SunPower T0 Washing System

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Statement of Confidentiality

The complete senior project report was submitted to the project advisor and sponsor. The results of this project are of a confidential nature and will not be published at this time.

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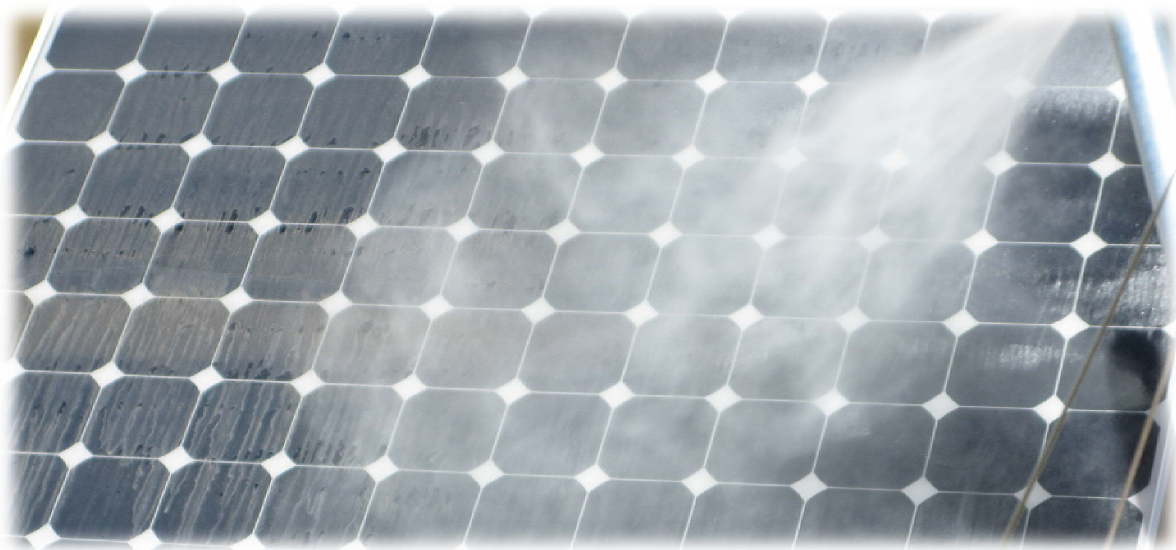
SunPower T0 Washing System



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Introduction

The initial purpose of this project was to develop a system to clean T0 ground mounted trackers installed in large solar power plants in order to improve overall electrical output. To justify cleaning, the system's operational costs needed to be less than the net additional revenue recovered from cleaning.

After presenting the initial design concepts to SunPower, the scope of this project was reduced. It was determined that initial groundwork was needed to identify ideal operating conditions. The purpose of the project was altered to develop a test rig to analyze the effects of different spraying parameters on the cleaning effectiveness and water consumption. Tests were performed using a high pressure water sprayer. SunPower provided a module for testing, which is used in their standard T0 ground mounted trackers. Data was collected and reduced to determine the ideal configuration for cleaning. If SunPower desires, this proof of concept rig can be expanded into a full scale and financially viable washing system.

Background

Cleaning Methods

There are several areas of research that are of interest to this project including residential photovoltaic (PV) cleaning services, methods of cleaning solar thermal parabolic troughs, and a report outlining the economic viability of cleaning a large PV system.

Online searches yielded two different companies that are currently in the business of cleaning PV solar systems. Solar Shine Cleaning manually washes residential and commercial systems with biodegradable cleaning products. Manually washing a system on the utility scale, however, would not be viable. Another company, Heliotex, actually integrates a sprinkler-like cleaning system into PV arrays. The systems are fully automated, much like a home automatic sprinkler system, and include wash cycles with biodegradable cleaners as well as rinse cycles. Similar systems have been implemented on plants as large as 6 MW, however the cost is prohibitive for use on a larger system.

During the background research, use of cleaning additives, water treatment, and alternative cleaning methods were encountered. A final cleaning system might address these issues in order to maximize cleaning effectiveness. For this initial design, only cleaning systems using pressurized water were of interest to SunPower.

Pressurized water is already used to clean similar solar power plants. A report sponsored by Abengoa Solar detailed the benefits of cleaning the parabolic troughs of a solar concentration power plant at Kramer Junction, CA. Three different methods of cleaning were considered:

Figure 1: Cleaning methods from left to right are a truck with leading and lagging spray heads, high pressure spraying with spinning nozzles referred to as “Mr. Twister”, and the direct contact “Zoom-Broom.”

The truck rig on the left utilizes a medium pressure, high flow rate (0.23 gal/m^2) and a large stand-off distance to achieve cleaning. “Mr. Twister” uses a high pressure spray (3000 psi) and a stand-off distance of roughly 3 feet in order to clean the solar troughs at Kramer Junction. This spray is achieved by a 150 horsepower positive displacement pump which delivers water at 45 gpm. The “Zoom-Broom”, on the far right, is a brushing device used for thorough cleaning which contacts the mirrors and utilizes low pressure and low water volume.

Based on the definition and requirements of the T0 project, the “Mr. Twister” approach is of greatest interest because it delivers high pressure water with a relatively close stand-off distance from the solar apparatus. According to testing of this device between the months of June and September, the reflectivity of the mirrors was consistently and sufficiently increased.

A study published by PowerLight details the benefits of cleaning a 20 MW Photovoltaic (PV) system in Nevada. The report covered several methods of cleaning including passive and active approaches. Active cleaning systems require physical removal of the soil whereas passive systems do not require any intervention for cleaning. The research, as shown in Figure 2, concluded that active cleaning several times during long stretches without rain yields the most benefit, but cleaning more than that would not be cost effective.

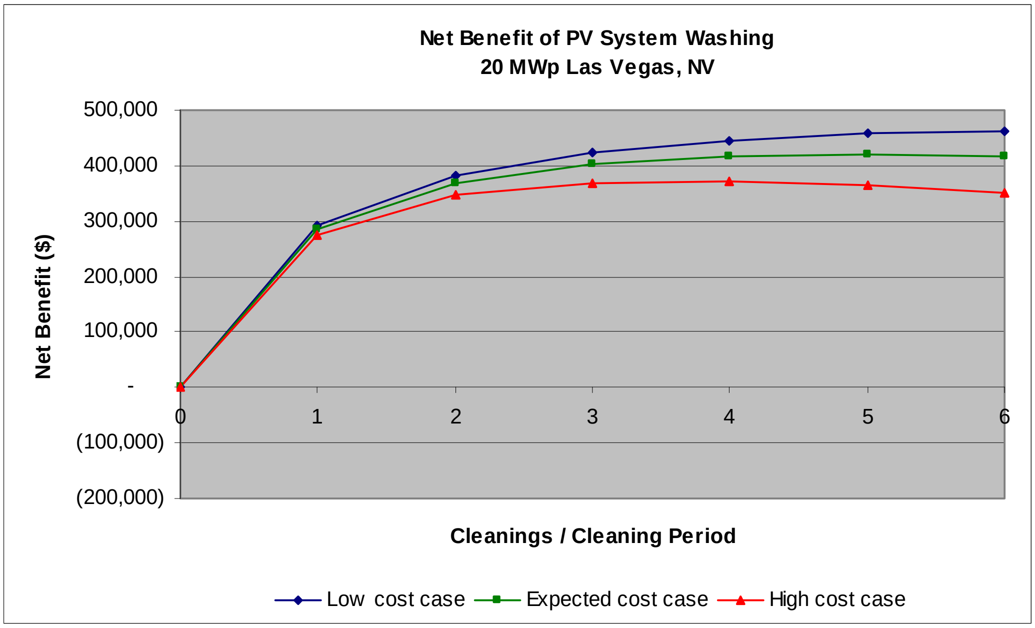

Figure 2. Net Benefit of cleaning a 20 MW single axis tracking system near Las Vegas.

Researchers have also investigated different passive systems. In one such passive system, glass is coated with a material which promotes the decomposition of organic matter when activated by ultra-violet light. A second coating provides hydrophilic properties to the glass, causing water to sheet off the surface easily. However, the coatings are dependent on water to clean away deposits and are ineffective in arid environments with little rainfall or where non-organic materials (i.e. smog, pollution, pesticides, etc.) are deposited. In addition, scientists at Purdue University have developed a product that can be added to water in order to clean glass surfaces soiled with oil and other non-organic materials. The benefits of these passive systems are difficult to quantify due to insufficient research, but the study performed in the PowerLight report suggests that passive techniques are not yet economically viable. Therefore, this project focused solely on the spraying parameters required to clean PV module glass.

Soiling Methods

In order to consistently test the cleaning effectiveness of various parameters, it was necessary to soil the panels uniformly and consistently. Two studies were found that detailed methods of artificially soiling glass. The first study, conducted by Saint Germain, was intended to observe the effectiveness of ultraviolet (UV) activated self-cleaning glass. A precursor to the testing involved the distribution of test glass throughout Europe to empirically determine what particulate adheres to glass. Using this data, an artificial soil and soiling method were created.

Another study was done by JPL to determine adhesion properties of different glass types used in photovoltaic modules. Similar to Saint Germain's testing, JPL placed many of these glass samples throughout the US. Some of the panels were located next to EPA particulate monitoring stations so the soil composition on the panels could be compared to the particulates in the air. Artificial soil and soiling methods were also created to accurately represent outdoor panel soiling.

Measuring Cleanliness

During the testing process, a system was needed to qualify and/or quantify cleanliness. Several methods were researched and considered, including visual inspection, observation with ultraviolet light, the "water break" test, gravimetric methods, measuring the current output of the panel being cleaned, and measuring the transmissivity of the glass being cleaned. Gravimetric methods were eliminated from consideration because the weight of the soil is miniscule in comparison to the weight of the solar module. Ultraviolet light can indicate cleanliness, but it will only illuminate organic compounds. The best way to determine cleanliness is a combination of visual inspection and measuring either module's electrical output or glass transmissivity.

Objectives

The objective of this project was to develop a proof-of-concept washing system that meets the following design requirements and specifications. This project evaluated many factors in order to minimize water consumption while effectively cleaning PV modules.

Design Requirements

These requirements were defined by SunPower and by considering the logistics and ethics of the project.

Our Design Must:

- Avoid direct contact with the solar panel surface
- Use high-pressure water
- Minimize water usage by varying cleaning parameters

  (i.e. pressure, flow rate, distance to module, etc.)
- Be consistent to evaluate cleaning parameters accurately
- Maintain a cleaning rate of 10000 m^2/hr
- Clean one row of PV modules on-site
- Avoid interfering with normal operation of the power plant
- Avoid etching the glass surfaces of panels
- Work independently of a tow vehicle
- Not harm operators or any part of the solar power plant

Engineering Specifications

Table 1. Engineering Specifications

Spec #	Description	Target	Risk	Compliance
1	Washing Speed	> 10,000 m^2/h	M	T
2	Water Usage	< 0.19 gal/m^2	H	T
3	Scrubbing Damage	< 1% change in I_{SC}/1000 washes	H	T
4	Power Restoration	within 1% of power before soiling	H	A, T
5	Weight		L	I
6	Power Consumption		M	A, T
7	Module Height	4-7 ft	L	I
8	Module Width	5 ft	L	I
9	Space Between Rows	12 ft	M	I
10	Ground Slope Change	5 degrees	M	T
11	Nozzle-to-Module Distance	<3ft	L	I
12	Pressure	< 1500 psi	H	A, T
13	Flow Rate	< 31.67 gpm	L	A, T
14	Cleaning Frequency	Bi-weekly	L	T
15	Row Length	85 ft	L	I
16	Row Gap for Drive Mechanism	4 ft	M	I
17	Number of Operators	1	M	T

L = Low, M = Medium, H = High

A = Analysis, T = Test, I = Inspection

Method of Approach

In order to achieve our design objectives, the following procedures were followed:

- Perform extensive background research
- Search for patents and existing technology
- Define quantitative specifications as well as project objectives
- Produce several conceptual designs
- Test various cleaning methods to determine the most effective nozzle
- Analyze concepts
- Create a decision matrix to determine the best solution
- Decide on a final concept design
- Detailed Design and Analysis of test rig
- Procurement of parts
- Manufacture and assemble test rig
- Test for optimal cleaning parameters
- Final design, analysis, and construction of prototype based on testing
- Present a working prototype

In order to divide the project into manageable sections, we will allocate the responsibilities as follows. However, it is understood that each team member will provide insight to all aspects of the project and that the assigned members are responsible for leading their categories.

Table 2. Team member responsibilities

Eric Wallace	Water Treatment
	CAD
	Communications
David Hohn	Testing
	Sprayer Components
Charlie Joy	Prototyping
	Procurement
Atlund Smith	Risk Mitigation
	Scheduling/Planning
	Editing
Entire Team	Manufacturing
	Documentation

Design Development

Initially, the understanding of this project was to produce a full scale prototype cleaning system able to be implemented at various site locations. Based on this goal, engineering specifications were developed to further define the project. Next, a variety of concepts were generated to meet the specifications. Below is a reduced sample of the top concepts as well as a brief description of each. A diagram of a power plant is provided to classify common nomenclature.

Figure 3. Sample T0 power plant layout with labeled nomenclature

Ride-on-Panel Concept

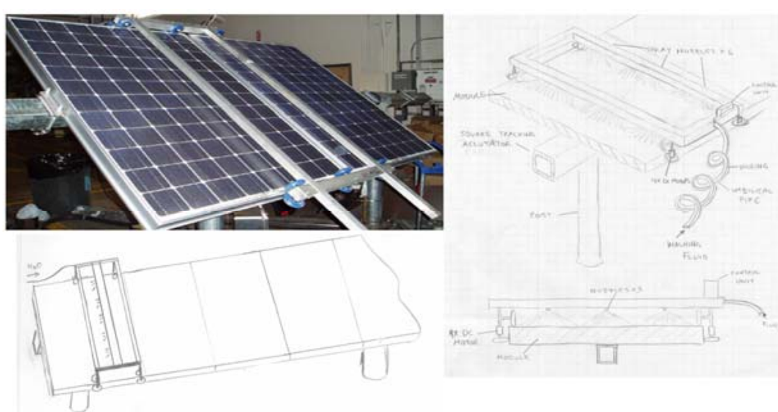

Figure 4. Concept sketches of ride-on-panel design. This method incorporates a lightweight frame with a nozzle array attached. This frame rolls directly on the module edges and travels down a row.

This system would be very effective in its water usage and cleaning effectiveness because this structure rides directly on the modules, maintaining nozzle alignment and stand-off distance. However, this direct physical contact compromises the safety of the power plant by exerting unnecessary forces on the

modules and the tracking system. This concept is also very labor intensive because there is no easy way to transfer it from row to row; an operator would have to carry the cleaner. Delivering water to this system is also a difficult challenge and would require a long hose or a small onboard water storage system. Due to sponsor feedback, this concept has been rejected because of the direct contact with the module surface.

