

NANOWINDOW: MEASURING WINDOW PERFORMANCE AND ENERGY  
PRODUCTION OF A NANOFLUID FILLED WINDOW

by

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## DISSERTATION ABSTRACT

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Title: Nanowindows: Measuring Window Performance and Energy Production of a Nanofluid Filled Window

Windows reduce heat loss and heat gain by resisting conduction, convection, and radiation using thermal breaks, low-emissivity films, and window gaps. Contrary to advancing these resistive qualities, this research introduced a highly conductive gap medium using  $\text{Al}_2\text{O}_3$  nanoparticles dispersed in deionized water to enhance thermal conductivity. The solution harnessed the photothermal properties of  $\text{Al}_2\text{O}_3$  nanofluids to trap, store, and transport thermally charged fluids to heat exchangers to preheat air and water, and to generate electricity forming a transparent generator—the Nanowindow.

Seven Nanowindow prototypes with varying orders of air and fluid columns were fabricated and tested using distilled water ( $\text{H}_2\text{O}$  windows) to establish a baseline of performance. A solar simulator was built to avoid environmental radiant flux irregularities providing a uniform test condition averaging  $750\text{--}850\text{ W/m}^2$ , and resulted in an undefined spectral match, Class B spatial uniformity, and Class B temporal stability. All Nanowindows were tested in a calibrated hot box determined to have a  $\pm 4\%$  degree of accuracy based on four laboratory samples establishing a framework to conduct U-factor and solar heat gain coefficient (SHGC) measurements.



Four heat exchange experiments and standardized window performance metrics (U-factor, SHGC, and visible transmission) were conducted on seven H<sub>2</sub>O windows. The top two H<sub>2</sub>O windows were then tested using Al<sub>2</sub>O<sub>3</sub> nanofluids. The highest performing Nanowindow improved total convective heat transfer rates using Al<sub>2</sub>O<sub>3</sub> by 90% over water baseline, and 61% improvement in preheat water experiments. Nanowindows coupled with thermoelectric generators generated a rated voltage of 0.31V<sub>DC</sub>/0.075A<sub>DC</sub> per 12in<sup>2</sup> Nanowindow, an improvement of 38% over baseline. Standardized window performance metrics confirmed Nanowindow U-factors ranging from 0.23 to 0.54, SHGC from 0.43 to 0.67, and visible transmittance coefficient (VT) ranging from 0.27 to 0.38.

The concept of nature as model system thinking provided a theoretical framework for the research and proof of concept experiment. Ultimately, the experiment shifted window gaps from resisting energy to harnessing solar energy. The Nanowindow thus presents a unique opportunity to turn vast glass facades into transparent generators to offset energy demand, and reduce greenhouse gases.

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# CHAPTER I

## INTRODUCTION

Windows are among the weakest insulating components in a building envelope with little to no renewable energy potential. Windows may be three to four times less efficient than walls,<sup>1</sup> and as window area increases so does the energy demand to heat and cool buildings. This results in an uptake in carbon emissions and greenhouse gases. However, despite these issues, our affinity with glass continues to dominate the built environment. This research presents the Nanowindow, a double-pane window coupled with nanofluid technology that retains optical clarity and high performance fenestration criteria to form a transparent generator.

In Los Angeles, glass continues to proliferate in commercial and residential midrise to skyscraper development.<sup>2</sup> Initially, a survey was conducted to establish the quantity, quality, and solar orientation of new development. The window-to-wall ratio (WWR), a calculation used to determine the percentage of total glass area compared to the total exterior surface area, was used to determine the extent glass was used on five recent projects.<sup>3</sup> The WWR is a vital aspect of building performance because it impacts heating and cooling loads, lighting demand, indoor environmental quality, and energy demand. As WWR increases,

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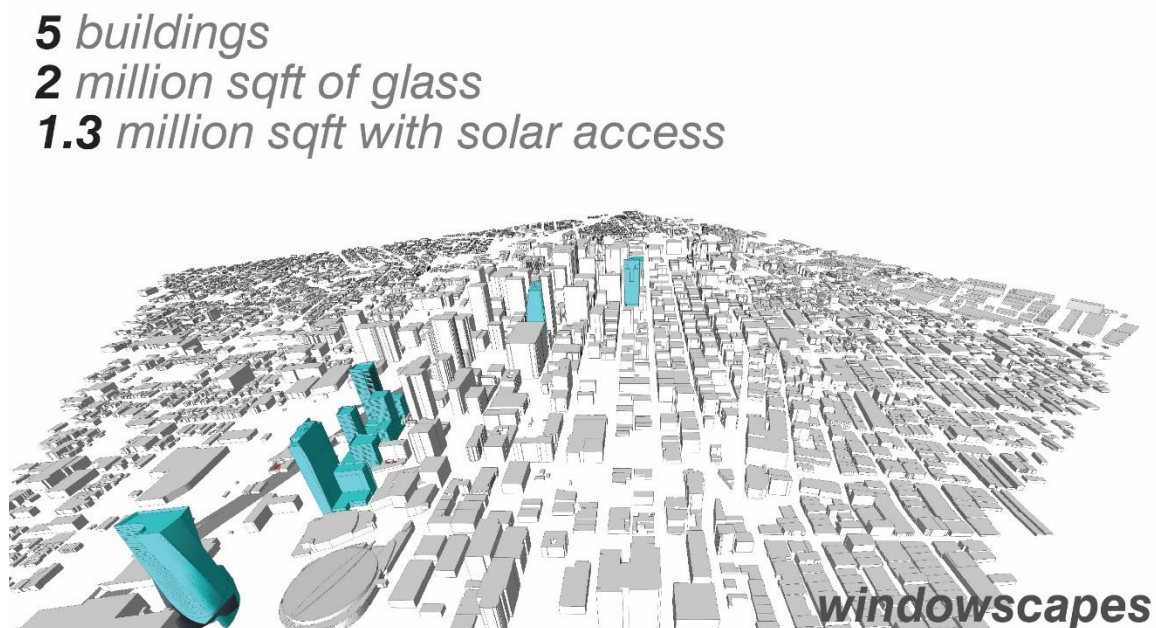
<sup>1</sup> Based on a wall U-factor of 0.086 which is a continuous insulated wall metal framed wall with R-6 CI and R-21 cavity insulation (Joint Appendix JA4) compared to a high performance window with U-factor of 0.31.

<sup>2</sup> Mid-Rise defined as 6-15 floors, High-rise 16+ floors, Skyscrapers 70+ floors.

<sup>3</sup> The surveyed buildings: Metropolis (2 Towers), Wilshire Grand Center, Los Angeles U.S. Courthouse, Ritz Carlton & Marriot Center

so does energy consumption to offset excessive heat gain and heat loss. Of the five high-rise buildings surveyed, the WWR is approximately 90%, an indicator that these buildings are nearly glass boxes. The cumulative gross glass area is approximately 2 million square feet, and of that, 1.3 million square feet has sun access during the 5.6 peak sun hours along this latitude. Transposing 1.3 million vertical square feet on the ground represents 13 city blocks.

In downtown Los Angeles, a square-foot of land is approximately \$255 or \$11 million per acre of undeveloped land. Considering the value of undeveloped land, it is surprising that developers are not exploring the potential of windowscapes, the unclaimed vertical land formed by development.



**Figure 1: Los Angeles Windowscapes**

The surveyed buildings used high performance insulated laminated glass with a U-factor of 0.31 (rate of heat transmission), visible transmittance (VT) of 0.37 (optical performance), and solar heat gain coefficient (SHGC) of 0.31 (the fraction of solar radiation passing through a window). These measures define glass performance and collectively aim to reduce heating and cooling loads, improve the quality and quantity of daylight, and ultimately reduce energy demand.

These five buildings contribute to 40% of all energy consumed by the entire U.S. building sector and 40% of the country's carbon emissions (U.S. Department of Energy, 2012). Research has shown that 22–32% of that energy demand arises from poor window performance and results in 2 quads a year in energy or \$20 billion dollars. Window performance is paramount in making a substantial impact on energy conservation measures. However, it is thought that windows have reached their theoretical limit of performance (Johnson, 1991). Windows continue to be widely applied as a fenestration material that offers aesthetic delight and transparency despite being directly attributed to energy consumption and carbon emissions (Aasteh & Selkiwitz, 1989).

If windows have reached their energy performance limit, then what opportunities exist to improve window performance? Can such vast windowscapes of glass inspire windows to be something else other than inefficient fenestration components and offer opportunities to harness the most durable source of renewable energy, the sun? What if 1.3 million square feet of windows could generate energy without compromising optical clarity and retain a sensible degree of energy performance?



Understanding the physics of the window-sun relationship is essential to answering these questions. Solar energy-generating solutions tend to rely on conductivity. This is why solar thermal panels are lined with black absorber plates to maximize conductivity and heat transfer. In contrast, windows focus on resisting energy transfer and optimize resistance using transparent technology such as low-emissivity films<sup>4</sup> and inert gases<sup>5</sup> that resist shortwave radiation and resist energy transmission. The physics of conduction and resistance are fundamentally opposite yet central to this research, as the two are coupled to promote a hybrid window—a window that resists energy flow to improve building performance while harboring conductive qualities to convert energy into a meaningful application.

The current portfolio of hybrid windows is relatively slim. Energy-generating solutions have embedded photovoltaic cells in windows called Building Integrated Photovoltaics (BIPV). However, as more cells are added to generate more electricity, the optical clarity is diminished to the point of creating opaque surfaces. While this may be helpful as a solar shading device, it diminishes optical clarity in the process of delivering energy (Figure 2).

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<sup>4</sup> Low-emissivity (low-e) window films resist incoming short wave radiation from the sun from passing through a window and entering the building, and blocks long-wave radiation from leaving space.

<sup>5</sup> Inert gases (Noble gases) resist energy transfer because they retain low conductivity values making them ideal within the gaps of double pane windows.

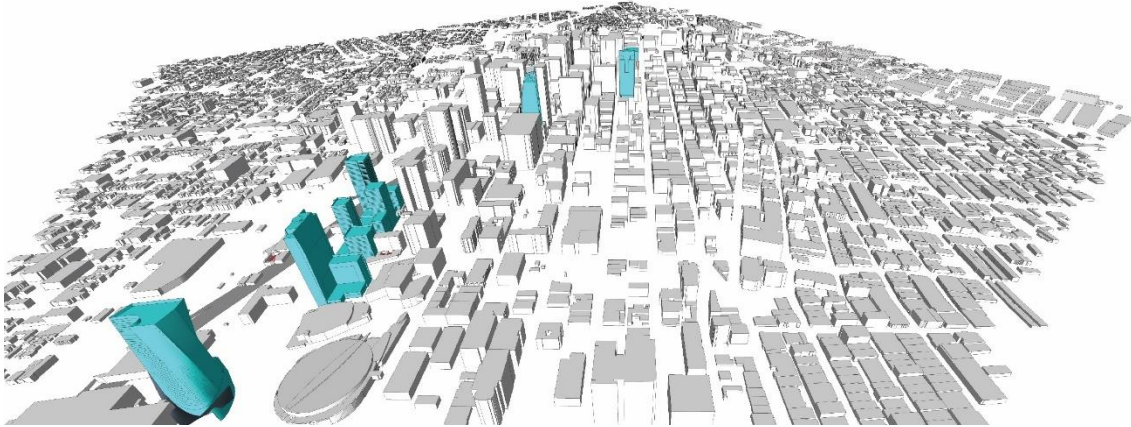


**Figure 2: Building Integrated PVs**

Left - SMA Solar Academy BIPVs integrated into the glass. Reduces optical clarity but offers shading electrical generation. (Meyer, 2010). Right – BIPV on Lillis Hall at the University of Oregon (Swimmer, 2004)

Of the five high-rise projects surveyed, none offered on-site renewable energy or utilized the static 1.3 million square feet of solar-oriented windowscape as an opportunity to harness solar energy (Figure 3). Considering that only 9 of the 41% of energy consumed by the built environment was generated from renewable energy, it begins to position vast uncharted windowscapes into transparent generators with prime exposure to the sun.

## *5 buildings - Zero Renewable Energy*



**Figure 3: 5 Buildings - Zero Renewables**

This research designed, prototyped, and tested a window assembly focused on optical clarity and energy production to address these unclaimed windowscapes. The window was comprised of various columns of aluminum oxide ( $\text{Al}_2\text{O}_3$ ) nanofluids, air columns, and suspended heat mirrors, which combined to form the Nanowindow. The nanofluids represent the conductive realm needed to harness solar thermal energy. Suspended within the nanofluid is a low-e film to further enhance a thermal trap effect. The air columns provide the resistive qualities as a function of its high viscosity and low conductivity characteristics. The trapped energy is then conveyed to a heat exchanger to preheat air and water, and generate electricity.

This research binds two unrelated knowledge realms at two distinct scales of technology. At the macroscale, the results of direct-gain water wall strategies of Balcomb and others have noted promising thermal performance and mass attenuation of interior temperature swings as a function of water's physical characteristics (McClelland et al., 1980).

However, these results have been ultimately limited by significant thermal losses. At the nanoscale, nanotechnology offers unprecedented augmentation to bolster water's physical characteristics by more than 30% (Murshed, 2005), though this has been untested in previous water wall research.

The significance of this research lays in its ability to surpass the theoretical performance limit of current window technology. Emerging window technologies are shifting toward ambidextrous opportunities. Opportunities like electrochromic glass exist that tint in response to solar radiation intensity, or switchable glass controlled by the occupant's desire for privacy, but neither are energy generators. At the same time as these progressive technocentric solutions are developing, advancements in building energy codes are mandating high performance windows, while government-sponsored research<sup>6</sup> stresses the need for high performance windows to support the nation's goal of net zero energy buildings.

The Nanowindow concept presented in this dissertation retains optical clarity and high performance characteristics comparable to today's window portfolio, and provides the foundation to transform the 1.3 million square feet of windowscapes into an energy generator equivalent to 5.2 Megawatts of energy.

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<sup>6</sup> U.S. Department of Energy's Building Technologies Program (BTP)

## Navigating the Research

In order to evaluate the Nanowindow, a standard testing environment was created for the sole purpose of this experiment, and each component was calibrated according to industry standards. The standard test environment included a low-cost solar simulator, calibrated hot box (CHB), and data acquisition center. Chapters 1, 2, and 3 introduce the research, discuss the theoretical framework of the study, and present a literature review. Chapter 4 characterizes the solar simulator and presents the calibration methodology and its results. Chapter 5 describes the CHB to establish a degree of uncertainty when measuring thermal flux. Chapter 6 introduces the design and fabrication of seven prototype Nanowindows and three baseline windows. Chapters 7 and 8 show how the Nanowindow uses distilled water to establish a baseline of performance referred to as H<sub>2</sub>Owindows. More specifically, Chapter 7 presents measurements of the H<sub>2</sub>Owindows' rate of heat loss (U-Factor), VT, and SHGC. Chapter 8 then illustrates the H<sub>2</sub>Owindows' energy generation potential. The collective performance discussed in Chapters 7 and 8 culminate in a narrowing down of the seven H<sub>2</sub>Owindows prototypes to two high performance Nanowindows. Chapters 9 and 10 subsequently detail the repeat tests conducted to evaluate these two prototypes, again measuring the Nanowindows' U-Factor, VT, and SHGC.

Chapter **4** Low-Cost Solar Simulator

Chapter **5** Calibrated Hot Box

Chapter **6** Nanowindow Design & Fabrication

Chapter **7&8** Baseline H<sub>2</sub>OWindows

Chapter **9&10** Nanowindow

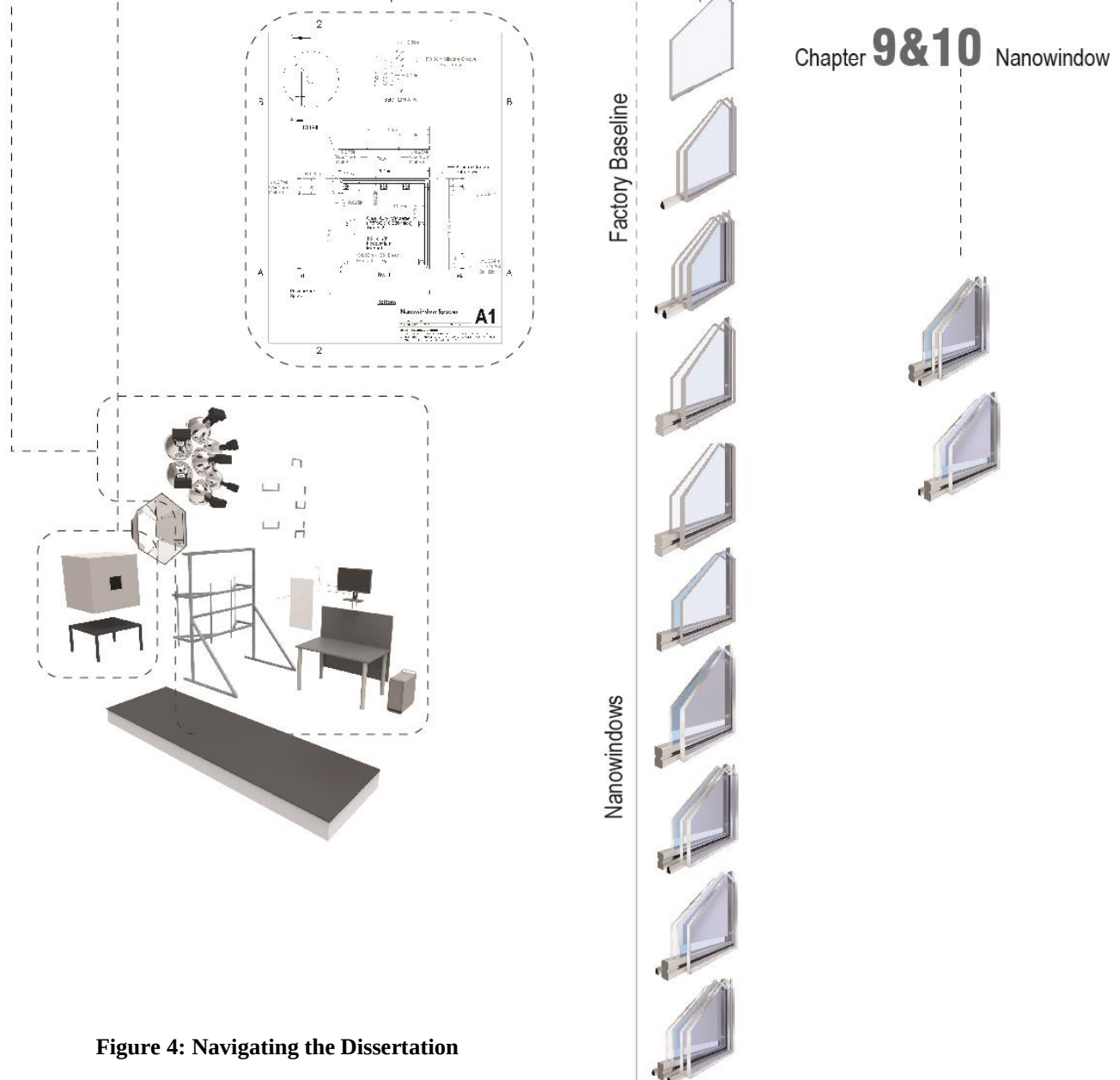


Figure 4: Navigating the Dissertation

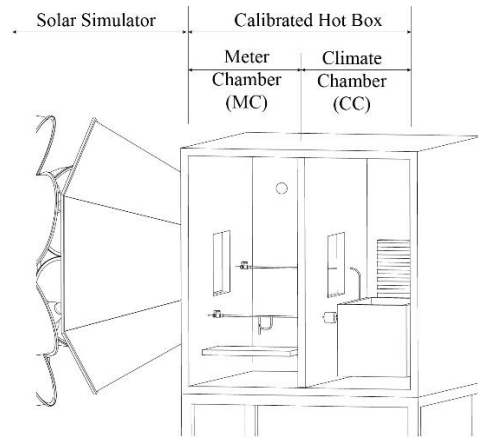
## Definitions

*American Society for Testing Material (ASTM).* An industry baseline understanding of testing methods, procedures, and protocols. The ASTM standards were consulted throughout this research, and certain liberties were allowed with each standard. Such liberties included the use of fewer sensors to develop average weighted results and detailed panel construction detail to limit heat transfer.

*Calibrated hot box (CHB).* An experimental chamber used to evaluate building materials in steady-state or dynamic-state conditions (Figure 5). The CHB was used to evaluate the U-factor, SHGC, and VT of the Nanowindows. The CHB in this experiment was a 4ft<sup>3</sup> box divided into two equal chambers: the meter chamber and the climate chamber. The CHB was fabricated from closed-cell polyisocyanurate (polyiso).

*Meter chamber (MC).* Also known as the hot side in some reference literature, this is the half of the Climate Chamber that has heating capability ranging between ambient air temperature and 50°C (Figure 5).

*Climate chamber (CC).* The CC is also referred to as the cold side in some reference literature. The climate chamber was equipped with cooling equipment to provide a differential in temperature between the two chambers of no less than 20°C (Figure 5).



**Figure 5: Calibrate Hot Box**

*Center of glass (COG).* The heat flux sensor was situated in the center of the glass and surface temperature sensors located halfway between the edge of the heat flux sensor and the edge of glass. This template was applied to all test series.

*Data acquisition system (DAS).* At the heart of the DAS was a Campbell Scientific CR10X datalogger capable of sensor measurement, timekeeping, data reduction, programming, and actuation of fans, lights, heating and cooling system, and pumps. The DAS was coupled with a relay control board that stepped up the 5.0 V digital I/O control port signal to line 120 V line voltage and 12 V low-voltage signal to actuate secondary devices (Figure 6).





**Figure 6: Data Acquisition System**

*Façade.* A composition of building components (e.g., doors, windows, openings, storefront, curtain walls, wall assemblies, etc) that may or may not have load bearing attributes, but is directly responsible for the heat gain and heat loss experienced by the building. Façades control daylight, views, solar gains and losses, and ventilation; and have a vital role in a building's energy and indoor environmental quality.

*Fluidized building envelopes.* A prototype experiment evaluating water walls as whole envelope assemblies (Issertes-Carbonnier, 2010)

*H<sub>2</sub>Owindow.* Because of the high cost of aluminum oxide nanofluid, the experiment used distilled water to narrow down the 10 potential Nanowindow candidates before deploying nanofluids. All Nanowindows using distilled water are referred to as H<sub>2</sub>Owindows.

H<sub>2</sub>Owindows as Nanowindows are double or triple pane windows assemblies with varying combinations of distilled water and air columns.

*Inherit gases (Noble gases).* Argon, xenon, and krypton are examples of noble gases used in lieu of air to fill the gap between glass. Such gases are used because they are less conductive than air thus reducing the rate of heat transfer.

*Low-emissivity (Low-e).* A window treatment that resists incoming short wave radiation from the sun from passing through a window and entering the building, and blocks long-wave radiation from leaving space. The low-e treatment is a means to reduce heat gain from entering the building and reduce heat loss from leaving the building.

*Nanowindow.* Is a high performance window capable of energy generation using nanofluids columns between the panes of glass in two, three, or four pane window assemblies.

*Specimen.* The specimen in this body of work included both H<sub>2</sub>O windows and Nanowindows. Both were 0.09m<sup>2</sup> (1ft<sup>2</sup>).

*Water walls.* Water walls are “vertical tubes made of translucent or transparent plastic to allow some light to pass through. The water can be left clear or tinted any color. Transparent tubes are especially beautiful because the way they refract the light. Test have shown that clear water is almost as efficient as tinted water or opaque containers when it comes to storing heat” (Nayak, 1987).

*Window.* For the purpose of this study, windows refers to conventional windows that have not been altered in this experiment. In this experiment baseline windows were

provided by Pilkington and Viracon accompanied with performance specifications noting SHGC, VT, and U-factor. These windows were used to calibrate the experiment to known specifications provided by the manufacturer (Chapter 6).

*Window gap (Gap).* The space between two sheets of glass, typically 0.25-inches to .05-inches

*Transparent water storage envelopes (TWSE).* A curtain wall composed of varying columns of air and water to improve building energy efficiency(L Xiangfeng & Tianxing, 2007) .

*Transwall.* A semitransparent water-based thermal storage wall that offers a number of advantages over conventional direct-gain and Trombe walls (McClelland et al., 1980)

#### *Thermal Conversion Factors*

U-factor (SI) to U-factor (IP) =  $U_{si}/5.678$

U-factor (IP) to U-factor (SI) =  $U_{ip} \times 5.678$

R-Value (IP) to R-Value (SI) =  $R_{ip} \times 0.1761$

R-Value (SI) to R-Value (IP) =  $R_{si} / 0.1761$

#### *Energy Conversion Factors*

kW to BTU/hr =  $1 \text{ kW} = 3412.142 \text{ BTU/hr}$

## CHAPTER II

### THEORETICAL FRAMEWORK

What if windowscapes could harness solar energy and apply it in a meaningful way? What if windows retained optical clarity and did not need to embed solar cells to generate electricity? To address these questions, this study utilized a theoretical framework rooted in the natural sciences. It was not required that an absolute condition of these natural sciences exist, nor were the natural sciences the only source of inspiration for this research. As this framework unfolded, evidence from biology and physiology was joined by physics, mathematics, and appropriate emerging technologies. Collectively, this multidisciplinary approach refrained from loose metaphorical comparison and biological fallacy,<sup>7</sup> which would have undermined the value of the research. Instead, this research focused on structures, organizations, relationships, and processes that provided a durable foundation to build upon, while retaining awareness of nature as model theory.

Precedent nature as model theory, such as regenerative theory and biophilia, propose that there are direct and beneficial applications of natural systems to the human artifact—architecture. The concept of biophilia proposes that humans have an “innate tendency to focus on life and lifelike processes” (Wilson, 1984, p. 1), and that retaining connectivity to nature in architecture bolsters spiritual, physical, and mental well-being (Issertes-Carbonnier, 2012, p. 60). Well ahead of his time, John Ruskin (Phusin & Ruskin, 1855) foreshadowed environmentalism, noting that nature is the ultimate judge of architecture,

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<sup>7</sup> The writings of Scott Geoffrey (Geoffrey, 1969) and Phillip Steadman (Steadman, 1979) cautioned the adaptation of biological influences in architecture. Without fully comprehending the methods, organizations, and relationships the influence may fall victim of biological fallacy.

and biomimicry's three pillars place ecology as the standard to judge the rightness of human innovation (Benyus, 1997). However, these broad based theories have not offered a systematic way to innovate, prototype, and validate the transition of knowledge from nature to architecture.

Bioaedificium is a system-based theory focused on the microscopic scaling of processes found in nature that may have applicability in architecture (Issertes-Carbonnier, 2012).

The etymology of the word bridges biological systems to the built environment.

However, it is not intended to be a social contract with nature, nor is it a postrationalization of artifact solutions rooted in nature. Bioaedificium does not attempt to reestablish or restore a connection with nature through architecture, much like biomimicry or biophilia. Instead, it seeks to understand the microscopic collaborations and processes that have scalability and adaptability to optimize architectural systems similar to the scalability of biomimetics.

The Schmitt trigger<sup>8</sup> (Steele & Schmitt, 1961) is one example of microscopic collaborations. It adopted biological nerve propagation in a squid's nervous system to innovate comparator circuits. This biological system thinking spurred bionics as the art of applying the understanding of living systems to the solution of technical problems (Steele & Schmitt, 1961). Bioaedificium has applied a similar ideology to adapt microscopic processes and techniques to advance high performance architecture coupled with scientific methods to validate these transitional concepts.

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<sup>8</sup> Otto Schmitt invented the Schmitt trigger

Defining the renewable energy potential of a window has been organized into three main areas of discourse. The first area examines the window's social contract with the environment through the lens of physics. That contract reveals where alternatives may emerge to form a more favorable relationship with the environment, supported by system theory that bridges nature as model theory to architecture. Important to this discourse is the understanding that building science would be inevitably tasked with validating the Nanowindow as a renewable energy technology, and that theoretical discourse alone is not proof of application.

### Windows: A Social Contract

Windows have a social contract with the environment. How we have defined that contract over two millennia has been forged in controlling sun, wind, light, snow, and rain. The current state of window ideology predominately favors resisting environmental forces (i.e., radiation, conduction, and convection) rather than harnessing it or working with it in a symbiotic way. At first, this may seem trivial, but from a theoretical perspective, it raises questions concerning our understanding of modern window ideology. What if the window were to harness energy flow rather than turn it away? Could this energy be converted into useful energy? What framework would be best to define the temporal and spatial beginnings of the theoretical juncture in the window's social contract?

Openings have a different social contract with the environment compared to windows. Vitruvius elegantly expressed this contract in the Ten Books of Architecture, describing

the performance of an opening as “conform[ing] to the physical qualities of nations, with regard to the course of the sun and to climate” (Morgan, 1960, p. 174). Vitruvius proposed that the outdoor environment and indoor environment are symbiotic and bound by qualities of nations that are best interpreted as energy flows by means of conduction, convection, and radiation. For this discussion and with some creative liberty, physics was proposed as the mechanism to define openings, window performance, and the temporal and spatial juncture where the antithetical emerges. This is not to say that other valuable derivatives of window performance do not exist, but that this inquiry focuses on energy flow through the window.

As we leap forward in the history of glass and window technology, the epicenter of window performance has been the double-pane window. The significance of the double-pane window has little to do with the two panes of glass, but what is formed between the panes—the gap. The gap is a complex choreography of energy transfer mechanisms, and the juncture that has inspired over a half century of advancements in resisting energy flow. Understanding the fundamental physics of energy flow was paramount in the genesis this research.

To understand how resistance is achieved in the gap, the underlying physics can be divided into three critical domains of energy transfer. The first concerns resisting convective energy across the panes: the medium that occupies the gap must have high kinematic viscosity ( $\nu$ ) to resist energy flow. The more viscous the medium, the slower the medium moves, ultimately reducing convective traffic and lowering heat transfer

across the two panes of glass. A commonly used medium is inert gas such as argon that has low conductive characteristics. The second domain is conductivity ( $k$ ), which is largely dependent on the buoyancy flow of natural convection or the Rayleigh number.<sup>9</sup> The third domain resists radiation flow by reflecting infrared traffic, while unencumbering the visible spectrum to transmit through the window. This is achieved using low-e films that reflect far infrared radiant heat back into the space it originates from, while permitting visible light to pass.

Thus, high viscosity and low conductivity result in greater resistance to energy flow and the formula to high performance windows. A dimensionless and simplified expression can be utilized to illustrate the underlying physics in resisting energy flow (Equation 1). Note that the “up” arrow adjacent to  $R_{\text{resistance}}$  indicates high resistive values.

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<sup>9</sup> Rayleigh number describes a fluids property when heat transfer occurs by conduction or convection.





Where:

r = radiation

v = viscosity

k = conductivity

R = resistance

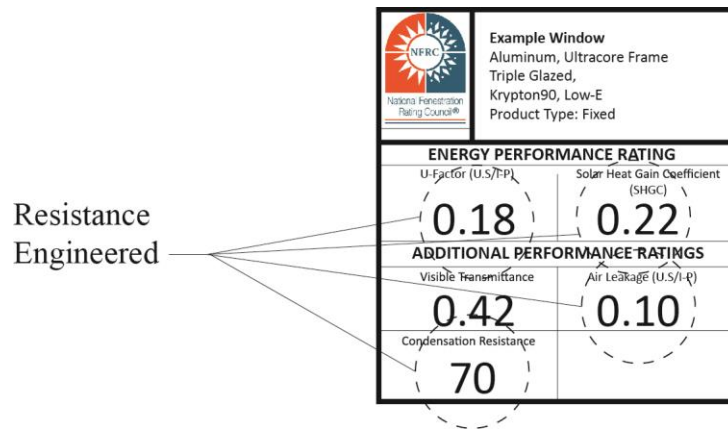
The arrows depict non-dimensional high or low values energy traffic rates.

Double pane windows are engineered to reflect thermal radiation and reduce the rate of thermal traffic across the panes resulting in high resistive values.

**Equation (1) Energy Flow Through Conventional Windows**

**Figure 7: Energy Flow Through Conventional Windows**

Modern window certifications further amplify the resistive nature toward the environment by claiming that high performance windows are predominately characterized by their resistive qualities. National Fenestration Rating Council (NFRC) performance certification drives resistance (Figure 8) using U-Factor, SHGC, condensation resistance, and air leakage resistance as measures of resistance that may otherwise be beneficial.

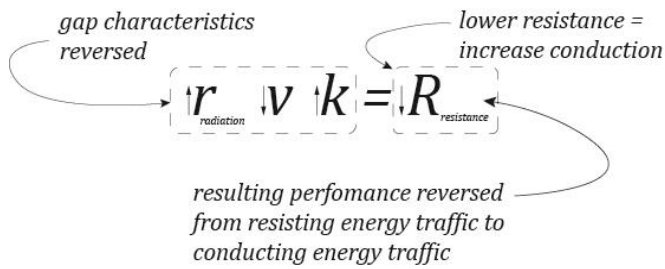


**Figure 8: NFRC Label**

Analyzing window performance through the lens of conduction, convection, and radiation illustrates that modern window ideology is fortified in resisting and deflecting energy flows across the window, and that the juncture from which a divergent ideology may emerge lies in gap technology. It is the physical gap between panes where new opportunities arise which may challenge the resistive nature of the gap.

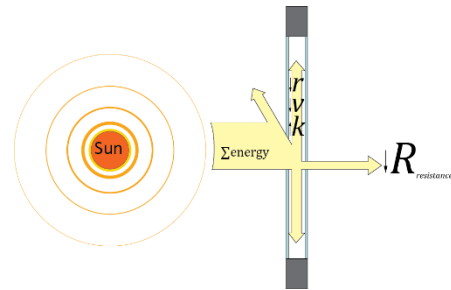
### Antithetical

If the antithetical to resistance is conduction, then Equation (1) can be rewritten such that low viscosity and high conductivity results in low resistance, meaning that the gap can be conceptualized as a conductive domain rather than resistive (Equation 2). Note that the arrow adjacent to  $R_{\text{resistance}}$  indicates lower resistivity resulting in higher conductive potential.



Where:  
 $r$  = radiation  
 $v$  = viscosity  
 $k$  = conductivity  
 $R$  = resistance

The arrows depict non-dimensional high or low values energy traffic rates.

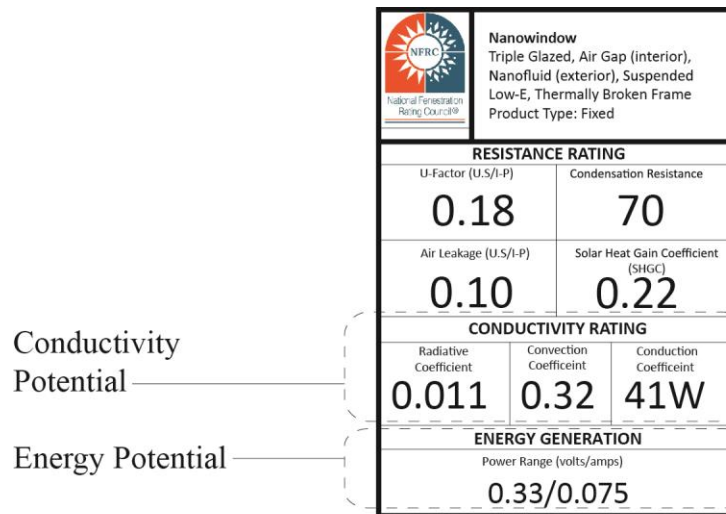


Conceptually the gap harnesses most thermal radiation rather than deflecting it. In both cases, some energy reflected and transmitted.

**Equation (2) Proposed Energy Flow**

**Figure 9: Proposed Energy Flow**

Expressing the gap with conductive potential (Equation 2) promotes a positive affiliation with the environment and the sun. Similarly, the NRFC label can begin to acknowledge conductive and energy potentials (Figure 10). In this case, the high-performance window is no longer singular in how it addresses energy; rather it becomes a hybrid window that harnesses both the resistive and conductive qualities that permit it to become a renewable energy technology.



**Figure 10: NRFC Label Reconsidered**

Shifting windows from resisting the environment to harnessing it permits the application of environmentally-centric system theory as new resources of inspiration, which were previously not applicable because the environment was excluded from the dialogue. This means that most modern windows do not have a mutual relationship with the environment because they simply reject energy flows.

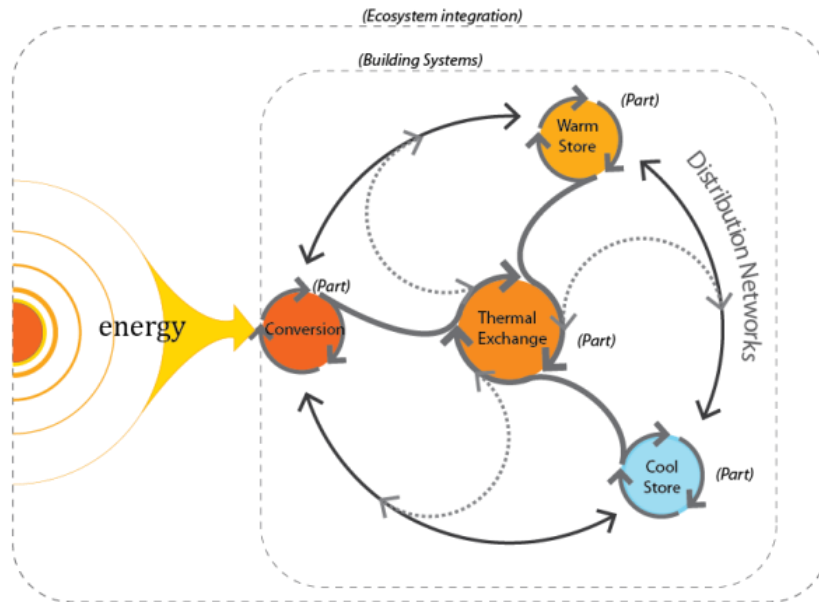
## System Theory

Nature as system theory (e.g., model, regenerative design theory,<sup>10</sup> and biomimetics<sup>11</sup>) interprets biological systems, functions, behavior, and structures as process-based solutions that may have application to complex human problems. System theory seeks mutual relationships between the environment and the artifact. To navigate this theory

<sup>10</sup> Nature as Model and Regenerative design theory based on John T. Lyle's works that defines a process that restores, renews, and revitalizes sustainable systems.

<sup>11</sup> Biomimetic architecture seeks to transfer working functions in nature into the built environment to optimize resources.

effectively, it is useful to consider two scales of the biological adoption: the macroscale and the nanoscale.



**Figure 11: Energy Model**

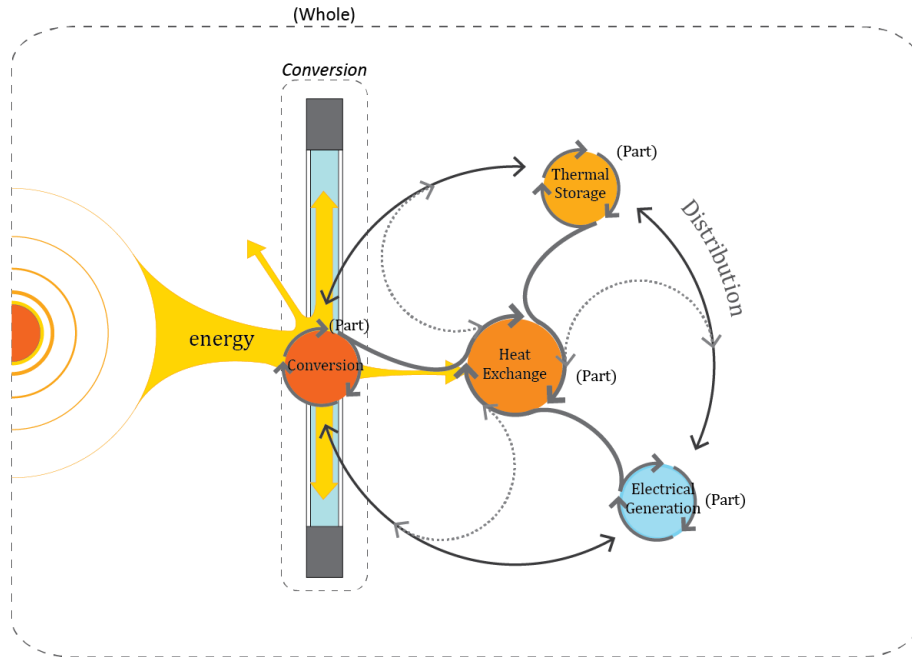
At the macroscale, nature as model theory proposes that the interconnectedness of the parts form an effective functional blueprint to whole system viability, and that equal concern should be placed on the interactions among the parts, the connections, as with the parts themselves (Lyle, 1994, p. 40). In nature, organisms are intrinsically interconnected in a cohesive manner, such that the amalgamation of parts contributes to the success of the whole. The energy flow model (Figure 11) conceptualizes that the window (direct-

gain system<sup>12</sup>) captures and converts solar energy and couples with vital parts (e.g., warm stores, cool stores, and heat exchangers) that contribute to whole system viability. This concept should not be confused with photovoltaic panels because the part itself has no continuous loop of interaction with the whole. This means that once radiant energy is captured and converted into electrical energy, there is no mechanism that reintroduces the expended electrical energy back into the system.

In contrast, the Nanowindow captures solar energy and converts it into usable energy. Thus, a closed loop is formed ( Figure 12) which has been unattainable in the current state of window technology. The window becomes a renewable energy technology with whole system attributes. The window harnesses solar energy that, in turn is distributed through a network to thermal stores or thermal exchange systems.

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<sup>12</sup> Direct gain is unobstructed solar radiation through a window into a space that is absorbed by a material's mass.



**Figure 12: Proposed Energy Model**

At the nanoscale, Vogel (2000, p. 285) contends that the emulation of biological systems is more successfully transferred to human scale issues. So what nanoscale biological properties exist that may offer insight into enhancing photothermal efficiencies? To that end, what fluid properties may transfer to a window's gap to enhance conductivity?

Fluids mediums, notably water, retain desirable characteristics. Water has promising conductivity and specific heat characteristics, low kinematic viscosity, excellent optical clarity, and can be easily integrated into a distribution system as illustrated in Figure 15. Gases were also considered, as they generally retain characteristics that favor low conductivity and high kinematic viscosity; hence, why argon and krypton are used to replace air in double-pane windows.

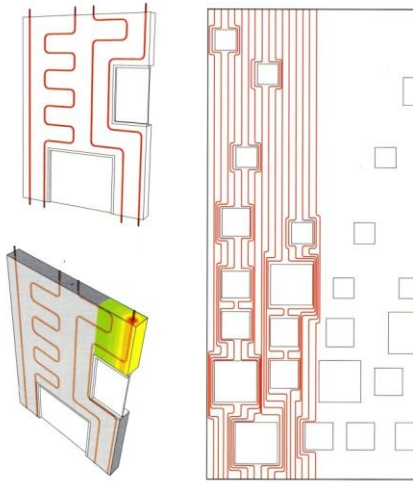
Gas was excluded because it retains a high viscosity and low kinematic characteristic as mentioned in Equation 1. An alternative material is one with phase change characteristics, but is historically opaque in both states and can be equally excluded because the underlying objective of a window is optical clarity. Thus, water became the baseline of this experiment.

Water retains significantly high heat capacity values ( $C_{p\text{water}} = 4.18\text{J/g}\cdot\text{K}$ ) that provides enhanced inertia against temperature swings as a function of the material's heat capacity, four times that of air ( $C_{p\text{air}} = 1.00\text{J/g}\cdot\text{K}$ ). This is why air is commonly used in the gap of dual-pane windows to resist energy flow, not water. However, hydronic systems such as radiators or radiant floors outperform forced-air systems (Feustel & Stetiu, 1995; Raftery, Lee, Webster, & Bauman, 2012), and are viable alternatives to the traditional forced-air systems commonly installed in residential and commercial applications.

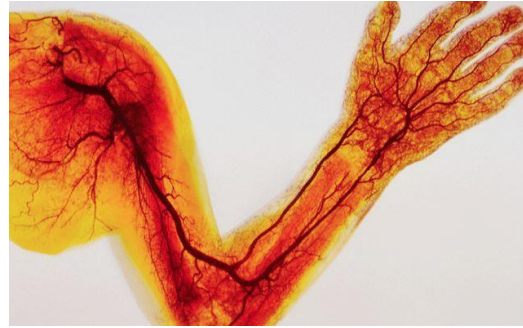
An example is the radiant heating system at the Zollverein School of Management (Moe, 2010, p. 146). The hydronic system is a complex network of water lines that weave through concrete walls and floors harnessing nearly  $30^{\circ}\text{C}$  geothermal water, offering a thermoregulated building environment. However, there is a distinctive discontinuity between the radiant wall system and the windows. Clearly, windows are not integral in the radiant system approach (Figure 13). The challenge is overcoming centuries of material ideology to redefine the window with the same fluid thinking that defined hydronic systems in the first place. Comparatively, the human circulatory system, as with



other animals, resembles an architectural hydronic system, and its parts and extremities are interconnected forming a thermoregulated assembly (Figure 14).



**Figure 13: Radiant Network (Moe, 2010)**

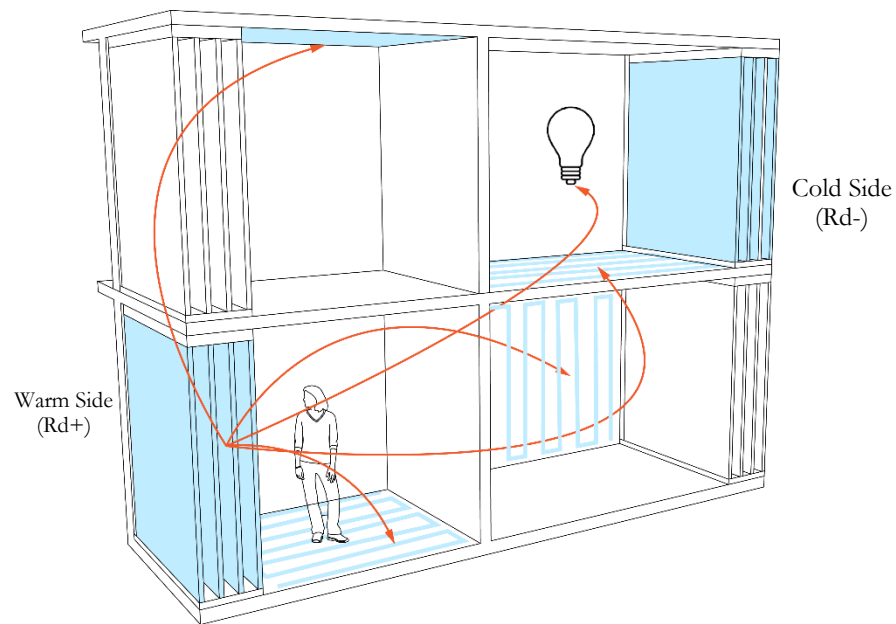


**Figure 14: Human arm and hand with blood veins (Lanting, 2014)**

This research proposes that connecting windows to hydronic systems or other forms of heat exchangers offers the opportunity for more mutual relationships to emerge, similar to that of the human circulatory system where the parts function to sustain system efficiency.

This study therefore proposed a hypothetical situation: Direct solar radiation ( $R_d^+$ ) would strike the warm side of a building's envelope (Figure 15), while the remaining sides of the building are losing heat by radiation ( $R_d^-$ ) and convection ( $C_v$ ). This is a typical occurrence in the built environment as the sun generally strikes only one to two sides of a building at any given time. The nanofluids would capture solar energy that would then be displaced to the cooler part of the building, reducing the need for additional heating. In

essence, the sun's energy would be captured and distributed to the cool side of the building that requires heating. A Nanowindow is therefore a material displacement<sup>13</sup> system, notably a displaceable thermal mass system.



**Figure 15: Nanowindows coupled with radiant floors, walls, and ceilings.**

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<sup>13</sup> Dennis Oppenheim's *Material Interchange* for Joe Stranard, Aspen, Colorado, hangs in the Metropolitan Museum of Art in New York City. Oppenheim characterizes the displacement of blood by a mosquito as material displacement.

## Biological Transfer

One possible source of biological transfer resides in the metabolic fluid in animals and plants. In certain species, fluids are integral for the conversion and transport of solar thermal energy. As such, uncovering nanoscale characteristics offers insight to expanding fluid mediums in window research. For example, blood and water share similar densities ( $1000 \text{ kg/m}^3$ ) and specific heat (3617 and 4187 J/kg/°C respectively), but the notable difference is blood's heterogeneous composition compared to water's homogeneity.

Previous research on the conductive water walls of Balcomb (Balcomb, McFarland, Perry, Wray, & Knoll, 1980), Fuchs and McClland (1979), and others has been restricted by the homogeneity of water, which limited the absorption rate for the larger scales of the built environment. This research posits that a heterogeneous fluid may yield higher conductive potential to capture thermal energy while retaining optical clarity present in previous research. One such possibility resides in nanotechnology and, specifically, nanofluids. Nanofluids have a specific heat capacity that significantly exceeds water and retains low viscosity that partially satisfies Equation 2, because they are heterogeneous in composition. A nanofluid's heterogeneous composition makes it a viable candidate because nanofluids using aluminum oxide ( $\text{Al}_2\text{O}_3$ ) and copper (Cu) are 36–720 times more thermally conductive ( $k$ )<sup>14</sup> than water (Terekhov, 2010, p. 2).

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<sup>14</sup> Thermal conductivity ( $k$ ) is the property of a material's ability to conduct heat

## CHAPTER III

### LITERATURE REVIEW

This literature review summarizes and bridges multiple research fields with the goal to define Nanowindow performance. The first part of the literature review focuses on the framework for the solar simulator. The second part focuses on previous technologies, namely water walls and transwalls, which represent a durable foundation of past and current fluid-based envelopes. Here, the review identifies constraints of past technology and knowledge realms that limited the initial research. The third part of the review presents nanofluids<sup>15</sup> as an emerging technology to enhance thermal transfer previously not used in water wall and transwall research. The fourth part then introduces a set of analytics to evaluate heat transfer potential generated by the Nanowindows. Finally, the literature review provides an overview of various frameworks, performance benchmarks, and known analytical expression and physical testing parameters to evaluate the Nanowindow.

### Solar Simulator

In this study, an in-situ solar simulator was favored over using the sun, to produce a steady and controlled amount of radiant energy throughout all experiments. Testing Nanowindows in the environment would have complicated the analysis because irregularity in radiant fluxes generated by atmospheric conditions would result in uneven variables for comparison. The greatest advantage is the controllability of radiant

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<sup>15</sup> Nano fluids contain nanometer-sized particles ranging about Ø10nm x Ø40nm – coined by Choi, Argonne National Laboratory

conditions for conducting high thermal research without perturbations due to solar resource intermittency (Li, Gonzalez-Aguilar, Pérez-Rábago, Zeaiter, & Romero, 2014, p. 590). A solar simulator offered controllability and replicability of test conditions by adhering to standard test conditions (STC). Current STC industry standards provide a uniform test environment of  $1000\text{W/m}^2$  at  $25^\circ\text{C}$  with a solar spectral irradiance of air mass 1.5 (AM1.5) defined by the International Electrotechnical Commission (IEC) 60904-9 (2<sup>nd</sup> ed.) and the American Society for Testing Materials (ASTM) E927-10 standards commonly used for photovoltaic testing and solar hot water panels.

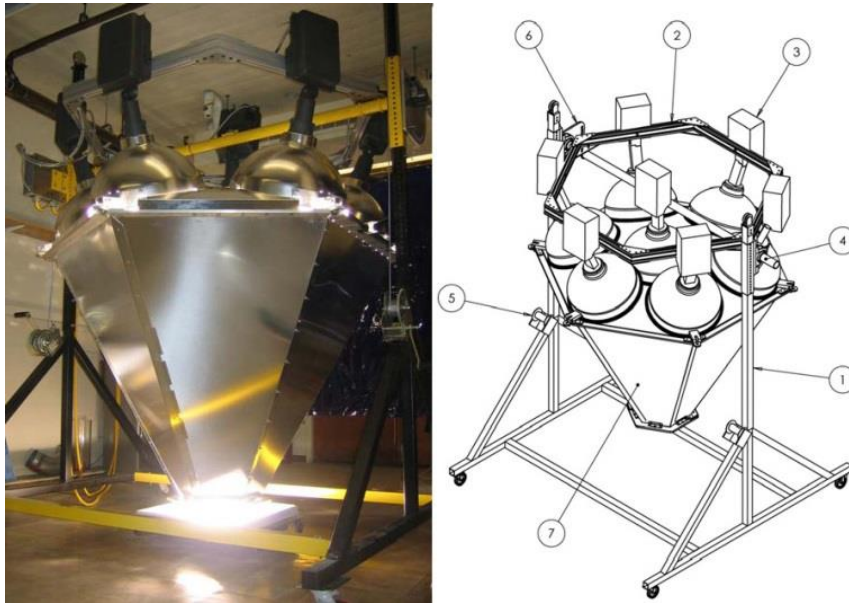
The ASTM and IEC testing standards are divided into three classifications that define the solar simulator's spectral match, irradiance spatial nonuniformity, and temporal instability. The three spectral characteristics are rated such that a Class AAA offers the highest spectral match and lowest percentage of irradiance nonuniformity and temporal instability.

The use of solar simulators is well documented and used in research labs to test window performance, weathering, accelerate ultraviolet degradation of materials, and the power output of photovoltaic panels and solar thermal panels (Wang & Laumert, 2014). Solar simulators are available on the market and range in size, performance classification, and cost. In this study, access to a state-of-the-art solar simulator was not an option, and so the researcher chose to engineer, prototype, and fabricate a low-cost solar simulator and test it against industry standards. The range of the literature review spanned from low-

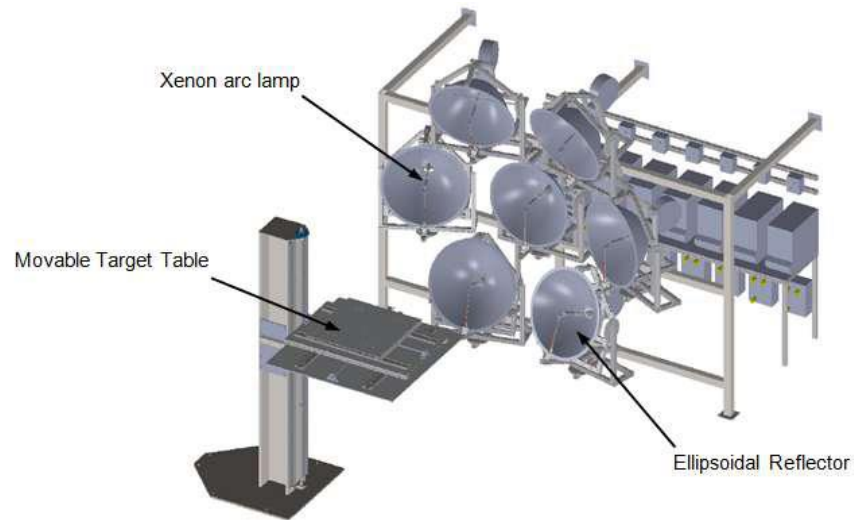
cost solar simulators, to national laboratory installations, to academic research grade systems.

### Lamp Selection

A high flux solar simulator ( Figure 16) was fabricated by MIT's Department of Mechanical Engineer averaging  $60 \text{ kW/m}^2$  (60 suns) using off-the-shelf products (Codd, Carlson, Rees, & Slocum, 2010). The solar simulator used seven 1500watt metal halide (MH) lamps that provided a satisfactory spectral match to natural sunlight (2010, p. 1). However, Codd et al. (2001) indicated that “unfiltered emission spectrum does not match the emission spectrum of sunlight as closely as xenon (Xe) arc lamps” (Codd et al., 2010, p. 3). Li et al. opted to use seven  $6\text{kW}_e$  Xe short-arc lamps yielding flux densities over  $3,000 \text{ kW/m}^2$  or 3,000 suns ( Figure 17).

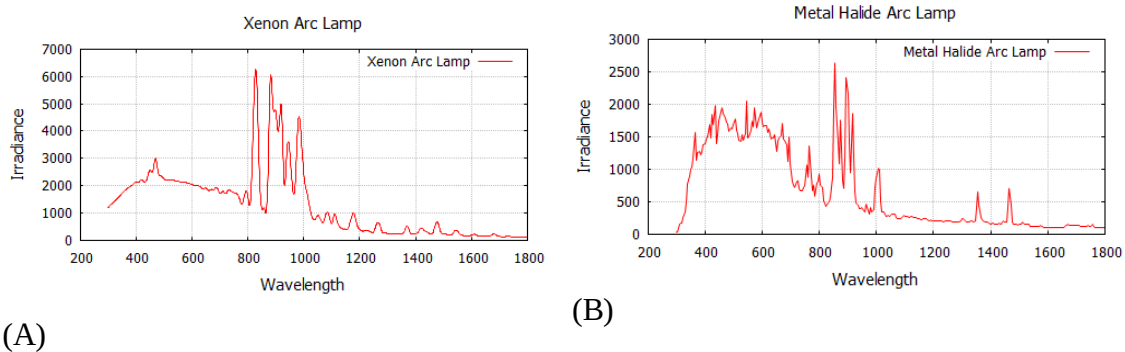


**Figure 16:** MIT Metal-Halide CSP Solar Simulator(Codd et al., 2010)



**Figure 17:** 42 Kwe High Flux Solar Simulator (Li et al., 2014)

Although xenon arc lamps offer a close approximation of air mass (AM0), which is equivalent to the solar spectrum outside the atmosphere, the xenon lamp comes with infrared spikes that must be attenuated ( Figure 18A). In comparison, a metal halide lamp is a suitable alternative and the spectral perturbations are greatly reduced ( Figure 18B).



**Figure 18:** Xenon and Metal Halide Wavelengths

Geometry

Codd et al. (Figure 16) and Li et al. (Figure 17) preferred the hexagonal seven-lamp configuration over a single luminaire. Doing so offers flexibility and cost efficiency when designing a high-flux solar simulator. These authors used ellipsoidal reflectors to maximize radiant flux, and so the simulator used NEMA 3 ellipsoidal reflectors formed from spun-aluminum, similar to MIT's solar simulator. Li et al. (2014) also mentioned that the hexagonal layout offers a compact and quasi-uniform spatial distribution of the radiation at the system common focal plane (p. 590).

Critical to the distribution of light is the geometry and placement of the luminaires in the hexagonal configuration (Figure 19). Krueger (2012) proposed a geometric configuration that addresses the location and orientation of the lamp-reflector units (p. 14). Krueger (2012) proposed the following geometric relationship such that:

$\theta_i$  = the projected orientation angle of each unit with respect to the horizontal plane crossing through the central unit,

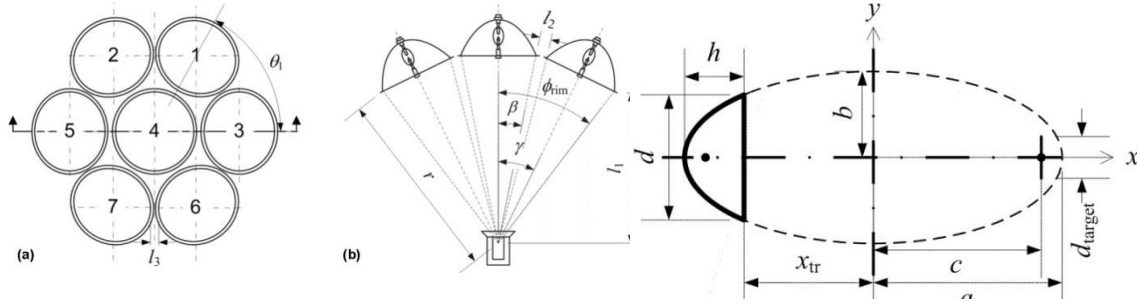
$d$  = the diameter of an individual reflector,

$l_1$ : the minimum distance between the focal plane and the nearest point of a radiation module,  $\gamma$ : Angle between the axis of the central module and the axis of any peripheral module, and

$l_2$ : minimum 50 mm between reflector surfaces for mounting purposes

“The goal is to achieve a rim angle ( $\phi_{rim}$ )—defined as the half-angle of the cone of light incident at the focal plane—maximized in the range of 35°–45°” (Krueger, 2012, p. 14).





**Figure 19:** Geometric Arrangement (Krueger, 2012)

## Calibration

As with each method, there is a degree of uncertainty. Building a solar simulator may bring about imperfections in the spectral quality and irradiance nonuniformity as a function of the arc lamps. In order to limit such uncertainty, the solar simulator in this study was calibrated using a blackbody pyranometer measuring radiation flux density ( $\text{W}/\text{m}^2$ ) across the 1-meter subject field. The flux density can be adjusted as a function of the distance between the MH lamps and the Nanowindow. For spectral distribution, a spectrometer in conjunction with spectroscopy software was used to compare simulator output from 350nm to 1000nm overlaid on terrestrial solar spectrum, following Codd et al.'s (2010) calibration methodology.

According to TS-Space Systems, a multisource solar simulator using quartz tungsten halogen (QTH) comingled with MH offers a multisource solar simulator that further enhances spectral quality. The MH works well in the visible spectrum, while QTH work in the near infrared (NIR) to long-wave infrared (LWIR). It might be a consideration to include QTH in the MH hexagonal pattern.

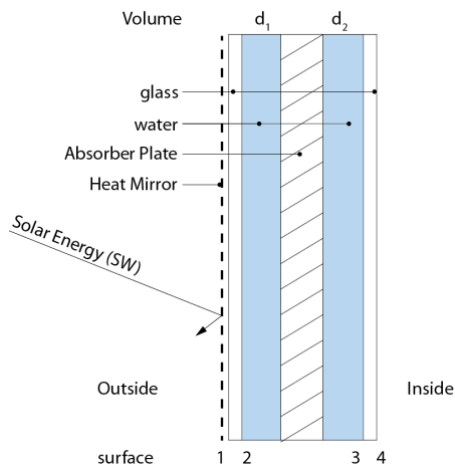
## Transwall and Waterwalls

Transwall and water walls are direct-gain strategies grounded in the mass' ability to “store high levels of heat that can readily move heat from a material's surface to its interior and back again to heat a room” (Brown & DeKay, 2013, p. 206). Conceptually, the greater the specific heat ( $C_p$ ), the greater the absorption potential; and the greater the thermal conductivity ( $k$ ), the more effective the displacement of energy will be.

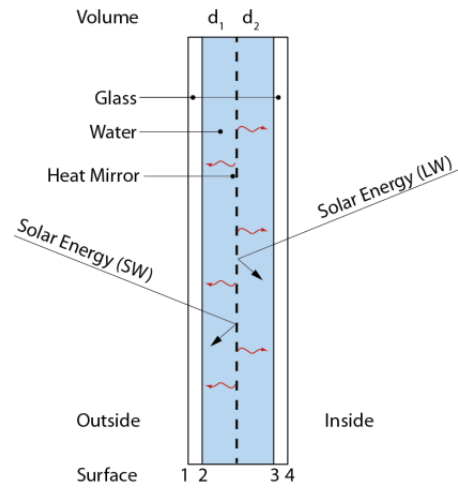
McClelland et al.'s (1980) transwall research presented a semitransparent thermal storage prototype capable of “damping interior air temperature oscillations.” This research indicated a noticeable reduction in temperature swings and cycled through average daily ranges of 8.3°C storing and releasing 23.3MJ (p. 5). As a result of summertime conditions, the test cell equipped with the transwall did not cool enough in the evening, though it retained lower daily maximum mean radiant temperature (MRT) compared to the direct-gain test cell. This observation brings to attention that transwalls are thermally overcharged in summertime conditions. Consequently, the current study aimed to displace excess thermally charged fluids into a warm store for later heat exchange, and replaced them with cool store water (Figure 1, Methodology Section).

The authors also applied a heat mirror film on the outside of the transwall to “absorb solar energy in the coating that can then be conducted by the thermal storage (water) rather than heating up the glazing.” However, the authors placed the heat mirror on the first (No. 1) surface, which was opposite to optimizing conductive potential (Figure 20)

At the very least, the heat mirror should be situated on the third (No. 3) surface. The current study therefore suspended the low-e film in the middle of the gap of the double-pane window (Figure 21). Thus, thermal radiation was reflected into a fluid trap and not to the environment or conducted to the window pane.



**Figure 20:** Transwall - McClelland



**Figure 21:** Proposed Nanowindow – Carbonnier

McClelland et al.'s prototype was an unseal water volume not burdened by the heat expansion and atmospheric conditions of a closed system. However, the authors mentioned that a closed system would provide for better water quality conditions. To mitigate concerns of algae, the authors used 100ppm copper sulfate ( $\text{CuSO}_4$ ) and 100ppm disodium ethylenedianime teracetate (EDTA). Further design strategies included capping the water surface with a flourosilicone, a low vapor pressure liquid that floats on and seals the top of the water surface from the atmosphere. Concerns of algae were present, however, so this study used deionized (DI) water as the fluid with an oleic acid and

cetyltrimethylammonium bromide (CTAB) commonly used in next-generation heat transfer fluids (Murshed, 2005).

Similar transwall research has “indicate[d] excellent thermal performance for a wide range of climates” (Hull et al., 1980). Hull et al.’s (1980) methods compared solar savings function (SSF)<sup>16</sup> to area load ratio (ALR),<sup>17</sup> as well as transwall thickness, plate absorptivity, and internal mass to determine building efficiency. Hull et al.’s schematic model<sup>18</sup> (Figure 22) illustrates the transwall’s energy pathways compared to the nanowindow model developed in this study (Figure 23). The SSF increased as the solar collector area increased, but eventually leveled out with relatively low gains.<sup>19</sup> In the present study, three transwall thicknesses were tested and resulted in negligible increases in SSF, and an optimum absorber plate of 10cm (4”) was determined. The data also indicated that node 10 (Figure 22) always had a lower temperature and low loss to the ambient during high insolation periods because transwall conductance removed excess heat. These conclusions are slightly contradictory to Nayak’s research discussed later in the literature review.

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<sup>16</sup> SSF is the percent of annual heating energy saved by using solar energy to space heat a building, compared to a nonsolar building with similar thermal characteristics” (Brown & DeKay, 2013, p. 346)

<sup>17</sup> Area Load Ratio = collector area m<sup>2</sup> / building load which is exclusive to the south wall (Hull et al., 1980, p. 397)

<sup>18</sup> Schematic model is a single line interpretation of energy pathways and resistance (Fuchs & McClelland, 1979, p. 124)

<sup>19</sup> Based on Madison, Albuquerque, and Boston

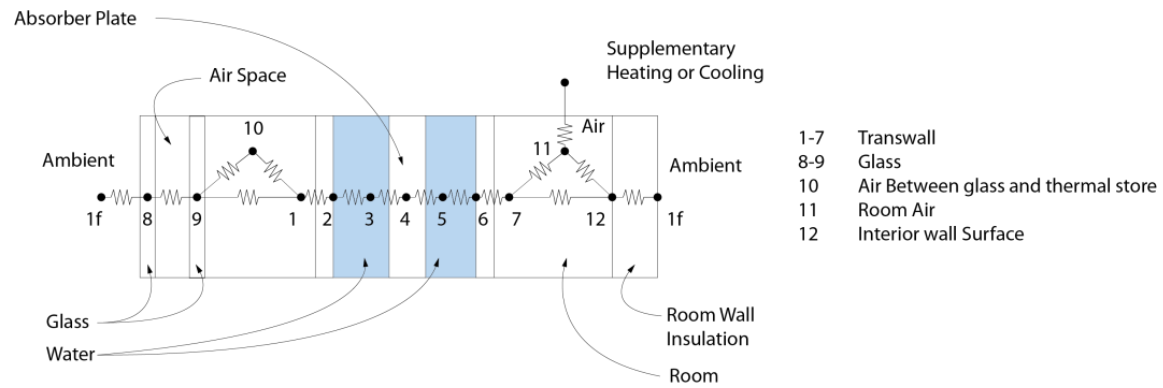


Figure 22: Reproduced Schematic of Transwall (Hull et al., 1980)

Critics of Hull et al.'s work have noted that the authors' steady-state analysis may have resulted in an "appreciable error" (Sodha, Bansal, & Ram, 1983, p. 36) because temperature fluctuations, stored heat, time-dependent heat flux, and heat radiated from the system were overlooked. Sodha et al. (1983) recommended a time-dependent thermal performance matrix that evaluates thermal load leveling.

