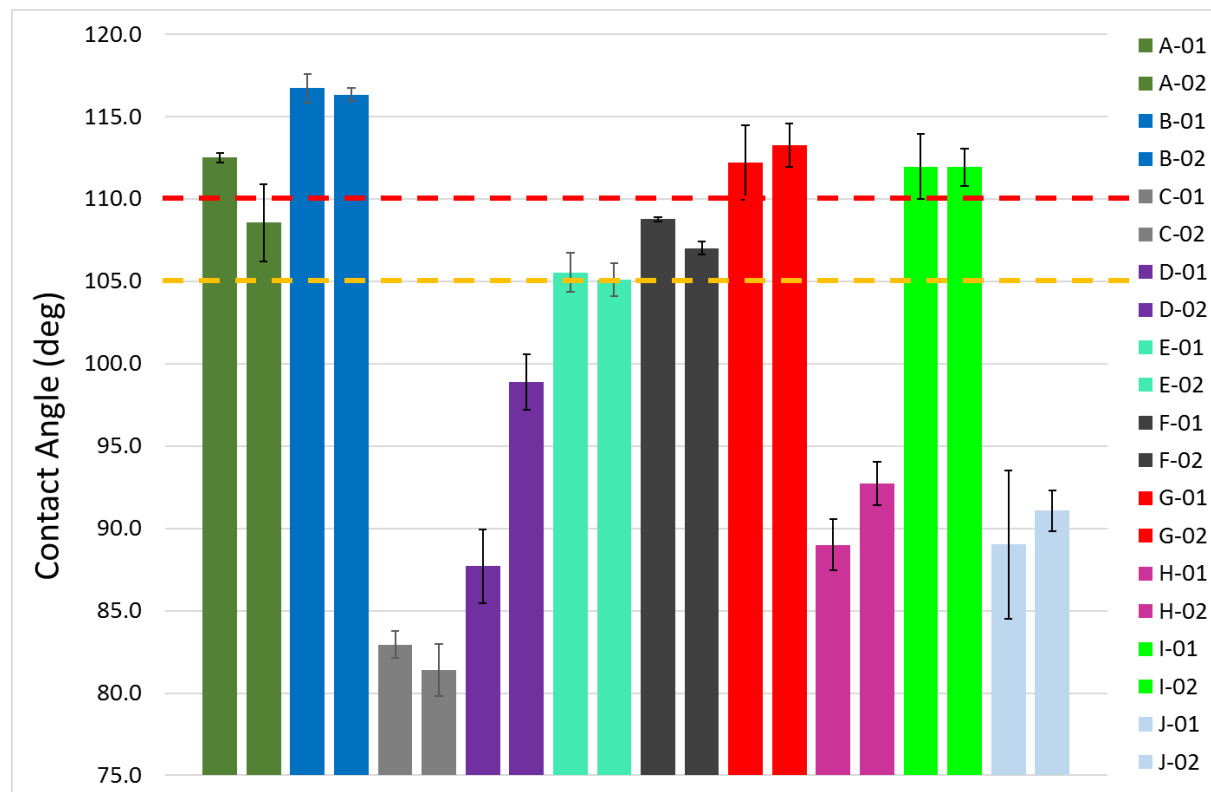


Figure 7. Summary of preliminary WCA for commercial hydrophobic coatings (error bar represents one standard deviation). Red dashed line represents minimum WCA criteria, while orange line defines a minus 5° tolerance for acceptance.

2.3 Coating Application Optimization

2.3.1 Materials and Methods

In order to increase coating repeatability and performance before the execution of the secondary screening procedure, RoA and transmission testing, the application processes for the coatings were evaluated. Manual wipe-on application methods, by nature, are not always a repeatable method to coat glass substrates. Alternative application methods include spin, spray, and dip coating. Of these, dip coating is the most convenient, highly uniform, and time-tested

application method for the deposition of thin film coatings [23]. However, due to the high cost of desk-top dip coaters, one was designed and constructed in the lab. Most commercial dip-coaters utilize a rack-and-pinion, belt-drive, or pulley system to achieve linear platform motion. To simplify the mechanics and save on cost, threaded rod-and-screw technology was borrowed from the CNC industry. A 3D cad model of the linear mechanism used in the dip coater can be seen in Figure 8a. A Nema 17 stepper motor is used to rotate the threaded rod. An Arduino Uno microprocessor controls the rpm of the stepper motor with high accuracy to allow for precise dipping velocity, measured in mm/min. The user has full control over dipping velocities and sample immersion times, and the entire dipping process is fully automated upon start, just as is found with most commercially available dip coaters. The completed dip coating tool can be seen in Figure 8b.

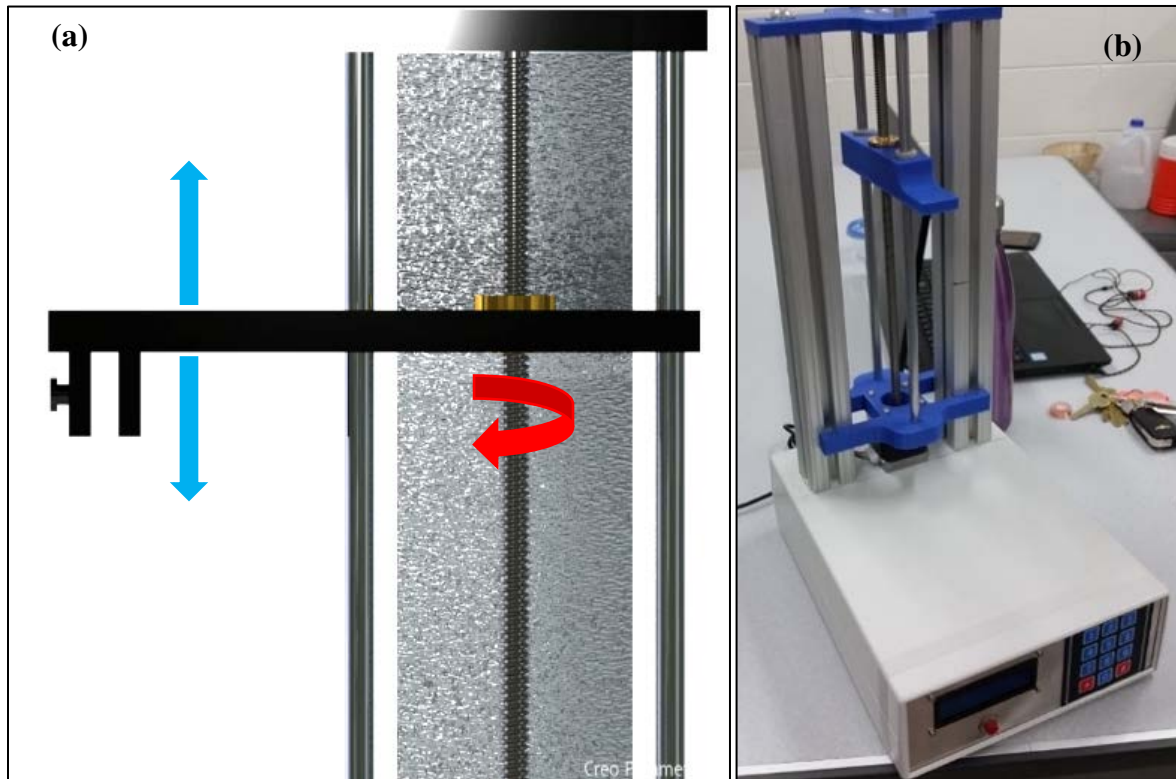


Figure 8. Design and fabrication of the dip coating tool for Coating I application optimization; (a) the 3D cad model showing threaded rod-and-screw mechanism used to achieve linear platform motion and (b) the completed dip coater.

Not all obtained coatings lent themselves well to a dip coating application process, mainly due to the difficulties in achieving homogenous surface wetting. This is often seen in coating formulations containing less viscous, higher surface tension solvents [23]. For these coatings, the manufacturer recommended application process was followed. The performance of Coating I however, was found to be highly optimized using the dip coating method. In order to determine optimal values for the dip coating parameters (dip speed and coating dilution levels), an experiment was designed. A total of 9 cleaned glass substrates were dipped into a diluted Coating I solution of solvent levels 40, 60, and 80 vol% each at a velocity of 100, 200, and 300 mm/min. This resulted in one sample per dilution-level/dip-velocity combination. After curing, each sample was then measured for static WCA at five locations (left-side, right-side, center, top, and bottom).

2.3.2 Results and Discussion

The 9 Coating I samples dip coated at various dilution levels and dip velocities resulted in a set of dipping parameters for optimized WCA. As seen in Figure 9, a general trend of decreasing WCA was observed for the three dipping velocities (100, 200, and 300 mm/min) as the dilution levels of the solvent increased. A general decrease in hydrophobicity uniformity, evident from the individual box-plot distributions, was also observed as dipping velocity increased. For example, the standard deviation for a dilution level of 40 vol% at 100, 200, and 300 mm/min was 0.19, 0.28, and 0.38°, respectively. The highest WCA at a value of $110.4 \pm 0.2^\circ$ was achieved at a dilution level of 40 vol% and a dip speed of 100 mm/min.

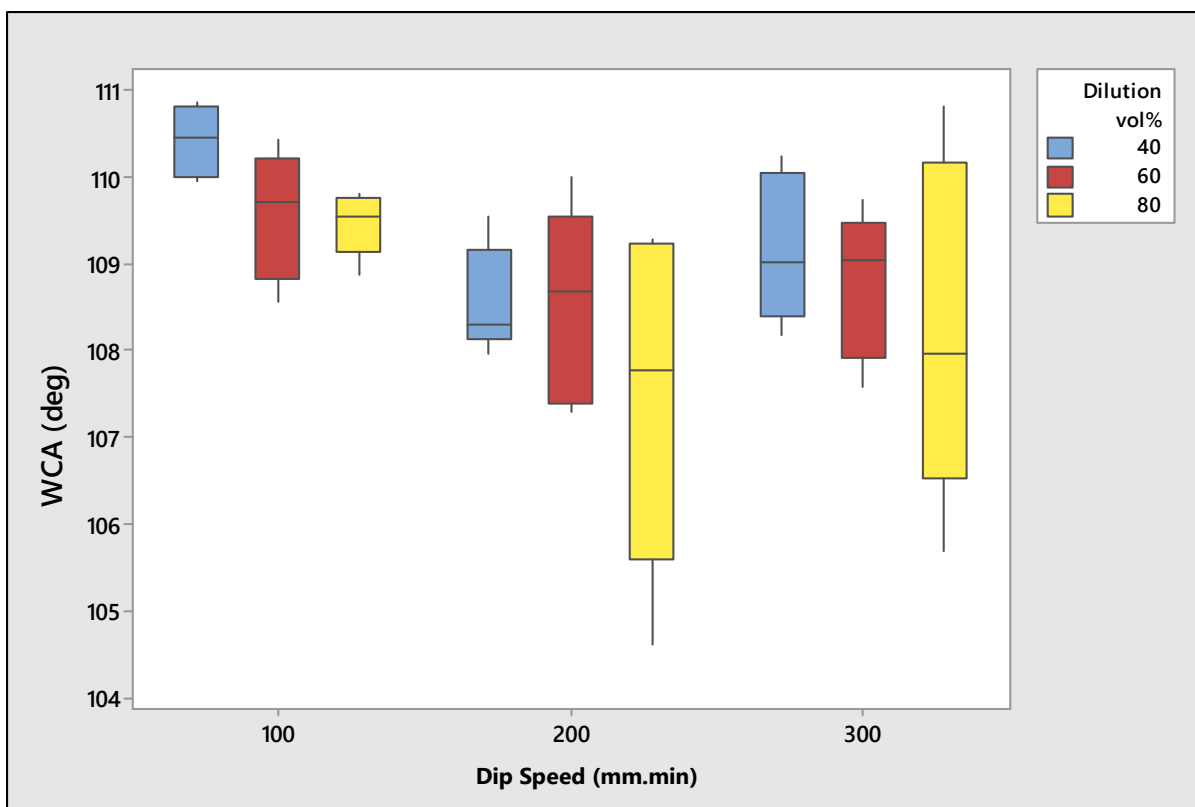


Figure 9. A standard box-plot of Coating I WCA as a function of dilution levels and dipping velocity. The medium value is marked by the horizontal lines for each box, with the whiskers defining upper and lower quartiles.

The dipping parameters (dip speed, immersion time, and solvent dilution levels) vary the thickness and adhesion of the coating to the glass surface, thereby altering the performance of the coating. By varying the amount of solvent used in the Coating I formulation, the viscosity of the coating and the time of complete solvent evaporation change. By changing the dipping velocity, varying coating thicknesses can be achieved (higher velocity leads to thicker coating [23]). Without knowing the exact chemical make-up of a given coating, it is hard to comprehensively explain the benefits of using one set of dipping parameters over another. For the Coating I formulation, a dip speed of 100 mm/min and a solvent dilution level of 40 vol% lead to the highest WCA. Therefore, these dip coating parameters were used throughout the subsequent fabrication of Coating I samples for this study. The higher levels of solvent, 60 and

80 vol%, most likely resulted in a less concentrated layer of the fluorinated silanes on the surface, thereby leaving unoccupied OH groups. Following further investigation of coating optimization, Coating I was also supplied in the form of aerosol containers by the manufacturer for this study. Therefore, this coating was both dip and spray applied, and will be referred to as Coating I(d) and Coating I(s) respectively.

2.4 Roll-Off Angle and Transmission Characterization

The preliminary WCA angle testing procedure discussed in section 2.2 is important in evaluating the hydrophobicity of the commercially obtained coating formulations. The WCA does not however tell the entire story when evaluating the water repellency of a hydrophobic coating. Although frequently misunderstood in the anti-soiling research community, hydrophobicity and water-repellency do not always mean the same thing. For example, a hydrophobic coating can possess a high WCA while also demonstrating a high RoA. This is a typical scenario seen when a droplet is in the Wenzel wetting state previously described in Figure 5. For PV anti-soiling applications, RoA is highly important as it provides insight to the ability of a coating to shed water droplets even at shallow panel tilt angles (low RoA).

In order to be viable for use as an anti-soiling coating for PV modules, the coating must demonstrate good transparency. Any losses in transmission due to the coating would reduce PV performance and negate potential benefits from the anti-soiling effects.

2.4.1 Materials and Methods

Twelve (5x5) cm samples of each coating formulation were fabricated using the low-iron Starphire cover glass substrate; this glass is an industry standard solar cover glass. With the removal of Coating B due to a high price point, five coating formulations (A, E, F, I, and G) were prepared. Coating I was fabricated using both a dip and spray application, the remaining

coatings were wipe applied in accordance to manufacturer recommended application methodologies. Therefore, six coatings overall were measured for RoA and transmission. The cut-off criteria for RoA was set at 25° ; this shallow angle allows for a coated solar module to shed water even when mounted at shallow angles (modules near the equator). Measuring the RoA however is a difficult undertaking in terms of repeatability. Quantifying the tilt angle at which a water droplet begins to move can also be a subjective and difficult task. In order to minimize human error and measurement subjectivity, and in order to increase repeatability, an automated tilting platform was constructed. The platform is tilted about a pivot point, and an accelerometer attached to the underside of the platform measures the angle. An infra-red break-beam sensor automatically records the tilt angle at which the water droplet disrupts the beam signal. The device is shown below in Figure 10. Each sample was measured at three locations (left, center, and right) with a $30\text{ }\mu\text{l}$ droplet volume and an average RoA was calculated. The same RoA measurement technique was used throughout the remainder of this research.

The criteria for transparency was set at 99% when compared to uncoated glass. Two representative samples from each coating were selected for optical measurements (% transmission) using a Perkin Lambda 2 spectrophotometer. Each sample was measured across a 300-1100 nm wavelength range. A weighted average was then taken using the air mass (AM) 1.5 standard spectrum for each of the two samples, which were then averaged resulting in one representative transmission value for each coating. These values were then normalized using the AM 1.5 weighted average of an uncoated glass substrate.

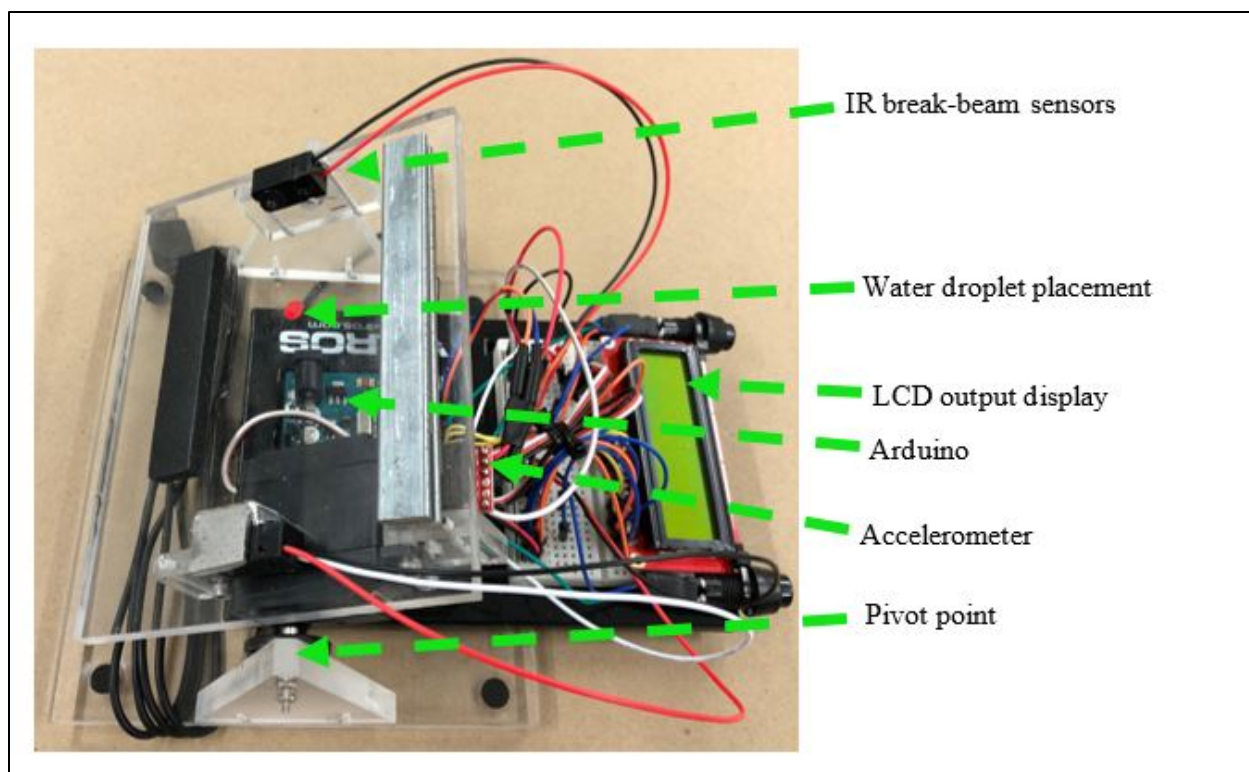


Figure 10. Automated tilting platform fabricated for accurate and repeatable RoA measurements

2.4.2 Results and Discussion

Coating A and Coating G fell far above the desired RoA criteria of 25° , with ranges of $47\text{-}56^\circ$ and $43\text{-}47^\circ$, respectively (Figure 11). Coating E and Coating F fell slightly above the RoA criteria with at ranges of $26\text{-}31^\circ$ and $26\text{-}31^\circ$. The large performance drops in RoA for Coating G and A were repeatedly measured during multiple trials. At a RoA this steep, the water droplet would not be easily shed from the surface of a module, thereby possibly preventing the self-cleaning benefit of a hydrophobic coating. Many attempts were made to reduce the RoA, including alterations in application methods, applying multiple layers, and curing the coating in the presence of high and low humidity. With no improvement seen, Coating G and A were eliminated from the study due to inconsistent and poor RoA performance. The WCA for both coatings, however, satisfied the WCA criteria, demonstrating why it is important to use both

measurements in quantifying the water-repellency of a coating. Therefore, four coatings (E, F, I(d), and I(s)) were deemed candidates for the remainder of this work.

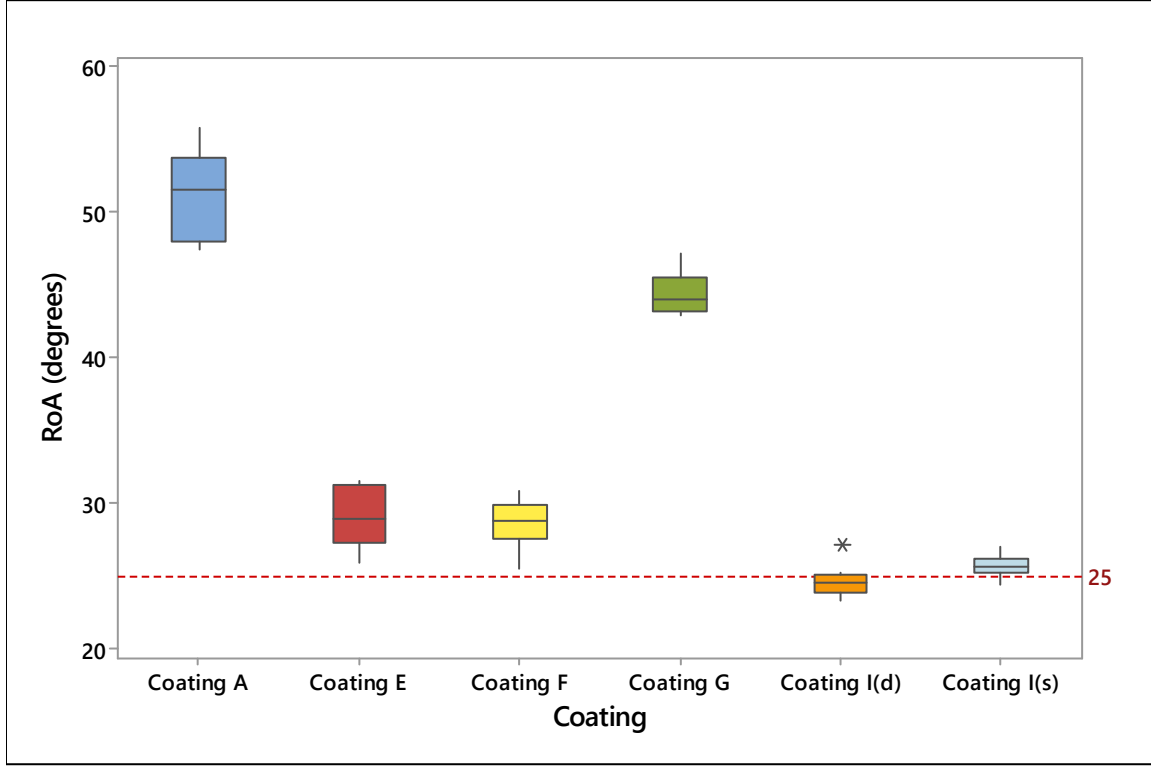


Figure 11. Box-plots of the RoA for the six candidate coatings. The red dashed line represents the targeted RoA criteria of 25°.

The optical measurements for all candidate coatings resulted in at least 99% average transmission (when normalized by an uncoated glass substrate) across a 300-1100 nm wavelength range, thereby satisfying the desired criteria (Figure 12). Coating I, both spray and dip applied, as well as Coating F demonstrated slight anti-reflective (AR) properties. These AR properties are likely due to the coating possessing a refractive index (RI) that lay somewhere in between glass ($n=1.5$) and air ($n=1$). This is mathematically given by the Fresnel equation, which gives the reflectance, r , with normally incidence light. This equation is defined as

$$r = \left[\frac{n_s n_{air} - n^2}{n_s n_{air} + n^2} \right]^2 \quad (4)$$

where n_s is the RI of the glass substrate, n_{air} is the RI of air, and n is the RI of the thin-film coating. From Equation (4), one can see as r approaches zero, n approaches $\sqrt{n_s n_{air}}$. Therefore, the RI of the coating must sit somewhere in between the RI of glass and air. Other criteria for anti-reflection to occur state that the reflected waves are 180° out of phase from one another, and the thickness of the film is an odd multiple of $\lambda/4$, where λ is the wavelength in nm [24]. From the minor observed anti-reflection behavior of Coating I and F, it can be assumed these coatings partially satisfy the criteria stated above. More optical investigation would be needed to definitively state the cause of the AR properties observed, as well as to maximize the potential AR benefits of these coatings.