Drive Up Row Concept

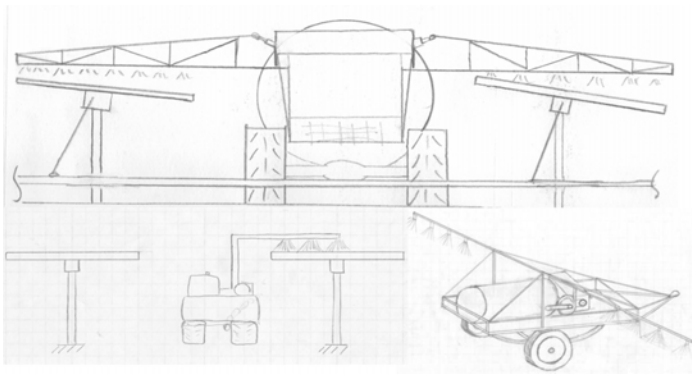

Figure 5. Concept Sketches of the Drive-Up-Row design. This method cleans panels by driving up each individual row.

The drive up row method would clean panels by driving a vehicle up each row. The vehicle has a boom arm which extends above the adjacent panel(s). The boom is equipped with an array of nozzles which spray down at the panel. This design is much more versatile than the ride on panel method because it can traverse between blocks and rows. This versatility also makes this design adaptable to most power plant layouts. This design is limited, however, by the linkages connecting each tracker within a block. Travelling over the linkages would be difficult and the rows are somewhat narrow, so this design would require an operator to back out of a row. Driving up each row would also be very labor intensive, and require continuous operator focus to avoid damaging panels or injuring the operator. Furthermore, this method would require a larger number of vehicles, which would impact the land at the power plant site as well as kick up dust. This dust could re-soil clean panels and may need to be suppressed with additional water.

Linear Move Concept

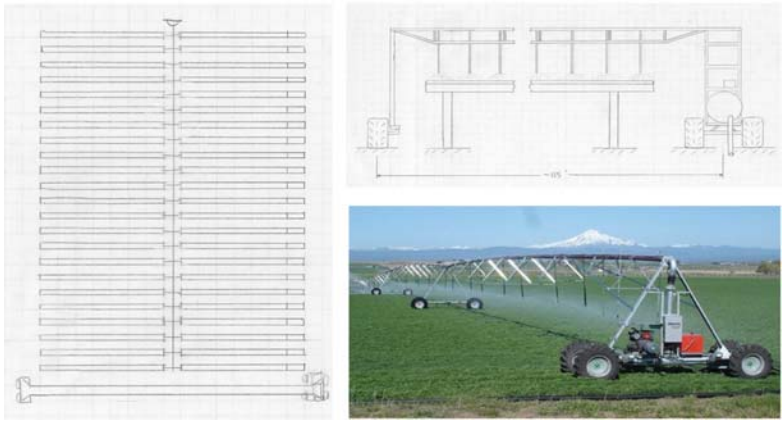

Figure 6. Concept sketches and a picture of the Linear Move design. This method spans the width of an entire block and can be repeated for multiple blocks.

The linear move concept has the potential to cover the largest area in a short amount of time because they can be constructed up to 1700 ft wide. The linear move system can span up to 120 ft between their support carriages, which is sufficient to span an entire block. These systems can be guided by buried or above ground wires, furrows in the ground or GPS systems. One problem with these systems is that they are designed to operate at a low pressure (30psi), whereas pressure wash systems require upwards of 1500 psi to clean glass effectively. Also, the water flow must be cycled on and off between each row to avoid wasting water. A linear move system would be ideal for rectangular plant layouts with adjacent blocks beginning and ending together. However, solar power plants are constrained by property lines and often assume abstract and inconsistent geometries to achieve proper alignment with the sun. So, adapting a linear move system to an entire solar power plant might not always be feasible. Water supply would also be a problem. Current linear move systems either drag a long hose (up to 750ft), or draw water from a trough along their path.

Aisle Concept

Figure 7. Concept sketches and pictures of the Aisle design. This method incorporates a large boom that spans half of a block on either side (100 feet total).

The aisle concept is a hybrid of the drive up row and linear move concepts. As opposed to driving up each row, a vehicle drives up the aisles between blocks. Two cantilevered booms span half of a block

(40-50 ft) on either side of the vehicle and nozzles along the booms clean the panels in the same direction of motion as the linear move concept. The aisle system also has a large cleaning rate like the linear move system, but has similar maneuverability to the drive up row method. This system relies on aisles, which are more consistent despite varying plant layouts. The aisle infrastructure throughout the plant could potentially allow one machine to clean an entire plant. This system does share the difficulty of cycling the water on and off between each row and incorporates large, difficult to build cantilever structures which could pose a potential threat to the solar modules.

Decision Process

In order to evaluate each concept, our team generated a decision matrix (see Appendix A). The criteria on the left are the driving factors in selecting the final design, and each is valued with a rank of importance. Next, each concept was ranked in its ability to meet the indicated criterion. The importance is multiplied with the ability to meet the requirement and the sum is computed to indicate the best design. Based on this analysis, we have determined that the linear move concept most effectively satisfies our design objectives. However, upon consideration of other factors, namely the time constraint of our senior project and the enormous scale involved with this approach, this project has been scaled down. Our goal became to develop a proof of concept to test and determine the ideal cleaning parameters to maximize the performance of T0 trackers (i.e.: pressure, flow rate, distance between module surface and nozzle, etc). Although our matrix indicates otherwise, we have decided to focus on developing a preliminary drive up row system to obtain data for future concepts.

Revised Project

The concepts above are all potential solutions for a large scale cleaning system. However, in order to design such a system, basic cleaning parameters must be known. After much consideration and consultation with SunPower, this project's goal was revised. Phase I of the new project was to produce a test rig to indicate ideal cleaning parameters. In Phase II, these parameters will be implemented on a system capable of cleaning one row of modules at an operating PV plant. The project has compiled necessary ground work for a full scale cleaning system in the future.

The desired parameters are pressure, flow rate, stand-off distance, nozzle fan angle, panel angle, and nozzle alignment. The alignment of the nozzle in 3-dimensional space can be defined by three angles: yaw, pitch, and roll. All these parameters together will be varied during testing to determine ideal values.

Decision Process for Test Rig

The test rig structural design is governed by the required degrees of freedom to allow for variable testing of spraying parameters. Several concepts have been developed to achieve the desired motion. These concepts include an industrial tripod concept, linear 8020 framing structure, and mast with guy wires. The industrial tripod would provide a rigid base structure with vertical variability. However, this design would require a sophisticated joint at the apex of the tripod to allow for pitch, yaw and roll. The linear 8020 structure would be easy to manufacture and the predesigned beams would provide vertical adjustments. Yet this design would require a series of hinges to produce the desired variability of the nozzle alignment. These hinges would increase the complexity and reduce the overall strength of the

structure. Also, the cost associated with the 8020 structure would be relatively high. Finally, the mast concept would utilize structural tubing fixed together with hinged fitting to provide all the necessary degrees of freedom. The mast concept (Figure 8) was selected based on ease of manufacturing, cost, and simplicity of variation. Preliminary bending and deflection analysis was completed to justify the size and material to use for the structural members. Static calculations ensured the stability of the cart (Appendix B). It was determined that guy-wires would be needed to further support the structure under dynamic loading (Figure 8), and improve the rigidity of the entire structure.

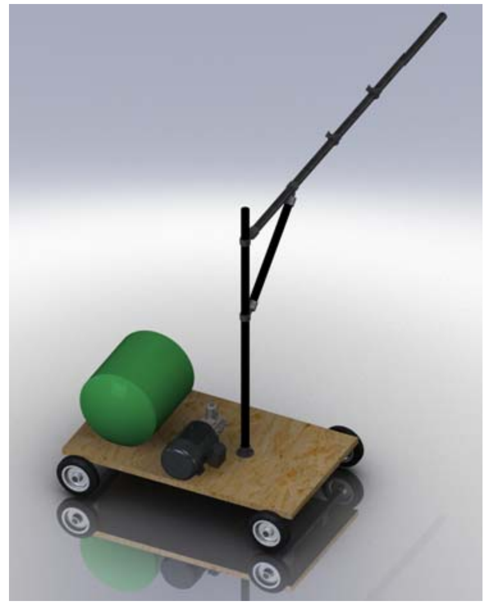

Figure 8. Example of mast concept

There was considerable discussion regarding how to move the test rig relative to the panel. The test rig and panel structure will likely be separate. The test rig will probably be heavier than the structure that holds the solar panel, so the notion of moving the panel instead of the test rig was proposed. This was ultimately dismissed because the panel would be more awkward to move due to its size. Also, the cleaning results may differ from those of a moving test rig. When moving the test rig, the water jet moves relative to the air, but does not in the case of the moving panel. Since the water jet momentum due to air resistance is difficult to predict, the results from moving the test rig more accurately represents the final application in Phase II.

Additionally, moving the test rig with or without a track was explored. The use of a track would mitigate bouncing due to ground roughness and would allow for more accurate control of the horizontal distance to the panel. After designing a track system (Figure 9), cost and stress analysis were performed. The track concept was rejected due to the additional loading it would experience in Phase II. Ultimately a cart was chosen because its 800 pound weight capacity and no track dependence allow it to be used for Phases I and II. Also, the cost of the cart was comparable to purchasing all the components of the tracked system.

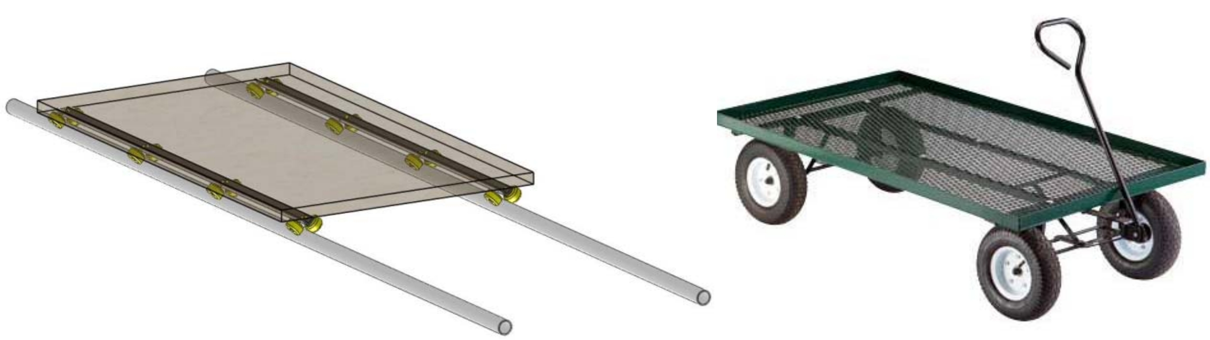

Figure 9. Left: PVC track system for accurate and repeatable movement of test rig. Right: Cart to provide easy mobility and sufficient load capacity for both phases of the project.

Description of Final Design

Design Description

The final design is a two phase project. Phase I is built on a cart capable of moving over varied terrain while carrying the cleaning apparatus. Phase I was to be modified to include additional nozzles and pumps for the Phase II requirement of cleaning an entire row.

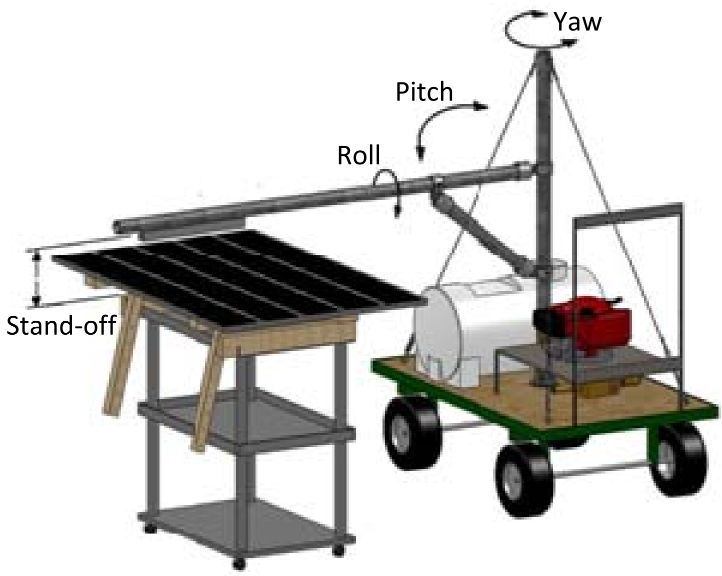

Figure 10. Final design of test spray rig and panel support.

Initially, the design called for plywood to be attached to the wagon bed to provide additional support and distribute the weight of the cleaning apparatus (Figure 10), but instead a ¼ inch thick steel plate was fastened to the frame of the cart and served as the anchor for the flange. A structure supports a water gun and nozzle. The structure consists of 3 members and is assembled in a form resembling a sailboat mast and boom. The mast is a 2 3/8 inch outer diameter galvanized steel pipe standing 5 feet tall, fixed to the cart with a 5 inch round flange. The boom is a pipe with the same cross sectional dimensions as the mast, but will be 7 ft long. The third member is 2 feet long and attached between the mast and boom to provide moment rigidity in the boom support. The joints connecting each of the members fasten using setscrews and can be rotated 180° in a single plane (Parts listed in Figure 11). All of these planes of rotation coincide, allowing the geometry of the structure to accommodate 4 degrees of freedom. By repositioning the joints using the setscrews, the boom is able to:

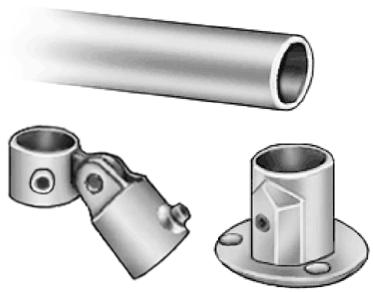

Figure 11. Galvanized structural pipe and its associated fittings

- **Pitch:** This will allow the manifold to remain parallel to a panel when the panel is tilted
- **Yaw:** This will allow testing with the cleaning boom swept forward or backward.
- **Roll:** This will allow testing of the nozzle array at different angles of incidence to the panel
- **Translate Vertically:** This adjustment will allow the system to accommodate varying module heights as well as varying stand-off distances.

In order to support the test panel, a wooden frame was constructed onto a lab cart. The frame has four angle settings to position the panel at 0, 15, 30, and 45 degrees. These settings correspond to the desired pitch angles for testing so that the panel and boom can remain parallel for each test. Since the size of the panel is much larger than the area of the base, tipping was of great concern. The pivot point was chosen such that the center of gravity of the panel will remain close to the center of the cart for all angle selections. To prevent tipping from the wind or being bumped, a bucket full of the soiling water was placed on the bottom shelf to act as a counter weight. Using a wheeled cart is an essential part of the design to facilitate testing passes and allowing relative ease in moving the panel.