Sodha et al. (1983) concluded that an absorber plate (Figure 22, Node 4) between water columns improves thermal load leveling, and that if no water is between the trap and south glazing then 0.09m is an optimal absorber thickness, which is similar to Hull et al.'s findings. Increasing water column thickness is also an effective way to promote thermal load leveling, however the first water column ( $d_1$ ) should be less than the second ( $d_2$ ; Figure 20) This is slightly different than the analytical studies of Upadhyaya, Tiwari, and Rai (1991), which concluded that equal water columns results in maximum thermal load leveling, and that maximum water temperatures. This is a vital conclusion because it

was the objective of the current study to maximize water temperature to store or transfer harnessed energy effectively.

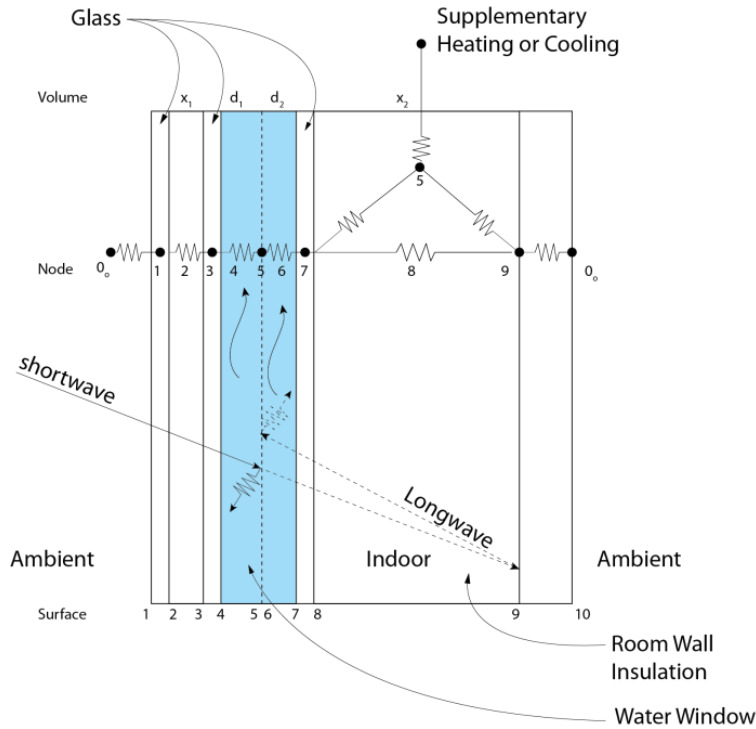
Nayak's (1987) research on water walls confirmed McClelland and Sodha's research, and similarly found that water columns on both sides of the absorber plate reduce heat flux thus improving thermal load leveling (Nayak, 1987, p. 86). Nayak also noted that increasing the first water column ( $d_1$ ) decreases heat flux as a function of the amount of increased energy lost to the outside, thus lowering overall heat flux. The present study compensated for known thermal losses to the outside with an additional layer on the climate side with variable degrees of resistance; thus forming a hybrid window. Further review of Nayak's (1987) data revealed that the lowest maximum heat flux of  $72.18 \text{ W/m}^2$  entering a space was achieved with equal water columns of  $0.2\text{m}$  (Figure 20) or the absence of a second water column. Thus, it was possible that a single water column with a variable resistance gap may offer similar results.

In the present study, the nanowindow's gaps (Figure 23) were adjusted to measure varying heat flux as a function of water column thickness. However, sufficient evidence illustrated that equal water columns totaling  $0.2\text{m}$  ( $14''$ ) or no second water column would capture similar heat flux ( $72.18 \text{ W/m}^2$  and  $76.58 \text{ W/m}^2$  respectively) and offer load-leveling performance. The nanowindow replaced the absorber plate<sup>20</sup> with a suspended low-e film forming a similar heat trap. Initially, at the beginning of the study, the conductive nature of the low-e film and its general impact on heat flux traffic was

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<sup>20</sup> In the Transwall experiments of Sodha the absorber plates were methyl methacrylate or commonly known as polymethyl methacrylate acrylic plastics (PMMA).

unknown. Also not known was the impact of the nanofluid's specific heat on heat flux traffic, and advantages of connecting the nanowindow with thermal stores.



**Figure 23:** Proposed Nanowindow

## NANOFLUIDS

Precedent water wall research typically used distilled water or an ethylene glycol-based medium as the energy transport mechanism. However, as with all fluid-based energy mediums, the strength in heating or cooling resides in such characteristics as thermal conductivity ( $k$ ), specific heat, thermal diffusivity, viscosity, and laminar flow.

According to the Argonne National Laboratory and numerous other studies, nanofluids “are expected to exhibit superior properties relative to those not only of conventional heat

transfer fluids, but also of fluids containing micrometer-sized metallic particles” (Choi, Zhang, Yu, Lockwood, & Grulke, 2001, p. 718). Nanofluids are fluids charged with nanoparticles, which are microscopic materials with a dimension between 1nm and 100nm. In context, one nanometer is 1 millionth of a millimeter, and a grain of silty sand is 0.004mm.

Nanoparticle research has consistently reinforced that base fluids’ specific heat can be augmented by adding nanoparticles (Shin & Banerjee, 2011), and that corresponding thermal conductivity can increase between 35–45% (Shin & Banerjee, 2015, p. 898). Nanofluids thus offer the ability to augment the thermal conductivity of previous water walls. Timofeeva, Yu, France, Singh, and Routbort (2011) proposed that heat transfer efficiency of EG/H<sub>2</sub>O (ethylene glycol (EG) water (H<sub>2</sub>O)) can be improved by introducing SiC (silicon carbide particles), forming a nanofluid typically used as a heat transfer fluid to cool electronics. Timofeeva et al.’s (2011) results indicated that thermal conductivity increased with particle size and viscosity decreased. The same study further indicated that 90nm particle yielded 4–5% by volume thermal improvement over H<sub>2</sub>O, and retained lower viscosity compared to smaller 16nm particles. Viscosity is therefore a valuable performance indicator for thermal models and a desired characteristic (Equation 2, Theoretical Perspective section). Additionally, in Timofeeva et al.’s (2011) study, heat transfer coefficient efficiency increased as temperature increased, and heat transfer was measured as high as 14.2%.



Based on these findings, there are two concerns. The first relates to SiC EG/H<sub>2</sub>O performance at lower temperature levels ranging from 10–50°C, which are average H<sub>2</sub>O ranges that have been experienced by previous water wall and transwall experiments. According to the Timofeeva et al. (2011), 57°C yields a heat transfer coefficient of approximately 110 W/m<sup>2</sup>K at 3.0 m/s, which appears to be a favorable condition and offers a promising advantage over H<sub>2</sub>O-only nanowindow systems. The second concern is SiC's overall performance gain, which clearly exceeded H<sub>2</sub>O: is the performance gain sufficient to supplant water and make a noticeable impact on building and heating and cooling strategies?

Water-based Al<sub>2</sub>O<sub>3</sub> nanofluid research is well characterized. Specific heat decreases gradually as the nanoparticle volume fraction  $\phi$  increases from 0.0 to 21.7% (Zhou & Ni, 2008, p. 92). Such results indicate that effective heat flow is influenced by volume fraction  $\phi$ . Base fluids containing small amounts of nanoparticles result in increased thermal conductivities (Murshed, 2005, p. 372). Furthermore, the surfactants that suspend the nanoparticle, and the particle size and shape collectively influence overall thermal conductivity (Murshed, 2005, p. 372).

Öğüt (2009) investigated natural convection heat transfer of Cu, Ag, CuO, Al<sub>2</sub>O<sub>3</sub>, and TiO<sub>2</sub> water-based nanofluids across a variable incline enclosure ranging from 0–90°. The test specimen was heated on one side with a constant heat flux, while the opposite was cooled, and all other sides adiabatic. Although the experiment focused on electronics and aerospace cooling solutions that require miniaturized solutions, the research holds

parallel applications to window environments. Similar to Timofeeva et al., heat transfer rates increased with water-based nanofluids, and as the solid volume fraction increased so did the conductive strength. This supports Timofeeva et al., in that the 90nm particle was the highest thermally conducting performer. Additionally, the Rayleigh number (Ra) exceeded 1000, indicating that convection had started and that fluids would move by natural convection, and could be used to circulate nanofluids through heat exchangers. Ögüt concluded that aluminum and copper are the most effective heat transfer nanofluids.

One of Ögüt's observations of particular interest to the present study concerned the heat source. Ögüt's methods examined the length of the heat source and the angle of incidence. Ögüt concluded that the longer the heat source, the lower the thermal transfer rate at small inclinations. Considering that solar radiation is a dispersed field of energy and not a perpendicular point source, this impacts the overall thermal performance of the nanofluid.

The present research procured two liters of  $\text{Al}_2\text{O}_3$  nanofluid-based medium.<sup>21</sup> The particle size mean was 10 nm  $\pm$  5 nm in a concentration of 1% by weight in deionized water, and particle purity (metals basis) of 99.95+%. As precedent water walls were successful at load leveling and reducing supplemental energy, it was anticipated that the use of nanofluids would augment thermal exchange previously unattainable in past water walls.

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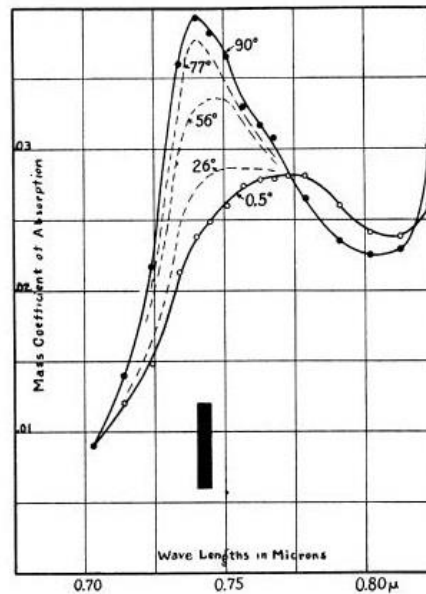
<sup>21</sup> Nanofluids provided by Meliorum Technologies, Inc., 620 Park Ave. Ste. 145, Rochester, NY 14607 USA

## Fluid Characteristics

An unexpected event during the present research reopened inquiry into fluid physiology and focused on water structure and spectral energy. This interest was brought on after several experiments revealed notable variations in incident flux energy measured in the visible light and near infrared spectrum passing through the Nanowindows. This effect was, in part, a function of the light scattering phenomenon and the absorption of light by a fluid medium (Hulst, 1957).

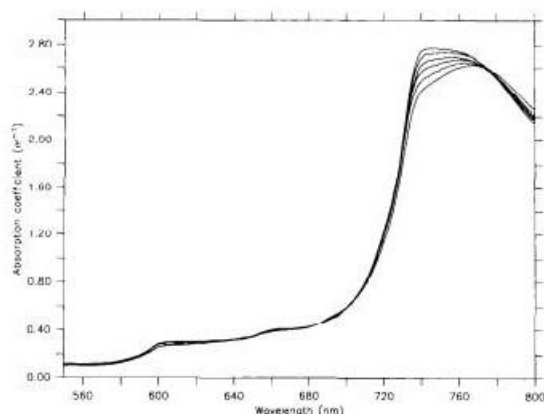
To better understand the conditions leading to the fluctuations recorded during the experiments, the chemical composition of water's influence on the solar spectrum was reviewed. It was ascertained that the absorption of water was a fundamental property that influences the passage of light through the water column (Pegau & Zaneveld, 1993, p. 188). Additionally, the absorption spectrum of the water column in the Nanowindows changes with an increase in temperature (Collins, 1925, p. 772).

Collin's (1925) early methodology bears striking resemblance to that of this research, deploying spectrometers and 6000 lumen street lighting incandescent lamps as a source of radiation. Collins (1925) noted that in all absorption bands of the spectrum, an increase in temperature shifted maximum absorption toward short wavelengths (p. 774). In Figure 24, note the wave drift from the apex of wavelength at  $0.5^\circ$  and absorption coefficient increased at temperature increases to  $90^\circ\text{C}$ .



**Figure 24:** Absorption Band (Collins, 1925, p. 774)  
(0.70-0.80  $\mu$ ) of liquid water at 0.5°C to 90°C

Collin's (1925) findings were similar to other researchers examining temperature-dependent absorption of water in the visible and near-infrared portions of the spectrum: there was an increase in absorption coefficient in the 600nm and 750nm bands (Pegau & Zaneveld, 1993). In repeated tests, there was a notable drift and absorption as a function of temperature in the 745nm range, and between 755–800nm the increase in temperature resulted in a decrease in absorption (Pegau & Zaneveld, 1993, p. 190; Figure 25).

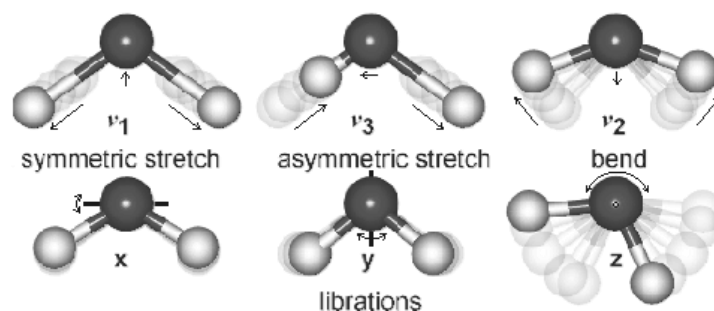


**Figure 25:** Absorption Temperature over Wavelength(Pegau & Zaneveld)

The curve represents absorption at temperatures of 5, 10, 15, 21, 25 and 30°C a read from bottom to top at 750nm.

Thus, portions of spectral wavelength through water molecules are absorbed (Sayinti, Kaya, & Vertiy, 2013, p. 2), while the balance of the spectrum is transmitted with minimal effect (Peacock, 2009, p. 1). In the present study, the spectral influence on a water column was further examined by looking at water's molecular structure, though with some restraint so as to remain focused on the research at hand.

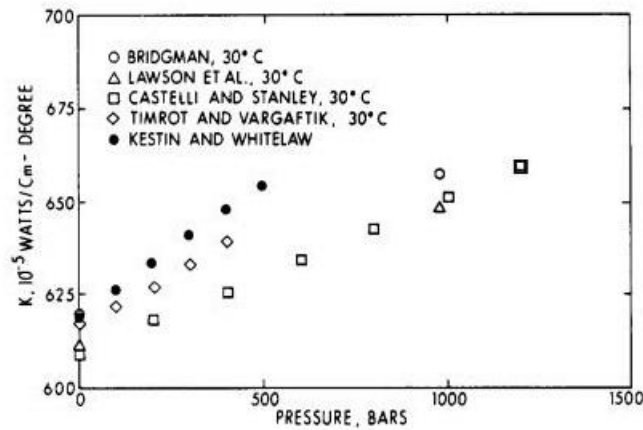
Key to understanding the linear dependence of the spectral absorptivity of water on temperature was the direct consequence of the microscopic changes in water structure that occurs as the temperature increases (Langford, McKinley, & Quickenden, 2001, p. 8921). The key to absorptivity lies within the covalent bonds between the hydrogen atoms and oxygen atom that produce vibrations. The hydrogen bonding dipole vibrates in varying amplitudes under spectra resulting in various movements from symmetric to asymmetric stretch, bending, and librations as illustrated in Figure 26 (Chaplin, 2015).



**Figure 26:** H<sub>2</sub>O vibrations (Chaplin, 2015)

These vibrations cause the molecular structure to shift to higher or lower frequencies depending on the temperature of the water. Water absorbs electromagnetic radiation in the infrared by molecular vibration, while the microwave region is absorbed by molecular rotation, and UV through x-rays are also successful at absorbing (Nave, 2016).

Pressure also has a direct impact on the absorption spectra of water by decreasing oxygen atom distance, thus decreasing the oxygen-hydrogen covalent bond distance which in turn lowers their stretching potential (Chaplin, 2015). In high pressure temperature variant experiments, Bridgman, Lawson, Castelli, and Stanley illustrated a correlation between pressure and conductivity, such that when pressure is increased so does conductivity (Castelli & Stanley, 1974, p. 11; Figure 27). The combined effect of a water column within a window system to absorb certain wavelength coupled with pressure and nanoparticles offers new possibilities to advance window performance beyond the current understanding.



**Figure 27:** Comparison of historic pressure data (Castelli & Stanley).

Why is this significant to the present research? Waste heat is the product of high performance windows and harvesting that waste heat and converting it into useful energy is at the center of this research. Thus, window gaps are radiation traps filled with nanofluids that can absorb, store, and displace trapped solar energy waiting to be converted into useful energy. Take it a step further and the nanofluids also offer the possibility of selective spectral blocking.

The Nanowindows were tested and compared to common window criteria established by the Nation Fenestration Rating Council (NFRC). Thus, incorporating wavelength protection criteria is achievable. Hypothetically speaking, a window label could incorporate an easily understood wavelength grade for architects and building occupants no different than the solar protection factor (SPF) for lotions. However, SPF protection is seldom discussed in high performance windows, though we have the means to define it and it has a vital role in protecting human life by absorbing dangerous wavelengths.

Solar radiation is a known human carcinogen along with broadband ultraviolet radiation (National Toxicology Program, 2014). Each year, there are over 5.4 million cases of nonmelanoma skin cancer, with the incidence increasing annually (Rogers, Weinstock, Feldman, & Coldiron, 2015). Considering the severity of skin cancer, it is surprising that biophilic design places so much importance on the physiological and psychological mechanisms that mandate connectivity with the outdoors with access to daylight, with no consideration for the potential hazards of harmful solar radiation transmitted through windows.

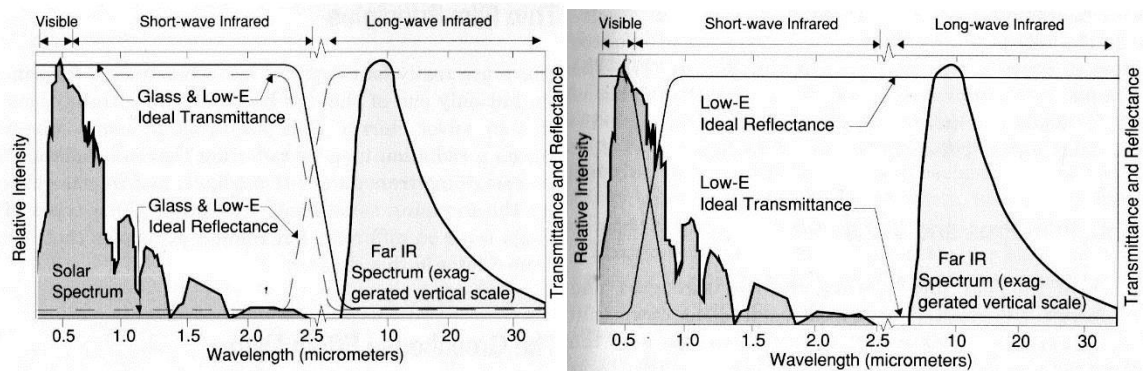
There is substantial literature advocating the inclusion of windows with views of all occupied spaces, advocating sun exposure as a vital health benefit and defending evolutionary theory which states that day-lit spaces are more effective (Kellert, Heerwagen, & Mador, 2008). But to what extent are such directives effective if there are no means to define wavelength protection when unprotected solar radiation entering through a window can be a serious health concern?

There appears to be a gap in consumer awareness and the window industry when it comes to a recognizable system to communicate the importance of skin protection and window selection. Sun protection factor is a recognizable and easily understood numeric value that communicates the importance of skin protection. Such a label would be a valued asset to architects and building occupants, seeing as how design theory's promotion of greater access to daylight also comes with consideration for skin care.



Knowing that the water column inside the Nanowindow experiences thermal change throughout the day, and that thermal change has a direct impact on wavelength absorption, there appears to be a benefit here to human health. The water column's temperature variability leading to absorptive wavelength variability is equally intriguing because it is responsive to environmental conditions, making it dynamic rather than the static low emissivity (low-e) films incorporated in today's window technology.

Low-e films or coating are applied to windows to limit the amount of shortwave radiation entering the space and limit long-wave radiation leaving the space while retaining acceptable visible transmittance levels. Typical residential low-e applications (Figure 28, left) illustrate low-e impact on the visible through infrared wavelengths. Note how the low-e (dash line) has slightly less VT than glass, but blocks significant regions of the far infrared spectrum. In essence, radiant energy is captured in the film/coating making it difficult to leave as radiation (Johnson, 1991, p. 27). In the commercial application, the low-e film can be configured so that the crossover is shifted toward the visible spectrum, reflecting more visible and shortwave infrared and resulting in an increase of solar heat being rejected by the low-e film to the outside. Low-e film is thus a solar heat mirror. The rejected heat, or waste heat, is the foundation of what the present research aimed to harvest and reuse as a heat exchanger, rather than releasing said waste heat into the atmosphere.



**Figure 28:** Low-e Film Comparison (Johnson, 1991, p. 26,29)  
 (Left) Ideal residential low-e characteristics compared with ordinary glass.  
 (Right) Ideal commercial low-e characteristics compared with ordinary glass.

In the waterwall literature reviewed, there was no mention of solar spectrum drifting and wavelength absorption. The waterwalls of Fuch, McClelland, Nayak, and the transwall water storage envelopes (TWSE) by Xiangfeng all discussed thermal performance, water column thickness, conductivity, and optical characteristics, but never mentioned the influence that solar spectrum shaping nanofluids or fluids might have on human wellness.

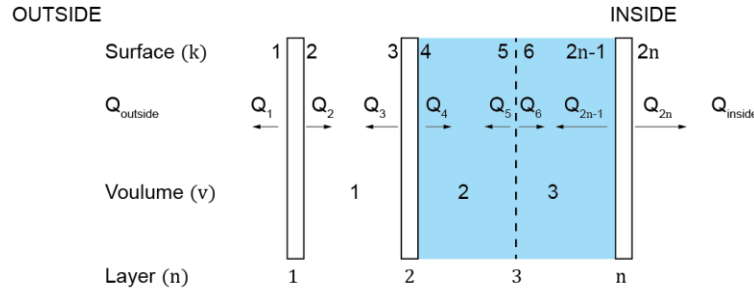
## Analytical Expression

This section proposes a mathematical expression to predict the heat flux and temperatures of each surface, volume, and layer. In doing so, the various parts of the system are examined and manipulated mathematically to predict the system's performance. Whilst the predictive expression itself can become overwhelmingly complex, it is not the intent to address all of the finite variables that exist in the physical world. Rather, such expression aims to inspire discussion beyond the normative ideology that high performance windows are solely based on resistive qualities.

Precedent water wall research has not examined the suspension of a polyethylene terephthalate low emissivity film (low-e) in conjunction with nanofluids to augment thermal conductivity. Additionally, no research has examined the potential of displacing thermally charged fluids to heat exchangers similar to hydronic radiant network as a means to offset heating and cooling loads. The proposed heat transfer equation builds on research completed by the Windows and Daylighting Group from the Lawrence Berkeley Laboratory (1982), in addition to ASHRAE's fenestration energy flow (2013), the water wall equations of Fush and McMelland (1987), Balcomb's passive solar design handbook (1980), and recent innovations in nanofluid research. The equation's flexibility takes into account the physical impressions made on each pane, coating, and fluid medium, while acknowledging it is an imperfect expression.

For the purpose of this research, the fluid filled assembly is denoted such that surfaces and layers are numbered from outside to inside, left to right respectively (Figure 29).

Layers (glass panes, film, and fluid material) are denoted as (n). Each layer's surface is denoted as (k). The sequence of layers (n) is express as 2n-1 and 2n, similar to Rubin's work.



**Figure 29:** Proposed Fluidized Window

A one-dimensional expression in a steady-state condition was used to examine heat flow in three forms: radiation exchanges between panes, convection, and conduction that acts on layers (n), surfaces (k), and volumes (v). Given a set of environmental conditions, temperature across each layer can be determined to optimize and maximize heat transport and heat storage. The new variable of conductivity of the nanofluid was added to Rubin's (1982) energy model:

$$\Delta n = (\sum Q^r) + (\sum Q^c) + (\sum Q^k) + (\sum Q^{k-nf}) - (A_n)(I) \quad (3)$$

*Where*

$\Delta n$  = Energy Balance Layer

$\Sigma Q^r$  = Total radiation flux at each layer

$\Sigma Q^c$  = Total conductive/convective at each layer

$\Sigma Q^k$  = Total conduction at each layer (excluding fluid layer)

$\Sigma Q^{k-nf}$  = Total conduction at nanofluid layer (added to Rubin's equation)

$A_n$  = Incident solar energy absorbed in each layer

$I$  = Solar Intensity

During the course of the experiment, it was determined that not all measures rely on the above stated analytical expression. As such, the following chapters introduce specific aspects of the analytical expression as it applies to the measures at hand and, in some cases, also introduce other analytical expressions to characterize the impact of the experiment.

## CHAPTER IV

### LOW-COST SOLAR SIMULATOR

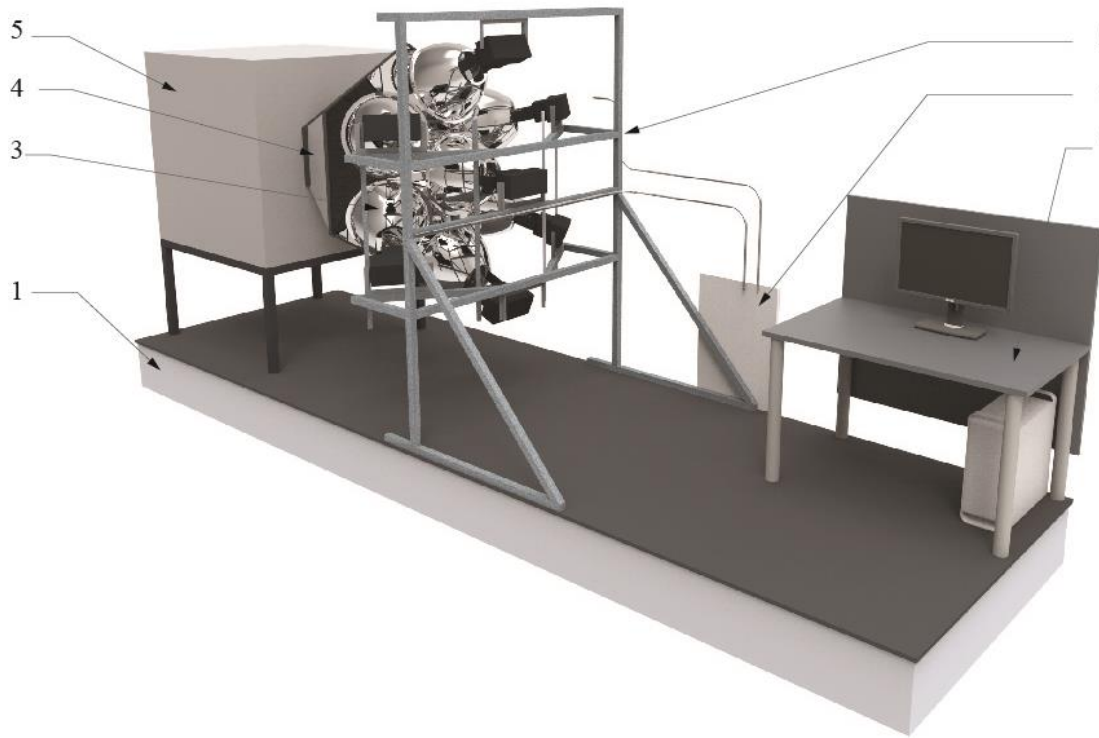
A key objective of building the solar simulator was to offer a steady state environment so that each test series could be compared knowing that energy emitted by the solar simulator was constant from one experiment to another. Using the sun is ultimately the best medium, but using the sun introduces unpredictable solar radiation as a function of meteorological conditions and limited the testing schedule. Ultimately the solar simulator offered flexible testing times not associated with daylight operations and allowed for 24-hour testing if desired.

In order to characterize the thermal, UV, and optical performance of the nanowindow a low cost solar simulator was designed and fabricated at a private Southern California facility<sup>22</sup> and erected outdoor under a 200 square foot canopy. The custom low-cost solar simulator Figure 30 was custom built to suite the means and methods needed to effectively execute the research. SolidWorks<sup>23</sup> 2015 was used to prototype the layout, space configuration, lamp configuration, electrical and sensor wiring. The planning took into consideration safety, circulation space, mobility, adaptability, cost, and irradiance output optimization. The design, fabrication, and deployment is covered in Appendix F.

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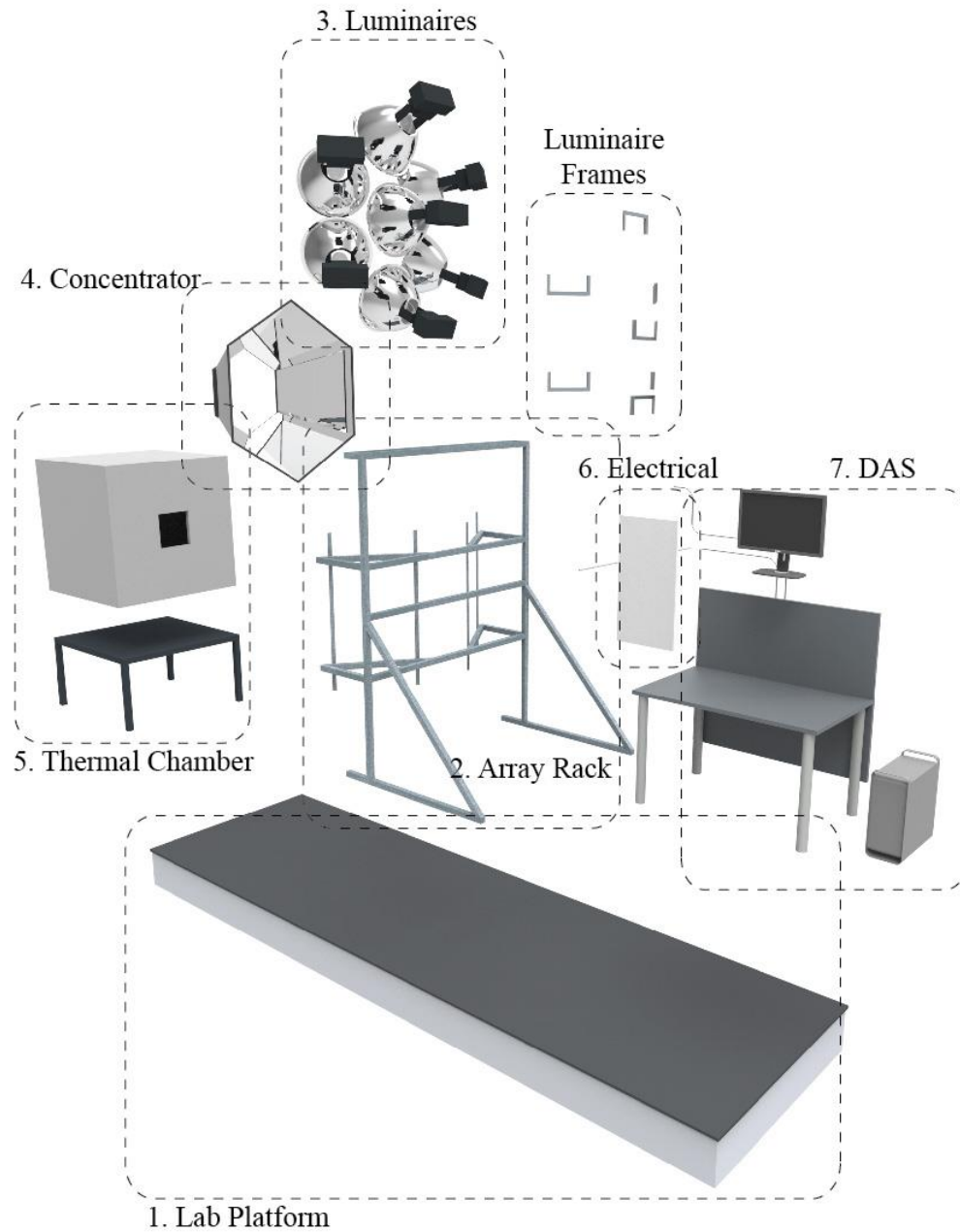
<sup>22</sup> The Bunker is a privately operated fabrication shop owned by the author.

<sup>23</sup> SolidWorks is a solid modeling computer-aided design (CAD) and computer-aided engineering (CAE) software produced by Dassault Systèmes, France.



**Figure 30: Solar Simulator**  
 (1. Lab Platform, 2 Array Rack, 3. Luminaires & Lamps 4. Concentrator, 5. Test Chamber, 6. Load Center, 7. Data Acquisition Center)

The solar simulator depicted in Figure 30 is exploded into seven major components and described in numerical order in the following sections (Figure 31). Ancillary systems such as sensor placement are not noted in this section and are discussed in the methods sections of each respective experiment. Additional illustrations provided in Appendix J.



**Figure 31: Solar Simulator Rendering**  
 (1. Lab Platform, 2 Array Rack, 3. Luminaires & Lamps 4. Concentrator, 5. Test Chamber, 6. Load Center, 7. Data Acquisition Center.)



## Calibration Methods

The solar simulator was evaluated using similar methods applied in research test facilities. The International Electrotechnical Commission (IEC), Association for Testing and Materials (ASTM), and relevant research in the conformity of electrotechnology was reviewed as guides to inform the design, fabrication, and characterizing its performance and effectiveness.

Solar simulators are characterized by 3 performance parameters: 1) Spectral Match; 2) Spectral Uniformity, and 3) Temporal Instability with respect to a specific air mass. Each of these characteristics is assigned an A, B, or C as a function of the degree of difference from the solar spectrum. As expected, an A rating is most similar to the solar spectrum and each rating thereafter is a percentage of difference from solar similarity. ASTM E927-10 is commonly used to characterize the three 3 performance parameters and a recognized standard to evaluate solar simulators.

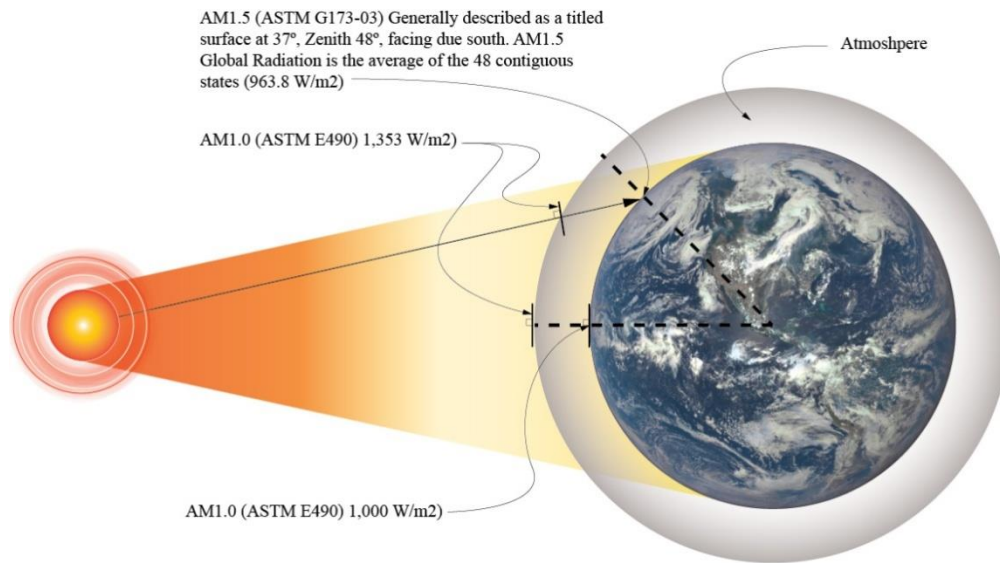
Table 1 reflects the allowable margins for each performance parameter, and the associate grading designation. Each of these parameters will be applied to the solar simulator and defined in the following discussion. The standard can be applied to steady state and pulse solar simulators, and conformity of mismatch as defined in Table 1 varies depending on the size of the test plane. The proposed 12-inch square test plane's allowable nonconformity are proposed in Table 1.

**Table 1** ASTM E927-10

| Performance Parameter             |         | ASTM        |
|-----------------------------------|---------|-------------|
| Spectral Match                    |         |             |
|                                   | Class A | 0.75-1.25   |
|                                   | Class B | 0.6-1.4     |
|                                   | Class C | 0.4-2.0     |
| Irradiance Spatial Non Uniformity |         |             |
|                                   | Class A | $\leq 3\%$  |
|                                   | Class B | $\leq 5\%$  |
|                                   | Class C | $\leq 10\%$ |
| Temporal Instability              |         |             |
|                                   | Class A | $\leq 2\%$  |
|                                   | Class B | $\leq 5\%$  |
|                                   | Class C | $\leq 10\%$ |

These performance standards are applicable to standardized global radiation throughout the 48 contiguous U.S. States (ASTM G173-03, 2010) and primarily used to evaluate solar simulators used for photovoltaic testing, material degradation research, and window performance simulators.

Unique to ASTM G173-03 and E927-10 is its reference to air mass. Air mass (AM) coefficient defines the length of incoming solar radiation through the earth's atmosphere. As such there are varying lengths depending on the zenith, but for the context of this researcher the standard spectrum at the earth's surface of AM1.5 Global was used. AM1.5G is defined as a tilted surface at 37°, zenith 48°, and facing south and reflects a standardized global radiation throughout the 48 contiguous U.S. States. AM1.5G has a maximum irradiance of 963.8 w/m<sup>2</sup> and was used as a baseline of comparison (Figure 32).



**Figure 32:** Air Mass 1.0 vs 1.5

## Spectral Match

Spectral match presents the greatest challenge in developing an accurate solar simulator. Spectral match compares wavelength-by-wavelength of the proposed simulator to solar spectral irradiance. For this exercise the low-cost solar simulator was compared to ASTM E927 (Appendix A). ASTM E927 is divided in 100nm intervals from 400 to 1100nm and each wavelength band is represented as a percentage of total irradiance (Table 2). This standard was used to establish a baseline of comparison to determine spectral match of the solar simulator.

| Wavelength (nm) | Direct | Global |
|-----------------|--------|--------|
| 300-400         | -      | -      |
| 400-500         | 16.9   | 18.4   |
| 500-600         | 19.7   | 19.9   |
| 600-700         | 18.5   | 18.4   |
| 700-800         | 15.2   | 14.9   |
| 800-900         | 12.9   | 12.5   |
| 900-1100        | 16.8   | 15.9   |
| 1100-1400       | -      | -      |

**Table 2: Spectral Irradiance AM1.5G (ASTM E927)**

Prior to evaluating the spectral match the proposed equipment underwent three series of tests and calibrations. Spectral Match Series 1 compared the metal arc lamp’s spectral output to Sylvania’s spectral output readings provided in the product specification. Spectral Match Series 2 compared ASTM E927’s (Appendix A) solar spectral readings to two handheld spectroradiometers. The objective focused on determining the accuracy of the equipment and identifying calibration factors that may need to be applied during data analysis. After Series 1 & 2, Spectral Match Series 3 compared the metal arc lamp’s spectral readings to ASTM E927 and cross referenced against Table 2 to determine Spectral Match Class as defined in Table 1.

|            | Series 1                                                                                  | Series 2                                                          | Series 3                                                           |
|------------|-------------------------------------------------------------------------------------------|-------------------------------------------------------------------|--------------------------------------------------------------------|
| Location   | In-Situ                                                                                   | Ex-Situ                                                           | Ex-Situ                                                            |
| Experiment | Compare Metal Arc Lamp Spectral Response To Manufacturers Specifications                  | Calibrate spectroradiometers to ASTM E927 Solar Spectral Response | Compare Metal Arc Lamp Spectral to Table 1                         |
| Objective  | This will assist with determining appropriate spectral filters to lower wavelength spikes | Provide a degree of calibration conformity before deployment      | Determine Solar Simulator Spectral Match Class as noted in Table 1 |

**Table 3: Spectral Match Test Series**

In-Situ testing is defined as an experiment taking place in a building science lab, and ex-situ testing reflects test series conducted in the outdoor Solar Lab described in the Low-Cost Solar Simulator section of this research.

### Series 1: In-Situ Testing

The objective of Series 1 focused on the accuracy of spectral response plots of the Sylvania 400watt MH400/U lamps deployed in the solar simulator. Although Sylvania provided spectral response plots in their product specification it was desirable to re-evaluate the lamps using equipment that would be used throughout this research. Knowing that metal arc lamps are “dominated by strong wavelengths” (Oriel Instruments, n.d., p. 11) reevaluating the lamps informed subsequent steps in the selection of appropriate wavelength suppression filters to reduce strong wavelengths.

### Series 1: Methods

Access was granted to the Lighting Lab in the College of Engineering at California State Polytechnic University, Pomona. The Lighting Lab (Figure 33) is a nationally recognized photometric laboratory<sup>24</sup>. The Lighting Lab is equipped with a Labsphere spectrometer and Labsphere 72-inch integrating sphere (Figure 34) in conjunction with Spectral Lamp Measurement System (SLMS) version 5.19.0.

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<sup>24</sup> The Lighting Lab is under directorship of Frank Smith and funded by National Science Foundation Grant where lighting and photometric experiments are conducted.



**Figure 33:** CalPoly Pomona - Lighting Lab

A single 400W Sylvania metal arc lamp and ballast was positioned in the Integrating Sphere (Figure 34). Using an integrating sphere collects the lamp's light through multiple reflections offering a stable comingled response. Before the light can reach the spectrometer sensor it passes through a second sphere so that only homogenized light is measured rather than direct and over saturated light.



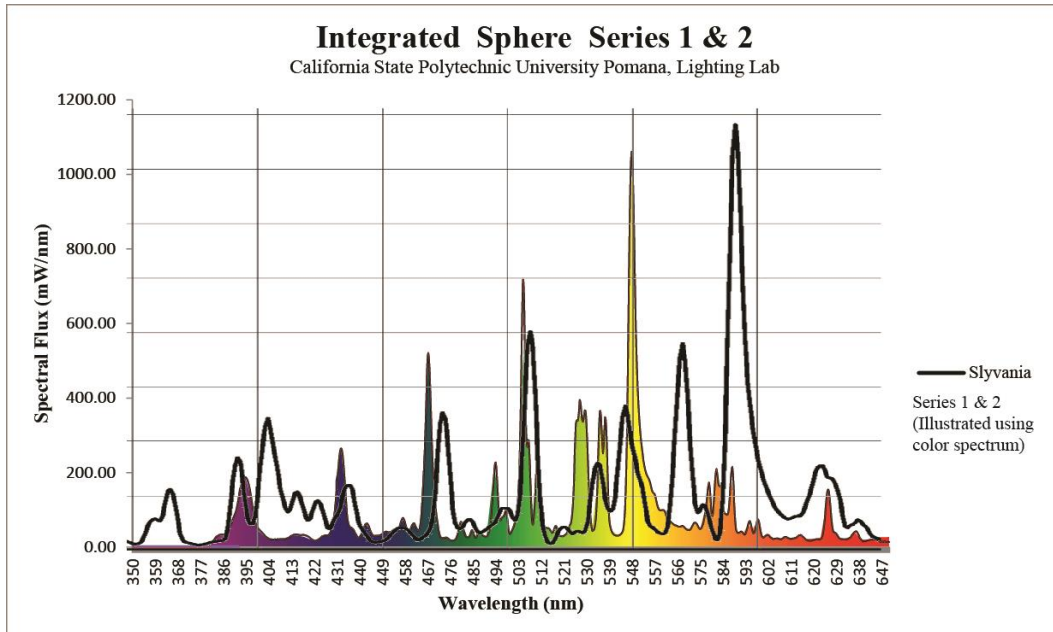
**Figure 34:** Lighting Lab Integrating Sphere - Metal Arc Placement

### Series 1: In-Situ Results

Sylvania was unable to provide the raw spectral distribution data of the M400 lamp so WebPlotDigitizer<sup>25</sup> was used to extract accurate numerical data from the graphic plot provided in Sylvania's product documentation. The extracted graphic data turned into numerical data was plotted over the in-situ integrated sphere test results. The Sylvania spectral plot (Figure 35, bold black line) was then overlaid on top of the integrated sphere readings (Figure 35, color spectrum infill) illustrating similar spectral spikes, but inconsistent in relationship to wavelengths (Figure 35). For instance Sylvania's dominant spike is in the 590nm were the in-situ testing illustrates the spike closer to 550nm.

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<sup>25</sup> WebPlotDigitizer is a free web based curve extraction algorithms to aid rapid extraction of a large number of data points from graphs. <http://aohatgi.info/WebPlotDigitizer/>



**Figure 35:** Integrated Sphere Test Series

The results illustrated that spectral data for the metal arc lamps provided by Sylvania was not entirely accurate and might have misdirected selecting the appropriate spectral filters to reduce certain saturated wavelengths. Based on Series 1 in-situ testing saturated wavelengths at 431, 467, 503, 530, 539, and 548nm will be filtered out in Series 3.

### Series 2: Ex-Situ Testing

The objective of Series 2 focused on the accuracy and calibration of the ex-situ testing. Handheld spectroradiometers<sup>26</sup> were brought on-site and two sets of evaluations were performed. Series 2A compare the equipment's nonconformity to ASTM E927's (Appendix A) solar spectral readings between 300-700 nm as a percentage. Series 2

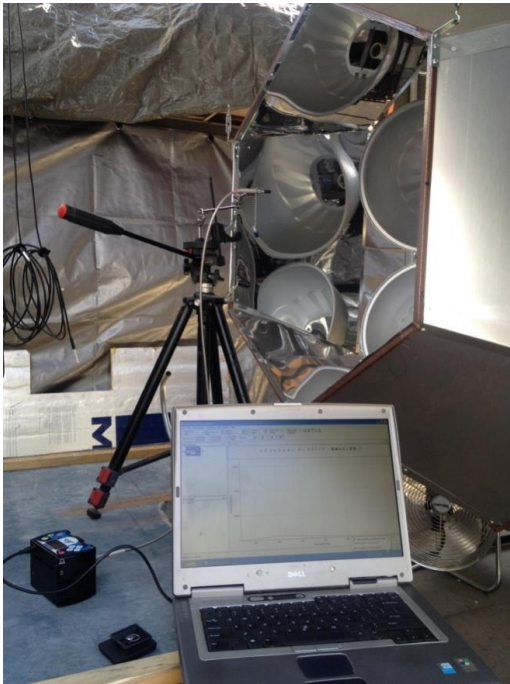
<sup>26</sup> Spectroradiometers are used to measure spectral power distribution: mainly radiometric, photometric, and colorimetric quantities and qualities.



compared the normalized data of Series 2A to the solar spectrum to graphically illustrate variations, and determine if further calibration is required for subsequent testing.

## Series 2A: Methods

Series 2A used two portable general purpose spectroradiometers to measure ultraviolet (UV), visible light (VIS), and near infrared (NIR). The first of two portable spectroradiometers was an Ocean Optics USB2000+VIS-NIR<sup>27</sup>. The USB2000 (Figure 36) is a general purpose ultraviolet, visible, and near infrared (UV-Vis-NIR) spectrometer covering wavelengths from 350 to 1100 nm. This range covers the prescribed range for Spectral Match conformity per to AM1.5G (ASTM E927).



**Figure 36:**Spectroradiometer Ocean optics



**Figure 37:** Spectroradiometer LightSpex

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<sup>27</sup> USB2000+VIS-NIR is equipped with a silicon Sony ILX511B detector, 2048 pixels, pixel size of 14  $\mu\text{m}$  x 200  $\mu\text{m}$ , and pixel depth of ~62,500 electrons.

The second spectroradiometer and slightly older was a LightSpex by McMahan Research Laboratories and calibrated according to the National Institute of Standards and Technology (NIST) (Figure 37). The handheld spectroradiometer used LightSoft software that only operates on Windows 95/98/NT at the 16-bit or 32-bit computer processor. A compatible computer was located after an extensive search not realizing that some software and hardware such as these are forever lost to upward incompatibility<sup>28</sup>.

The rationale to use two LightSpex spectroradiometers was mainly based on the ability to retain the spectroradiometers for an extended duration of time. The Lightspex was on loan for several weeks with limited restrictions, while the Ocean Optics was a rental unit and used to establish a baseline and calibration for the Lightspex. The two spectroradiometers were ideal for measuring absorption, transmission, reflectance, emission, and color between 350-1100 nm wavelengths.

## Series 2A: Ex-Situ Solar Results

Two consecutive test series recorded solar spectral readings and compared readings to ASTM G173-03 Reference Spectra Derived from SMARTS<sup>29</sup> v. 2.9.2 data (Appendix A) to establish a credible baseline to determine spectral match precision.

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<sup>28</sup> McMahan Research Laboratories is no longer operational and the technology was sold several times and dissipated. Hardware lock complicated the installation process, but was eventually overcome. Hardware Against Software Piracy (HASP) drivers by Sentinel were used in conjunction with LightSoft and worked accordingly.

<sup>29</sup> SMARTS (Simple Model of the Atmospheric Radiative Transfer of Sunshine), developed by Dr. Christian Gueymard, is a spectral model to predict global irradiance incident on the Earth's surface. SMARTS covers the solar spectrum (280 to 4000 nm) including UVA, UVB, Visible and Near-Infrared bands. SMARTS is the basis for American Society of Testing and Materials (ASTM) reference spectra (ASTM G-173 and ASTM G-177).

However, the LightSpex spectroradiometer has a narrow wavelength range from 350-750nm. In order to evaluate this narrow range the raw data from ASTM E927 was recalculated such that 100nm increments from 400-700 nm results in the proportional percentage of total irradiance from 400-700 nm – referred to as the Narrow Band Evaluation in Table 4. Note that ‘Narrow Band’ simply refers to wavelengths between 400-700 and that the Average Degree of Difference was defined as

$$\frac{\left|ASTM_{global} - SolarSpectral_{Series1}\right| + \left|ASTM_{global} - SolarSpectral_{Series2}\right|}{2} \quad (4)$$

Having defined the amount of irradiance as a percentage of total irradiance between 400-700nm the data collected from the ex-situ handheld spectroradiometer was compared. Two data collection on two separate days were performed and reported in Table 4. The average difference between the two series compared to ASTM SMARTS data in the 400-500 nm is  $\pm 1.68\%$ , between 500-600 nm is  $\pm 1.01\%$ , and between 600-700 nm is  $\pm 0.98\%$ . The solar spectral average non-conformity between the LightSpex and ASTM SMARTS data is  $\pm 1.22\%$ .

| Spectral Irradiance (ASTM E927) |        |        |                                                 | Solar Spectral Irradiance using Lightspex |                                 |                              |
|---------------------------------|--------|--------|-------------------------------------------------|-------------------------------------------|---------------------------------|------------------------------|
| Wavelength (nm)                 | Direct | Global | Narrow Band Evaluation                          | Narrow Band Evaluation Series 1           | Narrow Band Evaluation Series 2 | Average Degree of Difference |
| 300-400                         | -      | -      | -                                               | -                                         | -                               | -                            |
| 400-500                         | 16.90% | 18.40% | 31.51%                                          | 30.01%                                    | 31.18%                          | 1.68%                        |
| 500-600                         | 19.70% | 19.90% | 34.76%                                          | 35.45%                                    | 35.41%                          | 1.01%                        |
| 600-700                         | 18.50% | 18.40% | 33.73%                                          | 34.55%                                    | 33.41%                          | 0.98%                        |
| 700-800                         | 15.20% | 14.90% | -                                               | -                                         | -                               | -                            |
| 800-900                         | 12.90% | 12.50% | -                                               | -                                         | -                               | -                            |
| 900-1100                        | 16.80% | 15.90% | -                                               | -                                         | -                               | -                            |
| 1100-1400                       | -      | -      | -                                               | -                                         | -                               | -                            |
|                                 |        |        | Spectral Average Difference between (400-700nm) |                                           |                                 | 1.22%                        |

**Table 4:** Spectral Match Using LightSpex

## Series 2B: Ex-Situ Results

Similar to Series 2A the ex-situ solar spectral irradiance measures were compared to American *Society* for Testing and Materials (ASTM) standard ASTM G173-03 Reference Spectra. In order to compare the two sets of data the unit of measurement was normalized using Pythagorean Theorem linear scaling where:

$$y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} \text{ where } \|y\| = \sqrt{y_1^2 + y_2^2 \cdots y_n^2} \quad (5)$$

The result is the general vector norm  $\|y\|$  and a nonnegative. The  $\|y\|$  is normalized by dividing  $y_i$  by  $\|y\|$  resulting in the norm of the vector.

$$\tilde{y} = \begin{bmatrix} \frac{y_1}{\|y\|} \\ \frac{y_2}{\|y\|} \\ \vdots \\ \frac{y_n}{\|y\|} \end{bmatrix} \text{ where } \|\tilde{y}\| = \sqrt{\tilde{y}_1^2 + \tilde{y}_2^2 \cdots \tilde{y}_n^2} = \sqrt{1} = 1 \quad (6)$$

The data in Appendix A used the aforementioned normalization formula where:

$y$  = Irradiance

$\tilde{y}$  = Normalized norm (new scale)

$\|\tilde{y}\|$  = Verification that norm of vector =1

Appendix B was partially captured in Table 5 and represents the solar spectrum, and ASTM G173-03 Reference Spectra. The Solar Simulator and the sun were measured on three separate occasions and irradiance values of each were normalized using linear algebra. The normalized value is denoted as  $\|y\|$ .

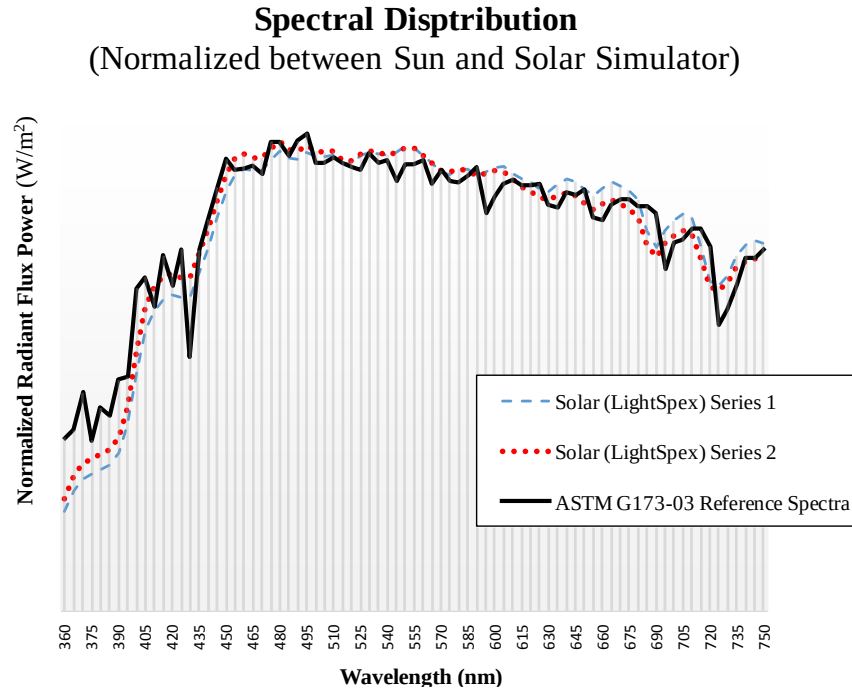
| Solar (LightSpex) Series 1             |                           |             |                  |                    |              |                  |             |
|----------------------------------------|---------------------------|-------------|------------------|--------------------|--------------|------------------|-------------|
| Saturday, November 21, 2015 at 3:23 PM |                           |             |                  |                    |              |                  |             |
| File: 21112015_152309                  |                           |             |                  |                    |              |                  |             |
| Wavelength<br>(nm)                     | Irradiance<br>(uW/cm2/nm) | Norm of y   |                  | Normalized<br>Norm | Verification |                  |             |
|                                        |                           | Square      | Sum of<br>Square |                    | Square       | Sum of<br>Square | Area        |
| 360                                    | 1.04E+01                  | 109.0040403 | 133900.3719      | 2.85E-02           | 0.000814068  | 1                | 0.157682334 |
| 365                                    | 1.26E+01                  | 159.7544324 | √                | 3.45E-02           | 0.001193084  | √                | 0.180619474 |
| 370                                    | 1.38E+01                  | 190.3792848 | 365.9239975      | 3.77E-02           | 0.001421798  | 1                | 0.192868602 |
| 375                                    | 1.44E+01                  | 208.2912833 |                  | 3.94E-02           | 0.001555569  |                  | 0.199913781 |

**Table 5:** Normalized Data

Figure 38 graphically illustrates the radiation flux power of ASTM G173-03 Solar Spectral Irradiance Reference data to measurements taken with the LightSpex spectroradiometer. The objective was to gain a relative confidence in the spectroradiometer's calibration before deployment in measuring the solar simulator. The overlay of normalized data illustrates that the spectroradiometer readings display similar characteristics to ASTM reference data.

Comparing the normalized area under the curve of ASTM G173-03 reference spectra resulted in 43.18 non-dimensional units compared to 42.79 non-dimensional units

generated by the LightSpex. The result was less than an average of 0.9% difference and acceptable for the proposed research.



**Figure 38:** ASTM reference data vs ex-situ readings

### Series 3: Spectral Match Classification

To recap, Series 1 qualitatively identified dominant spectral spikes from 400 to 600nm wavelengths, and in this series, a corrective solution is proposed. Series 2 calibrated ex-situ spectroradiometer against ASTM G173-03 Reference Spectra Derived from SMARTS and resulted in a  $\pm 1\%$  mismatch which was deemed as an acceptable margin for this research. Series 3 quantified the spectral output of the solar simulator using the calibrated spectroradiometer and compared the results to ASTM G173-03 Reference Spectra. Series 3 also corrected dominant spectral spikes from 400 to 600nm wavelengths

to achieve a lower percentage of mismatch, and a designated Spectral Class as defined in Table 1.

### Series 3: Methods

All lamps were removed from the solar simulator except for the center lamp #7 (Figure 114). A tripod was mounted in front of the concentrator and the spectroradiometer's sensor was attached to the tripod and centered to the lamp (Figure 36). The readings were collected (Appendix J) and then normalized using linear algebra Formulas 1 & 2 and compared to normalized ASTM G173-03 Solar Spectral Irradiance Reference Data (Appendix B). Normalizing the data is required as the measure of power varies between data sets, and normalization does not impact the lamp's spectral output or comparative analysis to establish Spectral Match classification.

After normalizing flux power (irradiance  $\text{w/m}^2$ ) the area under the spectral curve from 400nm to 700nm was calculated using the definite integral in Formula 3.

$$\text{Area under spectral curve} = \int_{400}^{700} f(x)dx \quad (7)$$

Once the overall area from 400nm to 700nm was calculated the area under each 100nm wavelength band was calculated. Similarly, the area in 100nm increments of ASTM G173-03 Solar Spectral Irradiance Reference Data was calculated using the same methods. The areas under each 100nm wavelength band from the Solar Simulator and Solar Spectral Irradiance Reference Data was compared



### Series 3: Results

The area under each 100nm increments between 400nm-700nm was tabulated in Table 6. Area on the left was taken from the Spectral Irradiance Reference Data and the area on the right reflects the Solar Simulator. The difference ( $\Delta$ ) was noted to the far right along with percentage of mismatch. The difference between the two spectral curves exceeds the allowable 2.0% spectral mismatch defined in Table 1.

| ASTM G173-03    |       | Solar Simulator |          |          |
|-----------------|-------|-----------------|----------|----------|
| Wavelength (nm) | Area  | Area            | $\Delta$ | Mismatch |
| 400-500         | 11.70 | 7.66            | -4.04    | 35%      |
| 500-600         | 12.55 | 16.54           | 3.99     | 32%      |
| 600-700         | 11.61 | 3.26            | -8.34    | 72%      |

**Table 6:** Spectral Match (400nm-700nm Bands)

In order to adjust the spectral mismatch to fall at or below the approved 2% margin the research examined wavelength blocking filters. Blocking select wavelengths can be an exhaustive process that requires far more sensitive equipment and the means required for this particular research. However, broadband wavelength blocking can be achieved using low-cost co-extruded polycarbonate and polyester filters<sup>30</sup>.

<sup>30</sup> Rosco Laboratories Inc., 52 Harbor View, Stamford, CT, USA, 06902

The following experiment applied eight different filters to each luminaire to block out saturated wavelengths. Table 7 plots the unfiltered spectral curve and the eight proposed filters.

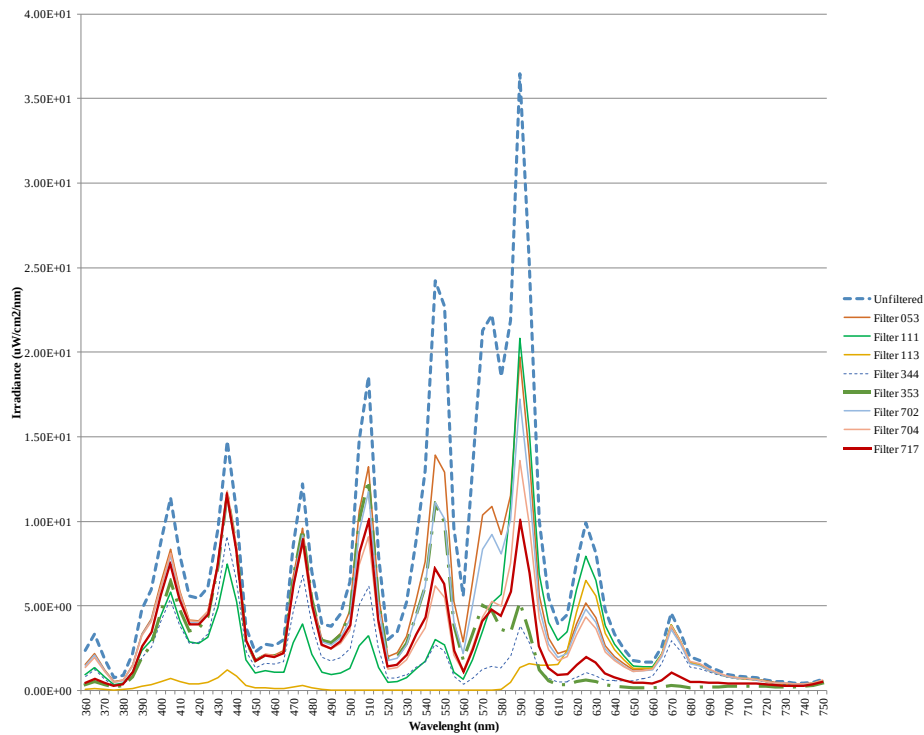


Table 7: Wavelength Filter Testing

Each filter was analyzed using the same methodology previously used in the early stages of this series, and recorded in Table 8. Each filter was compared to the Solar Spectral Irradiance Reference Data and the percentage of difference recorded in the far right column of each filter table.

| ASTM G173-03    |       |  |  | Solar Simulator |          |          |  |  |  |
|-----------------|-------|--|--|-----------------|----------|----------|--|--|--|
| Wavelength (nm) | Area  |  |  | Area            | $\Delta$ | Mismatch |  |  |  |
| 400-500         | 11.70 |  |  | 7.66            | -4.04    | 35%      |  |  |  |
| 500-600         | 12.55 |  |  | 16.54           | 3.99     | 32%      |  |  |  |
| 600-700         | 11.61 |  |  | 3.26            | -8.34    | 72%      |  |  |  |

| Filter 053      |       |          |          | Filter 111 |          |          | Filter 113 |          |          | Filter 344 |          |          |
|-----------------|-------|----------|----------|------------|----------|----------|------------|----------|----------|------------|----------|----------|
| Wavelength (nm) | Area  | $\Delta$ | Mismatch | Area       | $\Delta$ | Mismatch | Area       | $\Delta$ | Mismatch | Area       | $\Delta$ | Mismatch |
| 400-500         | 7.57  | -4.12    | 35%      | 7.76       | -3.94    | 34%      | 2.52       | -9.17    | 78%      | 18.61      | 6.91     | 59%      |
| 500-600         | 17.01 | 4.46     | 36%      | 11.79      | -0.77    | 6%       | 2.25       | -10.30   | 82%      | 8.28       | -4.27    | 34%      |
| 600-700         | 4.00  | -7.60    | 66%      | 7.48       | -4.13    | 36%      | 17.96      | 6.35     | 55%      | 4.70       | -6.90    | 59%      |
| Total Area      |       | 16.19    |          |            | 8.83     |          |            | 25.82    |          |            | 18.08    |          |

| Filter 353      |       |          |          | Filter 702 |          |          | Filter 704 |          |          | Filter 717 |          |          |
|-----------------|-------|----------|----------|------------|----------|----------|------------|----------|----------|------------|----------|----------|
| Wavelength (nm) | Area  | $\Delta$ | Mismatch |            | $\Delta$ | Mismatch |            | $\Delta$ | Mismatch | Area       | $\Delta$ | Mismatch |
| 400-500         | 13.32 | 1.63     | 14%      | 10.52      | -1.18    | 10%      | 12.50      | 0.80     | 7%       | 13.56      | 1.87     | 16%      |
| 500-600         | 13.11 | 0.56     | 4%       | 15.15      | 2.60     | 21%      | 12.42      | -0.13    | 1%       | 12.71      | 0.16     | 1%       |
| 600-700         | 0.82  | -10.78   | 93%      | 4.49       | -7.11    | 61%      | 5.31       | -6.29    | 54%      | 2.33       | -9.28    | 80%      |
| Total Area      |       | 12.97    |          |            | 10.89    |          |            | 7.22     |          |            | 11.30    |          |

Values reflect normalized area under the spectral curve using definitive integration.

**Table 8: Spectral Filters**

The percentage of mismatch recorded on Filter 704 presented the most improvement over the mismatch recorded on the Solar Simulator. In the 400 nm - 500 nm the mismatch reduced from 35% to 7%, 500 nm-600 nm the mismatch reduced from 32% to 1%, and in the 600 nm-700 nm the mismatch reduced from 72% to 54%. Ultimately the precision required to block specific wavelengths is beyond the means of this research, but strides to align spectral behavior was attempted to understand and provide reasonable solutions.

Series 3 Spectral Match was unable to offer a mismatch with 2% (Class C) as required by ASTM E927. It should be noted that spectral mismatch within the 2% threshold was achieved in several wavelengths, but not achieved consistently across the entire spectrum. Although the Solar Simulator's spectral match does not operate within the defined ASTM parameters the dimension of spectral mismatch resulted in a negative 18% deficiency

from 300nm to 1100nm. This deficiency was carried forward as a contingency factor during the analysis of the Nanowindow experiment.

The following sections defined the Spatial Non-Uniformity and Temporal Instability which had favorable results, and all meeting ASTM E927 standards.

### Irradiance Spatial Non-Uniformity

Solar radiation is generally uniform, but within a solar simulator that uniformity can vary depending on geometry, lamp placement, lamp age, and fluctuating electrical current to name a few variables. To evaluate the solar simulator's uniformity the maximum and minimum irradiance was measured over a 1-squarefoot surface area at the aperture of the concentrator, hereby referred to as the test plane.

To evaluate spatial uniformity a new the LP02 Solar Radiation Pyranometer<sup>31</sup> was used in the direct normal position. The nanowindows will eventual reside in the test plane, therefore, understanding the energy being received by the test plane and future placement of the nanowindow was critical to the study. Equally important was the amount of lamp-based radiation received in comparison to solar radiation.

The test plane covered the concentrator's aperture and lined with pre-mirror TALBPREM 304 stainless steel panel to match the reflectivity of the concentrator. The test plane was divided into 13 analysis points that provided relatively adequate coverage of the one

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<sup>31</sup> Hukseflux LP02 Pyranometer is a hemispherical solar radiation sensor with calibration uncertainty  $\pm 0.21 \times 10^{-6}$  v/(W/m<sup>2</sup>).

square foot test plane. Each hole was counter sunk to receive the pyranometer and provide adequate exposure of the pyranometer's dome inside the simulator.

Non-uniformity is expressed as

$$\text{Non-uniformity (\%)} = \frac{E_{\max} - E_{\min}}{E_{\max} + E_{\min}} \times 100\% \quad (8)$$

Where

$E_{\max}$  = Maximum Irradiance (W/m<sup>2</sup>)

$E_{\min}$  = Minimum Irradiance (W/m<sup>2</sup>)

Two sequential irradiance test series were conducted using 13 analysis points each lasting 5 minutes per analysis point. Considering that there was only one pyranometer available the pyranometer was physically moved to each of the 13 analysis points  $\pm$  every 5 minutes. One second interval collection was used providing  $\pm 300$  data points per analysis points providing sufficient coverage.