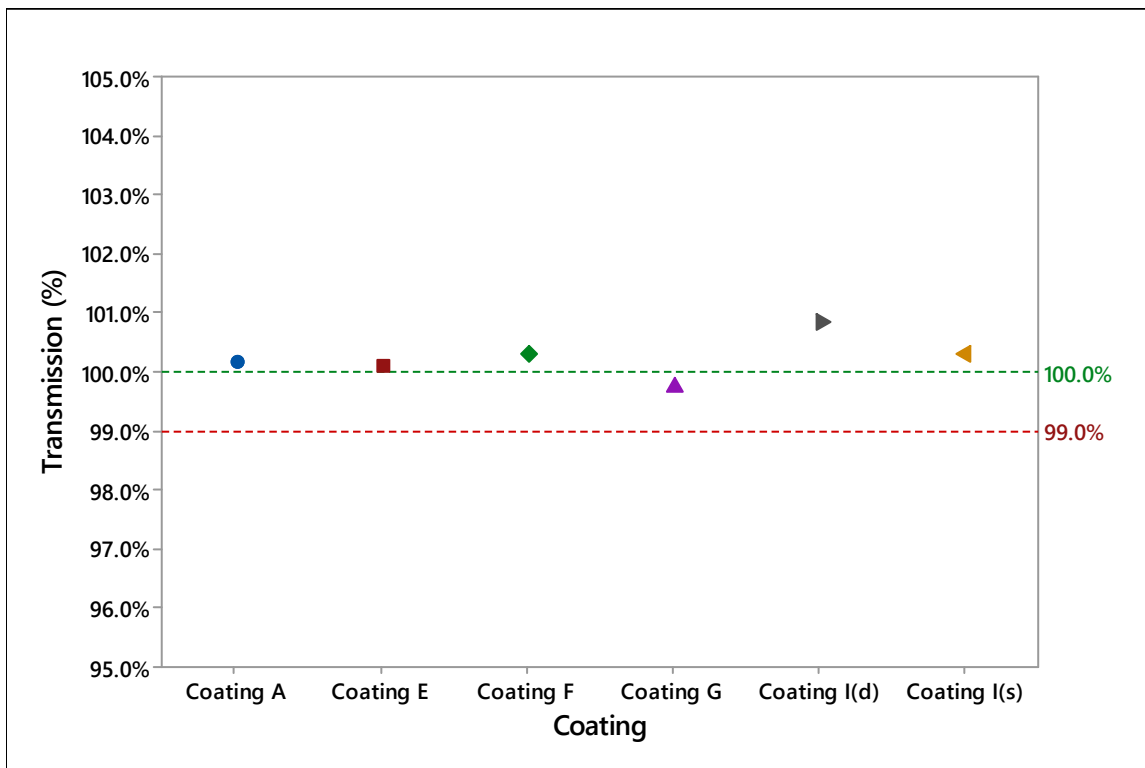


Figure 12. AM 1.5 weighted average transmission of each coating normalized by uncoated glass substrate. The red dashed line represents the desired transparency criteria. The green dashed line highlights 100% transparency.

CHAPTER 3. ACCELERATED DURABILITY TESTING PROCEDURE: DEVELOPING AN UNDERSTANDING OF THE DEGRADATION MECHANISMS

The overarching objective of this research is in determining the suitability of utilizing commercially available hydrophobic coatings for soiling mitigation in the PV industry. An important part in this investigation is in providing data and insight on coating durability. To be an effective anti-soiling coating for PV, the coating must be able to withstand the outdoor environmental conditions seen by a module throughout its lifetime. While the coating may not need to last the full duration of a module's life (25+ years), reapplication every 5+ years could be acceptable. Developing an understanding of the degradation mechanisms is key in determining the durability potential of the hydrophobic coatings, in addition to providing insight for in-field performance. Additionally, understanding the degradation mechanisms can inform subsequent research and enable the development of improved formulations. In collaboration of Professor J. M. Walls and his research team at Loughborough University, candidate hydrophobic coatings from this work were exposed to an accelerated durability testing methodology developed specifically for hydrophobic coatings on solar cover glass [22]. Using characterization techniques such as scanning electron microscopy (SEM) imaging, x-ray photoelectron spectroscopy (XPS), WCA, RoA, and transmission measurements, an understanding of coating degradation mechanisms was developed. All subsequent tests and data collection for this chapter were performed in collaboration with Professor Walls and his research team.

3.1 Testing Methodology

In addition to the candidate coatings identified from the screening procedures discussed in section 2.2.2 and 2.4.2, an additional coating was included for the accelerated durability testing procedure. Coating J, which was eliminated during the preliminary WCA characterization

early on, was re-introduced for the durability testing phase. The justification for this decision was two-fold: (1) Coating J is the only commercially available coating in this research developed specifically for solar module anti-soiling use, therefore our team was curious to understand its durability. (2) After further discussion/instruction from the applications team for Coating J, a WCA near 108° was achieved. For each of the five coating formulations (E, F, J, I(s), and I(d)), ten (5x5) cm and ten (1x1) cm Starphire cover glass substrates were cut to size, cleaned in an ultrasonic bath process, and coated. The (1x1) cm sample size was selected to enable SEM imaging and XPS analysis. All coated samples were then measured for WCA and RoA in order to ensure sufficient RoA and WCA of $\sim 25^\circ$ and $\sim 110^\circ$, respectively. This data can be found in Table A - 1 in the appendix. The prepared samples were then mailed to Loughborough University for accelerated testing and characterization.

The candidate coatings were exposed to external stressors in order to induce degradation. The primary testing procedures used in this research include damp heat (DH) and UV exposure generally following tests outlined in IEC 61215 PV qualification standards. The DH test expose the samples to a constant 85°C and 85% relative humidity for a duration of 1000 hours. Samples of each coating formulation were pulled out of the DH chamber periodically to observe any induced degradation using SEM imaging, WCA, RoA, and transmission/reflection measurements. The WCA and RoA was measured at five locations across the surface in a quincunx pattern, with droplet volumes of 2 μl and 50 μl respectively, and an average value was reported. The transmission and reflection were measured across a 350 to 800 nm wavelength range using an integrated sphere spectrophotometer. To simulate UV degradation caused by prolonged exposure to sunlight, a QUV chamber with UVA-30 lamps were used in accordance with the IEC 61215:2016 standard. The UV exposure spanned 2000 hours, which roughly

translates to about two and a half years of outdoor sun exposure. An extended timeframe of accelerated exposure is ideal, however, 2000 hours is a preliminary testing duration. Elevated temperatures do occur during UV exposure due to residual heat from the bulb, but at a much lower value than that of DH (85°C). Similarly, samples of each coating were pulled at intermittent exposure times to observe any UV induced degradation using the same characterization techniques as in DH testing.

3.2 Results and Discussion

3.2.1 Damp Heat

The WCA and RoA results for DH exposure are reported through a duration of 1000 hours and can be seen in Figure 13. Referencing Figure 13a, all coatings apart from Coating J, demonstrated stable WCA (represented by the red dashed line at 110°) up through 300 hours of DH exposure. The WCA for Coating J fell rapidly after 50 hours of DH and continued dropping until it leveled out around a WCA of 40° after 300 hours exposure. Coating F experienced a rapid decline in WCA after 300 hours of exposure. The WCA for coatings I(s), I(d), and E remained stable throughout the 1000 hours of DH. Figure 13b shows the RoA data up through 1000 hours of DH exposure; the red dashed line marks the desired criteria of 25°. A general increasing trend was observed in RoA for all five hydrophobic coatings throughout the testing duration. With the exception of coating E, the remaining coatings measured an “as received” RoA at or below 25°. Almost immediately, the RoA for coatings E, F, and J increased above the desired criteria. Coating I, both spray (s) and dip (d) applied, demonstrated the longest duration of stable RoA through 400 hours of DH exposure, after which point began rapidly increasing.

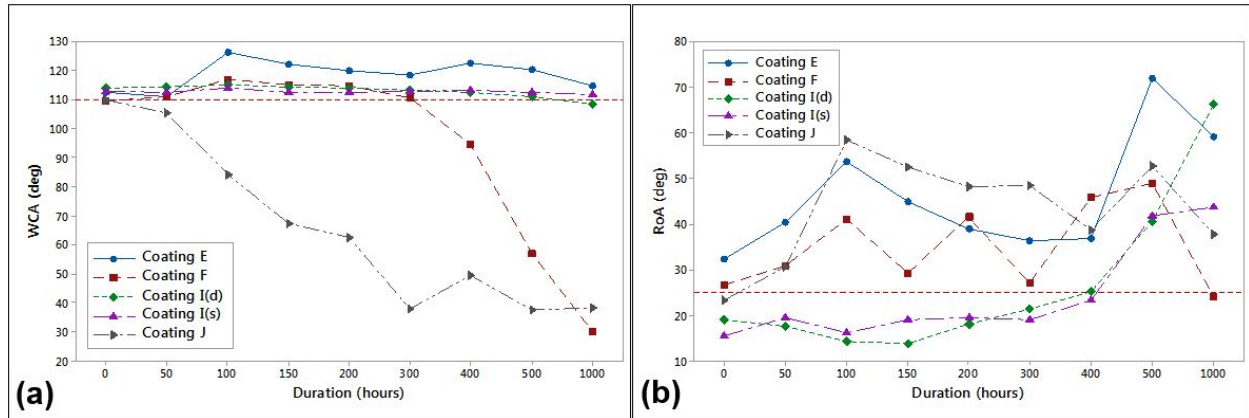


Figure 13. (a) WCA and (b) RoA data as a function of exposure duration to DH for the five candidate coatings. The red dashed lines represent the WCA and RoA criteria of 110° and 25°, respectively.

The transmission and reflection data for the DH testing can be found in Appendix A.2. All coatings except Coating I(d) demonstrated changes in reflection values as a function of DH exposure. For coatings E, I(s), and J, these changes in reflection can be due to the morphological changes occurring on the coating surface, thereby altering the optical properties. The morphology will be further discussed in subsequent paragraphs. The reflection changes measured for Coating F were attributed to water droplets wetting the back-side (bare glass) surface of the samples during DH exposure. Upon drying, distinct white stains were visible, thereby affecting the reflection values. Coating I(s) however did see a large decrease in percent transmission. This corresponded to a blistering process discussed in the subsequent section of SEM imaging, giving the coating a hazy appearance.

In order to better understand the degradation mechanisms behind the evolving WCA and RoA, and the change in optical properties observed throughout the DH testing procedure, SEM imaging was performed. An “as received” image was taken for all five coatings, followed by intermittent imaging at DH test durations of 100, 500, and 1000 hours. For ease of representation, Figure 14 is composed of one image from each DH duration (as received, 100,

500, and 500) for each coating formulation. The image magnifications were chosen to best represent the morphological features occurring at each stage. With the exception of coating E, all of the “as received” samples (pre-stress testing) show minimal morphological features (i.e. the surface are relatively smooth in nature). The features seen in Coating E may be remnants of the cloth applicator provided by the manufacturer and used in applying the coating. At 100 hours of DH exposure, all coatings begin to show some changes in morphology. The increased RoA seen in coatings E, F, and J after 100 hours can be explained by the increased surface roughness visible in the SEM images. More knowledge of the coating chemistries and additional experimentation would be needed to fully understand the causes of the observed morphological changes.

In the Wenzel wetting state (refer to Figure 5b), the water droplet fully wets the surface features, thereby an increase in surface roughness increases the overall liquid-solid interfacial contact area. This increases the adhesion forces between the droplet and the solid surface. The development of new surface roughness features due to DH exposure can also induce contact line pinning, which is undesirable in the pursuit to achieve low RoA. Both of these mechanisms, increased liquid-solid contact area and line pinning, will increase the contact angle hysteresis (CAH) of the surface. The RoA (α) is related to CAH through the mathematical relationship

$$\sin \alpha = \frac{\gamma_{lv}w(\cos \theta_r - \cos \theta_a)}{\rho V g} \quad (5)$$

where γ_{lv} is the liquid surface tension, w is the work done by the droplet moving some distance dl , θ_r and θ_a are the receding and advancing contact angles respectively, ρ is the density of water, V is the droplet volume, and g is the gravitational constant. Remember that CAH is equal to the difference between θ_a and θ_r . Therefore, as CAH increases, the term $(\cos \theta_r - \cos \theta_a)$ increases. At a constant droplet volume, Equation 5 shows that this increase will lead to an increase in the

RoA, α . If the droplet were in the Cassie-Baxter state (Figure 5c), surface roughness would lead to a decrease in CAH, thereby decreasing the RoA. Therefore, because an increasing trend is observed in the RoA for all five coatings, it is valid to assume the droplets are not in the Cassie-Baxter wetting state and are instead in the Wenzel state, or some hybrid of the two.

Coatings I(s) and I(d) did not experience a dramatic increase in RoA until after 500 hours of DH exposure. Coating I(d) in fact experienced a period of gradual decline in RoA up through 150 hours DH. Looking at Figure 14, a “blister” formation process is visible for both I(s) and I(d) at 500 hours, correlating to the observed increase in RoA. At 100 hours, Coating I(d) does show the development of nanometer-scale texture features, possibly moving the droplet into a quasi Cassie-Baxter state and slightly reducing the RoA. As more blisters are formed however, the surface roughness increases, leading to the observed steady incline of RoA for both coatings I(s) and I(d) after the initial blistering event. At 1000 hours of DH, all five coatings appear to have experienced a similar blistering process. For coatings J and F, this process may have been so severe nearly the entire functional part of the coating was effectively removed from the surface, explaining the complete loss of hydrophobicity (WCA). It is theorized that the blister formation, especially for coatings I(s) and I(d) where the thickness is on the order of 1-2 microns, is due to entrapped solvents remaining from the coating application process. As the coatings spend a prolonged time in the DH chamber, these “pockets” of volatiles build up enough pressure to rupture through the surface, creating the blisters observed and increasing the surface roughness.

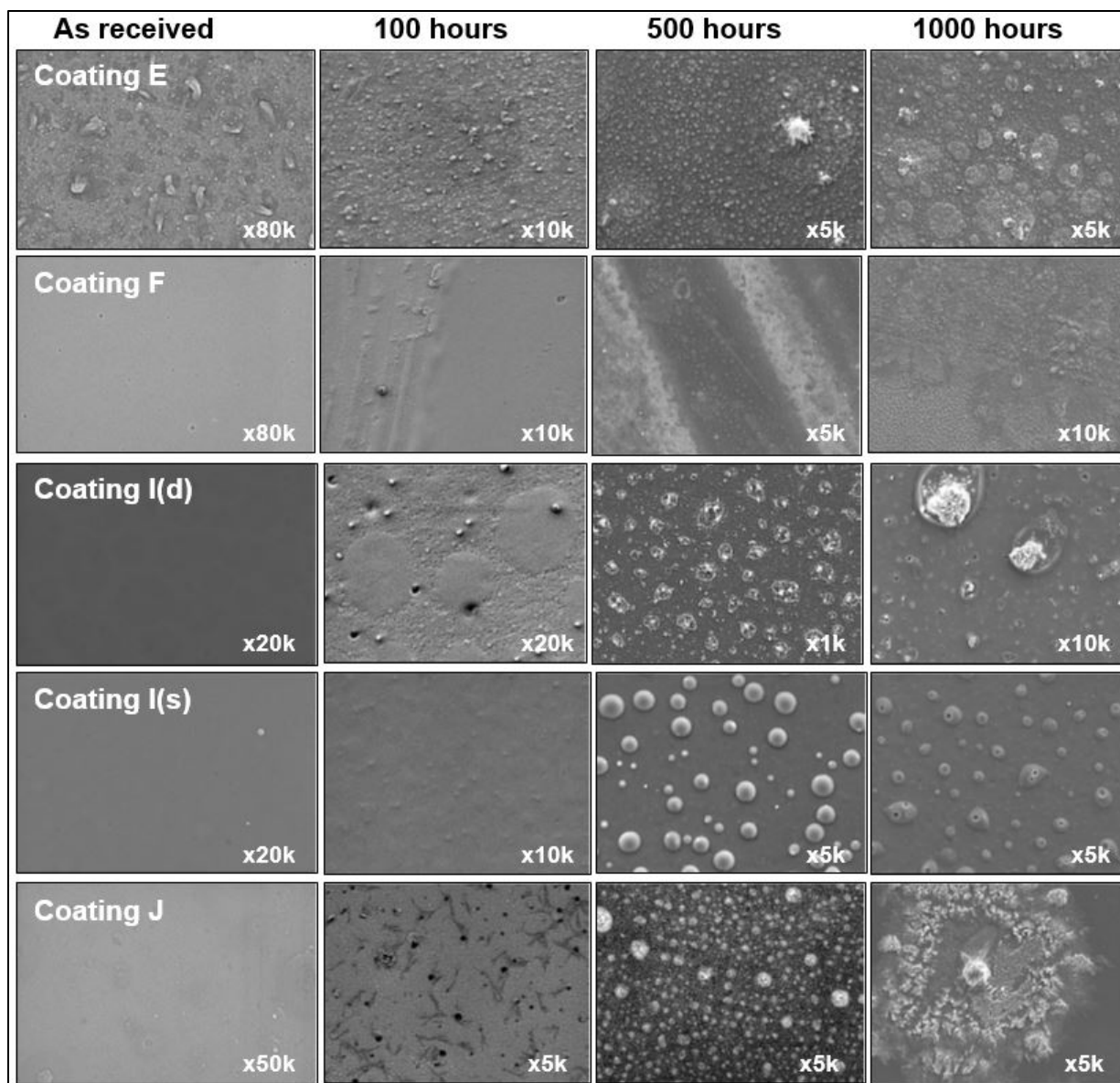


Figure 14. SEM imaging of the five candidate coatings at various DH exposure durations (listed on the top). The image magnifications were chosen to best represent the morphological changes occurring at each stage. (SEM imaging: Fabiana Lisco)

The larger thickness of Coating I(s,d) enabled cross-sectional SEM to observe any variations in coating thickness; the other coatings were too thin. Figure 15 shows the cross-sectional images for both Coating I(s) and I(d) up through 500 hours of DH. The as received coating thicknesses for I(s) and I(d) were 3.7 and 1.2 μm , respectively. After 500 hours of DH,

the thickness was reduced to 1.9 and 0.4 μm for coatings I(s) and I(d), respectively. The formation of blisters is clearly visible from the cross-sectional images for both coatings, showing the increase in surface roughness theorized previously. It is hypothesized the reduction in thickness comes from exfoliation of the blisters, in addition to the loss of material through coating/volatile evaporation. Further testing involving alterations in coating solvents and cure schedules is needed to better understand the origin of the blistering process.

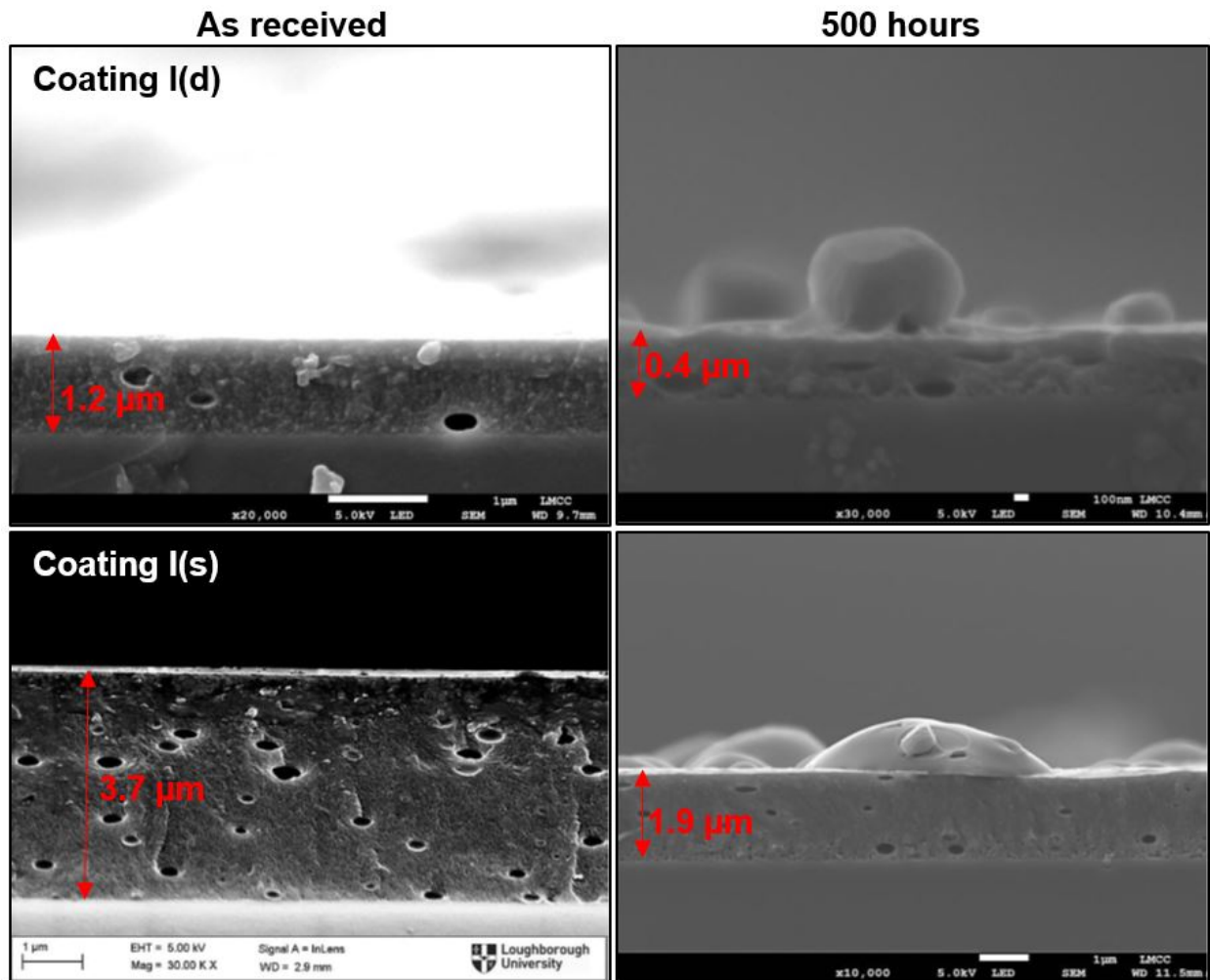


Figure 15. DH exposure cross-sectional SEM imaging of Coating I(d) and I(s), showing thickness reduction due to blister forming process. Magnifications on top left, top right, bottom left, and bottom right are 20k, 30k, 30k, and 10k respectively. (SEM imaging: Fabiana Lisco)

3.2.2 Accelerated UV exposure

The WCA and RoA was measured up through 2000 hours of UV exposure and is reported in Figure 16. The red dashed lines once again represent the desired WCA and RoA criteria of 110° and 25° respectively. Referencing Figure 16a, all coatings demonstrated a fairly stable WCA up through 500 hours UV exposure. Coating J, as seen in the DH exposure testing, was the first to see significant decline in WCA. Coatings I(s), I(d), and F were stable up to 1000 hours of UV, at which point they began dropping off. Coating E saw an increase in WCA after the initialization of the testing and remained relatively stable in WCA throughout the 2000 hours of UV exposure. Similar to the trend observed in DH, a general increase in RoA was observed across all five coatings (Figure 16b). All coatings, with the exception of Coating E, started near or below the criteria of 25° . Coatings I(s) and I(d) showed relative stability in RoA up through 450 hours of UV exposure. Coating E saw the most dramatic increase in RoA after only 50 hours, however remained relatively stable thereafter up to 1000 hours. Coatings F and J surpassed the 25° criteria after roughly 100 hours of UV exposure.

The transmission and reflection plots for all five coatings can be found in Appendix A.3. No significant changes in either transmission or reflection were observed though the 2000 hours of UV exposure. This is likely due to the lower humidity inside the UV chamber when compared to the DH. Therefore, there is less “soiling” occurring from water droplets forming and drying on the coating surface, thereby altering the optical properties. In addition, the lower temperatures seen in the UV chamber lead to differing mechanisms of morphological changes in the coatings, therefore resulting in differing optical effects.

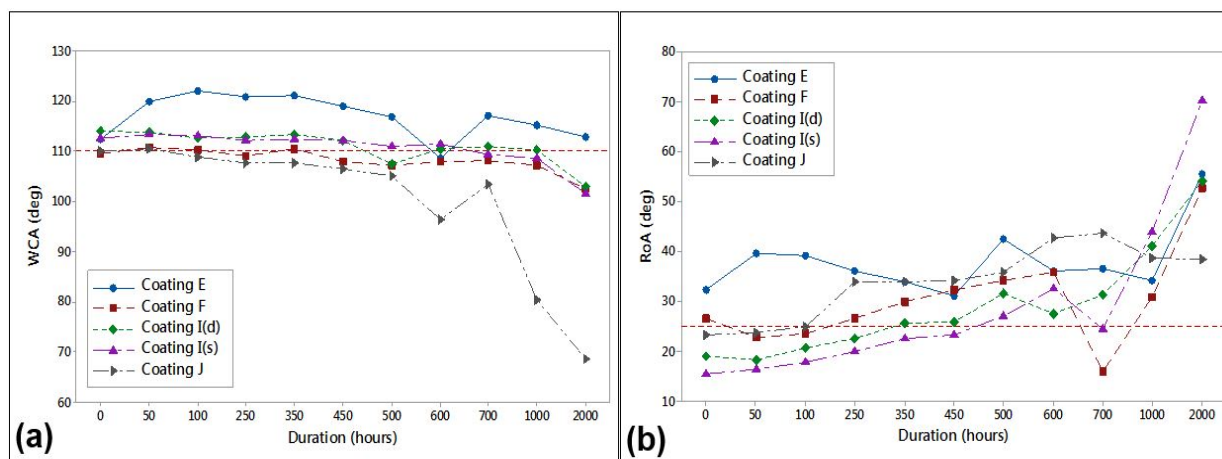


Figure 16. (a) WCA and (b) RoA data as a function of exposure duration to UV for the five candidate coatings. The red dashed lines represent the WCA and RoA criteria of 110° and 25°, respectively.