Figure 12. Selected Pressure Washer

To avoid expensive pressure washer rental costs ($80/day), a small gasoline pressure washer was specified for purchase (Figure 12). As with most pressure washers, this system incorporates a positive displacement pump, and therefore operates at a constant flow rate for a given rotational speed. An adjustable unloader valve can be used to divert flow from the outlet of the pump straight back to the pump inlet, reducing the flow rate and backpressure in the main delivery line. A pressure gauge was specified for purchase to measure this backpressure. The pressure washer is rated at 2200 psi and can pump 2.2 gpm. This is sufficient to supply two 1/8'' MEG nozzles used to determine the ideal operating characteristics. A different pressure washer was purchased by SunPower that was able to supply 3800 psi and 4 gpm. The pump supplies two nozzles; however water will ultimately need to be supplied to several nozzles. Positive displacement pumps can be added in parallel to achieve the higher flow rate required. In order to select these pumps, testing must be done to determine the flow requirements of the system. Phase I of the project consisted of developing a two-nozzle spray rig prototype to collect cleaning data. This was to reduce the high costs associated with large pump and motor assemblies and identify the ideal cleaning parameters. The rig can be scaled up to include an array of nozzles, using a pump(s) capable of cleaning an entire row in Phase II.

A 25 gallon water tank was specified for Phase I, which is more than enough water to clean a full row of solar panels stretching 100 ft long using the maximum flow rate of 0.19 gal/m^2. SunPower purchased a different tank that holds 30 gallons. The tank was mounted to the cart using ratchet straps.

Figure 13. Horizontal water tank

The Phase II system can also be designed to clean a row of solar panels on a power plant site. The same boom and mast assembly from Phase I will have manifolds attached to house an array of nozzles or a spinning nozzle system with multiple rotor arms (Figure 14). The manifolds are able to distribute water to the nozzles and cover the entire width of a SunPower photovoltaic (PV) module. Each manifold, made by McMaster Carr, has 10 outlets spaced 2 inches apart, so the number of nozzles and nozzle to nozzle distance can be varied.

Figure 14. Dual rotor arm.

Analysis

Stress and deflection analysis were done on the structure to ensure the design's integrity. Deflection calculations indicated insignificant deflections due to dynamic loading using a 3 manifold design. Stress calculations indicated that a 2-3/8 inch structural tube will not fail under dynamic loading conditions. Additionally, static calculations indicate that the apparatus will not tip during normal operation. See appendix B for calculations.

The selected cart has a dynamic load rating of 800 lb, which can support a full 25 gallon water tank, 3 pressure washers, and the structure with manifolds. The selected wire rope can support a static load of 4700 lb which is reduced by dynamic loading and the stress concentrations in wrapping the wire to form loops. The eyebolts are rated at 1200 lb, however when loaded at a 45 degree angle, their working load is reduced by as much as 75%. The turnbuckles support a working load of 400 lb. Based on these parameters, the guy wire system can be tensioned up to approximately 350 lb. The operating tension will much be lower than this and will be determined empirically.

Additional analysis can be carried further to understand the effects of motor vibrations, heat generation from the engine to the water, deflection analysis of the mast and base, and forces required to accelerate the structure to the desired speeds. However, it has been determined that these considerations are superfluous and that each issue can be resolved during testing as they manifest. This conclusion has been justified based on the time required to model each aspect accurately versus the time saved during the build phase.

Safety Considerations

Safety is a primary factor in our design. Namely, damage to the solar modules, injury to operators, and excessive environmental impact must be avoided. Solar modules are very expensive pieces of equipment, and typically the power plants are owned by third parties. So, it is essential that the cleaning system in no way damages or interferes with the operation and performance of the power plant. Additionally, when working with large machinery there is a potential risk of injury to the operators. Proper precautions must be taken to minimize this risk. Lastly, the appeal of solar power must be maintained by mitigating environmental impact due to the cleaning system.

A low moment rigidity of the boom structure in the yaw direction results from the fact that setscrews are used to hold the joints together. These setscrews have low resistance to torsion, so if the boom were to collide with the panel structure, the setscrews would slip, allowing the boom to swing backward as opposed to dragging across the panel structure.

Since the pressure washing system operates at high pressures (1000-3800 psi), care was taken in selecting pressure bearing components. All of the manifolds, hoses, pumps, and fittings are off the shelf components, rated to capacities well above the operating point of the pressure washing system.

Maintenance

The nozzles are the most sensitive component in the washing system. Lower operating pressures also increases nozzle life. Periodic cleaning of nozzles is needed and proper installation of nozzles must also be ensured. The positive displacement pump needs to be oiled periodically.

Build Plan

The build plan consists of two phases: the test-rig and the final sprayer. The test-rig will be used to determine optimal flow parameters and size the pump system, and the final sprayer will be constructed according to these parameters.

The construction of the test-rig commenced when parts were received during Winter quarter. The main body of the device consists of a trailer with a platform that can easily be pulled. An off-the-shelf pressure washer, including gas tank, motor, and pump was mounted onto the platform during storage, however because it needed to be fed from a tap, it was removed and remained stationary during testing. The spraying components of the washer were attached to a boom with four degrees of freedom. The spray rig consists of a vertical pipe that is about 5’ tall and is connected to the trailer frame via a galvanized iron floor flange and four bolts. The rig also consists of a boom pipe, about 7’ long. This boom is supported by a 45° pipe of about 2’. All pipes are galvanized steel, have a diameter of 2.375”, and are connected using adjustable angle tee joints, which are made of galvanized iron and hold the pipe with set screws. If the set screws are not strong enough, it may be necessary to drill holes in the joints and pipes for pins. The boom supports the hose and lance of the pressure washer with two pipe clamps. All of the necessary pressure washer components are connected using high pressure hosing.

Guy wires were formed into loops using the combination wire rope clips and attached to the cart frame using 4 eyebolts and turnbuckles. The guy wires were also attached to the mast using eye bolts. The cable was tensioned slightly before tightening the rope clips and fine tensioning was done using the turnbuckles (cable tension corresponds to torque applied to the turnbuckle).

For the final sprayer in Phase II, there can be an array of MEG nozzles or a rotating spray bar mounted to the end of the boom pipe. The 6061 aluminum alloy manifolds are 2’ long and consist of 10 outlets and 2 inlets each, and can be attached to the structural pipe with single backing plate u-bolts made of galvanized steel.

The actual assembly of the test rig and panel holder went mostly according to plan. Since the specified pressure washer and tank were not received some adjustments were made to get the correct fittings and the orientation of the tank was changed to clear the guy wires. Figure 15 shows the network of fittings required for spraying water. The proposed plywood board for the cart bottom was replaced with a small steel plate for added strength. A high pressure hose was used to switch between using a single nozzle and the spinning bar, and also to provide easy adjustments when sliding the nozzle up or down the boom. An aluminum plate was machined to rigidly support a single nozzle or the swivel joint for the spinner. The plate has additional holes in order to be attached to the boom with U-bolts. The U-bolts are tightened down with wing nuts in order to reduce the time to secure the plate during testing. A removable shelf was attached to the panel to position the reference cell parallel to the panel face.

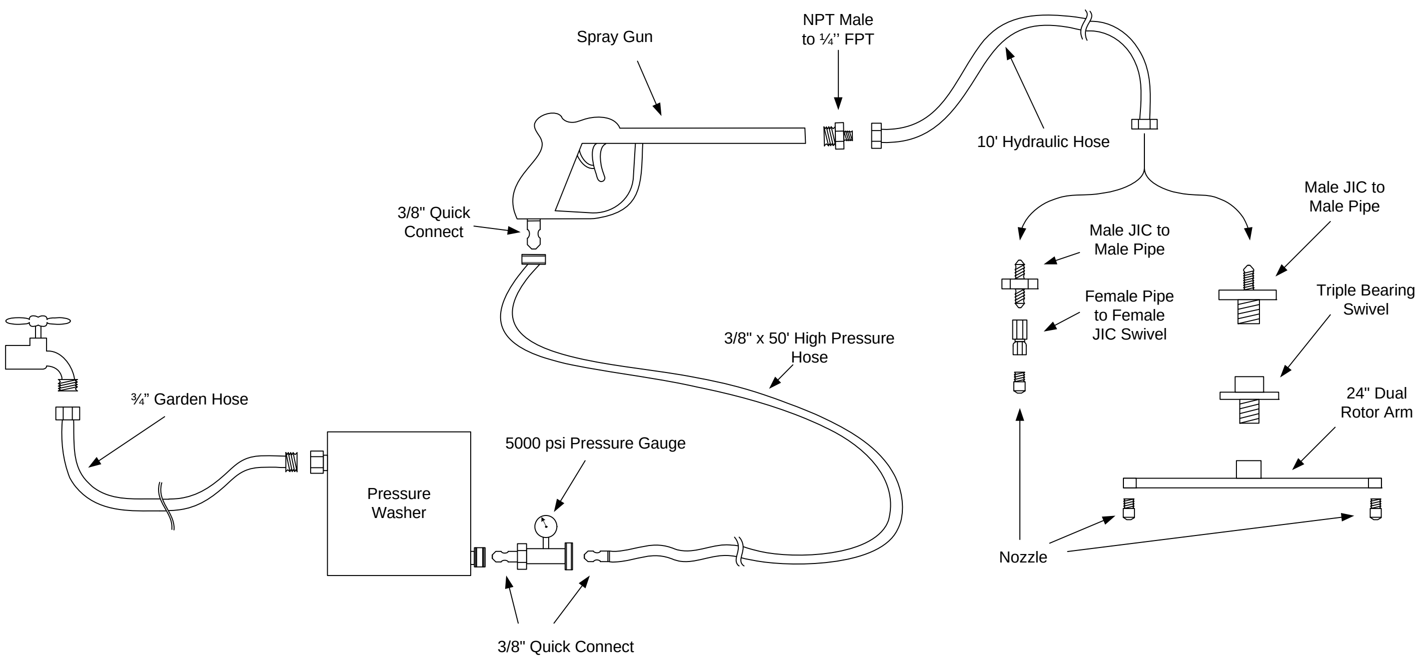

Figure 15. Water flow diagram depicting all of the water carrying components used in the T0 test rig.

Verification Plan

This project consisted of testing in order to determine several parameters of the design. Testing consisted of selecting nozzle parameters in order to size a pump and motor for the next phase. The cleaning effectiveness of several parameters was assessed while keeping other parameters fixed. Both rotating and linear nozzle arrays were tested, at nozzle spray angles between 0° and 40° in order to determine optimal stand-off distance, roll angle, lead angle, pressure and flow rate. The cleaning ability of a given arrangement was determined in two ways. The first was a visual test, and the second was a short circuit current comparison test. A detailed test plan is included in Appendix E.

In addition to testing these parameters, the linear velocity of the test rig was recorded to compare cleaning effectiveness at different speeds. In order to soil panels, dirt and dust were mixed with water and applied to the solar panel provided by SunPower. A variety of other soiling techniques were also attempted.

After the Phase II design has been constructed, there will need to be more testing to verify that it meets the design requirements and specifications provided by SunPower. The main requirement is to maintain sufficient cleaning effectiveness while minimizing water usage. To test speed, which must be at least 10,000 m^2/hr, one row of panels will be cleaned by the device, and then extrapolated to values on the scale of a full plant. To test the quality of the cleaning, which must return the panels to within 1% of their output when unsoiled, the current outputs of unsoiled, soiled, and device-cleaned modules will be taken and compared. Lastly, to test the flow rate, which must be under 31 gpm, the device will spray water into a bucket for a set amount of time and then the bucket will be weighed to determine the amount of water used.

Testing

Experimental Procedure

Experiments initially started with a clean panel in order to normalize the testing conditions and to reduce variations due to residual soil and water deposits for later comparison. The panel was thoroughly cleaned with water, a commercial, biodegradable glass cleaner (409), and finally scrubbed with a sponge. After a final rinse, drying was expedited with a squeegee to eliminate hard water build-up. Measurements were then made on the clean panel to establish a base line reference for the subsequent panel conditions. These measurements included the cell temperature, the ambient temperature, the short circuit current from the panel, the voltage of the pyranometer, the open circuit voltage from the reference cell, and the voltage across the shunt resistor in the reference cell. The voltage across the shunt resistor was then used to find the short circuit current of the reference cell.

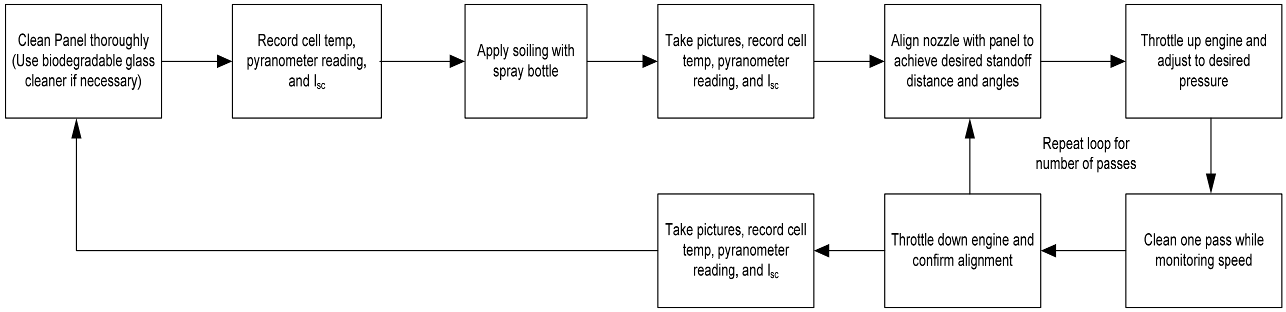

Figure 16: Flow chart of experimental procedure

Next, the panel was soiled by spraying a dirty water mixture through a spray bottle onto the panel. Even soiling was achieved by visual inspection. Although the exact composition of the water mixture is not rigidly monitored, the ratio of dirt to water was roughly 1 to 6. After the panel fully dried, the aforementioned measurements were again recorded. Additionally, pictures were taken as a visual reference for later analysis. At this point the panel was positioned along with the test rig. The test rig was configured for the desired geometry of the test (i.e. stand-off distance, boom angles, and panel angle). Next, the pressure washer was started and tuned to the desired test pressure. The initial pass over the panel was made while carefully monitoring the speed display. Then, the engine was throttled down while the test rig and panel alignment are confirmed. The nozzle was repositioned down the boom and the next pass was performed. This process was repeated until all passes were completed and the panel was *clean.* The average speed per pass was calculated and recorded. Finally, the panel's performance measurements were recorded and additional pictures were taken. The test cycle was then repeated from the beginning while changing one primary variable.

Equipment List

The devices used for testing are as follows. Pictures of the electrical components are in Appendix H.

- Photovoltaic Solar Panel – T0 module model SPR-305-WHT-I
- Digital Multimeters
    - Craftsman 82312
    - Kosmos RE830B
    - CEN-TEC
- Monocrystaline Photovoltaic Reference Cell 23
- Pyranometer- Hollis Observatory, model MR-5, part number 3002-A-1
- Thermocouple- Omega model HH23
- Non Contact Thermometer- Kintrex model IRT0421
- Spedometer- CATEYE Mity8
- Spray bottle(s)
- Buckets

Data Analysis

Several corrections had to be made to the recorded measurements in order to compare results. Because they are made out of semiconductor material, the output of solar panels vary significantly with temperature. Panel temperatures were recorded at every step using a thermocouple taped to the center of the back of the panel. This temperature was used with the measured short-circuit current to determine the effective irradiance on the panel. Another equation was used to determine the temperature of the reference cell using the voltage measurements, and this was then used to calculate the effective irradiance on the cell.