### Irradiance Spatial Non-Uniformity Results

Spatial Uniformity Series 1 started at the same time the Solar Simulator was powered up and lasted for 90 minutes with filters in place. Series 2 followed immediately after Series 1 and lasted an additional 90 minutes with filters in place. The raw data is provided in Appendix C and reflects the  $\pm 300$  data point for each of the 13 analysis points totaling

4,300 entries. The mean irradiance value ( $\text{W/m}^2$ ) of each of the 13 analysis points was plotted in Table 9.

|       |       |       |       |       |
|-------|-------|-------|-------|-------|
| 767.7 |       | 762.8 |       | 761.8 |
|       | 789.2 |       | 754.0 |       |
| 787.4 |       | 830.2 |       | 821.4 |
|       | 784.9 |       | 809.0 |       |
| 784.9 |       | 782.4 |       | 807.6 |

Series 1 : 13 Analysis Ponits ( $\text{W/m}^2$ )

|       |       |       |       |       |
|-------|-------|-------|-------|-------|
| 758.4 |       | 734.1 |       | 752.1 |
|       | 764.1 |       | 743.3 |       |
| 752.3 |       | 784.5 |       | 759.5 |
|       | 748.2 |       | 755.1 |       |
| 754.4 |       | 747.4 |       | 757.0 |

Series 2 : 13 Analysis Ponits ( $\text{W/m}^2$ )

**Table 9:** Mean Irradiance Levels at Test Plane

Note that the variance between values may be a result of lamp placement, geometric inconsistencies, or luminaire alignment, but that sufficient characterization can be formed from the data. From the data plotted in Table 9 the sample mean and standard deviation for Series 1 and 2 are performed (Table 10). In series 1 the mean irradiance across the test plane was  $787.9 \text{ W/m}^2$  which is roughly equivalent to 80% of a standard sun according to ASTM G173-03 direct normal maximum irradiance of  $963.8 \text{ W/m}^2$  at AM1.5G. Series 2 yielded  $753.6 \text{ W/m}^2$  which is roughly equivalent to 78% of a standard test sun. Although the overall irradiance of  $787.9 \text{ W/m}^2$  and  $753.6 \text{ W/m}^2$  is just one of several factors that define solar simulators, it is a strong indicator that the simulator will provide the required irradiance levels to carry out the nanowindow experiment.

Although ASTM G173-03 is a known standard for solar simulators actual irradiance levels at the site were collected and compared to ASTM G173-03 and the simulator's output. The maximum direct normal irradiance according to ASTM G173-03 is 963.8 W/m<sup>2</sup>. However, the maximum direct normal irradiance between September and November was 886 W/m<sup>2</sup> using the same pyranometer used in the solar simulator. Based on actual readings from the Los Angeles<sup>32</sup> research site the low-cost solar simulator is roughly equivalent to 88% of a standard sun, and more likely to reflect atmospheric conditions relative to this region.

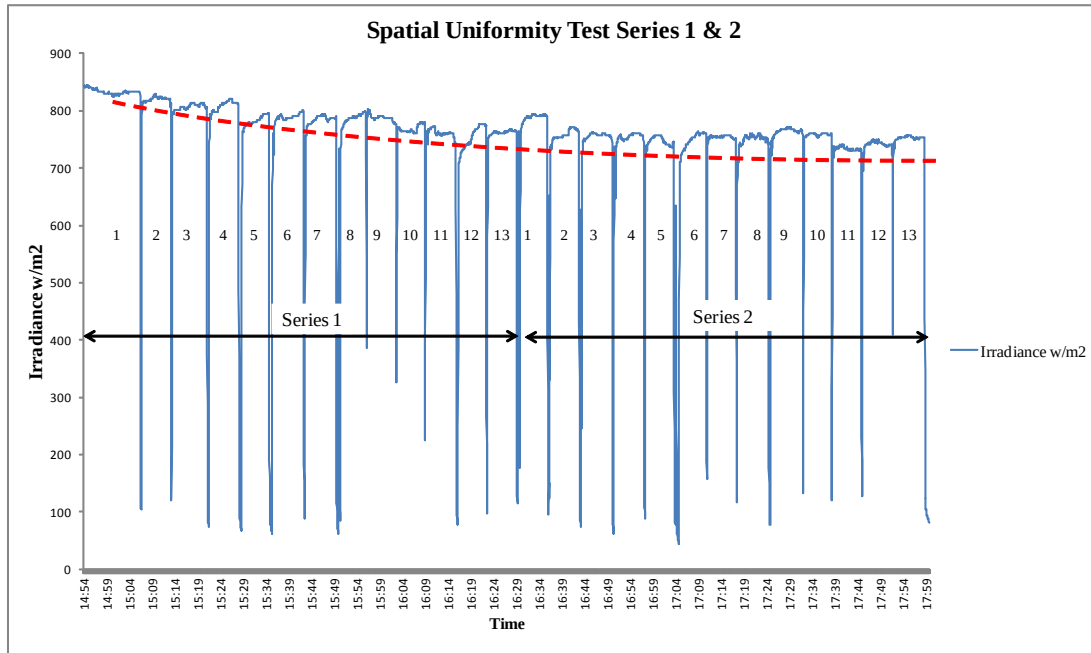
| Series 1                        |         | Series 2                        |         |
|---------------------------------|---------|---------------------------------|---------|
| Sample Mean (w/m <sup>2</sup> ) | 787.9   | Sample Mean (w/m <sup>2</sup> ) | 754.6   |
| Standard Deviation:             | 556.0   | Standard Deviation:             | 140.366 |
| Population Standard Deviation:  | 23.5792 | Population Standard Deviation:  | 11.85   |

**Table 10:** Summary of Series 1 & 2

Figure 39 plots Series 1 and 2 consecutively. Note that each of the 13 analysis points was preceded by a significant drop in irradiance levels. This is a result of physically moving the pyranometer from one location to another.

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<sup>32</sup> The research facility is privately owned and situated in Los Angeles. Latitude: 34°03'08" N  
Longitude: 118°14'37" W



**Figure 39: Solar Simulator Series 1 & 2**

A distinct observation noted during the initial start-up was the diminishing irradiance levels over the course of the first hour, and begins to level out starting around the second hour (Figure 39). This may indicate the lamp's steady state operating condition was fully reached between 1 and 2 hours after start-up. To confirm this population standard deviation was applied to Series 1 and 2. The standard deviation for Series 1 was 23.6 and for Series 2 was 11.9 (Table 10). This further reinforced that the system's stable operating condition is best 1 to 2 hours after start-up (Table 10). Future nanowindow testing should allow for no less than 2 hours to reach a stable testing condition. This promoted a third series (Series 3) to identify the time required to reach steady operational state.



Although all these observations lead to characterizing the solar simulator against known standards, the initial objective focused on irradiation non-uniformity. Using the Non-uniformity equation, the experimental data collected in Series 1 and 2 were computed. The results illustrate that the test plane received a non-uniformity of 2.05% in Series 1 and 1.7% in Series 2 (Table 11 and Table 12). Based on ASTM E927-10 (Table 1) the solar simulator's Irradiation non-uniformity is <2% and receives a Class A designation. However, depending on the subtle characteristic of lamp placement and other non-characterized variables it is safe to designate the simulator as a Class B.

|                                           |              |       |       |       |       |       |       |       |       |       |       |       |       |
|-------------------------------------------|--------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| <b>Spatial Uniformity Test - Series 1</b> |              |       |       |       |       |       |       |       |       |       |       |       |       |
| Series 1                                  |              |       |       |       |       |       |       |       |       |       |       |       |       |
| December 13, 2015                         |              |       |       |       |       |       |       |       |       |       |       |       |       |
| Sensor Location                           | 1            | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    | 11    | 12    | 13    |
| Mean Irradiance (w/m2)                    | 830.2        | 821.4 | 807.6 | 809.0 | 782.4 | 784.9 | 784.9 | 787.4 | 789.2 | 767.7 | 762.8 | 754.0 | 761.8 |
| Max (w/m2)                                | 835.0        | 829.0 | 814.0 | 821.0 | 794.7 | 794.7 | 794.7 | 799.4 | 803.0 | 779.5 | 773.8 | 775.7 | 768.1 |
| Min (w/m2)                                | 825.0        | 814.0 | 802.0 | 786.1 | 761.5 | 722.6 | 762.4 | 752.9 | 779.5 | 760.5 | 741.6 | 716.9 | 746.3 |
| Nonuniformity                             | 0.60%        | 0.91% | 0.74% | 2.17% | 2.13% | 4.75% | 2.07% | 3.00% | 1.48% | 1.23% | 2.12% | 3.94% | 1.44% |
| Average Nonuniformity                     | <b>2.05%</b> |       |       |       |       |       |       |       |       |       |       |       |       |

**Table 11:** Spatial Uniformity Series 1

|                                           |             |       |       |       |       |       |       |       |       |       |       |       |       |
|-------------------------------------------|-------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| <b>Spatial Uniformity Test - Series 2</b> |             |       |       |       |       |       |       |       |       |       |       |       |       |
| Series 2                                  |             |       |       |       |       |       |       |       |       |       |       |       |       |
| December 13, 2015                         |             |       |       |       |       |       |       |       |       |       |       |       |       |
| Sensor Location                           | 1           | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    | 11    | 12    | 13    |
| Mean Irradiance (w/m2)                    | 761.4       | 759.5 | 757.0 | 755.1 | 747.7 | 748.2 | 754.4 | 752.3 | 764.1 | 758.4 | 734.1 | 743.3 | 752.1 |
| Max (w/m2)                                | 791.8       | 771.9 | 762.4 | 760.5 | 757.7 | 764.3 | 756.7 | 760.5 | 771.9 | 760.5 | 741.6 | 749.2 | 756.7 |
| Min (w/m2)                                | 751.0       | 749.1 | 747.2 | 745.4 | 734.9 | 707.4 | 741.6 | 737.8 | 720.7 | 750.1 | 730.2 | 734.0 | 734.0 |
| Nonuniformity                             | 2.64%       | 1.50% | 1.01% | 1.00% | 1.53% | 3.87% | 1.01% | 1.52% | 3.43% | 0.69% | 0.77% | 1.02% | 1.52% |
| Average Nonuniformity                     | <b>1.7%</b> |       |       |       |       |       |       |       |       |       |       |       |       |

**Table 12:** Spatial Uniformity Series 2

## Temporal Instability

Similar to spatial uniformity the objective of temporal stability examines spectral uniformity across the test plane's 13 analysis points as a function of time.

The same data collected for Series 1 and 2 was used to evaluate the temporal stability, but now taking into account time. To recap, two sequential irradiance test series were conducted of the 13 analysis points each lasting 5 minutes per analysis point. One second interval collection was used providing  $\pm 600$  data points per analysis points providing sufficient coverage.

Temporal stability is expressed as:

$$\text{Temporal Stability (\%)} = \frac{E_{Max}^T - E_{Min}^T}{E_{Max}^T + E_{Min}^T} \times 100\% \quad (9)$$

Where

$E_{Max}^T$  = Maximum Irradiance ( $\text{W/m}^2$ ) at a designated time

$E_{Min}^T$  = Minimum Irradiance ( $\text{W/m}^2$ ) at a designated time

## Temporal Instability Results

As noted in the spatial uniformity section, Series 1 started at the same time the Solar Simulator was powered up and lasted for 90 minutes. Series 2 followed immediately after Series 1 and lasted an additional 90 minutes. The raw data is provided in Appendix C and reflects the  $\pm 300$  data point for each of the 13 analysis points totaling 4,300 entries.

In both Series 1 and 2 the beginning, middle and end of each series was calculated using Equation 2. Series 1 indicated that the highest temporal instability was 7.37% at the beginning, 4.31% at midpoint, 4.55% at the end, and average temporal instability was 5.18% - all with the of the nominated time (Table 13).

| <b>Temporal Stability Test - Series 1</b> |              |        |        |        |        |        |        |        |        |        |        |        |        |
|-------------------------------------------|--------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Series 1                                  |              |        |        |        |        |        |        |        |        |        |        |        |        |
| Decemeber 13, 2015                        |              |        |        |        |        |        |        |        |        |        |        |        |        |
| Temporal stability @ midpoint             | 829.00       | 821.00 | 810.00 | 814.00 | 782.30 | 787.10 | 790.90 | 789.90 | 790.90 | 764.30 | 760.50 | 760.50 | 760.50 |
| Max (w/m2)                                | 829.00       |        |        |        |        |        |        |        |        |        |        |        |        |
| Min (w/m2)                                | 760.50       |        |        |        |        |        |        |        |        |        |        |        |        |
| Temporal Stability at beginning           | 7.37%        |        |        |        |        |        |        |        |        |        |        |        |        |
| Temporal Stability at midpint             | 4.31%        |        |        |        |        |        |        |        |        |        |        |        |        |
| Temporal Stability at end                 | 4.55%        |        |        |        |        |        |        |        |        |        |        |        |        |
| Average Temporal Stability                | <b>5.18%</b> |        |        |        |        |        |        |        |        |        |        |        |        |

**Table 13: Temporal** Instability - Series 1

The heightened temporal instability in Series 1 was anticipated to be higher during the warm-up phase as operational steady state was reached. Series 2 is a fair representation of metal arc lamps at steady state. The temporal instability at the beginning was of 3.12%, 2.53% at midpoint, 3.99% at the end, and the average temporal instability was 2.3% - all within the nominated time (Table 14).

|                                           |              |        |        |        |        |        |        |        |        |        |        |        |        |
|-------------------------------------------|--------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| <b>Temporal Stability Test - Series 2</b> |              |        |        |        |        |        |        |        |        |        |        |        |        |
| Series 2                                  |              |        |        |        |        |        |        |        |        |        |        |        |        |
| Decemeber 13, 2015                        |              |        |        |        |        |        |        |        |        |        |        |        |        |
| Spatial Non-Uniformity                    | 756.70       | 756.70 | 758.60 | 756.70 | 742.50 | 752.90 | 754.80 | 754.80 | 768.10 | 753.90 | 730.20 | 745.40 | 755.80 |
| Max (w/m2)                                | 768.10       |        |        |        |        |        |        |        |        |        |        |        |        |
| Min (w/m2)                                | 730.20       |        |        |        |        |        |        |        |        |        |        |        |        |
| Temporal Stability at beginning           | 3.12%        |        |        |        |        |        |        |        |        |        |        |        |        |
| Temporal Stability at midpint             | 2.53%        |        |        |        |        |        |        |        |        |        |        |        |        |
| Temporal Stability at end                 | 3.99%        |        |        |        |        |        |        |        |        |        |        |        |        |
| Average Temporal Stability                | <b>2.30%</b> |        |        |        |        |        |        |        |        |        |        |        |        |

**Table 14:** Temporal Instability - Series 2

Comparing Series 1 and 2 to ASTM E927-10 (Table 1) the solar simulator falls within the range of a Class C during warm-up phase considering it is greater than the allowable 5%. However, once a stable state is achieved the low cost solar simulator has a nonconformity of 2.3% and well within the Class B designation.

### Low-Cost Solar Simulator Conclusion

The low-cost solar simulator was evaluated against ASTM E92-2015 Standard Specifications for Solar Simulation and a resulted in an undefined Spectral Match, Class B Irradiance Spatial Non-Uniformity, and Class B Temporal Stability. The results provided an appropriate but not perfect in-situ solar simulator to evaluate window performance.

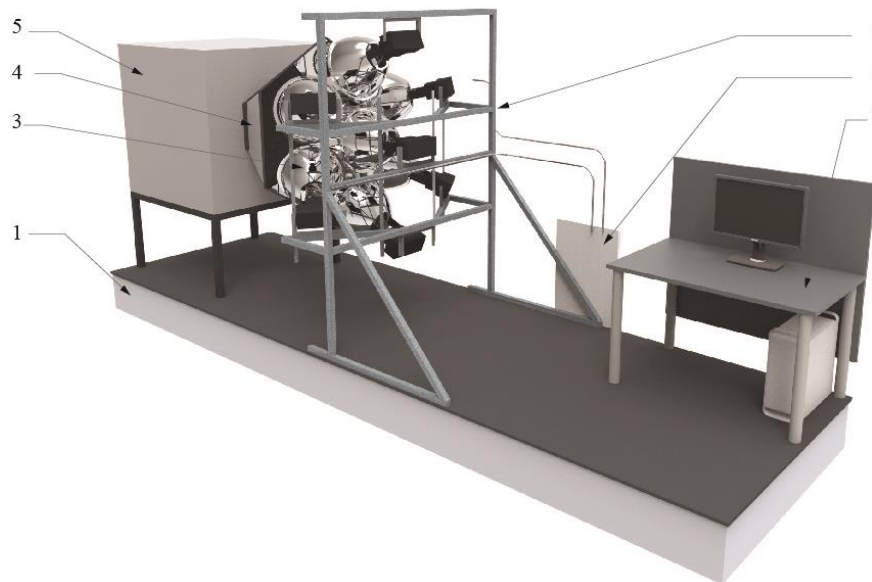
Throughout the experiments several challenges emerged because of situating the simulator in an unconditioned space. Dust collection consistently accumulated on the concentrator's mirrors resulting in increased soiling factors that may have impacted simulator performance. The concentrator was also suspended in between the calibrated

hot box and the lamp array. Throughout the experiment it became increasingly challenging to maintain the exact location of the concentrator in relation to the CHB and Lamp Array.

## CHAPTER V

### LOW-COST CALIBRATED HOT BOX APPARATUS

A hot box provides a steady state environment to evaluate building material performance. In this research the application of the hot box and the solar simulator provided a near steady state condition so that each repetitive test occurred in nearly the same environmental context. Thus, the results of each test series were compared to one another knowing that the environmental conditions were nearly equal and the change in performance rests with the Nanowindow specimen. This concept aligns with ASTM criteria that holds all the control parameters constant thereby reducing variability of surface heat transfer coefficients on the specimen during the research (ASTM C1363-11, 2011, p. 29). The hot box was situated in front of the solar simulator (Figure 40) and fabrication is documented in Appendix N.

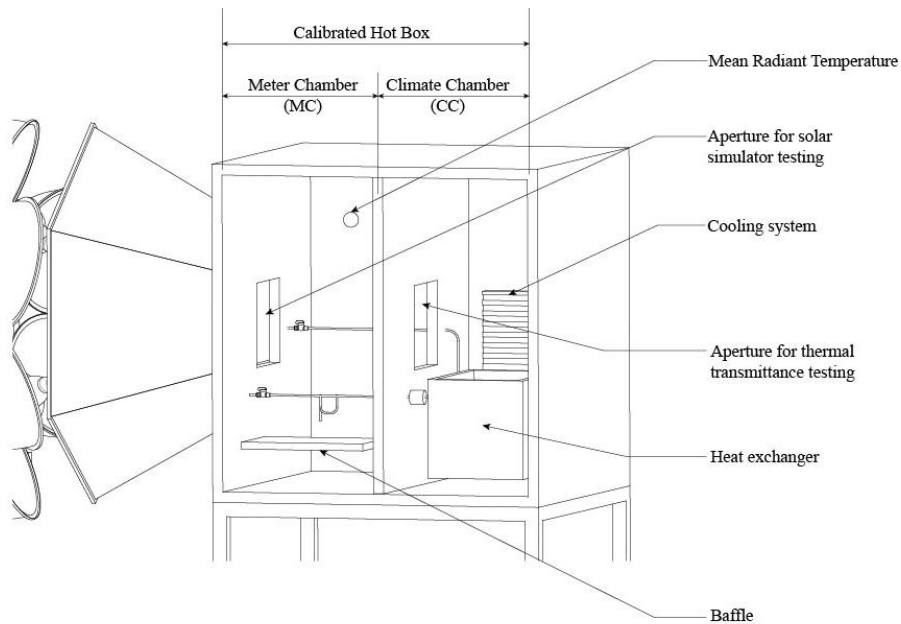


**Figure 40:** Solar Simulator

(1. Lab Platform, 2 Array Rack, 3. Luminaires & Lamps 4. Concentrator, 5. Calibrated Hot Box, 6. Load Center, 7. Data Acquisition Center.)

The hot box apparatus was composed of a Climate Chamber and Metering Chamber (Figure 41). The opposing chambers were provided with variable heating and cooling capabilities achieving a 40-50 °C difference in temperature.

This hot box apparatus was divided into two equal chambers: Climate Chamber and Meter Chamber. Both chambers were equipped with baffles to limit erroneous readings from sensors impacted by cooling and heating radiant waves. According to Miller the baffles also “confine air to a uniform channel, thus maintaining an air curtain over the specimen surface” (Miller, 1987, p. 10). The baffles were painted black to meet emittance criteria recommended by ATSM C1363 of  $\varepsilon = 0.8$ .



**Figure 41:** Proposed Calibrated Hot Box (CHB)

The guarded hot box and calibrated hot box are the two most commonly used hot box apparatus found in many research and certification laboratories. The advantages of the

guarded hot box is a second chamber on the metering side that allows for the specimen to extend beyond the meter area to account for flanking loss. Another advantage is the guard area around the metering chamber. This further “reduces heat transfer from the ambient environment by controlling the temperature in the guard area around the metering box” (Cho, Kerfoot, Stepowski, Cox, & Lin, 2006, p. 19). Although the guarded hot box has its advantages the cause for concern was the required guard area width defined as

$$G_{width} = 3(NW_d^2) \quad (10)$$

(source unknown)

where  $NW_d$  is the depth of the Nanowindows. Since the Nanowindow’s depth varied from 1-inch to 2.5-inches it made the guard area incompatible with the Nanowindow’s overall surface area of 1sqft and in some cases would occupy the entire surface area. Thus a modified Calibrated Hot Box (CHB) was deployed.

| Nanowindow | Depth (inches) | Guard Area (inches) |
|------------|----------------|---------------------|
| Series 5   | 1              | 3.0                 |
| Series 6   | 1              | 3.0                 |
| Series 7   | 1.75           | 9.2                 |
| Series 8   | 1.75           | 9.2                 |
| Series 9   | 2.5            | 18.8                |
| Series 10  | 2.5            | 18.8                |

**Table 15:** Guard Area Depth

A low-cost Calibrated Hot Box (CHB) was designed, fabricated and calibrated according to the American Society for Testing Materials (ASTM) Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus (C1363-11). The objective was to fabricate a CHB with the capability to



characterize visible transmittance (VT), thermal transmittance (U-factor), and solar heat gain coefficient (SHGC). ASTM standards note that the CHB design should attempt to reduce metering chamber heat transfer, flanking loss, and infiltration knowing that a perfectly balanced chamber is not possible and correction are needed to accurately characterize all the heat flow paths (ASTM C1363-11, 2011, p. 1)

### Hot Box Calibration Methods

The hot box's size, cooling and heat ranges were compared to 13 other hot box apparatus throughout the U.S. and Canada reported in a survey by Miller. Miller's survey noted that there was an almost equal amount of guarded and calibrated hot box apparatus and sample areas ranged from 0.92m<sup>2</sup> (10,8ft<sup>2</sup>) to 13.8m<sup>2</sup> (150ft<sup>2</sup>). The report mentioned that ASTM methods were applied to characterize the hot boxes, and that the calibration R-value range was much smaller than the tested R-value range potentially leading to error (Miller, 1987, p. 153).

The final measurements of the Climate Chamber was 4-feet cubed (64ft<sup>3</sup>) with a minimum sample area of 0.92m<sup>2</sup> (1ft<sup>2</sup>) with the option to expand to a maximum of 0.18m<sup>2</sup> (2ft<sup>2</sup>) while maintaining full irradiance immersion under the solar simulator. Although this is significantly smaller than the survey results the CHB was appropriately sized for the Nanowindow samples which are based on industry standards.

## Experimental Procedures

Three CHB tests series were performed to identify the cooling and heating ranges compared to the 13 hot boxes surveyed by Miller. Each test was conducted over a 5 to 12-hour period and measured the power (Watts), time to reach steady state (hh:mm:ss), and temperature gradient in Celsius (Fahrenheit). For this exercise the CHB aperture for thermal transmittance testing and aperture for solar testing were capped with a solid piece of 2” polyiso with known thermal resistance properties. A dedicated weather station to the outdoor solar lab collected exterior ambient conditions in conjunction with CHB sensors.

Series 1: Heated the metering chamber with no flanking cooling

Series 2: Cooled the climate chamber with no flanking heating

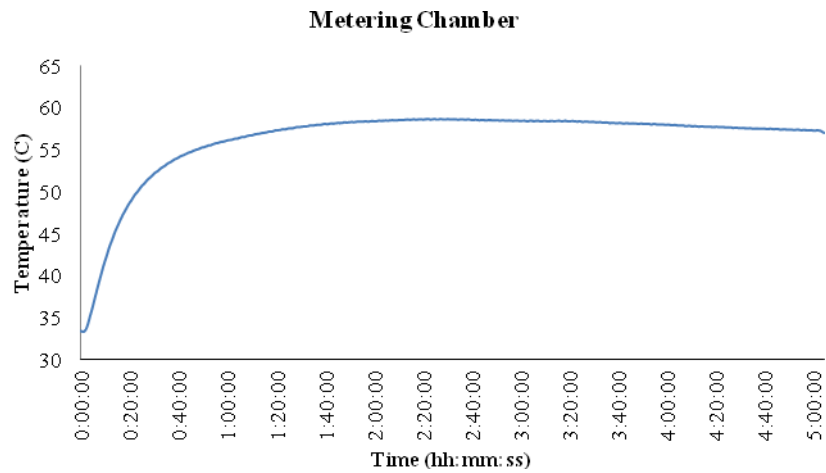
Series 3: Heated and cooled simultaneously

Each Series was automated using the Data Acquisition System (DAS) and environmental variables were collected every 10 seconds over 5-12 hours depending on the series.

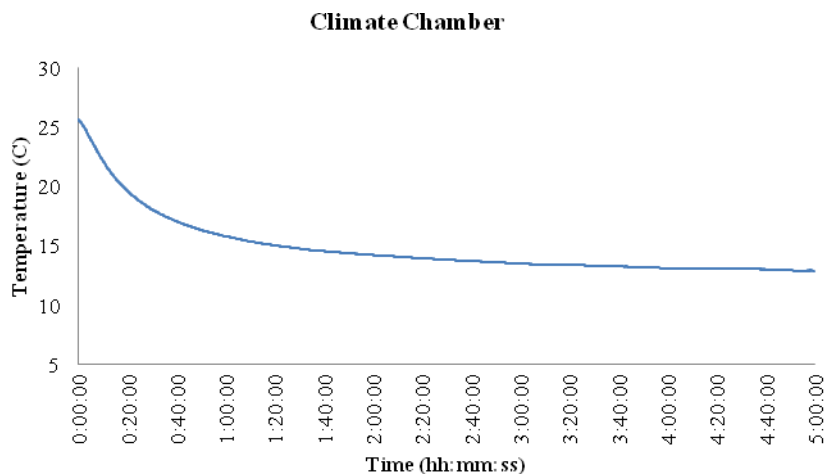
Ambient temperature sensors were centered horizontally and vertically in both chambers. Sensors were shielded from radiant sources using a low-emissivity baffle panel. The only data that was reported was the data once steady state was reached which begins to define normal operating procedures for subsequent testing.

## Results

In Series 1 the metering chamber reached steady state in less than 2-hours to a maximum of 58°C (134°F) using 160Wh (Figure 42). In Series 2 the climate chamber reached steady state in approximately 2-hours to a maximum low temperature of 12°C (53°F) using 290Wh (Figure 43).



**Figure 42:** Series 1 Metering Chamber



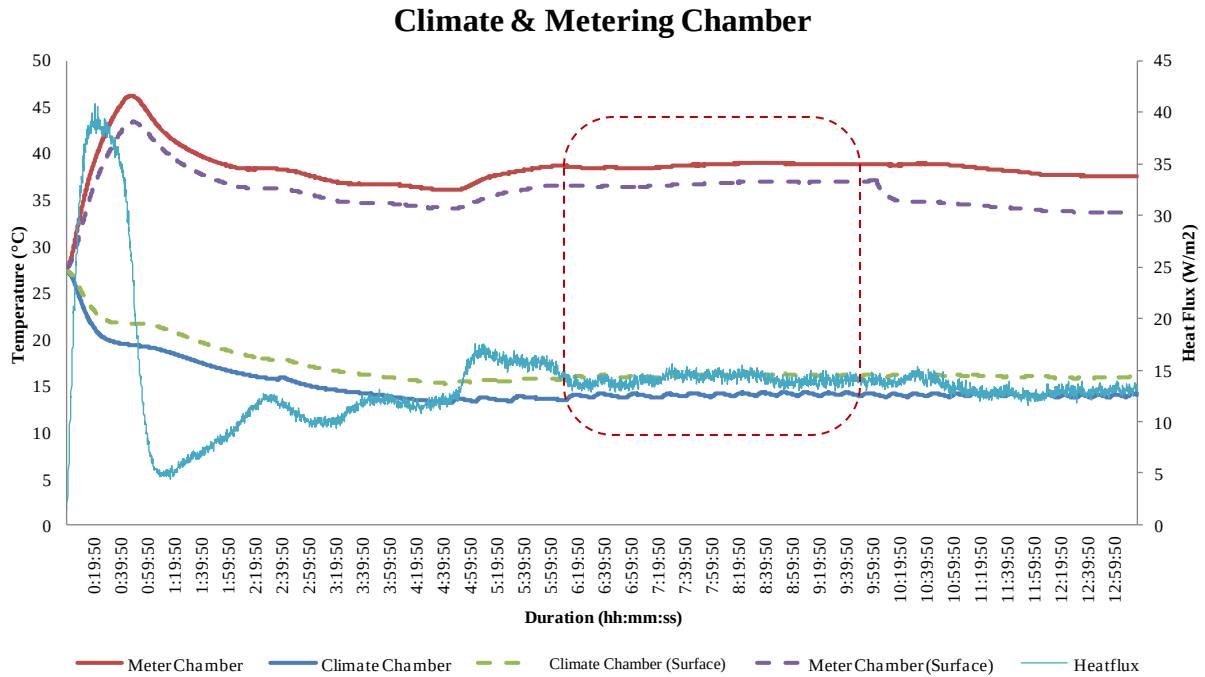
**Figure 43:** Series 2 Climate Chamber

Based on Series 1 and 2 several adjustments were made to improve near steady state conditions in Series 3. The cooling thermostat was adjusted to maintain a more moderate cooling temperature above 15 °C (59 °F), and the thermostat on the heating side was modified to maintain temperatures  $\pm 37$  °C (98.6 °F). This proved to be relatively problematic to implement in the Climate Chamber and in the Metering Chamber<sup>33</sup>.

Series 3 lasted 12 hours making minor adjustments to achieve near steady state conditions. The average temperature reached in the Metering Chamber was 38.7°C (101.7 °F) using 80 Wh, and the average steady state temperature reached in the Climate Chamber was 14 °C (57.2 °F) using 60 Wh (Figure 44). This condition offered the required differential between chambers of 22 °C (40 °F) which is the desired temperature differential for resistance testing (ISO 12567-1, 2010, p. 14).

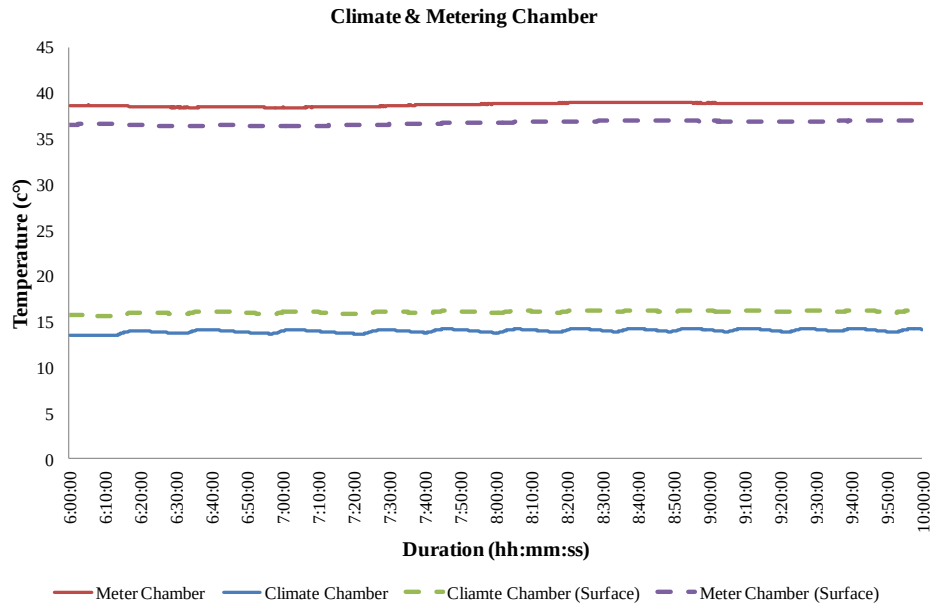
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<sup>33</sup> The heating element's thermostat was a traditional bi-metal switch. The metals on these switches bend at varying rates as a function of temperature. When cold the bi-metals form a bridge allowing for electricity to pass through. As the bi-metals warm-up the bi-metal separate and the electrical circuit is interrupted until the metals cool down and once again forms a bridge. Using the Data Acquisition System and temperature sensor to supplement the built-in thermostat did not have the desired response time. To overcome these issues the bi-metal thermostat's pointer was modified to accommodate lower temperatures, and a bidirectional triode thyristor was installed to lower current below the 290w range.



**Figure 44:** Series 3 Climate & Meter Chamber with Heat Flux Overlay

A second analysis of Series 3 focused on the time frame between 6 and 10 hours into the testing. This was deemed to have the greatest near steady state conditions throughout the exercise. This time frame accounted for ideal modification to the hot box apparatus and outlined operational procedures for subsequent Nanowindow testing ( Figure 45). The results of the modifications offered a heating profile that with a 1.5% ( $0.62^{\circ}\text{C}$ ) differential between high and low temperature oscillations during the 6-hour time frame. Similarly, the cooling profile resulted in a 5.5% ( $0.79^{\circ}\text{C}$ ) differential between high and low temperature oscillations. The differential in temperature in both chambers is acceptable per ASTM and ISO which allows for  $\pm 1^{\circ}\text{C}$  ( $\pm 2^{\circ}\text{F}$ ). The oscillation in temperature is associated with air infiltration, flanking loss, and thermostat accuracy which will be addressed in the calibration section.



**Figure 45: Series 3 Near Steady State Conditions**

## Industry Comparison

The heating and cooling potentials were compared to other hot box apparatus (Figure 46). The low-cost approach offered relatively similar results except for cooling potential. In all of the surveyed labs the lowest temperature was below freezing while the lowest temperature achieved by the system was 10°C (50°F). Although freezing temperatures may have been desirable the important factor between the climate chamber and metering chamber was achieving 10°C-20°C difference between the two at steady state.

| Laboratory              | Temperature Ranges   |                       |                      |                      |
|-------------------------|----------------------|-----------------------|----------------------|----------------------|
|                         | Metering Chamber     |                       | Climate Chamber      |                      |
|                         | °C                   | °F                    | °C                   | °F                   |
| 1                       | 24 to 66             | (75 to 150)           | -29 to 24            | (20 to 75)           |
| 2                       | -32 to 66            | ( -25 to 150)         | -32 to 66            | (-25 to 150)         |
| 3                       | 24 to 52             | (75 to 125)           | -18 to 10            | (0 to 50)            |
| 4                       | 16 to 66             | (60 to 150)           | -23 to 66            | (-10 to 150)         |
| 5                       | 10 to 66             | (50 to 150)           | -23 to 67            | (10 to 100)          |
| 6                       | 2 to 74              | (35 to 165)           | -21 to 49            | ( - 5 to 120)        |
| 7                       | 18 to 27             | (65 to 80)            | -26 to 54            | (-15 to 150)         |
| 8                       | 24 to 66             | (75 to 150)           | -18to 66             | (0 to 150)           |
| 9                       | 10 to 66             | (50 to 150)           | -40 to 66            | ( -40 to 150)        |
| 10                      | 0 to 60              | (32 to 140)           | -40 to 25            | (-40 to 77)          |
| 11                      | 18 to 66             | (65 to 150)           | -23 to 24            | ( -10 to 75)         |
| 12                      | 18 to 38             | (65 to 100)           | -18 to 66            | (0 to 150)           |
| 13                      | 21 to 49             | (70 to 100)           | -1 to 32             | (30 to 90)           |
| <b>Proposed Hot Box</b> | <b>Ambient to 58</b> | <b>Ambient to 132</b> | <b>Ambient to 12</b> | <b>Ambient to 53</b> |

**Figure 46:** Temperature Capabilities of Hot Boxes

During the research, it was determined that there is no singular standard for CHB operating temperatures, and that manufacturers use varying applications of industry standards making it challenging to select a single standard to define CHB characteristics. In an uncertainty analysis of CHB procedures by the University of Perugia it was noted that ASTM and ISO standards resulted in very similar thermal transmittance resulting all within  $\pm 3\%$  of each other (Asdrubali & Baldinelli, 2011, p. 1625).

|                     | Metering Chamber                        | Climate Chamber    |
|---------------------|-----------------------------------------|--------------------|
| <b>Proposed CHB</b> | <b>38 °C</b>                            | <b>14 °C</b>       |
| ASTM C1363          | 21.1 $\pm$ 0.3 °C                       | -17.8 $\pm$ 0.3 °C |
| ISO 12567-1:2012    | Temperature difference of 20 $\pm$ 2 °C |                    |
| ISO 15099           | 20 °C                                   | 0 °C               |
| NFRC 200-2004       | 24 °C                                   | -18 °C             |

Based on the CHB's known operating potential and time to achieve steady state the research goals were satisfied by operating the CHB's Meter Chamber and Climate Chamber at 38°C (100 °F) and 14 °C (57 °F), respectively. This operational condition generates a positive thermal energy in the Metering Chamber with thermal transfer to the ambient and to the Climate Chamber to reinforce equation(11).

### Material Calibration Methods

To determine the accuracy and confidence of upcoming thermal transmittance testing a series of calibration exercises were performed. Four know specimens with laboratory certification of SHGC, TVis, and U-Factor was used. The specimens included single pane, double pane, triple pane glass, and a 2" thick polyiso board.

The hot box was calibrated using ASTM C1363 standards and included supporting literature review that deployed similar CHB systems to evaluate the thermal resistance of homogeneous<sup>34</sup> and inhomogeneous<sup>35</sup> materials. The intent was to account for the CHB's accuracy by measuring the energy delivered and the energy lost through the MC to the environment, and the MC to the CC. Thus if all six faces of the MC's losses can be accounted for and compared to the energy provided then the difference is the heat loss through the specimen. Conversely, if heat loss through the specimen is compared to the heat delivered the difference is the total heat loss experience by the entire MC.

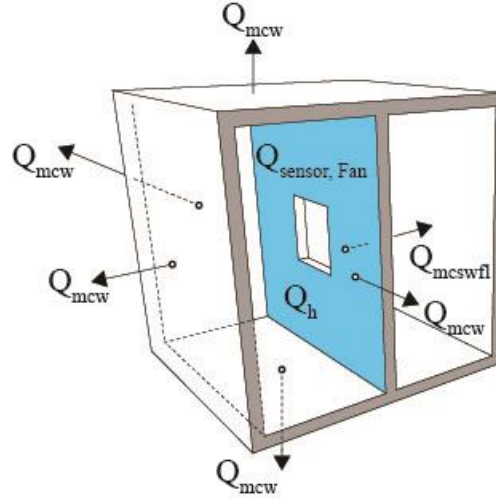
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<sup>34</sup> Homogeneous material assumes a building material that has a constant conductivity value and uniform physical structure. Plastic, glass, metal are such a material.

<sup>35</sup> Inhomogeneous materials are composed of dissimilar materials and varying thermal conductivity. Doors and windows are examples.



The total heat balance is the total energy supplied to the MC from the radiant heat source ( $Q_h$ ) minus the thermal energy removed from the MC. The energy can only leave through the MC's walls and the flanking wall. The flanking wall is the wall that separates the MC from the CC and highlighted in Figure 47.



**Figure 47:** Energy Flow

Note that electric motors including the fan ( $Q_{mcf}$ ) and thermistors based sensors ( $Q_{sensor}$ ) generate heat and contribute to the energy provided to the MC. This is commonly referred to as self-heating effect and in most instances a thermistor's thermal contribution is 1.5 mW/°C in still air and considered negligible for this exercise. The fan had a slightly higher thermal contribution of approximately 1.4 W.

The proposed equation for total heat balance of the CHB is:

$$Q = Q_h + Q_{mcf} - Q_{mcw} - Q_{mcswf} + Q_{sensor} \quad (11)$$

Where:

$Q$  = heat flow through the specimen window

$Q_h$  = heat generated from the heater

$Q_{mcf}$  = heat generated from Meter Chamber fan (Excluded)

$Q_{mcw}$  = heat flow through Meter Chamber walls

$Q_{mcswf}$  = heat flow through Meter Chamber side walls flanking loss

$Q_{sensor}$  = heat generated by thermistor sensors (Excluded)

and thermal transmittance is defined as:

$$U = \frac{Q}{(T_{MC} - T_{CC})} \quad (12)$$

Where:

$U$  = thermal transmittance (W/m<sup>2</sup>K)

$Q$  = heat flow through the specimen (heatflux)

$T_{MC}$  = Meter chamber ambient temperature (C°)

$T_{CC}$  = Climate chamber ambient temperature (C°)

The proposed CHB was not intended to replace laboratory CHB, but rather aid in defining the limitations of the low-cost CHB, and define the thermal losses that are not occurring through the test specimen.

## Experimental Procedures

Two groups of experiments were conducted. The Group A measured the thermal transmittance of the three window specimens (single, double and triple pane) referred to as Series 1,2, and 3 respectively, and Series 0 which was a 2” polyiso panel.

The CHB was brought up to steady state over a 12-hour period and the heat flux, U-factor, ambient and surface temperatures were measured, including the power delivered to the MC. Specimens were tethered with a surface temperature sensor on each side of the

specimen, and a heat flux sensor. Each Ambient temperature sensors were place 2”-3” away from the specimen and all sensors were generally centered to the specimen. Similar to the previous section the all heating, cooling, and fan operations were controlled using the DAS. Data was collected every 10 seconds and averaged after steady state was achieved.

Group B measured the heat flux through the flanking wall, side walls, and top and bottom of the metering chamber. Using equation (11) the objective was to characterize heat flux through the envelope and by deduction determine the heat flux through Series 1 (Single Pane) specimen. During the experiment the MC was always at a loss to the ambient as it was to the CC<sup>36</sup>. The experiment ran consecutively for seven days with each wall having 12 hours of testing.

The heat flux plate, surface and ambient temperature sensors were moved from each face of the MC every 12 hours, and the DAS was downloaded and reset for each experiment to avoid any data overlap.

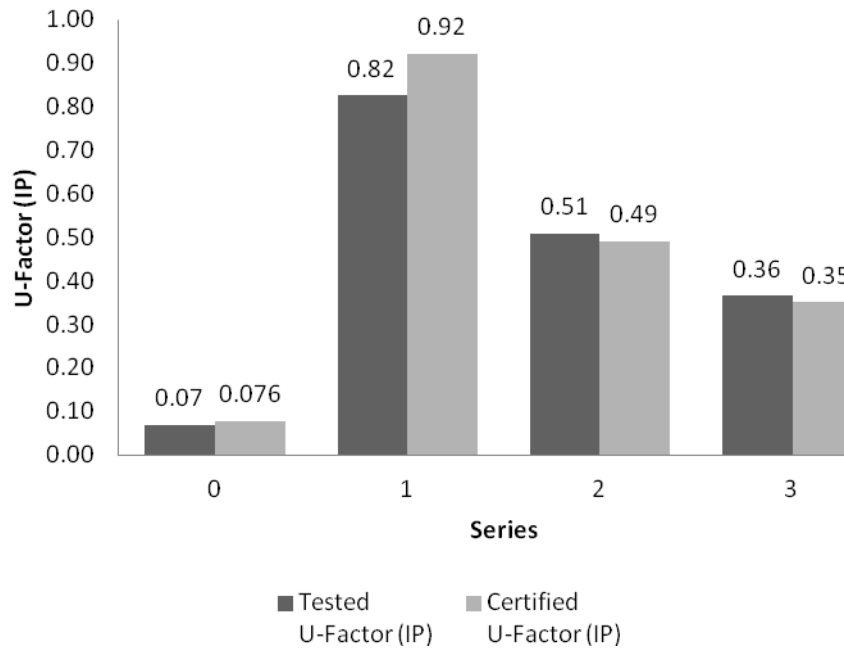
## Calibration Results

Group A is depicted in Figure 48 and compares four known specimens to the readings collected during the calibration exercise. Based on the findings Series 0 (polyiso) thermal transmittance was  $\pm 8\%$  less compared to the certified value. Series 1 (single pane) thermal transmittance was  $\pm 10\%$  less than the certified value. Series 2 (double pane)

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<sup>36</sup> In order to maintain a positive thermal flux from inside the MC to the ambient the Metering Chamber set-points were always higher than the ambient environment. The Climate Chamber was set to maintain a  $\pm 20^\circ$  difference compared to the Metering Chamber. Temperature adjustments were maintained by the datalogger.

thermal transmittance was  $\pm 4\%$  more than the certified value. Series 3 (triple pane) was  $\pm 3\%$  more than the certified value (Figure 48).



**Figure 48:** U-Factor Baseline Calibration

It was anticipated that the results be slightly skewed since the CHB is not a precision hot box and does not account for various losses to air infiltration, thermal loss at the specimen's edge as it comes in contact with the flanking sidewall, and radiant energy exerted on the MC that could not be accounted for. However, the average of the four baseline conditions resulted in  $\pm 6\%$  degree of accuracy and considered to be sufficient to characterize the Nanowindows. Figure 48 also confirms the general workability of the CHB and that U-factor methods are being properly deployed.



| A                      | B                        | C    | D     | E     | F   | G          | H         |                              |
|------------------------|--------------------------|------|-------|-------|-----|------------|-----------|------------------------------|
|                        | Average Heat Flux (W/m²) | kWh  | hrs   | kW    | W/h | Area (ft²) | Area (M²) | Heat Flux based on SA (W/m2) |
| Series 1 (Single Pane) | 160.46                   | 0.92 | 12.46 | 0.074 | 74  | 1          | 0.09      | 14.91                        |
| Flanking Wall          | 14.49                    | 0.97 | 13.4  | 0.072 | 72  | 12         | 1.11      | 16.15                        |
| Side Wall A & B        | 7.89                     | n/a  | n/a   | n/a   | n/a | 8.25       | 0.77      | 6.05                         |
| Bottom                 | 7.14                     | 3.66 | 56.26 | 0.065 | 65  | 8.25       | 0.77      | 5.47                         |
| Top                    | 8.60                     | 0.85 | 11.6  | 0.073 | 73  | 8.25       | 0.77      | 6.59                         |
| Back Side Wall         | 9.82                     | 0.85 | 11.65 | 0.073 | 73  | 13         | 1.21      | 11.86                        |

**Table 16:** Calibrated Hot Box, Gains and Loss

The results are further digested in Table 17 were the sum of total envelope heat flux is accounted for base on Table 16, Column H. The power delivered to the heating element was averaged over the course of the entire 7 days based on Table 16, Column E. Using Equation (13) the heat loss through the window including phantom losses can be determined.

$$Q = Q_h - \left[ (2 \times Q_{mcsw}) + Q_{mcswfl} + Q_{mcbottom} + Q_{mctop} + Q_{mcback} \right] \quad (13)$$

Where:

$Q$  = heat flow through the specimen window

[ ] = Envelope

$Q_h$  = heat generated from the heater

$Q_{mcsw}$  = heat flow through Meter Chamber sidewalls

$Q_{mcswfl}$  = heat flow through Meter Chamber side walls flanking loss

$Q_{mcbottom}$  = heat flow through bottom of the Meter Chamber

$Q_{mctop}$  = heat flow through top of the Meter Chamber

$Q_{mcback}$  = heat flow through back of the Meter Chamber

|                                     |                        |
|-------------------------------------|------------------------|
| Envelope Heat Flux                  | 52.2 W/m <sup>2</sup>  |
| Energy Added to the System          | 71.5 W/m <sup>2</sup>  |
| Heat Flux by Deduction for Series 1 | 19.3 W/m <sup>2</sup>  |
| Series 1 Measured                   | 14.91 W/m <sup>2</sup> |
| Phantom Losses                      | 4.43 W/m <sup>2</sup>  |

**Table 17:** Summary Heat Gains & Losses

Thus the total heat flow through the envelope is 52.2 W/m<sup>2</sup> and the total energy delivered to the MC was on average 71.5W. If the only other area for heat exchange is through the specimen it is deducted that the specimen accounts for 19.3 W/m<sup>2</sup> heat transfer. However, this is slightly misleading considering that there are phantom losses that were not accounted for including fan energy, thermistor energy, thermal bridging, and air infiltration as the CHB was not designed as a finite solution.

To isolate phantom losses a window specimen was measured using the same methods for measuring envelope thermal transmission. The weighted value was 14.91 W/specimen area and deducted from the total loss of 19.3 W/m<sup>2</sup> resulting in phantom losses of 4.43 W/m<sup>2</sup>. Expressed differently 6.2% of the energy supplied can not be accounted for using the methods describes herein. The phantom energy might be lost through thermal bridging and air infiltration. Similarly, not all energy delivered was measured, including fan energy and subtle energy pulse from the dozen or so sensors distributed throughout the CHB.

## Recommendations

The objective of the hot box apparatus research focused on establishing near steady state conditions. Test Series 1,2, & 3 offered insight on the overall performance and range of

temperatures the Climate and Metering chamber could attain. However, with more time and funding a dynamic state solar simulator would be desirable. Dynamic condition was limited by the selected metal arc lamps inability to dim and provide variable light levels. To achieve dimmable light levels the system would require a constant wattage autotransformer (CWA) transformer coupled with magnetic ballasts that were not used in this research. The reason for choosing steady state was to align with standard test conditions (STC) that are typically applied to energy generating systems seek industry certification.

### Limitations

Although great care was taken during fabrication to seal all joints there was no pressure regulation between chambers or chamber infiltration testing. According to Burch (1990) at the National Institute of Standards and Technology (NIST) there is a value of applying a slight suction in the climate chamber in to prevent cold air from infiltrating into the meter chamber and impacting the overall energy balance (Burch, Licitra, & Zarr, 1990, p. 36).

The number of sensors allocated throughout the hot box apparatus for calibration was largely dictated by the financial means thus limited to one sensor of each type except for the two Campbell Scientific 110PV-L Surface-Mount Thermistor surface temperature sensor (See the Data Acquisition chapter for complete sensor descriptions and applications). Multiple surface and air temperature sensors would have rendered a more



detailed thermographic comprehension of the metering chamber, climate chamber, and test specimen.

According to a survey conducted by Miller (1987) on hot box operating techniques most U.S. and Canadian laboratories use the following ASTM equation to determine the minimum of sensors

$$S_{\#} = \frac{A_s}{(0.07 + 0.08\sqrt{A_s})} \quad (14)$$

where  $A$  is the area of the test specimen in square meters (Miller, 1987, p. 153). Based on this equation the number of sensors required would be

$$S_{\#} = \frac{0.0929}{(0.07 + 0.08\sqrt{0.0929})} = 0.984 \uparrow = 1$$

1 per type of sensor. Thus the test series conducted on the Nanowindow (specimen) was within the recommend range of sensors and common practice in North American testing laboratories. Unfortunately, this criteria was subsequently amended in ASTM C1363 so that “the required minimum of sensors per side shall be at least two per square meter of metering area but not less than nine (ASTM C1363-11, 2011, p. 13). The result of only having a limited number of sensors for each specific task ruled out the possibility of area weighting of the averages for each test series.

### Center of Glass Averaging

In determining the heat flow ( $Q$ ) throughout this research it was not possible to generate an area weighted average because the specimen's size was relatively small, and there was only one heat flux sensors and two surface temperature sensors. All measurements were taken from center of glass (COG) and to increase significance in the findings multiple tests of some series were conducted and averaged the COG.

### Ambient Conditions

Chamber temperatures varied as a function of environmental conditions even though the laboratory was under a canopy. Ambient temperature influenced the ability of the compressor and evaporator coils to release sensible heat to the environment. The warmer the ambient air the less cooling potential was reached inside the climate chamber.

To address these variations of ambient conditions the majority of the tests were performed in the evening when ambient temperatures during the test period were relatively similar. No ambient data collection was collected to substantiate this condition.

## CHAPTER VI

### NANOWINDOW - DESIGN & FABRICATION

A solar simulator was designed and fabricated to provide a uniform and constant source of energy across a  $1\text{m}^2$  surface area with adequate temporal instability, irradiance spatial non-uniformity, and spectral match. The solar simulator offered a 2.3% temporal instability (ATSM Class B designation); Irradiance non-uniformity of  $<2\%$  (ASTM Class B); and a spectral match  $\pm 18\%$  out of range of ASTM E927 range, but corrected using filters to lower mismatch and deemed adequate for this research.

A Calibrated Hox Box (CHB) made of closed-cell polyisocyanurate was designed, fabricated and calibrated within a certainty of  $\pm 4\%$  based on three known glass samples tested by an independent testing laboratory. The CHB and Solar Simulator are not deemed to be laboratory precision equipment, but offer a degree of confidence that can identify strengths and weaknesses in subsequent experiments. With the infrastructure complete the focus shifted to the design, fabrication, and testing of the Nanowindow.

This Section focuses on transferring the theoretical discussion into a programmatic context outlining the specifications to inform the design, fabrication, and testing of the Nanowindow specimens. Central to this research was introducing a fluid medium to harness solar thermal energy for reuse in heat exchangers or thermoelectric generation as defined in Chapter II.

The fluid medium became a design challenge as it would need to circulate from the Nanowindow to the heat exchanger and back. The Nanowindow system would need to be filled, emptied, and have adequate room for expansion. It would need to resist slight hydrostatic pressure and have room to include micro sensors to record temperature.

During the dissertation proposal, the initial intent was to fabricate 1m<sup>2</sup> Nanowindows, but the cost, weight, and manipulating said specimens exceeded the possibilities at the test facility. 1/4" glass weighs 3.27 lb/ft<sup>2</sup> which results in a dual pane glazing assembly of slightly over 70lb. Thus, a more conventional 1 square foot (1ft<sup>2</sup>) Nanowindow was designed, fabricated, and assembled. The 1ft<sup>2</sup> is also a standard sample size provided by the two glass manufacturers that contributed glass material. Aside from the change in size the specification was such that the Nanowindow:

1. Maintain the 0.5" gap and overall thickness of the Nanowindow to align with commercial window systems. Maintain dimensional similarity with common window thickness offers greater flexibility to be adopted with less resistance
2. Provide the ability to measure fluid temperature
3. Provide a filling port
4. Provide an expansion port to accommodate fluid expansion when the temperature rises
5. Provide an effluent port
6. Provide an influent hole port for re-circulating fluid
7. Provide a framework to suspend the heat mirror within the 0.5" gap
8. Provide a spacer material that can be drilled/milled and tapped to accommodate the above criteria
9. Spacer to be as light-weight as possible
10. Provide a water tight seal

11. Use clear uncoated 0.25” heat strength glass
12. No low-e films on any of the glass

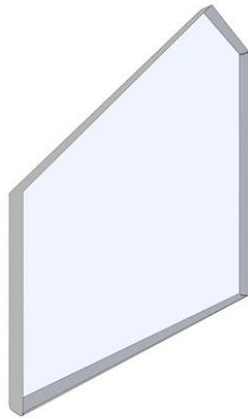
### Nanowindows and Baseline Configurations

Seven Nanowindow and three baseline specimens were configured to this specification to test a broad range of conditions to reveal strengths and weaknesses with the goal to optimize thermal conductivity, thermal transmittance, visible transmittance, and solar heat gain coefficient, and energy exchange.

Baseline 1-3<sup>37</sup> are baseline glazing units composed of single pane, double pane, and triple pane, respectively. Nanowindows 4-10 alternate the location of the fluid filled gap and heat mirror in double pane, triple pane, and quad pane configurations (Figure 50). All glass was contributed by Pilkington and Viracon.

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<sup>37</sup> Baseline 1,2, & 3 were applied in the calibration exercise in Part 3 of this research.



**Baseline 1:** Single pane uncoated heat strength glass.

Composition

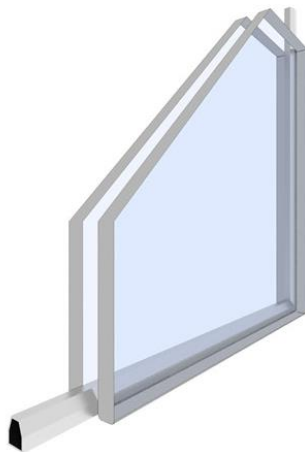
$\frac{1}{4}$ " (6mm) clear heat strength glass

Performance

TVis: 88%

SHGC: 0.82

U-Factor: 0.92



**Baseline 2:** Double pane with uncoated heat strength glass.

Composition

$\frac{1}{4}$ " (6mm) clear heat strength glass

$\frac{1}{2}$ " (13.2 mm) air gap

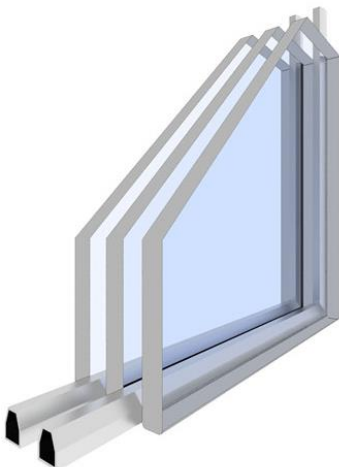
$\frac{1}{4}$ " (6mm) clear heat strength glass

Performance

TVis: 76%

SHGC: 0.72

U-Factor: 0.49



**Baseline 3:** Triple pane with uncoated heat strength glass.

Composition

$\frac{1}{4}$ " (6mm) clear heat strength glass

$\frac{1}{2}$ " (13.2 mm) air gap

$\frac{1}{4}$ " (6mm) clear heat strength glass

$\frac{1}{2}$ " (13.2 mm) air gap

$\frac{1}{4}$ " (6mm) clear heat strength glass

Performance

TVis: 38%

SHGC: 0.49

U-Factor: 0.35

**Figure 50:** Baseline 1-3 Units



**Nanowindow 4:** Double pane unit uncoated heat strength glass and an air gap. No nanofluids are applied to this unit.

**Composition**

$\frac{1}{4}$ " (6mm) clear heat strength glass

$\frac{1}{2}$ " (13.2 mm) air gap

$\frac{1}{4}$ " (6mm) clear heat strength glass



**Nanowindow 5:** Double pane Nanowindow unit pane, uncoated heat strength glass, and nanofluids.

**Composition**

$\frac{1}{4}$ " (6mm) clear heat strength glass

$\frac{1}{2}$ " (13.2 mm) fluid filled gap

$\frac{1}{4}$ " (6mm) clear heat strength glass



**Nanowindow 6:** Double pane Nanowindow unit pane, uncoated heat strength glass, and a heat mirror suspended in nanofluids.

**Composition**

$\frac{1}{4}$ " (6mm) clear heat strength glass

$\frac{1}{2}$ " (13.2 mm) fluid filled gap w/ suspended heat mirror film

$\frac{1}{4}$ " (6mm) clear heat strength glass

**Figure 51:** Nanowindows 4-6

**Nanowindow 7 & 8\*** are triple pane Nanowindow units, uncoated heat strength glass, and a heat mirror suspended in nanofluids.

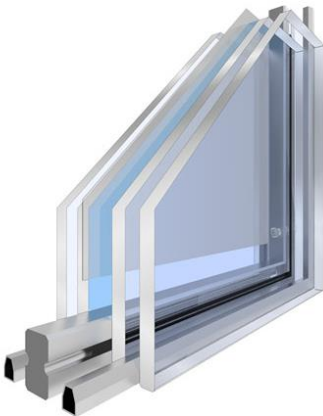


**Composition**

$\frac{1}{4}$ " (6mm) clear heat strength glass  
 $\frac{1}{2}$ " (13.2 mm) fluid filled gap w/ suspended heat mirror film  
 $\frac{1}{4}$ " (6mm) clear heat strength glass  
 $\frac{1}{2}$ " (13.2 mm) air gap  
 $\frac{1}{4}$ " (6mm) clear heat strength glass

\*Nanowindow 8 is the reverse of Nanowindow 7

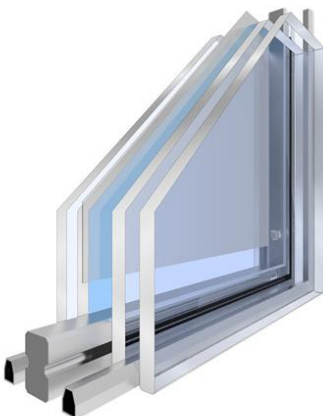
**Nanowindow 9** is a quad pane Nanowindow unit, uncoated heat strength glass, and a heat mirror suspended in nanofluids.



**Composition**

$\frac{1}{4}$ " (6mm) clear heat strength glass  
 $\frac{1}{2}$ " (13.2 mm) air gap  
 $\frac{1}{4}$ " (6mm) clear heat strength glass  
 $\frac{1}{2}$ " (13.2 mm) fluid filled gap w/ suspended heat mirror film  
 $\frac{1}{4}$ " (6mm) clear heat strength glass  
 $\frac{1}{2}$ " (13.2 mm) air gap  
 $\frac{1}{4}$ " (6mm) clear heat strength glass

**Nanowindow 10** is a quad pane Nanowindow unit, composed of Viracon 1" VUE1-63, and a heat mirror suspended in nanofluids.

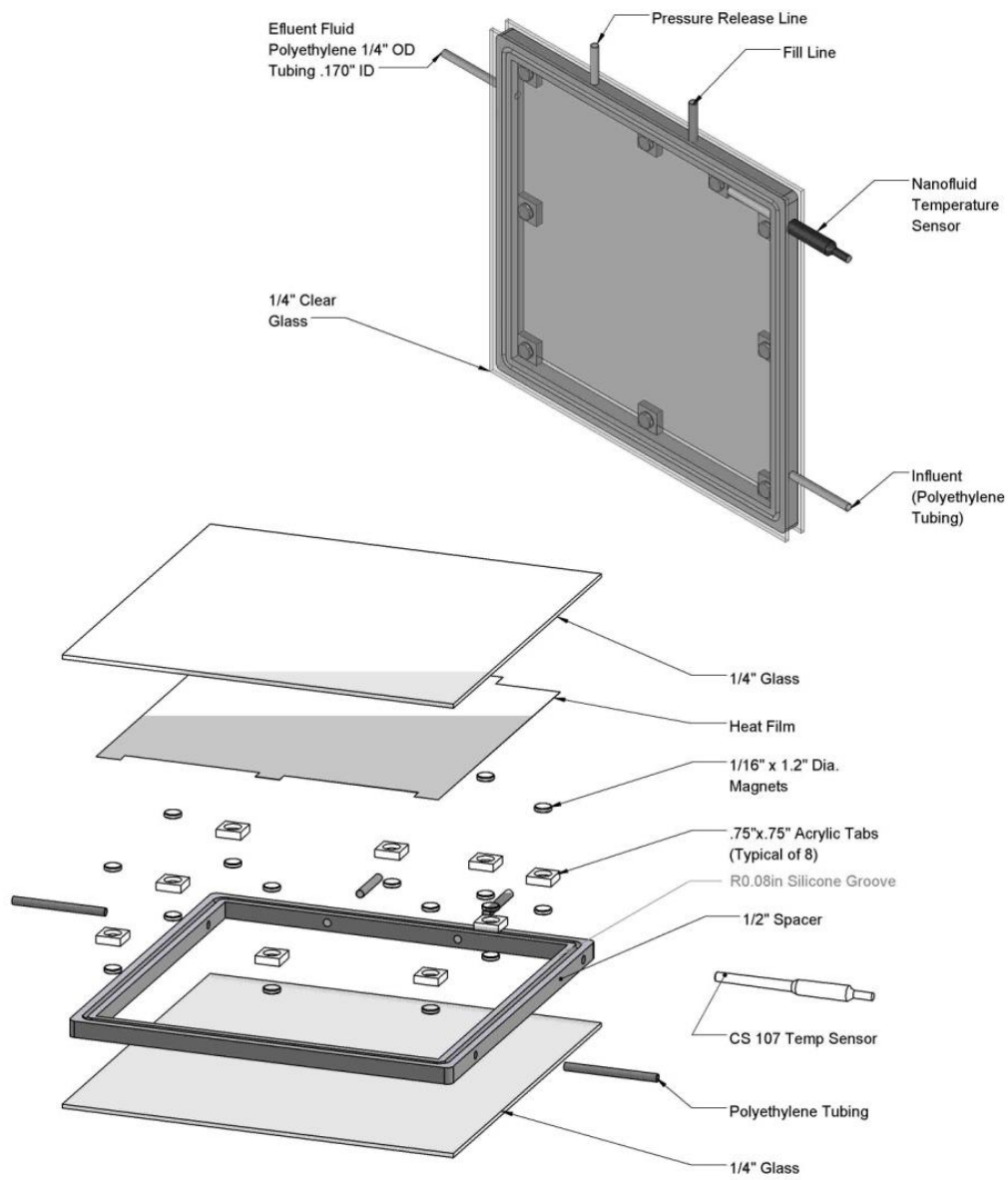


**Composition**

$\frac{1}{4}$ " (6mm) clear heat strength glass  
 $\frac{1}{2}$ " (13.2 mm) air gap  
 $\frac{1}{4}$ " (6mm) clear heat strength glass  
 $\frac{1}{2}$ " (13.2 mm) fluid filled gap w/ suspended heat mirror film  
 $\frac{1}{4}$ " (6mm) clear heat strength glass w neutral low-e  
 $\frac{1}{2}$ " (13.2 mm) air gap  
 $\frac{1}{4}$ " (6mm) clear heat strength glass

**Figure 52:** Nanowindows 7-10





**Figure 53:** Nanowindow

### Spacer Design

Historically glass spacers are fabricated from aluminum, stainless steel, or a biopolymer infill in the spacer's cross section. Aluminum is most commonly used because of its

malleability and lightweight characteristics. Stainless steel is preferred over aluminum because it has  $1/10^{\text{th}}$  the conductivity of aluminum, and the combined stainless steel/biopolymer further reduces edge conductivity, and in turn reducing thermal transfer into the building. Low-conductivity non-metal window warm edge spacers made of composite, structural foam, and thermoplastic represent the next generation spacers with enhance thermal conductivities (Van Den Bergh, Hart, Jelle, & Gustavsen, 2013, p. 12). Unfortunately, these high-performance spacers were not conceived to retain fluids. Thus, a spacer had to be designed to accommodate fluids, internal pressure, fluid circulation, influent and effluent ports, fluid expansion, and sensors to monitor fluid temperature.

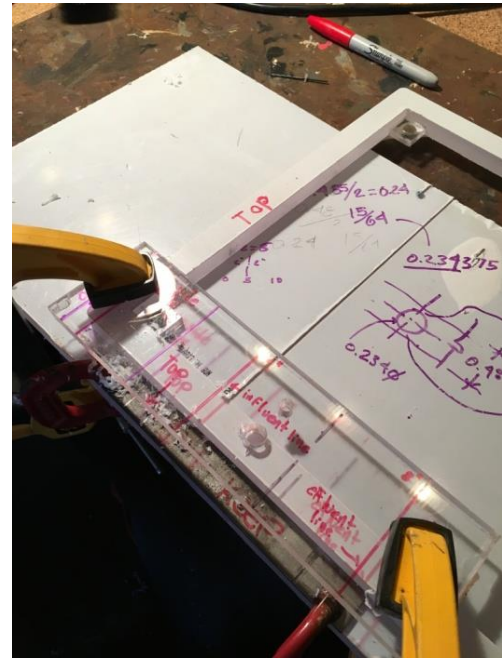
A custom spacer was made from thermoplastic polycarbonate rather than attempting to modify or manipulate existing aluminum or stainless steel spacers. Polycarbonate can be milled, drilled, and fitted to accommodate the specificity of this research much easier than the alternative metals. Also, polycarbonate has a lower thermal conductivity of  $0.19\text{--}0.22\text{ W/(m}\cdot\text{K)}$  compared to stainless steel at  $16\text{ W/(m}\cdot\text{K)}$ , and retains optical clarity which is unique to all other applications.

Maintaining water tightness was a top priority in the spacer design. All breaches into the sidewall of the spacer including influent/effluent ports, and sensors ports were scrutinized and tested repeatedly to ensure water tightness under varying pressures. Figure 54 illustrates the water tightness test with varying port diameters and various connectors. Ultimately  $0.23''$  port holes were selected to accommodate  $0.25''$  (6mm) polyethylene tubing to fill and return fluids to the Nanowindow. Figure 54 illustrates a thermistor

sensors being tested and later determine that a a probe diameter of 0.16cm by 5.84cm long making it ideal for this application a probe sensor of 0.16cmø by 5.84cm long was ideal for this application and more appropriate due to space requirements.