SEM imaging was taken on all five coatings throughout the duration of the UV exposure testing. Images were taken on “as received” samples, and again at 600, 1000, and 2000 hours. Figure 17 shows the SEM images of the five coatings as they progress from left to right through 2000 hours of UV exposure. Once again, the magnifications were chosen to best capture the morphological changes occurring on the surface during each stage of UV for the coatings. The “as received” images for all coatings, with the exception of Coating E, show minimal textural heterogeneity. After 600 hours of UV, visible textural changes can be seen on coatings I(s), I(d), J, and F. A “sweating” phenomenon appears to be occurring on Coating I(s,d), while a process similar to the blistering observed in DH SEM images is visible on Coating F and J. Either way, it appears entrapped solvents and volatiles are escaping from the bulk of the coatings. At 1000 hours of UV exposure, the solvents appeared to have fully evaporated from the surface of the four coatings discussed previously. Visible “pitting” can be seen on Coating I(s), and an increased surface roughness is apparent for coatings J and F. After 2000 hours of UV, the pitting is more pronounced on Coating I(s), thereby increasing the surface roughness. While it may be

difficult to see in Figure 17, small pitting is visible on Coating I(d). Due to the significant decrease in WCA for coatings J and F, it is hypothesized the functional part of the coatings have been almost completely removed from blister exfoliation process observed under SEM. Cross-sectional SEM imaging showed these two coatings were very thin to begin with, so any loss of material (reduction of thickness), may expose the bare glass underneath. Coating E, however, did not exhibit any dramatic visible changes in morphology throughout the UV exposure. The relatively stable WCA and RoA results for Coating E summarized in Figure 16 appear to agree with this observation. There may have been a “sweating” or blistering event for Coating E early on, around 100 hours UV, that may have correlated with the observed increase in RoA.

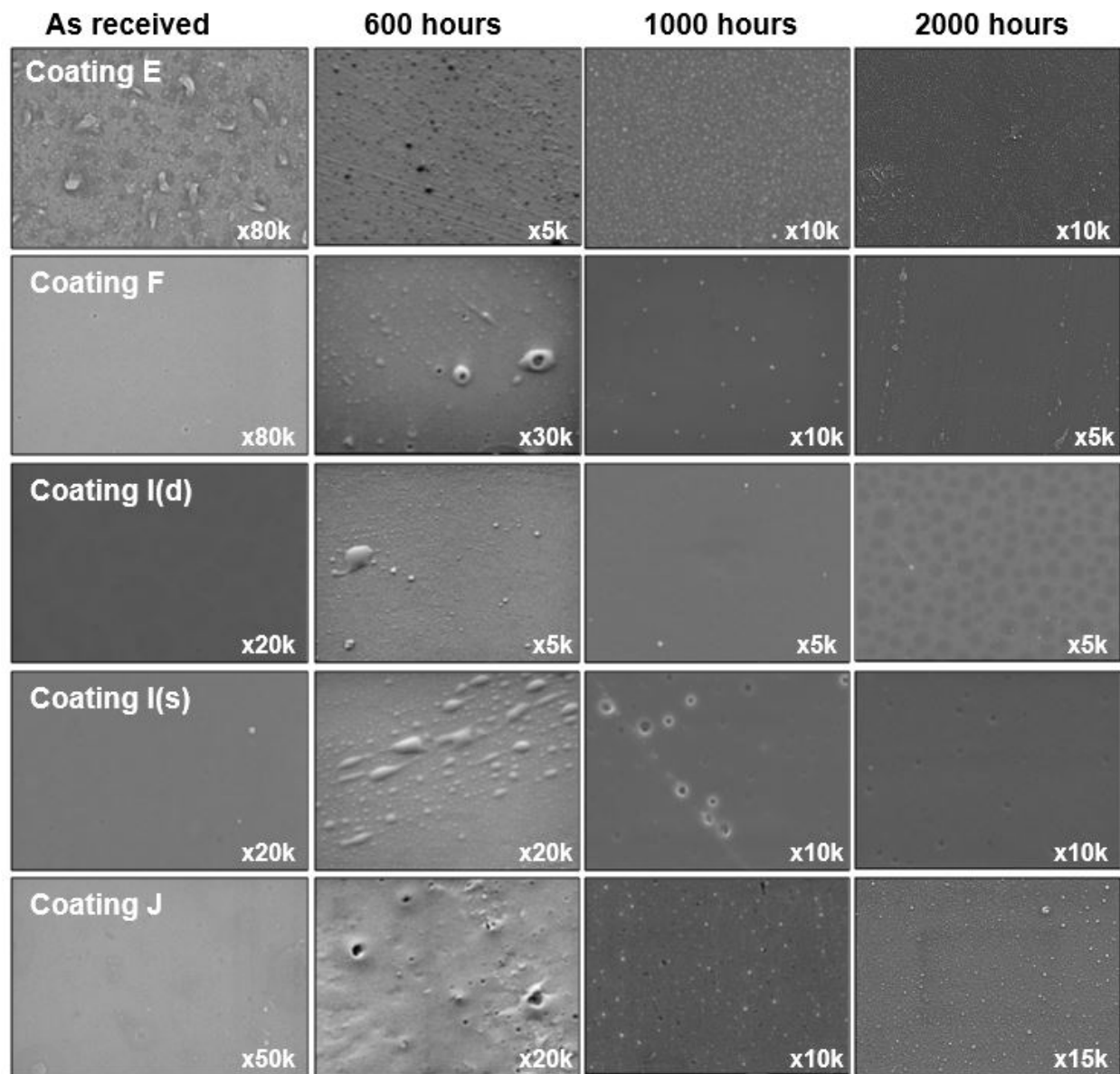


Figure 17. SEM imaging of the five candidate coatings at various UV exposure durations (listed on the top). The image magnifications were chosen to best represent the morphological changes occurring at each stage. (SEM imaging: Fabiana Lisco)

Cross-sectional SEM was once again performed on Coating I(s) and I(d) due to sufficient thickness. SEM images were taken at 0, 100, 600, 1000, and 2000 hours. For both coatings, the thickness appears to reduce under UV stress, reaching a minimum after 600 hours of UV. From 600 hours to 2000 hours UV, the thickness remained relatively constant. Figure 18 shows SEM

imaging for the as received through 600 hours of UV. Starting at thicknesses of 1.2 μm , Coating I(d) reduced to a thickness of ~ 700 nm after 600 hours UV. With an as received thickness of 3.7 μm , Coating I(s) reduced to a thickness of ~ 1.8 μm after 600 hours. The cross-sectional findings showing coating thickness reduction correlate strongly to the sweating process observed in the top-down SEM imaging. After this sweating process is no longer observed, the coating thickness appears to level out. Therefore, the thickness reduction is attributed to the loss of bulk material due to solvent/volatile evaporation and blister exfoliation. Similar to the DH case, additional coating formulation and cure schedule experimentation to reduce the entrapped solvent is needed to further support this hypothesis.

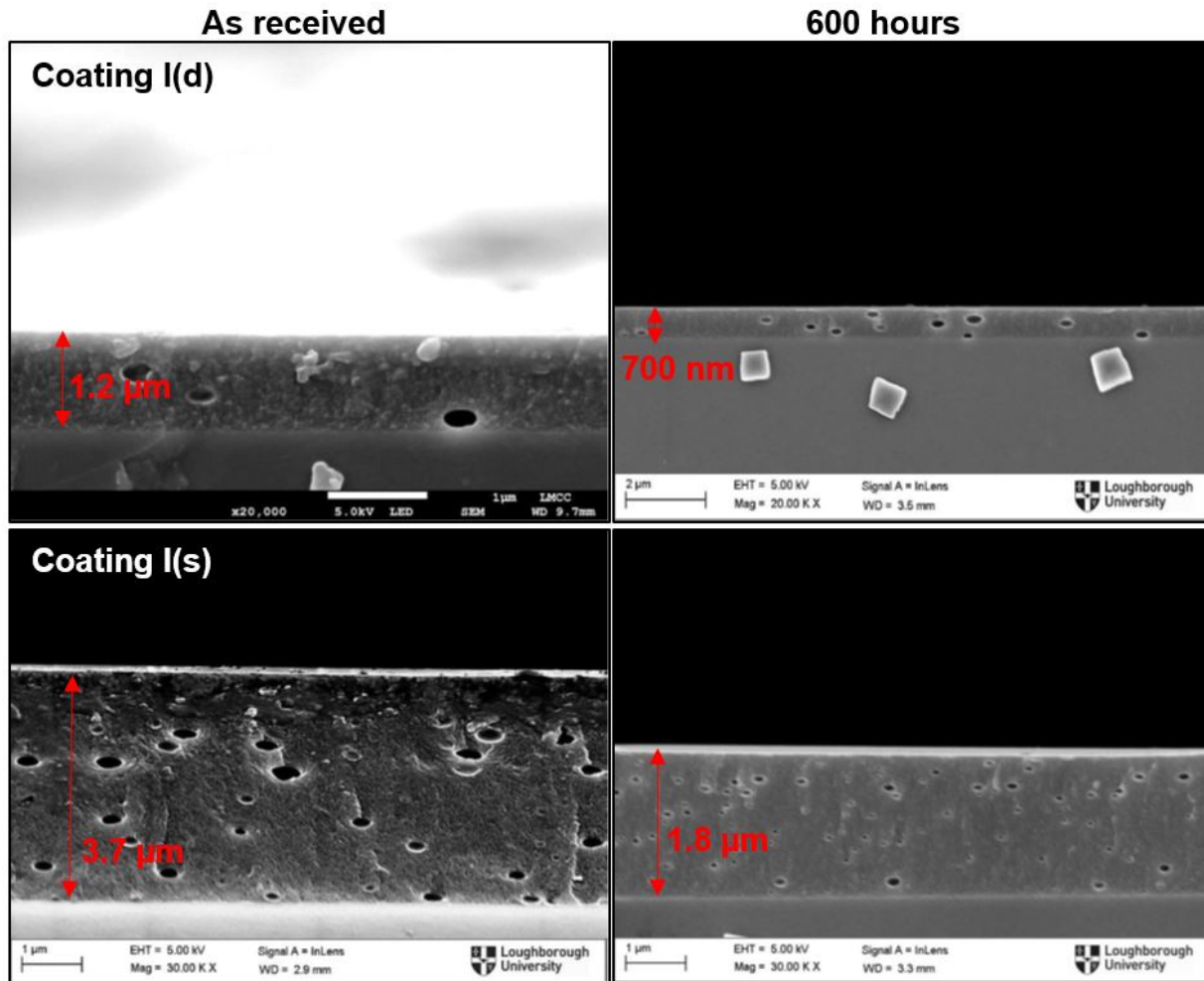


Figure 18. UV exposure cross-sectional SEM imaging of Coating I(d) and I(s), showing thickness reduction due to “sweating” process. Magnifications on top left, top right, bottom left, and bottom right are 20k, 20k, 30k, and 30k respectively. (SEM imaging: Fabiana Lisco)

3.3 XPS Surface Analysis of Coating I(s)

SEM imaging provides insight to the morphological changes occurring on the coating surface due to environmental stress testing. This, however, does not tell a complete story of the degradation mechanisms involved in reducing coating performance. Up to this point, Coating I has demonstrated an elevated durability performance compared to the alternative coatings. Therefore, subsequent XPS surface analysis was taken on Coating I(s) to gain insight to the chemical changes occurring throughout DH and UV testing. Table 3 summarizes the data of XPS

surface analysis of Coating I(s), taken “as received” and after 1000 hours of DH exposure. A reduction of fluorine and presence of chlorine is apparent after 1000 hours. The basic structure of Coating I(s) is a silane head group with a fluorinated tail. The silane head group attaches to the hydroxyl groups on the glass, bonding the coating to the surface, while the fluorinated tail (non-polar) essentially composes the coating surface. According to the chemist of Coating I, the solvent used in Coating I(s) contains both chlorine and fluorine. Since fluorine is responsible for the hydrophobicity of the coating, a reduction in this element would lead to a decrease in coating performance. Decreasing the hydrophobicity of the coating would lead to a decrease in WCA, however this is not observed for Coating I(s) under DH exposure. As discussed in section 1.4, when existing in a Wenzel wetting state, an increase in surface roughness results in an increased apparent WCA (Equation 2). Therefore, in the event fluorine loss is originating from the coating structure and not the evaporating solvent, the increased surface roughness due to the blistering process would aid in canceling out the otherwise decreasing WCA. The increasing surface energy from the loss of fluorine does support the observed increase in RoA. The presence of chlorine on the surface is most likely from the solvent escaping through the surface from the bulk of the coating.

Table 3. XPS survey analysis on Coating I(s) as received – 1000 hours DH. (XPS analysis: Fabiana Lisco)

	Si2p (At%)	Cl2p3 (At%)	C1s (At%)	N1s (At%)	O1s (At%)	F1s (At%)	Na1s (At%)
As received	11.7	-	33.7	3.1	22.3	29.3	-
1000hrs DH	9.9	2.8	43.9	3.2	21.1	18.5	0.5

Table 4 summarizes the results from XPS analysis done on Coating I(s) through 2000 hours of UV exposure. When compared to DH exposure, UV exposure resulted in a higher loss rate of fluorine, dropping from 29.3 to 19.3 At% in only 500 hours. This suggests the UV is cleaving bonds and accelerating the release of fluorine. Looking at the results of UV exposure in Figure 16 for Coating I(s), there is a significantly greater reduction in WCA when compared to DH. This correlates to the increased fluorine loss measured in the XPS analysis. The same concept as discussed in the previous paragraph, concerning the Wenzel state enabling a “canceling-out” effect of reduced WCA, still applies for the UV exposure results. The presence of chlorine also measured in the XPS for UV exposure suggests entrapped solvent is escaping from the bulk of the coating material. The loss of fluorine may be a combination of both solvent evaporation and loss of structural fluorine in both DH and UV. Further formulation and cure schedule experimentation is needed to further understand these loss mechanisms and their origins.

Table 4. XPS survey analysis on Coating I(s) as received – 2000 hours UV. (XPS analysis: Fabiana Lisco)

	Si2p (At%)	Cl2p3 (At%)	C1s (At%)	N1s (At%)	O1s (At%)	F1s (At%)
As received	11.7	-	33.7	3.07	22.3	29.3
500hrs UV	14.2	2.3	36.9	1.9	25.3	19.3
2000hrs UV	16.3	1.3	36.2	1.2	32.3	12.6

3.4 Reciprocal Abrader Results for Coating I(s,d)

Understanding the mechanical durability of a hydrophobic coating is important in determining PV suitability. Although used for anti-soiling, the coating still needs to withstand handling, shipping, installation, and regular cleaning cycles. Also, in arid regions especially, air born dust can act as an abrasive to the coating when carried by high wind speeds. This is particularly true in areas with dust storms. Therefore, testing the coating durability through both reciprocal abrasion tests and sand blast tests is key. For this work, preliminary results of reciprocal abrasion testing will be discussed for Coating I(s,d), as it demonstrated the best performance throughout DH and UV durability testing. Two testing procedures were used: (1) BS EN 1096-2 test using a CS10 abrader, and (2) ISO 9211-4 test using a cheese cloth. Both standardized procedures used a load of 5N, and an abrasion rate of 50 cycles/min. The results in Figure 19 present the WCA and RoA results for Coating I(s) and I(d) up through 50 cycles for both procedures. Referring to Figure 19a, a minimal decrease in WCA was observed after 50 cycles with a cheese cloth for both coatings. Similarly, a minimal increase in RoA was observed. Coating I(s) and I(d) demonstrate sufficient mechanical durability under 50 cycles of abrasion using a cheese cloth and a load of 5N. Looking at Figure 19b, a more pronounced drop in WCA and increase in RoA is observed for both coatings. Coating I(s) didn't fall below the criteria of 110° for WCA under 50 cycles, however, the decreasing trend suggests this criterion would be crossed given more cycles of abrasion. The RoA increased passed the criteria of 25° for both coatings. These results show limited mechanical durability after 50 cycles with a more aggressive CS10 abrader. For both WCA and RoA measurements, the spray applied Coating I demonstrated a slower rate of mechanical degradation compared to the dip applied Coating I. During application, the dip coated formulation is diluted with additional solvent in order to

achieve proper viscosity; the spray applied formulation is undiluted. Therefore, the coating “hardness” and mechanical durability may be stronger in the spray applied coating due to the concentration of the formula during application. The spray applied Coating I is also thicker to begin with. Further testing and coating application optimization is needed to confirm or deny this hypothesis.

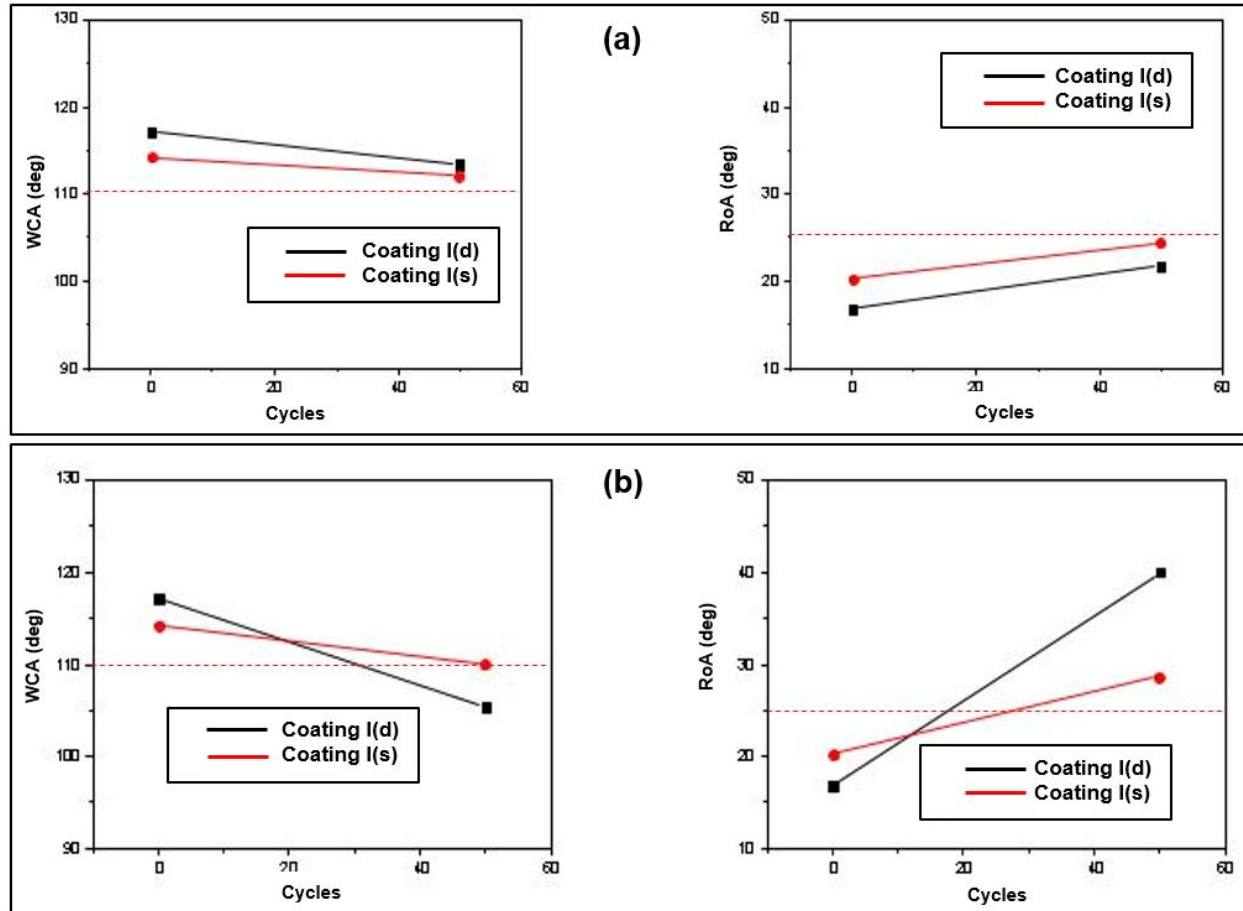


Figure 19. WCA and RoA as a function of cycles of abrasion with (a) a cheese cloth and (b) a CS10 abrader. The red dashed lines represent the WCA and RoA criteria of 110° and 25°, respectively. Each test was done with a 5N load and a rate of 50 cycles/min.

CHAPTER 4. EXAMINATION OF ANTI-SOILING PROPERTIES OF CANDIDATE COATINGS THROUGH ARTIFICIAL DUST DEPOSITION, DUST REMOVAL EXPERIMENTS, AND FIELDED MODULE TRACKING

A large aspect in determining the suitability of a hydrophobic coating for soiling mitigation is of course its anti-soiling properties. The anti-soiling properties of a hydrophobic coating are defined in this work as the coating's ability to reduce the dust adhesion forces observed at the glass and dust particle interfacial contact area. These forces, as discussed in greater detail in section 1.3, can be reduced by lowering the surface energy of the glass substrate using hydrophobic coatings. An experimental testing methodology and procedure was developed, utilizing an artificial dust deposition chamber and dust removal apparatuses, to quantify the anti-soiling properties of the candidate coatings. Two dust deposition conditions were investigated, deposition under high and low relative humidity, to enable differing dust adhesion mechanisms. In addition, two dust removal methods were utilized, both of which investigate the use of forced air at varying velocities. Providing insight on the effectiveness of using waterless cleaning techniques was deemed a significant outcome of this research. In addition to laboratory testing conditions, a thin-film module was coated and installed in an outdoor array for real-time performance tracking. With the development of this anti-soiling testing methodology, the performance of uncoated versus coated substrates and modules can be quantifiably compared.

4.1 The Design, Construction, and Uniformity Testing of a Dust Deposition Chamber

To properly quantify the anti-soiling properties of the candidate hydrophobic coatings, a method for repeatable and uniform dust deposition onto test samples is required. Placing a coated panel outdoors for a prolonged period is one way the anti-soiling properties were examined in

this work. However, there are some shortcomings with solely using this approach: (1) it only represents the specific region in which the panel is located, (2) repeatability between trials is uncontrollable, and (3) the process is very time intensive. Therefore, an artificial dust deposition chamber was constructed, allowing for dust deposition in a uniform, repeatable, and controllable fashion.

The chamber design was based on work by Mantha from Arizona State University [25]. At its core functionality, the chamber uses compressed nitrogen gas to create a suspended dust cloud above the samples. Nitrogen was chosen as it is inert in nature. The fine air-borne dust then settles on the test substrates through gravitational assistance. Significant modifications were made to Mantha's original chamber design to allow for both automation of the dust deposition process and health safety for the user. A control module operated by a microprocessor was introduced, which allows for closed-loop percent relative humidity (%RH) control and nitrogen gas burst duration for greater repeatability. An external ultra-sonic humidifier is used in the %RH closed-loop control. The compressed nitrogen is sourced from an upright gas cylinder, and an electronic solenoid valve opens and closes the gas line. An LCD screen attached to the control module displays the humidity setpoint, %RH, and temperature inside the chamber, and alerts the user when the dust cloud has been formed. The control module itself, which pulls in power from a wall outlet, is encased in an electrically safe 3-gang box. The dust used in the anti-soiling experiments is called Arizona road dust. This is an ISO standardized test dust (ISO 12103-1, A2) that has been widely used for testing filtration systems in the automotive and heavy machinery industries [26]. ISO silica test dust is known to cause cancer upon excessive exposure and inhalation. Therefore, HEPA-rated particulate filters were added to the chamber to allow for

positive pressure release during dust deposition, while containing the dust within the chamber. The dust chamber and featured components can be seen in Figure 20.