Since the available power from the sun is not consistent, the results of each series of measurements had to be normalized for them to be meaningfully compared. The effective irradiance on the panel was normalized against that of the reference cell as well as the voltage measured from the pyranometer. Lastly, these normalized values were then divided by the amount of water used for that particular configuration. This allowed the data points to be directly compared to one another in order to determine optimal parameters. The necessary calculations are as follows:

Effective Irradiance on panel:

$$I_{SCO} = \frac{I_{SC}}{[6.140(1+0.00057(T_m - 25))\}}$$

Temperature of panel:

$$T_m = T_{measured} + 3$$

Effective Irradiance on cell:

$$E_e = \frac{V_{shunt}*1000}{[58.94\left(1+0.0002(T_c - 25)\right)]}*1000$$

Water used:

$$V = \frac{N*Q*(5.117\,ft)}{v}$$

Reference Cell Temperature:

$$T_C = \left[\frac{V_{OC} - 0.67 + (298.15)(-0.177)}{(1.158)\left(\frac{1.38066*10^{-23}}{1.60218*10^{-19}}\right)*\ln\left(\frac{V_{shunt}*1000}{58.94}\right) - 0.002}\right] - 273.15$$

$I_{SCO} =$ Effective Irradiance on panel [W/m^2]
$I_{SC} =$ Short-circuit current of panel [mA]
$T_m =$ Effective temperature of panel [°C]
$T_{measured} =$ Thermocouple temperature reading [°C]
$T_c =$ Temperature of reference cell [°C]
$V_{OC} =$ Open-circuit voltage of reference cell [V]
$V_{shunt} =$ Voltage across reference cell shunt resistor [V]
$E_e =$ Effective Irradiance on reference cell [W/m^2]
$V =$ Volume of water used in cleaning [ft^3]
$N =$ Number of passes made
$Q =$ Flow rate of pressure washer at given pressure [ft^3/s]
$v =$ Average velocity [ft/s]

Future Considerations

While executing the testing phase of the project many unanticipated problems occurred. Some of these problems were corrected to the best of our ability, but others were circumvented due to financial and time constraints. The following sections detail problems we encountered and our recommendations for resolving these issues and continuing the research.

Water tank

In order to accommodate the stand-alone trailer requirement, a water tank was purchased to feed the pressure washer. At the time of designing the device and ordering equipment, it was unknown that most commercial pressure washers require a certain pressure and flow rate at the pump inlet. The pump that was acquired requires an inlet pressure of 20 psi and a flow rate of 4 gpm. This inlet pressure and flow rate could be accomplished in one of three ways: gravity, hose-feed or a booster pump. In order to gain the required pressure with a gravity feed system, the tank would have to be placed about 46 ft above the pump inlet, neglecting friction losses through the hose.

$$P_{suc} = \rho g h$$

$$h = \frac{P_{suc}}{\rho g} = \frac{20psi\left(144\,\frac{in^2}{ft^2}\right)\left(32.17\,\frac{lb_m}{lb_f}\frac{ft}{s^2}\right)}{\left(62\,\frac{lb_m}{ft^3}\right)\left(32.17\,\frac{ft}{s^2}\right)} = 46.45\;ft$$

This option is very impractical. The use of an additional centrifugal pump between the tank and pressure washer would resolve this issue. However, since the use of the tank would marginally increase the learning achieved through testing, it was decided to operate the washer from the tap water source at Bonderson Project Center (which was adjacent to the testing site). This required running a hose from the building to the pressure washer. This solution allowed the proposed testing to proceed, but prevented the rig from being used as a stand-alone device. If in the future it is desired to regain this mobility, a pump can easily be fixed between the tank and pressure washer.

Water Treatment

Initial research into the topic of solar panel cleaning suggested that water treatment would be necessary to mitigate reduced panel output due to mineral deposits. There are several options for treating water including Reverse Osmosis, Distillation, Filtration, Deionization, and Water Softening.

The water from the Bonderson Project Center was hard water, which resulted in minerals drying on the panel (water spots). The water was used for both soiling and cleaning and seemed to leave traces of minerals. The concern was that the mineral deposits would get progressively worse if the panel was not returned to a clean state after each set of passes.

Several tests were performed to determine the effect of these water spots on our ability to collect meaningful data. Tests were performed by cleaning the panel with solvent and repeatedly rinsing it with tap water and allowing it to dry. These tests showed little or no decrease in panel output due to mineral deposits. However, the prolonged effects of hard water would probably be much more significant in reducing panel output. To avoid compromising our efforts, the panel was cleaned thoroughly with 409 biodegradable glass cleaner and a squeegee after each set of passes. This ensured consistent starting conditions which would negate the effect of the water spots.

Figure 17. Example of corroded MEG nozzle

The water supply at Bonderson was also detrimental to the cleaning system. Despite efforts to clear the water lines and keep the system dry, rust deposits formed on the nozzle heads, hoses, and fittings. Also, after prolonged use, heavily mineralized water would likely contribute to premature nozzle orifice wear and corrosion.

For the continuation of this research, it is highly recommended to use treated water. An alternative to washing with the treated water could be to use it in a final rinse. The only problem with this method is that untreated water, or water treated through a process such as water softening, could negatively impact the environment below the panels. At the Kramer Junction CSP plant, reverse osmosis (RO) water was used to clean the parabolic troughs. RO water minimizes environmental contamination and will not form mineral deposits on solar panels.

Repeatability

Maintaining consistent nozzle alignment during each pass was of great concern. Deviations in consecutive passes could affect overlap and lead to variations in output. Sources of these deviations include pulling the cart parallel to the panel, lateral play in the boom arm, and the boom bouncing. Maintaining a parallel path proved to be nontrivial. In order to best follow a straight path a line on the ground was used as a visual guide for the wheel to follow. The boom has about ±5 degrees of lateral play due to tolerances in its construction with pin joints. From video shot of a test, it appears the boom sways away from the direction of travel. This position is constant until after the pass when the rig slows down. Since this motion is consistent it can be corrected for. The carts pneumatic tires have a relatively low spring rate and can result in a significant height variation of the nozzle when traversing bumpy terrain. To minimize this potential problem, all the testing performed was done on a level, paved surface. Also, the water flow is started before pulling begins to allow the oscillation caused by the thrust from the nozzle to damp out. Visually, the bouncing motion afforded by the tires is minimal during testing.

Accurate speed measurement, of the cart, proved to be difficult to obtain. The initial solution was to implement a Cateye bicycle speedometer, which determines speed by counting wheel revolutions over time and multiplying by its circumference. The speed display jumped significantly between the beginning and end of a pass. This is attributed to limitations of the device, because there are large changes in speed and only a few measurements are taken during each pass. To make the speed reading more accurate three more magnets were placed, evenly

distributed, around the cart wheel. This resulted in a speed reading four times greater than the actual speed but much more accurate since the sensor received four times the information and there was less fluctuation between consecutive measurements. The maximum wheel rolling frequency for a single magnet was determined based on the data from Cateye. Care was taken to ensure that, for this application with additional magnets, the sensor was within the products detecting frequency limits.

In order to validate repeatability, consistency in test results needs to be verified. Using consistent pre-cleaning, soiling, and cleaning conditions, two different testing configurations were repeated several times each. For the continuation of this project, the consistencies of speed and nozzle alignment are crucial and it is recommended that steps are taken to ensure this.

Soiling method

Initially a soiling method was developed using a spray bottle to cover the panel surface with a mist of dirty water, which resulted in a consistent and even soiling upon drying. Unfortunately, the spray bottle nozzles weren't intended to pass the necessary dirt flux and would frequently clog up, and became permanently blocked. To continue testing, a sloshing method was devised that worked equally well to reduce the panel output, however the soiling wasn't as uniform. If the spray technique is used, it is recommended that the nozzles are cleaned thoroughly and frequently.

Developing a better understanding of the soiling that accumulates on a panel in a Mediterranean climate could have been beneficial as well. Our soiling method mimicked the effect of soiling on the panel power output but may have differed greatly from the consistency of actual soiling.

Data collection

In order to correct for fluctuations in the output of the solar panel due to reasons other than soiling, such as clouds, sun angle, and temperature, several measurements were taken at each stage. These included panel output, panel temperature, reference cell open-circuit voltage and shunt voltage, and pyranometer voltage. Sometimes some of these could vary significantly in a matter of seconds because of changing conditions. In order to more accurately and easily collect data in the future, the use of a data acquisition system (DAQ) is strongly recommended.

Reference Cell Use

There was some confusion regarding what measurements to take from the reference cell. The instructions identified two measurements that needed to be collected, which were an open circuit voltage (V_{oc}) and a short circuit current (I_{sc}). The reference cell contains four leads; two of which to read voltage (black-red) and two to read current (white-green). The confusion was with regards to the short circuit current (I_{sc}) measurement. The white and green leads communicate a voltage reading which is used to calculate the I_{sc}, but the I_{sc} cannot be measured directly from the leads. Since the instructions indicated measuring the Isc from the appropriate wires that is

what was measured. It wasn't until after the data seemed incoherent that measuring voltage to get I_{sc} was learned. A numerical relationship was determined in an effort to salvage data taken by measuring the I_{sc} directly. Assuming ohm's law (V=IR), the Thevenin equivalent impedance was determined for the reference cell over the green-white leads. This result was constant for several measurements taken, and could therefore be used to determine the voltage that should have been read from the reference cell (green-white leads). These voltages were then used to calculate the desired I_{sc} information.

It was assumed that the reference cell could accurately compensate for the changes in lighting conditions experienced throughout the day. The reference cell and solar panel were tested together to determine the validity of the comparison ratio (I_{SCO}/E_e) values. This validity was tested by orienting the panel in an arbitrary direction and taking 3 sets of T_{ref}, I_{SC}, $V(I_{SC})_{shunt}$, and V_{OC} measurements before reorienting the panel again. The conditions for testing were very favorable for this confirmation test.

The test results indicated roughly a 2% fluctuation in the comparison ratio while solely varying the panel orientation. The changes in the comparison ratio due to soiling are on the order of 5%, so this fluctuation likely contributes to some inconsistency in the results. In the future, a more precise means of normalizing the data is recommended, such as a pyroheliometer.

Two phase

Simplifying the two phase approach into a hybrid device had some serious drawbacks. Phase one was to determine the necessary spray characteristics. Phase two was to implement the results from phase one into a vehicle that could clean a row at a power plant. Our design was a compromise of the two designs in an attempt to have the versatility and control of the phase one idea, while still being adaptable for use in a PV plant. Ideally, phase one would be done in a controlled environment where the nozzle would follow a track for speed and accuracy and the lighting would be controlled to achieve consistent panel output. Other options to make testing more accurate include testing with glass and measuring transmissivity, reducing the scale to allow single passes, or using a manifold to have several nozzles at once, and implementing a motor to achieve consistent speed. Phase two should have been a separate trailer designed to clean a row, however the hybrid of the two devices was limited for both functions, but was a way to accomplish both goals.

Implementing some of these recommendations could also improve testing efficiency. The hybrid nature of the design made repeated testing a long process. In the controlled setting proposed, tests could be made much faster

Safety

Over the course of building and performing tests several areas of safety concern were identified. These issues include burs on cut bolts, square corners in the aluminum plate, the high speeds of the spray bar, and the potential for the cart to roll away. To make the rig safe for operation by anyone, these concerns should be addressed. Potential solutions to these problems include adding a chamfer to the U-bolts that secure the aluminum plate to the boom, rounding off the

corners of the aluminum plate, implementing a shroud for the spinning spray bar, and adding a brake for the cart.

Alternative Cleaning Methods

Two other techniques were investigated for cleaning with pressurized water to assess their cleaning effectiveness qualitatively.

The first was a shear technique where the nozzle was aligned so that it was behind the panel and at almost the same angle. In this way, only one pass is needed to clean the entire panel, however the small angle between the nozzle and panel greatly reduces the impact of the water on the glass. To compensate for this, a test was performed with a 0° fan angle and 2500 psi. This method seemed to clean the panel well, but there were some significant issues. The technique proved to be difficult set up and aim the nozzle because a slight error in the angle greatly affects the cleaning area.

Figure 18. Cleaning a panel with the shear cleaning method.

Figure 19. The “up the aisle” cleaning method using the spinning spray bar.

The main tests that were performed assumed an “up-the-row” technique, which might not be the final desired method of cleaning. The second technique tried was cleaning across the panel instead of along the panel, as would be done by a linear irrigation system or “up-the-aisle” concept. Because this method would be able to clean multiple panels at once, it is possible to move much slower. For this reason, the rotating nozzles were used. The main issue with this method, however, is the variation in stand-off distance if the panel is at an angle; at one end the nozzles are very close and at the other very far. This technique was first tried with the panel at 45°, a minimum stand-off of 6 inches, and a pressure of 1500 psi. It was clearly seen that there was little cleaning done with a stand-off over 20 inches. So, the test was repeated with the panel at 15° to reduce the variation of stand-off, and with a maximum stand-off of 18 inches. This method yielded good results, yet some cleaning effectiveness was probably lost because of the panel’s small pitch angle.

In the future, it is recommended to investigate the second method further because of its need if the linear move or aisle concepts are used. The shear method is extremely sensitive to alignment, so it is not recommend for further use.

Ethical Design

Several ethical concerns need consideration when designing a cleaning system for a large scale photovoltaic (PV) power plant. Often these plants are placed in rural locations which may be environmentally sensitive.

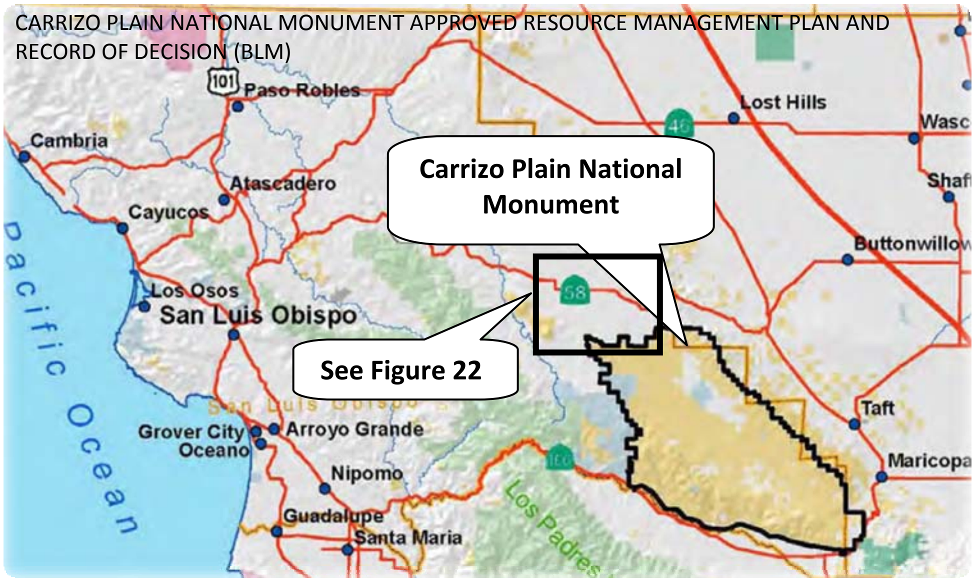

Figure 20. The location of the Carrizo Plain National monument and the region where the power plants would be placed.