**Figure 54:** Breach Testing



**Figure 55:** Breach Template

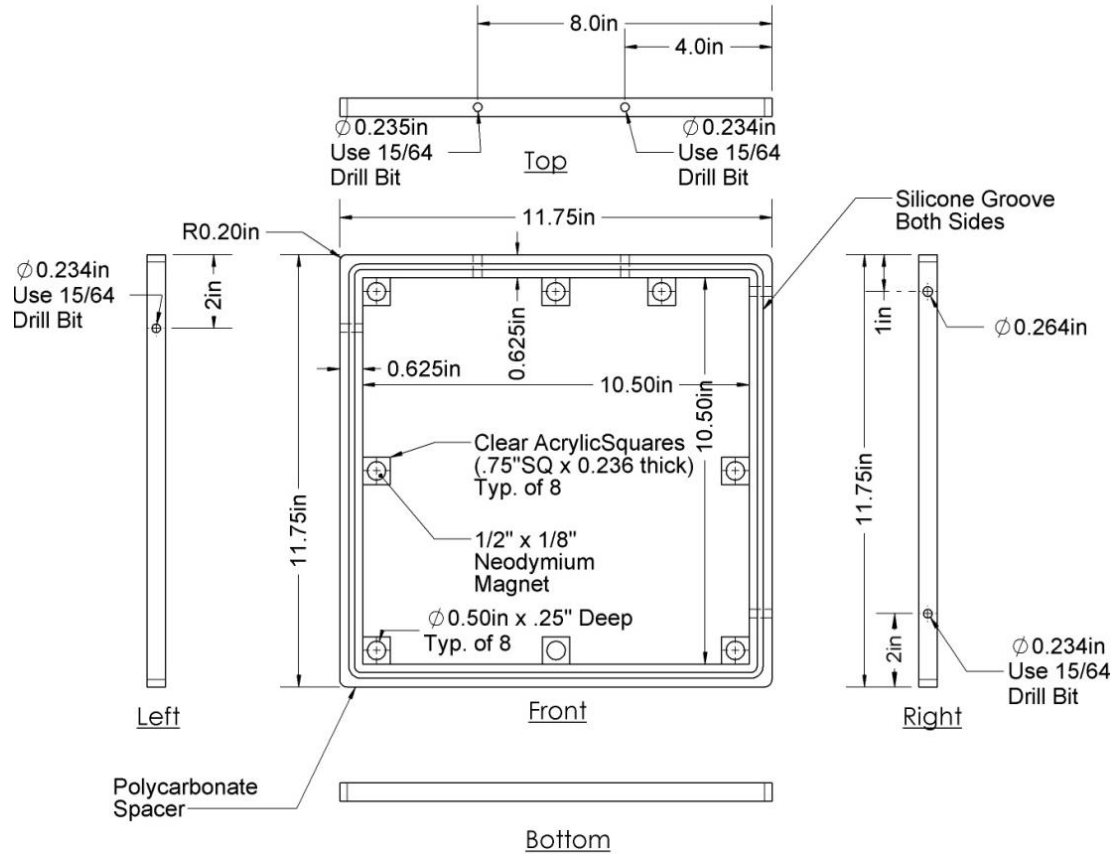
Historically widow spacers are 0.5” and the prototype adopted the same thickness, but the spacer’s width was raised from 0.3” to 0.75”. This was done to accommodate future connections that required threaded ends, and the added width improved workability and strength of the prototype.

Spacers were prototyped in Solidworks and waterjet cut<sup>38</sup> out of thermoplastic polycarbonate sheets. Ports were manually drilled in the shop using a standardized template based on water tightness testing results (Figure 55).

To facilitate suspending the heat mirror the prototype used clear acrylic tabs with counter-sunk neodymium magnets situated along the inside of the spacer. Conceptually each heat mirror sheet was positioned over the tabs and the magnets clamped down on the heat mirror sheet keeping it in tension and in place. The concept worked effectively, but the corrosion inhibiting coating on the magnets failed and caused immediate corrosion and rusting. It was later discovered that multi-layer Nickel-Copper-Nickel plating was insufficient to prevent corrosion in under water conditions. In lieu of magnets a double-sided 3M tape was used to secure the suspended heat mirror in place, and simplified fabrication time.

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<sup>38</sup> Waterjet cutting provided the best results when cutting polycarbonate, maintained dimensional stability, and doesn't melt or scar the surface similar to laser cutting, especially at these thicknesses.



**Figure 56: Nanowindow Prototype**

All specimens were  $12\text{in}^2$  and tested without a frame. The Vision Area was defined as

$$A_{vis} = V_1 \times H_2$$

such that

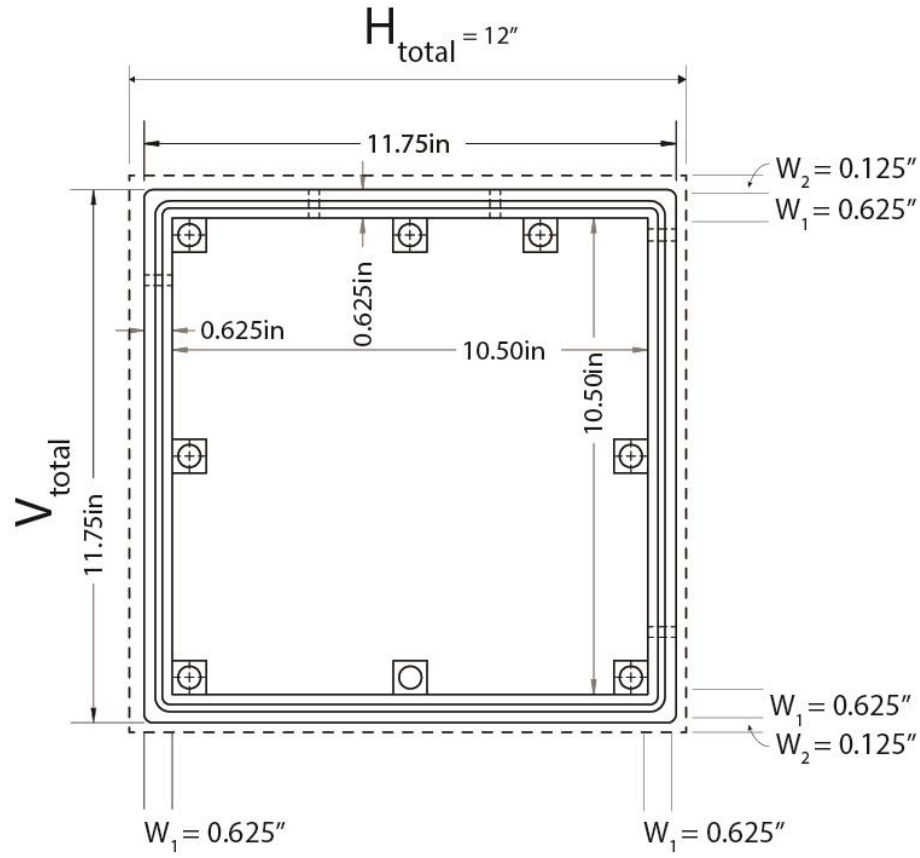
$$V_1 = V_{total} - 2w_1 - 2w_2$$

$$H_1 = H_{total} - 2w_1 - 2w_2$$

(15)

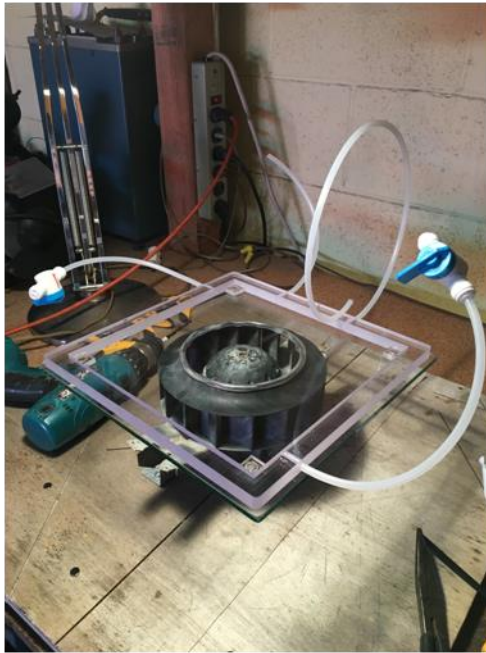
(Finlayson, Arasteh, Huizenga, Rubin, & Reilly, 1993, p. 3)

Resulting in a Vision Area of  $110.25\text{in}^2$  (Figure 1) or 76% clear.



**Figure 57: Vision Area**

Water tightness of the Nanowindow was especially challenging between the spacer and glass panes. Several reiterations were preformed resulting in numerous leaks caused by hydrostatic pressures in the system. The first attempt placed the silicone around the perimeter as historically prepared in the glass industry. To achieve a constant silicone bead, a turn-table like device was fabricated from a reclaimed fan motor to spin the Nanowindow around while silicone was applied (Figure 58). After a 24-hour curing period the silicone failed to resist water pressure under atmospheric pressure and notably failed under additional pressure applied by handheld pressure pump gauge tool.



**Figure 58: Nanowindow Assembly Process**

(Left - without silicone. Above - Silicone applied around the outside of the Nanowindow. Filling tubes and sensors attached in both pictures.

Rather than applying the silicone to the outside face of the Nanowindow the silicone was applied on the spacer's face that meets the glass. A 0.18" (4.76mm) perimeter channel groove was milled on both sides of the spacer to receive a silicone bead. When the glass panes were applied to the spacer the silicone beads compressed and spread across the spacer face to form a complete seal around the entire perimeter (Figure 59, Figure 60).





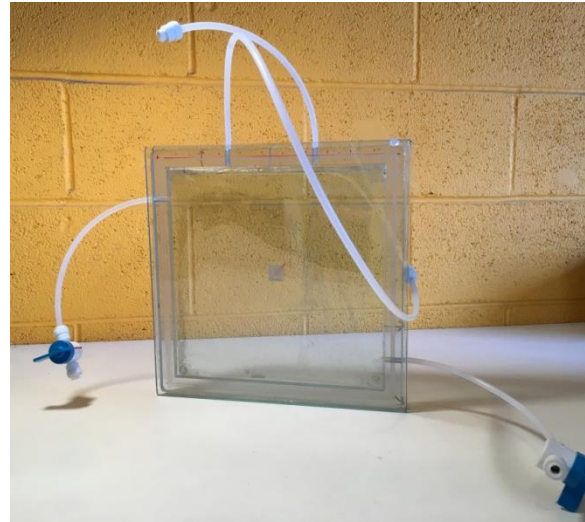
**Figure 59:** Nanowindow recessed silicon channel



**Figure 60: Nanowindow**  
Silicone pressed between glass panes

Once the silicone cured the Nanowindows were placed in a filling station salvaged and reconfigured from a metal engine stand and fit to accommodate a 0.26 gallon (1.0L) separatory funnel that matched the Nanowindow's fluid capacity of 0.24gallons (0.94 L). All Nanowindows were fabricated and filled at the same time (Figure 61).





**Figure 61:** Nanofluid Filling Station  
Separatory funnel and filling lines leading to Nanowindow prototype (left). Nanowindow prototype (above)

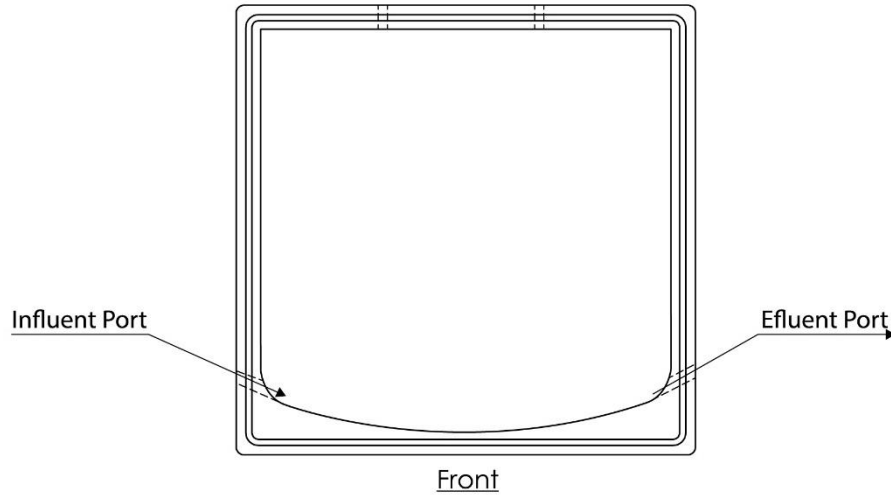
### Recommendations

The spacer redesign met the needs of the experiment, but a stainless steel/biopolymer infill spacer would perform better. Doing so would reduce thermal bridging which adds to overall performance. Spacer depth was 0.75" and reducing the depth to 0.5 or less would further improve window performance and weight. The polycarbonate spacer was 10oz. and typical aluminum spacers are 1.7oz. This was a 488% weight increase that could be mitigated using a smaller polycarbonate profile and hollowed out.

All polyethylene tubing was pressed into the ports with a layer of silicon, but the ideal solution would tap the spacer and introduce a standard quick connect to facilitate

plumbing connectivity. The temperature probe at the top was eliminated in subsequent prototypes because it was subject to direct incident light emitted from the solar simulator that resulted in false readings. While the redesign of the sensor probe location may have been an option, the simplest way to address the concern was to remove the sensor from the window and place it in-line with the effluent and influent fluid lines. This eliminated the possibility of direct incident light. Shielding the probe was considered, but the configuration of lamps and the use of the concentrator comingled radiant flux from all directions and from low angles. Sufficient shielding to address these low angles resulted in a shield that covered a significant portion of the window prototype.

Using nanoparticles adds new dimensions to the gap geometry that was not previously anticipated. Prolonged static condition does result in particle settlement but easily agitated if the particle build-up is within a circulation stream. As such the influent line that was originally situated at the top is best located at the bottom to induce particle mixing. To further guarantee particle mixing the bottom of the spacer may want to avoid corners that may cause circulation dead zones. The spacer's bottom is better conceived as a parabolic or semi-circular bottom with influent ports in-line with the bottom's edge (Figure 62).



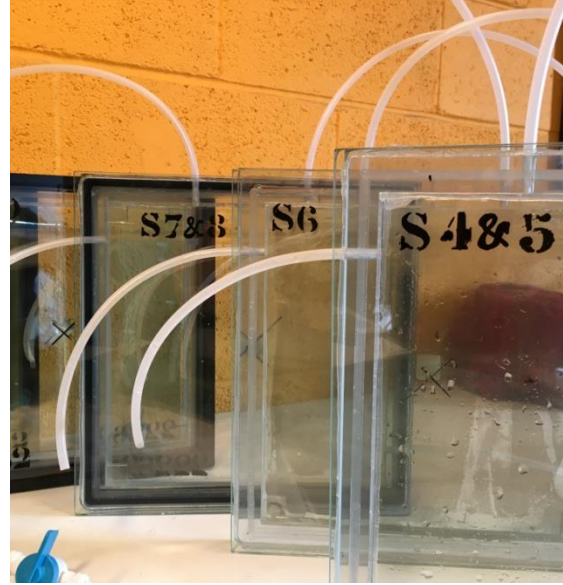
**Figure 62: Spacer Enhancements**

Using polycarbonate as spacer material added a layer of transparency to the Nanowindow that was not anticipated. However, the effect was muted because the polycarbonate was not polished on both sides. Had the sides of the polycarbonate been polished then the space and window would have retained equal transparency.

The programming, design, and fabrication phase resulted in six (6) unique Nanowindows resulting in seven (7) possible test solutions as a function of window orientation (Figure 63, Figure 64). An additional three (3) glazing factory assembled and tested units were included to establish a known, reliable, and tested reference point and baseline for comparison.



**Figure 63:** Nanowindows & baseline



**Figure 64:** Nanowindows

Chapter VII measures factory windows 1-3 and Nanowindows 4-10 for visible transmittance (VT), rate of thermal resistance (U-Factor), and Solar Heat Gain Coefficient (SHGC) to establish a baseline of reference.

## CHAPTER VII

### H<sub>2</sub>OWINDOW TVIS, U-FACTOR, & SHGC (BASELINE)

A solar simulator, calibrated hot box (CHB), and six Nanowindows were built, one of which can be oriented in two directions, resulting in seven Nanowindow configurations. The seven prototypes were first tested using distilled water rather than aluminum oxide (Al<sub>2</sub>O<sub>3</sub>) nanofluids to establish a baseline of reference. Nanowindows filled with distilled water are referred to as H<sub>2</sub>Owindows to avoid any confusion with test specimens using nanofluids. From the baseline results only the top performers would advance to nanofluid testing in an effort to minimize costs associated with nanofluids.

All seven H<sub>2</sub>Owindow prototypes (FIGURE 65) were filled with distilled water and tested for U-factor, Visible Transmittance (VT), and Solar Heat gain Coefficient (SHGC). U-Factor, VT, and SHGC were performed on the seven Nanowindows and three factory windows to establish a baseline of reference.

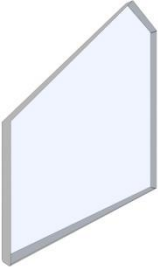
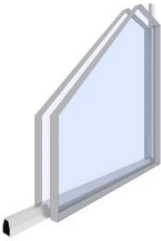
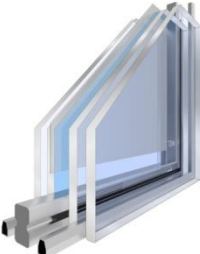
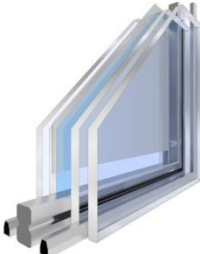
#### Baseline Methods

Iterative tests conducted:

Test 1 characterized the thermal transmittance (U-factor) of all 10 specimens.

Test 2 characterized the Visible Transmittance (TVIS).

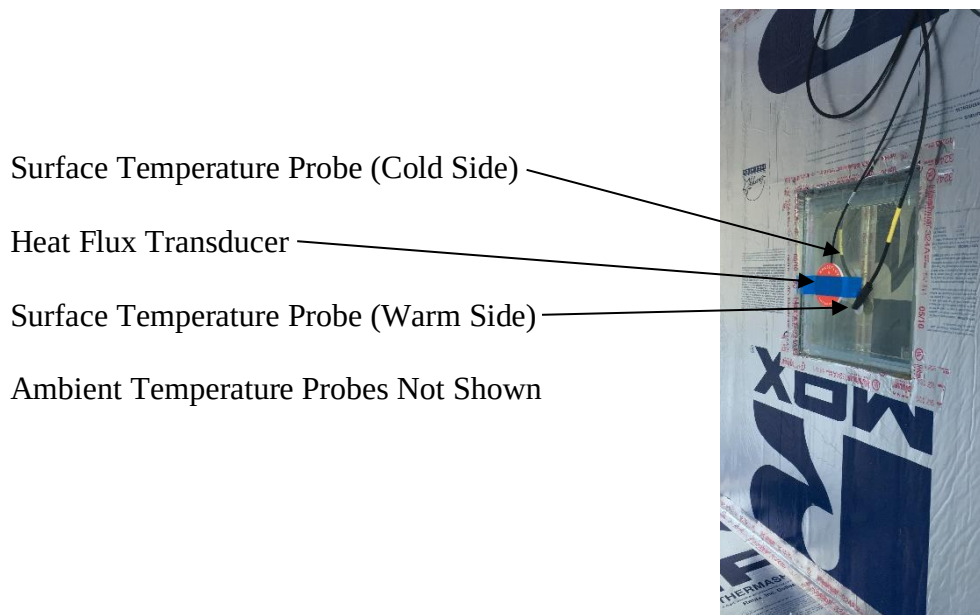
Test 3 Solar Heat Gain Coefficient (SHGC)

|            |                                                                                    |                                                                                    |                                                                                    |                                                                                     |
|------------|------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| Baseline   |   |   |  |  |
|            | 0: Polyiso                                                                         | 1: Single Pane                                                                     | 2: Double Pane                                                                     | 3: Triple Pane                                                                      |
| Nanowindow |   |   |  |  |
|            | 4: Double Pane, No Fluid                                                           | 5: Double Pane + Fluid                                                             | 6: Double Pane +Fluid+Heat Mirror                                                  | 7 & 8: Triple Pane +Fluid+Heat Mirror                                               |
| Nanowindow |  |  |                                                                                    |                                                                                     |
|            | 9: Quad Pane +Fluid+Heat Mirror                                                    | 10: Quad Pane High Performance Double+Fluid+Heat Mirror                            |                                                                                    |                                                                                     |

**Figure 65: Nanowindow Overview**

### H<sub>2</sub>Owindow U-Factor Method

H<sub>2</sub>Owindow specimens were installed in the CHB and sensors placed in approximately the exact location for every test. Each specimen was attached with a heat flux sensor at the center of glass (COG), surface temperature sensor halfway between the edge of the specimen and the heat flux sensor, and ambient temperature sensors placed 2-4 inches away from the specimen surface adhering to ASTM C1363-11, 2011 (Figure 66).



**Figure 66: U-Factor Sensor Placement**

Once the window specimen was installed the remaining chamber sensors were double checked for location accuracy and the chamber doors were closed and sealed with tape to reduce air infiltration. The CHB was brought up to steady state over a 12-hour period measuring heat flux, ambient temperature, and surface temperature, including the power delivered to the Metering Chamber (MC). The data acquisition system (DAS) collected data every 10 seconds and averaged after steady state was achieved.

### H<sub>2</sub>Owindow U-Factor Results

Test 1 measured the thermal transmittance of known baseline specimen 0 (2" polyiso panel) and baseline factory windows 1,2, and 3(single, double and triple pane).

Thermal transmittance was defined as:

$$U = \frac{Q}{(T_{MC} - T_{CC})} \quad (16)$$

Where:

$U$  = thermal transmittance ( $\text{W}/\text{m}^2\text{K}$ )

$Q$  = heat flow through the specimen ( $\text{W}/\text{m}^2$ )

$T_{MC}$  = Meter chamber ambient temperature ( $^{\circ}\text{C}$ )

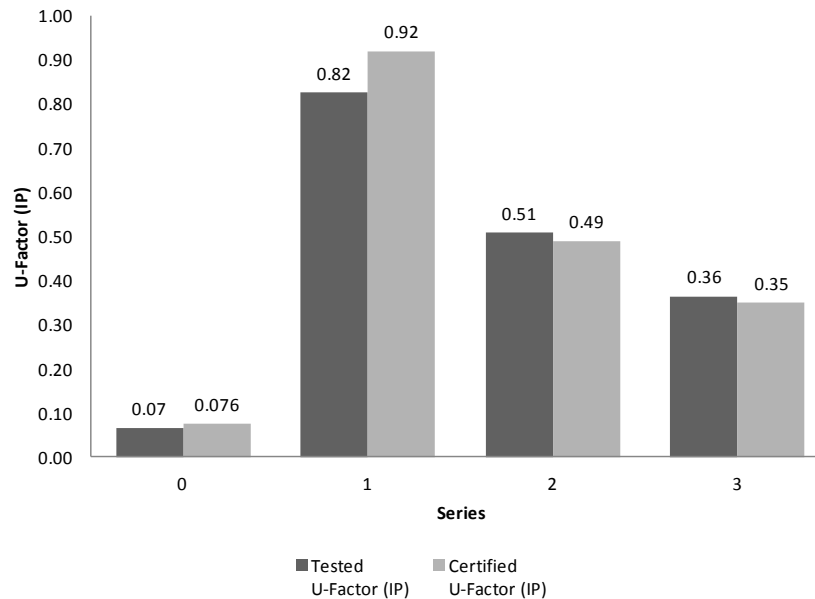
$T_{CC}$  = Climate chamber ambient temperature ( $^{\circ}\text{C}$ )

Baseline 0 (polyiso) thermal transmittance was 8% less compared to the certified value.

Baseline 1 (single pane) thermal transmittance was 10% better than the certified value.

Baseline 2 (double pane) thermal transmittance was 4% less than the certified value.

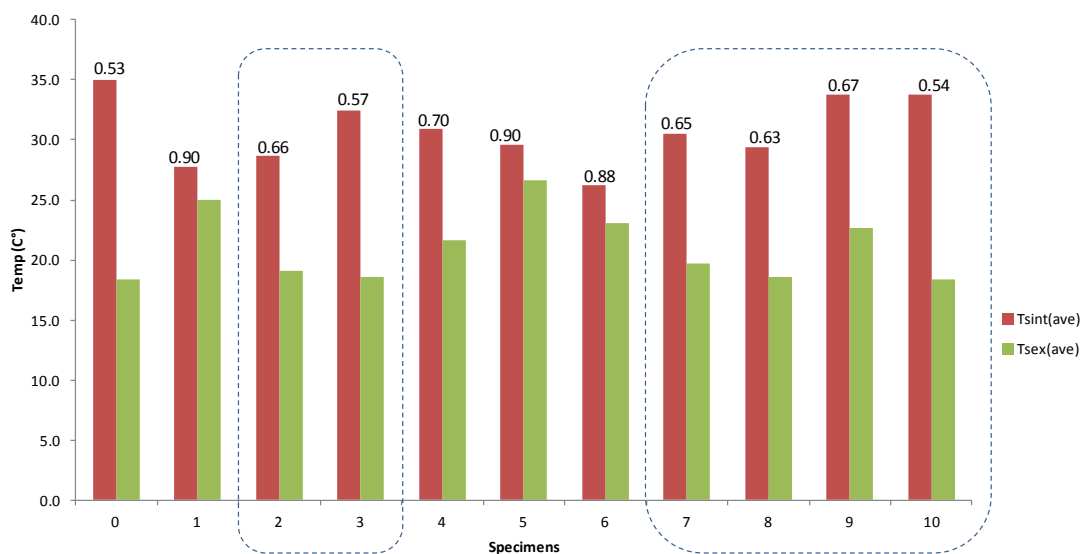
Baseline 3 (triple pane) was 3% better than the certified value. This resulted in a  $\pm 6\%$  degree of accuracy (Figure 48).



**Figure 67: U-Factor Baseline Calibration**



Since water has a high thermal conductivity it was anticipated that the H<sub>2</sub>O windows would perform poorly because the rate of energy transmitted would be significant. Water was a very effective thermal bridge and illustrated by recording the surface temperatures in Figure 68. The specimens with the highest difference in surface temperature difference resisted thermal transmittance more effectively.



**Figure 68:** H<sub>2</sub>O window's Surface Temperatures

Surface temperature was used as an early determination of performance and represented as a dimensionless number. The lower the number the better. The baseline double pane and triple panes (Specimen 2 & 3) were high performers with temperature differential of

0.66 and 0.57. Applying the same criteria to the remaining specimens H<sub>2</sub>O windows 7-10 with 0.65, 0.63, 0.67, and 0.54, respectively. Although this was not the only means to identify performance it began to inform which systems may yield stronger results.

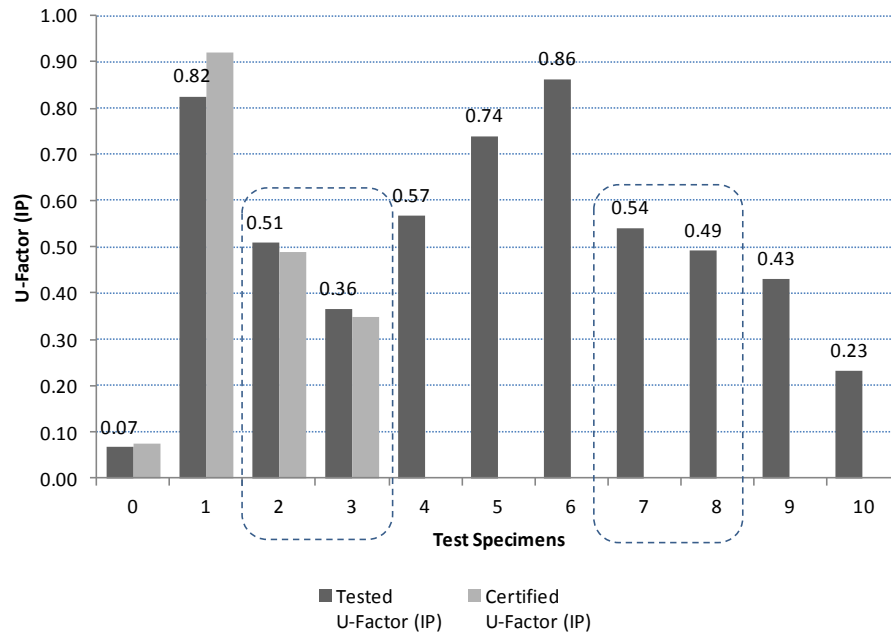
Looking closer at specimens 7-10 the triple panes 7 & 8 were relatively stronger performers and specimen 10 (quad pane) exceeded all baseline windows and equal to the solid polyiso board. Interestingly the only difference between 7 & 8 was the orientation of the water column indicating that performance may be improved by placing the water column on the warm side (metering chamber side).

Using Equation (16) U-factors were calculated for each specimen and plotted in Figure 69. Specimens 7 & 8 resulted in U-factors 0.54 & 0.49 respectively which were similar to specimen 2 (double pane) with a U-factor of 0.51. The highest U-factor performer was specimen 10 with a U-Factor of 0.23.

Although the all specimens are within the range of 0.20 to 1.20 according to the National Fenestration Rating Council (NFRC) requirements the key factor lies in compliance with international and national building codes. Based on the International Energy Code (IEC) that was adopted by the California Energy Code (CEC) the maximum Area-Weighted performance rating is 0.35 to 0.65 depending on the climate zone; thus, all H<sub>2</sub>O window specimens with the exception of 5 & 6 are code compliant.

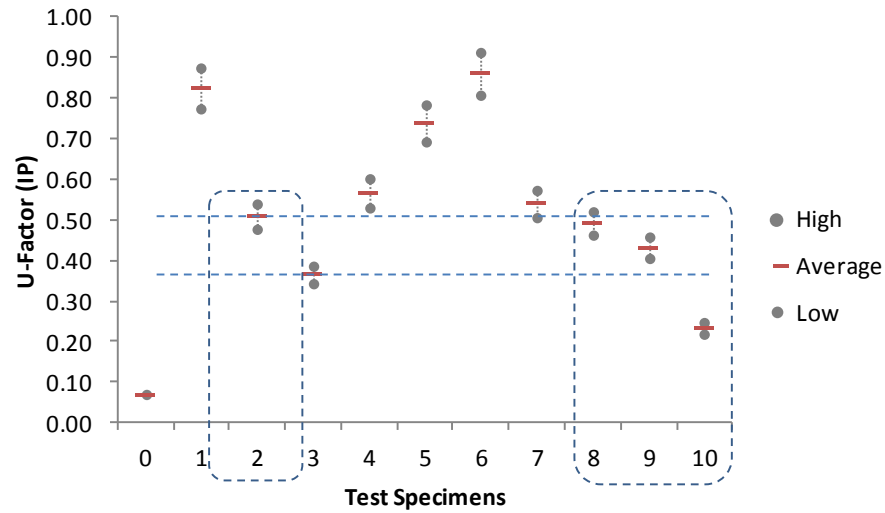
Based on U-Factor only it was determined that a water column without an additional insulated glass unit (IGU) would be unable to match double pane and triple window

performance. Specimen 5 and 6 are single water column Nanowindows and are not code compliant or perform to the current levels of double pane windows.



**Figure 69:** H<sub>2</sub>Owindow U-Factor

From the calibrated hot box experiment it was determined that a 6% variability may exists in the reported U-factors. As such an additional overlay on the U-factor plot was evaluated to offer additional performance insight. The 6% margins of uncertainty were plotted in Figure 70. This places specimen 7 slightly equivalent to specimen 2, but emphasizes that specimens 9 & 10 with quad pane characteristics offer equal and superior performance.



**Figure 70: 4% Variability**

### H<sub>2</sub>Owindow U-Factor Conclusion

Test 1 calculated the U-factor for 7 H<sub>2</sub>Owindows, 3 Baseline windows, and a polyiso board. For this exercise distilled water was used instead of naofluids and reported in Table 18. Using water was determined to be an effective method to establish a baseline of comparison and aligned with the means of this research. It was determined that uninsulated water columns are ineffective at meeting U-factor targets established by International Energy Codes (IEC). Triple pane and quad pane H<sub>2</sub>Owindows that were coupled with insulated glass units were far more effective at meeting u-factor requirements. Triple Panes (H<sub>2</sub>Owindows 7 & 8) had comparable performance characteristics as traditional double pane windows, and quad pane (H<sub>2</sub>Owindow 10) exceed traditional triple pane windows by as much as 36%. U-Factor was only one of many variables that were analyzed throughout this research and alone does not define modern window performance.

| U-FACTOR |                         |                         |                            |
|----------|-------------------------|-------------------------|----------------------------|
| Specimen | Tested<br>U-Factor (SI) | Tested<br>U-Factor (IP) | Certified<br>U-Factor (IP) |
| 0        | 0.38                    | 0.067                   | 0.076                      |
| 1        | 4.67                    | 0.825                   | 0.92                       |
| 2        | 2.87                    | 0.508                   | 0.49                       |
| 3        | 2.06                    | 0.365                   | 0.35                       |
| 4        | 3.20                    | 0.566                   |                            |
| 5        | 4.18                    | 0.738                   |                            |
| 6        | 4.87                    | 0.861                   |                            |
| 7        | 3.05                    | 0.540                   |                            |
| 8        | 2.78                    | 0.491                   |                            |
| 9        | 2.43                    | 0.430                   |                            |
| 10       | 1.32                    | 0.233                   |                            |

**Table 18:** H<sub>2</sub>Owindow U-Factors

### H<sub>2</sub>Owindow Visible Transmittance (VT) Introduction

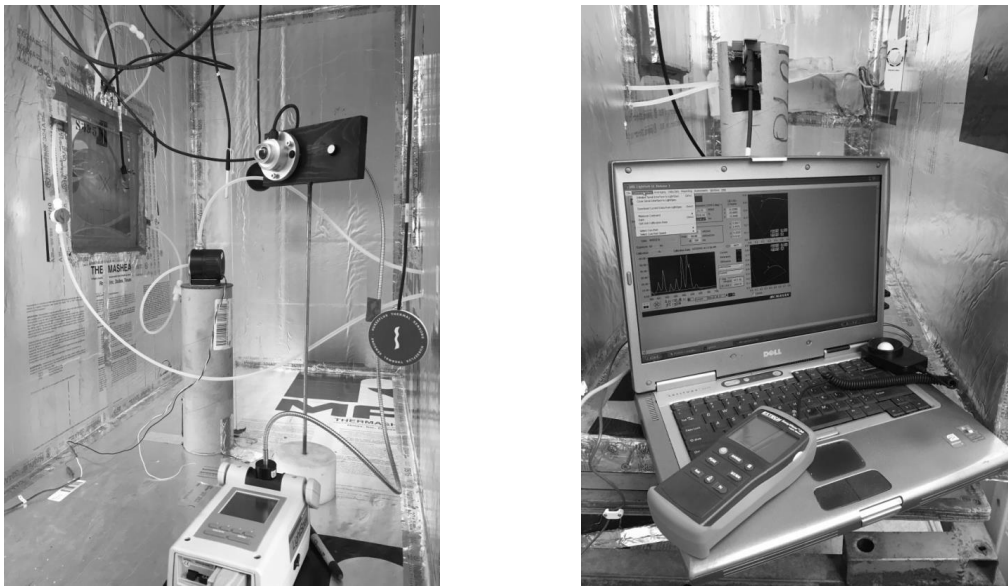
Visible transmittance (VT or TVis) is the ratio of visible light transmitted through a window weighed against the standard solar spectrum or in this case the standard baseline for the solar simulator defined in Part 2 of this research. The higher the VT the more daylight is allowed to enter the space.

VT is a requirement of the International Energy Conservation Code (IECC) and expressed as a value between 0 and 1. To meet code compliance the minimum VT is 0.42 for vertical fixed fenestration and 0.32 for vertical operable fenestration. Additional constraints exist for curtain walls/storefronts at 0.46 and 0.17 for glazed doors. For this research the results were compared to vertical fixed fenestration.

## H<sub>2</sub>Owindow Visible Transmittance (VT) Methods

All 10 specimens were tested one at a time by placing them in the calibrated hot box (CHB) aperture facing the solar simulator. The solar simulator was brought up to steady state within 1-2 hours and each specimen was added and removed from the CHB without interrupting the solar simulator allowing for lamps to remain active during the entire test.

During this test an Ocean Optics spectroradiometer was not available so the slightly older spectroradiometer by McMahan Research Laboratories was deployed (Figure 71). The spectroradiometer was used to measure absorption, transmission, reflectance, emission, and color between 350-1100 nm wavelengths. The spectroradiometer is defined in Part 2.



**Figure 71:** Chamber Spectroradiometer  
(Left) Chamber open illustrating spectroradiometer sensor adjacent to pyranometer. 2) Computer taking realtime measurements

The VT test focused on the visible spectrum range between 400nm to 700nm which is covered by the spectroradiometer. Measurements were taken from the center-of-glass (COG) and approximately 1” from the edge-of-glass (EOG). Values were averaged and divided by the incident illuminance across the same spectral range measured in Part 2. Similar methodologies are applied in ANSI/NFRC 200-2014 by the National Fenestration Rating Council (NFRC) and calculated such that VT is

$$VT = \frac{(\sum ti_{eog} + \sum ti_{cog}) \times 0.5}{\sum ii_{ss}} \quad (17)$$

Where:

$\sum ti_{eog}$  = sum of transmitted illuminance between 400nm - 750nm at the edge-of-glass

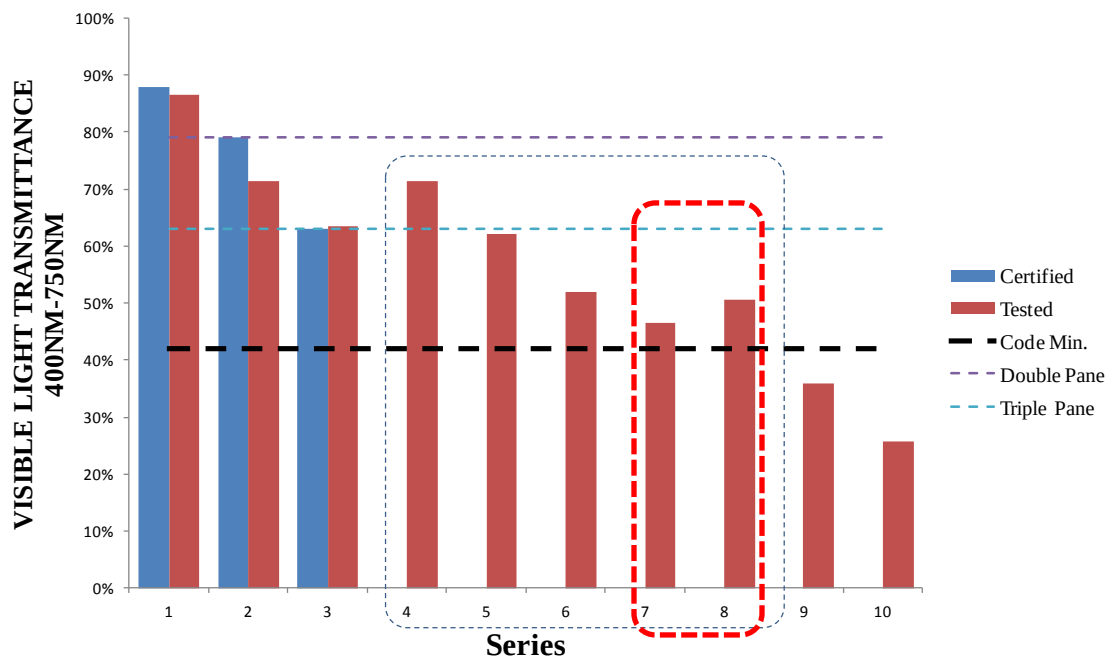
$\sum ti_{cog}$  = sum of transmitted illuminance between 400nm - 750nm at the center-of-glass

$\sum ii_{ss}$  = sum of incident illuminance between 400nm - 750nm as tested in Part 2

### H2Owindow Visible Transmittance (VT) Results

Iterative in-situ visible transmittance results for Specimens 1,2, and 3 are compared to the NFRC labels provided on each specimen. Reminder that specimens 1-3 provided laboratory certified VT values. Specimen 1 (single pane), specimen 2 (double pane), and specimen 3 (triple pane) factory VT was 0.88, 0.79, and 0.63, respectively. In-situ testing resulted in 0.87, 0.71, and 0.64, respectively. The average difference was less than 4.6% offering strong bases for establishing the VT for specimens 4-10.

VT for specimens 4-10 were plotted and minimum code threshold was overlaid. Code minimum VT is 0.42(42%) there by excluding specimens 9 and 10 although these had exceptional U-factor performance. Specimens 4-8 all meet code but poor U-factor performance would exclude specimens 4-6; thus, narrowing down a Nanowindow to specimens 7 and 8 (Figure 72).



**Figure 72:** H<sub>2</sub>Owindow Visible Transmittance



## H<sub>2</sub>Owindow Visible Transmittance (VT) Conclusion

H<sub>2</sub>Owindows 4-8 offered exceptional visible transmittance (VT) performance.

H<sub>2</sub>Owindow 5 reduced VT by 10% compared to the empty H<sub>2</sub>Owindow 4 indicating that water was capable of absorbing parts of the electromagnetic spectrum in near static state<sup>39</sup>.

H<sub>2</sub>Owindow 4-8 remained above code minimum which helped narrow down Nanowindows for testing, but VT alone was insufficient to define window performance. VT was coupled with the U-factor results in Test 1 confirming that H<sub>2</sub>Owindow 7 and 8 appear to be the highest performing H<sub>2</sub>Owindows.

## H<sub>2</sub>Owindow Solar heat gain coefficient (SHGC)

Solar heat gain coefficient (SHGC) is as vital to window performance as visible transmittance (VT) and the rate of thermal transmittance (U-factor). SHGC is the fraction of incident long wave solar radiation that is transmitted through a window and the short wave radiation that is emitted from the window itself compared to the incident solar radiation. SHGC is dimensionless unit that ranges from 0 to 1. The lower the number the less thermal energy is transmitted through the window, and the higher the value the more

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<sup>39</sup> Static state should not be confused with steady state. The state of the water in this testing was not circulated. Subsequent testing will examine absorption of electromagnetic radiation by water depending on the state of the water.

thermal energy is transmitted. Careful selection of VT, U-factor, and SHGC vary depending on climate.

Climate has a role in selecting the appropriate window with characteristics that complement the desired indoor thermal experience. Cold climates may desire more thermal gain thereby considering a higher SGHC to improve passive heating strategies, while in warm climates a lower SHGC may be an effective solution to lower heat gain as a passive cooling strategy.

#### H<sub>2</sub>Owindow Solar heat gain coefficient (SHGC) Methods

Based on the California Energy Commission (CEC) the maximum Relative Heat Gain Coefficient (SHGC) for a fixed window is 0.25, 0.22 if operable, 0.26 for curtainwall/storefronts, and 0.23 for glazed doors (California Energy Commission, 2013, p. 180). The term Relative SHGC takes into account horizontal projections over the window. RSHGC as defined by the CEC is such that

$$RSHGC = SHGC_{win} \left[ 1 + \frac{aH}{V} + b \left( \frac{H}{V} \right)^2 \right] \quad (18)$$

Where :

$SHGC$  = Solar Heat Gain Coefficient

$a$  = -0.41 for north-facing windows, -1.22 for south-facing windows, and -0.92 for east and west-facing windows

$H$  = Horizontal projection of the overhang from the surface of the window in feet, but not greater than  $V$

$V$  = Vertical distance from the window sill to the bottom of the overhang in feet.

$b$  = 0.20 for north-facing windows, 0.66 for south-facing windows, and 0.35 for east and west-facing windows.

(California Energy Commission, 2013, pp. 159–160)

Since there are no overhangs ( $H$ ) then equation (18) is rewritten such that

$$\begin{aligned} RSHGC &= SHGC_{win} [1] \\ RSHG &= SHGC_{win} \end{aligned} \tag{19}$$

Thus  $RSHGC$  was assumed to be equal to  $SHGC$  in this exercise. However, since the experiment excludes overhangs it does not necessarily indicate that the  $SHGC$  tested will meet the code compliance considering that code compliance takes into account overhang conditions to establish the maximum value. Therefore, it was anticipated that  $SHGC$  values perform less than code compliance.

The National Fenestration Rating Council (NFRC) ANSI/NFRC 200-2014 and 201-2014 were reference and adapted in quantifying the  $SHGC$ . Similar to  $U$ -factor and  $VT$  the  $SHGC$  testing was not intended to replace laboratory testing methods or invalidate previously quantified results, but offer insight using simplified solutions to determine the preliminary performance of each specimen.

SHGC was calculated by measuring the difference between the heat flux across the specimen and the U-factor divided by the specimen area the amount of incident solar energy falling on the surface of the specimen. SHGC was determined such that

$$SHGC = \frac{Q_{hf} - Q_{U-factor}}{A_{specimen} ii} \quad (20)$$

*SHGC* = Solar Heat Gain Coefficient

$Q_{hf}$  = Heat Flux (W/m<sup>2</sup>) as defined in Chapter IV

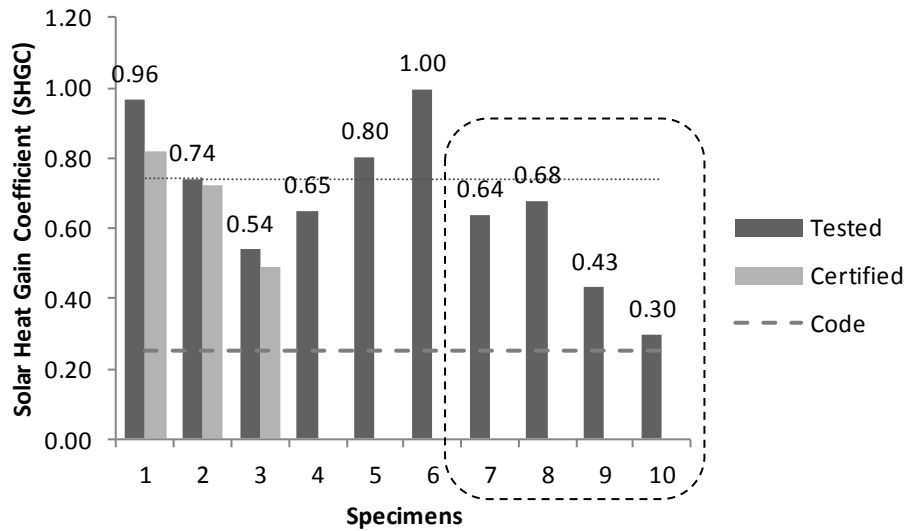
$Q_{U-factor}$  = Specimen U-factor as defined in Chapter II

*ii* = incident illuminance (W/m<sup>2</sup>) as defined in Chapter II

In Chapter IV the solar simulator was defined as having an average 787 w/m<sup>2</sup> of incident solar radiation falling on the specimen (*ii*). Chapter V measured each specimen's U-factor ( $Q_{u-factor}$ ) and heat flux ( $Q_{hf}$ ). The area ( $A_{specimen}$ ) of specimens is known to be 0.092m<sup>2</sup>.

#### H<sub>2</sub>O window Solar heat gain coefficient (SHGC) Results

Factory certified specimens 1-3 were compared to in-situ testing for calibration purposes. Specimen 1 (single pane), specimen 2 (double pane), and specimen 3 (triple pane) factory SHGC was 0.82, 0.72, and 0.49, respectively. In-situ testing resulted in 0.96, 0.74, and 0.54, respectively (Figure 73). The average difference was less than 9% offering relatively firm bases for establishing the SHGC for specimens 4-10.

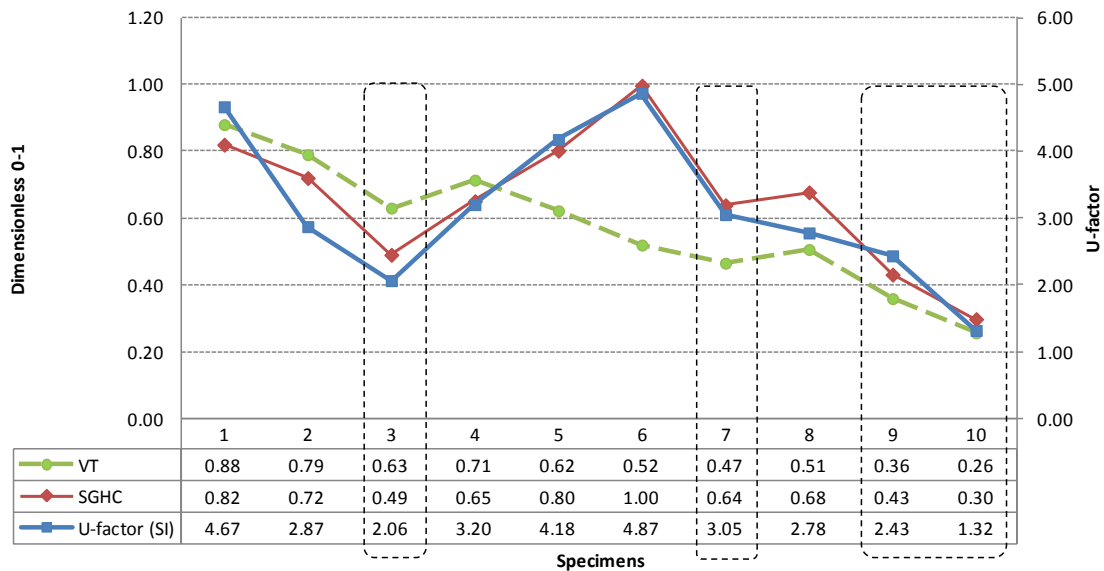


**Figure 73:** H<sub>2</sub>Owindow Solar Heat Gain Coefficient

Specimens 4-10 were plotted in Figure 73. None of the specimens met code compliance, but as previously mentioned this was not an indicator of poor performance. However, comparing the SHGC of the certified specimens (1-3) offer insight on the performance of specimens 4-10. As such solar heat gain increased 20% from specimen 4 to 5 and 6 as a function of fluidizing the gap. This was an indication that fluidizing the gap had a direct impact on heat gain as the water enhanced thermal bridging between the warm side and cold side of the H<sub>2</sub>Owindow. This was illustrated in Figure 68 which plotted the surface temperature and specimen 4, 5, and 6 had the smallest surface temperature differential between surfaces indicating a high degree of thermal bridging as a function of the gaps conductivity.

## H<sub>2</sub>Owindow Solar heat gain coefficient (SHGC) Conclusion

Visible transmittance, solar heat gain coefficient, and thermal transmittance were plotted in Figure 74. H<sub>2</sub>Owindow specimens that excelled were 7-10. These units combined fluidized gaps with known double pane or quad pane technology reducing solar heat gain and losses. From a weight perspective the triple pane specimens 7 and 8 use less material compared to the quad pane specimens 9 and 10. However, only the quad pane specimens 9 and 10 outperformed all of the other H<sub>2</sub>Owindow specimens and the baseline specimen 3.



**Figure 74:** H<sub>2</sub>Owindow VT, SHGC, U-factor Results

The cost of nanofluids limits the number of specimens that advanced to final stage of testing. Specimens 7 and 8 are one of the same and only differ by the fluid column's

orientation to the environment. This was deemed as influential to the research to determine the impact direct incident solar radiation has on the system. Specimen 9 advanced as it was assembled of unprotected glass compared to specimen 10 which is composed of low-e coatings in addition to the suspended heat mirror.

## CHAPTER VIII

### H<sub>2</sub>O WINDOW AS ENERGY GENERATOR

Chapter 7 qualified the performance of H<sub>2</sub>O windows using standardized metrics such as U-factor, solar heat gain coefficient (SHGC), and visible transmittance (VT). These experiments established which combination of air and water columns resulted in window performance equal to or better than the baseline double and triple panes. While this provided a clear understanding of the H<sub>2</sub>O window's performance in comparison to other non-fluidized windows it does not answer the question how a window can conduct energy, transfer that energy, or produce energy while not sacrificing optical clarity and thermal performance. Four experiments were conducted.

#### **Experiment 1: Pre-Heat Air (Convection & Radiation)**

This experiment set out to determine the rate an H<sub>2</sub>O window can preheat ambient air. Fluids from the H<sub>2</sub>O windows were circulated to a water block (heat exchanger) in Chamber 2 which is isolated from the solar simulator. Surface temperature sensors, fluid temperature sensors, and two ambient air temperature sensors were deployed and logged data over multiple 5-hour test sequences. This experiment measured the convective and radiation heat transfer coefficient and the role forced air circulation had on the system.

Experiment 1A was natural convection

Experiment 1B was with forced convection



## **Experiment 2: Pre-Heat Water**

This experiment set out to determine the rate an H<sub>2</sub>Owindow can preheat water. The water block in Experiment 1 was placed in a 2-gallon water tank, and equipped with a water temperature sensor, and the water block's effluent and influent water lines were equipped with in-line temperature sensors.

## **Experiment 3: Pre-Heat Water (Larger Heat Exchanger)**

Experiment 3 is like Experiment 2 but employed a larger heat exchanger and only used the highest performing H<sub>2</sub>Owindow identified in Experiment 1 and 2. This experiment was added to determine the impact a larger heat exchanger would have on the system.

## **Experiment 4: Electrical Production**

This experiment set out to determine if H<sub>2</sub>Owindows can generate electricity. A thermoelectric generator was coupled with the water block heat exchanger in Experiment 1 and electrical potential (voltage) and current (I) was measured in four conditions:

Test 1 Thermoelectric generator only

Test 2 Thermoelectric generator + Air circulation, No Heat Sink.

Test 3 Thermoelectric generator + Heat Sink, No Air circulation

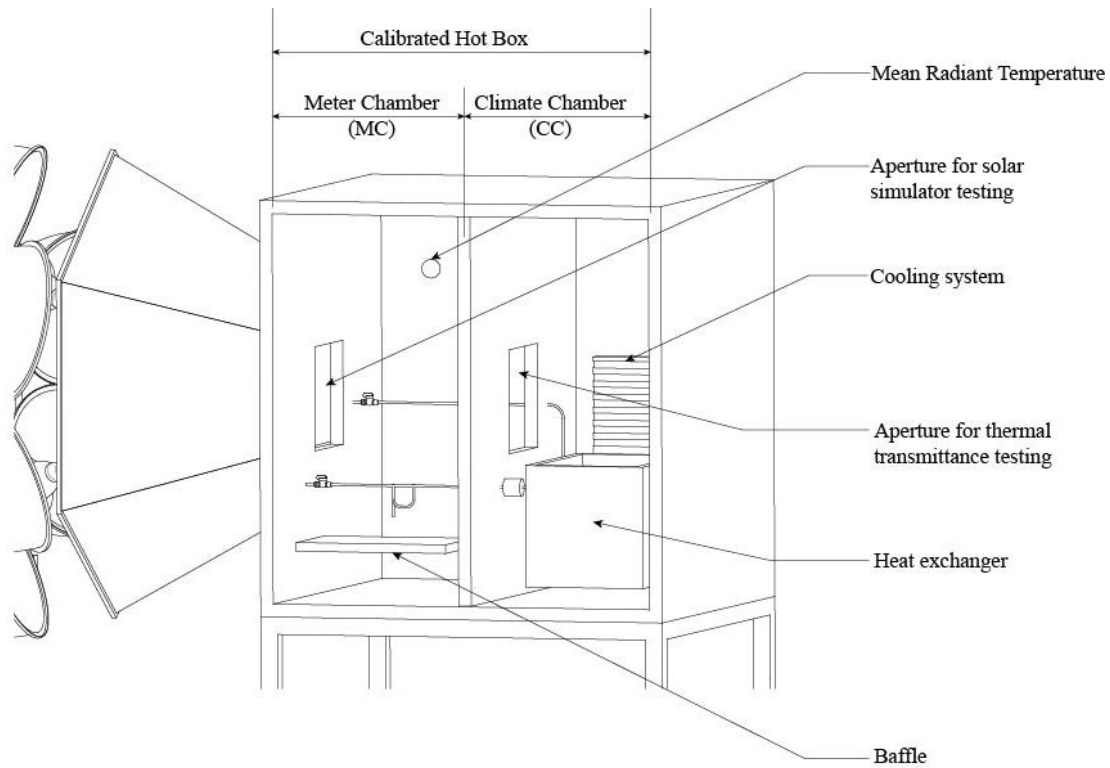
Test 4 Thermoelectric generator + Heat sink + Air Circulation

## Energy Generation Test Methods

H<sub>2</sub>O window were filled with distilled water and installed on the solar simulator side (Chamber 1) of the calibrated hot box (CHB), edges taped and sealed. H<sub>2</sub>O windows effluent and influent plumbing tubes were connected to the water pump and heat exchanger assembly in Chamber 2, previously referred to as the Climate Chamber. The solar simulator was brought up to steady state and Chamber 2 was cooled to a steady state temperature. This sequence took approximately three-hours and during that time fluid temperature, ambient air temperatures, irradiance, electrical production, and heat exchanger surface temperatures were continuously measured. At the end of the three-hour start-up sequence the following four experiments and sub-experiments were conducted.

### H<sub>2</sub>O window Experiment 1: Radiant Heating Simulation

H<sub>2</sub>O window 5-10 were filled with 0.23 gallons (0.9l) of distilled water using a separator. H<sub>2</sub>O window were placed in the metering chamber side facing the solar simulator and connected to a 12v, 400L/h, water pump using 1/4" polyethylene tubing (Figure 75). The aperture used for measuring visible transmittance, solar heat gain coefficient, and thermal transmittance was infilled with similar polyisocyanurate thermal insulation used to construct the calibrated hot box, and edges taped and sealed.



**Figure 75:** Calibrated Hot Box

The Data Acquisition System (DAS) was described Chapter 4. In brief, all sensors, AC power, and DC power running to the CHB interfaced with DAS and the relay controller. DAS was coded using Edlog which allowed for the actuation of the pump, fans, and cooling systems. Water temperature in the H<sub>2</sub>O windows was measured using the 1099SS thermistor probe sensor. An 110PV-L surface-mount thermistor sensor was placed on the heat exchanger, and ambient air temperature in the same chamber as the heat exchanger used a L107 thermistors sensor.

Experiment 1 was composed of three parts: A 2-inch square (50mm square) copper water block connected to the fluid lines serving the H<sub>2</sub>O windows and pump; 3.5inchØ x

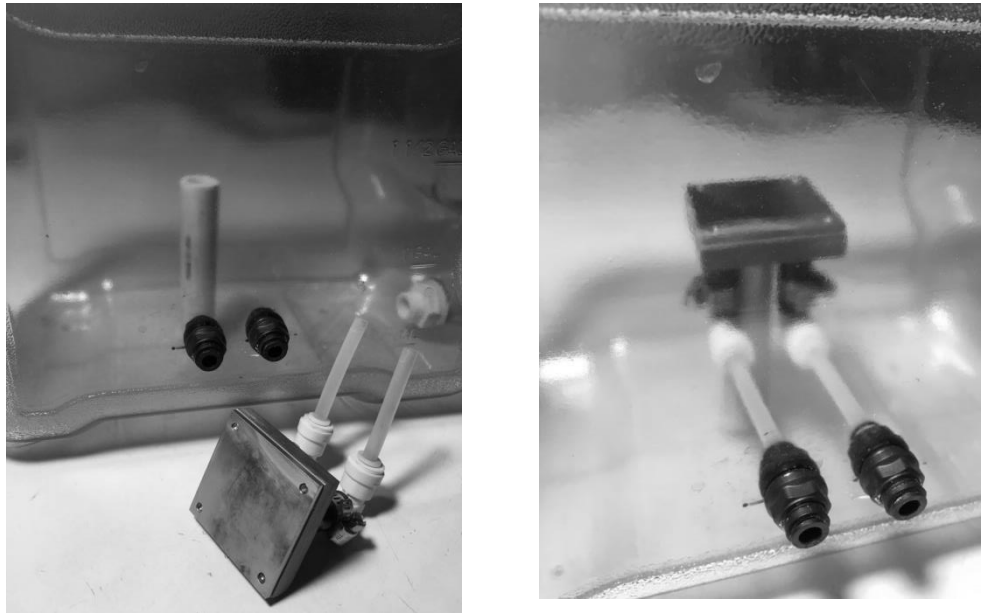
1.5inch tall (90mmØ x 38mm tall) aluminum heat sink; and a 12v fan with 30CFM/400fpm (Figure 76).



**Figure 76:** Heat Exchanger Assembly. (Left to right) 1.98-inch square water block (radiator) with fluid ports. Heat sink. Fan to augment convective forces.

## H<sub>2</sub>Owindow Experiment 2: Solar Hot Water Simulation I

The water block in Experiment 1 was submerged in a 2 gallon (7.5liter) transparent water reservoir. The 1/4" polyethylene tubing breached the reservoir using inline bulkhead unions for 1/4" tubing. Polyethylene tubing outside the reservoir was not insulated during these trial runs (Figure 77).



**Figure 77:** Water block  
Water block outside of reservoir (right). Water block in water reservoir (Left).

### H<sub>2</sub>Owindow Experiment 3: Solar Hot Water Simulation II

A custom heat exchanger<sup>40</sup> was fabricated from 0.25-inchØ copper tubing. The heat exchanger was submerged in 3.5 gallon (13.2liter) tank and similarly used inline unions and connected to the pump and H<sub>2</sub>Owindows (Figure 78).

#### Specifications

Diameter 0.25in (0.0064m)

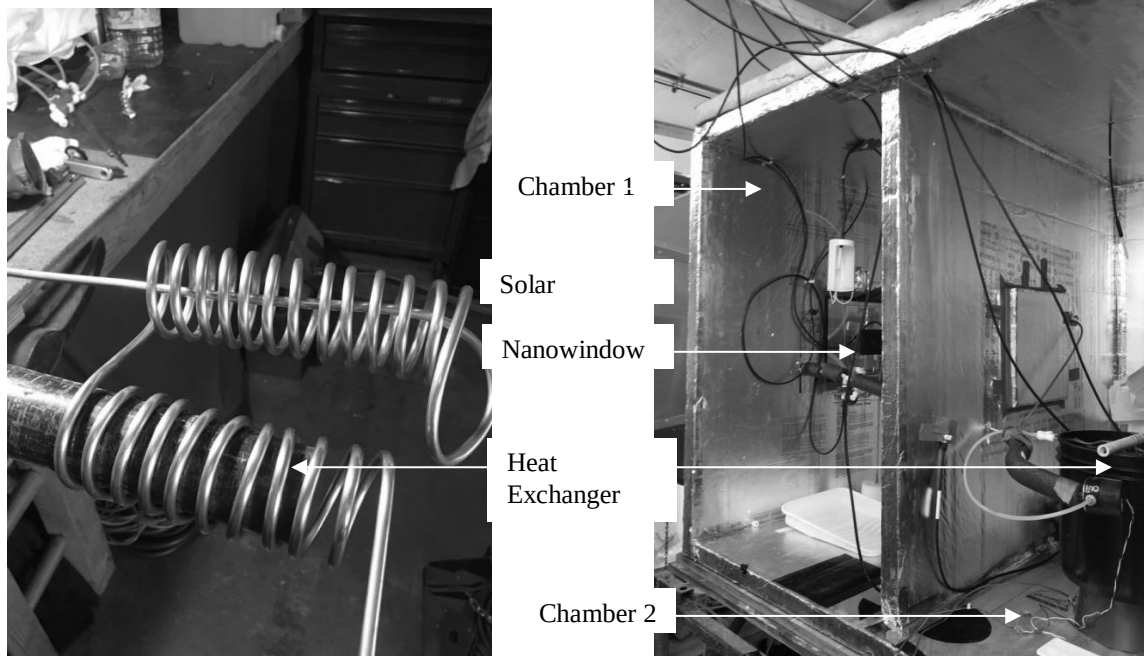
Wall Thickness 0.039in (0.001m)

Length 18ft (5.48m)

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<sup>40</sup> The copper tube was pulled around a 2-inch black pipe creating two heat exchange columns. Tubing was filled with salt to maintain the cylindrical profile. Once the two heat exchange columns were finalized it was impossible for the salt to be evacuated from the tubing because it had compressed. Small holes were drilled throughout the tubes and water pressure was applied until the heat exchanger was free and clear. All holes were soldered closed. Although the custom heat exchanger meet the means of the research it is advisable that future research invest in computer cooling heat sinks and waterblocks to save time and money.

Surface Area 170in<sup>2</sup> (0.11m<sup>2</sup>)



**Figure 78:** Custom heat exchanger

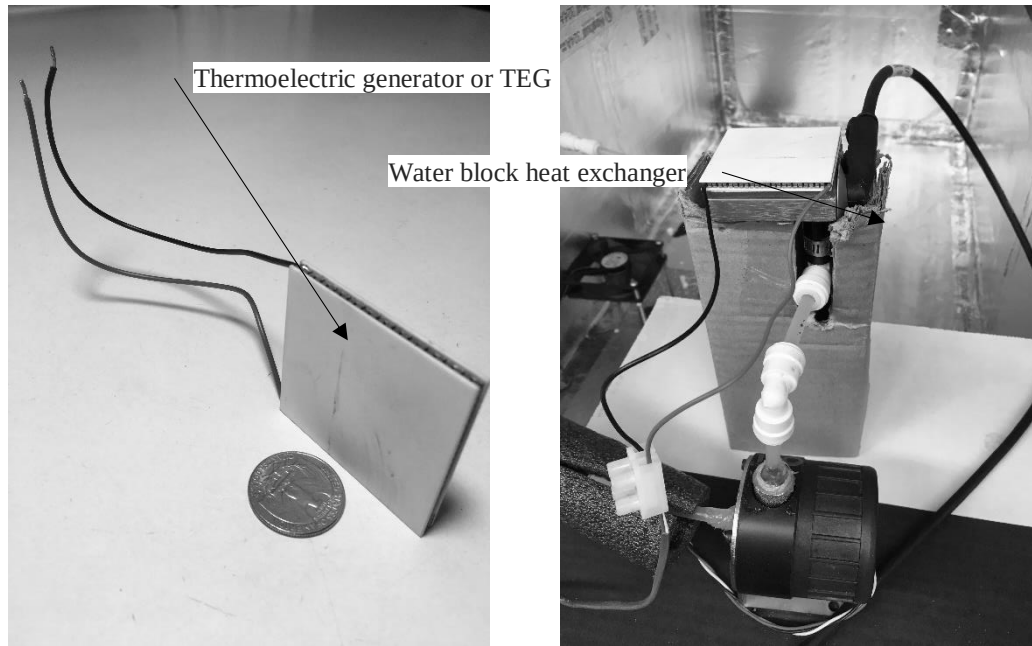
#### H<sub>2</sub>Owindow Experiment 4: Thermoelectric Generation

This experiment focused on the H<sub>2</sub>Owindow's ability to produce electricity using a thermoelectric generator (TEG). A TEG is a solid state device that converts waste heat into electrical energy. The thermoelectric effect is built on the Seebeck theory that temperature difference across certain materials can be converted into electricity. A thermoelectric/Peltier module<sup>41</sup> was procured measuring 1.97-inches square to fit directly over the water block heat exchanger in Figure 79.

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<sup>41</sup> Custom Thermoelectric Generator model 28711-5M31-12CW was procured.  $I_{\max}$ (Amps)12.0,  $Q_{\max}$ (Watts)255.3,  $V_{\max}$ (Volts)34.4

The TEG is composed of two ceramic substrate faces made of alumina ceramic  $\text{Al}_2\text{O}_3$ , sandwiching a network of semiconductor pellets (dice). The thermoelectric core is made of bismuth telluride with known conductivity of 1.5 w/m K (Custom Thermoelectric, 2016).



**Figure 79:** Thermoelectric Generator Components

The four Tests performed used similar 3-hour start-up procedures establishing steady state. At steady state the pump was actuated and fluids were circulated from the  $\text{H}_2\text{O}$  window to the water block in Chamber 2 equipped with the thermoelectric generator (Figure 79). The TEG was connected to a multimeter and measured electric potential (voltage) and Current (I) in direct voltage (DC) over the course of 4-hours. During the 4-hour experiment four different Tests were evaluated each lasting one-hour.

## Custom Calculator for Convection, Radiation, and Conduction

Convection is the transfer of heat through the displacement of material, much like the displacement of energy through vascular systems or hot water furnaces. In each case, a medium is used to displace the energy from one location to another. In the case of a fluid domain, the fluid itself becomes a mechanism to displace energy and does so through forced or natural convection. Forced convection is the displacement of energy through active means (e.g., pumps, fans, a human heart). Natural convection on the other hand is passive and relies on displacement by buoyancy as a function of kinetic excitation of molecules and density.