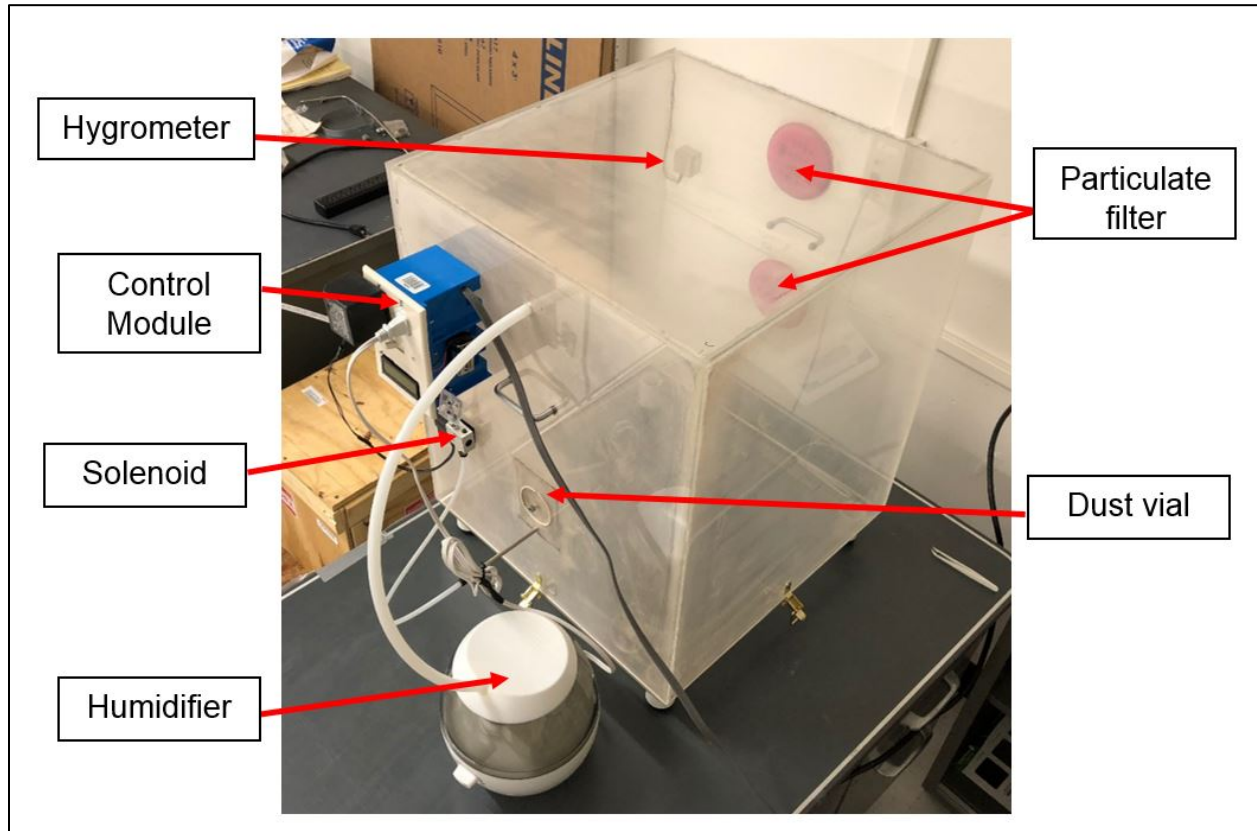


Figure 20. Artificial dust deposition chamber with labeled feature components.

A series of experiments were designed and executed to gather data on the uniformity and repeatability of the chamber. All of the following tests are considered “dry tests”, meaning no intentional humidity was introduced into the chamber via the humidifier (i.e. all experiments were run at ambient %RH around 19%). Therefore, only three parameters, (1) glass substrate location within the chamber, (2) line pressure, and (3) nitrogen burst duration, were altered to achieve the highest level of dust uniformity and repeatability.

The first experiment examined the uniformity of dust deposition across the sample holder at various nitrogen burst durations. A (10x10) cm substrate stand was fabricated to support the

samples and allows the glass samples to be tilted at a desired angle. For these initial uniformity and repeatability experiments, the sample holder was adjusted to a 0° tilt, and four microscope slides were placed along its edges (Figure 21a). The amount of dust collected on each slide was quantified by measuring the weight before and after each dust deposition cycle using a scale accurate out to 1/10,000 of a gram. Five trials were run per set of parameters, and an average standard deviation was calculated between the four slide locations. The standard deviation was then converted into a percentage of the total amount of dust accumulated on the slide. Table 1 below summarizes the first two uniformity experiments run at one and two second nitrogen bursts, both at 100 psi. The location of the sample stand within the chamber for this test was based on the experiments done by Mantha [25], and is illustrated in Figure 21b. The results show a noticeable increase in uniformity across the substrate holder with an increase in nitrogen burst duration.

Table 5: Summary of Dust Uniformity Tests for Trials 1-5 and 6-10.

Nitrogen Burst (sec)	Line Pressure (psi)	StDev Cycle 1	StDev Cycle 2	StDev Cycle 3	StDev Cycle 4	StDev Cycle 5	Average StDev
1	100	20%	21%	6%	12%	21%	16%
2	100	8%	12%	15%	5%	16%	11%

An additional experiment was then executed in which a grid of 24 microscope slides were placed along the right half of the chamber floor (Figure 21c) without the sample holder. Following the previous two tests, this test was designed to identify the location at which dust deposition uniformity was highest within the chamber specifically. All microscope slides were weighed before and after one dust deposition at 100 psi and a two second burst duration. The difference in weight for each slide was calculated, giving the individual dust deposition amount in grams. Each grouping of four adjacent slides was examined to determine the area of least dust

deposition variance. This was determined by finding the location of the smallest (maximum – minimum) weight difference value between all groups of 4 adjacent slides (marked by the red circle in Figure 21d). A set of experiments similar to those described by Table 5 were then run at this new location, resulting in a 5% average standard deviation for both 100 and 120 psi with a two second burst duration.

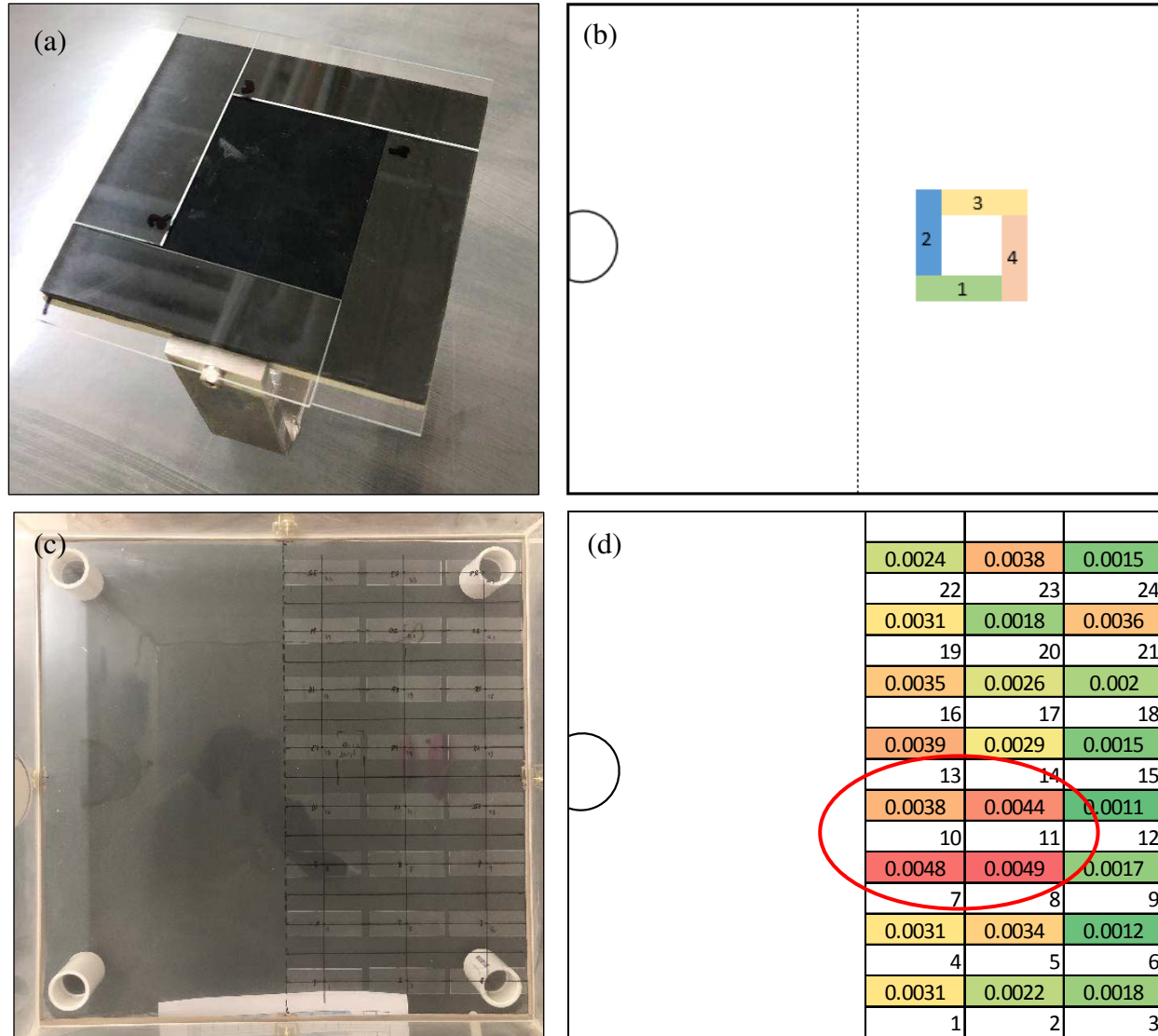


Figure 21. (a) Substrate holder with four microscope slides placed along the edges for uniformity testing. (b) Placement of the substrate stand within the chamber for testing. (c) Experimental setup for determining the location of best dust deposition uniformity. (d) Dust weight accumulation on each of the 24 slides. Numbers in white cells are sample numbers. Red circle marks the best uniformity and the new sample stand location for further testing.

The repeatability of dust accumulation between deposition cycles is also important. A (7 x 9) cm glass coupon was placed on the sample stand at the above defined location, and six deposition trials were performed for both 100 and 120 psi with a 2 second burst duration. Table 6 summarizes the data from these experiments. The experiments described above ultimately showed that a line pressure of 120 psi with a two second burst duration results in the best deposition uniformity and highest repeatability between cycles. The longer two second burst duration, when compared to shorter one second burst duration, most likely resulted in better uniformity across the sample holder due to the increased element of turbulence introduced in the dust cloud formation process. This increased turbulence essentially drives the randomization in distribution of the dust particles throughout the chamber. The higher amount of randomness amongst dust particle distribution leads to higher dust deposition uniformity. The same explanation might apply to the increased repeatability with the higher line pressure of 120 psi. Introducing more turbulence at a longer duration seems to result in a more uniformly distributed dust cloud, which then increases dust deposition uniformity and repeatability across the sample holder. Additional optimization experiments testing a wider range of line pressure, burst durations, and sample holder locations, could be executed to further optimize dust deposition.

Table 6: Summary of the Dust Deposition Repeatability Tests

Nitrogen Burst (sec)	Line Pressure (psi)	Dust (g) Cycle 1	Dust (g) Cycle 2	Dust (g) Cycle 3	Dust (g) Cycle 4	Dust (g) Cycle 5	Dust (g) Cycle 6	Average Dust (g)	StDev
2	120	0.0119	0.0128	0.0121	0.0125	0.014	0.0114	0.01245	7%
2	100	0.0105	0.0109	0.0086	0.0117	0.0102	0.0127	0.01077	13%

4.2 Fabrication of Dust Removal Testing Apparatuses

The artificial dust deposition chamber allows for the uniform and repeatable deposition of dust onto test glass substrates. In order to quantify the anti-soiling properties of the candidate hydrophobic coatings, dust removal testing apparatuses were designed and constructed. While the coatings being investigated were hydrophobic coatings (i.e. water-repellent), the two dust removal methods utilized in the anti-soiling testing were air-based. The lower surface energy of hydrophobic coatings leads to a reduction in dust adhesion forces, resulting in potential anti-soiling properties even in the absence of water. In many regions where sunlight is plentiful and intense, including the Middle East and North Africa (MENA) regions and numerous locations near the equator, water is a scarce resource. Therefore, exploring the anti-soiling properties of the candidate hydrophobic coatings in absence of water is important. The results from forced-air dust removal testing will also provide insight to the capabilities of using compressed air as a cleaning method as opposed to the current water-intensive methods used in practice. Low velocity and high velocity forced air removal methods were used in quantifying the anti-soiling properties between coated and uncoated glass substrates.

4.2.1 Fabrication and Profiling of a Low Velocity Wind Tunnel

A low velocity method was developed to simulate a mild breeze often present in outdoor PV plants and arrays. The low velocity testing enables investigation of the weaker dust particle drag forces seen in low wind speeds. It is important to understand the natural cleaning effects of a coated panel to that of an uncoated panel in absence of water and without any intentional cleaning interventions (compressed air or washes). A wind tunnel was designed and fabricated to produce a uniform air profile over the glass sample in a repeatable fashion. The tunnel is constructed out of PVC piping with an inside diameter of 10.16 cm and initial length of 120 cm.

Connected to a variable voltage supply, a 24V DC computer fan with a 10 cm blade diameter is used to generate the airflow at various wind velocities. The wind tunnel apparatus can be seen below in Figure 22.

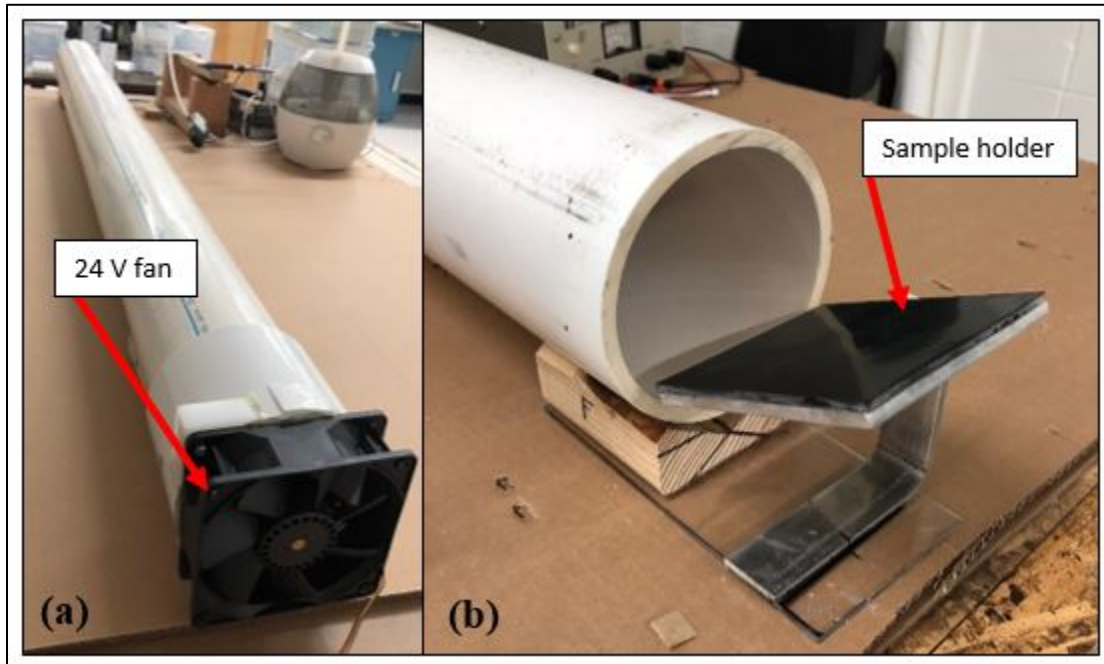


Figure 22. The low velocity wind tunnel with (a) a 24 V computer fan to generate air flow and (b) a glass sample holder mounted at the opening of the tunnel.

In order to ensure the glass sample at the end of the wind tunnel sees a uniform velocity profile, an experiment was designed to determine the necessary entrance length. In fluid dynamics, the entrance length is the distance at which the fluid (air) flows before it has become fully developed (i.e. a uniform velocity profile). In this experiment, a correlation was also made between the supplied voltage and measured wind speed. A Hold Peak HP-866B anemometer was used to measure the wind speeds at the end opening of the PVC piping with a 4, 8, 12, and 16 V supply to the fan. A total of 6 measurements were taken at each voltage in a randomly determined order. The results of this test are summarized in Figure 23. To calculate the entrance

length, we need to know whether the flow is turbulent or laminar. This can be done by calculating the Reynolds number (Re) for a cylindrical pipe as defined by

$$Re = \frac{V*D}{\nu} \quad (4)$$

where V is the measured free-stream velocity, D is the inside diameter of the pipe, and ν is the kinematic viscosity of air. To determine the nature of flow for the entire range of voltages (4 – 16 V), we need only to calculate the Re for the lowest velocity. At a supply voltage of 4 V the average velocity was 2.2 m/s, which corresponds to a Re of 14,600 according to Equation 4. A Re above roughly 3,000 signifies turbulent flow, therefore the flow associated with all supply voltages will be turbulent. An accepted approximation used in fluid dynamics to calculate the entrance length of turbulent flow in a pipe is 10x the inner diameter. With an inner pipe diameter of 10.16 cm, the approximated entrance length is 101.6 cm. Therefore, the initial pipe length of 120 cm is sufficient to enable fully developed flow.

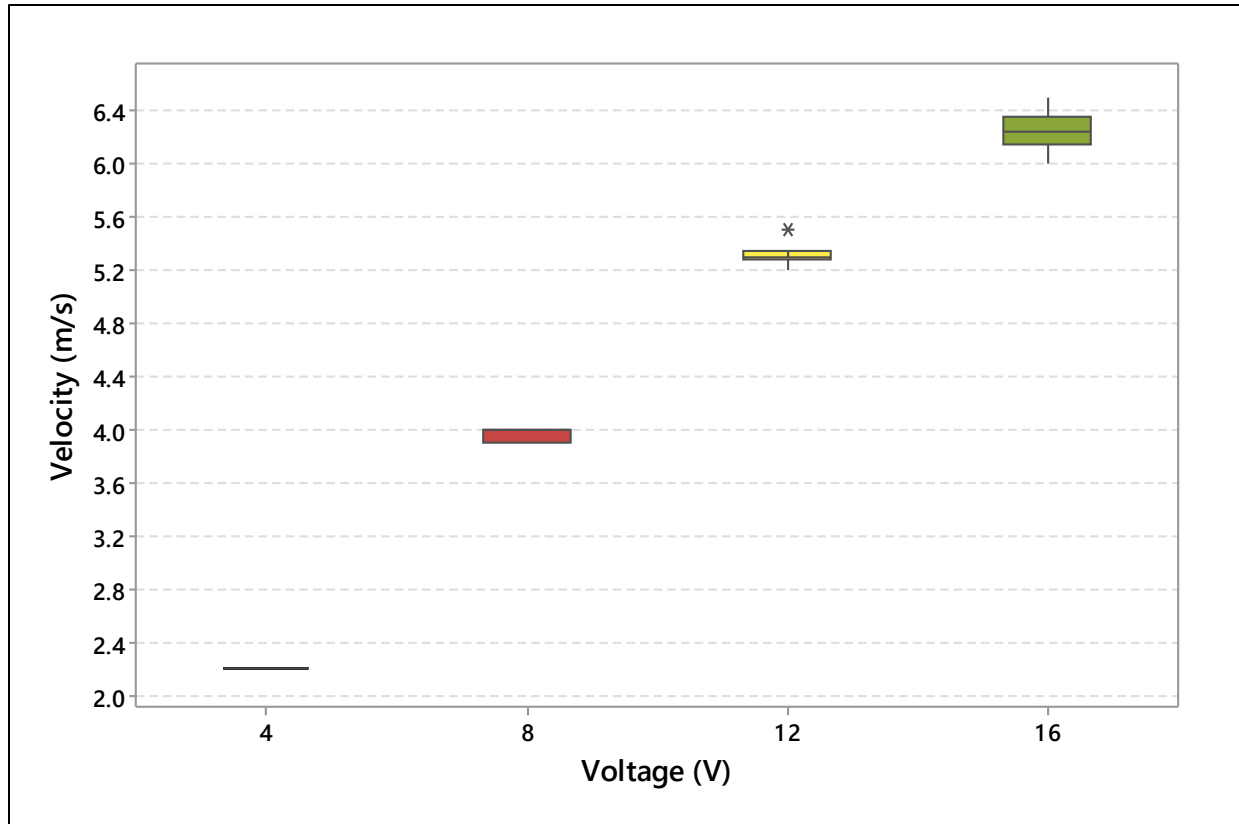


Figure 23. Measured wind velocities at the opening of the wind tunnel as a function of supplied DC voltage to the fan, with a sample size of 6 for each voltage.

From Figure 23 the average wind velocities generated at the sample holder for 4, 8, 12, and 16 V are 2.2, 4.0, 5.3, and 6.3 m/s respectively. To determine a representative low velocity wind speed for the subsequent anti-soiling testing, the average annual wind speeds taken near 5 utility scale PV plants around the world were obtained. An average speed was then calculated between the five selected regions. Table 7 summarizes these findings, with a resulting average wind speed of 5.1 m/s. Therefore the 12 V supply, producing a 5.3 m/s wind velocity, was chosen as the representative setting for the low velocity wind tunnel dust removal experimentation.

Table 7. Summary of average annual wind speeds taken near five utility scale PV plants across the globe.

PV plant name	Location of facility	Average annual wind speed (m/s)	Source of data
Solar Star	California	4.3	[27]
Copper Mountain Solar Facility	Nevada	4.7	[28]
Tengger Desert Solar Park	China	5.1	[29]
Bhadla Solar Park	India	7.2	[30]
Villanueva Solar Park	Mexico	4.2	[31]
	Average	5.1	

4.2.2 Fabrication of a High Velocity Compressed Air Testing Apparatus.

Providing evidential data on the suitability of using compressed air to remove soiling build-up on hydrophobically coated solar cover glass would hold high value in the PV industry. The current methods for cleaning panels at utility scale PV plants include the use of water, and in some cases detergents. These methods have proven to be cost and time intensive, especially in regions where water is a scarce resource. Therefore, a testing apparatus was designed and fabricated to expose glass samples to a steady stream of compressed air under repeatable and controllable conditions.

The design consists of a translational platform that passes under a compressed air gun at a user defined linear velocity. The platform moves along two guide rods and is driven by a stepper motor turning a threaded rod to translate the platform. An electronic solenoid valve turns on and off the supply of compressed air to the gun. A single microprocessor controls the motor and solenoid functionality. A limit switch allows the platform to be “zeroed out” at the start of each test, fully automating the device upon the press of a start button. This automation enables repeatability and uniformity between trials. The pressure of the compressed air line is set using a regulator attached to the gas cylinder responsible for providing the compressed air. Turning on

the tool, the platform initially resets to the zero position. Once the user presses the start button, the solenoid valve opens, and simultaneously the platform moves at a constant linear velocity for a set distance. The platform and solenoid valve are then concurrently shut off once this distance is reached. The tool then waits for the user to zero the platform and another test can begin. The completed tool is illustrated in Figure 24. The multi-colored buttons allow the user to adjust the linear velocity, however for the subsequent compressed air removal tests a single linear velocity was used. With the construction of this high velocity dust removal testing apparatus, compressed air cleaning methods can be quantified.

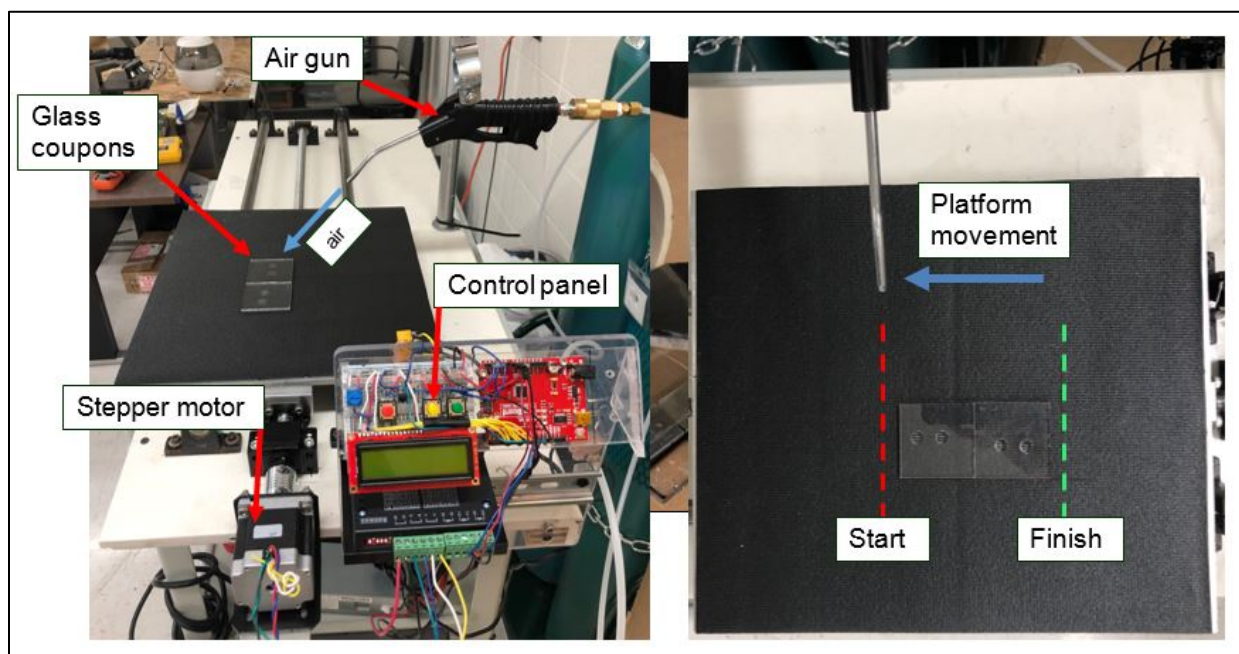


Figure 24. Compressed air testing apparatus used for high velocity anti-soiling testing.