The Carissa Plains is an area in San Luis Obispo County that covers 750 square miles of land. Within the Carissa Plains is the Carrizo Plains National Monument, which attained monument status in 2001 and covers 330 square miles.

Two major utility scale photovoltaic installations are planned that will cover portions of the Carissa Plains, just bordering the National Monument. First Solar plans to construct a 550 MW plant (6.5 square miles) and SunPower plans to construct a 250 MW plant (3 square miles). Environmental care needs to be taken both during the construction and the operation of these large plants to avoid negatively impacting the area. Such a large scale development could potentially displace plant or animal species or encroach on land that some view as sacred. The land being used for these plants is also home to threatened species such as the San Joaquin Kit Fox. SunPower and First Solar have been careful in placing and designing the power plants to minimize these impacts both during construction and operation.

Figure 21. A picture of the SunPower power plant site.

Arguably, one of the most significant impacts during the O&M of a photovoltaic power plant would be the panel cleaning process. Driving vehicles on the land below the power plant and spraying cleaning liquid over such a large area could significantly disturb the land below. As such, the most pressing ethical concern pertaining to the Cal Poly T0 Washing System Project is this issue of cleaning.

As the world population increases, potable drinking water is becoming a limited resource. Rankine Cycle power plants use treated water extensively for turbine and cooling tower operation. Photovoltaic power plants do not require any water to operate, but their performance can be improved by periodic cleaning with water. To maintain this environmental advantage, a balance between PV system performance and water use is critical. The T0 Washer Project is intended to determine this balance.

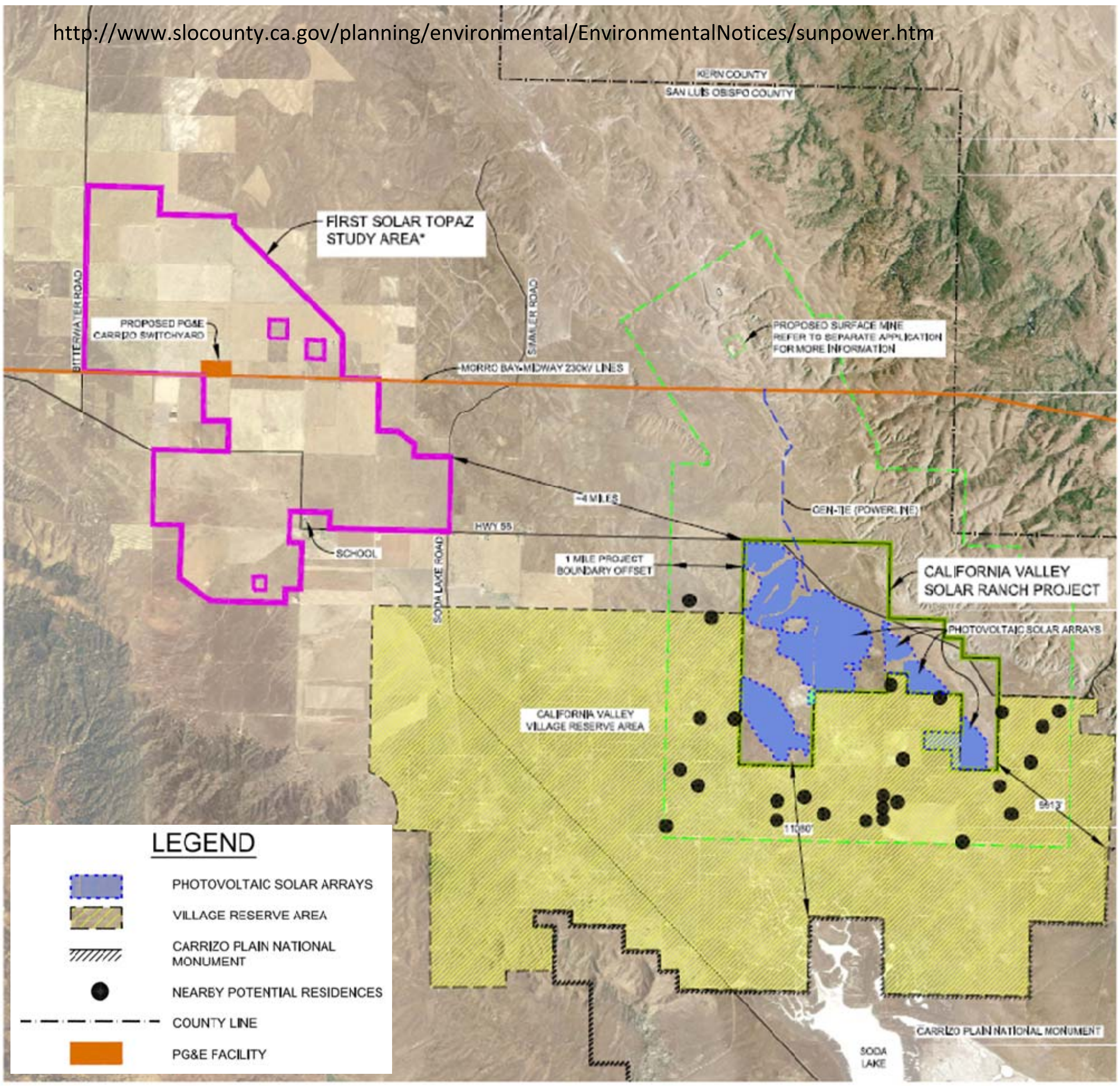

Figure 22. A diagram showing the sites for the proposed photovoltaic power plants. SunPower land is outlined in green and First Solar land is outlined in pink.

Conclusions and Recommendations

Nozzle Type

After considerable research, it was determine that WashJet (MEG) nozzles provided the best option, both for cost and quality. These nozzles are used in a wide variety of applications including car washing, which was assumed to be similar to cleaning PV modules. Additionally, MEG nozzles offer a wider range of variation than typical commercial pressure washer nozzles. The selection of 1/8" MEG 02 sized nozzles was based on pressure washer sizing concerns. The 02 nozzles required the lowest flow rates to provide pressure in the intended range. However, selecting nozzles with larger orifice diameters will require larger flow rates to maintain the same pressures. As the orifice diameter increases, the cleaning effectiveness and water consumption both increase. The ideal orifice diameter for this application has not clearly been determined.

Nozzle Fan Angle

Nozzles can be purchased with different fan angles (Figure 23). As seen in Appendix G, the MEG nozzles have the same flow rate and pressure performance for a given size, even as spray angle varies. However, in this application, there is a trade-off between the nozzle fan angle and water consumption because larger fan angles cover larger areas at the same stand-off. Consequently, it has been determined that a fan angle of 40° provides sufficient cleaning effectiveness with the least amount of water usage. However, lower fan angles allow for larger stand-off distances, which would be beneficial for systems where maintaining high clearance is paramount. For example, without sufficient stand-off, an Aisle type system with long cantilevered booms could deflect during operation and collide with panels.

Figure 23: MEG Spray Nozzles

A spinning nozzle arrangement was also investigated. However even with 0 degree fan angles, there was too much atomization of the spray and not enough impact on the panel. This is because of the linear speed at which the cart had to move in an up-the-row scenario. The spinning nozzles could be implemented in a different method such as the linear move aisle concepts. This is discussed in the "Alternative Cleaning Methods" section above.

Stand-Off

Similarly, the stand-off distance between the nozzle and the panel surface is directly related to water consumption. Based on the testing (with 1/8" MEG 02 nozzles) it has been determined that stand-off distances greater than 16 inches do not provide sufficient cleaning effectiveness to justify their implementation.

Operating Pressure

Increasing operating pressure seems to have a diminishing return, which is likely due the fact that the impingement (Appendix G) is proportional to the square root of the pressure. Using the MEG 02 nozzles, a pressure of 2000 to 2500 psi seemed sufficient in cleaning the panels. Below this range, cleaning was insufficient, and above this range, cleaning was not significantly improved.

Panel Orientation

Almost immediately, it was determined that inclining the panel would facilitate soil removal. As water cascades down the panel, it carries dislodged soil with it. Also, tilting the panels expedites drying, which decreases the likelihood that the panel will become re-soiled. As a result, cleaning was almost exclusively tested with the panel at a 45° pitch.

Boom Orientation

Different boom orientations were tried in an attempt to increase the shearing effect of the water jet on the surface of the panel. Visual inspection suggested that these different orientations yielded little change in cleaning effectiveness. Therefore, it is recommended to use roll and yaw angles of 0° in order to maximize the water's impact on the panel.

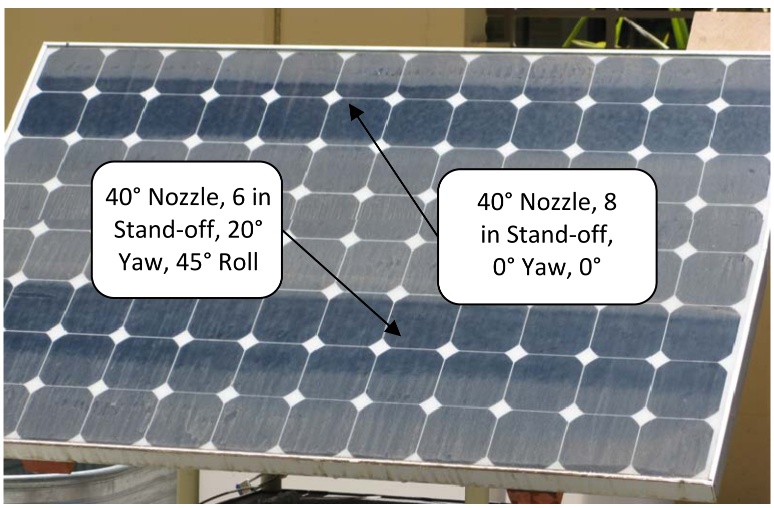

Figure 24. Qualitative testing indicating little benefit from changes in yaw and roll angle.

Hard Water Mitigation

Another apparent issue is that of water leaving deposits on the surface of the panel. The use of treated water is highly recommend, however more research is needed to determine the exact application. It is unknown which type of treated water (reverse osmosis, deionized, distilled, etc.) is the best option. Both cleaning effectiveness and environmental effects must be taken into account when determining how to treat the water. Also, the treated water could be used as the main pressurized cleaning fluid or just as a final rinse. Regardless, this is an important issue that must be addressed in the implementation of the final cleaning system.

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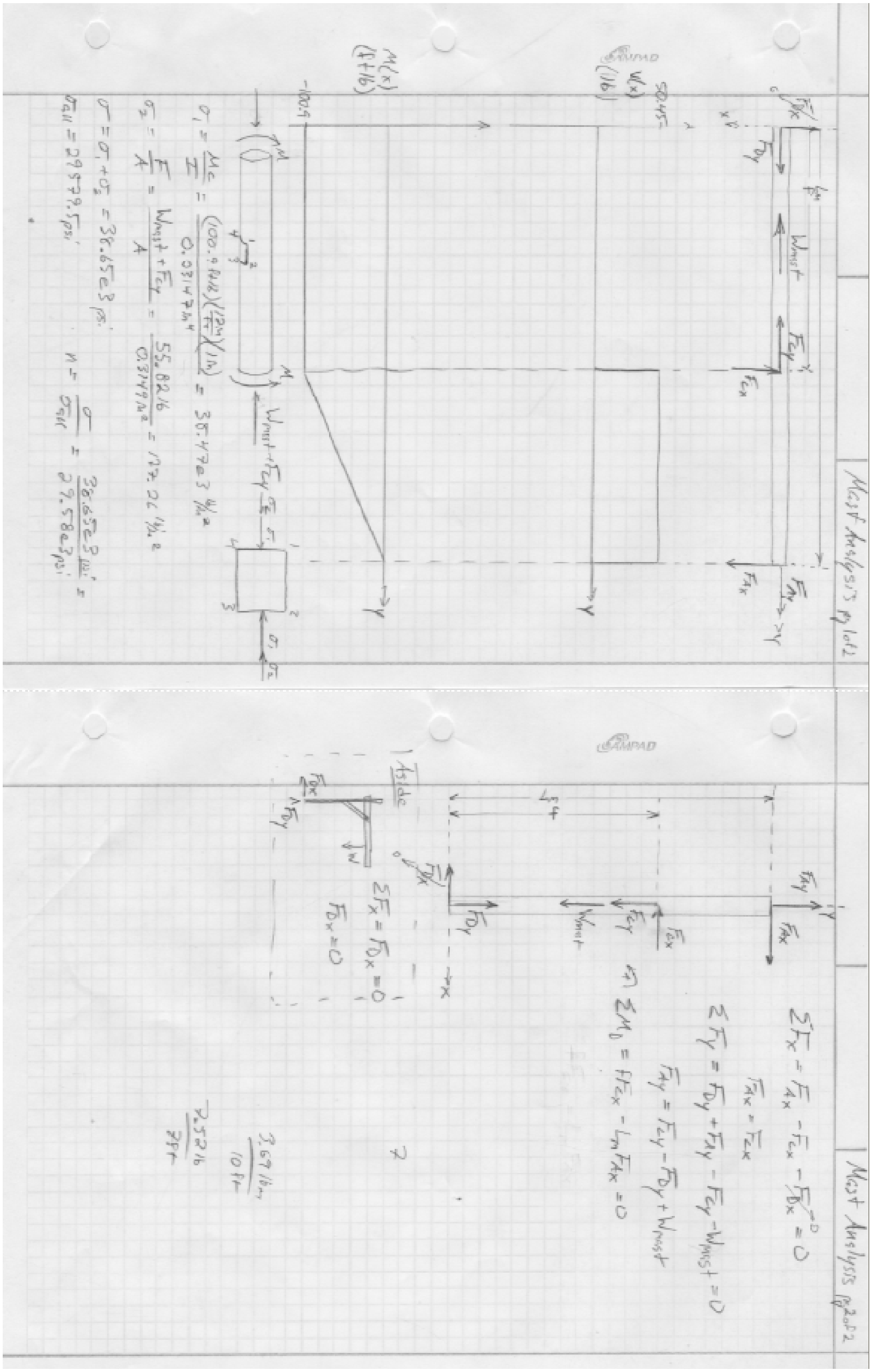
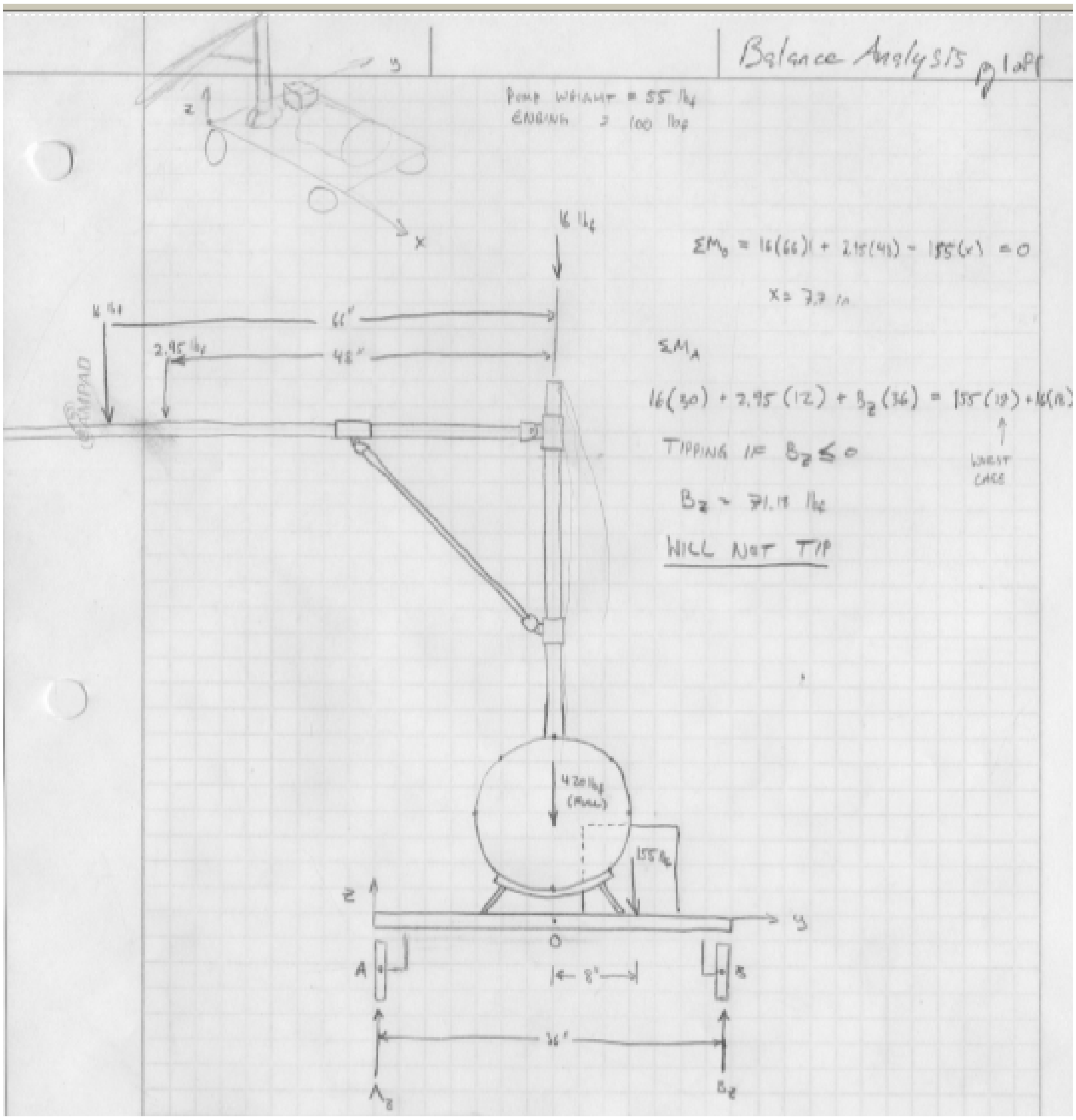
Appendix A: Decision Matrix