There is no simplified equation for convective heat transfer and it “cannot be confidently predicted over all the parameter of interest” (ElSherbiny, Raithby, & Hollands, 1982, p. 96). These parameters that influence convective forces range from geometry and orientation, to surface roughness, to the fluid’s laminar or turbulent properties - just to name a few. To best capture a working correlation of convective heat transfer in a water fluid medium the Transwalls research of Fuch and McClelland, water walls of Nayak, and Transparent Water Storage Walls of Xiangfeng are considered. Their work is further supported by finite heat transfer correlations across vertical isotherm layers research by Elsherbiny, and Window calculation procedures outlined by Finlayson.

However, this defines an unobstructed fluid medium and the proposed system incorporates a suspended polyethylene terephthalate low emissivity film within the fluid



medium. Since the film is suspended in the fluid medium it will impact the overall heat transfer rate. For convective correlations with integrated elements within a fluid medium the research turns to convective studies of integrated blinds in the air cavity as a close ally of the proposed system.

The following discussion describes convective potential of a fluid. The convective heat transfer rate measured and quantified the thermal exchange between the heat exchanger and chamber air. The simple iterative calculation focuses on the heat exchanger's fluids, geometry and material composition, while heat loss in the plumbing lines, couplings, and associate parts were excluded. The following classic thermodynamic formulas were applied to calculate the impact of the three experiments.

The convective heat transfer rate applied was

$$Q = h_c A (t_s - t_\infty) \quad (21)$$

*Where :*

$Q$  = heat transfer (W)

$h$  = Heat Coefficient (W/m<sup>2</sup>k)

$A$  = Surface area of water block (m<sup>2</sup>)

$t_s$  = Plate temperature (°C)

$t_\infty$  = Air Temperature near water block (°C)

Fluids create calculation complexities considering that the water block will not exhibit pure isothermal characteristics because of unique geometry, thickness, and relationship to internal circulation channels. Thus all surfaces are prone to unequal temperatures. The

proposed Raleigh number and Nusselt number are used to approximate the case for non-isothermal surfaces assuming that surface temperature represents an average value.

The Rayleigh number is used to calculate natural convection and indicates whether a fluid domain is turbulent or laminar. The Rayleigh number applied was

$$Ra = Gr Pr = \frac{g\beta(T_s - T_\infty)P_c^3}{\nu^2} Pr \quad (22)$$

Where:

$Ra$  = Raleigh number (dimensionless)

$GrPr$  = Is the product of the Grashof and Prandtl numbers

$g$  = acceleration due to gravity ( $m^2/s$ )

$\beta$  = thermal expansion coefficient ( $1/T_f$ ) ( $^{\circ}C$ )

$T_s$  = surface temperature ( $^{\circ}C$ )

$T_\infty$  = ambient temperature near the surface ( $^{\circ}C$ )

$P_c$  = length of waterblock which is area/perimeter (m)

$\nu$  = kinematic viscosity ( $m^2/s$ )

For the Rayleigh number the film temperature was used

$$T_f = \frac{T_s + T_\infty}{2} \quad (23)$$

Where :

$T_f$  = Film temperature ( $^{\circ}C$ )

$T_s$  = Surface temperature ( $^{\circ}C$ )

$T_\infty$  = ambient air temperature ( $^{\circ}C$ )

The Prandtl number is dimensionless and used to define the kinematic viscosity of fluid mediums. In the case of high performing windows, the higher the kinematic viscosity and

the lower the thermal conductivity ( $k$ ) the higher the insulating value (Johnson, 1991, p. 38). In the Transwall research of Xiang and Tianxing, the Prandtl number was used to “indicate the ratio of momentum transfer ability to heat transfer ability in a fluid” (2008, p. 110). The Prandtl number will vary as a function of temperature

$$\text{Pr} = \frac{C_p \mu}{k} \quad (24)$$

Pr = Prandtl number (dimensionless)

$C_p$  = Specific heat (kJ/kg °C)

$\mu$  = Dynamic viscosity Pa s=N (s/m<sup>2</sup>)

$k$  = Thermal conductivity (W/m °C)

The Nusselt number is a function of the Rayleigh number (Ra), Prandtl number (Pr), and aspect ratio. The Nusselt number represents the heat transfer through a fluid medium as a function of convection relative to the conduction across the same medium. Simplified, the larger the Nu the greater the convection, and a Nu=1 represents heat transfer across the medium by pure conduction.

$$\text{Nu} = \frac{h_c A}{k} = \text{CRa} \quad (25)$$

Where :

$Nu$  = Nusselt number (dimensionless)

$h_c$  = heat transfer coefficient (W/m<sup>2</sup>)

$A$  = area/perimeter (m<sup>2</sup>)

$k$  = thermal conductivity (W/m K)

$C$  = Constant

$Ra$  = Rayleigh

The heat exchanger was considered an isothermal horizontal surface knowing that it is more non-isothermal. Empirical correlations were used for free convection and the Nusselt number is a function of the Rayleigh number such that

$$Nu = \begin{cases} 0.59Ra^{0.25} & 10^4 < Ra < 10^7 \\ 0.15Ra^{0.33} & 10^7 < Ra < 10^{11} \end{cases} \quad (26)$$

Thermal radiation was also quantified and governed by the Stefan-Boltzmann law.

Radiation calculation applies was

$$P = e\sigma A(T_s^4 - T_\infty^4) \quad (27)$$

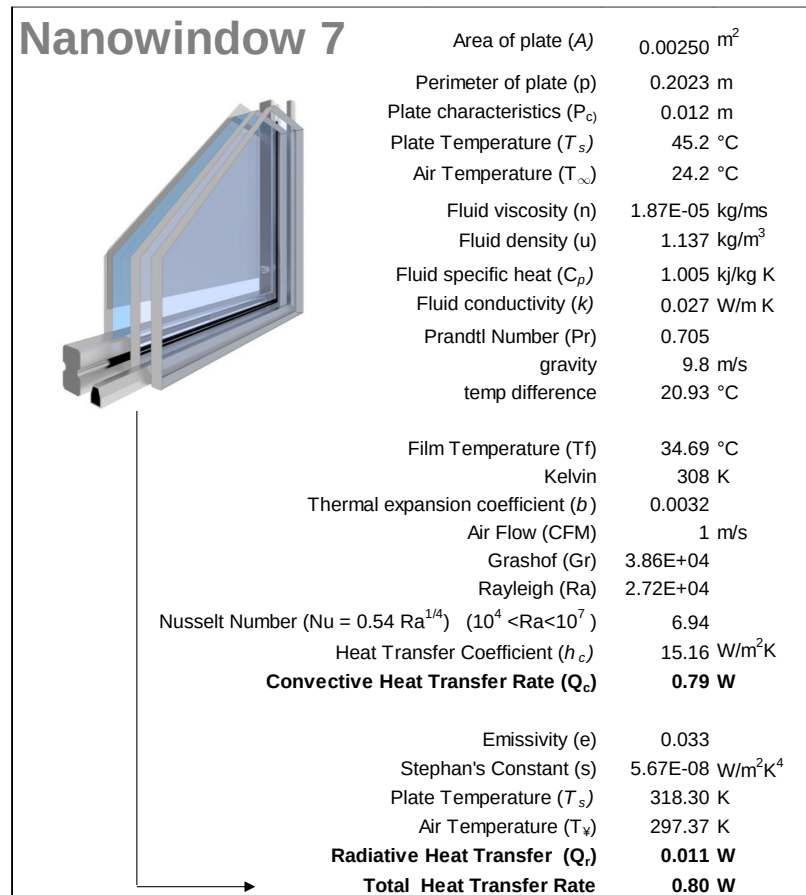
$P$  = Net radiating power (W)

$e$  = Emissivity (copper 0.333)

$\sigma$  = Stefan Constant (5.67X10<sup>-8</sup> W/m<sup>2</sup> K)

The order of calculations: film temperature (23), Grashof number (22), Prandtl number (24), Rayleigh number, Nusselt number (25), heat transfer coefficient / heat rate transfer (21), and the additive of total radiation emitted by the heat exchanger(27). A custom net

radiation & convection calculator was developed (Figure 80) that cross references data collected from the data acquisition system (DAS). The same calculator was applied to all experiments to define the heat transfer rate.



**Figure 80: Heat Transfer Rate Calculator (Example)**

### Conductivity (k)

Conduction at the fundamental level is the heat transfer from a high body temperature to a low body temperature. In the case of a fluid, as the molecules of water increase in thermal energy they begin to vibrate. As the high energized molecules of water collide

with lesser energized molecules they pass that high thermal vibration to a less thermally charged molecule.

At the particle level Fourier's laws of thermal conduction is expressed as the heat flux energy, ( $Q$ ), equal to the product of thermal conductivity, ( $k$ ), and the difference in temperature ( $\Delta t$ ).

$$Q = \frac{kA\Delta t}{d} \quad (28)$$

Where

$Q$  = heat flux density (W)  
 $A$  = Area of surface ( $m^2$ )  
 $K$  = material's conductivity (W/m K)  
 $\Delta t$  = temperature difference ( $^{\circ}C$ ) ( $T_{hot}-T_{cold}$ )  
 $d$  = thickness ( $m$ )

It is not the intent of this topic to re-evaluate the assumed conductivities of certain materials, but mention that sufficient research into known values comes with limited experimental uncertainties. As such, thermal conductivity of water used for this investigation was based on the International Association for the Properties of Steam (IAPS) developed by *Sengers et al.*, and International Temperature Scales (ITS-90). The recommended correlation between thermal conductivity of water is a function of temperature, water's density, and atmospheric pressure. The following conductivity of water was taken at 298.15K (77° F) and 0.1 MPa.

$$k = 0.605 \pm 0.0036 \text{ Wm}^{-1}\text{K}^{-1} \text{ (Ramires et al., 1995)}$$

A custom heat transfer rate calculator (Table 19) was developed using equation (28) and embedded into each data log collected by the DAS. All heat transfer variables remained constant except for surface temperature and ambient water temperature.

| Heat Transfer by Conduction Q/T                                                   |                                                        |
|-----------------------------------------------------------------------------------|--------------------------------------------------------|
|  | 38 Fluid Temperature (°C)                              |
|                                                                                   | 34 Reservoir Temp (°C)                                 |
|                                                                                   | 400 Copper K (W/m)*                                    |
|                                                                                   | 205 Aluminum K (W/m)*                                  |
|                                                                                   | 0.00318 Thickness (m)                                  |
|                                                                                   | 0.00280 Heat Exchanger Area (copper m <sup>2</sup> )   |
|                                                                                   | 0.00470 Heat Exchanger Area (Aluminum m <sup>2</sup> ) |
|                                                                                   | 2618 Heat Conduction Q/Time (W)                        |
|                                                                                   | 8934 BTU/hr                                            |
|                                                                                   |                                                        |

**Table 19:** Energy Calculator (Example)

## Heat Capacity

Heat capacity is the amount of heat added to a mass that results in a change in temperature. This is another method used to determine the amount of heat added to the water tanks or ambient air. In essence it was an indicator of how much heat was produced and release by the H<sub>2</sub>Owindow assuming isotherm conditions at the heat exchanger and negligible losses along the circulation path connected the H<sub>2</sub>Owindow and heat exchanger.

$$Q = cm\Delta T \quad (29)$$

$Q$  = Amount of heat added (Joules)

$c$  = Specific Heat Capacity of fluid (joule/gram °C)

$m$  = mass (gm)

$\Delta T$  = Change in temperature (°C)

and to convert Joules to Watts the following was applied

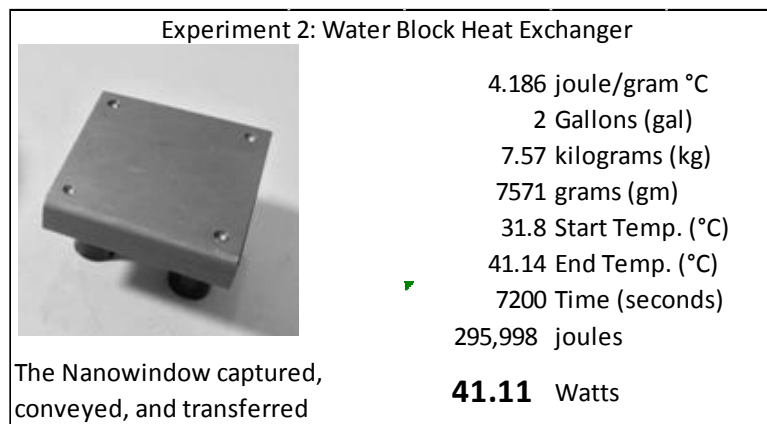
$$P_{(watts)} = E_{(J)} / t_{(s)} \quad (30)$$

$P_{(watts)}$  = Watts (Energy Added to the system)

$E_{(J)}$  = Joules

$t_{(s)}$  = Time in seconds

Similar to other calculations a custom calculator was developed to interface with the data acquired by the datalogger acquisition system (Figure 81).



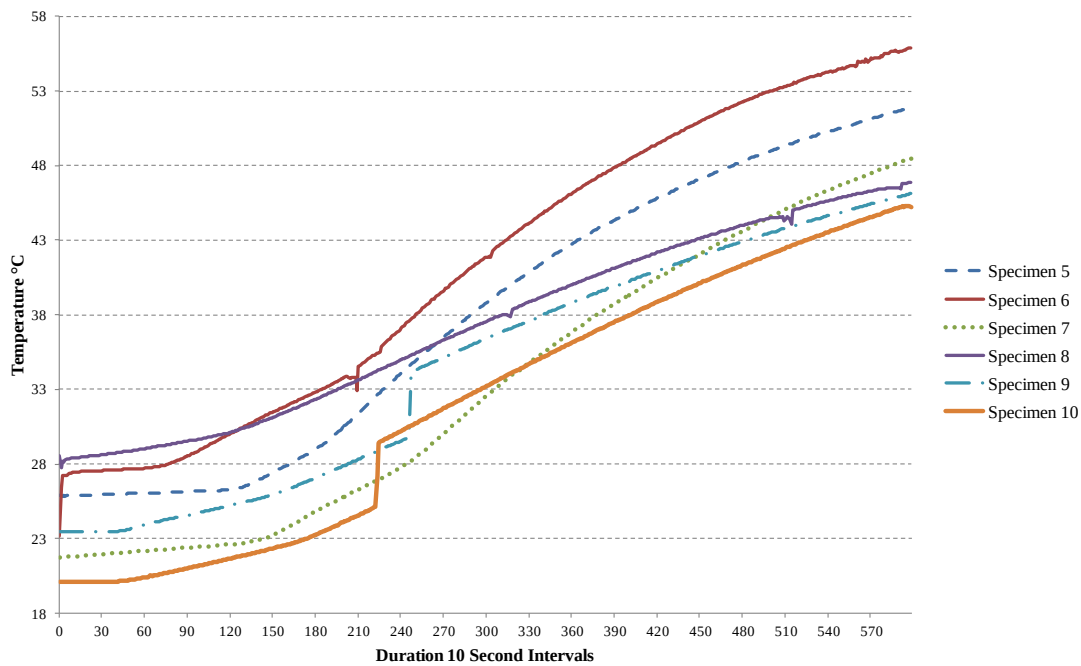
**Figure 81:** Energy Calculator (Example)



## Results

### H<sub>2</sub>Owindow, Experiment 1: Radiant Heating Simulation

Water temperature alone was not a good indicator of performance. Instead it was a combination of the fluid's ability to recharge and provide a steady heat transfer coefficient. Maximum water temperature sustain during the two-hours warm-up was collected and compared. Specimens 5,6,7,8,9, and 10 reached maximum temperatures of 57.3°C, 60.2°C, 66.5°C, 48.9°C, 53°C, and 49°C, respectively (Figure 82). These readings were questionable and compared to other water wall research data.



**Figure 82:** Water Temperature Characteristics

In previous waterwall research the water, mixed water/glycol, and pure glycol water columns generated between 25°C - 40°C temperatures (Issertes-Carbonnier, 2010, pp.

55–58). This also aligns waterwall research that concluded that water temperatures ranged  $\pm 20^{\circ}\text{C}$  - although the geographic location and season was not mentioned in that research so water temperature could be higher depending on solar exposure (Upadhyaya et al., 1991, p. 101). The significant difference in temperature recorded was further investigated.

There was some speculation that the stainless-steel probe was exposed to direct incident light emitted by the solar simulator causing inaccurate temperature readings. Some attempt was made to reduce direct incident by placing black tape over the glass to prevent stray light while allowing enough glass surface area to be exposed to the direct incident light. This proved to be difficult because not all light was parallel to the test surface so it was entirely possible that the temperature probe continued to be influenced by extraneous radiation sources. In mid-experiment the location of the temperature probe was reevaluated.

In subsequent experiments the temperature probe was removed from the specimens and placed in the effluent line going to the pump and out of sight of any direct incident light. The unfortunate drawback of this solution was the inability to measure water temperature as a function of radiant heat flux emitted from the solar simulator since the probe was no longer in contact with the water column. In order to capture water temperature the pump was periodically actuated for 60-seconds to record water temperature. The second drawback from running the pump during the start-up sequence for as little as 60-seconds resulted in heat transfer occurring in Chamber 2 thus lowering the water temperature ever

so slightly. The limited frequency and duration of running the pump during warm-up was assumed to have negligible effect on the four Experiments.

Additional observations were gathered from the water temperature readings in Figure 82. Starting water temperatures were not equal causing some concern that this would create an unequal baseline of reference because varying start temperatures impact heat transfer as the rate diminishes as the difference of temperature decreases. This was addressed in subsequent experiments by attempting to maintain the distilled water and specimens in a refrigerator so that they all started with equal temperatures.

#### Heat Transfer Rate (Convection & Radiation)

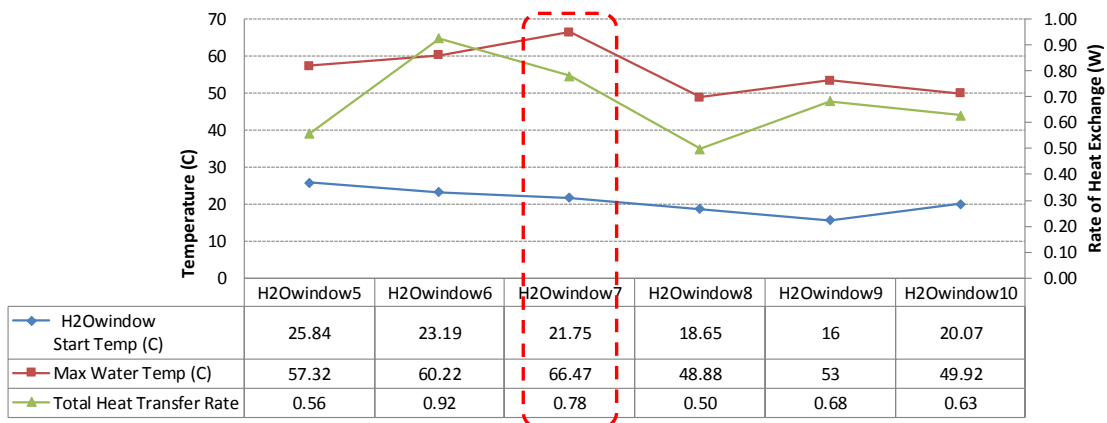
Experiment 1 used the custom heat transfer calculator (Figure 80) to determine the total heat transfer rate, conductive heat transfer rate (W), conductive heat transfer coefficient ( $\text{W/m}^2\text{K}$ ) and the radiative heat transfer rate (W) in natural convection and force convection modes. H<sub>2</sub>Owindow6 generated the highest convective and radiative heat transfer rate (W), but tested with poor U-factor and SHGC resulting in less than desirable performance. H<sub>2</sub>Owindow7 offered a second highest convective heat transfer coefficient transfer rate in natural convection and force convection mode. (Table 20). H<sub>2</sub>Owindow7 overall heat transfer rate of 0.78 W combined with promising SHGC, VT, and U-factor results made it a viable renewable energy candidate. H<sub>2</sub>Owindow 8, 9, and 10 performed well in previous SHGC, VT, and U-factor experiments, but were unable to match the performance of H<sub>2</sub>Owindow7 (Figure 82).

| Convective Heat Transfer Coefficient (W/m <sup>2</sup> K) |              |             |         |
|-----------------------------------------------------------|--------------|-------------|---------|
|                                                           | Rate w/o fan | Rate w/ fan | Average |
| H2Owindow 5                                               | 0.36         | 0.36        | 0.49    |
| H2Owindow 6                                               | 0.94         | 0.58        | 0.82    |
| H2Owindow 7                                               | 0.94         | 0.54        | 0.68    |
| H2Owindow 8                                               | 0.60         | 0.28        | 0.44    |
| H2Owindow 9                                               | 0.74         | 0.49        | 0.60    |
| H2Owindow 10                                              | 0.69         | 0.37        | 0.55    |

**Table 20:** Natural Convection & Forced Convection

Figure 82 and compares heat transfer rate overlaid with water temperatures.

H2Owindow7 had the highest rate of temperature increase, and as previously noted resulted in the highest rate of heat transfer of 0.78 W (Figure 83).



**Figure 83:** Heat Transfer Rate & Water Temperatures

Experiment 1 was retested because there was some concern that the stainless-steel temperature probe immersed in the fluid column was unshielded from direct incident light and may be overstating water temperatures, thus influencing the overall outcome.

Experiment 1 was retested with sensors placed in-line with water lines, and it was determined that the temperature probe was affected by direct incident light (Figure 84). While the water temperature dropped on average by 13 °C, the behavior of the system was similar. H<sub>2</sub>Owindow7 continued to exhibit highest heat transfer rate and high water temperature (Figure 84).

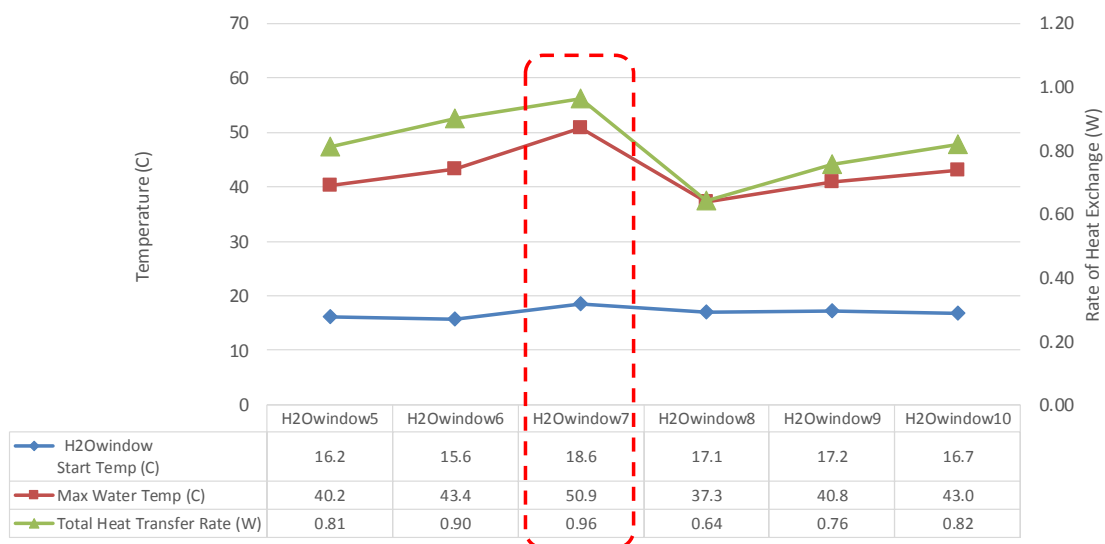


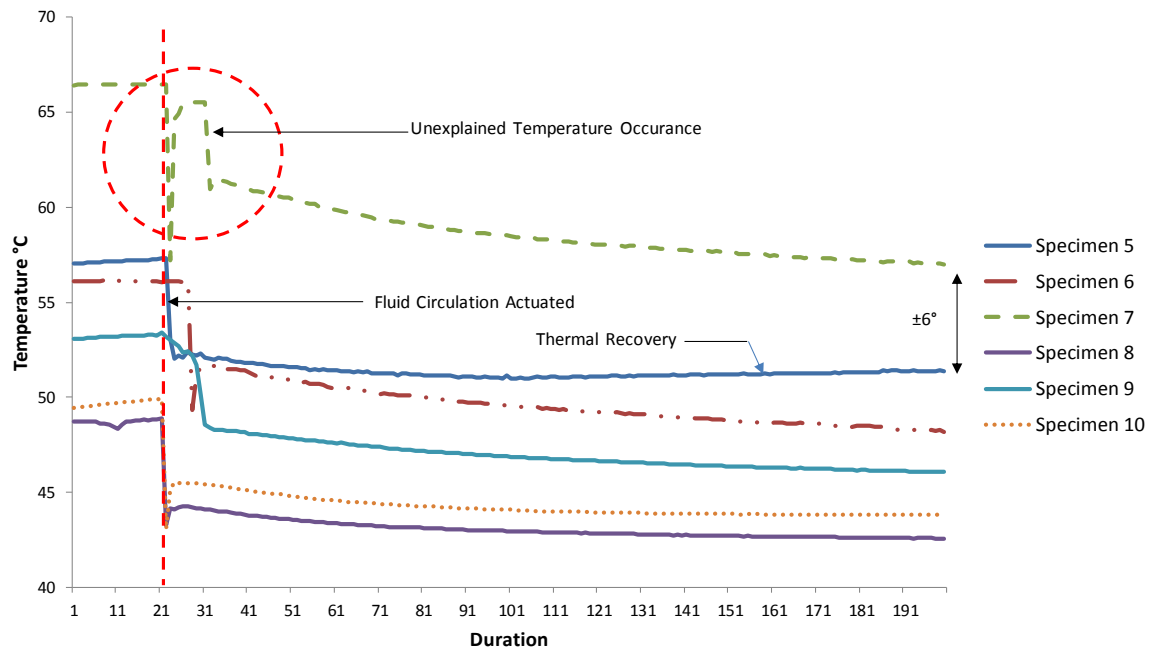
Figure 84: Heat Transfer Rate Redo

Water temperature fluctuations were analyzed immediately before and after fluid circulation as notable variations were apparent (Figure 84). As fluid temperatures reached near steady state the pump was actuated circulating fluids through the heat exchanger and

higher rates of heat exchange (H<sub>2</sub>Owindow7) resulted in higher temperature differenced (8.1°C) taken before and after the pump was turned on. The temperature difference confirms heat exchange, but also highlights that the lowest temperature recorded of H<sub>2</sub>Owindow7 was higher than all the other specimens before and after circulation commenced (Table 21).

|                          | Max Temp<br>°C | Ave. Temp during<br>pump cycle | $\Delta T$ |
|--------------------------|----------------|--------------------------------|------------|
| H <sub>2</sub> Owindow5  | 57.3           | 51.5                           | 5.8        |
| H <sub>2</sub> Owindow6  | 56.1           | 48.2                           | 7.9        |
| H <sub>2</sub> Owindow7  | 66.5           | 58.4                           | 8.1        |
| H <sub>2</sub> Owindow8  | 48.9           | 42.8                           | 6.1        |
| H <sub>2</sub> Owindow9  | 53.4           | 46.3                           | 7.1        |
| H <sub>2</sub> Owindow10 | 49.9           | 44.4                           | 5.5        |

**Table 21:** Temperature Max/Low/ $\Delta T$



**Figure 85:** H<sub>2</sub>O Temperature Before/After Pump Sequence

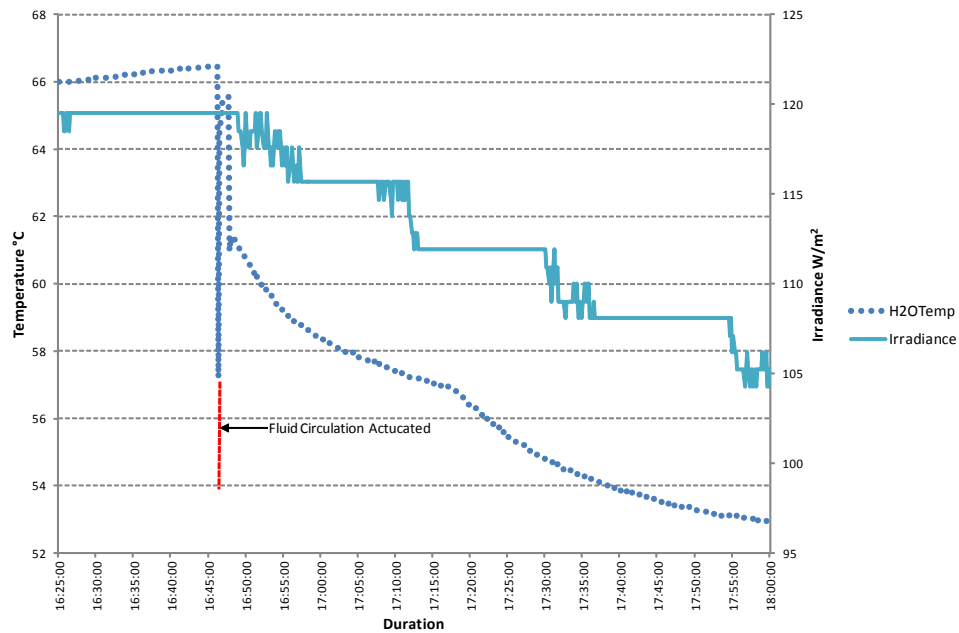
This reinforced H<sub>2</sub>Owindow7's ability to absorb more radiant energy and during heat exchange maintain  $\pm 6^{\circ}\text{C}$  more than the next specimen – Specimen 5. More important, the greater the difference between before and after circulation indicates that the system has more capacity to capture energy and deliver more energy to the heat exchanger.

H<sub>2</sub>Owindow5's heat recovery time was significantly faster than other specimens – see the tail end of Figure 85 where Specimen 5's temperature was recovering at a faster rate than others. In these initial experiments Specimen 5 was the only specimen to undergo thermal recovery, and questioned the validity of the readings as they may have been influenced by the direct incident light energy on the temperature sensor previously mentioned. One interesting physical difference was that Specimen 5 was the only specimen without a suspended heat mirror. It is possible that the heat mirror reduced the rate of thermal recovery as illustrated by Specimen 5. Subsequent experiments revisited Specimen 5's temperature anomaly and discussed later.

### Spectral Absorption Observation

Not clearly understood at the time of the experiment was the apparent relationship between irradiance and the circulation of fluids. To recap the pump was actuated when the solar simulator reached steady state and a notable change occurred in irradiance readings inside Chamber 1. As fluid temperatures dropped as a function of heat exchange, irradiance levels dropped at an equal rate. This indicated that fluids at rest (static) did not act the same way as fluids in movement (dynamic), and that irradiance transmitted through the window was influenced by the fluid's static or dynamic state considering all other variables remained constant (Figure 86).

This was an interesting discovery in the first series of experiments. If circulating water impacted spectral transmittance, then it could possibly impact spectral absorption. Meaning that circulating water may have unknown benefits in the 285nm to 3000nm range which covers the tail end of the UV spectrum, visible spectrum, and near-infrared. There is also some speculation that chamber temperature played a role in the solar radiation decay. This phenomenon occurred in all fluid based specimens only when the pump was actuated.



**Figure 86:** Irradiance vs Fluid Temperature

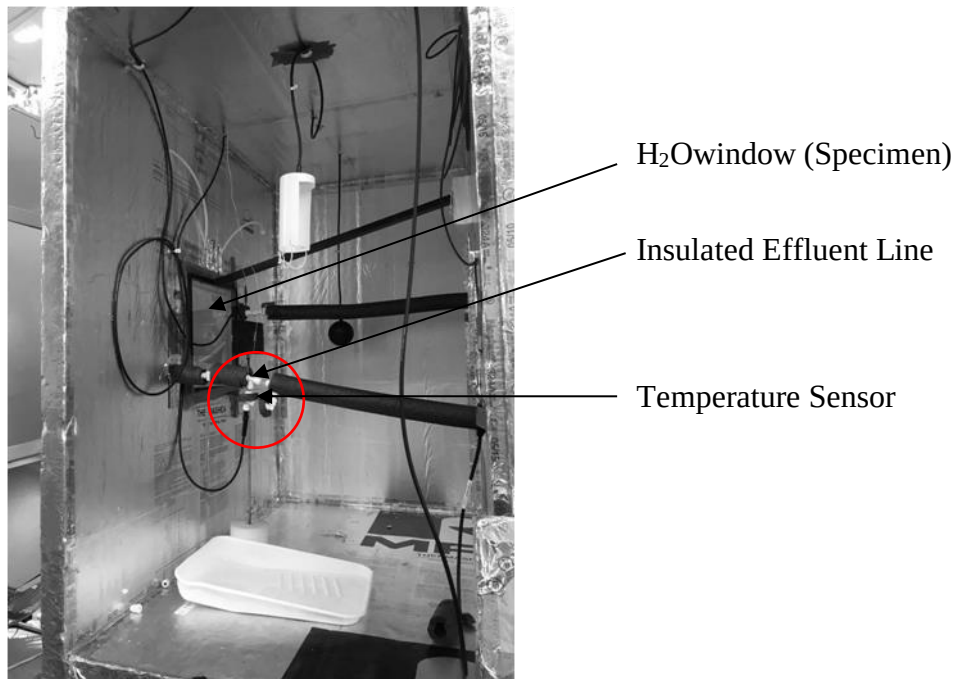


## H<sub>2</sub>Owindow, Experiment 2: Solar Hot Water Simulation I

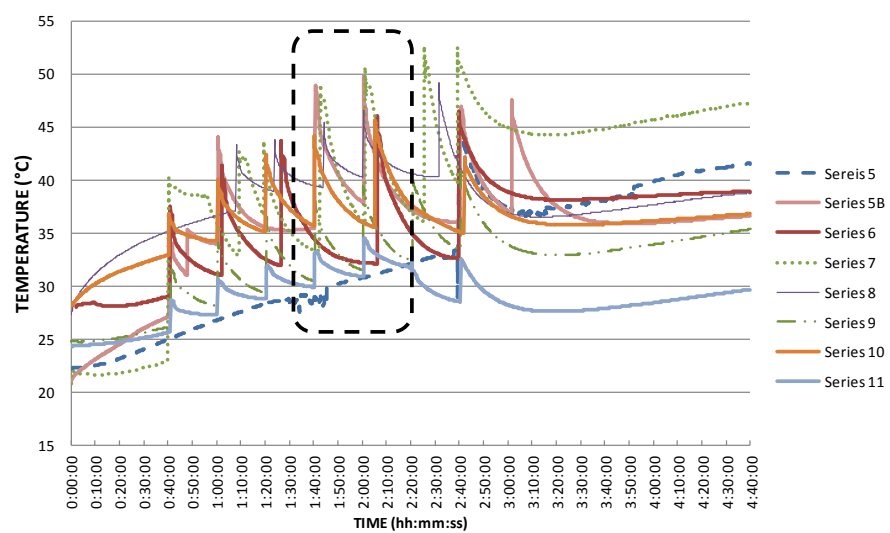
Experiment 2 measured the impact thermally charged fluids harnessed by the H<sub>2</sub>Owindows had on a water storage tank located in Chamber 2. This was to simulate opportunities to preheat water for domestic use or for thermal storage. Conceptually, if Nanowindows can preheat water and reduce fossil fuel energy require to heat water then consumers could lower energy demand, save money, and lower their carbon footprint.

### Water Temperature Characteristics

In Experiment 1 there was some concern that the temperature probe was providing skewed results because the sensor was unprotected from incident light emitted by the solar simulator. In this experiment the fluid sensor was removed from the specimens and placed in the effluent line and out of sight of direct incident light (Figure 87). Since the sensor was no longer within the specimens the pump was actuated every 15 minutes to take water temperature readings and compared to Experiment 1.



**Figure 87:** Water Temperature Sensor Relocated



**Figure 88:** Experiment 2 Temperature Readings

Temperature profiles of all the specimens were plotted in Figure 88. Every 15-minute the pump was actuated for 60-seconds as to drive the fluids out of the specimen and across the temperature probe. The spikes in the temperature bands reflect that pump sequence. H<sub>2</sub>Owindow 5,6,7,8,9, and 10 reached maximum temperatures of 49.8°C, 46.5°C, 52.6°C, 49.2°C, 41.3°C, and 45.7°C respectively. This was significantly less than what was recorded in Experiment 1 (Table 22). The average temperature difference was approximately 15% over actual. This confirmed that Experiment 1 readings were overstated and that the revised method of temperature assessment was more accurate. This does not invalidate Experiment 1's heat transfer rates and coefficients because surface temperature of the heat exchanger was used rather than the fluid's temperature.

|                           | Experiment 1<br>Max Temp. (°C) | Experiment 2<br>Max Temp (°C) |
|---------------------------|--------------------------------|-------------------------------|
| H <sub>2</sub> Owindow 5  | 57.3                           | 49.8                          |
| H <sub>2</sub> Owindow 6  | 60.2                           | 46.5                          |
| H <sub>2</sub> Owindow 7  | 66.5                           | 52.6                          |
| H <sub>2</sub> Owindow 8  | 48.9                           | 49.2                          |
| H <sub>2</sub> Owindow 9  | 53.4                           | 41.3                          |
| H <sub>2</sub> Owindow 10 | 49.9                           | 45.7                          |

Table 22: **Max Temperature Comparison**

While Specimen 7 provided the highest fluid temperature (52.6°C) (Table 22) it had the greatest rise in the reservoir's water temperature (23.98°C) which confirmed the ability of fluids in the Nanowindow to effectively heat a secondary water reservoir using a water block heat exchanger. The reservoir's water temperature was plotted (Figure 89). The

slight bumps in temperature between 0 and 2-hours indicated the impact the every 15-minute fluid circulation had on the reservoir's temperature. When the pump was placed into continuous circulation (approximately the 2-hour mark) the rise in temperature was denoted by a sharp rise in temperature. Specimens were evaluated based on the rate of change and specimen 7 and 8 had the highest rates of 15% and 11% respectively.

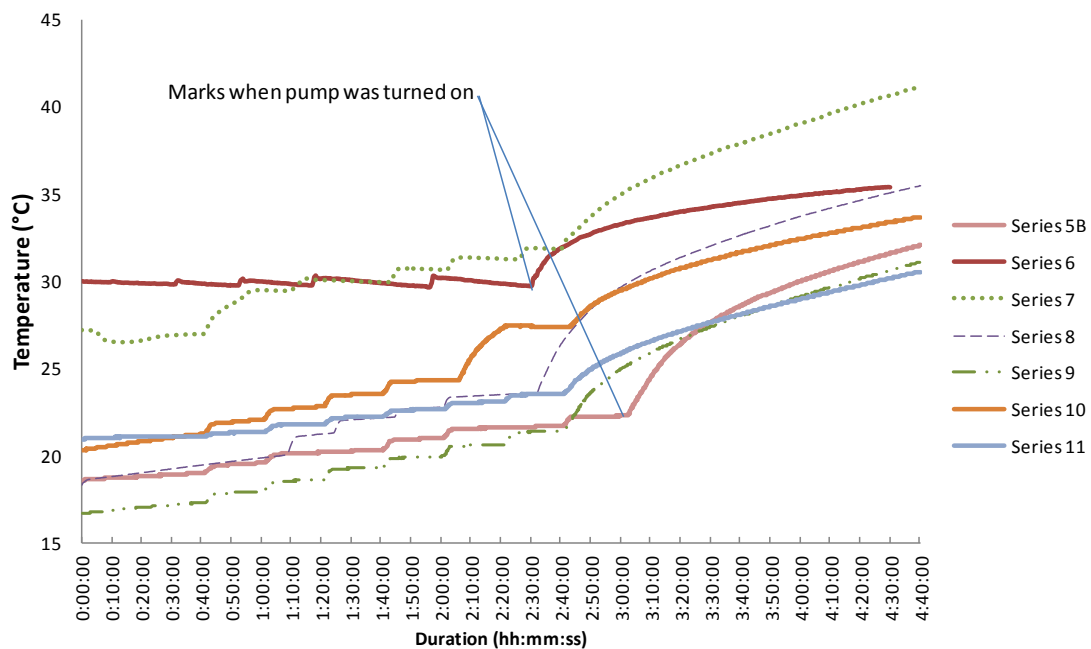
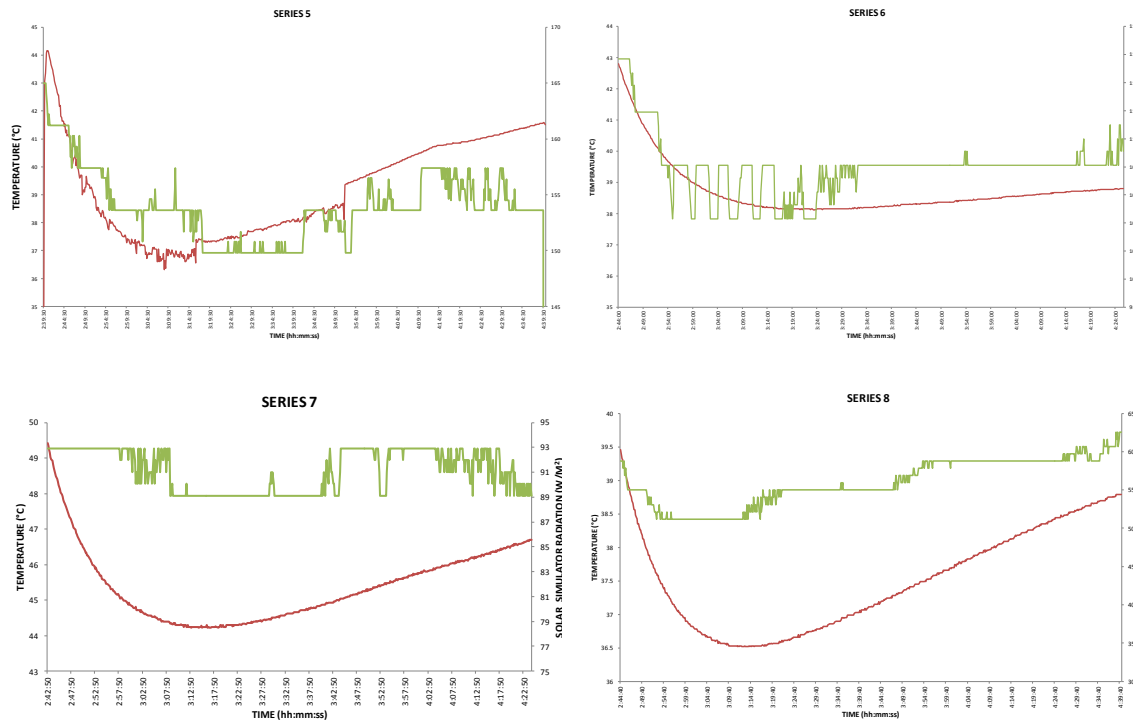


Figure 89: **Water Reservoir Temperature**

## Spectral Absorption Observation

Building on Experiment 1 the fluctuation in solar energy passing through the specimens was evaluated. Each specimen compared solar energy entering the system overlaid with the fluid's temperature & circulation since these were the only variables that changed (Figure 90). In each instance, the level of solar energy passing through the specimen mimicked the drop in temperature indicating that solar energy was influenced in part by fluid temperature.



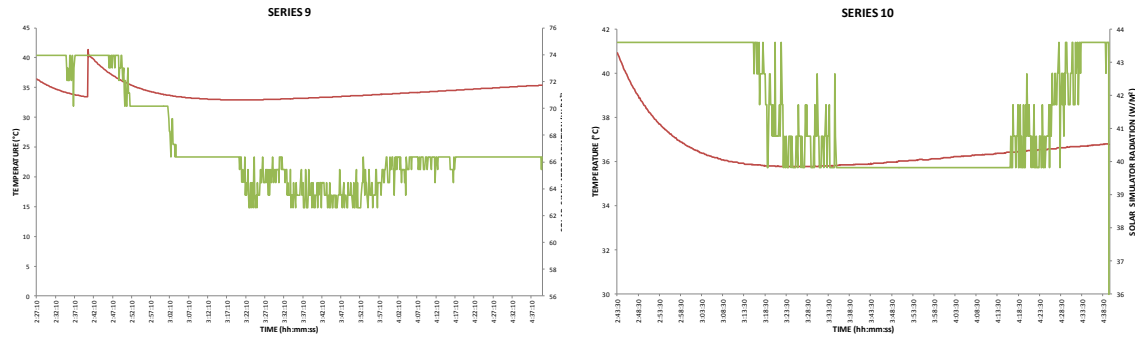


Figure 90: Spectral Absorption w/ Water Fluid Circulation

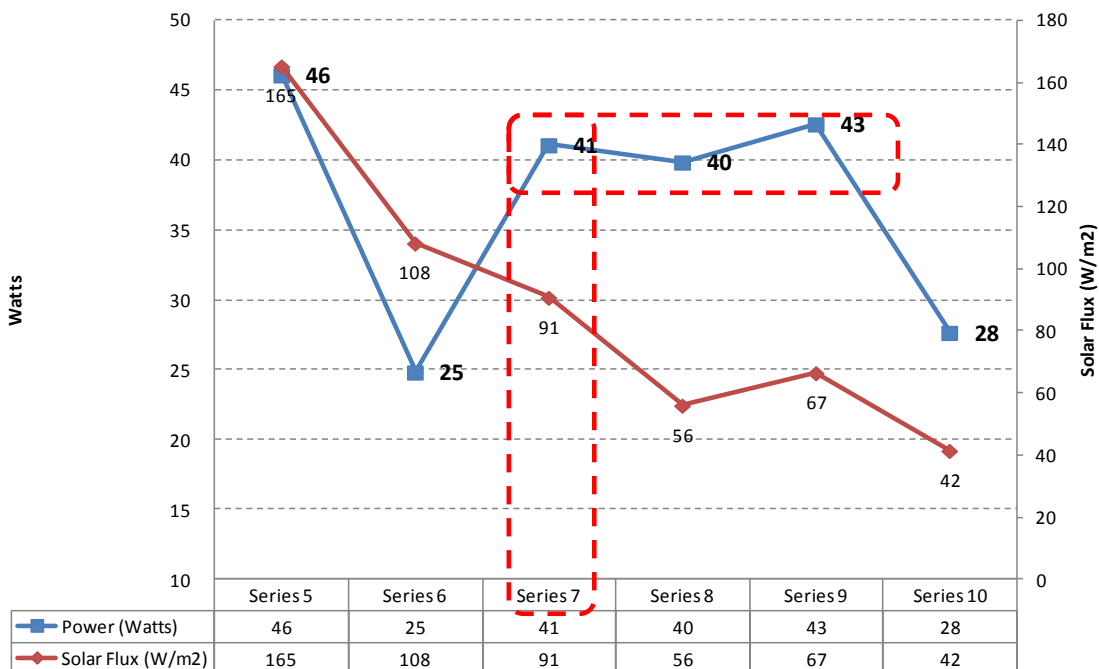
The literature review presented research that the absorption of water was a fundamental property that influenced the passage of light through the water column (Pegau & Zaneveld, 1993, p. 188), and that the absorption spectrum of the water column in the Nanowindows changes with an increase in temperature (Collins, 1925, p. 772). The cause of this lies within the microscopic changes in water structure that occurs as the temperature increases (Langford et al., 2001, p. 8921) causing covalent bonds of the water molecule to produce vibrations that absorb spectral radiation at varying wavelengths. While this was not the focus of the research it offers unique advantages that will be discussed in the conclusion.

## Conclusion

A vital characteristic to defining the Nanowindows' performance was determining its power potential. Much like a photovoltaic panel or a household light bulb the performance of such systems are defined by their power in Watts. In order to calculate this, the custom Power Added calculator was used. The Power Added calculator applied

formulas (29) and (30) and measured the change in the water's temperature in the storage tank. In these experiments Chamber 2 isolated the water tank from all other thermal inputs attempting to reduce unwanted gains or losses from the surrounding environment. Thus the results reflected the power delivered to the water tank from the heat exchanger fueled by the Nanowindow.

Specimens 7, 8, and 9 power potentials were plotted in Figure 91 and yielded 41W, 40W, and 43W respectively. Although specimen 7 in prior experiments was generally favored in this exercise Specimens 8 and 9 offered promising power potential. The amount of solar flux entering the system through Specimen 8 and 9 was less than Specimen 7, yet produced more power at the heat exchanger. Specimen 8 was This was a result of the waters ability to absorb radiant energy at the cost of reducing visible transmittance.



**Figure 91:** H<sub>2</sub>Owindow Power (Watts)

## H<sub>2</sub>Owindow, Experiment 3: Solar Hot Water Simulation II

Experiment 3 evaluated preheating water using a custom-made coil heat exchanger with 30-times more surface area than Experiment 2, and submerged in a 3.5-gallon water tank. In Experiment 2, Specimen 7 delivered 295,000J (41W) and in Experiment 3 delivered 417,060J (58W) – a gain of 17W. Since all other variables remained constant the gain in Watts was attributed to the large surface area of the heat exchanger.

Heat transfer was noticeable in Experiment 2 and 3 (Figure 92 and Figure 93). The higher rate in heat transfer was a function of the surface area of the heat exchanger from 0.005m<sup>2</sup> to 0.11m<sup>2</sup>. The effect corresponded in the fluid's drop in temperature denoted as  $\Delta$  in Figure 92 and Figure 93 were the difference from the highest temperature to the lowest fluid temperature recorded in Experiment 2 and 3 was 6.78°C and 14.1°C respectively.

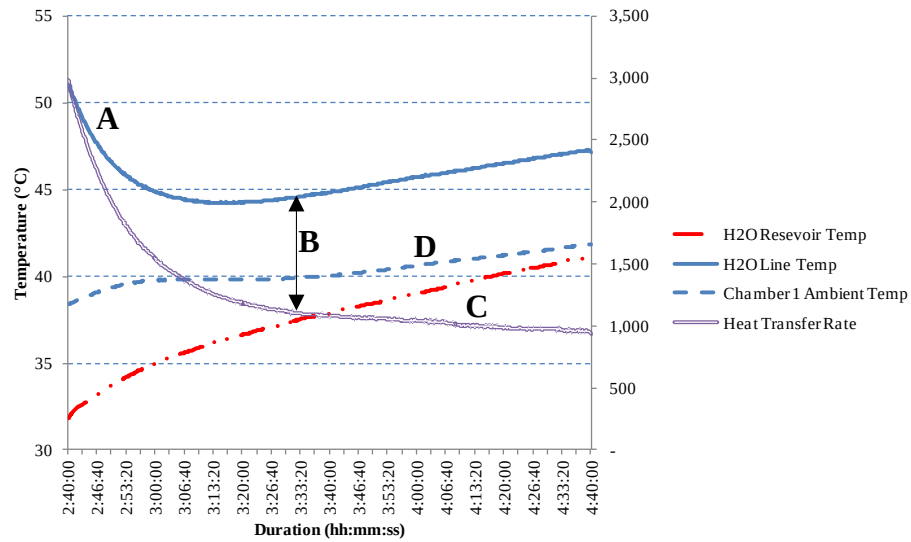
The effect also had an impact on Chamber 1<sup>42</sup> (Figure 75) which was slightly unexpected. In Experiment 2, Chamber 1 ambient temperature (Figure 92, Line D) increased as a function of the solar gains coming through the window. This was expected as not all solar gain can be prevented from entering the flanking space even with the best high performance windows available on the market. In Experiment 3 the ambient temperature

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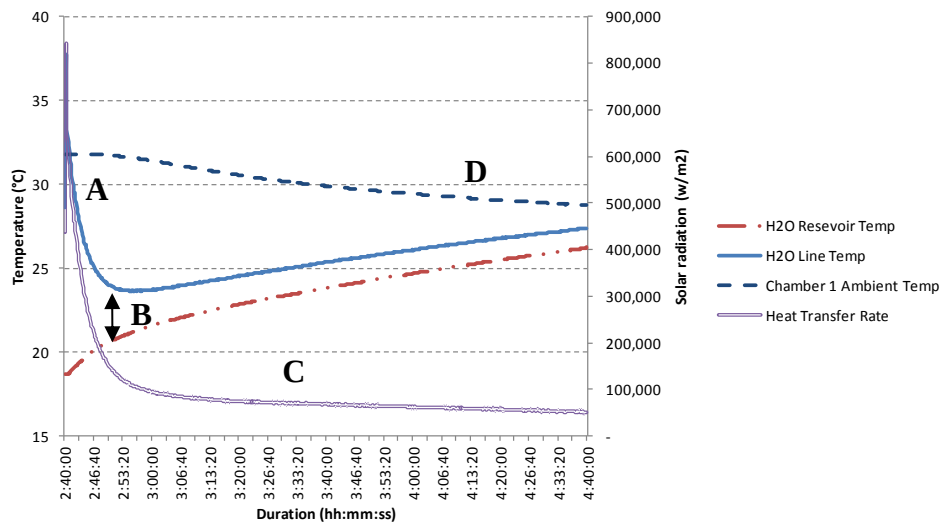
<sup>42</sup> As a reminder Chamber 1 flanks the solar simulator and the specimen is in Chamber 1. Chamber 1 is closed and without air circulation.



in Chamber 1 decreased (Figure 93, Line D). This was unusual considering the results of Experiment 2.



**Figure 92:** Experiment 2



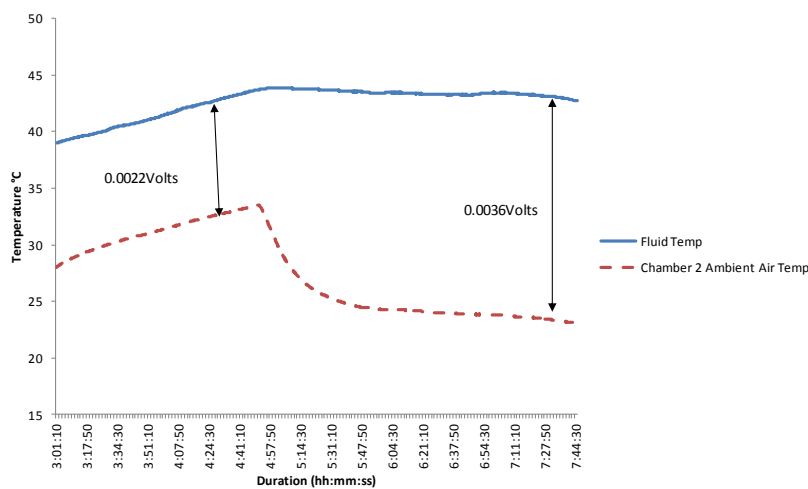
**Figure 93:** Experiment 3

Based on the data gathered and not taking into consideration extraneous variables such as air infiltration or the outdoor environmental conditions it appeared that the H<sub>2</sub>Owindow

may have been serving as a heat sink to Chamber 1. Meaning it was absorbing excess solar heat gain that entered the space during the experiment. However, there were several variables that possibly impacted the results including irregular starting temperatures as well as ambient air surrounding the solar simulator laboratory.

#### H<sub>2</sub>Owindow, Experiment 4: Thermoelectric Generation

Experiment 4A focused on the H<sub>2</sub>Owindow's ability to produce electricity. A 3.88in<sup>2</sup> thermoelectric generator (TEG) was coupled with the water block heat exchanger (Figure 94Figure ) and evaluated the electrical production of the H<sub>2</sub>Owindow. The ambient temperature in chamber 2 for half of the experiment was not held to a constant temperature allowing the chamber's ambient temperature to rise as a function of the heat exchange. About halfway through the experiment the chamber was cooled to a steady temperature of 22°C.



**Figure 94:** Thermoelectric Generation Series 1

During the first half of the experiment the fluid temperatures reached 43°C and the power output maintained a constant 0.022volts. When the chamber was cooled the voltage increased as a function of the increased temperature gradient resulting in an average of 0.036volts.

The results are scalable. Assuming that 12volts or 24volts direct current was desired then the circuit would need to be arranged in series which adds the voltage while maintaining the current. System Size Factor was used to determine system size relative to the desired voltage output to the actual voltage output

$$SSF = \frac{VDC_{desired}}{VDC_{actual}} \quad (31)$$

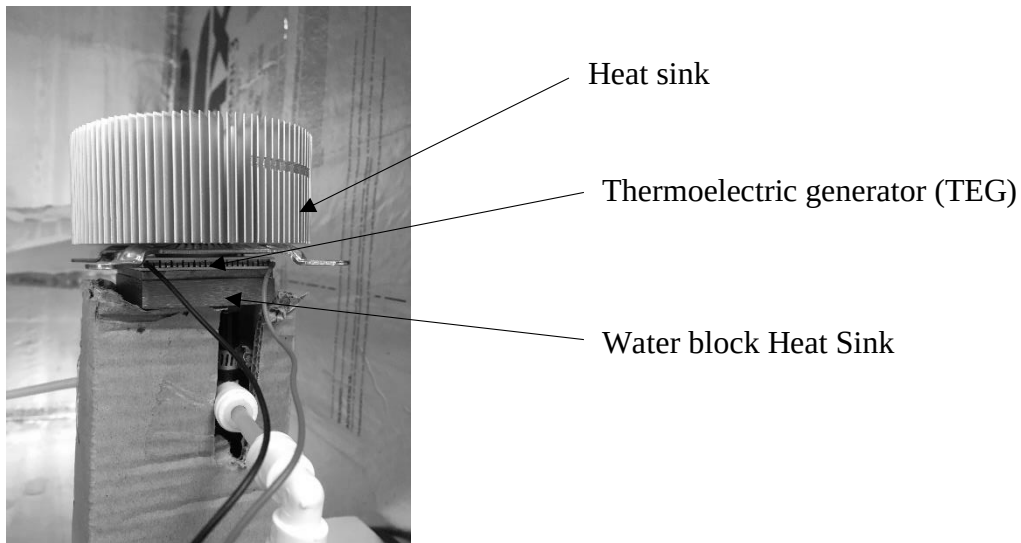
$SSF$  = System Size factor

$VDC_{desired}$  = Voltage level desired (12 or 24vdc)

$VDC_{actual}$  = Voltage actual from experiment

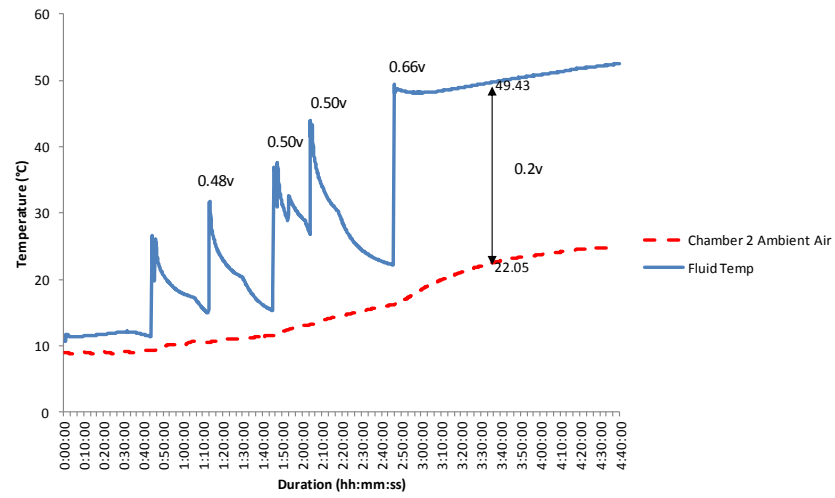
Based on a 12vdc desired output and an average 0.036vdc actual the System Size Factor was determined to be approximately 333. Thus the 3.88in<sup>2</sup> thermoelectric generator surface area would need to be increased to 1,294 in<sup>2</sup> (8.9ft<sup>2</sup>) coupled with 333ft<sup>2</sup> of H<sub>2</sub>O window system – assuming all other variables remain constant.

Experiment 4B attached a circular heat sink (previously described in the methods section) to the cold side of the TEG (Figure 95). Chamber 2 was cooled similar to Experiment 4A of this experiment.



**Figure 95:** TEG with Heat Sink

In this series the fluid temperatures were slightly higher (48°C) and the power output ranged from 0.19 to 0.20volts (Figure 96). The heat sink contributed to the increased power output and previous calculations were revised. Based on a 12vdc desired output the system size factor was determined to be in or about 60 – nearly doubling the power in the previous exercise. Thus 233 in<sup>2</sup> (1.6ft<sup>2</sup>) of thermoelectric generator surface area would be required coupled with 60ft<sup>2</sup> of nanowindow system.

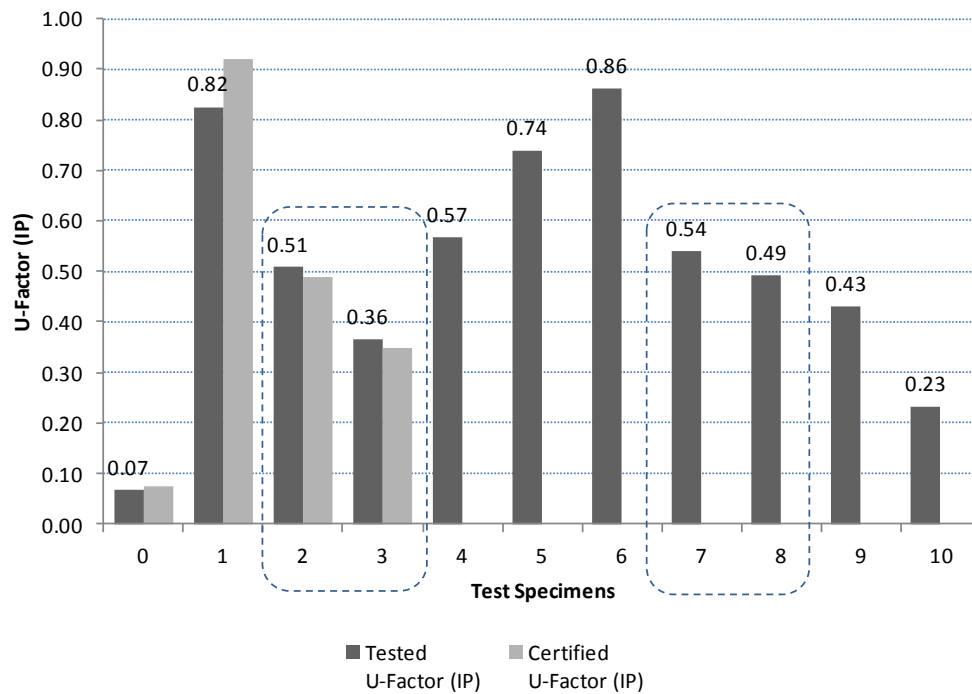


**Figure 96:** Thermoelectric Generation Series 2

## CHAPTER IX

### NANOWINDOW VT, U-FACTOR, & SHGC

Based on the initial distilled water findings, H<sub>2</sub>Owindow 7 and 8 offered equitable rate of thermal resistance (U-Factor) compared to traditional double pane windows (Table 23). Quad-pane H<sub>2</sub>Owindow 9 and 10 resulted in improved U-factor performance, but energy generation was not as promising as H<sub>2</sub>Owindow 7 or 8. As a function of the limited resources of Al<sub>2</sub>O<sub>3</sub> only Nanowindows 7 and 8 were evaluated for U-factor, Visible Transmittance (VT), and Solar heat Gain Coefficient (SHC). No methods varied from the H<sub>2</sub>Owindow tests thus methods are not revisited in this section. The only variation between the H<sub>2</sub>Owindow and Nanowindows is the aluminum oxide nanofluid (Al<sub>2</sub>O<sub>3</sub>).



**Table 23: H<sub>2</sub>Owindow U-factor Results**

## Nanowindow U-Factor Results and Conclusion

U-factor, Visible transmission (VT), and Solar Heat Gain Coefficient (SHGC) alone are not indicators of a high performance window. However, the combination of these and other variables collectively define high performance windows. The U-factor for Nanowindow 7 and H<sub>2</sub>Owindow 7 were within  $\pm 0.013$  Btu/(hr) (ft<sup>2</sup>)(°F) of each other. Similarly Nanowindow 8 and H<sub>2</sub>Owindow 8 were  $\pm 0.009$  Btu/(hr) (ft<sup>2</sup>)(°F) of each other (Figure 97). Based on the calibrated hot box's accuracy and uncertainty defined in the conclusion of Chapter 5 it was deemed that the aluminum oxide nanofluid (Al<sub>2</sub>O<sub>3</sub>) had little to no impact on thermal resistance. This further reinforces that conducting Al<sub>2</sub>O<sub>3</sub> experiments on all the Nanowindows would not yield results favorable to H<sub>2</sub>Owindow 7 and 8.

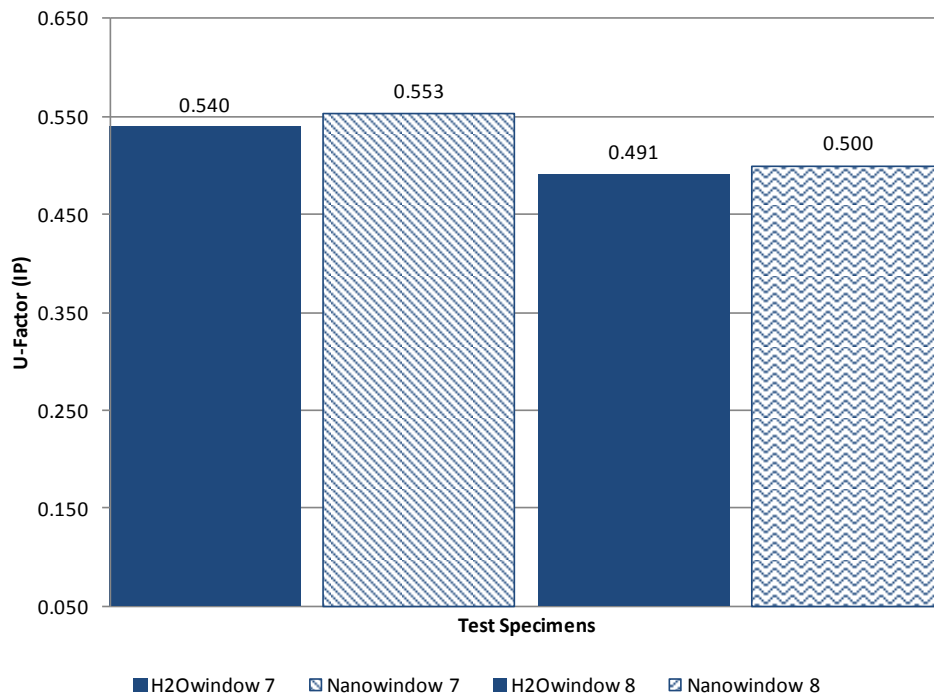


Figure 97: Nanowindow U-factor

Al<sub>2</sub>O<sub>3</sub> nanofluid is not a single variable as tested in these experiments. Nanofluids are complex structures that involve a far greater inquiry into fluid dynamics including variable volumetric flow rates and variable pressure. Future experiments examining these variables may offer new dimensions to enhance the rate of thermal resistance.

### Nanowindow Visible Transmission (VT) Results

For Visible Transmittance the International Energy Conservation Code (IECC) was used to establish a relative baseline of comparison, and it was determined that H<sub>2</sub>Owindow 7 and 8 were above the minimum criteria established by IECC. To recap H<sub>2</sub>Owindow 7 and 8 resulted in a VT of 0.47 and 0.51 respectively, both of which are well above the 0.42(42%) VT code compliance for fixed windows. Nanowindow 7 and 8 resulted in 0.27 and 0.23 respectively which is below code compliance (Figure 98). These results are explained.