4.3 Dry-Air Dust Deposition with Low Velocity Air Dust Removal

In these experiments, dust was deposited onto the glass substrates using two techniques. Each technique aimed to simulate differing dust adhesion mechanisms through deposition under dry and wet conditions. Dry-air dust deposition is defined in this work as having ambient RH and room temperature conditions during the deposition process within the soiling chamber. Under

these conditions, the dust adhesion mechanisms are largely composed of Van der Waals (VDW) forces and any existing electrostatic attraction between the particles and the substrate surface. Dust cementation, the more aggressive adhesion mechanism, is not induced during the dry-air deposition testing conditions as it requires the presence of liquid water. Therefore, in order to quantify any differences in dust adhesion between coated and uncoated samples under dry-air deposition conditions, the low velocity forced air removal method was used. This method, when compared to compressed air removal, generates relatively small drag forces to remove the particles from the glass surface. VDW and electrostatic forces are relatively weak compared to those seen in cementation, hence the use of a low-force removal method for the dry-air anti-soiling testing procedure.

4.3.1 Testing Methodology

From section 2.4.2, coatings E, F, I(dip), and I(spray) were identified as candidate coatings following the RoA screening procedure. However, recalling back to section 3.1 in the durability chapter, the Loughborough and CSU coating teams agreed to bring Coating J back into the research scope despite its initial poor performance in the preliminary WCA screening procedure. This was done to fully investigate the performance of a manufacturer-claimed anti-soiling coating for PV. Coating J was the only one marketed for PV specific application amongst all the obtained commercially available hydrophobic coatings.

Eight samples for coatings E, F, I(d), I(s), and J were each fabricated on (5 x 5) cm Starphire glass substrates in preparation for the dry-air anti-soiling testing procedure. Eight samples of uncoated glass were also fabricated to act as the control group for this testing procedure. The glass substrates were cleaned using an ultra-sonic cleaning method, and the coatings were applied to the cleaned substrates. After a 48-hour cure time in ambient

temperatures, the samples were measured for RoA. During the RoA characterization stage of the dry-air testing procedure, a significant increase in RoA for Coating E was observed, reaching angles around 45-50°. Having observed a much lower RoA in the past, a new batch of Coating E was applied using the same manufactured-suggested application procedure, glass substrate, and cure time as before. The RoA measured from 35-50° for this batch. This process was repeated a few times with similar results. Coating E was eliminated from further anti-soiling testing in interest of saving time and moving forward with the experimentation. Inconsistent and often high RoA measurements also provided objective justification in the elimination of Coating E.

Direct transmission measurements were used as the quantification technique for the dry-air anti-soiling testing procedure. Using an automated transmission measurement platform fabricated for this experiment, the measurements were taken at four locations (left, left-center, right-center, and right) across the substrate. A Mikropack DH-2000_BAL light source coupled with an Ocean Optics USB4000 sensor was used in the transmission measurement set-up. Prior to each transmission reading, the tool was calibrated using a respective calibration sample set aside from each batch of the fabricated samples. The spectrum of the light source spanned a 350-1050 nm wavelength range. Because the measurements were normalized against a clean calibration sample, the transmission data was reported as a single average value.

The fabricated samples for all 4 coating variations, including the batch of uncoated glass, were initially measured for transmission before any dust deposition. As previously mentioned, the transmission tool was calibrated using a calibration sample for each coating variation. Therefore, this initial measurement was taken to normalize any transparency differences from sample to sample within a given batch due to the coating. The design of the artificial dust deposition chamber and the low-velocity wind tunnel apparatus allow for only one sample to be

tested at a given time. Therefore, the testing was split up by coating formulation, with uncoated glass being the first to complete the dry-air anti-soiling testing procedure. The following step-by-step process describes one trial of this testing procedure. The sample is coated with the particular coating, cured and measured for transmission. After the initial transmission measurement, the sample is placed onto the substrate holder located within the dust chamber. 2.5 g of Arizona test dust is loaded into the dust vial. With a line pressure of 120 psi and a burst duration of 2 seconds, the dust cloud is then suspended above the sample. The dust is then allowed to settle onto the sample for a period of 10 minutes following the compressed nitrogen burst. The sample is then carefully removed from the chamber to not disrupt the dust and a direct transmission measurement is taken using the methods previously described. The sample is then carefully placed into the wind tunnel apparatus, where it is exposed to 30 seconds of a low-velocity air stream at 5.3 m/s. The sample is then measured again for transmission. This completes one trial of the dry-air anti-soiling testing procedure. All samples for each coating variation and the uncoated glass were run through this process resulting in 40 trials.

Statistical analysis was then run on the transmission data to identify any significant differences in dust removal (i.e. soiling reduction) existent between the coated vs uncoated samples. Both parametric and non-parametric two-sample t-tests were used in the statistical analysis depending on the distribution behavior of the 8 samples for each coating. A significance level of 5% was used across the board for all comparisons.

4.3.2 Results and Discussion

As mentioned in the previous section, transmission measurements were taken after dust deposition, and again after the forced air removal. All transmission measurements were normalized by a respective clean calibration sample for each coating and the uncoated substrates.

As seen in Figure 25a, all 4 coating variations had a median post-dust deposition transparency value that fell within 3% of the plain glass (PG) median value of 72.8%, marked by the red dashed line. Coatings J, I(s), and I(d) showed no statistically significant difference in post-dust transmission when compared to PG. With a P-value of 0.014, Coating F did demonstrate a larger loss in transparency after the dust deposition. Executing the dry-air/low-velocity testing procedure took about 4 hours for each coating variation, so approximately 15-20 days (were needed to complete the testing. Therefore, the difference detected in Coating F when compared to PG is most likely due to day-to-day variation in ambient conditions and variability in the artificial dust deposition chamber. There may also exist slight differences in electrostatic forces between the coatings, which may partially explain the higher dust accumulation on Coating F. Surface charge measurements would be needed to objectively confirm or deny significant electrostatic force differences between the coatings. However, after the formation of the dust cloud, the deposition of dust onto the surface of the test sample is driven primarily through gravity assistance. Therefore, it is expected the initial transmission losses between all coatings and uncoated glass be similar in value.

Transmission measurements taken after the low-velocity air removal revealed statistically significant differences between all coatings and the uncoated glass substrates, with the highest P-value of 0.032 for Coating J. Figure 25b shows the box-plot distributions of soiled coating transmissions after exposure to low-velocity air removal. Coating F, although demonstrating a larger loss in transmission after dust deposition, showed the largest recovery in percent transmission after the air removal at 92.6%. This further suggests the differences seen in transmission after dust deposition were due to deposition chamber variations as opposed to enhanced electrostatic forces. Coatings I(s), I(d), and J had median post-air transmissions values

of 86.5%, 83.6%, and 81.9% respectively, compared to uncoated glass with a median transmission of 80.2% marked by the red dashed line. As previously discussed in section 1.4, hydrophobic coatings reduce VDW forces due to their lower surface energy. These forces are a dominant dust adhesion mechanism under dry dust deposition conditions. Therefore, reducing these interfacial forces leads to the greater transmission recovery observed with the hydrophobic coatings under constant low-velocity air removal. From these results, it can be stated with statistical significance that the hydrophobic coatings tested demonstrate anti-soiling properties when compared to uncoated solar cover-glass.

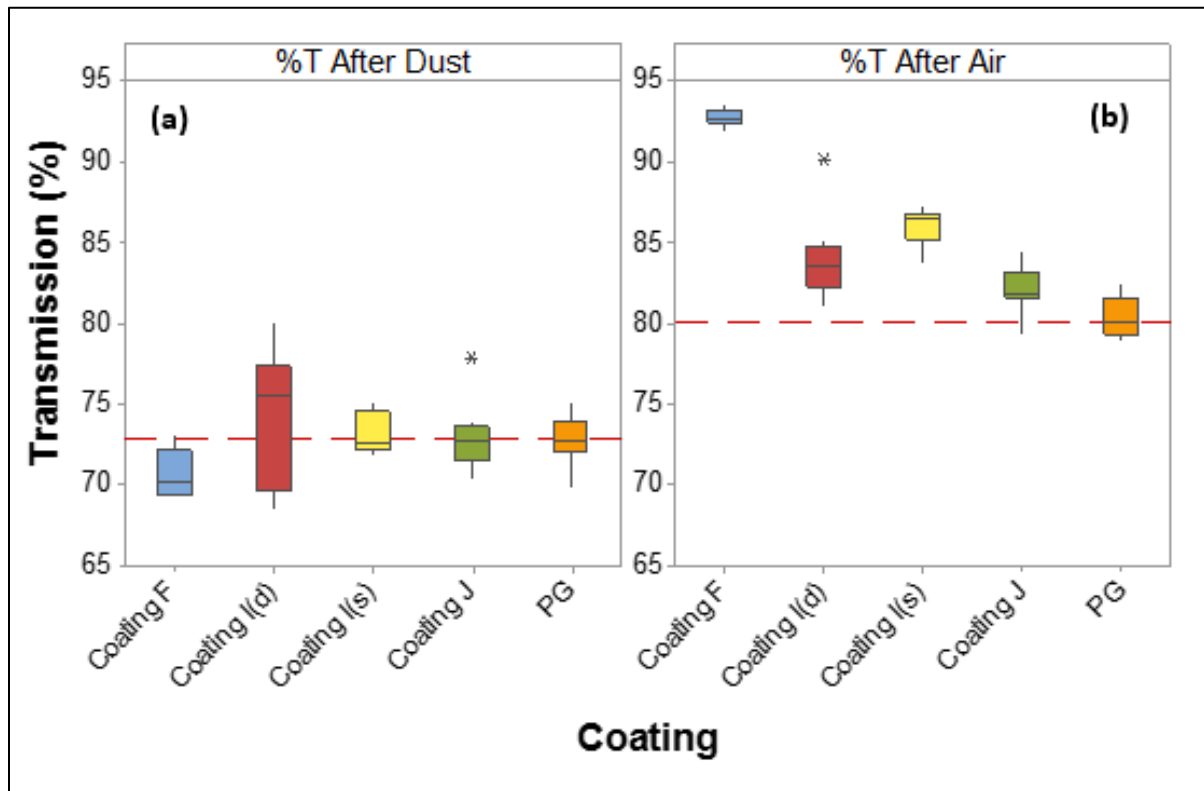


Figure 25. Standard box-plot of the 8 average direct transmission measurements for each coating formulations and the uncoated glass, all normalized using a clean calibration sample. (a) The transmission measurements after dust deposition. (b) Transmission after the low-velocity air removal.

4.4 Humid-Air Dust Cementation with Compressed Air Removal

Cementation is one of the strongest adhesion mechanisms responsible for binding dust particles to a solid surface such as glass. Cementation is also one of the most common dust adhesion mechanisms seen in outdoor environments with to the presence of water in the form of rainfall, snowfall, various ambient humidity levels, and dew formation. Therefore, a significant component of this research was in examining the anti-soiling properties of the candidate coatings in the presence of dust cementation. Due to the significantly higher adhesion forces of cementation, high-velocity compressed-air removal was used in quantifying anti-soiling properties of the coatings. The investigation of using waterless cleaning methods was also an important contributor in using compressed-air removal methods for cemented dust.

As discussed in section 1.3, cementation is the process in which salts within dust particles dissolve when in contact with water. This creates a saltwater solution that upon evaporation, leaves behind a cemented layer of salt adhering the dust particles to the glass substrate. In order to replicate this adhesion mechanism for anti-soiling testing, water must be introduced during the dust deposition process within the soiling chamber. There are a few of ways in which water can be introduced during deposition, including utilizing a dust-water mixture, misting the glass substrates, increasing the humidity to points of saturation, or inducing the formation of dew condensation. Of these methods, dew condensation is most representative of the cementation process seen in large scale utility plants found in arid/desert regions. While rainfall can induce cementation when infrequent and light in nature, it mostly acts as a cleaning event for soiled modules [13]. Therefore, modifications were made to the soiling chamber to enable the simulation of dew formation.

4.4.1 Modification of Artificial Dust Deposition Chamber to Enable Dust Cementation

The process of dew formation essentially depends on two parameters: (1) the relative humidity and (2) the temperature of the condensing surface. For water to condense out of the air, the surface must be at or below the dew point temperature for a given relative humidity. To recreate condensation in a laboratory setting with ambient room temperatures, the glass substrates must be cooled below the dew point temperature. In order to accomplish this, thermoelectric generators (peltier coolers) were installed into the soiling chamber. These devices operate based on the peltier, or thermoelectric, effect. By applying a voltage across the peltier cooler, heat is transfer through the material creating a temperature difference between the two opposite surfaces. This allows one side of the thermoelectric to become significantly colder than room temperature, while the opposite side becomes significantly warmer. Typically, peltier coolers are characterized by a maximum delta temperature corresponding to a maximum operating power. Rejecting heat from the “hot” side at an accelerated rate will allow lower temperatures to be reached on the “cold” side. Therefore, the peltier coolers were attached to a heat sink fitted with cooling fans in order to maximize heat rejection. This peltier cooler module was then fitted to the floor of the soiling chamber in the same location deemed “most uniform and repeatable” from the deposition uniformity testing discussed in section 4.1. In order to prevent the cooling fans from introducing turbulence within the soiling chamber, a portion of the floor was cut away, allowing the cooling fans to sit outside and underneath the chamber. The peltier cooler modification of the soiling chamber can be seen in Figure 26.

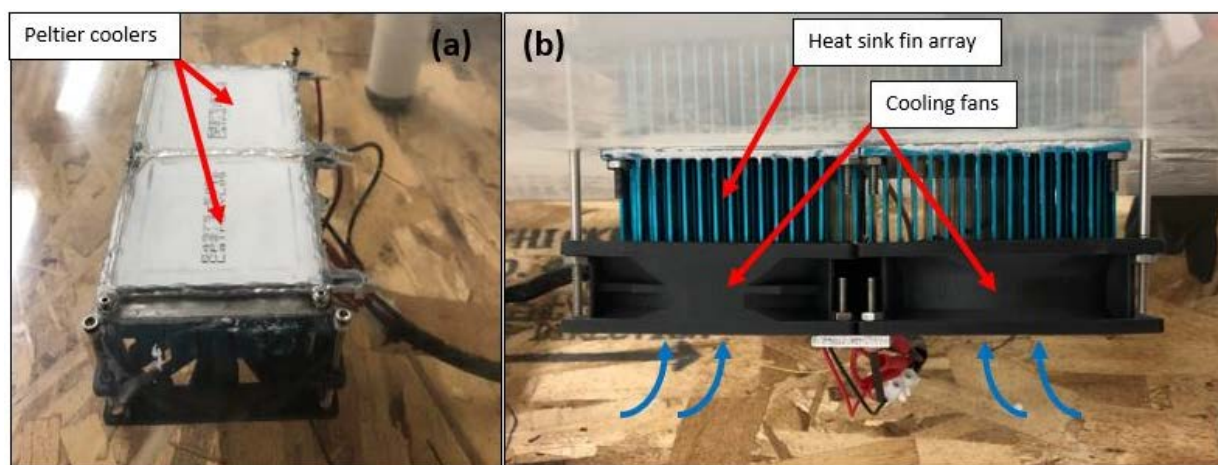


Figure 26. Modification of the soiling chamber allowing for simulated dew condensation using (a) two peltier coolers installed into the chamber floor and (b) heat sinks fitted with cooling fans to reject excess heat.

4.4.2 Testing Methodology

Preliminary trial runs of dew simulation and dust cementation in the soiling chamber revealed, qualitatively, a variation in dew condensation patterns between the samples of uncoated glass substrates. Due to the presence of water in the cementation anti-soiling testing procedures, any surface energy heterogeneity on the glass surface resulted in varying degrees of “wetness”, thereby resulting in differing patterns of soiling after dust deposition and bake. In other words, some areas of the glass surface may be more hydrophilic than others depending on these gradated surface energies. Therefore, these areas possess a higher affinity for water and will subsequently attract a larger volume of condensed water. This led to a variation in observed patterns of wetness between glass samples, even under the same condensation parameters. When dust is then deposited onto these wetted surfaces, the particles get absorbed into the water droplets/pools, resulting in varying patterns of soiling between the glass samples. Figure 27 shows the soiling patterns observed in back-to-back cementation trials of uncoated glass substrates.

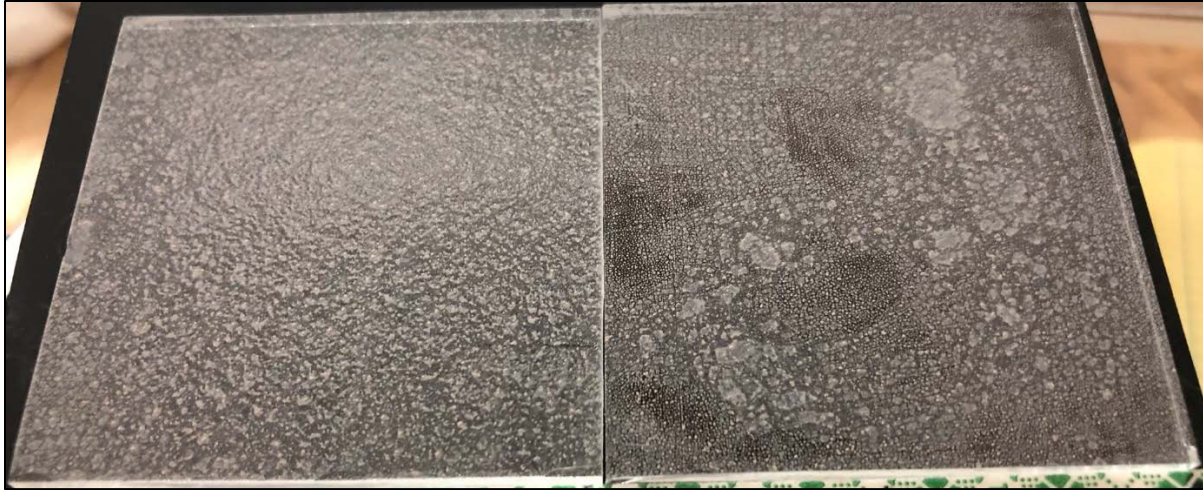


Figure 27. Side-by-side comparison of two uncoated glass substrates after exposure to dust cementation process. The samples were cemented one at a time consecutively. Observed soiling pattern differences can be seen.

The variation seen in the soiling patterns has a direct effect on the transmission measurements, the quantitative parameter used in this anti-soiling testing procedure. Therefore, it introduces inaccuracies to compare the soiling losses from one trial to another. To accommodate for this, one coated and one corresponding uncoated sample were tested concurrently (i.e. dust deposition, cementation baking, and compressed air removal) and a direct pairwise comparison was made. This process also helps to mitigate variations in ambient temperature/humidity differences, dust deposition distributions, and other inter-trial errors and inconsistencies.

In preparation for the subsequent compressed air/cemented dust anti-soiling testing procedure, a batch of Starphire solar cover-glass was cleaned using an ultra-sonic cleaning procedure. These cleaned substrates were then cut into (5x5) cm size coupons and coated with formulations J, F, I(s), and I(d). A total of nine samples were fabricated for the coating formulations and uncoated glass. All coated samples were then characterized using WCA and RoA. A dramatic increase in RoA was observed for Coating J, reaching values as high as 53° with an average RoA of 46°. As was done with Coating E in section 4.3.1, new samples of

Coating J were fabricated and subsequent RoA measurements were taken. RoA measurements were observed ranging from 20° to values higher than 50°. Inconsistencies in RoA, in conjunction with poor durability performance discussed in section 3.2.1 and 3.2.2 of the durability chapter, resulted in the decision to eliminate Coating J from further anti-soiling testing.

Of the nine samples fabricated for each coating formulation, one representative sample was reserved for transmission tool calibration. Therefore, a sample size of eight was used for the subsequent cementation/compressed-air testing procedure. Direct transmission measurements were taken on Coating F, I(s), I(d), and the uncoated samples to get a clean baseline. The following step-by-step process defines one trial of the dust cementation/compressed air removal testing procedure. As previously mentioned, two samples (one coated and one uncoated) were simultaneously tested during each trial to enable direct comparison analysis. The coated and uncoated glass sample are each placed on a peltier cooler, as seen in the above Figure 26. The lid is latched back into place on the soiling chamber, the peltier coolers are powered on, and a period of three minutes is allotted to reach an equilibrium temperature of 34°F on the glass substrate surface measured by a thermocouple. The peltier coolers remain on throughout the deposition process to ensure the samples stay at this temperature to prevent premature droplet evaporation. The humidity is set to 50% inside the chamber, at which point the humidifier turns on until this target value is reached. It is during this process where condensation on the cooled glass surfaces can be visibly seen. Once the humidity has reached 50%, 2.5 g of Arizona test dust is swiftly loaded into the test vial, followed immediately by a 2 second nitrogen burst at a 120 psi line pressure. This process is done quickly to prevent the dust from absorbing too much moisture before being suspended into a dust cloud. The dust is then allowed ten minutes to settle onto the

wetted samples. The lid is removed from the soiling chamber, the peltier coolers are turned off, and the baking apparatus is placed above the samples. The baking apparatus consists of an IR heat lamp positioned atop an aluminum box structure at a height of 50 cm above the samples (Figure 28a). The reflective aluminum material allows for enhanced radiative heating and accelerated droplet evaporation. The samples are allowed to bake under the heat lamp for 20 minutes, reaching surface temperatures of 115°F and enabling complete water evaporation (Figure 28b). At this stage, dust cementation onto the samples is complete. The samples are then measured for direct transmission using the same methodology as described in the dry-air testing process. The samples are placed side-by-side on the high velocity compressed air testing apparatus as demonstrated in Figure 24. The line pressure is set to 90 psi (standard shop air pressure), and the compressed air nozzle is set at a distance of 3 inches from the sample surfaces with a 45° line of attack. These parameters mimic how one might use compressed air to clean a module in the field. A pressure of 90 psi at this distance correlates to roughly a 30 mph wind speed. The translational speed (85 mm/s) of the platform is set to the maximum capability of the stepper motor. One pass of compressed air at the above parameters is executed across the two adjacent samples. The samples are then measured once more for direct transmission. This completes the cementation/compressed air anti-soiling testing procedure.

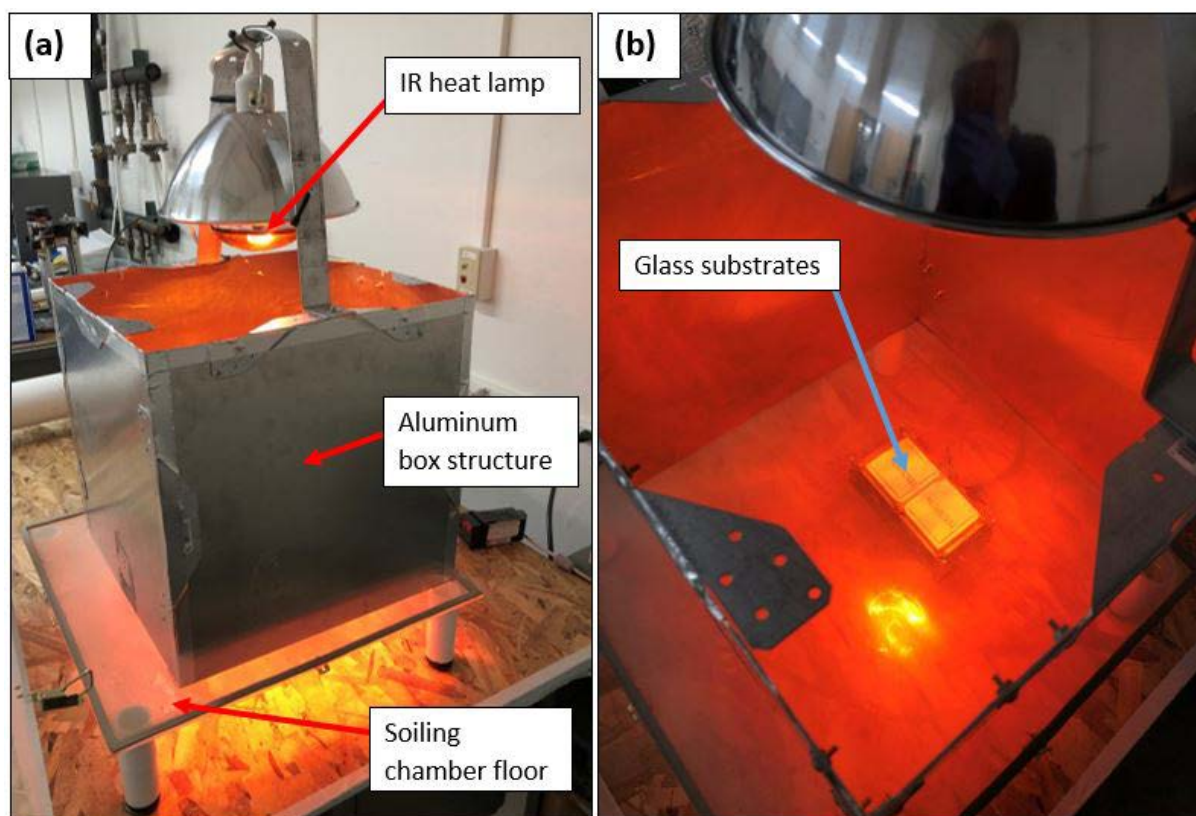


Figure 28. Baking apparatus enabling water droplet evaporation in the dust cementation process. (a) Shows the apparatus in its entirety, while (b) shows the position of the samples underneath the IR heat lamp.