Table 3. Decision Matrix to evaluate full scale cleaning systems

	Criteria	Importance	On Panel	Drive up Row	Aisle	Linear Move
Cleaning	Water Use	5	5	4	3	3
	Positioning	3	5	4	3	4
	Re-soiling	5	5	2	3	4
	Cleaning Speed	3	2	3	4	5
	Water Access	3	2	3	4	3
Labor	Labor Intensity	4	1	2	4	5
	Number of Operators	4	2	2	4	5
	Automation	3	2	1	2	5
	Operator Safety	5	4	2	3	4
	Maintenance	4	3	4	3	2
	Ease of Use	2	2	1	4	5
Motion	Mobility	4	3	2	4	5
	Repositioning	4	1	4	3	1
	Distance Traveled	2	1	1	4	5
Other	Panel Contact	4	1	5	5	5
	Plant Safety	4	3	2	3	4
	Adaptability	4	5	4	3	2
	Storage	3	4	3	3	4
	Capital	2	4	3	3	2
	Number of Units	2	2	2	4	5
	Complexity	3	4	4	2	2
	Feasibility	4	5	5	3	2
	Aesthetics	1	4	2	4	3
		Weighted Sum	245	230	261	285

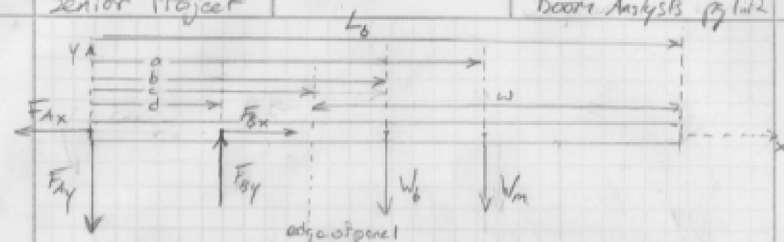
Appendix B: Supporting Analysis





Balance Analysis pg 1 of 1
PUMP WEIGHT = 55 lbf
ENGINE = 100 lbf
16 lbf
ΣM0 = 16(66) + 2.95(48) − 155(x) = 0
X = 7.7 in
66"
48"
2.95 lbf
ΣMA
16(30) + 2.95(12) + Bz(36) = 155(18) + 16(18)
WORST CASE
TIPPING IF Bz ≤ 0
Bz = 71.18 lbf
WILL NOT TIP
420 lbf (FULL)
155 lbf
z
y
x
O
A
B
8"
36"
Az
Bz

Senior Project | ME 428 | Boom Analysis pg 1 of 2



$\Sigma F_x = F_{Bx} - F_{Ax} = 0$

$F_{Bx} = F_{Ax}$

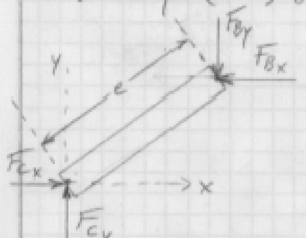
$\sigma_y = 29579.5\ psi$

$\Sigma F_y = -F_{Ay} + F_{By} - W_b - W_m = 0$

$F_{By} = F_{Ay} + W_b + W_m$

$\circlearrowleft \Sigma M_A = dF_{By} - bW_b - aW_m = 0$

$\circlearrowleft \Sigma M_B = dF_{Ay} - (b-d)W_b - (a-d)W_m = 0$



$\Sigma F_x = F_{Cx} - F_{Bx} = 0$

$F_{Cx} = F_{Bx}$

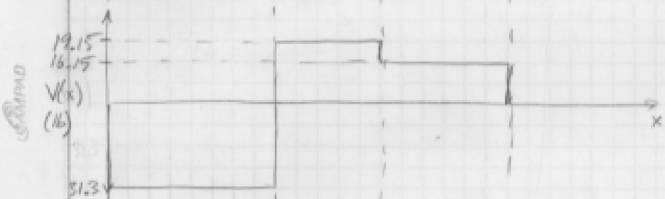
$\Sigma F_y = F_{Cy} - F_{By} = 0$

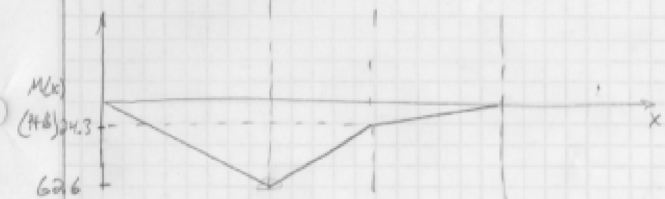
$F_{Cy} = F_{By}$

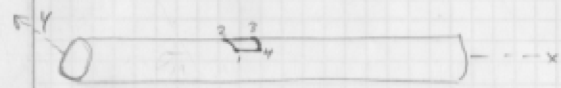
$\circlearrowleft \Sigma M_C = (L_m - f)F_{Bx} - dF_{By} = 0$

$\circlearrowleft \Sigma M_B = (L_m - f)F_{Cx} - dF_{Cy} = 0$

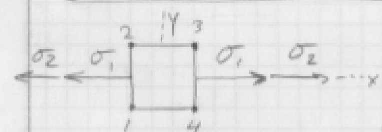
Boom Analysis pg 2 of 2







.113 m



$\sigma_1 = \frac{F_{Bx}}{A} = \frac{F_{Bx}}{\pi/4(D_o^2 - D_i^2)}$

$\sigma_1 = \frac{50.45\ lbf}{0.3149\ in^2} = 160\ psi$

$\sigma_{total} =$

$11.94e3\ psi = \sigma_2 = \frac{Mc}{I} = \frac{(62.6\ ft\text{-}lb)(\frac{12\ in}{1\ ft})(\frac{1\ in}{2})}{.03147\ in^4}$

$S_{y\,Al} = 31183\ psi$

$I = \frac{\pi}{64}(D_o^4 - D_i^4) = .03147\ in^4$

Appendix C: Bill of Materials

Description	Supplier	Model #	Quantity	Shipping	Cost per unit	Total
7'X2-3/8" Galvanized Steel Pipe	McMaster Carr	*4936T916*	2		$65.10	$130.20
Adjustable 180 degree Angle Tees	McMaster Carr	*4936T99*	3		$30.64	$91.92
5" Floor Flange	McMaster Carr	*4936T122*	1		$17.00	$17.00
3/16" Steel Wire rope	McMaster Carr	*3498T65*	50		$0.77	$38.50
Hook and Eye Turnbuckles	McMaster Carr	2998T51	4		$13.28	$53.12
Combination Wire Rope Clamps and Thimbles 3/16 "	McMaster Carr	*3467T15*	8		$10.00	$80.00
3/8"-16 x 3'' Eye Bolt for top of mast	McMaster Carr	*3014T63*	2		$12.50	$25.00
3/8"-16 x 2.5'' Eye Bolt for cart attachment	McMaster Carr	3018T16	4		$5.26	$21.04
25 Gallon Horizontal Leg Tank	NTOtank	*FM0025-16S*	1	$40.00	$60.00	$100.00
3/4" PP Bulkhead Fitting	NTOtank	*075PPBH*	1		$9.00	$9.00
Request Fitting Install	NTOtank		1		$15.00	$15.00
2200 Psi 2.2 gpm Briggs and Stratton Gas Powered Pressure Washer - 020387	Every Pressure Washer	*BAS1088*	1	$0.00	$250.00	$250.00
DYF Triple Bearing Swivel, Carbide Seal w/ Flange 3/8" FPT inlet	Ultimate Pressure Washer	*MO-58.163*	1		$184.00	$184.00
24" Dual Rotor Arm	Ultimate Pressure Washer	*MO-82.815*	1		$93.00	$93.00
0 degree 1/8" Stainless MEG nozzle	Ultimate Pressure Washer	*SM-250100*	2		$8.00	$16.00
15 degree 1/8" Stainless MEG nozzle	Ultimate Pressure Washer	*SM-250105*	2		$8.00	$16.00
25 degree 1/8" Stainless MEG nozzle	Ultimate Pressure Washer	*SM-250110*	2		$8.00	$16.00
40 degree 1/8" Stainless MEG nozzle	Ultimate Pressure Washer	*SM-250115*	2		$8.00	$16.00
Pressure Gauge Kit - 5000 PSI	Ultimate Pressure Washer	*BE-85-305-001*	1		$50.00	$50.00
3/8" FNPT to Quick-Connect - Plated Steel	Ultimate Pressure Washer	*BE-85-300-104*	1		$10.00	$10.00
1 Roll of Teflon Tape	Ultimate Pressure Washer	*BE-85-400-110*	1		$5.00	$5.00

3/8" MNPT to Quick-Connect (Plated Steel)	Ultimate Pressure Washer	*BE-85-300-105*	1		$7.00	$7.00
3/8" x 3/8" Elbow	Ultimate Pressure Washer	*SM-9.802-023.0*	1		$7.00	$7.00
3/8" MNPT x 1/4" MNPT	Ultimate Pressure Washer	*PP-5404-06-04*	1		$5.00	$5.00
Coupling 1/4 x 1/8 F	Ultimate Pressure Washer	*SM-140502*	1		$4.00	$4.00
Strap Hinges for panel mount	McMaster Carr	1526A53	2		$3.36	$6.72
2 In. x 4 In. x 10 Ft. Dimensional Lumber	Home Depot	5240	4		$2.47	$9.88
Machine Screws 8-32	Bolt Depot	1558	10		$0.08	$0.80
#8 washers	Bolt Depot	2943	10		$0.05	$0.50
#8 Hex Nuts	Bolt Depot	2559	10		$0.05	$0.50
1 Lb. Bo x 2-1/2 In. x 10, Exterior Screw	Home Depot	PTN212S1	1		$7.89	$7.89
Columbia Forest Products 3/4 In. 4 Ft. x 8 Ft. C-3 Whole Piece Red Oak Domestic Plywood	*Home Depot*		1		$39.95	$39.95
2 " 5/16-18 hex Bolts for tank	Bolt Depot	39	4		$0.21	$0.84
washers 5/16	Bolt Depot	2948	4		$0.07	$0.28
Metal Deck Wagon Garden Cart — 60in.L x 36in.W, 800-Lb.	Northern Tool + Equipment	4775	1	$150.00	$229.99	$379.99

20% Shipping	$341.43
Tax	$153.64
Grand Total	$2,202.20

Appendix D: Build and Test Plan – Phase I

Build the structure to hold the module and reference cell at varying angles

- Structure allows the module to tilt to several angles for repeatable testing
- Structure is built onto a wheeled cart to allow for adequate mobility

Assemble spray rig which will be used for Phase I tests

- Spray rig will be built onto a wheeled cart as shown in design images
- Attach 25 gal water tank to cart
- Attach mast and boom arm assembly to cart, and attach guy wires
- Attach pressure washer module to cart
- Connect washer input and output lines, and secure them to tank and boom

Hypothesize how deviations from nominal parameters will benefit cleaning

- Steep panel pitch angles may increase the cleaning effectiveness of the water
    - Water hitting the top of the panel will cascade down the rest of the panel, removing more soil with less water
- Closer stand-off distances will provide more impact
- Narrower angles will provide more impact
- The rotating nozzle bar will allow higher impact with greater stand-off distances
    - The rotating nozzle bar will use narrower spray angle nozzles while still providing excellent coverage via the nozzle rotation
    - The rotating bar will also decrease the number of nozzles necessary to clean
- Lead (Yaw) angles may facilitate a cascade effect
- Roll angles varying from nominal may positively affect rinsing
- Increasing pressure and increasing flow rate will increase cleaning effectiveness
    - The cleaning effectiveness will increase with impact, so the cleaning effectiveness won't necessarily peak
    - The change in cleaning effectiveness due to varying parameters will most likely decrease sharply at some point, which will indicate the optimum operating point for water use

Test Plan Outline

- Short the leads of the module
- Place panel and reference cell outside in the same location and at the same angle
- Measure I_{SC} of reference cell and module before soiling
- Soil Test Panel
    - Apply water/dirt mixture evenly to panel surface
    - Allow panel to dry
        - Use fans or other method to expedite drying
- Measure the I_{SC} of the panel and reference cell
- Measure cleaning water temperature in the reservoir
- Measure flow rate
    - Weigh a bucket after timing how long it takes to fill
- Measure the pressure behind each nozzle
    - Read pressure gauge, located before nozzle, for each nozzle
- Visual Testing
    - Limit testing scope by testing at the defined normal configuration and vary cleaning speed to determine the approximate impact range required to clean
    - Adjust required tests accordingly
- Configure Testing Arrangement
    - Single Variable Tests
        - Vary nozzle spray angles from 15 to 40°
            - Smaller spray angles have greater impact, but cover less area
        - Vary Stand-off height every 6 inches between 8 and 36 inches (all other parameters fixed at nominal configuration)
            - Panel at zero degrees (Level)
            - Boom perpendicular to edge and parallel with panel face
            - Nozzles at zero degree angle (normal to panel)
            - Constant movement speed (about 4 mph)
        - Vary Lead (Yaw) angle (-45 to 45 degrees every 15 degrees)
            - Measure lead angle
        - Vary Pitch angle (0 to 45 degrees every 7.5 degrees)
            - Rotate Panel angle to match pitch angle
            - Use angle finder to measure pitch
        - Vary Roll angle (-45 to 45 degrees every 15 degrees)
            - Use angle finder to measure roll
        - Vary Flow rate which will also vary pressure
            - Use unloader valve to vary flow rate
    - Combined Variable tests

        - Combine parameters from the most successful tests to see if their effects compound beneficially
    - Rotating nozzle tests
        - Vary spray angles from 0 to 40°
        - Vary pitch of panel and rotating bar
        - Vary flow rate which will also vary pressure
- Clean Panel at each configuration
- Measure I_{SC} of panel and reference cell again
    - Compare the percent difference in I_{SC} before and after cleaning for both the panel and reference cell

Interpret the results

- Which cleaning parameters provide sufficient cleaning with the lowest flow of water?
    - Plot results for each parameter water use versus percent increase and analyze results.
- Which combinations of cleaning parameters provide sufficient cleaning with the lowest flow of water?