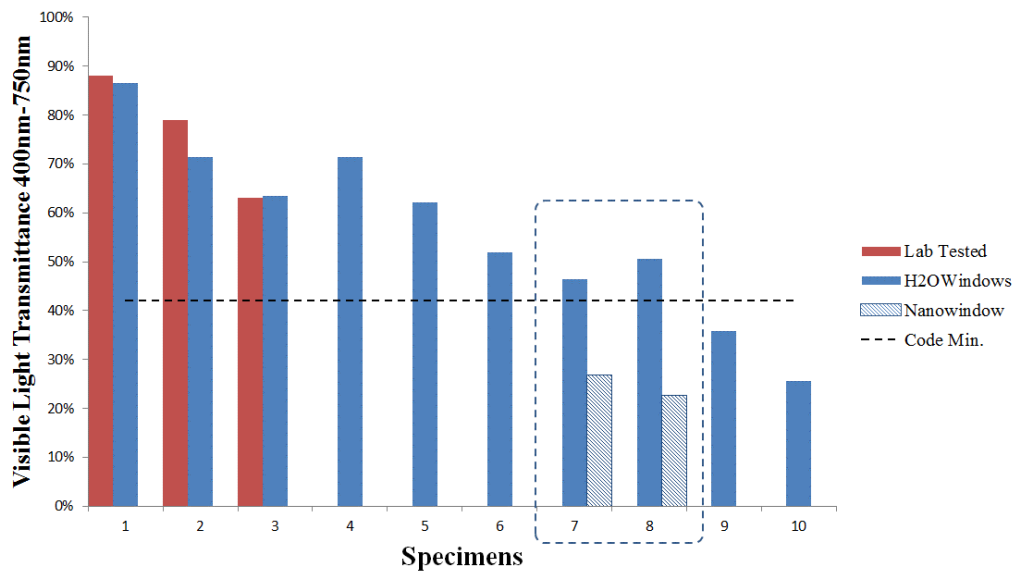


Figure 98: Nanowindow VT Results



During preliminary discussions with the nanofluid manufacturer the criteria for optically clear nanofluid was agreed upon. However, optically clear apparently had varying meanings. From the perspective of the research it was requested as optically clear like water, but in correspondence with Dr. Jason Rama, a Senior Research Scientist at Meliorum Technologies, he notes that if “the particle size is significantly smaller than the wavelength of light, then there should be some appreciable degree of solution clarity, otherwise, if the concentration is relatively high, then the nanofluid acts somewhat like a photonic crystal<sup>43</sup>”. Thus the interest of the research struggled between optically clear and optimizing thermal wavelength trapping. In effect, to optimize thermal and wavelength trapping resulted in a degree of solution clarity slightly less than the distilled water that the aluminum oxide nanofluid ( $\text{Al}_2\text{O}_3$ ) is dispersed in.

#### Nanowindow Visible Transmission (VT) Conclusion

While visible transmission (VT) results were less than favorable the desired optical clarity was not achieved within the framework of this exercise. However, the capability for aluminum oxide nanofluid to be in a clear solution can be achieved as long as the concentration balances nanoparticle weight to volume of concentration. Alternatively, sonication is recommended. Sonication uses sound energy to agitate the nanoparticles to keep them dispersed in the distilled water, and improves optical clarity.

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<sup>43</sup> A photonic crystal is an optical nanostructure that allows some wavelength of light to pass while preventing others. Photonic engineering can control the behavior of light waves which is central to this research. Photonic crystal was discussed in Chapter III Literature review.

## Nanowindow Solar Heat Gain Coefficient (SHGC) Results

H<sub>2</sub>Owindow 7, 8, 9 and 10 Solar Heat Gain Coefficient (SHGC) yielded favorable results (Figure 99). H<sub>2</sub>Owindow 7 and 8 resulted in comparable results to double pane and triple pane windows, while H<sub>2</sub>Owindow 9 and 10 outperformed all the baseline windows and H<sub>2</sub>Owindows. As mentioned in Chapter VII SHGC is not an absolute condition for code compliance and largely influence by exterior solar shading strategies.

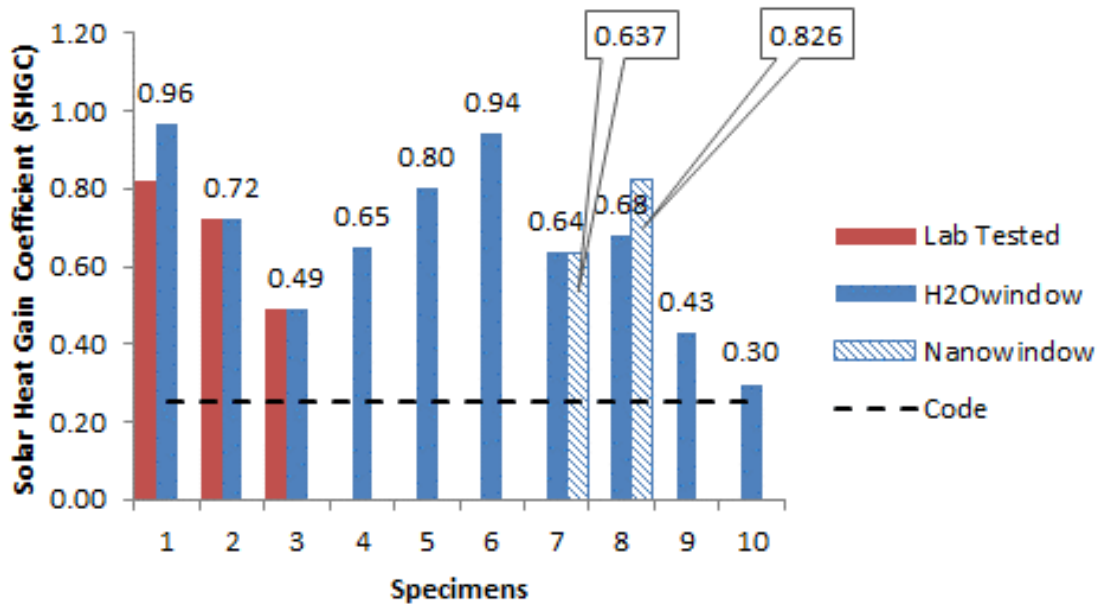


Figure 99: H<sub>2</sub>Owindow SHGC Results

Nanowindow 7 and 8 were loaded with aluminum oxide (Al<sub>2</sub>O<sub>3</sub>) nanofluids and tested. Nanowindow 7 was within  $\pm 0.007$  (1% difference) of H<sub>2</sub>Owindow 7, and the SHGC for Nanowindow 8 was surprisingly 0.049 or 7% more than H<sub>2</sub>Owindow 8 (Figure 99). This raised concerns that a testing error may have occurred as the rate of heat transfer between

H<sub>2</sub>Owindow 8 and Nanowindow 8 should be similar. After closer examination of the data it was determined that the Climate Chamber had cooled beyond its set-point by 5°C reaching a low of 10°C compared to other test conditions that ran at a steady state of  $\pm 15^\circ\text{C}$ .

#### Nanowindow Solar Heat Gain Coefficient (SHGC) Conclusion

Measures were taken to ensure viable SHGC data but the outdoor research lab within a semi-enclosed space may have been insufficient to filter out all the possible extraneous variables. Fluctuations in the outdoor environment may have influenced the climate chamber, and the refrigeration system's ability to modulate a steady temperature. This impacted steady state in the cooling side resulting in varying temperatures between test series. Future refrigeration systems should be doubled to accommodate any outdoor environmental variability so that response time is not limited by outdoor temperatures on the refrigeration's heat pump. On the meter side of the CHB the heating element was able to maintain steady temperatures throughout all the experiments.

An alternative would have been a guarded calibrated hot box (GCHB) to isolate the test chambers from extraneous variables. A GCHB requires a larger space, and additional sensors to monitor the guard.

## CHAPTER X

### NANOWINDOW AS ENERGY GENERATOR

#### Nanowindow Experiment 1: Radiant Heating Simulation

Experiment 1 set out to simulate how effective a Nanowindow could be as a radiant heater as illustrated in Figure 15. The Nanowindow was isolated from the heat exchanger in Chamber 2, and was measured and compared to H<sub>2</sub>Owindows. Based on the H<sub>2</sub>Owindow experiments the most promising specimens were H<sub>2</sub>Owindow7 & 8. Aside from the aluminum oxide nanofluid (Al<sub>2</sub>O<sub>3</sub>) the methods discussed in Chapter VIII remain the same.

As previously mentioned a custom Heat Transfer Calculator (Figure 100) was developed and inserted into each data set to determine the convective and radiative heat transfer coefficient. H<sub>2</sub>Owindows and Nanowindow results were plotted and compared (Figure 101).

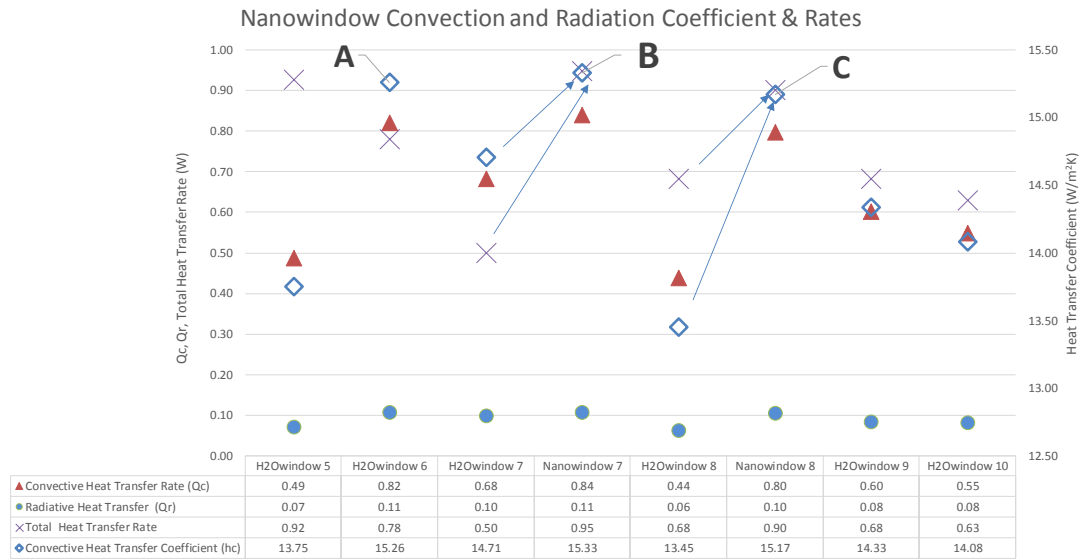
## H<sub>2</sub>Owindow 8



|                                                                |                                          |
|----------------------------------------------------------------|------------------------------------------|
| Area of plate ( $A$ )                                          | 0.00250 m <sup>2</sup>                   |
| Perimeter of plate ( $p$ )                                     | 0.2023 m                                 |
| Plate characteristics ( $P_c$ )                                | 0.012 m                                  |
| Plate Temperature ( $T_s$ )                                    | 38.2 °C                                  |
| Air Temperature ( $T_\infty$ )                                 | 25.2 °C                                  |
| Fluid viscosity ( $\eta$ )                                     | 1.87E-05 kg/ms                           |
| Fluid density ( $\rho$ )                                       | 1.137 kg/m <sup>3</sup>                  |
| Fluid specific heat ( $C_p$ )                                  | 1.005 kJ/kg K                            |
| Fluid conductivity ( $k$ )                                     | 0.027 W/m K                              |
| Prandtl Number ( $Pr$ )                                        | 0.705                                    |
| gravity                                                        | 9.8 m/s                                  |
| temp difference                                                | 12.98 °C                                 |
| Film Temperature ( $T_f$ )                                     | 31.74 °C                                 |
| Kelvin                                                         | 305 K                                    |
| Thermal expansion coefficient ( $\beta$ )                      | 0.0033                                   |
| Air Flow (CFM)                                                 | 1 m/s                                    |
| Grashof ( $Gr$ )                                               | 2.40E+04                                 |
| Rayleigh ( $Ra$ )                                              | 1.69E+04                                 |
| Nusselt Number ( $Nu = 0.54 Ra^{1/4}$ ) ( $10^4 < Ra < 10^7$ ) | 6.16                                     |
| Heat Transfer Coefficient ( $h_c$ )                            | 13.45 W/m <sup>2</sup> K                 |
| <b>Convective Heat Transfer Rate (<math>Q_c</math>)</b>        | <b>0.44 W</b>                            |
| Emissivity ( $e$ )                                             | 0.3                                      |
| Stephan's Constant ( $s$ )                                     | 5.67E-08 W/m <sup>2</sup> K <sup>4</sup> |
| Plate Temperature ( $T_s$ )                                    | 311.38 K                                 |
| Air Temperature ( $T_\infty$ )                                 | 298.39 K                                 |
| <b>Radiative Heat Transfer (<math>Q_r</math>)</b>              | <b>0.063 W</b>                           |
| <b>Total Heat Transfer Rate</b>                                | <b>0.50 W</b>                            |

**Figure 100: Heat Transfer Rate Calculator (Example)**

H<sub>2</sub>Owindow 6 was a double pane assembly and yielded the highest convective and radiative heat transfer coefficients of all the H<sub>2</sub>Owindows and Nanowindows (Figure 101, A). This was to be expected considering that it was composed of a single fluid column allowing the system to charge at a faster rate because the fluid column was unobstructed by flanking column(s) of air as with all the other Nanowindows. Air's low conductivity and high viscosity reduces the rate of heat transfer as previously discussed in the literature review.



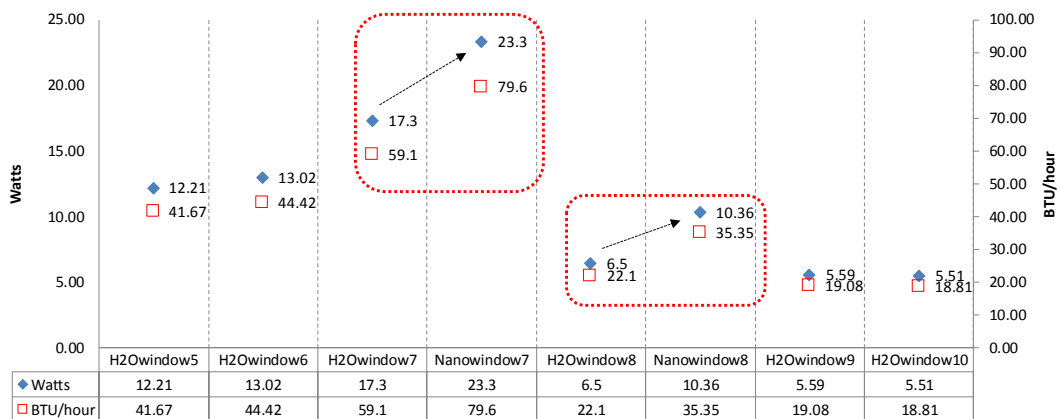
**Figure 101: Experiment 1 Nanowindow Results**

While H<sub>2</sub>Owindow 6 had a high heat transfer rate (Figure 101, A) it had the lowest U-Factor as defined in Chapter VII and illustrated in Figure 69. Thus, H<sub>2</sub>Owindow 6 was not a favorable fluidized assembly because it would experience tremendous heat loss compared to the other specimens.

Nanowindow 7's total heat transfer rate (Convective + Radiative Heat Transfer) performed 90% better than H<sub>2</sub>Owindow 7 (Figure 101, B). This was a 23% improvement in convective heat transfer. Similarly, Nanowindow 8's total heat transfer rate (Convective + Radiative Heat Transfer) performed 23% better than H<sub>2</sub>Owindow 8 (Figure 101, C). While Nanowindow 8's convective and radiative coefficients improved significantly it was not as impactful as Nanowindow 7 that was nearly 4% better than Nanowindow 8. Thus Al<sub>2</sub>O<sub>3</sub> nanofluid had measurable impact on the convective and

radiative heat transfer coefficient and was capable of trapping solar radiation, storing thermal energy, and displacing nanofluids to a heat exchanger to preheat air.

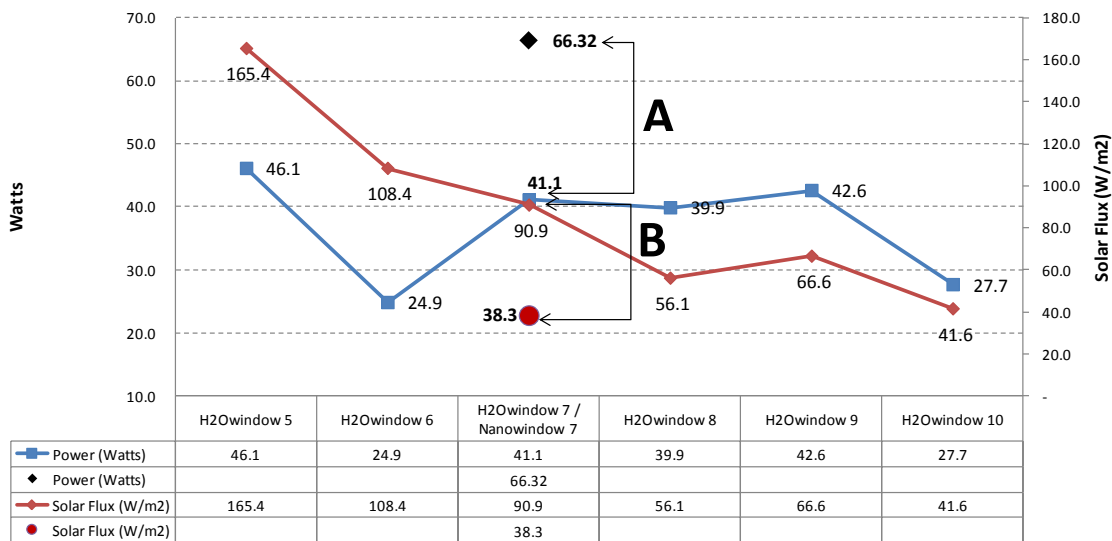
Experiment 1 was evaluated using a different set of data points collected during the experiment. This evaluation examined the difference in ambient temperature experienced in Chamber 2 to better understand the convective impact by the heat exchanger measured in Watts and BTU. Nanowindows 7 and 8 exhibited 33% improvement over H<sub>2</sub>Owindow 7 and 8 which aligns with the convective and radiation coefficients previously discussed in Figure 101.



**Figure 102: Nanowindow Watts & BTU/hour**

## Nanowindow Experiment 2: Solar Hot Water Simulation I

Experiment 2 submerged the water block in Experiment 1 in a 2 gallon water tank. This evaluated the Nanowindow's ability to preheat domestic or commercial hot water systems. H2Owindow 7 resulted in favorable rates of heat exchange at 41W. This was determined using the Power Added Calculator that applied formulas (29) and (30). The results of the H2Owindows and the Nanowindow 7 were plotted in Figure 103.



**Figure 103: Nanowindow Power (Watts)**

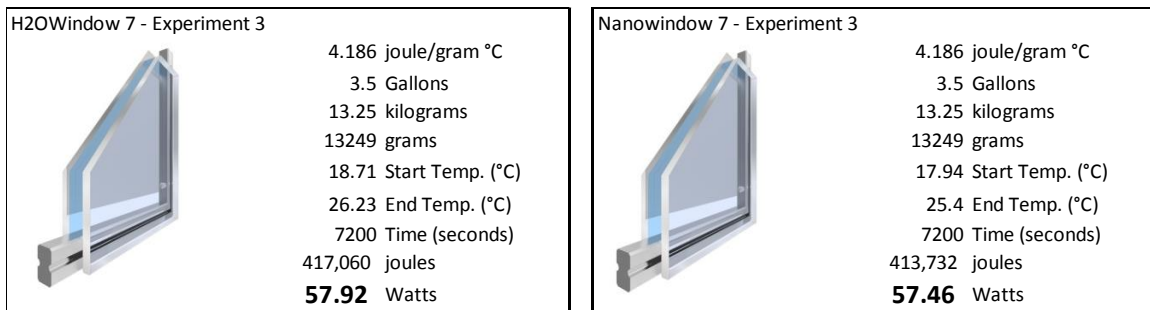
Nanowindow 7 resulted in 66W compared to the H2Owindow 7 with 41W - a 61% improvement (Figure 103, A). Also notable is that the 61% improvement was achieved with 57% less radiant heat flux (Figure 103, B) entering Chamber 1 compared to H2Owindow 7 (Figure 103).



### Nanowindow Experiment 3: Solar Hot Water Simulation II

Similar to Experiment 2, Experiment 3 used a custom fabricated coil heat exchanger submerged in a 3.5 gallon tank of water and placed in Chamber 2 of the Calibrated Hot Box (Figure 78). The objective was to determine the Nanowindow's ability to function as a renewable source of energy to preheat water in a closed loop system. Solar hot water (SHW) systems are widely used for domestic and commercial water heating to reduce fossil fuel demand.

The heat exchange calculator was used to evaluate the Nanowindow data (Figure 104). The baseline H<sub>2</sub>Owindow 7 resulted in a rate of heat exchange of 57.92 w, and Nanowindow 7 resulted in 57.46 w – almost identical heat exchange rates. While the results were relatively disappointing the low heat rate was examined.



**Figure 104: Nanowindow Calculator**

The data revealed that the baseline H<sub>2</sub>Owindow and Nanowindow rates were nearly equal. Most notable was the significantly lower radiant heat flux transmitted through the Nanowindow that resulted in lower heat exchange rates. The H<sub>2</sub>Owindow's average

radiant heat flux was  $78 \text{ w/m}^2$  and the Nanowindow was  $38 \text{ w/m}^2$  – a 47% drop in heat flux through the Nanowindow (Figure 105, C). This was largely attributed to the dispersion of aluminum oxide in the distilled water causing a slightly opaque condition that reflected long wave radiation back out into the fluid and atmosphere. Despite the near 47% reduction in transmitted heat flux the Nanowindow had a higher starting temperature of  $47^\circ\text{C}$  compared to the H<sub>2</sub>Owindow's starting temperature of  $37^\circ\text{C}$  – a 27% improvement in conducting thermal energy (Figure 105, A & B).

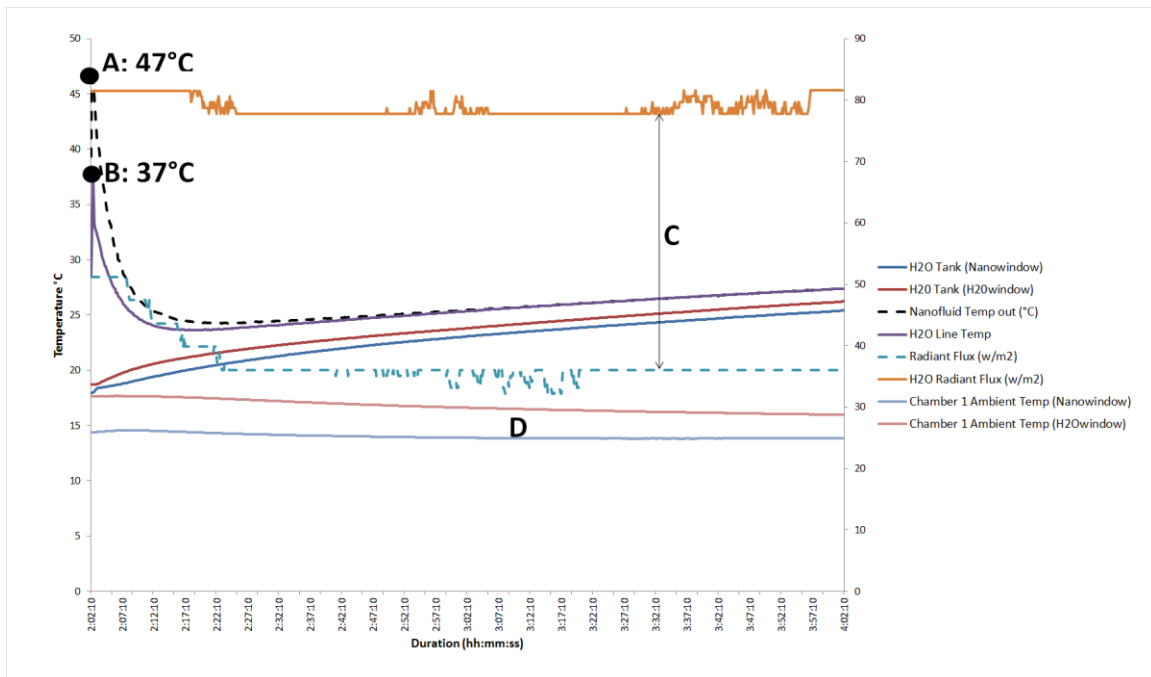


Figure 105: Experiment 3 Nanowindow Results

As seen in the H<sub>2</sub>Owindow experiment Chamber 1's ambient temperature decreased during the pump cycle. This was attributed to the window's ability to absorb sensible heat in Chamber 1 via the window's fluid and released through the heat exchanger in Chamber

2. In essence the Nanowindow can be characterized as a long wave absorber plate.

Nanowindow7 displayed identical qualities by lowering Chamber 1's ambient temperature during the pumping cycle (Figure 105, D).

Similar to the H<sub>2</sub>Owindow experiments the Nanowindow exhibited similar spectral shifting when fluids were in circulation (Figure 106, A). This was determined to be a fundamental property of light passing through a column of water as explained on page 202. As previously noted the cause of this lies within the microscopic changes in water structure that occurs as the temperature increases (Langford et al., 2001, p. 8921) causing covalent bonds of the water molecule to produce vibrations that absorb spectral radiation at varying wavelengths.

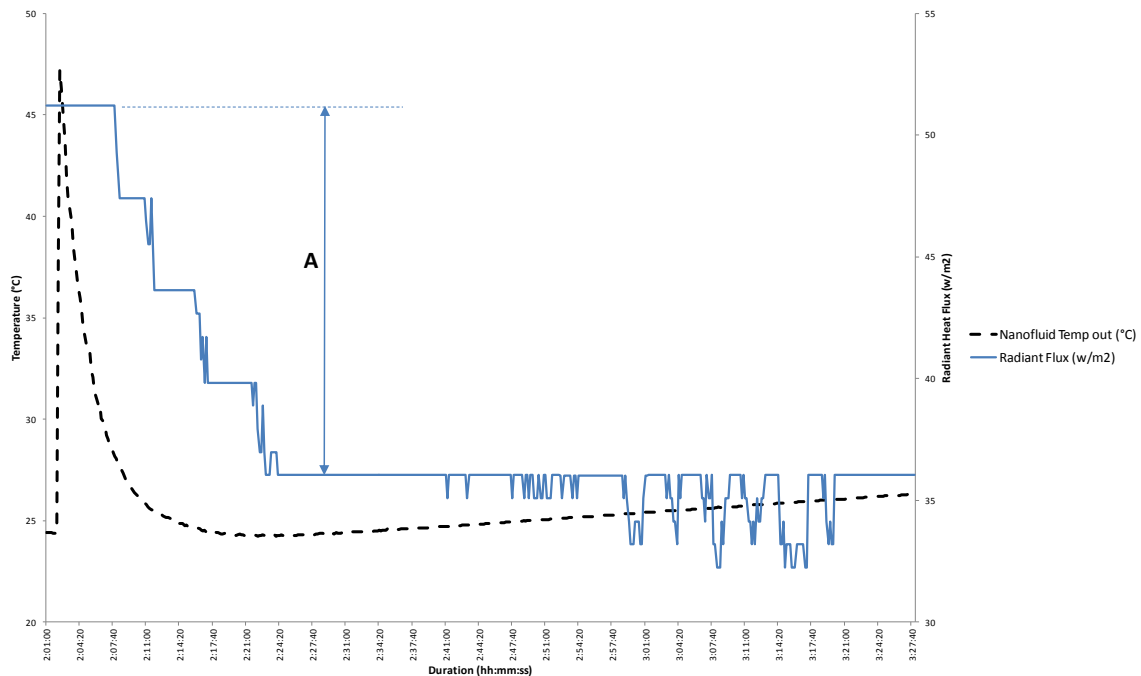


Figure 106: Spectral Absorption w/ Nanofluid Circulation

A spectroradiometer was used to evaluate the circulating nanofluid's influence in the visible spectrum. It was found that there were notable differences between the distilled water and aluminum oxide nanofluid. Irradiance ( $\mu\text{W}/\text{cm}^2/\text{nm}$ ) at 435nm, 535nm, and 580nm wavelengths was reduced by 38%, 25%, and 26% respectively. While this was helpful in determining which wavelengths were impacted, the spectroradiometer's range was limited to the visible spectrum between 360-750nm. Generalization of thermal energy states that 46% of energy content is transmitted in the visible spectrum, 46% in the infrared, and the remaining 8% in the ultraviolet. The proposed findings illustrate that Nanowindows have the capacity to trap thermal energy in the visible spectrum, but that unknown quantities in the ultraviolet and infrared are to be determined.

## Conclusion

Experiment 3 compared Nanowindow 7 to the  $\text{H}_2\text{O}$  window 7 in a closed-looped heat exchange scenario. The results indicate that the two performed equally at face value, but further inquiry into the data proposes that the nanofluid's particle size, concentration, solvent, and particle purity may collectively influence the performance of the Nanowindow. While this experiment used a particle size mean of  $10\text{nm} \pm 5\text{nm}$ , 1% concentration by weight, and particle purity of 99.95+% there may be other particle combinations that favor stronger conductivity properties and enhanced visible transmittance. Using this nanoparticle specification resulted in a column temperature that was 27% higher than the  $\text{H}_2\text{O}$  window.

Future experiments are encouraged to study the ultraviolet (UV), visible, and infrared spectrum to form a more robust understanding of thermal trapping at specific wavelength. It is speculated that other nanofluids and carbon-nanotubes may impact thermal trapping at different wavelengths and promote favorable results.

#### Nanowindow Experiment 4: Thermoelectric Generation

To recap H<sub>2</sub>Owindow 7 produced 0.022volts at ambient temperature and 0.036volts at a steady state of 25°C. Adding a heat sink increased the voltage output by a factor of 4 to 0.19volts resulting in a system size factor of 63 (Table 24). The objective was to determine the impact aluminum oxide (Al<sub>2</sub>O<sub>3</sub>) nanofluids had on electrical production. Methods applied were identical as stated in Chapter VIII and all other variables remain the same.

|        | Fan | Heat Sink | H2Owindow 7A<br>Chamber Temp Variable |                          | H2Owindow 7B<br>Chamber Temp 25°C |                          | H2Owindow 7C<br>Chamber Temp 22°C |                          |
|--------|-----|-----------|---------------------------------------|--------------------------|-----------------------------------|--------------------------|-----------------------------------|--------------------------|
|        |     |           | Voltage (VDC)                         | System Size Factor (SSF) | Voltage (VDC)                     | System Size Factor (SSF) | Voltage (VDC)                     | System Size Factor (SSF) |
| Test 1 |     |           | 0.022                                 | 545                      | 0.036                             | 333                      | -                                 | -                        |
| Test 2 | •   |           | -                                     | -                        | -                                 | -                        | -                                 | -                        |
| Test 3 |     | •         | -                                     | -                        | -                                 | -                        | 0.19                              | 63                       |
| Test 4 | •   | •         | -                                     | -                        | -                                 | -                        | -                                 | -                        |

Table 24: H2Owindow Thermoelectric Results

To accomplish this, four thermoelectric tests were conducted on Nanowindow 7 & 8, two more than the H<sub>2</sub>Owindow experiments.

Thermoelectric Test Series measured electrical power and current under varying conditions (Table 25).

Test 1 Thermoelectric Generator Only

Test 2 Thermoelectric Generator + Air Circulation, No Heat Sink.

Test 3 Thermoelectric Generator + Heat Sink, No Air Circulation

Test 4 Thermoelectric Generator + Heat Sink + Air Circulation

Nanowindow 7 Test 1 resulted in 0.047volts resulting in a 113% improvement over the H<sub>2</sub>Owindow Test 1. Nanowindow 7 outperformed H<sub>2</sub>Owindow 7B Test 1 by 30% without the need to establish steady state temperature of 25°C. Nanowindow 7 Test 2, 3, and 4 resulted in increased voltage outputs as a function of larger temperature differential across the thermoelectric generator. The optimal arrangement coupled the thermoelectric generator with a heat sink and fan (Table 25, Test 4).

|               |     |              | Nanowindow 7<br>Chamber Temp Variable |                             | Nanowindow 8<br>Chamber Temp Variable |                             |
|---------------|-----|--------------|---------------------------------------|-----------------------------|---------------------------------------|-----------------------------|
|               | Fan | Heat<br>Sink | Voltage Output<br>(V-DC)              | System Size<br>factor (SSF) | Voltage Output<br>(V-DC)              | System Size factor<br>(SSF) |
| <b>Test 1</b> |     |              | 0.047                                 | 225                         | 0.019                                 | 632                         |
| <b>Test 2</b> | •   |              | 0.115                                 | 104                         | 0.085                                 | 141                         |
| <b>Test 3</b> |     | •            | 0.130                                 | 92                          | 0.180                                 | 67                          |
| <b>Test 4</b> | •   | •            | 0.31                                  | <b>39</b>                   | 0.227                                 | 53                          |

Table 25: Nanowindow Thermoelectric Results

Nanowindow 7 Test 4, resulted in a System Size Factor (SSF) of 39 which was 38% better compared to all other H<sub>2</sub>Owindow and Nanowindow experiments (Table 25, Test

4). Thus 151 in<sup>2</sup> (1.04ft<sup>2</sup>) of thermoelectric generator surface area is required for every 39ft<sup>2</sup> of nanowindow system based on a system size factor of 39.

Based on the findings a 1sqft Nanowindow generated 0.31volts and a rated current of 0.075Adc . The Nanowindow was scaled to have meaningful impact as a renewable technology. As such a hypothetical 24volt assembly was assumed and Ohm's Law was applied to derive the Nanowindow's electrical potential such that

$$\frac{Vd}{Va} = Nano_{Assembly}$$

Where :

$Vd_{(dc)}$  = Voltage Desired (vdc)

$Va_{(dc)}$  = Voltage Actual (vdc/sqft)

$Nano_{Assembly}$  = Nanowindow Assembly Size (sqft)

Applied: 24vdc/0.31vdc = 77.42sqft

(32)

Thus a 24vdc circuit requires approximately 77sqft of Nanowindow and 2sqft of thermoelectric generator to produce 1.8Watts of electricity. On its own the impact is less than impressive but begins to frame the potential for scalability when considering that the last 5 high rise buildings in Los Angele resulted in 1.3 million square feet of window area with direct solar access.

## CHAPTER XI

### CONCLUSION

This proof of concept research transformed the gap in double- and triple-pane windows into solar energy traps, turning windows into transparent energy generators. To transform the gap into an energy trap, the research turned to nanotechnology, specifically aluminum oxide ( $\text{Al}_2\text{O}_3$ ) nanofluids that have unique photothermal efficiencies that exceed water by 80% (Choi, 1998, p. 13) and retain acceptable levels of optical clarity. The research designed, fabricated, and built seven prototype windows that were filled with nanofluids to create the Nanowindow. The Nanowindows were tested in a custom-built solar lab equipped with a CHB and an artificial sun producing 750-850  $\text{W}/\text{m}^2$ , and calibrated to ASTM E92-2015 solar simulation standards and the ASTM C1363-11 standard test method for hot box apparatus. Scientific-grade dataloggers and sensors collected over 7 million data points that were overlaid with several custom programs that evaluated heat transfer rates.

Nanowindows achieved U-factors ranging from 0.23 to 0.54, and SHGC from 0.43 to 0.67, which adhere to IECC standards. One potential drawback was low VT that ranged from 0.27 to 0.38 (Figure 98), which is 7% below IECC standards. While the optical clarity was slightly compromised, there is confidence that the correct combination of nanoparticle type, size, and dispersion will achieve optical clarity.

Four experiments coupled the seven Nanowindows with three different heat exchangers and a thermoelectric generator to assess the Nanowindow's ability to heat air and water,



and to produce electricity. The iterative process investigated convection, radiation, conduction, and electrical production by comparing the Nanowindows to similar prototypes using distilled water.

Using  $\text{Al}_2\text{O}_3$  nanofluid illustrated stronger convective, radiative, and conductive heat transfer rates over water-based  $\text{H}_2\text{O}$  windows (Figure 101). In some instances, the total heat rate was nearly 90% better as a function of the nanofluid column. Coupling the Nanowindow with a thermoelectric generator produced a rated voltage of 0.31VDC and rated current of 0.075ADC (Table 25). In all experiments, the nanofluid column proximal to the outside and the air column closest to the interior offered the best collective results of the seven prototypes.

In all experiments, circulating nanofluids reduced irradiance level transmitted compared to nanofluids fluids at rest (Figure 86). The literature review presented research that the absorption of water was a fundamental property that influenced the passage of light through the water column (Pegau & Zaneveld, 1993, p. 188), and that the absorption spectrum of the water column in the Nanowindows changes with an increase in temperature (Collins, 1925, p. 772). The cause of this change lies within the microscopic changes in water structure that occur as the temperature increases (Langford et al., 2001, p. 8921), causing covalent bonds of the water molecule to produce vibrations that absorb spectral radiation at varying wavelengths. While this was not the focus of the present research, it offers unique advantages that a Nanofluid column may have on limiting

various portions of the solar spectrum to protect indoor occupants from harmful wavelengths.

Experiment 3 illustrated that large heat exchangers may turn Nanowindows into a cooling device. In this experiment, Chamber 1's ambient temperature started to drop as a function of the increased size of the heat exchanger (Figure 93). It is possible that the Nanowindow reduced the amount of incoming solar thermal energy and dissipated it at a high rate, allowing the Nanowindow to absorb the sensible heat in Chamber 1.

## CHAPTER XII

### DISCUSSION

This proof of concept research was inspired by the lack of meaningful dimension of the vertical landscapes of glass called windowscapes. This vast unclaimed territory combined with Nanowindow technology may transform windows into transparent generators capable of thermal and electric production. This research provided small but promising impact and, if scaled to a city context, holds the potential for meaningful impact.

To best illustrate the nanolevels of energy production, five new buildings in Los Angeles were surveyed. The combined windowscape resulted in 2 million square feet of glass, 1.3 million of which has solar access for 5.6 hours on average per day. If one were to take the 1.3 million square feet of glass and replace it with photovoltaics, the solar array would produce 18,116 kW-DC (18.1 megawatts),<sup>44</sup> cover 13 city blocks,<sup>45</sup> service over 14,275 homes,<sup>46</sup> take 2,400<sup>47</sup> cars off the street, and eliminate 13,655 tons of CO<sub>2</sub> (Figure 107). Conceptually, replacing windows with photovoltaic panels is not an option because it would eliminate daylight and views, turning workplaces into dark, miserable high-rise caves with astronomical lighting bills—not to mention that workplace health would be devastatingly bleak.

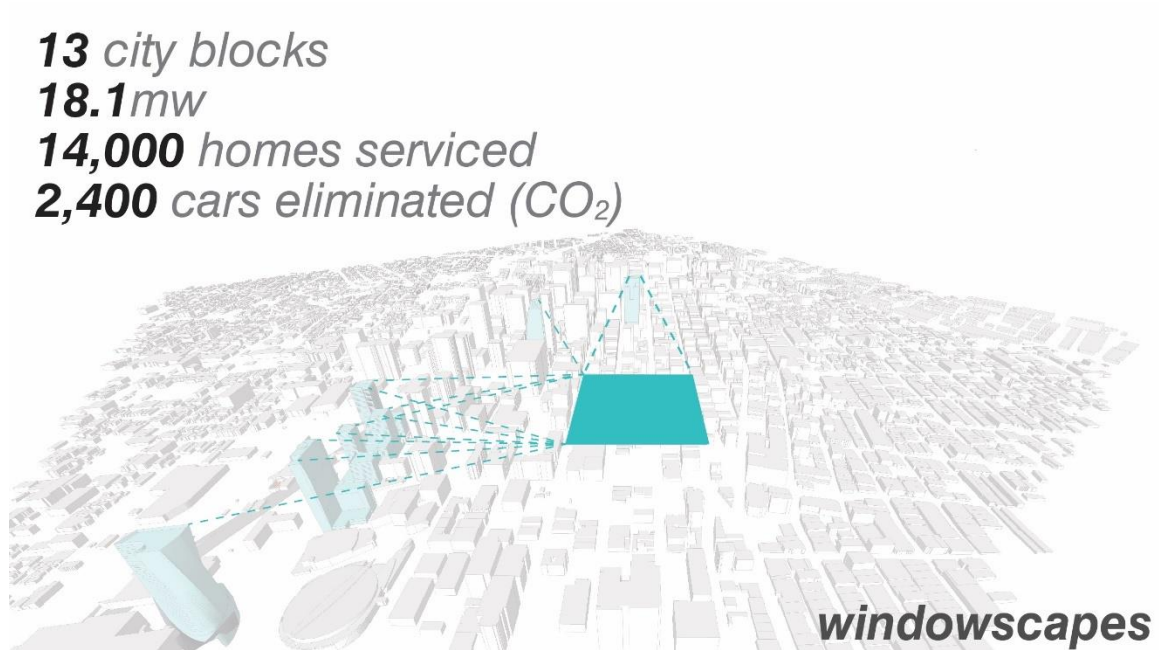
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<sup>44</sup> PVWatts Calculator was used to derive the values. 18116kW-DC was based on a standard module at 34° tilt along the 34° latitude with 5.6 kWh/m<sup>2</sup>/day of solar radiation.

<sup>45</sup> Based on a 100,000sqft city block module

<sup>46</sup> U.S. Energy Information Administration (EIA) notes that in 2015 the average U.S. residential home consumed ±901kWh per month.

<sup>47</sup> EPA states that a typical passenger vehicle emits ±4.7 metric tons of CO<sub>2</sub>/year



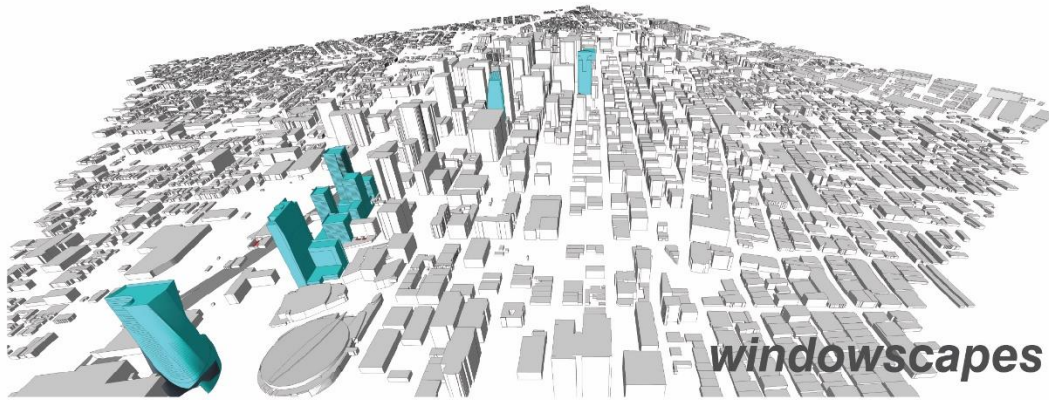
**Figure 107: Environmental Impact of Windowscapes**

Based on this research, the scalability proposes that 1.3 million square feet of Nanowindows coupled with 33,800 square feet of thermoelectric generators could result in 18,100 W (18 kW)<sup>48</sup> of electricity, service 14 homes, take 2.4 cars off the street, and eliminate 13 tons of CO<sub>2</sub> (Figure 108). While the impact may not be as significant as photovoltaics, it illustrates that Nanowindows possess the potential to be considered as a renewable technology alternative with viable beginnings.

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<sup>48</sup> Based on PVWatts the tilt angle was adjusted to 90-degrees to simulate a vertical solar panel. It was determining that there is a 40% degradation in energy production compared to 34-degrees. 18 kW takes into consideration 90-degree tilt.

*1.3 million sqft of nanowindow*  
**33,800 sqft TEG**  
*14 homes off-grid*  
**13 tons of CO<sub>2</sub> eliminated**



**Figure 108: Windowscapes & Nanowindows**

Framing research infancy is key to the discussion and vital to progress. Becquerel was credited with the discovery of the photovoltaic effect in 1839. In 1954, Bell Labs realized the first photovoltaic silicon cell with 4% conversion efficiency (U.S. Department of Energy, 2016, p. 3). In 2016, researchers at the University of South Wales achieved the highest photovoltaic efficiency of 34% (Da Silva, 2016). In 63 years, photovoltaic advancement improved tenfold.

In the last 10 years, advancement in nanoparticles and carbon nanotubes reached unprecedented ability to supercharge a base liquid like water by 80% (Choi, 1998, p. 13). Similar research of varying metallic nanoparticle and oxide nanoparticles found that thermal conductivity was enhanced by 5–60% (Choi et al., 2001; Eastman, Choi, Li, Yu,

& Thompson, 2001; Murshed, 2005). Research into the thermo-physical properties of plasmonic titanium oxide-based silver ( $\text{TiO}_2/\text{Ag}$ ) has shown remarkable enhancements, and 95% of incoming light can be absorbed with low particle volume (Xuan, Duan, & Li, 2014, p. 16206).

Nanotechnology brings unique mechanical, optical, electrical, magnetic, and thermal properties; and challenges the current state of window technology that has reached a theoretical performance limit (Johnson, 1991, p. viii). Within one-sixth the time of PV development, nanoparticle technology has eclipsed the rate of photothermal efficiency tenfold.

The potential for window gap technology to shift from resisting energy to harnessing solar energy presents a unique opportunity to turn windows into renewable energy power plants. This research shifts windows into a realm of dynamic controllability and hybrid characteristics. This research highlights the possibility to harness nanofluid photothermal strengths to return favorable environmental impacts.

The built environment is focused on large-scale energy conservation measures, while this research focused on virtual obscurity. Smaller can be better, and the future of the building industry is posed to gain tremendous advancement in energy conservation if greater attention is focused on miniscule energy bionics.

## CHAPTER XIII

### LIMITATIONS

This proof of concept experiment, in part, attempts to answer a very finite question, and so not all conditions could be explored with equal depth and consideration. The following outline presents various themes present in the research that warrant further consideration, and identifies limitations that may be reengineered in future experiments to enhance the significance of the results.

Weight is a key factor in construction as it influences structural dead loads to accommodate nanofluid weight, pumps, plumbing, and heat exchangers. The combined weight of these systems was anticipated at 6.6 lb/sqft<sup>49</sup> of dead load applied to the structure's envelope. While less significant, the dead loads contained in the distribution of nanofluids in cross-linked polyethylene (PEX) plumbing was approximately 0.4 lb/sqft.<sup>50</sup> In consultation with structural engineers and cost estimators, the collective impact would result in an escalation in construction cost of \$20 per square foot.

The Nanowindow system is envisioned as a closed-loop system that may face biological contamination and oxygen diffusion that lead to algae and corrosion. Biological contamination measures are required to maintain optical clarity and fluid sterilization. Several water treatment systems are readily available to remove biological contamination

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<sup>49</sup> 2.18 lb of Nanofluid/SF + 3.24 lb/SF of glass + 1.2 lb/= 6.62 lb/SF

<sup>50</sup> Based on 8" O.C. and 0.75-inch PEX piping embedded in concrete. Concrete not included and assumed necessary regardless of radiant piping.

to reduce algae. Ultraviolet germicidal disinfection appears to be best suited to deactivate bacteria and protozoa microorganism that may appear in the closed-loop system without damaging the nanoparticles.

From a planning perspective, the Nanowindow's ancillary systems described above can be easily accommodated without additional space. Pumps, UV disinfection systems, and hydronic manifolds can be disaggregated and placed in the plenum of each floor without the need to take-up valuable leasable floor area. To simplify service and maintenance, the equipment could be housed in drop-down ceiling enclosures like the enclosures used for zone and wireless cabling.

Safety and wellbeing was of upmost concern and continues to drive a solution that protects building occupants. Material Safety Data Sheets (MSDS) classify  $\text{Al}_2\text{O}_3$  nanofluid as a nonhazardous material that, when coupled with a distilled water surfactant, has no possibility of skin and eye irritation or sensitization. Considering that the nanofluid column is proximal to the outside it would have an outward dispersal of no more than 80 gallons of nanofluid per assembly if the laminated glass were to break. Airborne dispersion and capillary retention exerted by the façade would reduce direct contact with outdoor occupants. If a full fracture occurred, then there is a possibility for water damage to occur. Only laminated glass bond with a polyvinyl butyral (PVB) or ethylene-vinyl acetate (EVA) was used during the experiment and is recommended in future development.



The cost of technology limited the nanoparticle selection to  $\text{Al}_2\text{O}_3$ . While the application of  $\text{Al}_2\text{O}_3$  illustrated proof of concept, it was apparent that other more highly conductive and viscous nanofluids were available but outside the financial means of the researcher. Meliorum Technology Inc. discounted the nanofluids for the experiment, and it was found that  $\text{Al}_2\text{O}_3$  prices range from \$180/kg upwards to \$100,000/kg depending on the substrate, volume by weight, and surfactant used. Tremendous research is required to identify the appropriate nanoparticle material and morphology that best aligns with the goals of this research. Nanotechnology also brings to the discussion carbon nanotubes that exhibit exemplary thermal conductivity and electrical characteristics.

Environmental costs and the embedded energy in developing, fabricating, installing, and maintaining the Nanowindow were not explored in this research. While the need to declare the new technology's environmental impact is important, the relative impact offset by the renewable aspect of the Nanowindow. A life cycle analysis is highly encouraged to compare double- and triple-pane windows to the Nanowindow and include the embedded energy in the production of nanofluids.

The solar simulator was design and fabricated to produce a steady state of energy that best resembled standard test conditions used in similar fields of solar energy testing. The simulator was engineered in a fixed position perpendicular to the CHB with no ability to adjust angle of incidence or the radiant energy emitted by the light source. This was, in part, a function of cost and space that limited these variables. Engineering an adjustable

angle of incidence would have required significant additional head height and structure to manipulate the lamps such that the desired angles could be achieved.

The switching configuration was also limited to two circuits that handled three and four lamps individually. As such, lamp control limited varying levels of radiant energy. Future circuit design should consider individual circuits for each lamp and ballast as to provide opportunities to study subject matter under varying radiant conditions. While adding a switch for each lamp increases hard costs, it offers opportunities to create symmetrical and asymmetrical energy patterns as a function of lamp arrangement and switching. Greater controllability of the ballasts and lamps offers unique opportunities to explore dynamic environmental conditions that align with actual conditions rather than the obscure standard test condition.

The Nanowindow experiments resulted in measurable outcomes that favored nanofluids over the distilled water. While every attempt was made to establish a standard testing environment from one experiment to another, it was possible that the dependent variable may have experienced extraneous influences imposed by environmental conditions. While the solar lab was outside under shelter, extreme weather conditions may have influenced operating conditions and imposed thermal forces on the test specimens, solar simulator, and calibrated hot box that were not measured. To overcome this limitation, a guarded hot box (GHB) or testing indoors in a climate-controlled environment would have reduced or eliminated these extraneous influences.

The CHB served the purposes of this experiment, but notable improvements are recommended for future application. First and foremost, a GHB is highly advisable. A GHB permits controlled temperature around the meter chamber so that no external forces influence the test subjects inside the hot box. Using the CHB was subject to environmental conditions that may have influenced the outcome of the various experiments.

In retrospect, the methodology of testing all H<sub>2</sub>O windows first and Nanowindows second may not have been the best procedure. If climate conditions influenced the dependent variable and outcome, then it would have been preferable to test H<sub>2</sub>O windows and Nanowindows in pairs. Thus, the climate's influence would have been equitable between two similar prototypes.

The solar simulator's intensity fluctuated by 25% at times. There was no conclusive explanation, but there was some speculation that the metal arc lamps were losing intensity as they aged or electrical loads were extraneously altered. It was possible that load spiking, line noise, under voltage/sag, and electrical swelling occurred. A future solution would be an uninterruptible power supply to isolate the lab from all other users.

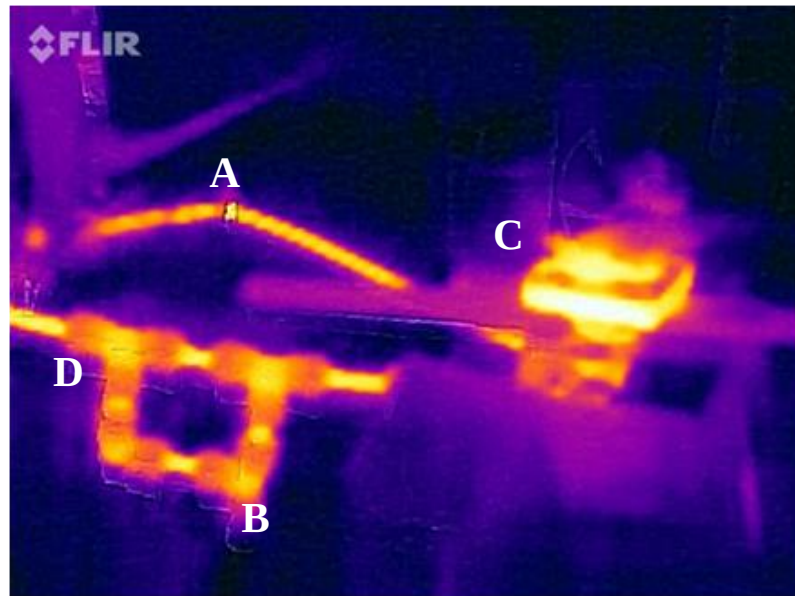
Maintaining similar starting temperature of the fluids was equally challenging. Every attempt was made to start each experiment in or around the same temperature. The difference in starting temperature may have impacted performance. Future fluid-based experiments should have a temperature-regulated procedure to maintain similar start

temperatures. An attempt was made to place Nanowindows in a mini-refrigerator, but the samples were either dimensionally incompatible or not all Nanowindows could be stored all at one time.

Experiments 1–3 were the most challenging due to the number of extraneous variables that may have influenced the outcome. Such unmeasured variables included the energy released into Chamber 2 (metering chamber) from the polyethylene tubing and from the electric pump (Figure 109). Every attempt was made to isolate or reduce the extraneous variable's influence by wrapping the tubing in polyisocyanurate thermal insulation and encasing the pump in a separate chamber.

Radiant loss  
before insulating  
fluid lines.

- A. Influent Line
- B. Temp Probe
- C. Heat Sink
- D. Effluent Line



**Figure 109: Infrared of Heat Exchanger**

Alignment between the CHB, concentrator, and lamps was problematic because all three components were independent of one another. Thus, one or more of these systems may have shifted without notice during the experiment, altering the amount of energy falling on the test subjects. The CHB and lamp frame were ground mounted while the concentrator was cable suspended, causing the greatest difficulty in centering the lamp's energy on the prototypes embedded in the CHB. Cable suspension resulted in constant realignment between the lamps and CHB. In subsequent testing, it is recommended that all three parts be ground mounted or that all three major parts be within the same armature.

## APPENDICES

### Appendix A (ASTM) Solar Spectral Irradiance Reference Data

The American Society for Testing and Materials (ASTM) G173 Terrestrial Reference Spectra used for photovoltaic performance evaluation was used to compare solar simulator spectra to solar reference spectra.

According to National Renewable Energy Laboratory (NREL) ASTM G173 captures standard direct normal spectral irradiance and standard total that can be used as a reference for “for evaluating spectrally selective PV materials with respect to performance measured under varying natural and artificial sources of light with various spectral distributions” (NREL, 2015).

ASTM G173 reflects reasonable average irradiance measures for the 48 contiguous states of the United States of America (U.S.A.) over a period of one year. The tilt angle selected is approximately the average latitude for the contiguous U.S.A. (NREL, 2015). ASTM G173-03 Reference Spectra Derived from Simple Model of the Atmospheric Radiative Transfer of Sunshine, or SMARTS can be downloaded from <http://www.nrel.gov/rredc/smarts/> .

For this research SMARTS v. 2.9.2 was used.

## Appendix B ASTM G173-03 Solar Spectral Irradiance Reference Data Noramlized

The data below was taken from ASTM G173-03 Solar Spectra Reference (Appendix A) and a linear algebra to normalize the power (y-axis) and overlay spectroradiometer data.

| ASTM G173-03 Reference Spectra       |            |                       |               |                 |              |               |            |
|--------------------------------------|------------|-----------------------|---------------|-----------------|--------------|---------------|------------|
| Saturday November 21 2015 at 3:23 PM |            | File: 21112015_140004 |               |                 |              |               |            |
| nm                                   | uW/cm2/nm  | Norm of y             |               | Normalized Norm | Verification |               | Area       |
|                                      |            | Square                | Sum of Square |                 | Square       | Sum of Square |            |
| 360                                  | 5.9817E-01 | 0.35780735            | 145.349739    | 4.96E-02        | 0.0024617    | 1             | 0.25334876 |
| 365                                  | 6.2359E-01 | 0.38886449            | √             | 5.17E-02        | 0.00267537   | √             | 0.28588414 |
| 370                                  | 7.5507E-01 | 0.5701307             | 12.0561079    | 6.26E-02        | 0.00392247   | 1             | 0.27877363 |
| 375                                  | 5.8930E-01 | 0.34727449            |               | 4.89E-02        | 0.00238923   |               | 0.26751378 |
| 380                                  | 7.0077E-01 | 0.49107859            |               | 5.81E-02        | 0.0033786    |               | 0.28498418 |
| 385                                  | 6.7355E-01 | 0.4536696             |               | 5.59E-02        | 0.00312123   |               | 0.30493672 |
| 390                                  | 7.9699E-01 | 0.63519306            |               | 6.61E-02        | 0.0043701    |               | 0.33275872 |
| 395                                  | 8.0772E-01 | 0.6524116             |               | 6.70E-02        | 0.00448856   |               | 0.39851584 |
| 400                                  | 1.1141E+00 | 1.24121881            |               | 9.24E-02        | 0.00853953   |               | 0.46972041 |
| 405                                  | 1.1511E+00 | 1.32503121            |               | 9.55E-02        | 0.00911616   |               | 0.45611735 |
| 410                                  | 1.0485E+00 | 1.09935225            |               | 8.70E-02        | 0.0075635    |               | 0.47160742 |
| 415                                  | 1.2258E+00 | 1.50258564            |               | 1.02E-01        | 0.01033773   |               | 0.48709754 |
| 420                                  | 1.1232E+00 | 1.26157824            |               | 9.32E-02        | 0.0086796    |               | 0.49186686 |
| 425                                  | 1.2488E+00 | 1.55950144            |               | 1.04E-01        | 0.0107293    |               | 0.44032038 |
| 430                                  | 8.7462E-01 | 0.76496014            |               | 7.25E-02        | 0.00526289   |               | 0.43957387 |
| 435                                  | 1.2452E+00 | 1.55052304            |               | 1.03E-01        | 0.01066753   |               | 0.53812972 |
| 440                                  | 1.3499E+00 | 1.82223001            |               | 1.12E-01        | 0.01253686   |               | 0.58306545 |
| 445                                  | 1.4619E+00 | 2.13715161            |               | 1.21E-01        | 0.01470351   |               | 0.62652893 |
| 450                                  | 1.5595E+00 | 2.43204025            |               | 1.29E-01        | 0.01673233   |               | 0.63907442 |
| 455                                  | 1.5224E+00 | 2.31770176            |               | 1.26E-01        | 0.01594569   |               | 0.63277055 |
| 460                                  | 1.5291E+00 | 2.33814681            |               | 1.27E-01        | 0.01608635   |               | 0.63538333 |

|     |            |                       |          |            |                        |
|-----|------------|-----------------------|----------|------------|------------------------|
| 465 | 1.5350E+00 | 2.356225<br>2.2731592 | 1.27E-01 | 0.01621073 | 0.6309457<br>4         |
| 470 | 1.5077E+00 | 9<br>2.6195422        | 1.25E-01 | 0.01563924 | 0.6482606<br>2         |
| 475 | 1.6185E+00 | 5<br>2.6182476        | 1.34E-01 | 0.01802234 | 0.6711535<br>8         |
| 480 | 1.6181E+00 | 1<br>2.4595648        | 1.34E-01 | 0.01801343 | 0.6607439<br>2         |
| 485 | 1.5683E+00 | 9<br>2.6321817        | 1.30E-01 | 0.0169217  | 0.6616355<br>8         |
| 490 | 1.6224E+00 | 6<br>2.7175522        | 1.35E-01 | 0.0181093  | 0.6782661<br>6         |
| 495 | 1.6485E+00 | 5<br>2.3873340        | 1.37E-01 | 0.01869664 | 0.6622369<br>4         |
| 500 | 1.5451E+00 | 1<br>2.3873340        | 1.28E-01 | 0.01642476 | 0.6407955<br>2         |
| 505 | 1.5451E+00 | 1<br>2.4445322        | 1.28E-01 | 0.01642476 | 0.6446110<br>2         |
| 510 | 1.5635E+00 | 5<br>2.3966136        | 1.30E-01 | 0.01681828 | 0.6452331<br>1         |
| 515 | 1.5481E+00 | 1<br>2.3451859        | 1.28E-01 | 0.0164886  | 0.6385767<br>3         |
| 520 | 1.5314E+00 | 6<br>2.3213569        | 1.27E-01 | 0.01613478 | 0.6334963<br>2         |
| 525 | 1.5236E+00 | 6<br>2.4903996        | 1.26E-01 | 0.01597084 | 0.6431802<br>1         |
| 530 | 1.5781E+00 | 1<br>2.3857891        | 1.31E-01 | 0.01713384 | 0.6475348<br>5         |
| 535 | 1.5446E+00 | 6<br>2.4133622        | 1.28E-01 | 0.01641413 | 0.6424337<br>0.6295564 |
| 540 | 1.5535E+00 | 5<br>2.1978062        | 1.29E-01 | 0.01660383 | 1<br>0.6274827         |
| 545 | 1.4825E+00 | 5<br>2.3823922        | 1.23E-01 | 0.01512081 | 7<br>0.6393854         |
| 550 | 1.5435E+00 | 5<br>2.3712920        | 1.28E-01 | 0.01639076 | 5                      |
| 555 | 1.5399E+00 | 1<br>2.4177140        | 1.28E-01 | 0.01631439 | 0.6417494<br>0.6280841 |
| 560 | 1.5549E+00 | 1                     | 1.29E-01 | 0.01663377 | 2<br>0.6208678         |
| 565 | 1.4740E+00 | 2.172676<br>2.3107040 | 1.22E-01 | 0.01494792 | 6<br>0.6224438         |
| 570 | 1.5201E+00 | 1<br>2.1951385        | 1.26E-01 | 0.01589754 | 3<br>0.6136516         |
| 575 | 1.4816E+00 | 6<br>2.1835972        | 1.23E-01 | 0.01510246 | 1<br>0.6178818         |
| 580 | 1.4777E+00 | 9                     | 1.23E-01 | 0.01502306 | 3<br>0.6292246         |
| 585 | 1.5020E+00 | 2.256004<br>2.3482497 | 1.25E-01 | 0.01552121 | 2<br>0.6020392         |
| 590 | 1.5324E+00 | 6<br>1.8793668        | 1.27E-01 | 0.01615586 | 3<br>0.5809710         |
| 595 | 1.3709E+00 | 1<br>2.0471886        | 1.14E-01 | 0.01292996 | 8<br>0.6026198         |
| 600 | 1.4308E+00 | 4<br>2.1765100        | 1.19E-01 | 0.01408457 | 5<br>0.6147921         |
| 605 | 1.4753E+00 | 9<br>2.2186102        | 1.22E-01 | 0.0149743  | 1<br>0.6134027         |
| 610 | 1.4895E+00 | 5<br>2.1567859        | 1.24E-01 | 0.01526394 | 7<br>0.6092969         |
| 615 | 1.4686E+00 | 6                     | 1.22E-01 | 0.0148386  | 7                      |



|     |            |                       |          |                             |                        |
|-----|------------|-----------------------|----------|-----------------------------|------------------------|
| 620 | 1.4697E+00 | 2.1600180<br>9        | 1.22E-01 | 0.01486083                  | 0.6103959<br>9         |
| 625 | 1.4739E+00 | 2.1723812<br>1        | 1.22E-01 | 0.01494589                  | 0.5964818<br>9         |
| 630 | 1.4026E+00 | 1.9672867<br>6        | 1.16E-01 | 0.01353485                  | 0.5795817<br>4         |
| 635 | 1.3924E+00 | 1.9387777<br>6        | 1.15E-01 | 0.01333871                  | 0.5885398<br>5         |
| 640 | 1.4458E+00 | 2.0903376<br>4        | 1.20E-01 | 0.01438143                  | 0.5971661<br>9         |
| 645 | 1.4340E+00 | 2.056356<br>2.1219748 | 1.19E-01 | 0.01414764                  | 0.5994264<br>5         |
| 650 | 1.4567E+00 | 9<br>1.8479683        | 1.21E-01 | 0.0145991                   | 0.5839571<br>1         |
| 655 | 1.3594E+00 | 6<br>1.8222300        | 1.13E-01 | 0.01271394                  | 0.5618106<br>6         |
| 660 | 1.3499E+00 | 1<br>1.9577606        | 1.12E-01 | 0.01253686                  | 0.5700637<br>4         |
| 665 | 1.3992E+00 | 4<br>2.0203779        | 1.16E-01 | 0.01346931                  | 0.5848902<br>5         |
| 670 | 1.4214E+00 | 6<br>2.0152641        | 1.18E-01 | 0.01390011                  | 0.5891204<br>7         |
| 675 | 1.4196E+00 | 6<br>1.9482576        | 1.18E-01 | 0.01386493                  | 0.5838119<br>6         |
| 680 | 1.3958E+00 | 4<br>1.9513296        | 1.16E-01 | 0.01340393                  | 0.5791048<br>0.5747501 |
| 685 | 1.3969E+00 | 1<br>1.8900750        | 1.16E-01 | 0.01342506                  | 6<br>0.5302084         |
| 690 | 1.3748E+00 | 4<br>1.3973604        | 1.14E-01 | 0.01300364                  | 2<br>0.5087670         |
| 695 | 1.1821E+00 | 1<br>1.6164579        | 9.80E-02 | 0.00961378                  | 1<br>0.5295448         |
| 700 | 1.2714E+00 | 6<br>1.6442932        | 1.05E-01 | 0.01112116                  | 6<br>0.5399130         |
| 705 | 1.2823E+00 | 9<br>1.7460979        | 1.06E-01 | 0.01131267                  | 5<br>0.5472122         |
| 710 | 1.3214E+00 | 6<br>1.7358062        | 1.10E-01 | 0.01201308                  | 5<br>0.5342105         |
| 715 | 1.3175E+00 | 5<br>1.5843256        | 1.09E-01 | 0.01194227                  | 5<br>0.4653657         |
| 720 | 1.2587E+00 | 9<br>0.9712102        | 1.04E-01 | 0.01090009                  | 7<br>0.4196005         |
| 725 | 9.8550E-01 | 5                     | 8.17E-02 | 0.00668189                  | 9<br>0.4492536         |
| 730 | 1.0380E+00 | 1.077444<br>1.2735122 | 8.61E-02 | 0.00741277                  | 1<br>0.4865376         |
| 735 | 1.1285E+00 | 5<br>1.4830368        | 9.36E-02 | 0.00876171                  | 1<br>0.5054077         |
| 740 | 1.2178E+00 | 4                     | 1.01E-01 | 0.01020323                  | 2                      |
| 745 | 1.2195E+00 | 1.48718025            | 1.01E-01 | 0.01023174                  | 0.51202262             |
| 750 | 1.2497E+00 | 1.56175009            | 1.04E-01 | 0.01074477                  |                        |
|     |            |                       |          | <b>Area under<br/>curve</b> | <b>43.19</b>           |