4.4.3 Results and Discussion

The cementation/compressed air results for each coating formulation, as seen in Figure 29, are plotted on a per-trial basis (separated by the vertical dotted lines), allowing for comparison of individual coated samples to their partner uncoated sample. As done previously in the dry-air testing, the clean transmission measurements were used to normalize out any transmission differences between coated samples due to variations in the coating itself. Therefore, the reported transmission values in the following figures are presented as a percentage of the sample in an unsoiled/clean state (marked by the red dashed line). The green data points represent the given hydrophobically coated samples, and the blue points represent the uncoated

plain glass samples, marked PG. Transmission losses due to dust cementation are defined by the circular data points, while the square data points signify the transmission after exposure to one pass of compressed air. The difference between the two signifies the anti-soiling properties of the coatings.

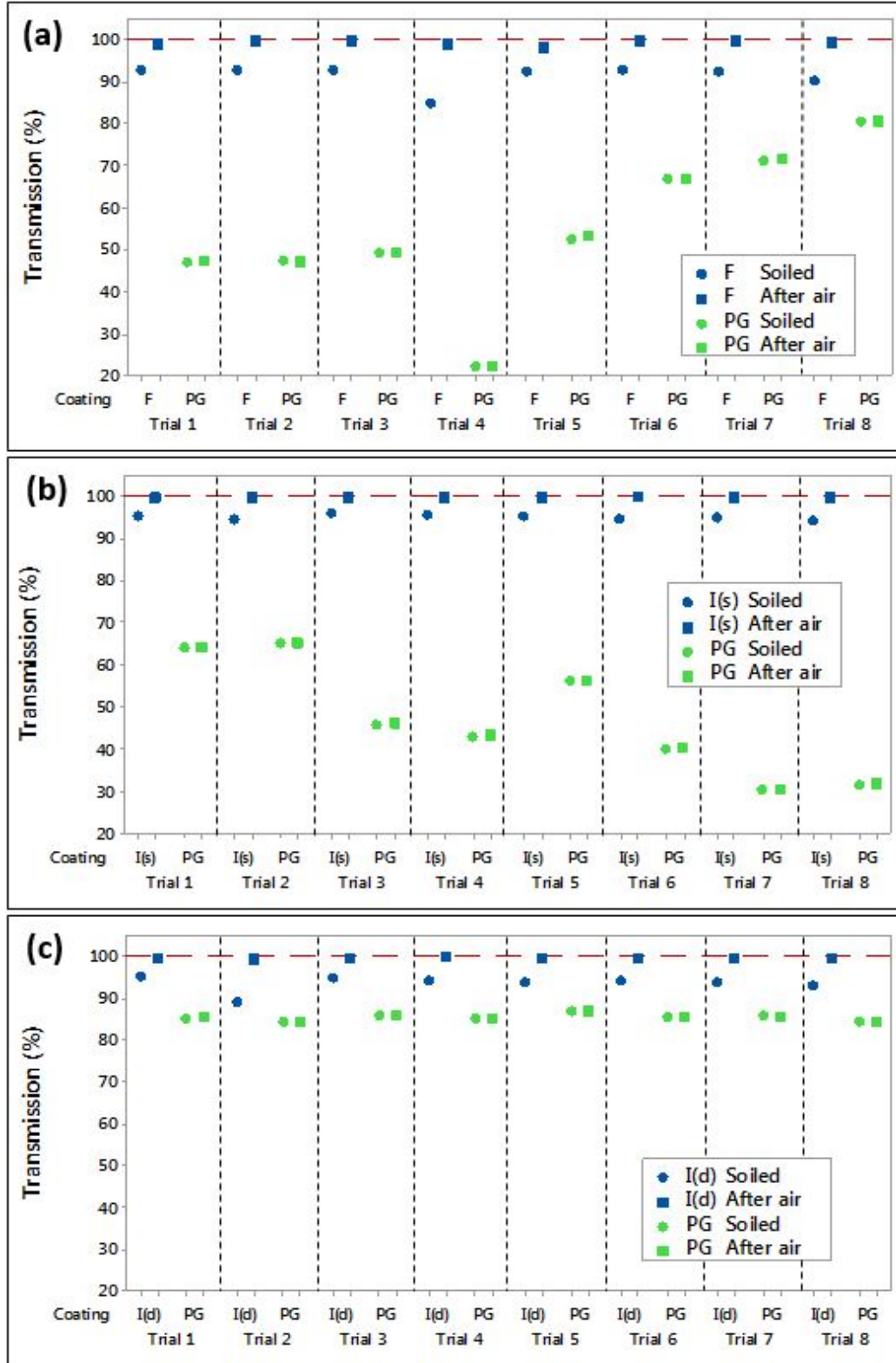


Figure 29. Pairwise comparison of (a) Coating F, (b) Coating I(s), and (c) Coating I(d) to uncoated glass (represented by the green data points) in terms of transmission loss due to soiling (circles) and post-compressed air transmission recovery (squares). Vertical dotted lines separate each trial, and the red dotted line represents the transmission of an unsoiled sample (zero losses).

Coating F (results shown in Figure 29a) demonstrated average transmission values of $91.4 \pm 2.7\%$ and $99.2 \pm 0.5\%$ after soiling and after compressed air removal, respectively. The trial with the largest soiling loss reduced the transmission of Coating F to 85.0%, and the lowest transmission after compressed air removal is 98.2%. The uncoated glass in Figure 29a showed average transmission values of $54.6 \pm 18.2\%$ and $54.7 \pm 18.1\%$ after soiling and after compressed air removal, respectively. The largest soiling loss seen with uncoated glass reduced the transmission to 22.0%. Minimal recoveries in transmission were seen after compressed air removal with all eight trials for uncoated glass. For uncoated glass, therefore, the lowest transmission after compressed-air removal is similar to the lowest transmission value after soiling, in this case 22.1%. This same trend was observed for the uncoated glass for all three coating variations (F, I(s), and I(d)). Shown in Figure 29b, Coating I(s) measured average transmission values of $95.1 \pm 0.7\%$ and $99.6 \pm 0.1\%$ after soiling and after compressed air removal, respectively. The lowest measured transmission from soiling losses and after compressed air removal was 94.1% and 99.5%, respectively. The corresponding uncoated glass samples demonstrated average transmission values of $47.1 \pm 13.6\%$ and $47.2 \pm 13.5\%$ after soiling and after compressed air removal, respectively. The largest soiling losses for the uncoated glass samples resulted in a transmission of 30.5%. Finally, Coating I(d) (Figure 29c) measured average transmission values before and after compressed air removal of $93.5 \pm 1.9\%$ and $99.5 \pm 0.2\%$, respectively. The lowest transmission after soiling was 89.0%, while the lowest transmission after compressed air removal was 99.1%. Uncoated glass for the I(d) experiments showed average transmissions of $85.3 \pm 0.9\%$ and $85.4 \pm 0.8\%$ after soiling and after compressed air removal, respectively. Interestingly, the uncoated glass samples for Coating I(d) experienced a much lower amount of soiling when compared to the uncoated glass from the other two

experiments (Coating F and I(s)). While all glass samples were cleaned in the same ultra-sonic bath process, the uncoated samples for Coating I(d) experimentation had been cleaned and left to sit for two weeks in a sealed container before the anti-soiling testing. The uncoated glass for the other two experiments were cleaned days before. Therefore, the ultra-sonic cleaning process must be affecting surface energy of the glass. More experimentation is needed to test this hypothesis. Transmission values of 84.2% and 84.3% were the lowest measured before and after compressed air, respectively.

Depending on the data distributions, either two-sample t or Mann-Whitney tests were used to detect differences in soiling losses and soiling recovery between each coating and between the coatings and uncoated glass samples. A significance level of 5% was used for all statistical tests. With a P-value of 0.0 across the board, the transmission after soiling and after compressed air for all three coatings and their corresponding uncoated samples were significantly different. The uncoated glass samples for each coating comparison demonstrated minimal soiling removal after the compressed air exposure. After soiling and after compressed air transmission measurements for the uncoated glass, corresponding to coatings F, I(s), and I(d), showed no statistically significant difference with P-values of 0.99, 0.991, and 0.990, respectively. Therefore, minimal dust was removed after compressed air for all uncoated glass samples, resulting in no measured transmission recovery. The before and after compressed air transmission measurements for Coating F, I(s), and I(d) were significantly different with P-values of 0.001, 0.001, and 0.0 respectively. Comparisons between the three coating formulations were also run to detect any difference in soiling losses. The only differences detected were between Coating F and I(s), where Coating I(s) demonstrated higher transmission values both after soiling and after compressed air with P-values of 0.001 and 0.047 respectively.

Therefore, Coating I(s) demonstrated lower transmission losses after soiling, and greater transmission recovery after compressed air than Coating F. This is most attributed to the elevated hydrophobicity of Coating I versus that of Coating F.

Findings from the cementation/compressed air removal anti-soiling testing quantitatively demonstrate a significant difference in transmission recovery (soil removal) for all three coating variations when compared to uncoated glass. These results provide strong evidence of anti-soiling properties for all three hydrophobic coatings under cementation soiling mechanisms in laboratory conditions, and the effectiveness of using compressed air to remove nearly 100% of the accumulated dust. The hydrophobic coatings appear to be completely preventing the cementation of dust particles on the substrate surface, whereas cementation is fully adhering the dust onto the uncoated glass samples. When the dissolved salts cement a dust particle to a flat surface, the overall solid-to-solid interfacial contact area is increased. This in turn increases the Van der Waals forces between the cement/dust particle and the glass surface. The reduced surface energy of hydrophobic coatings is known to reduce Van der Waals forces [13], thereby reducing the effectiveness of cementation in adhering dust to the substrate surface. In addition, salts such as NaCl commonly found in dust particles [32, 33], are extremely polar ionic compounds. Hydrophobic coatings occupy the hydroxyl groups on glass rendering it non-polar, thereby reducing the polar attractive forces normally present with cementation on uncoated glass. While these two adhesion mechanism reductions should significantly lessen cementation effects on hydrophobic surfaces, the results from this anti-soiling testing are showing an almost complete prevention in cementation. The question then arises, “What other mechanisms are at play here?”. Turns out, the answer to this question lies in an investigation of another observed phenomenon made during the anti-soiling testing experimentation.

Looking at the circular data alone in Figure 29 (soiling losses), a statistically significant difference was detected between every coated sample and the corresponding uncoated glass samples (green vs blue circles). Even though the coated and uncoated samples were cemented with dust simultaneously, side-by-side for each trial, the uncoated glass repeatedly demonstrated significantly more transmission loss prior to compressed air removal. Figure 30a-c shows side-by-side comparisons of Coating F, I(s), and I(d) with the paired uncoated sample after dust cementation, respectively. From initial visual inspection, the logical hypothesis says the hydrophobic coated samples are receiving much less soiling than the uncoated counterpart in terms of sheer dust accumulation. However, due to the soiling chamber uniformity per dust cycle, the samples should be seeing nearly the same amount of accumulation. Therefore, a short experiment was performed to test the hypothesis of varying dust accumulation amounts between the coated and uncoated samples. Eight samples of Coating F and Coating I(s) were fabricated, in addition to 16 samples of cleaned uncoated glass. Following the exact procedure as described previously in section 4.4.2, all paired coated and uncoated samples were cemented with dust. This time however, the samples were weighed before and after cementation using a high precision scale accurate to one-thousandth of a gram. This way, taking the difference in weight before and after cementation, a dust accumulation metric is acquired. Using two-sample t-tests with a significance level of 5%, no significant difference was detected in the amount of dust (g) accumulated between the coated and uncoated samples ($P = 0.283$ for Coating F and $P = 0.06$ for Coating I(s)). Therefore, the hypothesis of less dust accumulation on the coated samples was rejected. Some other mechanism must be responsible for the large differences seen in the soiling losses between coated and uncoated samples.

To develop a better understanding, the soiling patterns were examined under magnification. In Figure 30d, differences in the soiling patterns between Coating I(d) and the uncoated glass is seen. This is further illustrated under 4x magnification, seen in Figure 30e and Figure 30f, where a clear distinction in soiling patterns is identified. The uncoated glass substrates repeatedly demonstrate a more dispersed soiling distribution, whereas the coated samples only show soiling in small “piles” along the surface. Therefore, the total area of exposed (unsoiled) glass is greater for coated samples, resulting in less severe transmission losses.

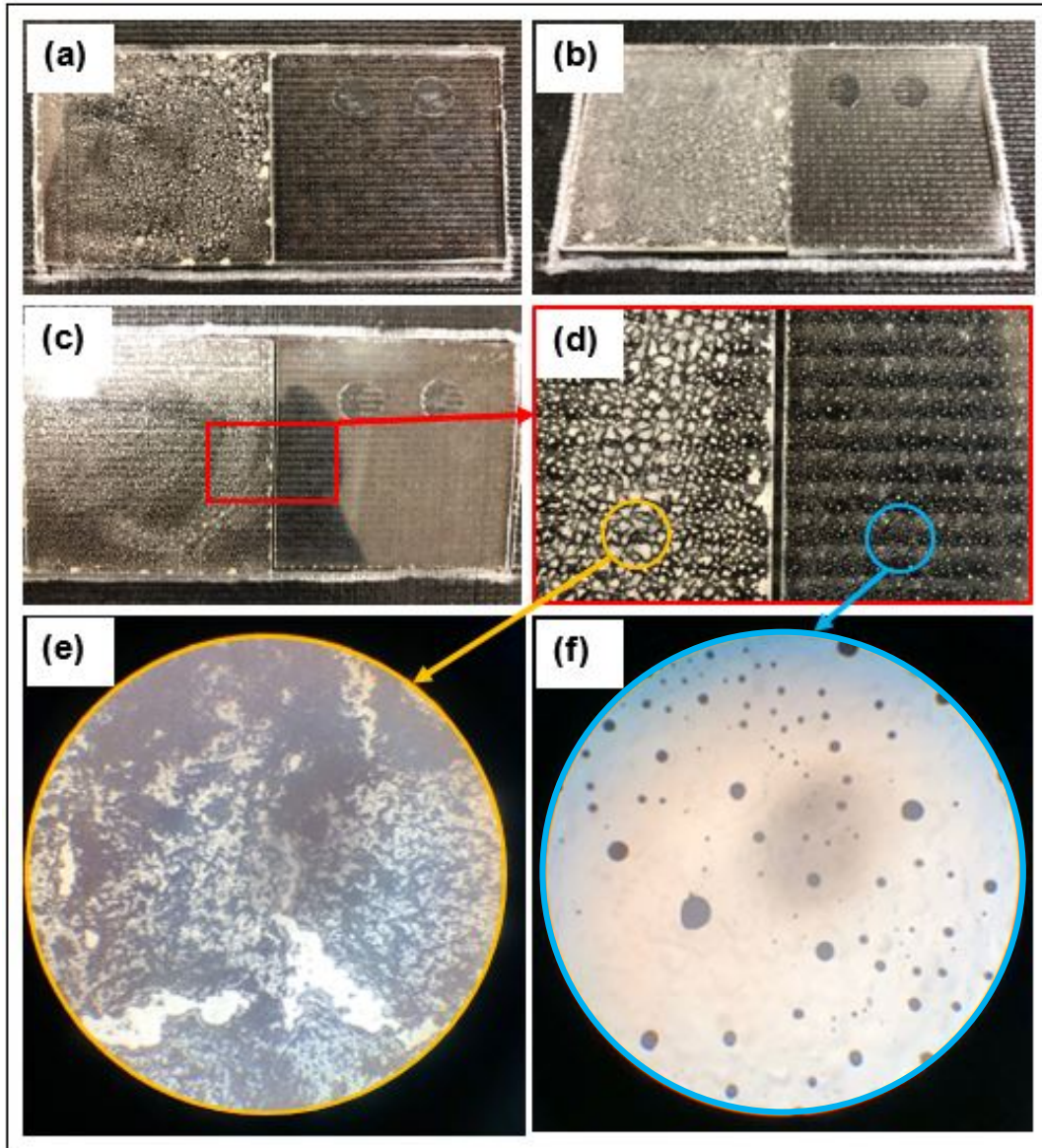


Figure 30. Dust cementation pattern differences observed between uncoated glass samples and (a) Coating F, (b) Coating I(s), and (c) Coating I(d). The hydrophobic coatings are the samples on the right of each frame. A closer inspection, (d) shows the soiling pattern differences more clearly, while (e) and (d) show 4x magnification of the soiling patterns for uncoated glass and Coating I(d), respectively. Coated and plain glass samples had statistically similar quantities of dust

The same amount of dust is being deposited onto the coated and uncoated surface. In dry-deposition conditions, the dust distribution looks similar between the coated and plain, uncoated substrates, and the transmission losses are the same. However, when dust is deposited on the

wetted surfaces, upon evaporation the soiling patterns/distributions result in significantly different visual appearances and transmission losses between coated and uncoated substrates. The dust is being essentially swept into “piles” during the water evaporation stage, exposing more unsoiled glass. Water droplets on low surface energy surfaces form more spherical droplets compared to higher surface energy (uncoated glass) surfaces, where the droplets spread out. The “roundness” of a droplet is essentially what the WCA is measuring. This roundness is explained by considering the force balance at the triple-phase contact line. Water, if isolated in weightlessness, will form a perfect sphere. This is because the surface tension of the droplet acts tangentially along the liquid-gas interface, while the bulk of the droplet pushes outward. Therefore, the most energetically favorable shape under these conditions is a sphere. When in contact with a solid surface, an additional force is introduced as the water wants to spread across the solid surface. The closer a solid surface comes to reaching a surface energy of zero, the more a droplet on this surface will behave as if it is isolated in a gas. Due to the lower surface energy of hydrophobic coatings when compared to glass, the water droplets under their own surface tension will bead up (higher WCA). Therefore, in the case of dust cementation, as the water evaporates on a hydrophobic surface the water droplet maintains its spherical-like shape. As the droplet shrinks in size, the entrapped dust particles are essentially “herded” into tiny piles along the surface. To demonstrate this concept, a simple test was developed. One sample of each coating and one sample of uncoated glass were placed in a four-square orientation under the IR heat lamp. A 600 μ l droplet mixture (60ml DI water and 1 g dust) was placed on the surface of each sample (Figure 31a) using a precision pipette. Notice the initial size differences in the equal-volume droplets on the coated versus uncoated surface. This is due to the droplets “beading up” on the coated surface, thereby decreasing the solid-liquid interfacial contact area.

The samples were then allowed to completely dry, and the entire process was filmed using time lapse video. In Figure 31b, about 19 minutes into the drying process, the water droplet on the uncoated sample is the first to completely evaporate. Notice how the size of the droplets on the coated surfaces have decreased in size from the initial frame. Figure 31c is about 35 minutes into the drying process. The cemented dust spot on the uncoated glass is about equal in size to the initial droplet, while the coated sample droplets are continuing to decrease in size. Finally, in Figure 31d, all four droplets have evaporated. From this process, albeit on a larger scale compared to condensed microdroplets, the concept of dust “herding” is clearly demonstrated. The droplet on the uncoated glass remains spread across the surface throughout the drying process, leaving a larger footprint of cemented dust behind. As the droplets dry on the coated surfaces, they hold their semi-spherical shape until they completely evaporate, leaving behind a significantly smaller dust footprint. This phenomenon clearly demonstrates the mechanism behind the varying soiling patterns observed, in addition to providing an explanation for the significant difference in transmission losses between the coated and uncoated substrates.

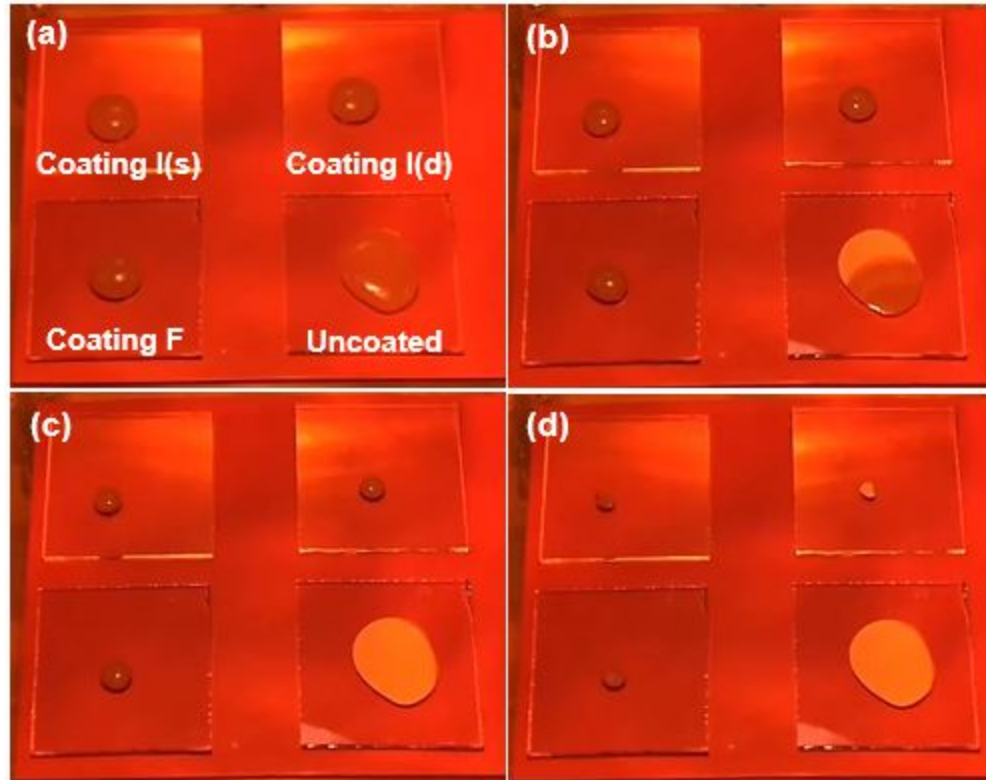


Figure 31. 600 µl water / soil droplet drying experiment with one sample from each coating and one sample of uncoated glass. (a) The IR heat lamp is turned on and the drying begins. (b) The droplet on the uncoated sample begins drying first (19 minutes). (c) The droplet is completely evaporated on uncoated glass, and the coated sample droplets have decreased significantly in size (35 minutes). (d) All droplets have dried (45 minutes).

Due to the significantly reduced footprint of the cemented dust on the hydrophobic surfaces, the overall adhesion forces are greatly reduced. The dust piles also have a much higher profile than the dust on the uncoated glass sample. Therefore, when exposed to the drag forces generated by compressed air, the dust is much more easily removed from the surface. For example, in the above droplet drying experiment, a compressed air pressure of only 20 psi was enough to remove the cemented dust “pile” from the surface of all three coated samples. The dust on the uncoated glass sample however, failed to be removed even at pressures as high as 120 psi. These same results were seen in the cementation/compressed air testing procedure. Therefore, the three hydrophobic coatings tested, due to a combination of reduced surface

energy, reduced polarity, and the dust “herding” phenomenon, demonstrated significant anti-soiling properties under dust cementation conditions. Not only were the coatings completely cleaned with compressed air, but the soiling losses due to cementation alone were significantly less when compared to uncoated glass. These results provide great insight to hydrophobic coating capabilities in significantly reducing soiling on PV modules in an outdoor environment, thereby increasing the overall power output of the module.

4.5 In-Field Coated vs Uncoated Module Performance

Testing in a laboratory setting is a necessary step in providing evidential data for the suitability of using a hydrophobic coating for soiling mitigation in the PV industry. Ultimately however, the coating needs to demonstrate sufficient anti-soiling capabilities in an actual outdoor environment in order to be considered suitable. Throughout this research project, Coating I has demonstrated high potential for use as an anti-soiling coating in the PV industry. Therefore, this coating was deemed by the CSU and Loughborough teams as the most successful from this research according to the many performance criteria established. Long-term in-field performance results of Coating I will provide direct evidence in its ability to act as an anti-soiling coating for solar modules.

4.5.1 Methods and Materials

From a test array located near the Next Generation Photovoltaic Center (Fort Collins, CO), one 70W thin-film module was safely unmounted and brought into the lab for coating application. The front and back side of the module were thoroughly cleaned using a combination of glass cleaner, IPA, and DI water. The Coating I formulation was then applied to the module using an HVLP sprayer at 14 psi and was allowed to cure in room temperature for 48 hours. The module was then remounted in the outdoor array next to an adjacent uncoated module of

identical make and power rating (Figure 32). The two adjacent uncoated modules were then cleaned using a microfiber cloth and glass cleaner solution. Due to the increased surface roughness, the reduced reflection can be seen on the coated module in the left image of Figure 32. For the next month, the modules were qualitatively tracked using photo-documentation to observe differences in soiling levels between the coated and uncoated module.