Plot and analyze results from combined parameter tests.

Appendix E: Main Test Data

				Test Parameters									
	Date	Run #	Description	Pressure	Standoff Distance	# of Passes	Actual Coverage	Angle [Degrees]					Speed
				[psig]	[inches]	[-]	[in]	Nozzle	Panel	Pitch	Yaw	Roll	[mph]
Hard Water Tests	5/13/2010	1	409 Clean with 4 rinses										
		2	Soiled, Clean										
		3	Rinse, Squeegie, 409										
		4	Soiled, Clean										
		5	Rinse, Squeegie, 409										
		6	409 Clean and 4 Rinses										
		7	Repeatability Test 1	1500	12	8	3.16	15	45	45	0	0	5.5
Tests 1-3 on matrix	5/14/2010	8	Repeatability Test 2	1500	12	8		15	45	45	0	0	5
		9	Repeatability Test 3	1500	12	8		15	45	45	0	0	5
		10	Nozzle Variation	1500	12	7		25	45	45	0	0	5
		11	Nozzle Variation	1500	12	4		40	45	45	0	0	4.5
	5/15/2010	12	40 repeatability 1	1500	12	4		40	45	45	0	0	4.5
		13	40 repeatability 2	1500	12	4		40	45	45	0	0	5
		14	40 repeatability 3	1500	12	4		40	45	45	0	0	4.5
Tests 4-7 on matrix	5/20/2010	15	Pressure Variation	2000	12	4		40	45	45	0	0	4.65
		16	Pressure Variation	2500	12	4		40	45	45	0	0	4.99
		17	Pressure Variation	3000	12	4		40	45	45	0	0	4.475
		18	Pressure Variation	3500	12	4		40	45	45	0	0	4.515
	5/25/2010	19		1500	12	4		40	45	45	0	0	4.64
		20		2000	12	4		40	45	45	0	0	4.41
		21	Mostly Cloudy	2500	12	4		40	45	45	0	0	4.41
		22	Extremely Cloudy	3000	13	4		40	45	45	0	0	3.73
	6/6/2010	23		2500	16	3		40	45	45	0	0	4.13

	Pre-Soil							Soiled							Cleaned						
Run #	V_{Pyran}	I_{SC}	T_{amb}	T_{cell}	V_{OC}	I_{shunt}	$V(I_{sc})$ Shunt	V_{Pyran}	I_{SC}	T_{amb}	T_{cell}	V_{OC}	I_{shunt}	$V(I_{sc})$ Shunt	V_{Pyran}	I_{SC}	T_{amb}	T_{cell}	V_{OC}	I_{shunt}	$V(I_{sc})$ Shunt
	[mV]	[A]	[C]	[C]	[mV]	[mA]	[mV]	[mV]	[A]	[C]	[C]	[mV]	[mA]	[mV]	[mV]	[A]	[C]	[C]	[mV]	[mA]	[mV]
1	54.1	5.4	23.1	41.8											49.0	4.9	27.2	40.6			
2								47.0	4.68	25.6	40.6				42.9	4.3	27.1	39.2			
3	41.2	4.2	26.7	34.2											40.2	4.0	25.6	33.0			
4								37.8	3.68	24.4	37.8				44.5	4.4	25.7	33.3			
5	43.2	4.3	24.8	35.0											43.8	4.3	24.6	31.8			
6	54.1	5.4	23.1	40.6											49.0	4.9	27.2	40.6			
7	35.1	3.5	24.6	35.7				32.4	3.08	24.5	36.2				44.9	2.3	22.4	37.1			
8	53.0	5.3	21.7	43.0				55.5	5.20	21.4	41.9				48.9	4.9	22.4	31.2			
9	45.5	4.6	22.2	34.1				49.8	4.95	22.4	40.9				53.7	5.4	22.5	33.2			
10	52.5	5.4	22.4	31.6				53.7	5.31	22.5	37.7				49.7	5.0	22.7	32.2			
11	53.4	5.4	23.2	33.1				53.1	5.29	23.0	36.4				52.1	5.3	23.2	34.2			
12	55.0	5.5	23.2	30.7				53.8	5.30	20.9	37.3				53.7	5.3	21.6	33.2			
13	53.2	5.4	23.3	33.3				52.2	4.45	21.7	35.1				49.6	4.5	21.7	33.3			
14	48.7	4.9	21.4	34.9				47.8	4.65	21.7	46.8				45.6	4.5		36.5			
15	40.2	3.9	22.2	33.2	641.0	16.5	34.7	43.2	4.28	22.9	37.3	642.0	17.8	37.4	49.2	4.9	23.9	28.5	645.0	20.5	43.1
16	49.0	4.8	23.3	30.6	639.0	16.0	33.6	48.8	4.82	23.9	35.7	628.0	19.3	40.5	50.3	5.0	24.3	32.2	633.0	20.8	43.7
17	51.4	5.2	25.4	37.0	627.0	21.0	44.1	52.7	5.23	25.6	41.1	615.3	20.5	43.1	54.1	5.4	25.5	34.9	642.0	20.3	42.6
18	54.7	5.5	25.6	36.1	637.0	15.5	32.6	54.6	5.40	25.7	38.3	627.0	20.5	43.1	54.4	5.5	25.7	44.9	636.0	25.7	54.0
19		2.3		20.5	645.0		22.0		2.21	16.4	23.9	645.0		23.0		2.9	16.5	29.2	650.0		29.0
20		3.0	18.7	25.9	646.0		28.0		2.66	18.7	26.4	645.0		27.0		3.3	18.6	30.4	653.0		33.0
21		4.0	21.9	30.8	646.0		40.0		1.26	26.1	26.6	617.0		13.1		1.3	21.3	21.1	632.0		15.2
22		2.8	22.4	27.1	647.0		30.7		2.50	20.5	22.5	640.0		29.4		0.6	19.3	18.1	612.0		6.4
23		5.92		52.2	619		58.2		4.82		35.5	641.0		53.3		4.77		34.9	636		53.2

Boxes highlighted in blue were determined from the I_{Shunt} values that were mistakenly measured in the adjacent column.

Run #	I_{SCO} Corrected (kW/m^2)			T_{ref} (°C)			E_e (kW/m^2)		
	Pre-Soil	Soiled	Clean	PS	S	C	PS	S	C
1	0.871		0.791						
2		0.754	0.697						
3	0.674		0.649						
4		0.594	0.712						
5	0.692		0.696						
6	0.872		0.791						
7	0.559	0.498	0.368						
8	0.853	0.837	0.792						
9	0.749	0.798	0.880						
10	0.867	0.857	0.816						
11	0.874	0.855	0.849						
12	0.896	0.856	0.861						
13	0.867	0.719	0.722						
14	0.792	0.747	0.722						
15	0.634	0.691	0.787	31.43	32.07	32.71	0.587	0.633	0.729
16	0.781	0.779	0.810	31.94	40.15	38.84	0.569	0.686	0.739
17	0.836	0.843	0.878	41.94	47.33	34.03	0.746	0.727	0.722
18	0.881	0.871	0.881	32.45	41.57	40.62	0.551	0.728	0.913
19	0.368	0.360	0.474	22.94	23.57	24.47	0.373	0.390	0.492
20	0.486	0.432	0.540	25.89	25.85	24.88	0.475	0.458	0.560
21	0.648	0.205	0.210	31.12	28.84	23.91	0.678	0.222	0.258
22	0.455	0.407	0.095	26.74	29.50	21.37	0.521	0.498	0.109
23	0.948	0.779	0.771	50.30	37.94	40.40	0.982	0.902	0.900

Run #	I_{SCO}/E_e Comparison Ratios			Percent Changes in I_{SCO}/E_e			Weighted Ratios I_{SCO}/E_e	
	PS	S	C	% Decrease	%Increase	%Cleaned	$(I_{SCO}/E_e)_C/(I_{SCO}/E_e)_{PS}$	$(I_{SCO}/E_e)_C/(ISCO/Ee)_{PS}/H_20$ used
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15	1.080	1.091	1.079	-1.0			0.999	124.48
16	1.372	1.136	1.095	17.2	-3.0	79.8	0.798	106.77
17	1.122	1.159	1.216	-3.3	5.1	108.4	1.084	130.02
18	1.597	1.197	0.965	25.0	-14.5	60.4	0.604	73.14
19	0.987	0.921	0.963	6.6	4.2	97.6	0.976	121.33
20	1.023	0.944	0.964	7.8	2.0	94.2	0.942	111.39
21	0.956	0.922	0.815	3.6	-11.2	85.2	0.852	100.73
22	0.873	0.817	0.871	6.5	6.2	99.8	0.998	99.74
23	0.965	0.864	0.857	10.5	-0.7	88.8	0.888	131.22

Run #	I_{SCO}/V_{pyran} Comparison Ratios			Percent Changes in I_{SCO}/V_{pyran}			Weighted Ratios	
	PS	S	C	% Decrease	%Increase	%Cleaned	$(I_{SCO}/V_{pyran})_C/(I_{SCO}/V_{Pyran})_{PS}$	$(I_{SCO}/V_{Pyran})_C/(I_{SCO}/V_{Pyran})_{PS}/H_20$ used
1	0.0161		0.0161					
2		0.0160	0.0162		1.19			
3	0.0164		0.0161					
4		0.0157	0.0160		1.79			
5	0.0160		0.0159					
6	0.0161		0.0161					
7	0.0159	0.0154	0.0082	3.59	-87.30	-0.04	0.515	37.94
8	0.0161	0.0151	0.0162	6.25	6.92	100.67	1.007	67.46
9	0.0165	0.0160	0.0164	2.70	2.30	99.60	0.996	66.74
10	0.0165	0.0160	0.0164	3.30	2.78	99.48	0.995	76.18
11	0.0164	0.0161	0.0163	1.67	1.25	99.58	0.996	120.11
12	0.0163	0.0159	0.0160	2.39	0.78	98.39	0.984	118.68
13	0.0163	0.0138	0.0146	15.47	4.72	89.25	0.892	119.61
14	0.0163	0.0156	0.0158	3.96	1.30	97.34	0.973	117.40
15	0.0158	0.0160	0.0160	-1.37	0.00	101.36	1.014	126.33
16	0.0159	0.0160	0.0161	-0.12	0.84	100.96	1.010	135.03
17	0.0163	0.0160	0.0162	1.75	1.47	99.71	0.997	119.60
18	0.0161	0.0160	0.0162	0.86	1.46	100.60	1.006	121.75

Appendix E : Reference Cell and Pyranometer Consistency Testing Results

Table 5. Method verification data comparing panel output to reference cell at several orientations. The panel is clean for each measurement.

Panel Orientation	T_{cell} [C]	I_{SC} [A]	V_{OC} [mV]	$V(I_{SC})_{shunt}$ [mV]	Tref [C]	Ee [kW/m^2]	T_{mod} [C]	I_{SCO} [kW/m^2]	I_{SCO}/E_e [-]			%diff
1	45.10	6.18	638.00	61.40	41.64	1.038	48.10	0.9934	0.9568	min	0.955	0.178
	47.10	6.17	631.00	61.30	45.12	1.036	50.10	0.9907	0.9564	max	0.957	
	50.40	6.19	626.00	61.50	47.68	1.039	53.40	0.9921	0.9551	avg	0.956	
2	53.00	5.86	617.00	58.00	51.24	0.979	56.00	0.9378	0.9580	min	0.953	0.573
	57.30	5.86	616.00	58.20	51.80	0.982	60.30	0.9356	0.9525	max	0.958	
	49.60	5.85	617.00	58.10	51.27	0.981	52.60	0.9380	0.9566	avg	0.956	
3	49.40	4.43	608.00	43.70	51.16	0.738	52.40	0.7104	0.9632	min	0.963	1.041
	47.00	4.44	609.00	43.40	50.56	0.733	50.00	0.7130	0.9732	max	0.973	
	49.10	4.47	609.00	44.10	50.81	0.744	52.10	0.7169	0.9631	avg	0.967	
4	49.70	6.11	614.00	61.30	53.64	1.034	52.70	0.9796	0.9473			
5	40.60	5.10	640.00	50.30	37.54	0.851	43.60	0.8219	0.9655			
6	42.90	5.59	635.00	55.00	41.41	0.930	45.90	0.8997	0.9673	min	0.965	0.247
	44.10	5.59	632.00	55.10	42.94	0.932	47.10	0.8991	0.9652	max	0.967	
	45.10	5.60	629.00	55.20	44.46	0.933	48.10	0.9002	0.9649	avg	0.966	
7	46.90	5.45	625.00	53.80	46.05	0.909	49.90	0.8752	0.9629	min	0.963	0.029
	46.80	5.45	625.00	53.80	46.05	0.909	49.80	0.8752	0.9629	max	0.963	
	47.70	5.44	623.00	53.70	47.01	0.907	50.70	0.8732	0.9626	avg	0.963	
8	49.40	3.90	612.00	39.90	47.75	0.674	52.40	0.6254	0.9281	min	0.928	0.282
	48.90	3.89	611.00	39.70	48.16	0.670	51.90	0.6240	0.9307	max	0.931	
	48.00	3.87	611.00	39.60	48.13	0.669	51.00	0.6211	0.9287	avg	0.929	

I_{SCO}/E_e Statistics	
% diff	4.72
min	0.928
max	0.973
avg	0.956

Table 5: Test data from several runs collected over two test days.