# Appendix C Lightspex Series 1 Data

## Solar Spectral Irradiance Reference Data (Normalized)

| Solar (LightSpex) Series 1                                      |           |            |               |                 |              |               |            |
|-----------------------------------------------------------------|-----------|------------|---------------|-----------------|--------------|---------------|------------|
| Saturday, November 21, 2015 at 3:23 PM<br>File: 21112015_152309 |           |            |               |                 |              |               |            |
| nm                                                              | uW/cm2/nm | Norm of y  |               | Normalized Norm | Verification |               | Area       |
|                                                                 |           | Square     | Sum of Square |                 | Square       | Sum of Square |            |
| 360                                                             | 1.04E+01  | 109.00404  | 133900.372    | 2.85E-02        | 0.00081407   | 1             | 0.15768233 |
| 365                                                             | 1.26E+01  | 159.754432 | √             | 3.45E-02        | 0.00119308   | √             | 0.18061947 |
| 370                                                             | 1.38E+01  | 190.379285 | 365.923998    | 3.77E-02        | 0.0014218    | 1             | 0.1928686  |
| 375                                                             | 1.44E+01  | 208.291283 |               | 3.94E-02        | 0.00155557   |               | 0.19991378 |
| 380                                                             | 1.48E+01  | 219.899241 |               | 4.05E-02        | 0.00164226   |               | 0.20564311 |
| 385                                                             | 1.53E+01  | 233.200387 |               | 4.17E-02        | 0.0017416    |               | 0.21768728 |
| 390                                                             | 1.66E+01  | 275.291146 |               | 4.53E-02        | 0.00205594   |               | 0.24625537 |
| 395                                                             | 1.95E+01  | 378.395866 |               | 5.32E-02        | 0.00282595   |               | 0.30537967 |
| 400                                                             | 2.52E+01  | 637.355467 |               | 6.90E-02        | 0.00475992   |               | 0.37333367 |
| 405                                                             | 2.94E+01  | 864.289441 |               | 8.03E-02        | 0.00645472   |               | 0.41479447 |
| 410                                                             | 3.13E+01  | 980.59791  |               | 8.56E-02        | 0.00732334   |               | 0.43723082 |
| 415                                                             | 3.27E+01  | 1068.16542 |               | 8.93E-02        | 0.00797731   |               | 0.4493112  |
| 420                                                             | 3.31E+01  | 1094.46504 |               | 9.04E-02        | 0.00817373   |               | 0.44984068 |
| 425                                                             | 3.28E+01  | 1073.23726 |               | 8.95E-02        | 0.00801519   |               | 0.44888488 |
| 430                                                             | 3.29E+01  | 1085.22807 |               | 9.00E-02        | 0.00810474   |               | 0.4662225  |
| 435                                                             | 3.53E+01  | 1245.9488  |               | 9.65E-02        | 0.00930504   |               | 0.50166497 |
| 440                                                             | 3.81E+01  | 1453.93503 |               | 1.04E-01        | 0.01085833   |               | 0.54149018 |
| 445                                                             | 4.11E+01  | 1691.44658 |               | 1.12E-01        | 0.01263213   |               | 0.58180251 |
| 450                                                             | 4.40E+01  | 1938.72896 |               | 1.20E-01        | 0.01447889   |               | 0.61289435 |
| 455                                                             | 4.57E+01  | 2086.48882 |               | 1.25E-01        | 0.0155824    |               | 0.62829782 |
| 460                                                             | 4.63E+01  | 2142.35677 |               | 1.26E-01        | 0.01599963   |               | 0.6312882  |
| 465                                                             | 4.61E+01  | 2126.66701 |               | 1.26E-01        | 0.01588246   |               | 0.63063437 |
| 470                                                             | 4.62E+01  | 2133.50686 |               | 1.26E-01        | 0.01593354   |               | 0.6387146  |
| 475                                                             | 4.73E+01  | 2237.1481  |               | 1.29E-01        | 0.01670756   |               | 0.65180475 |
| 480                                                             | 4.81E+01  | 2314.17761 |               | 1.31E-01        | 0.01728283   |               | 0.6523315  |
| 485                                                             | 4.74E+01  | 2244.44748 |               | 1.29E-01        | 0.01676207   |               | 0.64708656 |
| 490                                                             | 4.73E+01  | 2240.90518 |               | 1.29E-01        | 0.01673562   |               | 0.6516278  |
| 495                                                             | 4.80E+01  | 2307.87042 |               | 1.31E-01        | 0.01723573   |               | 0.65350046 |
| 500                                                             | 4.76E+01  | 2266.93111 |               | 1.30E-01        | 0.01692998   |               | 0.65007762 |
| 505                                                             | 4.75E+01  | 2259.98504 |               | 1.30E-01        | 0.01687811   |               | 0.65109012 |
| 510                                                             | 4.78E+01  | 2281.06536 |               | 1.31E-01        | 0.01703554   |               | 0.64666912 |
| 515                                                             | 4.69E+01  | 2198.87842 |               | 1.28E-01        | 0.01642175   |               | 0.64010902 |
| 520                                                             | 4.68E+01  | 2190.26808 |               | 1.28E-01        | 0.01635745   |               | 0.64536079 |
| 525                                                             | 4.77E+01  | 2271.56139 |               | 1.30E-01        | 0.01696456   |               | 0.65358654 |
| 530                                                             | 4.80E+01  | 2304.41282 |               | 1.31E-01        | 0.01720991   |               | 0.65553298 |
| 535                                                             | 4.79E+01  | 2298.79974 |               | 1.31E-01        | 0.01716799   |               | 0.65317799 |
| 540                                                             | 4.77E+01  | 2271.43747 |               | 1.30E-01        | 0.01696364   |               | 0.6533768  |

|     |          |            |          |                         |              |
|-----|----------|------------|----------|-------------------------|--------------|
| 545 | 4.80E+01 | 2301.59103 | 1.31E-01 | 0.01718883              | 0.65955841   |
| 550 | 4.86E+01 | 2358.50095 | 1.33E-01 | 0.01761385              | 0.66300995   |
| 555 | 4.85E+01 | 2350.3201  | 1.32E-01 | 0.01755275              | 0.65702851   |
| 560 | 4.77E+01 | 2274.23118 | 1.30E-01 | 0.0169845               | 0.64548718   |
| 565 | 4.68E+01 | 2189.37896 | 1.28E-01 | 0.01635081              | 0.63385772   |
| 570 | 4.60E+01 | 2114.77658 | 1.26E-01 | 0.01579366              | 0.62664925   |
| 575 | 4.57E+01 | 2091.75425 | 1.25E-01 | 0.01562172              | 0.62832583   |
| 580 | 4.62E+01 | 2137.40707 | 1.26E-01 | 0.01596267              | 0.63238132   |
| 585 | 4.63E+01 | 2146.40404 | 1.27E-01 | 0.01602986              | 0.62847545   |
| 590 | 4.57E+01 | 2084.87213 | 1.25E-01 | 0.01557032              | 0.62580345   |
| 595 | 4.59E+01 | 2110.31822 | 1.26E-01 | 0.01576036              | 0.63115429   |
| 600 | 4.64E+01 | 2157.00798 | 1.27E-01 | 0.01610905              | 0.63492488   |
| 605 | 4.65E+01 | 2161.3294  | 1.27E-01 | 0.01614132              | 0.63112969   |
| 610 | 4.59E+01 | 2105.71772 | 1.25E-01 | 0.015726                | 0.62252203   |
| 615 | 4.52E+01 | 2045.77099 | 1.24E-01 | 0.01527831              | 0.61610608   |
| 620 | 4.49E+01 | 2020.4126  | 1.23E-01 | 0.01508892              | 0.609602     |
| 625 | 4.43E+01 | 1960.559   | 1.21E-01 | 0.01464192              | 0.60286426   |
| 630 | 4.40E+01 | 1932.72778 | 1.20E-01 | 0.01443407              | 0.60569408   |
| 635 | 4.47E+01 | 1997.41062 | 1.22E-01 | 0.01491714              | 0.61420405   |
| 640 | 4.52E+01 | 2043.79943 | 1.24E-01 | 0.01526358              | 0.6155035    |
| 645 | 4.49E+01 | 2014.44778 | 1.23E-01 | 0.01504438              | 0.60843851   |
| 650 | 4.42E+01 | 1951.36878 | 1.21E-01 | 0.01457329              | 0.59930956   |
| 655 | 4.35E+01 | 1896.28895 | 1.19E-01 | 0.01416194              | 0.59938676   |
| 660 | 4.42E+01 | 1952.36725 | 1.21E-01 | 0.01458075              | 0.60855397   |
| 665 | 4.49E+01 | 2014.9505  | 1.23E-01 | 0.01504813              | 0.61107498   |
| 670 | 4.46E+01 | 1985.11238 | 1.22E-01 | 0.01482529              | 0.60581979   |
| 675 | 4.41E+01 | 1946.48616 | 1.21E-01 | 0.01453682              | 0.59591883   |
| 680 | 4.31E+01 | 1858.07551 | 1.18E-01 | 0.01387655              | 0.56687796   |
| 685 | 3.99E+01 | 1589.48134 | 1.09E-01 | 0.01187063              | 0.53273153   |
| 690 | 3.81E+01 | 1452.17393 | 1.04E-01 | 0.01084518              | 0.53253681   |
| 695 | 3.98E+01 | 1587.20966 | 1.09E-01 | 0.01185366              | 0.55162821   |
| 700 | 4.09E+01 | 1672.95724 | 1.12E-01 | 0.01249404              | 0.56313606   |
| 705 | 4.15E+01 | 1724.25919 | 1.13E-01 | 0.01287718              | 0.56622141   |
| 710 | 4.14E+01 | 1710.10369 | 1.13E-01 | 0.01277146              | 0.54232027   |
| 715 | 3.80E+01 | 1445.96147 | 1.04E-01 | 0.01079879              | 0.49592129   |
| 720 | 3.46E+01 | 1194.53184 | 9.45E-02 | 0.00892105              | 0.46858433   |
| 725 | 3.40E+01 | 1157.6666  | 9.30E-02 | 0.00864573              | 0.4728598    |
| 730 | 3.52E+01 | 1238.18127 | 9.62E-02 | 0.00924703              | 0.49502766   |
| 735 | 3.73E+01 | 1388.99327 | 1.02E-01 | 0.01037333              | 0.51641871   |
| 740 | 3.83E+01 | 1468.33043 | 1.05E-01 | 0.01096584              | 0.52673438   |
| 745 | 3.88E+01 | 1503.8186  | 1.06E-01 | 0.01123088              | 0.52766558   |
| 750 | 3.85E+01 | 1478.79472 | 1.05E-01 | 0.01104399              |              |
|     |          |            |          | <b>Area under curve</b> | <b>42.79</b> |

# Appendix D Lightspex Series 2 Data

## Solar Spectral Irradiance Reference Data (Noramlized)

| Solar (LightSpex) Series 2                                      |           |            |               |                 |              |               |            |
|-----------------------------------------------------------------|-----------|------------|---------------|-----------------|--------------|---------------|------------|
| Saturday, November 21, 2015 at 3:23 PM<br>File: 21112015_140004 |           |            |               |                 |              |               |            |
| nm                                                              | uW/cm2/nm | Norm of y  |               | Normalized Norm | Verification |               | Area       |
|                                                                 |           | Square     | Sum of Square |                 | Square       | Sum of Square |            |
| 360                                                             | 1.90E+01  | 359.868488 | 349742.643    | 3.21E-02        | 0.00102895   | 1             | 0.17701842 |
| 365                                                             | 2.29E+01  | 524.620701 | √             | 3.87E-02        | 0.00150002   | √             | 0.20198881 |
| 370                                                             | 2.49E+01  | 618.870104 | 591.390432    | 4.21E-02        | 0.0017695    | 1             | 0.21461118 |
| 375                                                             | 2.59E+01  | 670.31799  |               | 4.38E-02        | 0.0019166    |               | 0.2215905  |
| 380                                                             | 2.65E+01  | 703.74009  |               | 4.49E-02        | 0.00201217   |               | 0.22745803 |
| 385                                                             | 2.73E+01  | 744.116562 |               | 4.61E-02        | 0.00212761   |               | 0.24008632 |
| 390                                                             | 2.95E+01  | 871.158837 |               | 4.99E-02        | 0.00249086   |               | 0.27044359 |
| 395                                                             | 3.45E+01  | 1187.47092 |               | 5.83E-02        | 0.00339527   |               | 0.33407752 |
| 400                                                             | 4.46E+01  | 1986.34228 |               | 7.54E-02        | 0.00567944   |               | 0.40666747 |
| 405                                                             | 5.16E+01  | 2665.79114 |               | 8.73E-02        | 0.00762215   |               | 0.4494683  |
| 410                                                             | 5.47E+01  | 2991.34613 |               | 9.25E-02        | 0.00855299   |               | 0.47096467 |
| 415                                                             | 5.67E+01  | 3216.75003 |               | 9.59E-02        | 0.00919748   |               | 0.48118803 |
| 420                                                             | 5.71E+01  | 3261.73485 |               | 9.66E-02        | 0.0093261    |               | 0.47966028 |
| 425                                                             | 5.64E+01  | 3175.88603 |               | 9.53E-02        | 0.00908064   |               | 0.47725747 |
| 430                                                             | 5.65E+01  | 3197.13347 |               | 9.56E-02        | 0.00914139   |               | 0.49401966 |
| 435                                                             | 6.03E+01  | 3638.52653 |               | 1.02E-01        | 0.01040344   |               | 0.52871248 |
| 440                                                             | 6.48E+01  | 4192.5625  |               | 1.09E-01        | 0.01198756   |               | 0.56726484 |
| 445                                                             | 6.94E+01  | 4821.9136  |               | 1.17E-01        | 0.01378703   |               | 0.60650837 |
| 450                                                             | 7.40E+01  | 5480.92951 |               | 1.25E-01        | 0.01567132   |               | 0.63673587 |
| 455                                                             | 7.66E+01  | 5866.10469 |               | 1.30E-01        | 0.01677263   |               | 0.65085809 |
| 460                                                             | 7.74E+01  | 5986.73588 |               | 1.31E-01        | 0.01711755   |               | 0.65164945 |
| 465                                                             | 7.68E+01  | 5894.81522 |               | 1.30E-01        | 0.01685472   |               | 0.64869582 |
| 470                                                             | 7.67E+01  | 5879.10163 |               | 1.30E-01        | 0.01680979   |               | 0.65560792 |
| 475                                                             | 7.84E+01  | 6148.5672  |               | 1.33E-01        | 0.01758026   |               | 0.66764565 |
| 480                                                             | 7.95E+01  | 6323.89162 |               | 1.34E-01        | 0.01808156   |               | 0.66627938 |
| 485                                                             | 7.81E+01  | 6097.98563 |               | 1.32E-01        | 0.01743564   |               | 0.65916648 |
| 490                                                             | 7.78E+01  | 6059.1123  |               | 1.32E-01        | 0.01732449   |               | 0.66172697 |
| 495                                                             | 7.87E+01  | 6192.95024 |               | 1.33E-01        | 0.01770716   |               | 0.66176375 |
| 500                                                             | 7.78E+01  | 6060.4668  |               | 1.32E-01        | 0.01732836   |               | 0.65732802 |
| 505                                                             | 7.76E+01  | 6028.90132 |               | 1.31E-01        | 0.01723811   |               | 0.65709425 |
| 510                                                             | 7.78E+01  | 6051.85976 |               | 1.32E-01        | 0.01730375   |               | 0.65131845 |
| 515                                                             | 7.63E+01  | 5818.59263 |               | 1.29E-01        | 0.01663678   |               | 0.64427868 |
| 520                                                             | 7.61E+01  | 5795.53329 |               | 1.29E-01        | 0.01657085   |               | 0.64922423 |
| 525                                                             | 7.74E+01  | 5998.44054 |               | 1.31E-01        | 0.01715101   |               | 0.65677001 |
| 530                                                             | 7.79E+01  | 6070.4979  |               | 1.32E-01        | 0.01735704   |               | 0.65759307 |
| 535                                                             | 7.76E+01  | 6028.63732 |               | 1.31E-01        | 0.01723735   |               | 0.65391572 |
| 540                                                             | 7.70E+01  | 5935.70089 |               | 1.30E-01        | 0.01697162   |               | 0.65329261 |
| 545                                                             | 7.75E+01  | 6005.76951 |               | 1.31E-01        | 0.01717197   |               | 0.65904854 |

|     |          |            |          |                         |               |
|-----|----------|------------|----------|-------------------------|---------------|
| 550 | 7.84E+01 | 6147.35971 | 1.33E-01 | 0.01757681              | 0.66237375    |
| 555 | 7.83E+01 | 6128.30637 | 1.32E-01 | 0.01752233              | 0.6568516     |
| 560 | 7.71E+01 | 5944.22496 | 1.30E-01 | 0.016996                | 0.64618817    |
| 565 | 7.58E+01 | 5739.72912 | 1.28E-01 | 0.01641129              | 0.63561351    |
| 570 | 7.46E+01 | 5564.75717 | 1.26E-01 | 0.01591101              | 0.6290062     |
| 575 | 7.42E+01 | 5505.3432  | 1.25E-01 | 0.01574113              | 0.62941668    |
| 580 | 7.47E+01 | 5579.25339 | 1.26E-01 | 0.01595245              | 0.63113297    |
| 585 | 7.46E+01 | 5565.75682 | 1.26E-01 | 0.01591386              | 0.62685153    |
| 590 | 7.37E+01 | 5428.97818 | 1.25E-01 | 0.01552278              | 0.6246212     |
| 595 | 7.41E+01 | 5487.31304 | 1.25E-01 | 0.01568957              | 0.62825881    |
| 600 | 7.45E+01 | 5556.52467 | 1.26E-01 | 0.01588747              | 0.62907257    |
| 605 | 7.43E+01 | 5515.86951 | 1.26E-01 | 0.01577122              | 0.62261279    |
| 610 | 7.30E+01 | 5331.0442  | 1.23E-01 | 0.01524276              | 0.61183861    |
| 615 | 7.17E+01 | 5143.78709 | 1.21E-01 | 0.01470735              | 0.6037437     |
| 620 | 7.11E+01 | 5055.08202 | 1.20E-01 | 0.01445372              | 0.59677369    |
| 625 | 7.01E+01 | 4910.0011  | 1.18E-01 | 0.0140389               | 0.59021711    |
| 630 | 6.95E+01 | 4836.93821 | 1.18E-01 | 0.01382999              | 0.59123505    |
| 635 | 7.03E+01 | 4943.80547 | 1.19E-01 | 0.01413555              | 0.59645326    |
| 640 | 7.08E+01 | 5010.16231 | 1.20E-01 | 0.01432528              | 0.59611042    |
| 645 | 7.02E+01 | 4932.40741 | 1.19E-01 | 0.01410296              | 0.589118      |
| 650 | 6.91E+01 | 4778.73569 | 1.17E-01 | 0.01366358              | 0.57977223    |
| 655 | 6.80E+01 | 4626.76121 | 1.15E-01 | 0.01322905              | 0.57830535    |
| 660 | 6.88E+01 | 4730.88099 | 1.16E-01 | 0.01352675              | 0.58508006    |
| 665 | 6.96E+01 | 4847.3482  | 1.18E-01 | 0.01385976              | 0.58592003    |
| 670 | 6.90E+01 | 4758.2542  | 1.17E-01 | 0.01360502              | 0.57988721    |
| 675 | 6.82E+01 | 4650.66714 | 1.15E-01 | 0.0132974               | 0.56976742    |
| 680 | 6.66E+01 | 4433.72203 | 1.13E-01 | 0.0126771               | 0.54408684    |
| 685 | 6.21E+01 | 3859.00622 | 1.05E-01 | 0.01103385              | 0.51579166    |
| 690 | 5.99E+01 | 3587.14749 | 1.01E-01 | 0.01025653              | 0.51615436    |
| 695 | 6.22E+01 | 3869.67352 | 1.05E-01 | 0.01106435              | 0.53142938    |
| 700 | 6.35E+01 | 4033.03744 | 1.07E-01 | 0.01153144              | 0.54021968    |
| 705 | 6.43E+01 | 4132.70265 | 1.09E-01 | 0.01181641              | 0.54200699    |
| 710 | 6.39E+01 | 4086.91704 | 1.08E-01 | 0.0116855               | 0.5213248     |
| 715 | 5.94E+01 | 3527.59972 | 1.00E-01 | 0.01008627              | 0.48283289    |
| 720 | 5.48E+01 | 3005.61615 | 9.27E-02 | 0.00859379              | 0.46065       |
| 725 | 5.41E+01 | 2931.80015 | 9.16E-02 | 0.00838274              | 0.46414726    |
| 730 | 5.57E+01 | 3097.01154 | 9.41E-02 | 0.00885512              | 0.48104219    |
| 735 | 5.81E+01 | 3380.57356 | 9.83E-02 | 0.00966589              | 0.49605216    |
| 740 | 5.92E+01 | 3504.8176  | 1.00E-01 | 0.01002113              | 0.50210738    |
| 745 | 5.96E+01 | 3549.19254 | 1.01E-01 | 0.01014801              | 0.50092542    |
| 750 | 5.89E+01 | 3471.7903  | 9.96E-02 | 0.0099267               |               |
|     |          |            |          | <b>Area under curve</b> | <b>42.924</b> |

## Appendix E Spatial Uniformity Series 1

The data below reflects irradiance levels of the test plane. Each entry collected at 1-second intervals.

|      | Spatial Uniformity Test - Series 1<br>Series 1<br>Decemeber 13, 2015 |     |     |       |       |       |       |       |     |       |       |       |       |
|------|----------------------------------------------------------------------|-----|-----|-------|-------|-------|-------|-------|-----|-------|-------|-------|-------|
| Time | Sensor Location                                                      |     |     |       |       |       |       |       |     |       |       |       |       |
| 1    | 1                                                                    | 2   | 3   | 4     | 5     | 6     | 7     | 8     | 9   | 10    | 11    | 12    | 13    |
| 2    | 831                                                                  | 817 | 802 | 794.7 | 763.4 | 741.6 | 762.4 | 752.9 | 801 | 771.9 | 764.3 | 716.9 | 746.3 |
| 3    | 832                                                                  | 817 | 802 | 794.7 | 763.4 | 749.1 | 764.3 | 756.7 | 802 | 771.9 | 764.3 | 716.9 | 749.1 |
| 4    | 832                                                                  | 817 | 802 | 794.7 | 764.3 | 752.9 | 768.1 | 760.5 | 802 | 771.9 | 760.5 | 718.8 | 749.1 |
| 5    | 833                                                                  | 817 | 802 | 794.7 | 764.3 | 756.7 | 768.1 | 760.5 | 803 | 771.9 | 758.6 | 718.8 | 750.1 |
| 6    | 832                                                                  | 817 | 802 | 794.7 | 764.3 | 757.7 | 769.1 | 760.5 | 802 | 771.9 | 760.5 | 718.8 | 752.9 |
| 7    | 833                                                                  | 817 | 802 | 794.7 | 764.3 | 759.6 | 771.9 | 763.4 | 802 | 771.9 | 760.5 | 718.8 | 752.9 |
| 8    | 832                                                                  | 817 | 802 | 794.7 | 764.3 | 760.5 | 771.9 | 764.3 | 802 | 771.9 | 764.3 | 718.8 | 752.9 |
| 9    | 831                                                                  | 817 | 802 | 791.8 | 763.4 | 752.9 | 771.9 | 764.3 | 802 | 771.9 | 762.4 | 718.8 | 752.9 |
| 10   | 831                                                                  | 817 | 802 | 790.9 | 761.5 | 743.5 | 771.9 | 764.3 | 802 | 771.9 | 762.4 | 718.8 | 754.8 |
| 12   | 830                                                                  | 817 | 802 | 792.8 | 764.3 | 735.9 | 771.9 | 768.1 | 802 | 771.9 | 760.5 | 718.8 | 754.8 |
| 13   | 829                                                                  | 815 | 802 | 791.8 | 764.3 | 730.2 | 773.8 | 768.1 | 802 | 771.9 | 741.6 | 718.8 | 754.8 |
| 14   | 829                                                                  | 814 | 802 | 787.1 | 766.2 | 728.3 | 773.8 | 768.1 | 802 | 771.9 | 749.1 | 718.8 | 756.7 |
| 15   | 829                                                                  | 816 | 802 | 786.1 | 768.1 | 726.4 | 773.8 | 768.1 | 802 | 771.9 | 752.9 | 720.7 | 756.7 |
| 16   | 829                                                                  | 816 | 802 | 789   | 768.1 | 726.4 | 773.8 | 768.1 | 802 | 771.9 | 756.7 | 722.6 | 756.7 |
| 17   | 829                                                                  | 816 | 802 | 790.9 | 769.1 | 722.6 | 774.7 | 768.1 | 802 | 771.9 | 760.5 | 722.6 | 756.7 |
| 19   | 829                                                                  | 816 | 802 | 794.7 | 770   | 730.2 | 775.7 | 768.1 | 802 | 771.9 | 762.4 | 722.6 | 756.7 |
| 20   | 829                                                                  | 816 | 802 | 796.6 | 771.9 | 741.6 | 775.7 | 768.1 | 802 | 771.9 | 764.3 | 722.6 | 756.7 |
| etc  | 829                                                                  | 816 | 802 | 798.5 | 771.9 | 752.9 | 775.7 | 769.1 | 802 | 771.9 | 764.3 | 724.5 | 756.7 |
|      | 829                                                                  | 815 | 802 | 798.5 | 771.9 | 757.7 | 775.7 | 771.9 | 802 | 771.9 | 764.3 | 725.4 | 756.7 |
|      | 829                                                                  | 816 | 802 | 798.5 | 771.9 | 764.3 | 775.7 | 771.9 | 802 | 770   | 766.2 | 726.4 | 756.7 |
|      | 829                                                                  | 816 | 802 | 800   | 771.9 | 768.1 | 775.7 | 771.9 | 802 | 768.1 | 767.2 | 726.4 | 756.7 |
|      | 829                                                                  | 816 | 802 | 800   | 771.9 | 771   | 775.7 | 771.9 | 802 | 769.1 | 768.1 | 726.4 | 756.7 |
|      | 829                                                                  | 816 | 802 | 799.4 | 771.9 | 771.9 | 775.7 | 771.9 | 802 | 769.1 | 768.1 | 726.4 | 756.7 |
|      | 829                                                                  | 817 | 802 | 798.5 | 771.9 | 773.8 | 775.7 | 771.9 | 802 | 768.1 | 766.2 | 726.4 | 756.7 |

|     |     |     |       |       |       |       |       |       |       |       |       |       |
|-----|-----|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 829 | 817 | 802 | 798.5 | 772.9 | 775.7 | 775.7 | 771.9 | 802   | 768.1 | 764.3 | 726.4 | 756.7 |
| 829 | 817 | 802 | 798.5 | 773.8 | 775.7 | 775.7 | 771.9 | 802   | 768.1 | 764.3 | 726.4 | 756.7 |
| 829 | 817 | 802 | 798.5 | 773.8 | 778.5 | 775.7 | 771.9 | 802   | 768.1 | 764.3 | 726.4 | 756.7 |
| 829 | 817 | 802 | 798.5 | 774.7 | 779.5 | 775.7 | 772.9 | 802   | 768.1 | 762.4 | 726.4 | 756.7 |
| 829 | 817 | 802 | 798.5 | 775.7 | 779.5 | 775.7 | 773.8 | 802   | 768.1 | 763.4 | 726.4 | 756.7 |
| 829 | 817 | 802 | 798.5 | 775.7 | 779.5 | 775.7 | 773.8 | 802   | 768.1 | 762.4 | 726.4 | 756.7 |
| 829 | 817 | 802 | 798.5 | 775.7 | 779.5 | 775.7 | 775.7 | 802   | 768.1 | 763.4 | 726.4 | 756.7 |
| 829 | 817 | 802 | 798.5 | 775.7 | 779.5 | 775.7 | 775.7 | 798.5 | 768.1 | 764.3 | 727.3 | 756.7 |
| 829 | 817 | 802 | 801   | 775.7 | 779.5 | 775.7 | 775.7 | 798.5 | 768.1 | 764.3 | 727.3 | 756.7 |
| 829 | 817 | 802 | 801   | 773.8 | 779.5 | 775.7 | 775.7 | 798.5 | 764.3 | 767.2 | 729.2 | 757.7 |
| 829 | 817 | 802 | 802   | 773.8 | 780.4 | 775.7 | 775.7 | 794.7 | 764.3 | 768.1 | 730.2 | 757.7 |
| 829 | 817 | 802 | 802   | 775.7 | 782.3 | 775.7 | 775.7 | 794.7 | 764.3 | 768.1 | 730.2 | 757.7 |
| 829 | 817 | 802 | 802   | 774.7 | 781.4 | 775.7 | 775.7 | 794.7 | 764.3 | 768.1 | 730.2 | 756.7 |
| 829 | 817 | 802 | 802   | 775.7 | 783.3 | 775.7 | 775.7 | 792.8 | 764.3 | 768.1 | 730.2 | 756.7 |
| 829 | 817 | 802 | 802   | 775.7 | 783.3 | 775.7 | 775.7 | 791.8 | 764.3 | 768.1 | 730.2 | 757.7 |
| 829 | 817 | 802 | 802   | 775.7 | 783.3 | 775.7 | 775.7 | 790.9 | 764.3 | 768.1 | 730.2 | 757.7 |
| 829 | 817 | 802 | 802   | 775.7 | 783.3 | 775.7 | 775.7 | 790.9 | 764.3 | 768.1 | 730.2 | 757.7 |
| 829 | 817 | 802 | 802   | 775.7 | 783.3 | 775.7 | 775.7 | 790.9 | 764.3 | 768.1 | 730.2 | 756.7 |
| 829 | 817 | 802 | 801   | 775.7 | 783.3 | 775.7 | 777.6 | 790.9 | 764.3 | 768.1 | 730.2 | 756.7 |
| 829 | 817 | 802 | 800   | 775.7 | 783.3 | 775.7 | 777.6 | 790.9 | 765.3 | 768.1 | 730.2 | 757.7 |
| 829 | 817 | 802 | 800   | 775.7 | 783.3 | 775.7 | 778.5 | 790.9 | 764.3 | 768.1 | 730.2 | 758.6 |
| 829 | 817 | 802 | 800   | 775.7 | 783.3 | 776.6 | 778.5 | 790.9 | 764.3 | 769.1 | 730.2 | 759.6 |
| 829 | 817 | 802 | 800   | 775.7 | 783.3 | 775.7 | 779.5 | 790.9 | 764.3 | 768.1 | 730.2 | 760.5 |
| 828 | 817 | 802 | 799.4 | 775.7 | 783.3 | 775.7 | 779.5 | 789   | 764.3 | 768.1 | 732.1 | 760.5 |
| 828 | 817 | 802 | 798.5 | 775.7 | 783.3 | 775.7 | 779.5 | 789   | 764.3 | 768.1 | 732.1 | 760.5 |
| 827 | 817 | 802 | 800   | 775.7 | 786.1 | 775.7 | 779.5 | 787.1 | 764.3 | 768.1 | 733   | 760.5 |
| 829 | 817 | 802 | 798.5 | 775.7 | 786.1 | 775.7 | 779.5 | 787.1 | 764.3 | 768.1 | 733   | 760.5 |
| 827 | 817 | 804 | 798.5 | 775.7 | 787.1 | 775.7 | 779.5 | 787.1 | 764.3 | 768.1 | 734   | 760.5 |
| 827 | 817 | 804 | 798.5 | 775.7 | 787.1 | 775.7 | 779.5 | 787.1 | 764.3 | 768.1 | 734   | 760.5 |
| 827 | 817 | 806 | 798.5 | 775.7 | 787.1 | 775.7 | 779.5 | 787.1 | 764.3 | 768.1 | 734   | 760.5 |
| 826 | 817 | 806 | 798.5 | 775.7 | 787.1 | 775.7 | 779.5 | 787.1 | 764.3 | 769.1 | 734   | 760.5 |
| 826 | 817 | 806 | 798.5 | 775.7 | 787.1 | 775.7 | 779.5 | 787.1 | 764.3 | 770   | 734   | 760.5 |
| 826 | 817 | 806 | 798.5 | 775.7 | 787.1 | 776.6 | 779.5 | 787.1 | 764.3 | 771   | 734   | 760.5 |

|     |     |     |       |       |       |       |       |       |       |       |       |       |
|-----|-----|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 827 | 817 | 806 | 798.5 | 775.7 | 787.1 | 775.7 | 779.5 | 787.1 | 764.3 | 771.9 | 734   | 760.5 |
| 825 | 817 | 806 | 798.5 | 775.7 | 787.1 | 775.7 | 779.5 | 787.1 | 764.3 | 771.9 | 734   | 760.5 |
| 827 | 817 | 806 | 798.5 | 775.7 | 787.1 | 775.7 | 780.4 | 787.1 | 764.3 | 771.9 | 734   | 760.5 |
| 827 | 817 | 806 | 798.5 | 775.7 | 787.1 | 776.6 | 781.4 | 787.1 | 764.3 | 771.9 | 734   | 760.5 |
| 826 | 817 | 806 | 798.5 | 775.7 | 787.1 | 775.7 | 780.4 | 787.1 | 764.3 | 771.9 | 734   | 760.5 |
| 827 | 817 | 806 | 798.5 | 775.7 | 788   | 775.7 | 780.4 | 787.1 | 764.3 | 771.9 | 734   | 760.5 |
| 827 | 817 | 806 | 798.5 | 775.7 | 789   | 776.6 | 782.3 | 787.1 | 764.3 | 771.9 | 735.9 | 760.5 |
| 827 | 817 | 806 | 798.5 | 775.7 | 790.9 | 775.7 | 781.4 | 787.1 | 764.3 | 771.9 | 737.8 | 760.5 |
| 827 | 817 | 806 | 798.5 | 776.6 | 790.9 | 777.6 | 781.4 | 787.1 | 764.3 | 771.9 | 737.8 | 760.5 |
| 827 | 818 | 806 | 798.5 | 775.7 | 790.9 | 779.5 | 781.4 | 787.1 | 764.3 | 771.9 | 737.8 | 760.5 |
| 826 | 818 | 806 | 798.5 | 776.6 | 790.9 | 779.5 | 782.3 | 787.1 | 764.3 | 771.9 | 737.8 | 760.5 |
| 827 | 817 | 806 | 798.5 | 777.6 | 790.9 | 779.5 | 781.4 | 787.1 | 764.3 | 771.9 | 737.8 | 761.5 |
| 825 | 818 | 806 | 798.5 | 777.6 | 790.9 | 779.5 | 783.3 | 787.1 | 764.3 | 771.9 | 737.8 | 761.5 |
| 825 | 818 | 806 | 798.5 | 779.5 | 787.1 | 779.5 | 783.3 | 787.1 | 764.3 | 771.9 | 737.8 | 762.4 |
| 825 | 818 | 806 | 798.5 | 778.5 | 787.1 | 779.5 | 782.3 | 787.1 | 764.3 | 771.9 | 737.8 | 762.4 |
| 825 | 818 | 806 | 798.5 | 779.5 | 786.1 | 779.5 | 781.4 | 787.1 | 764.3 | 771.9 | 737.8 | 761.5 |
| 825 | 819 | 806 | 798.5 | 779.5 | 786.1 | 779.5 | 781.4 | 787.1 | 764.3 | 771.9 | 737.8 | 762.4 |
| 825 | 818 | 806 | 798.5 | 779.5 | 785.2 | 779.5 | 782.3 | 787.1 | 764.3 | 771.9 | 737.8 | 762.4 |
| 825 | 817 | 806 | 798.5 | 779.5 | 785.2 | 779.5 | 782.3 | 787.1 | 764.3 | 771.9 | 737.8 | 762.4 |
| 826 | 819 | 806 | 798.5 | 779.5 | 785.2 | 779.5 | 783.3 | 787.1 | 764.3 | 771.9 | 737.8 | 763.4 |
| 826 | 817 | 806 | 798.5 | 779.5 | 785.2 | 779.5 | 783.3 | 787.1 | 764.3 | 771.9 | 737.8 | 762.4 |
| 827 | 819 | 806 | 798.5 | 779.5 | 785.2 | 779.5 | 783.3 | 787.1 | 764.3 | 771.9 | 738.7 | 762.4 |
| 827 | 821 | 806 | 798.5 | 779.5 | 786.1 | 779.5 | 783.3 | 785.2 | 764.3 | 771.9 | 739.7 | 763.4 |
| 828 | 819 | 806 | 798.5 | 779.5 | 785.2 | 779.5 | 783.3 | 785.2 | 764.3 | 771.9 | 740.6 | 762.4 |
| 829 | 821 | 806 | 798.5 | 779.5 | 785.2 | 779.5 | 783.3 | 785.2 | 764.3 | 771.9 | 741.6 | 762.4 |
| 829 | 820 | 806 | 798.5 | 779.5 | 785.2 | 779.5 | 783.3 | 784.2 | 764.3 | 771.9 | 741.6 | 762.4 |
| 829 | 821 | 806 | 798.5 | 779.5 | 786.1 | 779.5 | 783.3 | 784.2 | 764.3 | 772.9 | 741.6 | 762.4 |
| 829 | 821 | 806 | 798.5 | 779.5 | 787.1 | 779.5 | 783.3 | 784.2 | 764.3 | 772.9 | 741.6 | 762.4 |
| 829 | 821 | 806 | 798.5 | 779.5 | 787.1 | 779.5 | 783.3 | 784.2 | 764.3 | 773.8 | 741.6 | 763.4 |
| 829 | 821 | 806 | 798.5 | 779.5 | 787.1 | 779.5 | 783.3 | 783.3 | 764.3 | 773.8 | 741.6 | 762.4 |
| 829 | 821 | 806 | 798.5 | 779.5 | 787.1 | 779.5 | 783.3 | 783.3 | 764.3 | 773.8 | 741.6 | 762.4 |
| 829 | 821 | 806 | 798.5 | 779.5 | 789.9 | 780.4 | 783.3 | 784.2 | 764.3 | 772.9 | 741.6 | 762.4 |
| 829 | 821 | 806 | 798.5 | 779.5 | 790.9 | 781.4 | 783.3 | 783.3 | 764.3 | 773.8 | 741.6 | 762.4 |



|     |     |     |       |       |       |       |       |       |       |       |       |       |
|-----|-----|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 829 | 821 | 806 | 798.5 | 779.5 | 790.9 | 779.5 | 783.3 | 783.3 | 764.3 | 773.8 | 741.6 | 762.4 |
| 829 | 821 | 806 | 798.5 | 779.5 | 790.9 | 781.4 | 783.3 | 783.3 | 764.3 | 773.8 | 741.6 | 762.4 |
| 829 | 821 | 806 | 798.5 | 779.5 | 790.9 | 781.4 | 783.3 | 783.3 | 764.3 | 773.8 | 741.6 | 763.4 |
| 829 | 821 | 806 | 798.5 | 779.5 | 790.9 | 782.3 | 783.3 | 783.3 | 764.3 | 773.8 | 741.6 | 763.4 |
| 829 | 821 | 806 | 798.5 | 776.6 | 790.9 | 782.3 | 783.3 | 786.1 | 764.3 | 773.8 | 741.6 | 763.4 |
| 829 | 821 | 806 | 798.5 | 775.7 | 790.9 | 781.4 | 783.3 | 787.1 | 764.3 | 773.8 | 741.6 | 763.4 |
| 829 | 821 | 806 | 798.5 | 775.7 | 790.9 | 783.3 | 783.3 | 787.1 | 764.3 | 773.8 | 741.6 | 763.4 |
| 829 | 821 | 806 | 798.5 | 775.7 | 790.9 | 783.3 | 783.3 | 787.1 | 764.3 | 772.9 | 741.6 | 762.4 |
| 829 | 821 | 806 | 798.5 | 775.7 | 790.9 | 783.3 | 783.3 | 787.1 | 764.3 | 773.8 | 741.6 | 763.4 |
| 829 | 821 | 806 | 799.4 | 775.7 | 790.9 | 783.3 | 783.3 | 787.1 | 764.3 | 773.8 | 741.6 | 764.3 |
| 829 | 821 | 806 | 800   | 775.7 | 790.9 | 783.3 | 783.3 | 787.1 | 764.3 | 772.9 | 741.6 | 763.4 |
| 829 | 821 | 805 | 801   | 775.7 | 791.8 | 783.3 | 783.3 | 787.1 | 764.3 | 772.9 | 741.6 | 762.4 |
| 829 | 821 | 805 | 802   | 775.7 | 790.9 | 783.3 | 784.2 | 787.1 | 764.3 | 772.9 | 741.6 | 764.3 |
| 827 | 821 | 804 | 802   | 775.7 | 791.8 | 783.3 | 784.2 | 787.1 | 764.3 | 772.9 | 742.5 | 762.4 |
| 827 | 821 | 804 | 802   | 775.7 | 792.8 | 783.3 | 785.2 | 787.1 | 764.3 | 773.8 | 743.5 | 762.4 |
| 827 | 821 | 804 | 802   | 775.7 | 792.8 | 783.3 | 787.1 | 787.1 | 764.3 | 771.9 | 742.5 | 763.4 |
| 827 | 822 | 804 | 802   | 775.7 | 793.7 | 783.3 | 787.1 | 787.1 | 764.3 | 768.1 | 742.5 | 762.4 |
| 828 | 823 | 804 | 804   | 775.7 | 793.7 | 783.3 | 787.1 | 787.1 | 764.3 | 768.1 | 743.5 | 763.4 |
| 828 | 823 | 805 | 806   | 775.7 | 794.7 | 783.3 | 787.1 | 787.1 | 764.3 | 764.3 | 742.5 | 762.4 |
| 828 | 823 | 805 | 805   | 775.7 | 794.7 | 783.3 | 787.1 | 787.1 | 764.3 | 764.3 | 741.6 | 763.4 |
| 828 | 825 | 804 | 806   | 775.7 | 794.7 | 783.3 | 787.1 | 787.1 | 764.3 | 764.3 | 742.5 | 762.4 |
| 829 | 825 | 804 | 806   | 775.7 | 794.7 | 783.3 | 787.1 | 787.1 | 764.3 | 764.3 | 741.6 | 762.4 |
| 829 | 825 | 804 | 806   | 775.7 | 794.7 | 783.3 | 787.1 | 787.1 | 764.3 | 764.3 | 741.6 | 762.4 |
| 829 | 825 | 803 | 806   | 775.7 | 794.7 | 783.3 | 787.1 | 787.1 | 764.3 | 762.4 | 741.6 | 762.4 |
| 829 | 825 | 803 | 806   | 776.6 | 794.7 | 783.3 | 787.1 | 787.1 | 764.3 | 762.4 | 741.6 | 762.4 |
| 829 | 825 | 804 | 806   | 775.7 | 794.7 | 783.3 | 787.1 | 787.1 | 763.4 | 761.5 | 741.6 | 762.4 |
| 829 | 825 | 803 | 806   | 775.7 | 794.7 | 783.3 | 787.1 | 787.1 | 763.4 | 760.5 | 741.6 | 761.5 |
| 829 | 825 | 803 | 806   | 775.7 | 790.9 | 783.3 | 787.1 | 787.1 | 764.3 | 760.5 | 741.6 | 762.4 |
| 829 | 825 | 803 | 806   | 777.6 | 790.9 | 783.3 | 787.1 | 787.1 | 764.3 | 760.5 | 743.5 | 761.5 |
| 829 | 825 | 802 | 806   | 776.6 | 790.9 | 783.3 | 787.1 | 787.1 | 763.4 | 760.5 | 743.5 | 761.5 |
| 829 | 825 | 802 | 806   | 776.6 | 790.9 | 783.3 | 787.1 | 787.1 | 764.3 | 760.5 | 742.5 | 761.5 |
| 829 | 825 | 802 | 806   | 776.6 | 789   | 783.3 | 787.1 | 787.1 | 762.4 | 760.5 | 742.5 | 760.5 |
| 829 | 825 | 802 | 806   | 777.6 | 788   | 783.3 | 787.1 | 787.1 | 764.3 | 760.5 | 742.5 | 760.5 |

|     |     |     |     |       |       |       |       |       |       |       |       |       |
|-----|-----|-----|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 829 | 825 | 802 | 806 | 777.6 | 787.1 | 783.3 | 787.1 | 787.1 | 764.3 | 760.5 | 743.5 | 760.5 |
| 828 | 826 | 802 | 806 | 778.5 | 787.1 | 783.3 | 787.1 | 787.1 | 764.3 | 760.5 | 744.4 | 760.5 |
| 828 | 827 | 802 | 806 | 777.6 | 787.1 | 783.3 | 787.1 | 787.1 | 764.3 | 760.5 | 743.5 | 760.5 |
| 829 | 826 | 802 | 806 | 777.6 | 787.1 | 784.2 | 787.1 | 787.1 | 764.3 | 759.6 | 744.4 | 760.5 |
| 828 | 827 | 802 | 806 | 777.6 | 787.1 | 785.2 | 787.1 | 787.1 | 764.3 | 758.6 | 745.4 | 760.5 |
| 827 | 828 | 802 | 806 | 777.6 | 787.1 | 786.1 | 787.1 | 787.1 | 764.3 | 757.7 | 745.4 | 760.5 |
| 827 | 828 | 802 | 806 | 777.6 | 787.1 | 787.1 | 787.1 | 787.1 | 764.3 | 756.7 | 745.4 | 760.5 |
| 826 | 828 | 802 | 806 | 777.6 | 787.1 | 787.1 | 787.1 | 787.1 | 764.3 | 756.7 | 745.4 | 761.5 |
| 826 | 827 | 802 | 806 | 778.5 | 787.1 | 787.1 | 787.1 | 787.1 | 764.3 | 756.7 | 745.4 | 760.5 |
| 826 | 828 | 802 | 807 | 778.5 | 787.1 | 787.1 | 787.1 | 787.1 | 764.3 | 756.7 | 745.4 | 760.5 |
| 827 | 828 | 802 | 808 | 779.5 | 787.1 | 787.1 | 787.1 | 788   | 764.3 | 756.7 | 745.4 | 761.5 |
| 827 | 827 | 802 | 808 | 779.5 | 787.1 | 787.1 | 787.1 | 788   | 764.3 | 756.7 | 745.4 | 760.5 |
| 827 | 827 | 803 | 810 | 779.5 | 786.1 | 787.1 | 787.1 | 789   | 764.3 | 756.7 | 742.5 | 760.5 |
| 827 | 825 | 804 | 810 | 779.5 | 785.2 | 787.1 | 787.1 | 789.9 | 764.3 | 756.7 | 741.6 | 762.4 |
| 827 | 827 | 803 | 810 | 779.5 | 785.2 | 787.1 | 787.1 | 789   | 764.3 | 756.7 | 741.6 | 760.5 |
| 828 | 827 | 804 | 810 | 779.5 | 786.1 | 787.1 | 787.1 | 788   | 763.4 | 756.7 | 741.6 | 760.5 |
| 829 | 828 | 804 | 810 | 779.5 | 786.1 | 788   | 787.1 | 789   | 764.3 | 756.7 | 741.6 | 760.5 |
| 827 | 828 | 805 | 810 | 779.5 | 785.2 | 789   | 787.1 | 789   | 763.4 | 756.7 | 741.6 | 762.4 |
| 827 | 827 | 804 | 810 | 779.5 | 786.1 | 789   | 787.1 | 788   | 763.4 | 758.6 | 741.6 | 761.5 |
| 828 | 828 | 804 | 810 | 779.5 | 783.3 | 789.9 | 787.1 | 789   | 763.4 | 760.5 | 743.5 | 762.4 |
| 827 | 828 | 805 | 810 | 779.5 | 783.3 | 790.9 | 787.1 | 789.9 | 763.4 | 760.5 | 743.5 | 762.4 |
| 827 | 828 | 805 | 810 | 779.5 | 783.3 | 790.9 | 787.1 | 789   | 764.3 | 760.5 | 743.5 | 760.5 |
| 827 | 829 | 804 | 810 | 779.5 | 783.3 | 790.9 | 787.1 | 789   | 764.3 | 760.5 | 743.5 | 760.5 |
| 827 | 829 | 806 | 810 | 779.5 | 783.3 | 790.9 | 787.1 | 790.9 | 763.4 | 760.5 | 744.4 | 760.5 |
| 827 | 829 | 806 | 810 | 779.5 | 783.3 | 790.9 | 789.9 | 789   | 763.4 | 761.5 | 743.5 | 760.5 |
| 828 | 826 | 806 | 810 | 779.5 | 783.3 | 790.9 | 790.9 | 789   | 764.3 | 760.5 | 744.4 | 760.5 |
| 829 | 825 | 806 | 810 | 779.5 | 783.3 | 790.9 | 790.9 | 789   | 763.4 | 760.5 | 745.4 | 760.5 |
| 829 | 825 | 806 | 810 | 779.5 | 783.3 | 790.9 | 790.9 | 789   | 764.3 | 762.4 | 745.4 | 760.5 |
| 829 | 825 | 806 | 810 | 779.5 | 783.3 | 790.9 | 790.9 | 789.9 | 763.4 | 762.4 | 745.4 | 760.5 |
| 829 | 825 | 806 | 810 | 779.5 | 783.3 | 790.9 | 790.9 | 790.9 | 763.4 | 763.4 | 745.4 | 760.5 |
| 829 | 825 | 806 | 811 | 779.5 | 783.3 | 790.9 | 790.9 | 790.9 | 763.4 | 764.3 | 745.4 | 760.5 |
| 829 | 825 | 806 | 811 | 779.5 | 783.3 | 790.9 | 790.9 | 789.9 | 763.4 | 764.3 | 745.4 | 760.5 |
| 829 | 825 | 806 | 812 | 779.5 | 783.3 | 790.9 | 790.9 | 790.9 | 764.3 | 764.3 | 749.1 | 760.5 |

|     |     |     |     |       |       |       |       |       |       |       |       |       |
|-----|-----|-----|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 829 | 825 | 806 | 812 | 779.5 | 783.3 | 790.9 | 790.9 | 790.9 | 763.4 | 760.5 | 749.1 | 760.5 |
| 829 | 825 | 806 | 812 | 779.5 | 783.3 | 790.9 | 790.9 | 790.9 | 762.4 | 760.5 | 751   | 760.5 |
| 829 | 825 | 806 | 813 | 779.5 | 783.3 | 790.9 | 790.9 | 790.9 | 762.4 | 760.5 | 752.9 | 760.5 |
| 829 | 825 | 806 | 812 | 779.5 | 783.3 | 790.9 | 790.9 | 790.9 | 762.4 | 760.5 | 752.9 | 760.5 |
| 829 | 825 | 806 | 812 | 779.5 | 783.3 | 790.9 | 790.9 | 790.9 | 764.3 | 760.5 | 752.9 | 760.5 |
| 829 | 825 | 806 | 812 | 779.5 | 783.3 | 790.9 | 790.9 | 790.9 | 764.3 | 760.5 | 752.9 | 760.5 |
| 829 | 825 | 806 | 812 | 779.5 | 783.3 | 790.9 | 790.9 | 790.9 | 764.3 | 760.5 | 754.8 | 760.5 |
| 829 | 825 | 806 | 813 | 779.5 | 783.3 | 790.9 | 790.9 | 790.9 | 764.3 | 759.6 | 754.8 | 760.5 |
| 829 | 825 | 806 | 812 | 779.5 | 783.3 | 790.9 | 790.9 | 790.9 | 764.3 | 760.5 | 756.7 | 760.5 |
| 829 | 825 | 806 | 811 | 779.5 | 783.3 | 790.9 | 790.9 | 790.9 | 764.3 | 760.5 | 756.7 | 760.5 |
| 829 | 825 | 806 | 812 | 779.5 | 783.3 | 790.9 | 790.9 | 790.9 | 765.3 | 760.5 | 756.7 | 760.5 |
| 829 | 825 | 806 | 812 | 779.5 | 783.3 | 790.9 | 790.9 | 790.9 | 766.2 | 760.5 | 756.7 | 760.5 |
| 829 | 825 | 806 | 811 | 779.5 | 783.3 | 790.9 | 790.9 | 790.9 | 767.2 | 758.6 | 756.7 | 760.5 |
| 829 | 825 | 806 | 812 | 779.5 | 783.3 | 790.9 | 790.9 | 790.9 | 768.1 | 758.6 | 757.7 | 760.5 |
| 829 | 825 | 807 | 811 | 779.5 | 783.3 | 790.9 | 790.9 | 790.9 | 768.1 | 758.6 | 758.6 | 760.5 |
| 829 | 825 | 806 | 812 | 779.5 | 783.3 | 790.9 | 790.9 | 790.9 | 768.1 | 760.5 | 759.6 | 760.5 |
| 829 | 825 | 808 | 812 | 779.5 | 783.3 | 790.9 | 790.9 | 790.9 | 768.1 | 760.5 | 760.5 | 760.5 |
| 829 | 825 | 806 | 811 | 779.5 | 785.2 | 790.9 | 790.9 | 790.9 | 768.1 | 760.5 | 760.5 | 760.5 |
| 829 | 824 | 810 | 811 | 779.5 | 785.2 | 790.9 | 790.9 | 790.9 | 768.1 | 760.5 | 760.5 | 760.5 |
| 829 | 823 | 810 | 812 | 779.5 | 786.1 | 790.9 | 790.9 | 790.9 | 768.1 | 760.5 | 760.5 | 760.5 |
| 829 | 823 | 810 | 812 | 779.5 | 787.1 | 790.9 | 790.9 | 790.9 | 768.1 | 760.5 | 760.5 | 760.5 |
| 829 | 822 | 810 | 812 | 779.5 | 786.1 | 790.9 | 790.9 | 790.9 | 766.2 | 760.5 | 760.5 | 760.5 |
| 829 | 821 | 810 | 812 | 779.5 | 787.1 | 790.9 | 789.9 | 790.9 | 766.2 | 760.5 | 760.5 | 760.5 |
| 829 | 822 | 810 | 812 | 780.4 | 787.1 | 790.9 | 789.9 | 790.9 | 764.3 | 760.5 | 760.5 | 760.5 |
| 829 | 821 | 810 | 814 | 782.3 | 787.1 | 790.9 | 789.9 | 790.9 | 764.3 | 760.5 | 760.5 | 760.5 |
| 829 | 821 | 810 | 812 | 783.3 | 787.1 | 790.9 | 789   | 790.9 | 764.3 | 760.5 | 760.5 | 760.5 |
| 829 | 822 | 810 | 812 | 783.3 | 787.1 | 790.9 | 788   | 790.9 | 764.3 | 757.7 | 762.4 | 760.5 |
| 829 | 821 | 810 | 812 | 783.3 | 787.1 | 790.9 | 789   | 790.9 | 763.4 | 758.6 | 762.4 | 760.5 |
| 829 | 821 | 810 | 812 | 783.3 | 787.1 | 790.9 | 788   | 790.9 | 764.3 | 758.6 | 763.4 | 760.5 |
| 829 | 823 | 810 | 813 | 783.3 | 787.1 | 790.9 | 789   | 790.9 | 763.4 | 757.7 | 764.3 | 760.5 |
| 829 | 822 | 810 | 813 | 783.3 | 787.1 | 790.9 | 789   | 790.9 | 764.3 | 758.6 | 764.3 | 760.5 |
| 829 | 823 | 810 | 813 | 783.3 | 787.1 | 790.9 | 789   | 790.9 | 763.4 | 758.6 | 764.3 | 760.5 |
| 829 | 825 | 810 | 812 | 783.3 | 787.1 | 790.9 | 787.1 | 790.9 | 763.4 | 757.7 | 764.3 | 760.5 |

|     |     |     |     |       |       |       |       |       |       |       |       |       |
|-----|-----|-----|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 829 | 825 | 810 | 814 | 783.3 | 787.1 | 790.9 | 787.1 | 790.9 | 764.3 | 757.7 | 764.3 | 760.5 |
| 829 | 825 | 811 | 814 | 783.3 | 787.1 | 790.9 | 787.1 | 790.9 | 764.3 | 758.6 | 764.3 | 760.5 |
| 829 | 823 | 812 | 814 | 783.3 | 787.1 | 790.9 | 787.1 | 790.9 | 764.3 | 757.7 | 764.3 | 760.5 |
| 829 | 822 | 813 | 814 | 783.3 | 787.1 | 790.9 | 787.1 | 790.9 | 764.3 | 756.7 | 764.3 | 760.5 |
| 829 | 823 | 812 | 814 | 783.3 | 787.1 | 790.9 | 789   | 790.9 | 764.3 | 756.7 | 764.3 | 760.5 |
| 829 | 823 | 812 | 814 | 783.3 | 787.1 | 790.9 | 788   | 790.9 | 764.3 | 757.7 | 764.3 | 760.5 |
| 829 | 821 | 812 | 814 | 783.3 | 787.1 | 790.9 | 789   | 790.9 | 764.3 | 756.7 | 764.3 | 760.5 |
| 829 | 822 | 814 | 814 | 783.3 | 787.1 | 791.8 | 788   | 790.9 | 763.4 | 757.7 | 764.3 | 760.5 |
| 829 | 823 | 813 | 814 | 783.3 | 787.1 | 791.8 | 789   | 790.9 | 764.3 | 756.7 | 764.3 | 760.5 |
| 829 | 823 | 814 | 814 | 783.3 | 787.1 | 791.8 | 789   | 790.9 | 764.3 | 757.7 | 764.3 | 760.5 |
| 831 | 825 | 813 | 814 | 783.3 | 787.1 | 790.9 | 789   | 789   | 763.4 | 757.7 | 765.3 | 760.5 |
| 833 | 823 | 814 | 814 | 783.3 | 787.1 | 791.8 | 788   | 790.9 | 763.4 | 756.7 | 766.2 | 760.5 |
| 833 | 823 | 814 | 814 | 783.3 | 787.1 | 790.9 | 788   | 789   | 764.3 | 756.7 | 765.3 | 760.5 |
| 833 | 823 | 814 | 814 | 783.3 | 787.1 | 790.9 | 787.1 | 790.9 | 763.4 | 758.6 | 765.3 | 760.5 |
| 833 | 824 | 814 | 814 | 783.3 | 787.1 | 791.8 | 788   | 790.9 | 763.4 | 757.7 | 766.2 | 760.5 |
| 833 | 823 | 814 | 814 | 783.3 | 787.1 | 791.8 | 788   | 790.9 | 762.4 | 758.6 | 766.2 | 760.5 |
| 833 | 823 | 814 | 814 | 783.3 | 787.1 | 792.8 | 788   | 790.9 | 762.4 | 757.7 | 768.1 | 760.5 |
| 833 | 823 | 814 | 814 | 783.3 | 787.1 | 792.8 | 789   | 789.9 | 761.5 | 759.6 | 767.2 | 760.5 |
| 833 | 825 | 814 | 814 | 783.3 | 787.1 | 793.7 | 789   | 790.9 | 762.4 | 759.6 | 768.1 | 760.5 |
| 833 | 824 | 814 | 814 | 783.3 | 787.1 | 792.8 | 789   | 789.9 | 760.5 | 760.5 | 768.1 | 761.5 |
| 833 | 825 | 814 | 814 | 783.3 | 787.1 | 794.7 | 789.9 | 789   | 761.5 | 760.5 | 768.1 | 761.5 |
| 833 | 823 | 814 | 814 | 783.3 | 787.1 | 792.8 | 790.9 | 788   | 761.5 | 760.5 | 768.1 | 760.5 |
| 833 | 824 | 814 | 814 | 783.3 | 787.1 | 792.8 | 789.9 | 788   | 760.5 | 760.5 | 768.1 | 762.4 |
| 834 | 824 | 814 | 814 | 783.3 | 787.1 | 791.8 | 789   | 787.1 | 760.5 | 760.5 | 768.1 | 762.4 |
| 834 | 823 | 814 | 814 | 783.3 | 787.1 | 792.8 | 789.9 | 787.1 | 760.5 | 760.5 | 768.1 | 762.4 |
| 834 | 824 | 814 | 815 | 783.3 | 787.1 | 792.8 | 790.9 | 787.1 | 761.5 | 760.5 | 768.1 | 762.4 |
| 834 | 824 | 814 | 814 | 783.3 | 787.1 | 790.9 | 790.9 | 787.1 | 760.5 | 760.5 | 768.1 | 762.4 |
| 835 | 825 | 814 | 815 | 783.3 | 787.1 | 792.8 | 790.9 | 787.1 | 760.5 | 760.5 | 768.1 | 762.4 |
| 834 | 824 | 814 | 815 | 783.3 | 787.1 | 792.8 | 790.9 | 787.1 | 760.5 | 760.5 | 768.1 | 762.4 |
| 835 | 825 | 814 | 816 | 783.3 | 787.1 | 791.8 | 790.9 | 787.1 | 760.5 | 760.5 | 768.1 | 762.4 |
| 835 | 825 | 814 | 816 | 783.3 | 787.1 | 792.8 | 790.9 | 787.1 | 760.5 | 760.5 | 768.1 | 763.4 |
| 835 | 825 | 814 | 816 | 783.3 | 787.1 | 792.8 | 790.9 | 787.1 | 760.5 | 760.5 | 768.1 | 762.4 |
| 834 | 825 | 814 | 816 | 783.3 | 787.1 | 792.8 | 790.9 | 787.1 | 760.5 | 760.5 | 768.1 | 762.4 |

|     |     |     |     |       |       |       |       |       |       |       |       |       |
|-----|-----|-----|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 833 | 825 | 814 | 816 | 783.3 | 787.1 | 792.8 | 790.9 | 787.1 | 760.5 | 760.5 | 768.1 | 762.4 |
| 833 | 825 | 814 | 816 | 783.3 | 787.1 | 794.7 | 790.9 | 787.1 | 760.5 | 760.5 | 768.1 | 762.4 |
| 833 | 825 | 814 | 817 | 783.3 | 787.1 | 794.7 | 790.9 | 787.1 | 760.5 | 760.5 | 768.1 | 763.4 |
| 833 | 825 | 814 | 817 | 783.3 | 787.1 | 794.7 | 790.9 | 787.1 | 760.5 | 760.5 | 768.1 | 762.4 |
| 833 | 825 | 814 | 817 | 783.3 | 787.1 | 794.7 | 790.9 | 787.1 | 760.5 | 760.5 | 768.1 | 764.3 |
| 833 | 823 | 814 | 817 | 785.2 | 787.1 | 794.7 | 790.9 | 787.1 | 760.5 | 760.5 | 768.1 | 762.4 |
| 833 | 823 | 814 | 817 | 787.1 | 787.1 | 794.7 | 790.9 | 787.1 | 760.5 | 760.5 | 768.1 | 764.3 |
| 833 | 821 | 814 | 817 | 787.1 | 787.1 | 794.7 | 790.9 | 787.1 | 760.5 | 760.5 | 768.1 | 764.3 |
| 833 | 821 | 814 | 817 | 787.1 | 787.1 | 794.7 | 790.9 | 787.1 | 760.5 | 760.5 | 768.1 | 764.3 |
| 833 | 823 | 814 | 817 | 787.1 | 787.1 | 794.7 | 791.8 | 787.1 | 760.5 | 759.6 | 768.1 | 764.3 |
| 833 | 822 | 814 | 817 | 787.1 | 787.1 | 794.7 | 793.7 | 787.1 | 760.5 | 758.6 | 768.1 | 764.3 |
| 833 | 821 | 814 | 817 | 787.1 | 787.1 | 794.7 | 794.7 | 787.1 | 760.5 | 758.6 | 768.1 | 764.3 |
| 833 | 821 | 814 | 817 | 787.1 | 787.1 | 794.7 | 794.7 | 787.1 | 760.5 | 758.6 | 768.1 | 764.3 |
| 833 | 822 | 814 | 817 | 787.1 | 787.1 | 794.7 | 794.7 | 787.1 | 760.5 | 758.6 | 768.1 | 764.3 |
| 833 | 822 | 812 | 817 | 789   | 787.1 | 794.7 | 794.7 | 787.1 | 760.5 | 760.5 | 768.1 | 764.3 |
| 833 | 822 | 811 | 817 | 789   | 787.1 | 794.7 | 794.7 | 787.1 | 760.5 | 760.5 | 770   | 764.3 |
| 833 | 821 | 810 | 817 | 790.9 | 787.1 | 794.7 | 794.7 | 787.1 | 760.5 | 758.6 | 771.9 | 763.4 |
| 832 | 821 | 810 | 817 | 790.9 | 787.1 | 794.7 | 794.7 | 787.1 | 760.5 | 760.5 | 771.9 | 762.4 |
| 833 | 821 | 810 | 817 | 789   | 787.1 | 794.7 | 794.7 | 787.1 | 760.5 | 758.6 | 771.9 | 764.3 |
| 831 | 821 | 810 | 817 | 788   | 787.1 | 794.7 | 794.7 | 787.1 | 760.5 | 759.6 | 771.9 | 764.3 |
| 831 | 821 | 810 | 817 | 787.1 | 787.1 | 794.7 | 794.7 | 787.1 | 760.5 | 760.5 | 771.9 | 762.4 |
| 831 | 821 | 810 | 817 | 788   | 787.1 | 794.7 | 794.7 | 787.1 | 760.5 | 760.5 | 771.9 | 762.4 |
| 831 | 821 | 810 | 817 | 787.1 | 787.1 | 793.7 | 794.7 | 787.1 | 764.3 | 760.5 | 771.9 | 762.4 |
| 832 | 821 | 810 | 817 | 788   | 787.1 | 793.7 | 794.7 | 787.1 | 764.3 | 760.5 | 771.9 | 762.4 |
| 832 | 821 | 810 | 817 | 787.1 | 787.1 | 792.8 | 793.7 | 787.1 | 768.1 | 760.5 | 771.9 | 761.5 |
| 833 | 821 | 810 | 818 | 787.1 | 787.1 | 793.7 | 794.7 | 787.1 | 768.1 | 760.5 | 771.9 | 762.4 |
| 833 | 821 | 810 | 819 | 788   | 787.1 | 792.8 | 793.7 | 787.1 | 768.1 | 760.5 | 771.9 | 762.4 |
| 833 | 821 | 810 | 819 | 789   | 787.1 | 792.8 | 792.8 | 787.1 | 768.1 | 760.5 | 771.9 | 763.4 |
| 833 | 821 | 810 | 819 | 789   | 787.1 | 792.8 | 792.8 | 787.1 | 770   | 759.6 | 771.9 | 764.3 |
| 833 | 821 | 810 | 821 | 789   | 787.1 | 790.9 | 792.8 | 787.1 | 771.9 | 760.5 | 772.9 | 764.3 |
| 833 | 821 | 810 | 821 | 789   | 787.1 | 790.9 | 792.8 | 787.1 | 771.9 | 760.5 | 772.9 | 764.3 |
| 833 | 821 | 810 | 821 | 789   | 787.1 | 790.9 | 791.8 | 787.1 | 771.9 | 760.5 | 773.8 | 764.3 |
| 833 | 821 | 810 | 821 | 790.9 | 787.1 | 790.9 | 792.8 | 787.1 | 771.9 | 760.5 | 773.8 | 764.3 |

|     |     |     |     |       |       |       |       |       |       |       |       |       |
|-----|-----|-----|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 833 | 821 | 810 | 821 | 790.9 | 787.1 | 790.9 | 790.9 | 787.1 | 771.9 | 760.5 | 773.8 | 764.3 |
| 833 | 821 | 810 | 821 | 790.9 | 787.1 | 790.9 | 792.8 | 787.1 | 771.9 | 760.5 | 775.7 | 764.3 |
| 832 | 821 | 810 | 821 | 790.9 | 788   | 790.9 | 792.8 | 787.1 | 771.9 | 760.5 | 775.7 | 764.3 |
| 830 | 821 | 810 | 821 | 790.9 | 788   | 790.9 | 792.8 | 787.1 | 771.9 | 760.5 | 775.7 | 764.3 |
| 829 | 821 | 810 | 821 | 790.9 | 789   | 790.9 | 792.8 | 787.1 | 773.8 | 760.5 | 774.7 | 764.3 |
| 829 | 821 | 810 | 821 | 790.9 | 790.9 | 790.9 | 792.8 | 787.1 | 773.8 | 760.5 | 775.7 | 764.3 |
| 829 | 821 | 810 | 821 | 790.9 | 790.9 | 790.9 | 792.8 | 787.1 | 773.8 | 760.5 | 775.7 | 764.3 |
| 829 | 821 | 810 | 821 | 790.9 | 790.9 | 790.9 | 793.7 | 787.1 | 773.8 | 760.5 | 775.7 | 764.3 |
| 830 | 821 | 810 | 821 | 790.9 | 790.9 | 790.9 | 793.7 | 787.1 | 775.7 | 760.5 | 775.7 | 764.3 |
| 830 | 821 | 810 | 821 | 790.9 | 790.9 | 787.1 | 794.7 | 787.1 | 774.7 | 760.5 | 775.7 | 764.3 |
| 831 | 821 | 810 | 821 | 791.8 | 790.9 | 787.1 | 794.7 | 787.1 | 775.7 | 760.5 | 775.7 | 764.3 |
| 833 | 821 | 810 | 821 | 794.7 | 790.9 | 785.2 | 794.7 | 787.1 | 775.7 | 760.5 | 775.7 | 764.3 |
| 833 | 822 | 810 | 821 | 794.7 | 790.9 | 785.2 | 794.7 | 787.1 | 775.7 | 760.5 | 775.7 | 764.3 |
| 833 | 821 | 810 | 821 | 794.7 | 790.9 | 785.2 | 794.7 | 787.1 | 775.7 | 760.5 | 775.7 | 764.3 |
| 833 | 821 | 810 | 821 | 794.7 | 790.9 | 784.2 | 794.7 | 787.1 | 775.7 | 760.5 | 775.7 | 764.3 |
| 833 | 821 | 810 | 821 | 794.7 | 790.9 | 783.3 | 794.7 | 787.1 | 775.7 | 760.5 | 775.7 | 764.3 |
| 833 | 821 | 810 | 821 | 794.7 | 790.9 | 783.3 | 794.7 | 787.1 | 775.7 | 760.5 | 775.7 | 764.3 |
| 833 | 822 | 810 | 821 | 794.7 | 790.9 | 783.3 | 794.7 | 787.1 | 775.7 | 760.5 | 775.7 | 764.3 |
| 833 | 821 | 809 | 821 | 794.7 | 790.9 | 783.3 | 794.7 | 787.1 | 775.7 | 759.6 | 775.7 | 766.2 |
| 833 | 823 | 808 | 821 | 794.7 | 790.9 | 783.3 | 794.7 | 787.1 | 775.7 | 759.6 | 775.7 | 766.2 |
| 833 | 821 | 809 | 821 | 794.7 | 790.9 | 783.3 | 794.7 | 787.1 | 775.7 | 760.5 | 775.7 | 766.2 |
| 833 | 822 | 809 | 821 | 794.7 | 790.9 | 783.3 | 794.7 | 787.1 | 775.7 | 760.5 | 775.7 | 766.2 |
| 833 | 821 | 809 | 821 | 794.7 | 790.9 | 783.3 | 794.7 | 787.1 | 775.7 | 760.5 | 775.7 | 766.2 |
| 833 | 821 | 810 | 821 | 794.7 | 790.9 | 782.3 | 794.7 | 787.1 | 775.7 | 760.5 | 775.7 | 766.2 |
| 833 | 822 | 810 | 821 | 794.7 | 790.9 | 781.4 | 794.7 | 787.1 | 775.7 | 760.5 | 775.7 | 766.2 |
| 833 | 822 | 810 | 821 | 794.7 | 790.9 | 779.5 | 794.7 | 787.1 | 775.7 | 760.5 | 775.7 | 766.2 |
| 833 | 821 | 810 | 821 | 794.7 | 790.9 | 779.5 | 794.7 | 787.1 | 775.7 | 760.5 | 775.7 | 766.2 |
| 833 | 821 | 810 | 821 | 794.7 | 790.9 | 779.5 | 794.7 | 787.1 | 775.7 | 760.5 | 775.7 | 767.2 |
| 833 | 821 | 810 | 821 | 794.7 | 790.9 | 779.5 | 794.7 | 787.1 | 775.7 | 760.5 | 775.7 | 767.2 |
| 833 | 821 | 810 | 821 | 794.7 | 790.9 | 779.5 | 794.7 | 787.1 | 775.7 | 760.5 | 775.7 | 768.1 |
| 833 | 821 | 810 | 821 | 794.7 | 790.9 | 779.5 | 796.6 | 787.1 | 776.6 | 760.5 | 775.7 | 767.2 |
| 833 | 821 | 810 | 821 | 794.7 | 790.9 | 779.5 | 795.6 | 787.1 | 777.6 | 760.5 | 775.7 | 768.1 |
| 833 | 821 | 810 | 821 | 794.7 | 790.9 | 779.5 | 796.6 | 787.1 | 778.5 | 760.5 | 775.7 | 767.2 |

|     |     |     |     |       |       |       |       |       |       |       |       |       |
|-----|-----|-----|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 833 | 821 | 810 | 817 | 794.7 | 790.9 | 779.5 | 796.6 | 787.1 | 777.6 | 760.5 | 775.7 | 767.2 |
| 833 | 821 | 810 | 816 | 794.7 | 790.9 | 779.5 | 797.5 | 787.1 | 777.6 | 760.5 | 775.7 | 768.1 |
| 833 | 821 | 810 | 816 | 794.7 | 790.9 | 779.5 | 797.5 | 787.1 | 778.5 | 760.5 | 775.7 | 768.1 |
| 833 | 821 | 810 | 816 | 794.7 | 790.9 | 779.5 | 797.5 | 787.1 | 778.5 | 760.5 | 775.7 | 766.2 |
| 833 | 821 | 810 | 815 | 794.7 | 790.9 | 782.3 | 798.5 | 787.1 | 777.6 | 760.5 | 775.7 | 766.2 |
| 833 | 821 | 809 | 816 | 794.7 | 790.9 | 783.3 | 798.5 | 787.1 | 777.6 | 760.5 | 775.7 | 766.2 |
| 833 | 821 | 808 | 816 | 794.7 | 790.9 | 783.3 | 798.5 | 787.1 | 779.5 | 760.5 | 775.7 | 767.2 |
| 833 | 821 | 808 | 815 | 794.7 | 790.9 | 783.3 | 798.5 | 787.1 | 779.5 | 761.5 | 775.7 | 766.2 |
| 833 | 821 | 807 | 814 | 794.7 | 790.9 | 783.3 | 798.5 | 787.1 | 779.5 | 760.5 | 775.7 | 767.2 |
| 833 | 821 | 807 | 814 | 794.7 | 790.9 | 783.3 | 798.5 | 787.1 | 779.5 | 760.5 | 775.7 | 767.2 |
| 833 | 821 | 807 | 814 | 794.7 | 790.9 | 783.3 | 798.5 | 787.1 | 779.5 | 760.5 | 775.7 | 767.2 |
| 833 | 821 | 807 | 814 | 794.7 | 790.9 | 783.3 | 798.5 | 787.1 | 778.5 | 760.5 | 775.7 | 767.2 |
| 833 | 821 | 807 | 814 | 794.7 | 790.9 | 783.3 | 798.5 | 787.1 | 778.5 | 761.5 | 775.7 | 766.2 |
| 833 | 821 | 809 | 814 | 794.7 | 790.9 | 784.2 | 798.5 | 787.1 | 779.5 | 761.5 | 775.7 | 766.2 |
| 833 | 821 | 810 | 814 | 794.7 | 790.9 | 783.3 | 798.5 | 787.1 | 779.5 | 762.4 | 775.7 | 767.2 |
| 833 | 821 | 810 | 814 | 794.7 | 790.9 | 784.2 | 798.5 | 787.1 | 779.5 | 762.4 | 775.7 | 766.2 |
| 833 | 821 | 810 | 814 | 794.7 | 790.9 | 784.2 | 798.5 | 787.1 | 779.5 | 762.4 | 775.7 | 767.2 |
| 833 | 821 | 810 | 814 | 794.7 | 790.9 | 784.2 | 798.5 | 787.1 | 779.5 | 762.4 | 775.7 | 766.2 |
| 833 | 821 | 810 | 814 | 794.7 | 790.9 | 785.2 | 798.5 | 787.1 | 779.5 | 762.4 | 775.7 | 765.3 |
| 833 | 821 | 810 | 814 | 794.7 | 790.9 | 786.1 | 798.5 | 787.1 | 779.5 | 762.4 | 775.7 | 766.2 |
| 833 | 821 | 811 | 814 | 794.7 | 790.9 | 785.2 | 798.5 | 787.1 | 779.5 | 761.5 | 775.7 | 765.3 |
| 833 | 821 | 811 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 787.1 | 779.5 | 760.5 | 775.7 | 766.2 |
| 833 | 821 | 812 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 787.1 | 779.5 | 760.5 | 775.7 | 765.3 |
| 833 | 821 | 812 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 787.1 | 779.5 | 760.5 | 775.7 | 766.2 |
| 833 | 821 | 812 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 787.1 | 779.5 | 760.5 | 775.7 | 765.3 |
| 833 | 821 | 812 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 787.1 | 779.5 | 760.5 | 775.7 | 766.2 |
| 833 | 821 | 814 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 787.1 | 779.5 | 760.5 | 775.7 | 764.3 |
| 833 | 821 | 814 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 787.1 | 779.5 | 760.5 | 775.7 | 764.3 |
| 833 | 821 | 814 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 787.1 | 779.5 | 760.5 | 775.7 | 764.3 |
| 833 | 821 | 814 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 787.1 | 778.5 | 760.5 | 775.7 | 764.3 |
| 833 | 821 | 814 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 787.1 | 779.5 | 760.5 | 775.7 | 764.3 |
| 833 | 821 | 814 | 814 | 794.7 | 790.9 | 787.1 | 799.4 | 786.1 | 779.5 | 760.5 | 775.7 | 764.3 |

|  |     |     |     |     |       |       |       |       |       |       |       |       |       |
|--|-----|-----|-----|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|  | 833 | 821 | 814 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 783.3 | 778.5 | 760.5 | 775.7 | 764.3 |
|  | 833 | 821 | 814 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 783.3 | 778.5 | 760.5 | 775.7 | 764.3 |
|  | 833 | 821 | 814 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 783.3 | 778.5 | 760.5 | 775.7 | 764.3 |
|  | 833 | 821 | 814 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 783.3 | 779.5 | 760.5 | 775.7 | 764.3 |
|  | 833 | 821 | 814 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 783.3 | 775.7 | 760.5 | 775.7 | 764.3 |
|  | 833 | 821 | 814 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 783.3 | 775.7 | 760.5 | 775.7 | 764.3 |
|  | 833 | 821 | 814 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 783.3 | 775.7 | 760.5 | 775.7 | 764.3 |
|  | 833 | 820 | 814 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 781.4 | 775.7 | 760.5 | 775.7 | 764.3 |
|  | 833 | 819 | 814 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 782.3 | 775.7 | 760.5 | 775.7 | 764.3 |
|  | 833 | 819 | 814 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 781.4 | 775.7 | 760.5 | 775.7 | 764.3 |
|  | 833 | 821 | 814 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 779.5 | 775.7 | 760.5 | 775.7 | 764.3 |
|  | 833 | 819 | 814 | 814 | 794.7 | 790.9 | 787.1 | 798.5 | 779.5 | 775.7 | 760.5 | 775.7 | 764.3 |



## Appendix F Solar Lab Fabrication

### Solar Lab

Envisioning the Solar Lab was complicated by the possibility of relocation during the experiment. Knowing that such a possibility existed, the entire Solar Lab was conceived as transportable and modular. The Solar Lab had to fit within a 10x20 shipping container or easily displaced on a flatbed truck. The solution resulted in the adaptive reuse of a metal framed deck (Figure 110) previously used as a theater stage set measuring 18-feet long by 5.5-foot wide. The sub-frame was composed of three 12-inch deep trusses running lengthwise and fabricated from 1.5-inch square metal tube. Each truss was bridged together using similar 1.5-inch square tube forming a durable platform with a 3/4-inch plywood top. The deck offered a level surface with a loading capacity of 500lb/sf - more than adequate structure to erect and build the solar simulator.