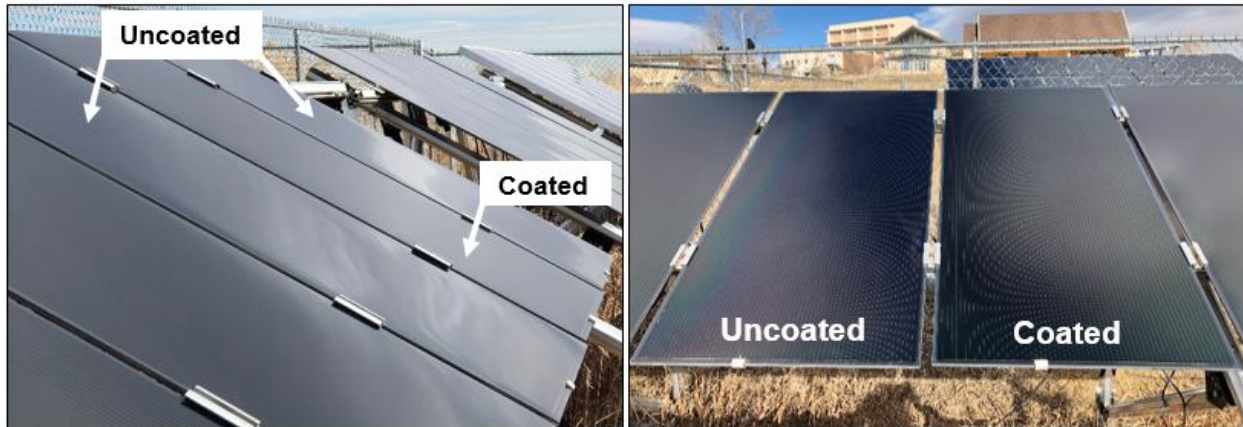


Figure 32. Coated module placed in test array between two adjacent uncoated modules.

Following the qualitative photo-documentation over the course of two months, the coated module and an adjacent uncoated module were measured for voltage over a resistive load and short circuit current over a period of one month. A variable power resistor was hooked up to each module to enable the load voltage measurement. From Ohm's law, the maximum operating current and max voltage listed on the label of each module were used to calculate the necessary resistance to approximate the max power point. The short circuit current and load voltage were measured using two hand-held multimeters (one for each module enabling simultaneous readings). Limitations with this method included only being able to take measurements on clear-sky days within the same time window (11am – 2pm), ensuring the day-to-day measurements were somewhat comparable. The presence of clouds can significantly impact the performance of a module due to interference with irradiant sunlight. This led to a limited number of data points

collected throughout the relatively short testing period of one month. At the start of testing, each module was thoroughly cleaned using a microfiber cloth and glass cleaner solution composed of IPA. Coating I(s) was previously tested for exposure to IPA via an hour long heated (80°F) ultrasonic IPA bath. Afterwards, the WCA and RoA were measured with no signs of performance degradation.

4.5.2 Results and Discussion

During the testing period (two months), three significant snowfalls had occurred. Therefore, photos were taken immediately after each snowfall, and then again after snow melt. Photos from the first snowfall can be seen in Figure 33 on the following page. As seen from the top photograph, the module coated with I(s) is completely snow free. Upon snow melt from the surface of the adjacent modules (bottom photo), a significant amount of soiling is left on the cover glass of the uncoated module. Forty-eight days later, another snowfall event occurred. The images, taken immediately after snowfall and again after snow melt, can be seen in Figure 34. Once again, the module with Coating I(s) is effectively preventing the accumulation of snow (top photograph). As the snow melts on the uncoated modules, it leaves behind dust and debris on the cover glass, increasing soiling losses (bottom photo). The soiling seen in both cases is dominantly adhered through cementation mechanisms, as the dust is wetted during the snow melt process.

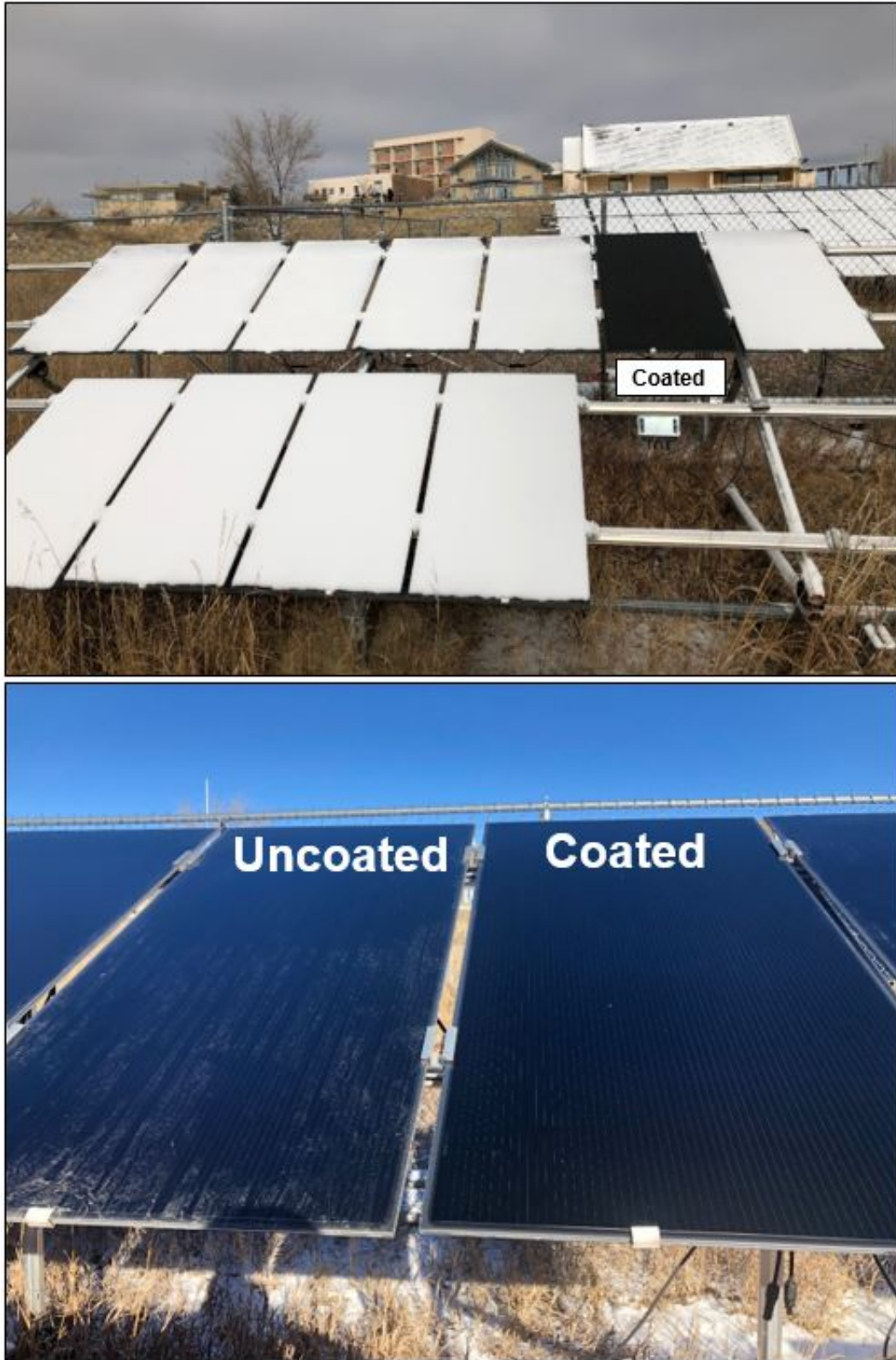


Figure 33. Prevention of snow accumulation on a module coated with Coating I(s). The top photo was taken immediately after the snowfall had ceased. The bottom photo was taken a day later after the snow had melted from the adjacent panels.

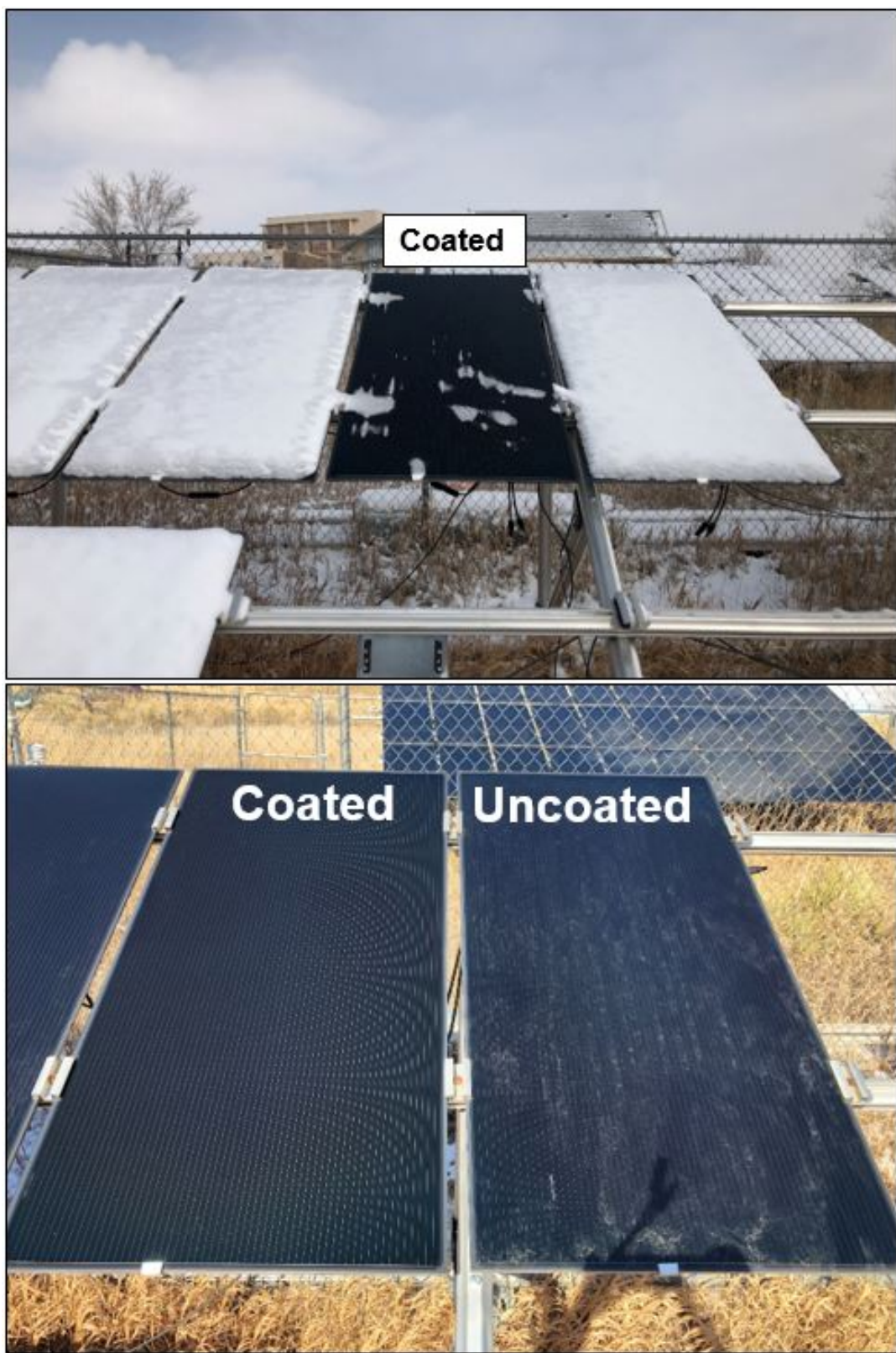


Figure 34. A module coated with I(s) preventing snow accumulation during a later snowfall event. The top photo was taken immediately after the snowfall had ceased. The bottom photo was taken a day later after the snow had melted from the adjacent panels.

During one of the intermittent snowfall events, twenty-four days after the first snowfall (Figure 33), photographs were taken in the middle of the snowstorm to better understand the snow-prevention process of the coated module. The photograph in Figure 35 was taken soon after the blanket of snow had broken free and slid from the coated module surface. The lower surface energy of Coating I(s) results in overall lower adhesion forces between the glass and snow, allowing the snow to break from a static position and slide from the module. A clear “break line” can be seen at the top of the module. The uncoated modules, due to a larger surface energy, are unable to shed snow as effectively. Essentially, the weight threshold before the snow blanket breaks from the surface is much lower for the coated surface. In addition, the spray applied coating layer is much rougher in comparison to the uncoated solar cover glass. Therefore, under “dry” snowfall conditions (below freezing temperatures), there is less solid-solid interfacial contact area due to the increased surface topography. This further reduces the adhesion forces between the snow and the module surface. It is hypothesized that the snow is in a sort of Cassie-Baxter wetting state on the coated module under these conditions. It is theorized the cyclical process of snow accumulation and snow blanket shedding is what keeps the coated module from accumulating a large layer of snow. However, in order to better understand the snow-accumulation prevention mechanisms at play, a time-lapse video of an entire snowfall event is necessary.

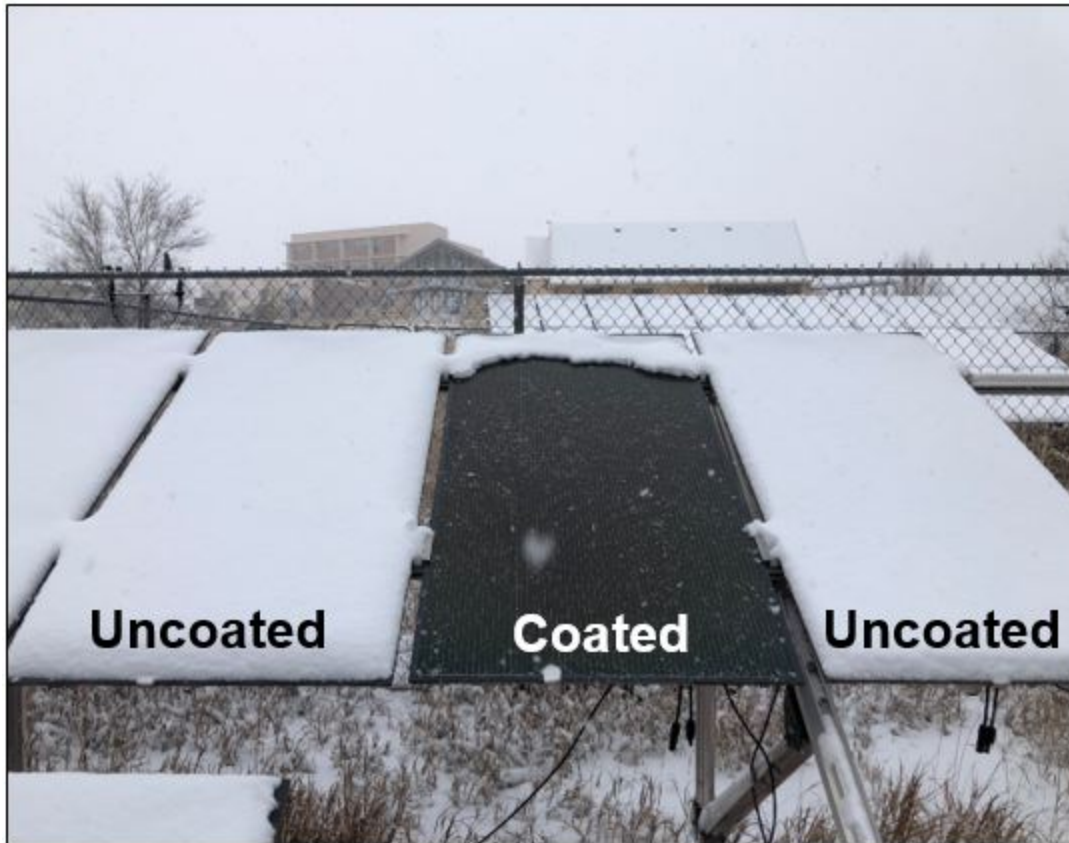


Figure 35. Photograph taken during snowfall of the Coating I(s) module and two adjacent uncoated modules. This image was taken soon after the “snow blanket” had broken free and slid from the surface of the module.

Photos were also taken after a 15 day-period of no snowfall to gain insight on how the coated versus uncoated module would soil in dry conditions. Figure 36 shows the coated module on the left versus the uncoated module on the right after this dry period. Soiling can be seen on both modules, however, much like is observed in the cementation/compressed air anti-soiling testing, the dust on the coated module is “herded” into small spots of soiling. From the soiling patterns observed, it appears dew/frost formation must have occurred being that there were no snow/rain events during this 15 day dry period. This explains the small droplet stains observed on the coated module, similar to those seen in lab testing.



Figure 36. Soiling patterns after a dry period (15 days) on the coated and uncoated module.

The load voltage (V_L) and short circuit current (I_{sc}) measurement results can be seen in Figure 37. This data spans twenty-two days, however, measurements were only taken on days of clear skies within a 11am-2pm time window. This was done to ensure similar levels of irradiance between measurements. On day 1, the modules were cleaned using a microfiber cloth and IPA glass cleaning solution. Due to the age of the modules, the baseline V_L and I_{sc} readings were not identical. The uncoated module read 70 mA higher than the coated module for I_{sc} , and 0.8 V lower than the coated module for V_L . Therefore, the data presented in Figure 37 is in terms of a voltage or current difference between the two modules, with a difference of zero being the corrected difference to accommodate for the clean baseline discrepancies. Any positive value differences detected in V_L and I_{sc} are theoretically due to increased soiling on the uncoated

module compared to the coated module. A general increasing trend in the differences for V_L is observed. However, the average V_L values measured for the coated and uncoated module over the test period were 25.1 ± 0.6 and 23.9 ± 0.6 V, respectively. Therefore, a maximum difference detected of 0.39 V is a fairly low percentage of the measured module voltages. The I_{sc} measurements showed no significant difference between the two modules, with a maximum difference of only 0.07 A. Although a slight increase in V_L is observed for the coated module, the soiling levels during the period of quantitative measurements were not severe enough to lead to significant differences. Due to the limitations of the methodology used, and the limited duration of testing, these results are not conclusive. More frequent data acquisition on the performance of identical class I modules, coated and uncoated, over a prolonged test period is needed to provide conclusive evidence on the anti-soiling capabilities of Coating I in an outdoor environment. The development for this type of in-field experimental procedure is currently underway. The qualitative results from the in-field testing do however provide strong insight for the suitability of using Coating I for soiling mitigation in the PV industry.

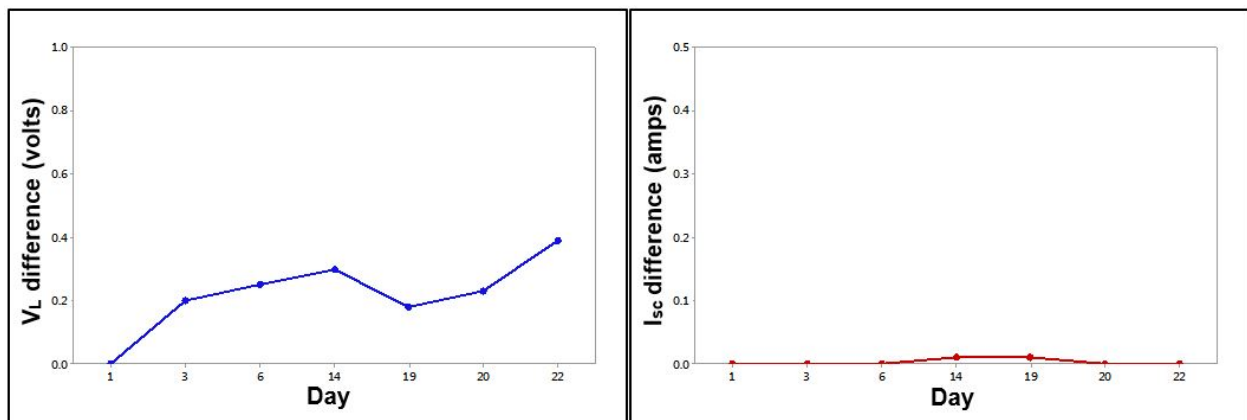


Figure 37. Load voltage (V_L) and short circuit current (I_{sc}) measured over a period of one month. Measurements taken on clear days in the time window of 11am – 2pm.

CHAPTER 5. CONCLUSIONS AND FUTURE WORK

The soiling of solar modules is a major power reduction mechanism, especially for utility-scale PV plants established across the globe. The utilization of hydrophobic coatings in reducing water and dust adhesion shows promise in providing a means of mitigating the performance losses associated with soiling. This research study was the first to investigate commercially available hydrophobic coatings, provide evidential data on their capabilities to reduce soiling losses, and suggest future improvements. Starting with ten coatings obtained from various industrial sectors, a group of candidate coatings were selected through a preliminary screening procedure. These coatings were then exposed to a standardized accelerated durability testing procedure design specifically for hydrophobic coatings on solar cover glass [22]. In addition, the anti-soiling properties of the candidate coatings were quantitatively examined using a first-ever anti-soiling testing methodology developed specifically for this research project.

Results from the anti-soiling testing procedure, both dry and cemented dust, demonstrated statistically significant anti-soiling properties for all candidate coatings. Coating F showed the most soil removal under dry-air dust deposition and low velocity air removal. Coating I(s,d) also exhibited good soil removal under dry-air dust deposition. Coating I(s) showed the best anti-soiling properties under dust cementation conditions. During the durability testing procedure, Coating I(s,d), Coating E, and Coating F demonstrated a stable WCA at or above 110° throughout the majority of UV exposure. Coating F however did show signs of early degradation in WCA for DH exposure, while Coating I(s,d) and Coating E remained stable. Coating J showed early signs of WCA degradation from both UV and DH exposure. All coatings saw a general increasing trend in RoA as a function of DH and UV. Coating I(s,d) however,

remained under the threshold of 25° for a prolonged period of time when compared to the other coatings, which saw rapid and immediate increases in RoA. Coating I(s,d) also exhibited the two lowest “as received” RoA amongst the coatings. Further testing of Coating I(s,d) showed promising mechanical durability under abrasion testing using a cheese cloth abrader, and reasonable durability under a CS10 abrader for I(s). The in-field testing for Coating I(s) resulted in astonishing observations, as the anti-soiling properties were visually significant. The ability to reduce snow accumulation was an unexpected, yet substantial, finding. Ultimately, the results from this research led to the identification of a single commercially available hydrophobic coating, Coating I, that demonstrates a strong potential for anti-soiling applications in PV.

Based on this work, a partnership is being formed between the coating research team and the company of Coating I to form a new research and development program. One of the key concerns lies in issues of durability for the hydrophobic coating. Although Coating I demonstrated stability of WCA for DH and UV exposure, and a lower rate of increasing RoA, it ultimately showed significant signs of degradation. A blister formation process was identified as the driving mechanism of physical degradation, which is hypothesized to be from entrapped solvents and volatiles escaping from within the coating. Partnering with the company’s chemist, variations in Coating I formulation, solvents used, and cure schedules will be investigated in an attempt to eliminate/reduce blister formation under accelerated DH and UV testing. Without blister formation, Coating I should remain stable under DH and UV in terms of WCA and RoA.

The in-field experimentation carries a lot of significance in providing data on Coating I’s suitability for PV use. The approach used in this research was technologically limited, over a short duration, and mostly qualitative. A more in-depth, longer-duration, and highly quantitative module performance tracking methodology must be used to provide conclusive data on the anti-

soiling properties for Coating I in an outdoor environment. A small array with brand new class I solar panels (multiple coated and uncoated) with data-logged performance tracking capabilities will be implemented over a period of at least 6 months. New modules will ensure an identical performance baseline, while a larger sample size of coated and uncoated modules will strengthen the statistical power of the study. Positive, conclusive findings from a study of this kind would carry significant weight in supporting the viability of Coating I as an anti-soiling solution.

A few show-stoppers for many high potential products in industry comes down to both economic viability (cost) and scalability. Coating I may pass durability testing, laboratory anti-soiling testing, and a prolonged fielded exposure with flying colors. However, none of this matter if the costs are too high, and the application processes cannot be integrated into existing high-volume solar manufacturing lines. The supplier of the coating must also be able to meet the high-volume demands of coating square-miles of modules. Further work with the company of Coating I will be executed to determine the economic viability of using their coating in the PV industry, to discuss alternative options in reducing the coating costs as much as possible, and to understand the capabilities for scaling up coating production. In addition, industrial level coating application techniques and optimization need to be examined. Further research and development may be needed to support the application of Coating I in a high throughput environment. The study may also need to investigate in-field versus in-factory application capabilities and methodologies of Coating I to enable coating or re-coating fielded modules.

Before this work, existing research efforts had not conclusively shown that hydrophobic coatings can survive the harsh environmental conditions experienced by a solar module during its lifetime. Research on the anti-soiling suitability of existing commercial hydrophobic coatings was also extremely minimal. This study is the first of its kind in identifying a commercially

available hydrophobic coating with great potential to solve a huge issue faced by PV electricity production across the globe. A reduction in soiling losses will enable the realization of making PV electricity a major source of energy.