I_{SCO}/E_e Comparison Ratios			Percent Changes in I_{SCO}/E_e		
PS	S	C	% Decrease	%Increase	%Cleaned
1.080	1.091	1.079	-0.99	0.00	0.00
1.372	1.136	1.095	17.20	-2.96	79.83
1.122	1.159	1.216	-3.30	5.10	108.40
1.597	1.197	0.965	25.04	-14.52	60.44
0.987	0.921	0.963	6.63	4.20	97.56
1.023	0.944	0.964	7.77	2.01	94.24
0.956	0.922	0.815	3.63	-11.15	85.22
0.873	0.817	0.871	6.47	6.24	99.77

Table 6. Reference Cell Consistency Results. The panel was oriented directly (Straight) at the sun, and clockwise (CW) and counterclockwise (CCW) of the straight direction by approximately 30° and 60°.

Orientation	I_{SC}	V_{OC}	$V(I_{SC})_{shunt}$	T_{cell}	T_{ref}	E_e	I_{SCO}	I_{SCO}/E_e		
1. Straight	5.73	635	56.4	41.4	41.81	0.954	0.925	0.969	min	0.968
	5.79	629	56.5	44.4	44.83	0.955	0.933	0.977	max	0.977
	5.74	628	56.5	45.3	45.33	0.955	0.924	0.968	avg	0.971
	5.74	627	56.5	45.6	45.83	0.955	0.924	0.968	%diff	0.917
2. CCW 30°	5.56	622	54	47.5	47.60	0.912	0.894	0.980	min	0.968
	5.49	621	54	47.4	48.10	0.912	0.883	0.968	max	0.980
	5.47	620	53.8	47.4	48.54	0.909	0.880	0.968	avg	0.971
	5.46	619	53.7	47.5	49.00	0.907	0.878	0.968	%diff	1.255
3. CW 30°	5.61	618	55.3	48.7	49.97	0.934	0.902	0.966	min	0.965
	5.62	617	55.4	48.7	50.50	0.935	0.903	0.966	max	0.967
	5.64	617	55.5	49.3	50.53	0.937	0.906	0.967	avg	0.966
	5.65	617	55.7	49.1	50.59	0.940	0.908	0.965	%diff	0.170
4. CW 60°	4.43	612	43.7	47.1	49.19	0.738	0.713	0.966	min	0.965
	4.44	612	43.8	47.4	49.22	0.740	0.714	0.965	max	0.966
	4.44	612	43.8	47.8	49.22	0.740	0.714	0.965	avg	0.965
	4.44	611	43.8	48.1	49.72	0.739	0.714	0.965	%diff	0.049
5. CCW 60°	4.22	610	41.7	46.6	49.43	0.704	0.679	0.964	min	0.964
	4.22	611	41.5	45	48.86	0.701	0.680	0.970	max	0.970
	4.21	611	41.5	43.9	48.86	0.701	0.678	0.968	avg	0.968
	4.2	611	41.4	44	48.83	0.699	0.677	0.968	%diff	0.559

Totals	
min	0.964
max	0.980
avg	0.968
%diff	1.648

Table 7. Pyranometer Consistency Results. The panel was oriented directly (Straight) at the sun, and clockwise (CW) and counterclockwise (CCW) of the straight direction by approximately 30° and 60°. Values highlighted in red are outliers.

Orientation	I_{SC}	V_{PYRAN}	$T_{cellact}$	$T_{cell}+3$	I_{SCO}	I_{SCO}/V_{PYRAN}		
1. CCW 60°	4.1	40	43.1	46.1	0.660	0.0165	min	0.0164
	4.1	39	43.2	46.2	0.660	0.0169	max	0.0169
	4.09	40	43	46	0.658	0.0165	avg	0.0166
	4.08	40	42.8	45.8	0.657	0.0164	%diff	3.02
2. CCW 30°	5.4	53	43.5	46.5	0.869	0.0164	min	0.0164
	5.4	53	44	47	0.869	0.0164	max	0.0164
	5.42	53	44.5	47.5	0.872	0.0164	avg	0.0164
	5.4	53	45.3	48.3	0.868	0.0164	%diff	0.41
3. Straight	5.76	56	46.1	49.1	0.925	0.0165	min	0.0165
	5.75	56	46.2	49.2	0.924	0.0165	max	0.0165
	5.76	56	46.2	49.2	0.925	0.0165	avg	0.0165
	5.76	56	46.4	49.4	0.925	0.0165	%diff	0.18
4. CW 30°	5.37	52	48.1	51.1	0.862	0.0166	min	0.0165
	5.36	52	48.3	51.3	0.860	0.0165	max	0.0166
	5.38	52	47.5	50.5	0.864	0.0166	avg	0.0166
	5.38	52	47.5	50.5	0.864	0.0166	%diff	0.42
5. CW 60°	4.66	45	47.9	50.9	0.748	0.0166	min	0.0166
	4.66	45	47.4	50.4	0.748	0.0166	max	0.0166
	4.66	45	47.1	50.1	0.748	0.0166	avg	0.0166
	4.66	45	46.3	49.3	0.749	0.0166	%diff	0.09
6. CW 60°	4.65	44.9	46	49	0.747	0.0166	min	0.0166
	4.65	44.9	46.4	49.4	0.747	0.0166	max	0.0167
	4.66	45	46.8	49.8	0.748	0.0166	avg	0.0166
	4.66	44.9	47	50	0.748	0.0167	%diff	0.21
7. CW 30°	5.54	54.4	46.9	49.9	0.890	0.0164	min	0.0164
	5.54	54.4	46.8	49.8	0.890	0.0164	max	0.0164
	5.54	54.4	46.9	49.9	0.890	0.0164	avg	0.0164
	5.55	54.4	47	50	0.891	0.0164	%diff	0.17
8. Straight	5.57	56.5	47.5	50.5	0.894	0.0158	min	0.0158
	5.77	56.5	47.7	50.7	0.926	0.0164	max	0.0164
	5.77	56.5	48	51	0.926	0.0164	avg	0.0162
	5.77	56.5	48	51	0.926	0.0164	%diff	3.49
9. CCW 30°	4.98	48.5	48.6	51.6	0.799	0.0165	min	0.0164
	4.98	48.5	48.7	51.7	0.799	0.0165	max	0.0165
	4.98	48.6	48.5	51.5	0.799	0.0164	avg	0.0165
	4.98	48.5	48.3	51.3	0.799	0.0165	%diff	0.22
10. CCW 60°	3.7	36	48.3	51.3	0.594	0.0165	min	0.0165
	3.7	35.9	47.9	50.9	0.594	0.0165	max	0.0165
	3.69	35.9	47.6	50.6	0.592	0.0165	avg	0.0165
	3.69	35.9	47.2	50.2	0.592	0.0165	%diff	0.30

Totals	
min	0.0164
max	0.0167
avg	0.0165
%diff	1.89

Appendix F. Picture Contents by Picture Number

(Pictures and Video Located on included DVD)

Charlie's	Category	Description	Nozzle	Standoff	Pressure	Pitch	Yaw	Roll
105	Hard Water Tests	409 Clean						
106		Soiled						
107		Spray Clean						
108		409 Clean						
109		Spray Clean						
110		Soiled						
111	Repeatibility Test-1	Pre-soil	15	12	1500	45	0	0
112		Pass1						
113		Pass2						
114		Pass5						
115		Pass6						
116		Done						
117	Repeatibility Test-2	Pass2	15	12	1500	45	0	0
118		Pass6						
119		Clean						
120	Repeatibility Test-3	Soiled						
121		Pass3	15	12	1500	45	0	0
122		Pass6						
123		Clean						
124	Nozzle Variation	Soiled						
125		Pass2	25	12	1500	45	0	0
126		Pass5						
127		Clean						
128	Nozzle Variation	Soiled	40	12	1500	45	0	0
129		Clean						
130								
131	Repeatibility Test-4	Soiled	40	12	1500	45	0	0
132		Clean						
133	Repeatibility Test-5	Soiled	40	12	1500	45	0	0
134		Clean						
135	Repeatibility Test-6	Soiled	40	12	1500	45	0	0
136		Clean						

Atlund's	Category	Description	Nozzle	Standoff	Pressure	Pitch	Yaw	Roll
1		Chuck						
2	Pressure Variation	Clean Panel						
3								
4		Dirty Panel						
5		Data Collection						
6		Cleaned Wet	40	12	2000	45	0	0
7		Cleaned Dry						
8		Dirty Panel						
9		Measuring Distance						
10		Final Pass						
11		Clean	40	12	2500	45	0	0
12		Dirty Panel						
13		Making Pass						
14		After Pass						
15	Movie	Final Pass						
16	Pressure Variation	Data Collection						
17								
18								
19								
20								
21								
22		Dirty	40	12	3000	45	0	0
23								
24		Pre-Pass						
25								
26								
27								
28		Consecutively Making Pass						
29								
30								
31								
32								
33								
34		After	40	12	3500	45	0	0
35		After						
70		Nice Day						

Atlund's	Category	Description	Nozzle	Standoff	Pressure	Pitch	Yaw	Roll
71	Qualitative	Dirty						
72		Pre-Pass						
73		While Wet	40	12	2000	45	0	45
74		Dried Result						
75		Pre-Pass	40	12	2000	45	0	70
76		After						
77		Durring Pass	40	12	3000	45	20	45
78		After						
79		Pre-soil						
80		Slowpass	40	12	20	45	0	0
81								
82								
83		after dry						
84		25deg slow	25	12	20	45	0	0
85		dry						
86		at 200025deg	25	12	2000	45	0	0
87		Adjusting Nozzle						
88								
89		Dry						
90		Pre-Pass						
91		Pass	25	12	3000	45	0	0
92		Dry						
93		Soiling Method						
94		Soiled						
95		Pre-Pass						
96		Yaw and Roll	25	6.5	3000	45	20	45
97		Pre-Pass						
98		Ref (No Yaw and Roll)	25	10	3000	45	0	0

Atlund's	Category	Description	Nozzle	Standoff	Pressure	Pitch	Yaw	Roll
102	Equipment	Speedometer						
103		Pressure Washer						
104		Pressure Gage						
105		Reference Cell						
106		Digital Multimeter						
107		Pyranometer						
108								
109								
110								
111		Digital Multimeters						
112		Thermocouple						
113								
114								
115		Panel Specs						
116		Washer Specs						
117		Washer Specs						
118		Angle Finder						
119								
120		Tank Specs						
121		Soiled						
122	Qualitative	Single Pass	25	16	2500	45	0	0
123		Zero Nozzle Shear Setup						
124								
125								
126	Movie	Shear Pass						
127		Shear Pass	0		2500			
128		3 Passes	40	16	2500	45	0	0
129		Perpendicular Spinner	0	Variable	1500	45		
130	Movie							
131			0	Variable	1500	45		
132			0	Variable	1500	45		
133		Perpendicular Spinner	0	Variable	1500	15		
134	Movie							
135			0	Variable	1500	15		
136			0	Variable	1500	15		

Appendix G: Nozzle Data from Spraying Systems Co. Technical Reference

Nozzle Type and Spray Angle																					Capacity Size	Capacity (gallons per minute)*										
1/8 MEG							1/4 MEG							1/4 MEG-SSTC																		
0°†	5°	15°	25°	40°	50°	65°	0°†	5°	15°	25°	40°	50°	65°	0°†	5°	15°	25°	40°	50°	65°		300	400	500	600	700	800	1000	1500	2000	2500	3000
									●					●		●			●		01	.27	.32	.35	.39	.42	.45	.50	.61	.71	.79	.87
									●												015	.41	.47	.53	.58	.63	.67	.75	.92	1.1	1.2	1.3
●	●	●	●	●			●	●	●	●	●		●	●		●		●	●		02	.55	.63	.71	.77	.84	.89	1.0	1.2	1.4	1.6	1.7
													●								025	.68	.79	.88	.97	1.0	1.1	1.3	1.5	1.8	2.0	2.2
●		●	●	●	●		●	●	●	●	●	●	●	●		●			●	●	03	.82	.95	1.1	1.2	1.3	1.3	1.5	1.8	2.1	2.4	2.6
							●		●	●	●										035	.96	1.1	1.2	1.4	1.5	1.6	1.8	2.1	2.5	2.8	3.0
●		●	●	●	●	●	●	●	●	●	●	●	●	●		●	●		●	●	04	1.1	1.3	1.4	1.5	1.7	1.8	2.0	2.4	2.8	3.2	3.5
●		●	●	●		●	●		●	●	●		●			●	●				045	1.2	1.4	1.6	1.7	1.9	2.0	2.3	2.8	3.2	3.6	3.9
●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●		05	1.4	1.6	1.8	1.9	2.1	2.2	2.5	3.1	3.5	4.0	4.3

IMPACT

Impact, or the impingement of a spray onto the target surface, can be expressed in several different ways. The most useful impact value with regard to spray nozzle performance is the impact per square inch (cm). Basically, this value depends on the spray pattern distribution and spray angle. To obtain the impact per square inch (cm) [pounds (kg)-force per square inch (cm)] of a given nozzle, first determine the theoretical total impact using the following formula.

$$I = K \times Q \times \sqrt{P}$$

I: Total theoretical spray impact

K: Constant

Q: Flow rate

P: Liquid pressure

I	pounds	kilograms
K	.0526	.024
Q	gpm	l/min
P	psi	kg/cm^2

Then, from the chart on the right, obtain the impact per square inch (cm) as a percent of the theoretical total impact and multiply by the theoretical total. The result is the unit impact in lbs.-f/sq. inch (kg/cm^2) at 12" (30 cm) distance from the nozzle.

The highest unit impact in lbs.-f/sq. inch (kg/cm^2) is provided by solid stream nozzles and can be closely approximated by the formula: 1.9 x [spraying pressure, psi (bar)]. As with all spray patterns, the unit impact decreases as the distance from the nozzle increases, thereby increasing the impact area size.

UNIT IMPACT PER SQ. INCH (CM)*

Spray Pattern	Spray Angle	Percent of Theoretical Total Impact
Flat Fan	15°	30%
	25°	18%
	35°	13%
	40°	12%
	50°	10%
	65°	7.0%
	80°	5.0%
Full Cone	15°	11%
	30°	2.5%
	50°	1.0%
	65°	0.4%
	80°	0.2%
	100°	0.1%
Hollow Cone	60°, 80°	1.0 to 2.0%

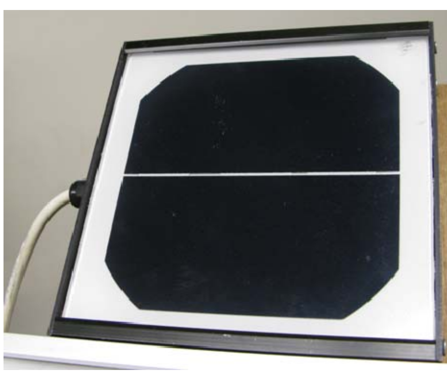
*At 12" (30 cm) distance from the nozzle.

Appendix H: Pictures of Equipment Used

Speedometer and Pressure Gauge


Non-contact Thermometer


Thermometer and Microprocessor


Reference Cell

Pyranometer


Digital Multimeters