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APPENDICES

A.1 Coating Characterization for Durability Testing

Table A - 1. Summary of WCA and RoA for all candidate coatings prepared for durability testing at Loughborough University.

Coating	Sample Number	Sample Size (cm)	Technology/Material	Application Method	WCA (deg)	Roll-Off Angle (deg)
Coating I(d)	85	5x5	Silane head with fluoro tail group	Dip	111.4	27
	86	5x5			111.8	24
	87	5x5			111.4	24
	88	5x5			111.6	23
	89	5x5			111.7	25
	90	5x5			111.1	25
	91	5x5			111.5	24
	92	5x5			111.7	24
	93	5x5			111.2	25
	94	5x5			110.9	25
Samples for SEM & XPS	95	5x5			111.4	24
Samples for SEM & XPS	96	5x5			111.4	25
				Average	111.4	24.6
Coating I(s)	97	5x5	Silane head with fluoro-tail group	Spray	110.5	26
	98	5x5			111.0	24
	99	5x5			110.3	25
	100	5x5			110.5	26
	101	5x5			110.5	26
	102	5x5			110.3	26
	103	5x5			110.5	25
	104	5x5			110.4	26
	105	5x5			110.1	24
	106	5x5			109.9	27
Samples for SEM & XPS	107	5x5			110.5	26
Samples for SEM & XPS	108	5x5			110.2	26
				Average	110.4	25.6

Coating E	50	5x5	Flouroalkylsilane (FAS17)	Wipe	113.2	31
	51	5x5			113.4	29
	52	5x5			112.4	28
	53	5x5			113.5	31
	54	5x5			112.5	31
	55	5x5			113.1	31
	56	5x5			111.1	31
	57	5x5			109.4	27
	58	5x5			111.7	29
	59	5x5			111.4	27
Samples for SEM & XPS	60	5x5			110.8	26
Samples for SEM & XPS	61	5x5			113.0	26
				Average	112.1	29.0
Coating F	60	5x5	Ethanol with special additives	Wipe	107.1	30
	61	5x5			107.1	30
	62	5x5			107.3	29
	63	5x5			107.6	31
	64	5x5			107.7	26
	65	5x5			107.2	29
	66	5x5			107.2	30
	67	5x5			107.6	28
	68	5x5			107.3	27
	69	5x5			107.5	28
Samples for SEM & XPS	70	5x5			107.5	27
Samples for SEM & XPS	71	5x5			107.4	29
				Average	107.4	28.6
Coating J	6	5x5	Covalently bonded nanoparticles	Wipe	107.9	31
	7	5x5			108.2	27
	8	5x5			107.0	28
	9	5x5			108.1	28
	10	5x5			108.5	30
	11	5x5			108.0	34
	12	5x5			106.5	25
	13	5x5			107.0	24
	14	5x5			107.0	24
	15	5x5			107.4	29
Samples for SEM & XPS	16	5x5			107.2	33
Samples for SEM & XPS	17	5x5			107.5	27
				Average	107.5	28.3

A.2 Transmission and Reflection Curves for DH Testing

The subsequent transmission plots were generated from measurements taken using an integrated-sphere spectrophotometer. The curves are not normalized by uncoated glass, and therefore contain transmission losses of the glass in addition to any losses from the coating.

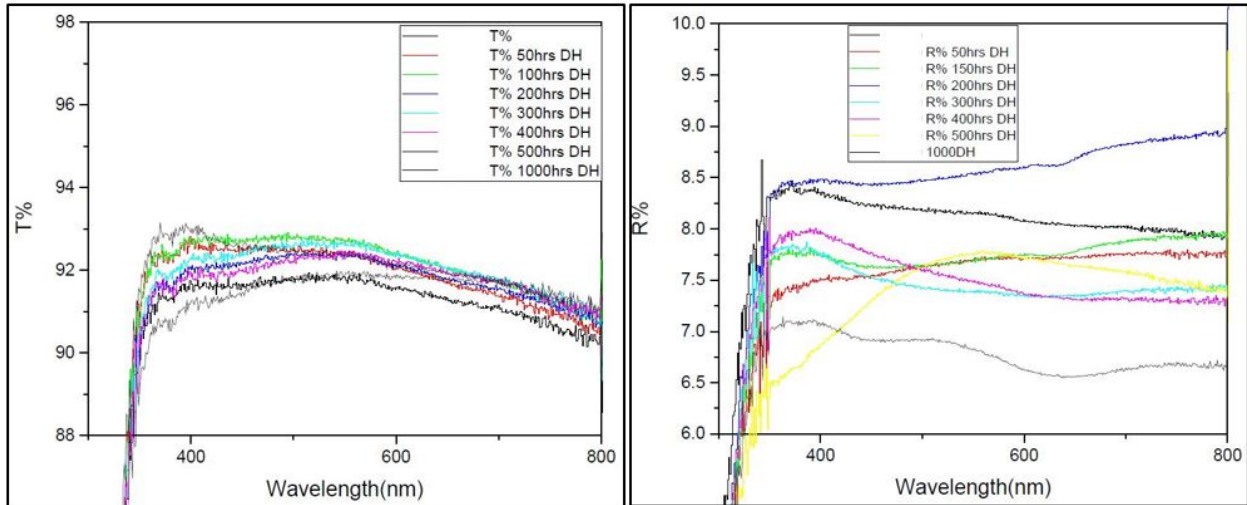


Figure A - 1. Coating E transmission and reflection data as a function of DH exposure.

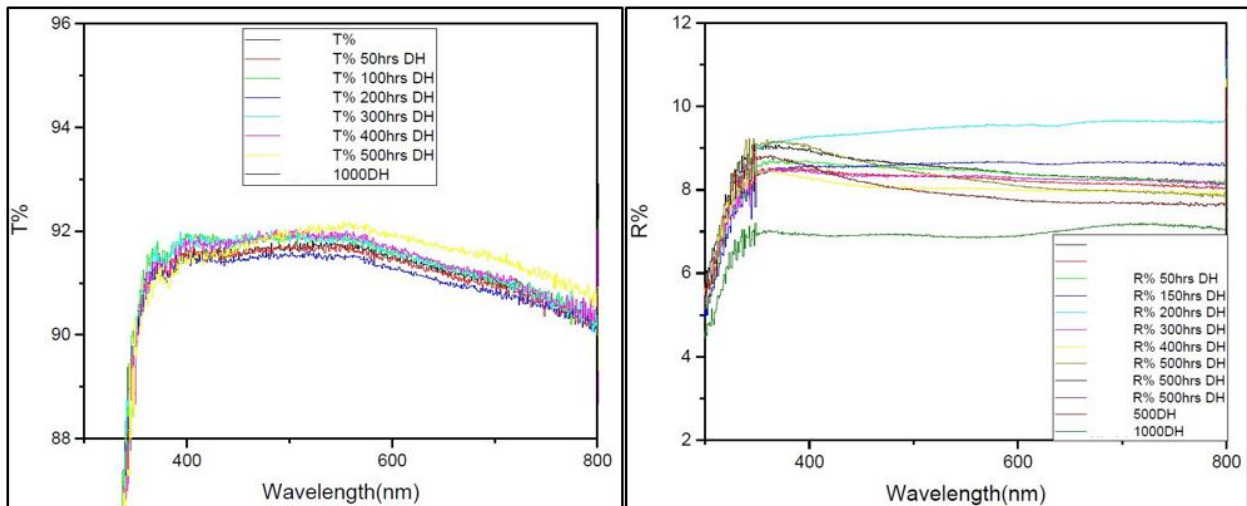


Figure A - 2. Coating F transmission and reflection data as a function of DH exposure.

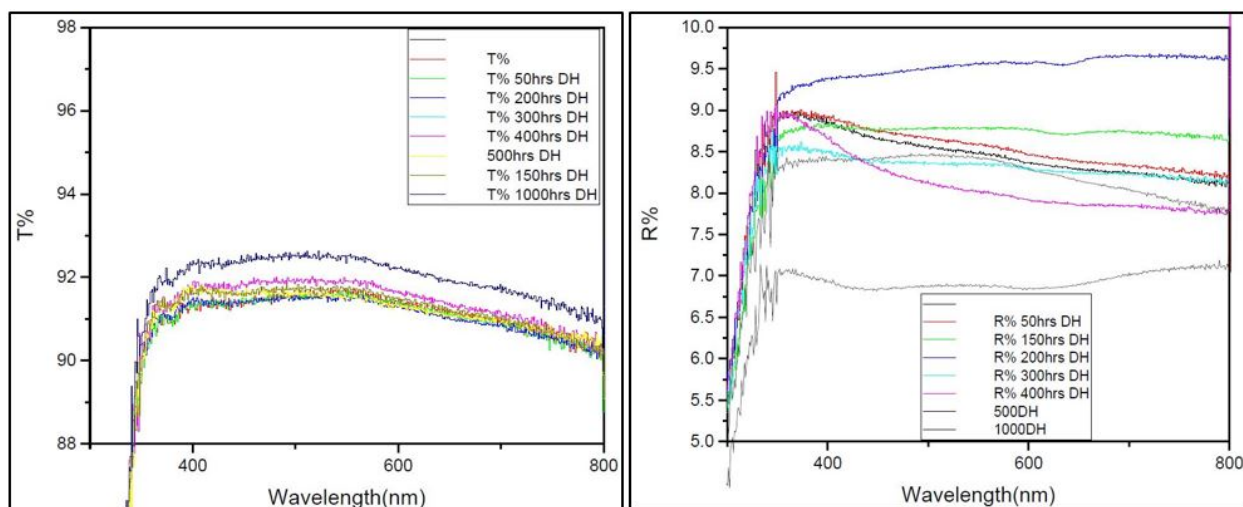


Figure A - 3. Coating J transmission and reflection data as a function of DH exposure.

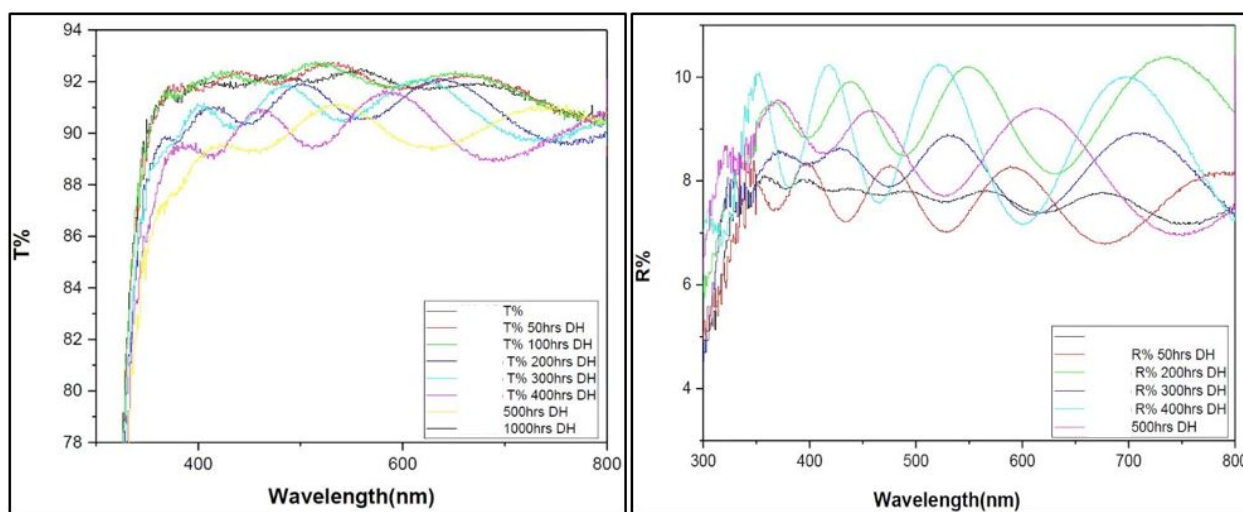


Figure A - 4. Coating I(d) transmission and reflection data as a function of DH exposure.

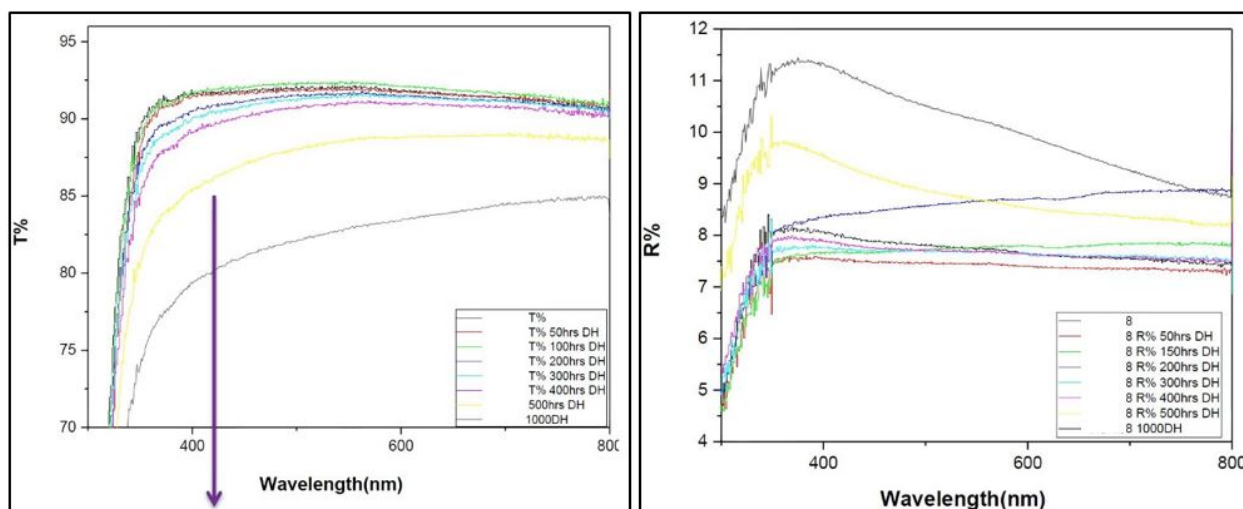


Figure A - 5. Coating I(s) transmission and reflection data as a function of DH exposure.

A.3 Transmission and Reflection Curves for UV Testing

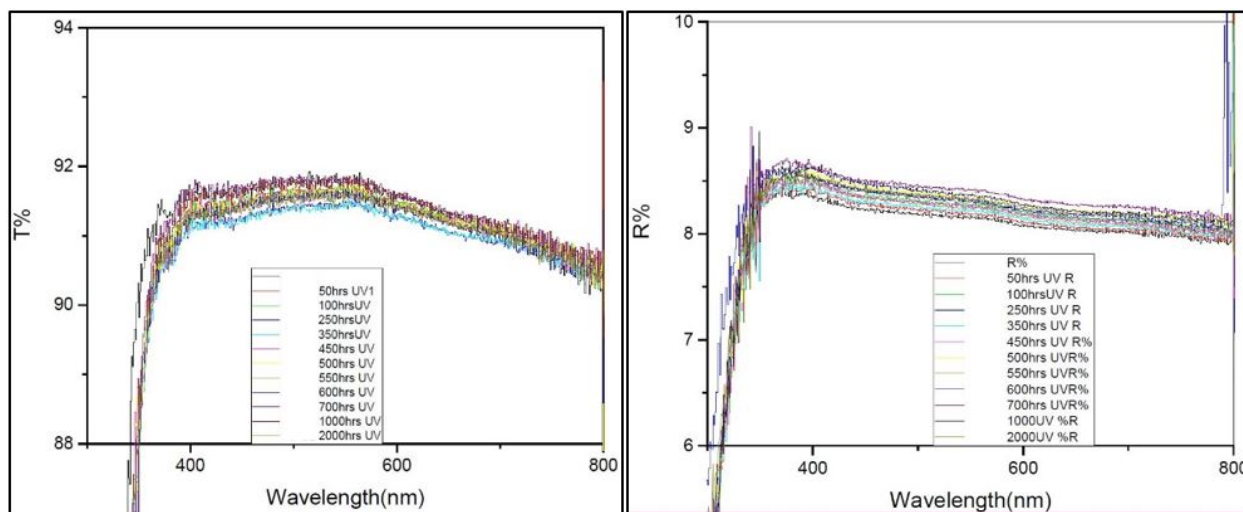


Figure A - 6. Coating E transmission and reflection data as a function of UV exposure.

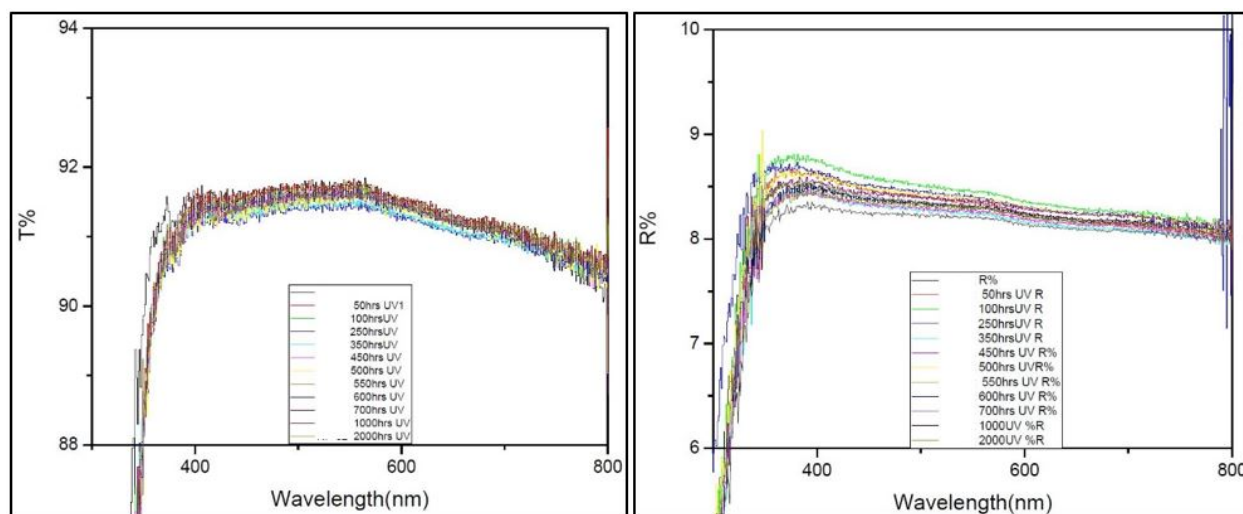


Figure A - 7. Coating F transmission and reflection data as a function of UV exposure.

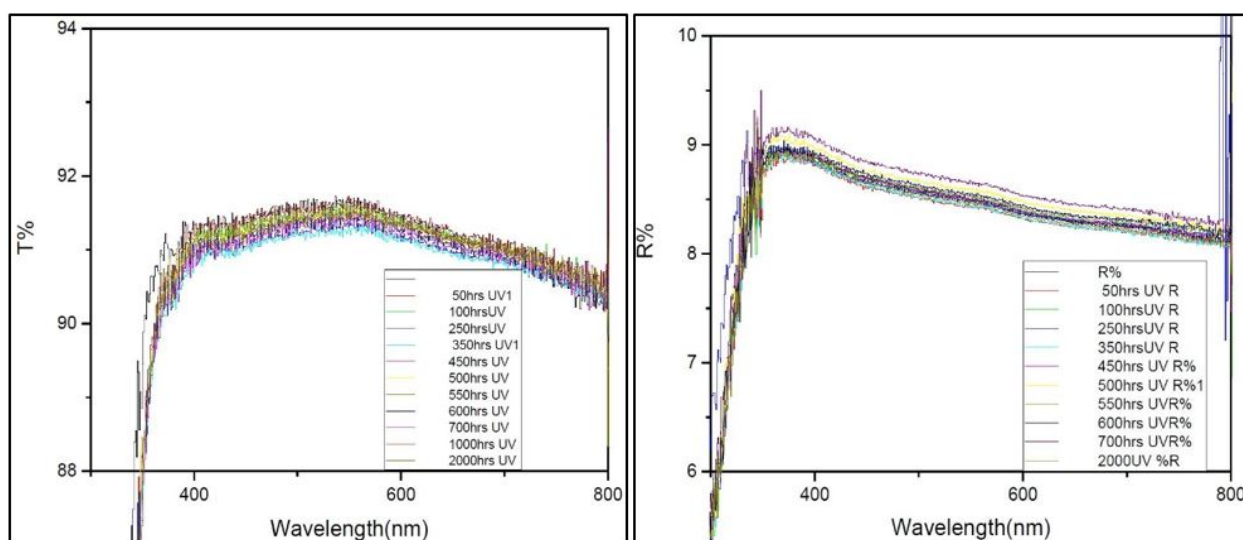


Figure A - 8. Coating J transmission and reflection data as a function of UV exposure.

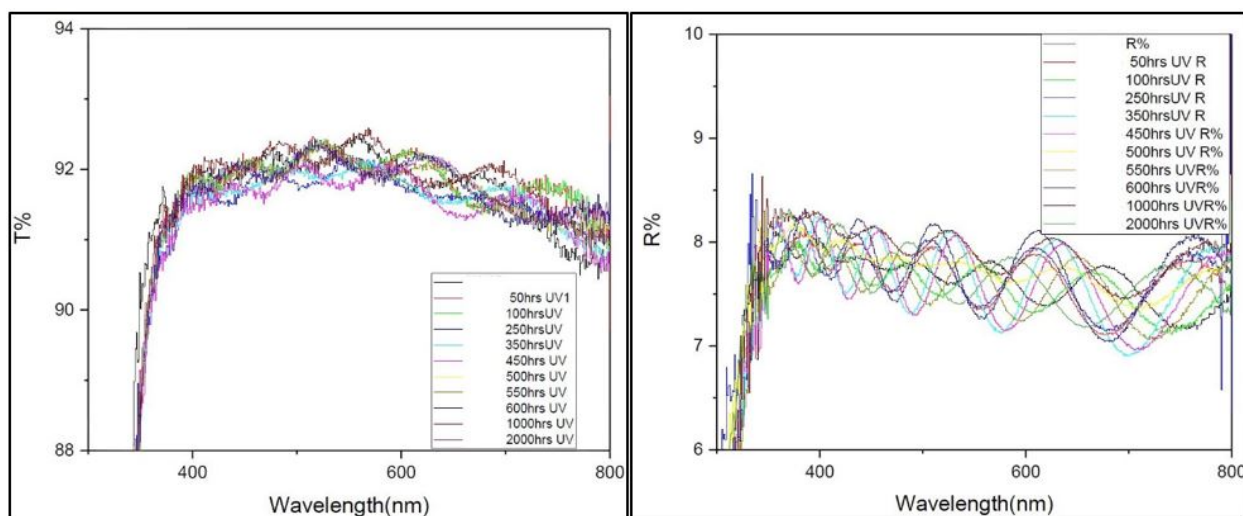


Figure A - 9. Coating I(d) transmission and reflection data as a function of UV exposure.

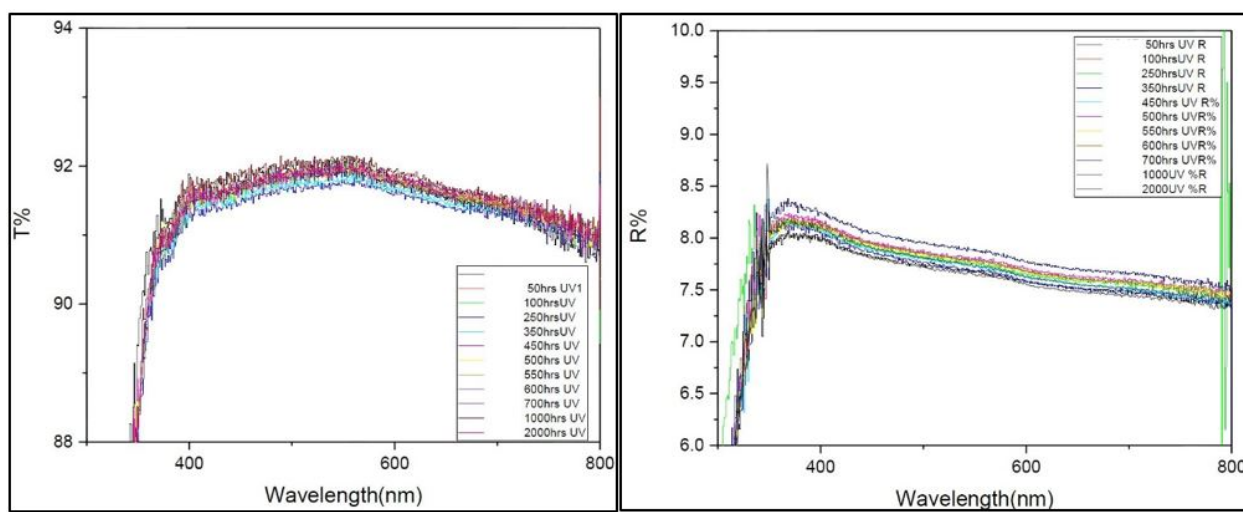


Figure A - 10. Coating I(s) transmission and reflection data as a function of UV exposure.