**Figure 110:** Metal Framed Deck & Canopy

After careful consideration of the thermal output of the lamps and impact on the cooling loads of the building the Solar Lab was situated outside under a protective canopy environment (Figure 110). Each arc tube at steady operating temperature generated approximately 180°C (356° F) resulting in a 50°C (120° F) ambient temperature at the high point of the concentrator (Figure 122) and 30°C (86° F) at the low point. Using the outdoor cooler ambient temperature and fans provided adequate cooling.

The Solar Lab was situated outside under a 200 square-foot canopy shelter (Figure 110) measuring 10-feet wide by 20-feet long, and 10-feet high to provide adequate air circulation. The canopy frame was composed of 1.5” galvanized steel tubes and anchored to the metal deck. The canopy was covered with UV shielded silver polyethylene tarps to block high levels of unwanted UV light leaving the test area, and blocked significant glare from the seven 36,000 lumen lamps. As determined later in this research the solar simulator resulted in  $\pm 1$  sun worth of energy based on ASTM<sup>51</sup> or CIE<sup>52</sup> published power density standards. Aluminum foil was used to block unwanted glare and potentially harmful wavelengths. Canopy was relatively weather compatible and operations were carried out in inclement weather conditions (Figure 111).

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<sup>51</sup> American Society for Testing and Materials (ASTM E 891 and ASTM E 892) AM1.5D =768Wm-2 and AM1.5G=963.8 respectively.

<sup>52</sup> Committee Internationale d'Eclairage (CIE 904-3) designates 1000Wm-2 at AM1.5G



**Figure 111:** Solar Lab Inclement Weather Operations

The only objects permanently fixed to the platform were the data acquisition center and the electrical distribution panel. The array rack, concentrator, and test chamber were positioned on the deck with temporary restraints to allow for minor repositioning if required. This offered the ability to easily service the Solar Simulator, and adjust luminous and radiant flux on the test surface as a function distance<sup>53</sup>.

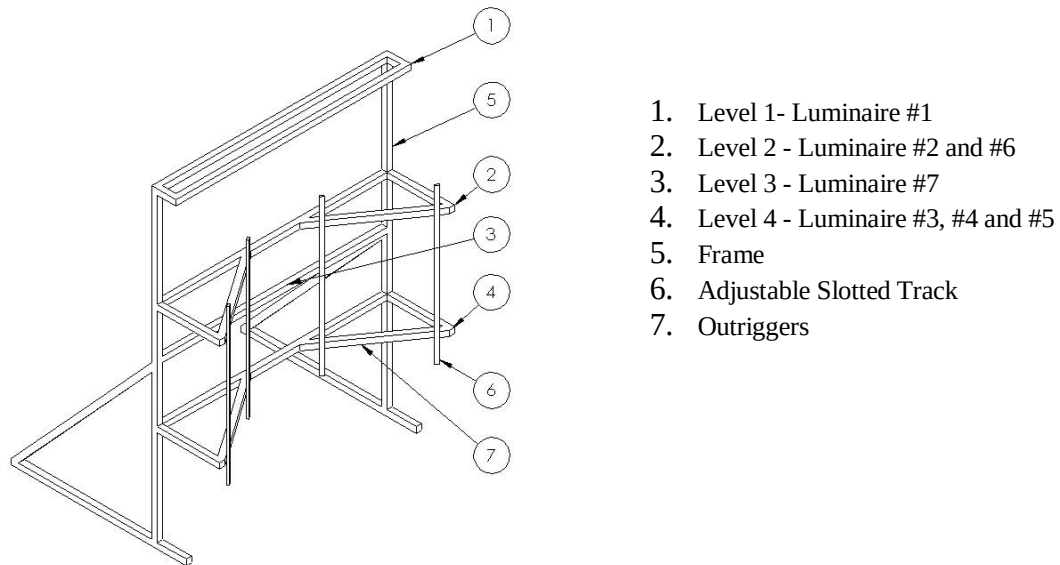
### Array Rack

The seven luminaires were affixed to a custom fabricated steel frame with flexibility as a key criterion of the design. The primary frame was fabricated from 1'-1/2" 16-gauge square tube welded together (Figure 112, #5). The secondary armature was comprised of

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<sup>53</sup> Inverse-square law: energy twice as far from the source is one-fourth the density.

slotted 5/8inch wide x 7/16-inch slotted track (Figure 112, #6). Four levels arranged the luminaires as illustrated in Figure 112 and Figure 118.



**Figure 112: Frame Array**

Each luminaire weighed approximately 15 pounds and each ballast box/luminaire required a secondary support system (Figure 113). The secondary support was made of an adjustable slotted track and bracket to provide horizontal support to pivot in the x-axis (Figure 116) of each luminaire. The array frame was field painted aerosolized flat black, and secured to the metal deck.



**Figure 113:** Frame Array

### Luminaire Selection

Similar to MIT's low cost high flux solar simulator this approach investigated the reuse of seven Cooper MHSS-M-400-MT VertX luminaires that have similar specifications to the off-the-shelf 1500 watt metal halides used by MIT. Since the objective was not 60 suns worth of energy flux (Codd et al., 2010, p. 1) this experiment focused on achieving 1 sun with interest on spectral match, temporal stability, and spectral uniformity at the lowest cost.

The reuse of used luminaires comes with some disadvantages mainly in the degradation of the magnetic ballast and inconsistencies in the amount of current in each circuit.

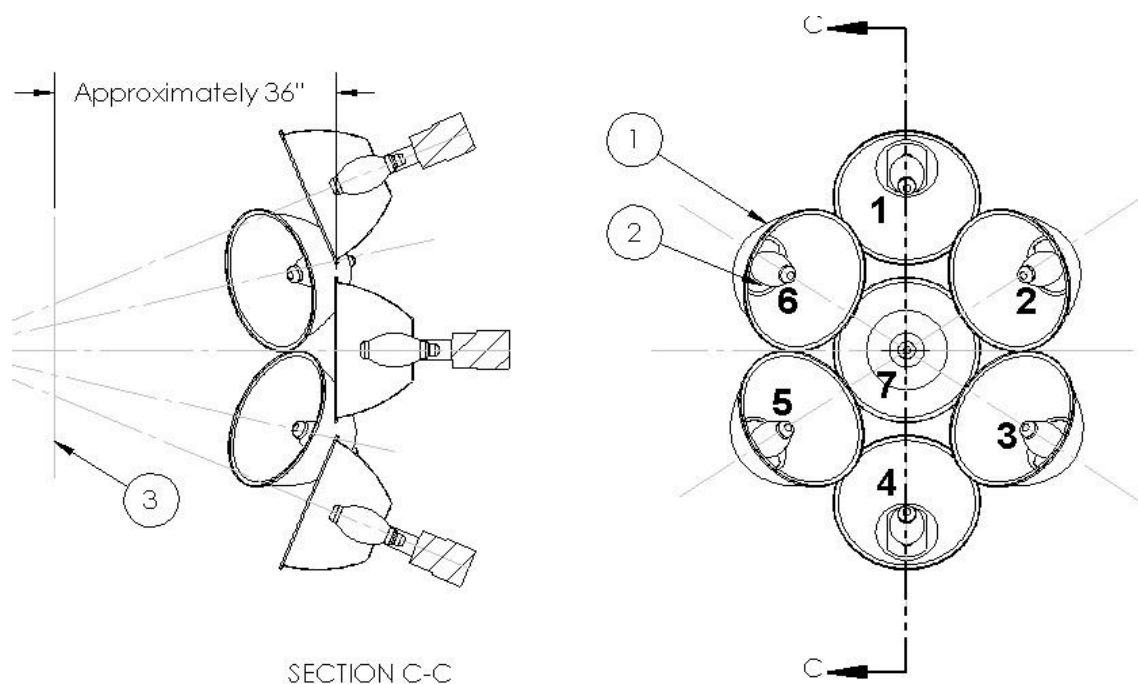
However, the replacement of the lamps alone will be helpful in optimizing the objective of achieving a stable solar simulator at  $\pm 1$  sun.

### Lamp Selection

The solar simulator utilized seven 400 watt metal halide arc lamps. Each luminaries came with a lamp and it was determine that each lamp had significant variation in luminance output and thermal flux. This is an indicator of end-of-life as the intensity and luminous flux decreases as much as 50% of the initial first start. The constant use of metal halide lamps result in the degradation of gases and electrodes in the arc tube, and eventually leads to inferior performance (Yang, Jang, & Park, 2011, p. 1). As such lamps were replaced with Sylvania 400 watt MH400/U bulbs with universal positioning allowed, which is a significant factor when the bulbs are in a near horizontal orientation rather than in the expected vertical position. The M400 are rated at 34,000 lumens and documented in the Characterizing The Solar Simulator section.

### Array Geometry

A similar geometric arrangement to Kruger's and Codd's solar simulator was applied, but with less scrutiny on optical properties of the ellipsoidal reflectors and greater focus on specification parameters of spectral match, temporal stability, and spectral uniformity. To solve for maximum flux output the geometric solution was reverse engineered using SolidWork simulation software. The array rack, ellipsoidal reflectors, and test plane was simulated to determine horizontal and vertical constraints that best focused flux energy on the test plane (Figure 114).



**Figure 114: Array Geometry**  
 (1. Aluminum Spun Ellipsoidal Reflectors, 2. Metal Arc Lamps, 3. Test Plane)

### Lamp Reflectors

Each lamp was equipped with a SS VertX spun aluminum ellipsoidal 19-inch reflectors (Figure 115). The socket position / distribution were set to amplify the amount of flux energy at the test surface. Reflector geometry is classified by the *National Electrical Manufacturers Association (NEMA)* and defines the focusing criteria. Unfortunately these were unmarked, but reverse engineering indicated that the reflectors were in the range of a NEMA 5 which has a beam spread of  $70^{\circ}$  to  $100^{\circ}$ . This is not ideal for a solar simulator in a compact arrangement and a narrower reflector ( NEMA 3) range may have been better suited for the experiment (Codd et al., 2010).

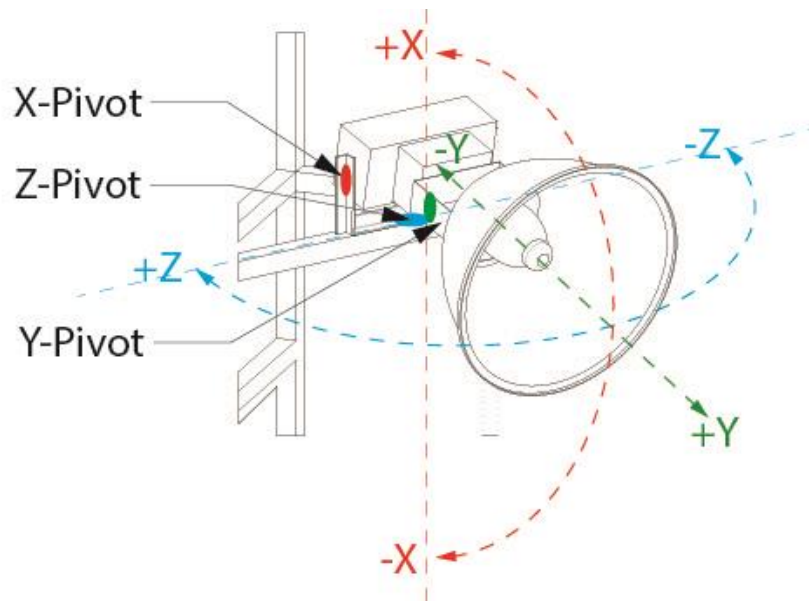


**Figure 115:** Luminaires, Lamps, and Dome

#### Luminaire Frame

Traditionally these luminaires are hung from the ballast enclosure. However, considering the desire to arrange the luminaires in a horizontal hexagonal concentrating pattern custom luminaire brackets had to be fabricated. The brackets were envisioned to secure the luminaire to the array rack, but more importantly provide 3-axis movement (Figure 116). A custom 3-axis bracket was designed and fabricated to allow luminaire positioning during setup (Figure 117, Left).





**Figure 116:** Luminaire Flexibility

To provide rotation in the x-axis a threaded pivot pin was installed in each ballast enclosure. Each enclosure was disassembled and a threaded pivot pin was welded to the inside of the enclosure providing flexibility to adjust and optimize light beam concentration (Figure 117, right).



**Figure 117:** Luminaire Brackets (left) & Pivot Pins (right)



**Figure 118:** Luminaire Positioning

### Concentrator

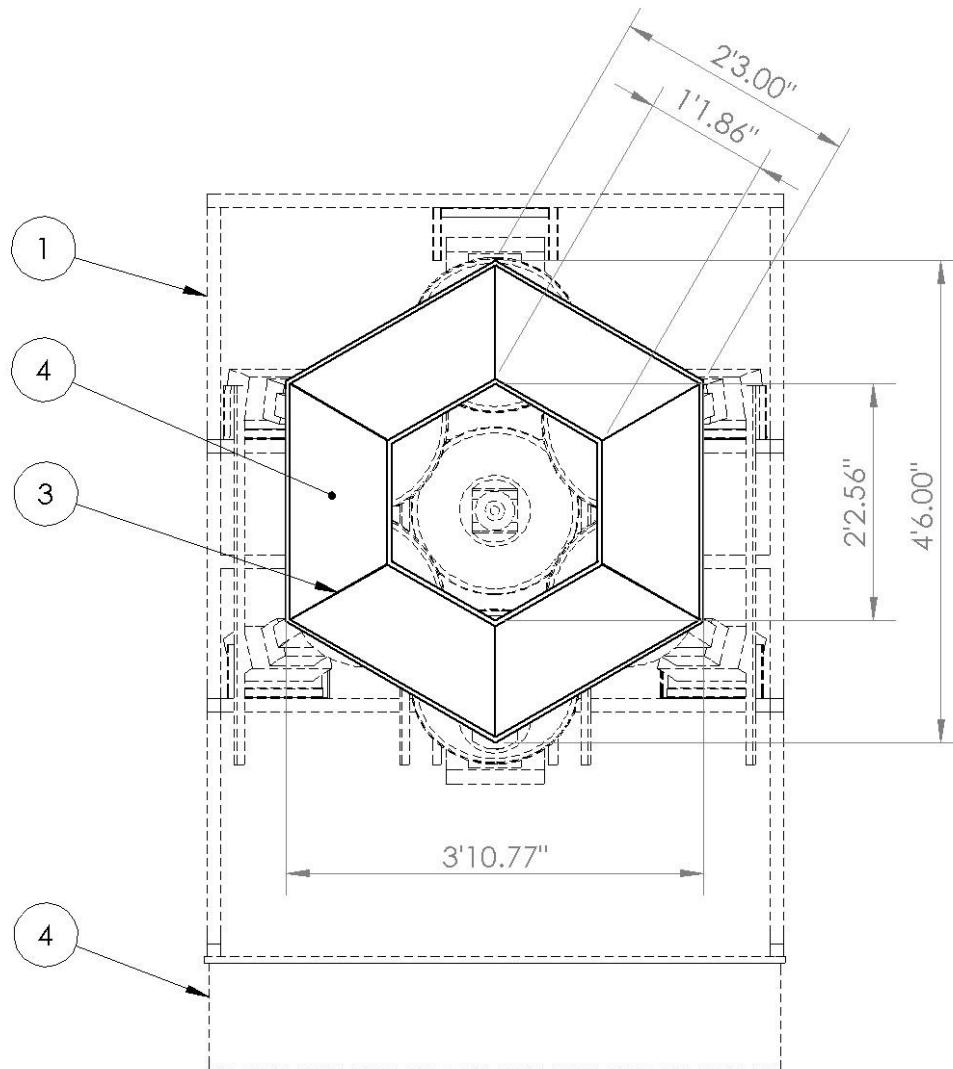
The hexagonal concentrator served several purposes, but its main function was concentrating flux energy at the test surface. In the development of a large-scale solar simulator in an orthogonal room the radiation characteristics using similar metal arc lamps noted an 81.6% improvement using reflective mirror-like stainless steel plates

surrounding the simulator room (Meng, Wang, & Zhang, 2011, p. 1). In another more applicable low-cost simulator the Department of Mechanical Engineering at Massachusetts Institute of Technology (MIT) fabricated a hexagonal concentrator oriented in the vertical with the lights facing downward (Codd et al., 2010).

As a function of space and desired operability of the proposed solar simulator the concentrator was arranged in the horizontal to lessen the need for overhead structural framing and support (Figure 30). The hexagonal geometry responded to the seven lamp configuration and maintained geometry as it truncated toward the test surface (Figure 119). The concentrator frame was made of two hexagonal frames made of 1/2" 16-gauge steel tube and welded at the joints (Figure 120). The frames were then clad in pre-mirror TALBPREM 304 stainless steel sheet with a #8<sup>54</sup> finish. The TALBPREM was secured to the 1/2" metal frame using aluminum 3/16" rivets (Figure 121).

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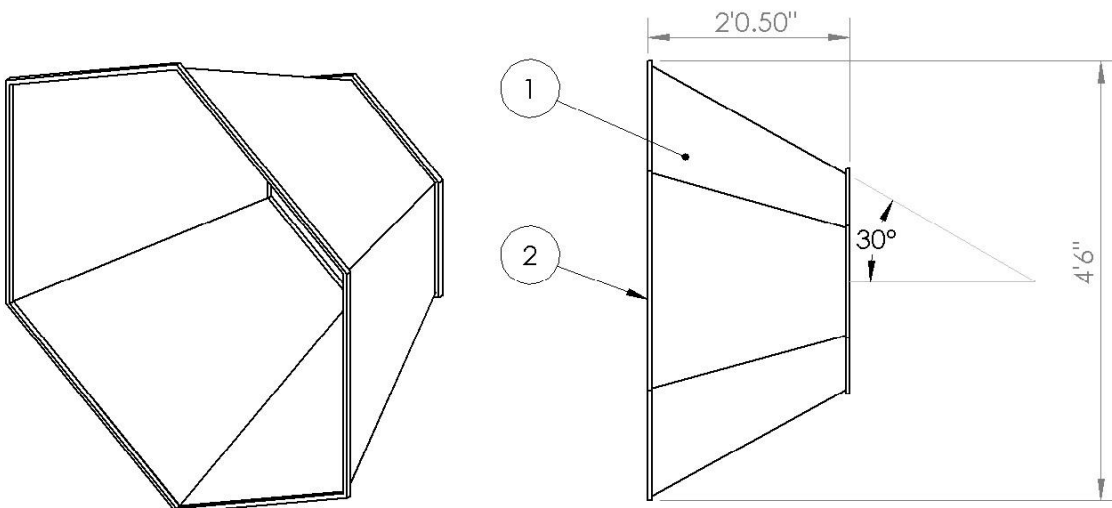
<sup>54</sup> #8 finish is a non-directional finish the highest ASTM reflective standard for stainless steel resulting in a pre-mirror condition.



**Figure 119:** Front View of Concentrator  
 (1. Concentrator, 2. TALBPREM, 3. 0.5-inch square tube, 4. Platform)



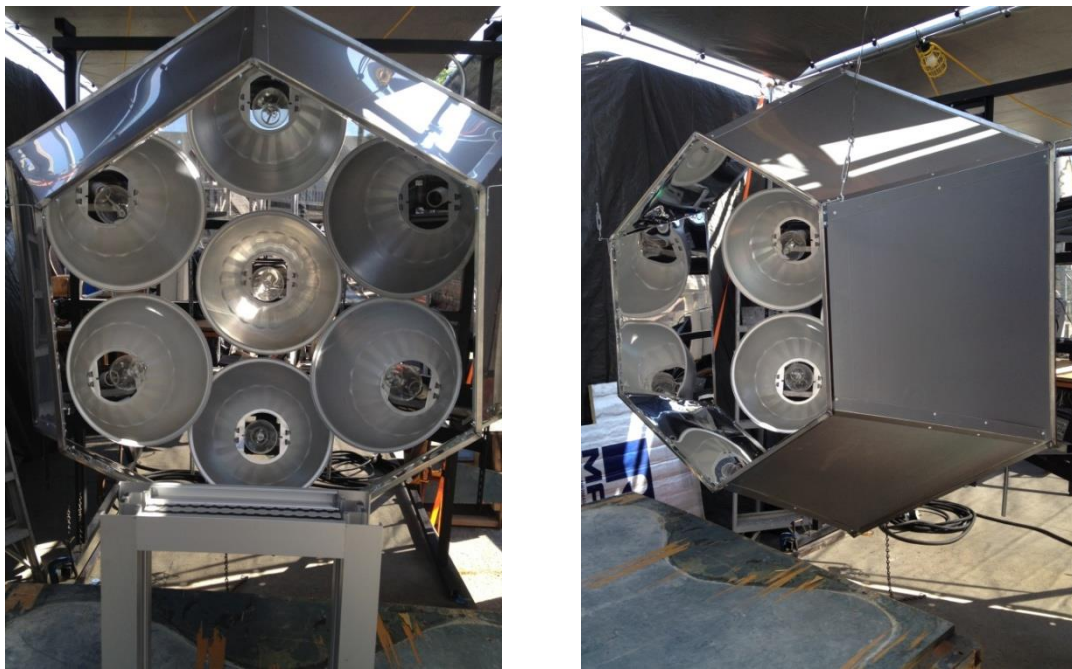
**Figure 120:** Concentrator Under Construction



**Figure 121:** Concentrator Geometry  
(1. TALBREM, 2. 0.05-inch square tube)

The side (s), height (h), and diagonal (d) measures 30-inches, 51.9-inches, and 60-inches respectively. The second smaller hexagonal and closest to the test surface measures 18-inches, 31.1-inches, and 36-inches, respectively. When situated over the seven metal arc lamps the area between the concentrator and the luminaire's domes were in filled with aluminum foil rather than the rigid TALBPREM.

The concentrator was hung from the canopy using guide wires and turnbuckles to adjust the position and angle to optimize focal point of the light (Figure 122). Heavy duty aluminum was used to enclose the space between the lamp domes and the concentrator as an alternative to fabricating custom enclosures.



**Figure 122:** Suspended Concentrator

## Load Center

Providing the adequate amperage to operate the solar simulator required careful planning and safety measures. National electrical Code (NEC) was followed to determine the appropriate wire gauge, switches, plugs and lugs. The system was envisioned with two circuits each drawing current from each side of a temporary portable power distribution unit (PDU). The PDU load was rated at 20 amps on each side of the distribution box providing the adequate current to the solar simulator.

Two 12gauge/3wire SEOW cables extended From the PDU to two isolate load centers. One load center carried 4 lamps and equipped with a 30amp breaker and the other load center carrying 3 lamps and equipped with a 15 amp breaker.

Cooper MHSS-M-400-MT fixtures were acquired and wired in single phase/120volts. This required 4amps per lamp for a total of 28 amps and a safety of 10% was added. To support the required load and safety the lamps were placed on two circuits: one containing 3 lamps and the second containing 4 lamps. Ideally the system could have been wiring in single phase/240 volts requiring one additional wire and ultimately reducing amperage in half.

An observation from early testing revealed that the 12-gauge/3-wire (12/3) was sufficient to operate the low cost solar simulator, but that current restriction may have played a role in minimizing the full potential of the solar simulator. Various test revealed that when the 12/3 wire was replaced with 10/3 wire the irradiance levels increased by 25%. For a low-



cost solar simulator, a 25% increase is a significant gain relative to the investment that costs approximately \$1 per linear foot.

### Data Acquisition System

A Campbell Scientific CR10X data acquisition measurement and control system was deployed for this experiment (Figure 123). The CR10X is a scientific grade acquisition system with 62,000 data point storage capable of storing months of consecutive data. The datalogger was powered by continuous line voltage and a 12-volt rechargeable battery backup. Low voltage was supplied to the datalogger through a Campbell Scientific Power Supply (PS12) with charging regulator. In order to interface with the CS I/O port on the datalogger an optically isolated RS232 Campbell Scientific SC32 was used. This interface isolates the computer and the datalogger from electrical noise, ground looping, and static discharge (Campbell Scientific, 2013, p. 32).



**Figure 123:** Data Acquisition



A Dell Latitude D800 laptop running Intel Pentium M processor and Microsoft Windows XP Professional was used. Communication between the laptop and data acquisition center was achieved using an RS232. PC200W was used to communicate with the datalogger along with monitoring and data retrieval. Shortcut 3.1 (SCWin) was used to write scripts and develop sensor wiring diagrams. See Wire Diagram section and Appendix H.

The CR10X datalogger's operating system was upgraded with CR10X-PakBus (PB) OS1.10. This was required in order to measure and record second interval data as the sensitivity to thermal fluctuations was more prevalent in shorter time frames. Program scripts use the CR10XPB option in PC200W rather than CR10X in order to capture the desired time intervals.

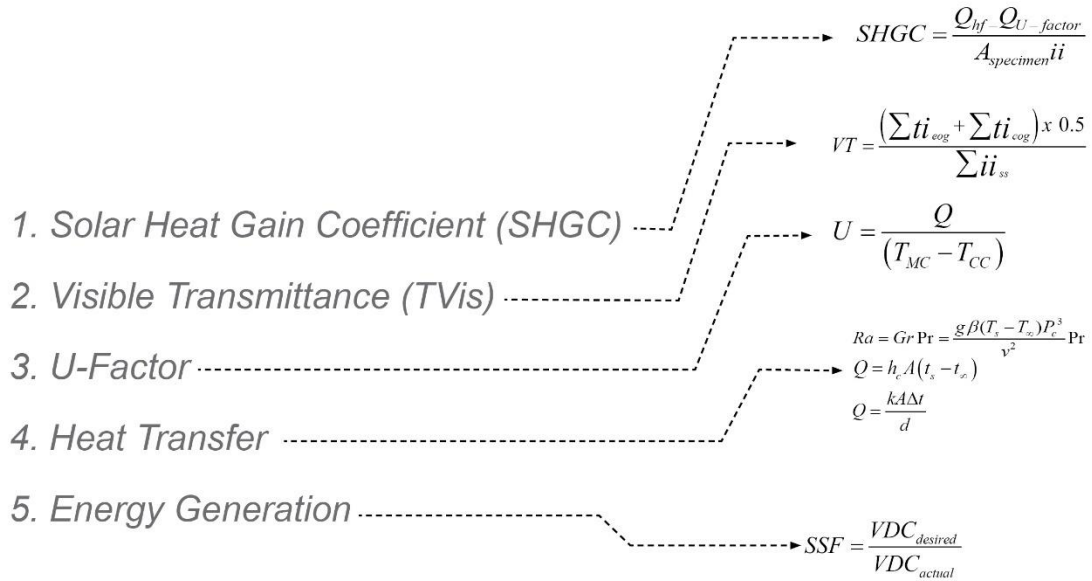
The datalogger was placed in a fiberglass-reinforced polyester Campbell Scientific weather-resistant enclosure (Figure 123). The datalogger, simulator, and electrical system were ground to a dedicated 5/8"Ø x 8-feet deep grounding rod.

### Wiring Diagram

Campbell Scientific's ShortCut program generator for Windows was used to generate programs and wiring diagrams for the CR10XPB (Appendix H). Shortcut's menu driven interface was chosen for its ease of use and ability to interface with pulse and bridge sensors, and support of algebraic expressions.

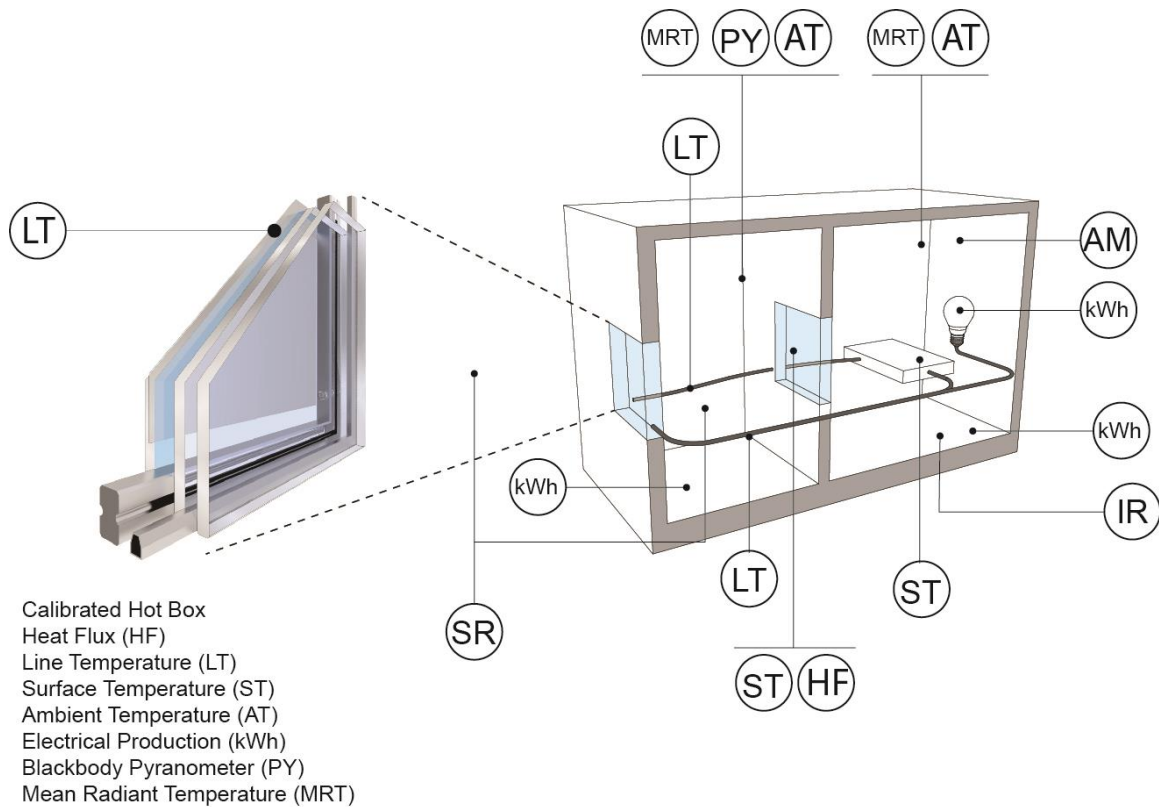
## Sensor Selection and Location

Sensors were selected based on the objectives defined in the methods sections in Chapter IV, V, VII, and VIII. Each objective was defined by its own unique equation that sought specific data from varying sensors ranging from surface temperature, ambient air temperature, mean radiant temperature, spectroradiometer, heat flux, irradiance, fluid temperature, electrical power, and infrared imaging (Figure 124).



**Figure 124:** Sensor Requirements Based on Methods

Each sensor was placed in the calibrated hot box and Nanowindow specimens, and seldom moved during the entire exercise (Figure 125).



**Figure 125: Sensor Placement**

Except for the spectroradiometer, infrared camera, and power meter, all other sensors connected to a single Campbell Scientific CR10X data acquisition system. All sensors were hung from the underside of the canopy structure at 10-feet above grade that allowed the sensors to move freely without interfering with daily operations.

The Sensor Hub also doubled as a weather station collecting daily environmental vitals including: temperature, ultra violet radiation (UV), and solar irradiance. This was

primarily helpful when calibrating sensors, but not essential during the actual nanowindow experiments.

The Sensor Hub was equipped with three (3) Campbell Scientific L107<sup>55</sup> thermistor temperature sensors that were routinely moved to other parts of the experiments depending on the need for spot temperature measurement.

An Apogee UV sensor SU100<sup>56</sup> was used to measure the light intensity from 250nm to 400nm. The spectral error for the SU-100 is 0.0% in clear skies and 2.8% under metal halide lamps. The SU-100<sup>57</sup> was connected to the Campbell Scientific CR10X datalogger as with all sensors, with the exception of spectroradiometers that are self-contained.

Measuring ultra violet radiation (UV) as a window performance indicator was equally important as thermal performance (U-Value) and visible transmittance (VT).

Two (2) Li-Cor LI200X<sup>58</sup> cosine-corrected silicon pyranometers providing solar radiation measurements in the spectral range of 400 to 1100nm were only used during the start-up phase to calibrate with the hemispherical LP02 Pyranometer<sup>59</sup>. The LI200X are not appropriate for artificial light measurement. Traditional silicon cell (photodiode-based) pyranometers are spectrally sensitive and temperature dependant (Bajons, Wernhart, & Zeiler, 1998, p. 125) and considered a disadvantage. Considering the nature of the simulator and its assumed spectral diversity and temperature sensitivity the use of a

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<sup>55</sup>) Campbell Scientific L107: Tolerance:  $\pm 0.2^{\circ}\text{C}$  over  $0^{\circ}$  to  $50^{\circ}\text{C}$  range. Deployment range:  $-35^{\circ}$  to  $+50^{\circ}\text{C}$

<sup>56</sup>) The Apogee UV sensors was on loan from the Energy Studies in Buildings Laboratory (ESBL).

<sup>57</sup>) Campbell Scientific Short Cut: Differential voltage generic sensors profile was used. Sensor voltage set to 250mV, measurement integration is to reject 60Hz noise, multiplier set to 1.5676, and offset set to 0.

<sup>58</sup>) LI200X were calibrated at Campbell Scientific against an Eppley precision spectral pyranometer (PSP).

<sup>59</sup>) Factory calibration of the LP02 hemispherical pyranometer meets second class ISO 9060 and moderate quality WMO-No.8. Sensitivity (S) is  $17.66 \times 10^{-6} \text{ V}/(\text{W}/\text{m}^2)$  with an expanded uncertainty ranging  $\pm 0.21 \times 10^{-6} \text{ V}/(\text{W}/\text{m}^2)$

thermal-pile pyranometer with temperature insensitive was a viable method to determine broadband irradiance(Michalsky, Perez, Harrison, & LeBaron, 1991, pp. 299–305).

One (1) hemispherical Hukseflux LP02 Solar Radiation Pyranometer<sup>60</sup> was selected for its use compatibility with measuring lamp based solar simulator in-situ experiments, and complies with ISO 9060 standard and the World Meteorological Organization WMO-No.8 classifications.

LP02 Pyranometer is suited to measure broadband irradiance emitted from the solar simulator measured in radiant flux density ( $\text{W}/\text{m}^2$ ). The hemispherical radiation sensor is cosine corrected up to  $180^\circ$  field of view. The broadband spectral range captures 285 to  $3000 \times 10^{-9}\text{m}$  and provides a generalized understanding of the radiant flux compared to the solar irradiance. The LP02 Pyranometer is a blackened thermal-pile under a glass dome sensor and utilized for characterizing indoor solar simulators rather than the traditional silicon cell (photodiode-based) pyranometers as noted earlier.

### Calibration Methods

Before deploying the LP02 Pyranometer<sup>61</sup> it was evaluated in a metrological setting adjacent to the research facility's weather station, which is open to the sky with no obstructions. The sensor was mounted on a cross arm (Figure 126) and situated adjacent to two Li-Cor LI200X<sup>62</sup> cosine-corrected silicon pyranometers providing solar radiation

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<sup>60</sup> Hukseflux LP02 Pyranometer is a hemispherical solar radiation sensor with calibration uncertainty  $\pm 0.21 \times 10^{-6} \text{ V}/(\text{W}/\text{m}^2)$ .

<sup>61</sup>) Factory calibration of the LP02 hemispherical pyranometer meets second class ISO 9060 and moderate quality WMO-No.8. Sensitivity (S) is  $17.66 \times 10^{-6} \text{ V}/(\text{W}/\text{m}^2)$  with an expanded uncertainty ranging  $\pm 0.21 \times 10^{-6} \text{ V}/(\text{W}/\text{m}^2)$

<sup>62</sup>) LI200X were calibrated at Campbell Scientific against an Eppley precision spectral pyranometer (PSP).

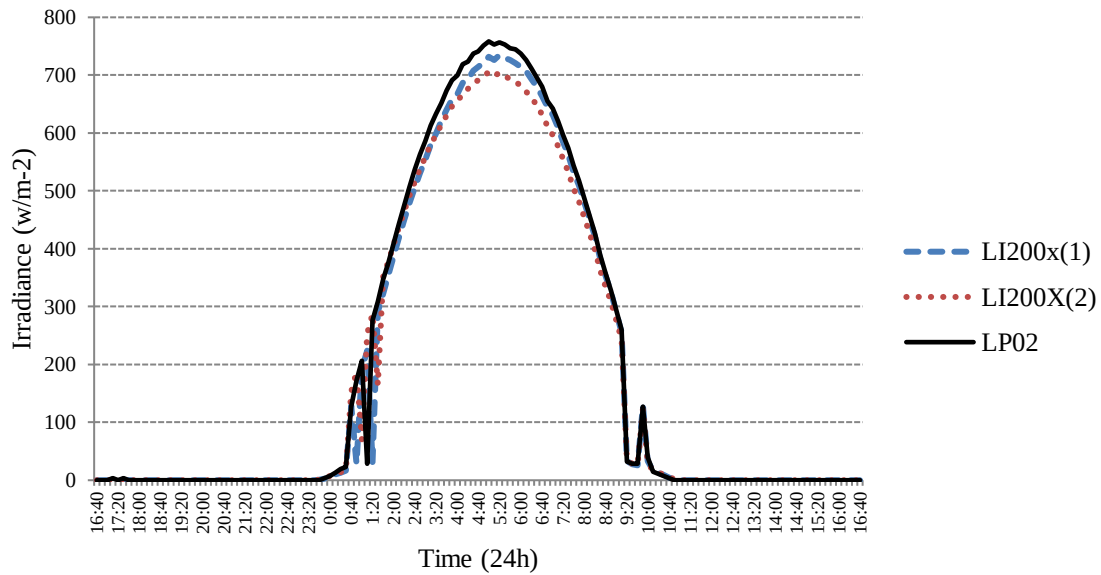
measurements in the spectral range of 400 to 1100nm. The ensemble was part of a larger data collection module defined in the weather station section of this research. All measurements were collected by a Campbell Scientific CR10X datalogger.



Figure 126: Pyranometer Calibration  
(Two silicon pyranometers, one hemispherical pyranometer, and one UV sensor)

### Calibration Results

Seven days of data was gathered and one-day represented in Figure 127. A statistical regression was performed to determine if there was a significant correlation between the LP02 Pyranometer and the Li200x.



**Figure 127:** Irradiance Calibration Results

The correlation coefficient was calculated to determine the strength of the relationship and accuracy of readings. Pearson product-moment correlation coefficient (Pearson's  $r$ )<sup>63</sup> is 0.99 which is a very strong positive correlation between the two groups. However, this doesn't indicate if the correlation is statistical significant.

|               | <i>LI200x</i> | <i>LP02</i> |
|---------------|---------------|-------------|
| <i>LI200x</i> | 1             | 0.99        |
| <i>LP02</i>   | 0.994         | 1           |

**Table 26:** Correlation Test (Pearson's  $r$ )

<sup>63</sup> Microsoft Excel Data Analysis was used to perform statistical analysis

Using the same data, a regression analysis is performed to determine the significance of the correlation. Using an  $\alpha = 0.05$  (95% confidence level) there is a significant positive relationship between the hemispherical and silicon pyranometers,  $r(143) = 0.99$ ,  $p < 1.212\text{e-}142$  (Table 26& Table 27).

**Table 27:** Regression Analysis

| <i>Regression Statistics</i> |       |
|------------------------------|-------|
| Multiple R                   | 0.99  |
| R Square                     | 0.98  |
| Adjusted R Square            | 0.98  |
| Standard Error               | 28.52 |
| Observations                 | 145   |

| ANOVA      |           |           |           |          |                     |
|------------|-----------|-----------|-----------|----------|---------------------|
|            | <i>df</i> | <i>SS</i> | <i>MS</i> | <i>F</i> | <i>Significance</i> |
| Regression | 1         | 10703147  | 107013147 | 13154    | 1.21E-142           |
| Residual   | 143       | 116322    | 813       |          |                     |
| Total      | 144       | 10816470  |           |          |                     |

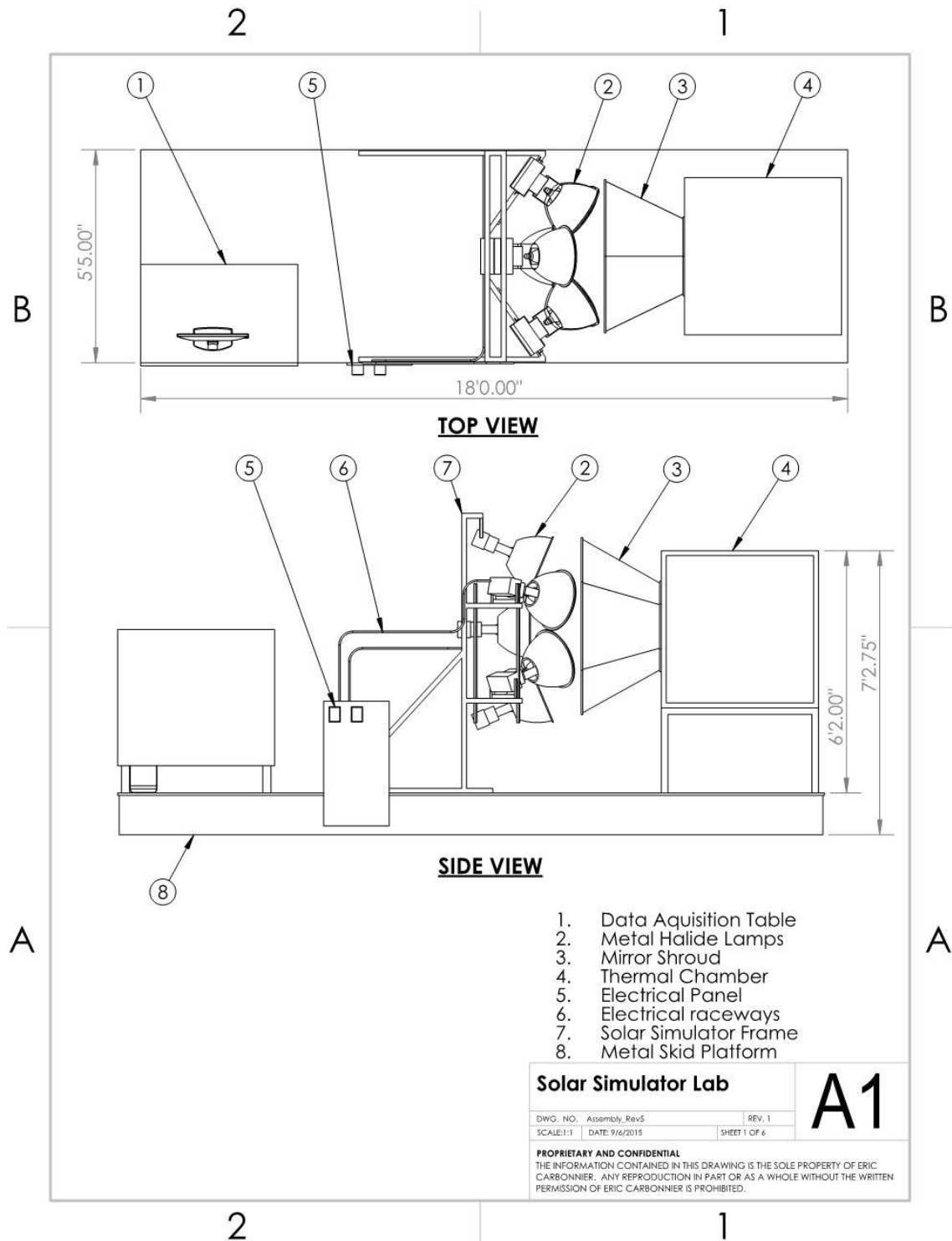
  

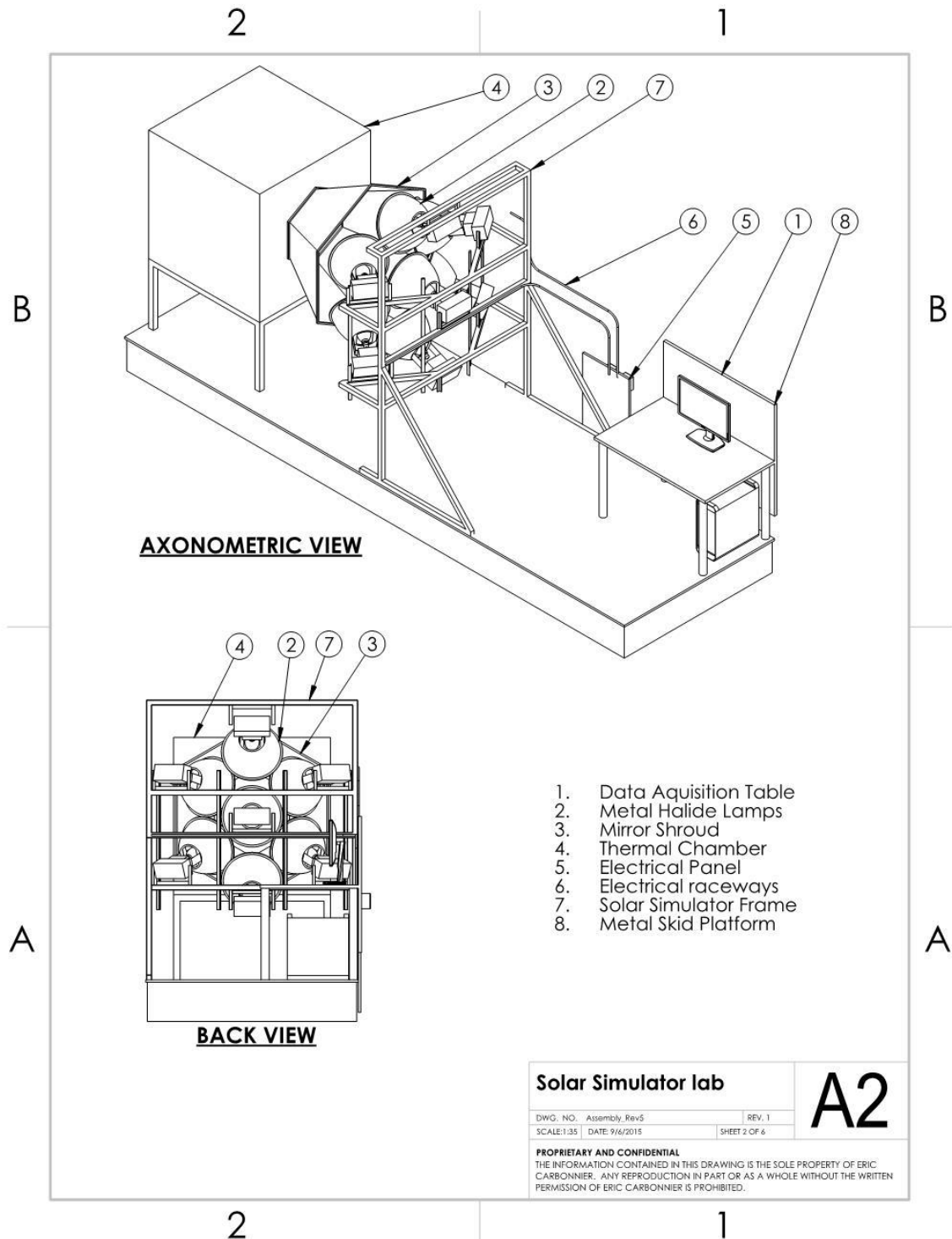
|        | <i>Coefficients</i> | <i>Standard Error</i> | <i>t5tat</i> | <i>P-value</i> | <i>Lower 95%</i> | <i>Upper 95%</i> |
|--------|---------------------|-----------------------|--------------|----------------|------------------|------------------|
| LI200x | -0.47               | 2.88                  | -0.16        | 0.086          | -6.18            | 5.22             |
| LP 02  | 0.96                | 0.008                 | 114.69       | 1.20E-142      | 0.94             | 0.0977           |

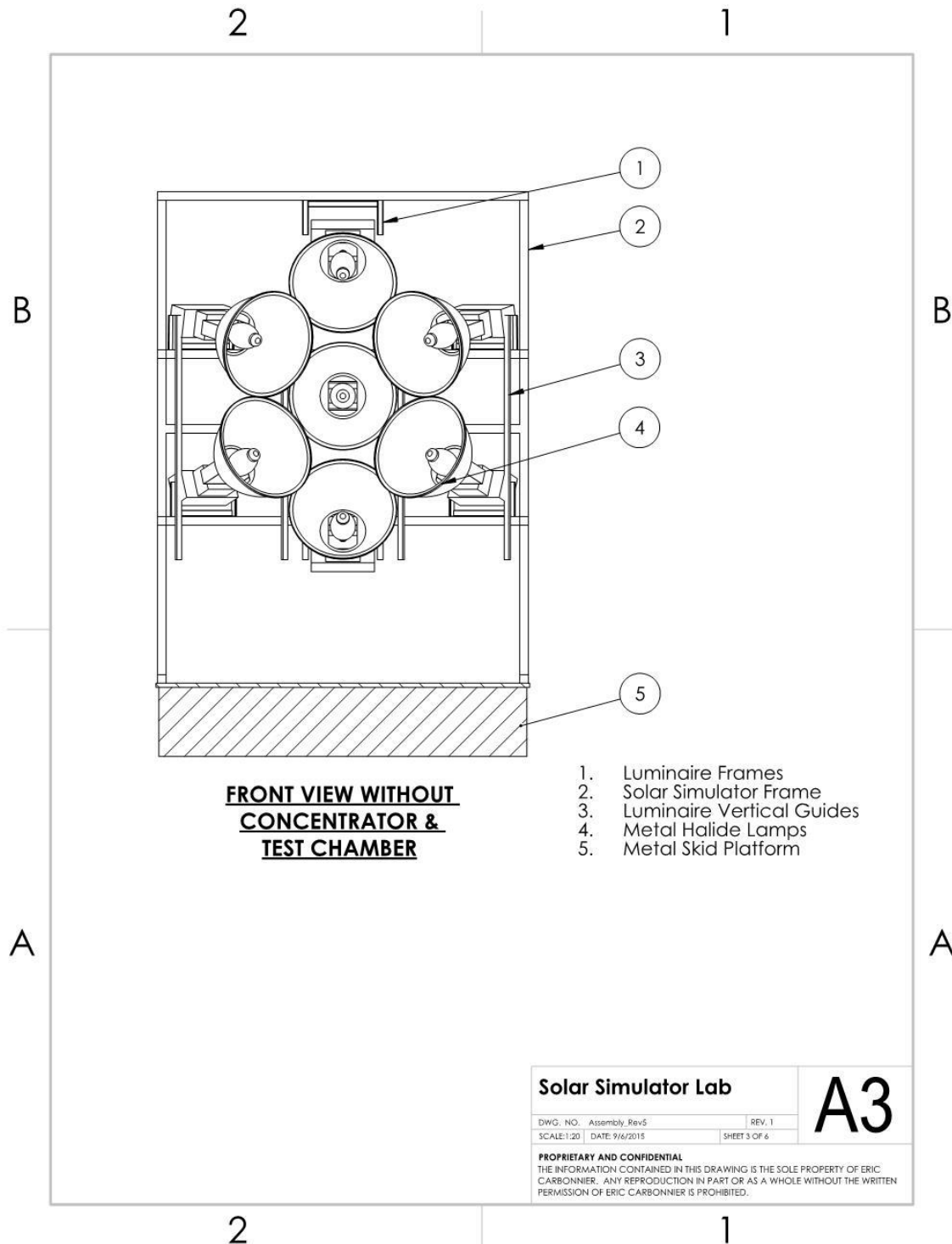


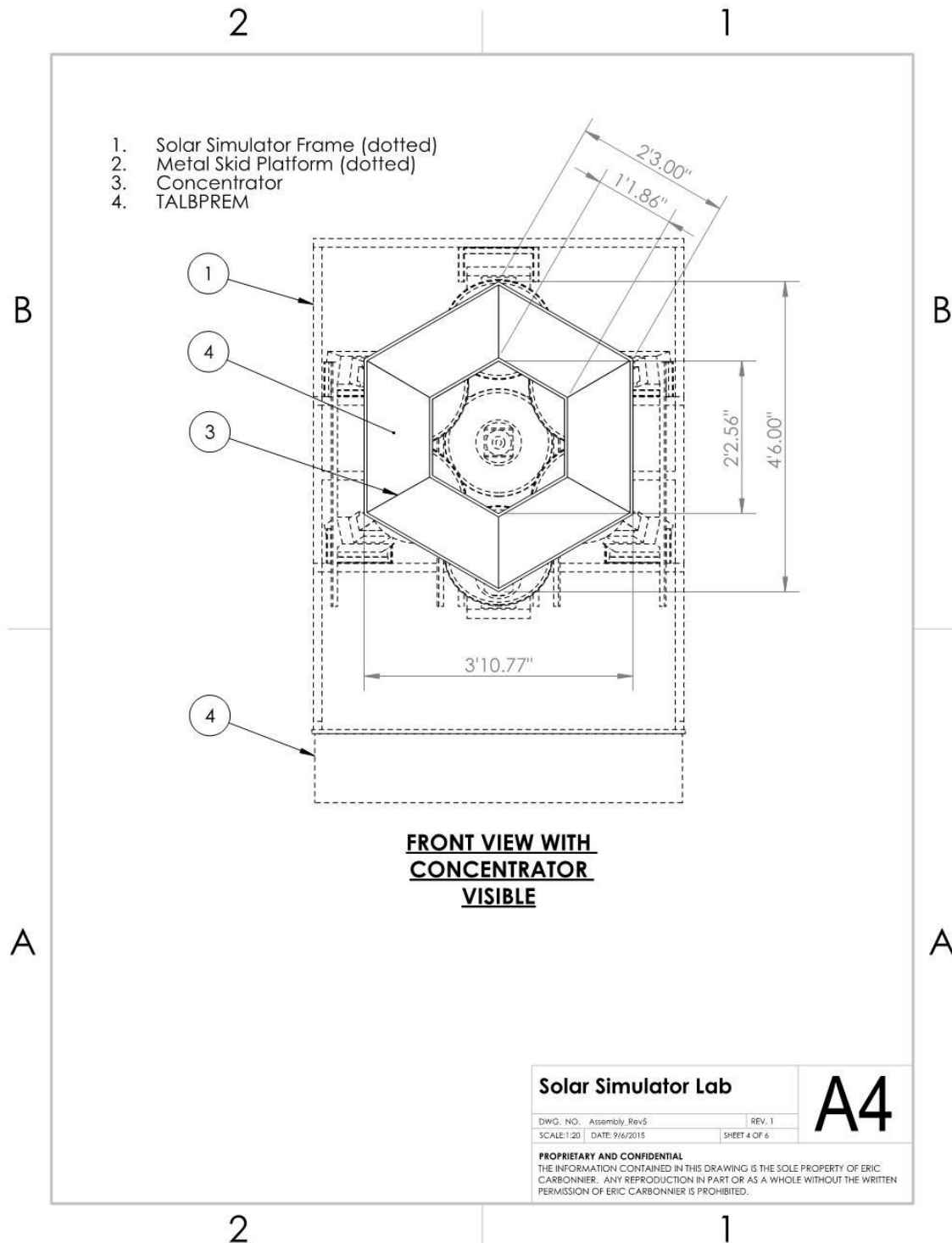
## Appendix G Solar Simulator Documentation

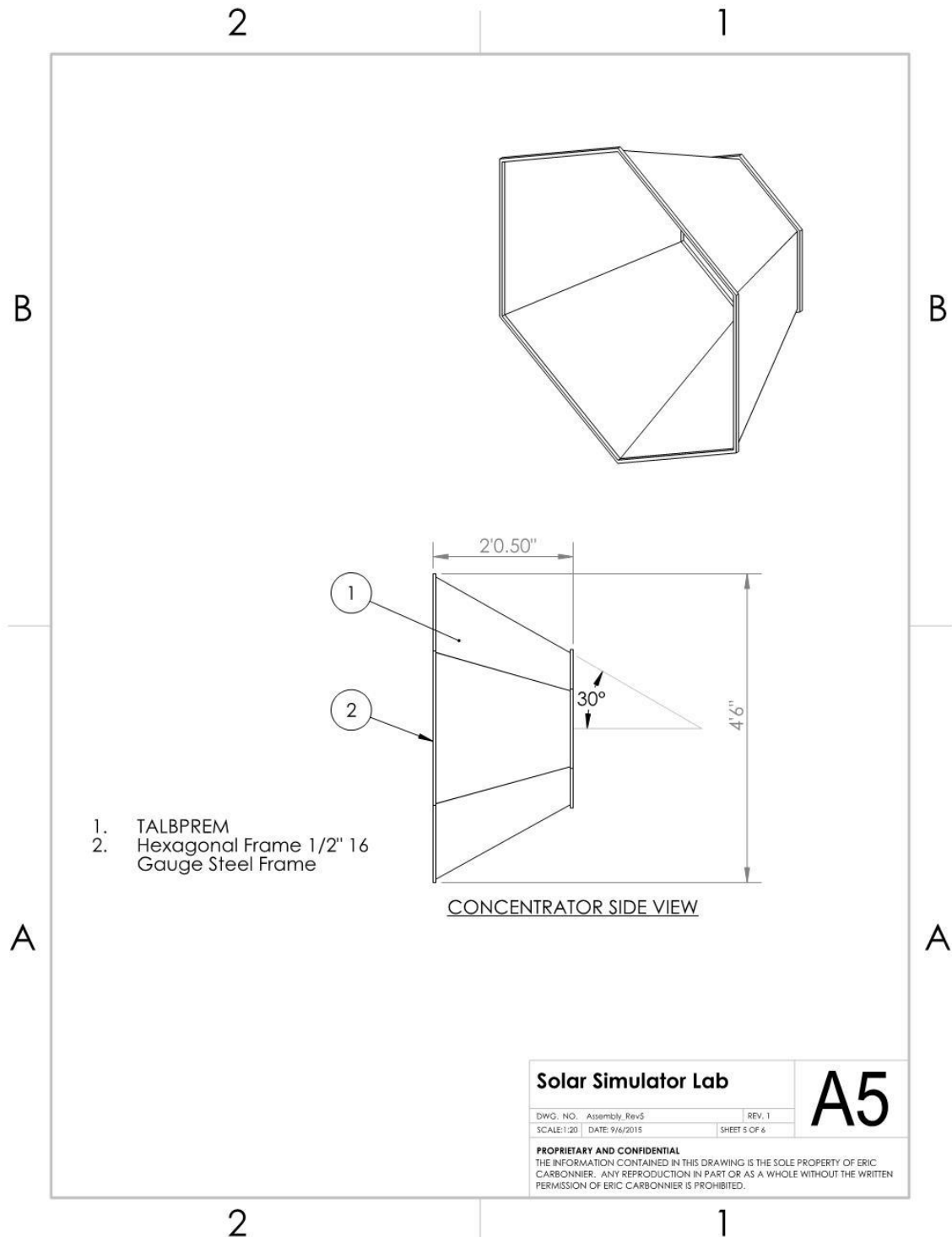
The solar simulator was documented using SolidWorks 2015, and fabricated based on the following construction documents. These record drawings are believed to be reliable and the author assumes no responsibility for the accuracy or potential errors and omissions for the record set. Those relying on this record document are advised to obtain independent verification of its accuracy, and consult with the appropriate local building officials and engineers for the required approvals and permits.

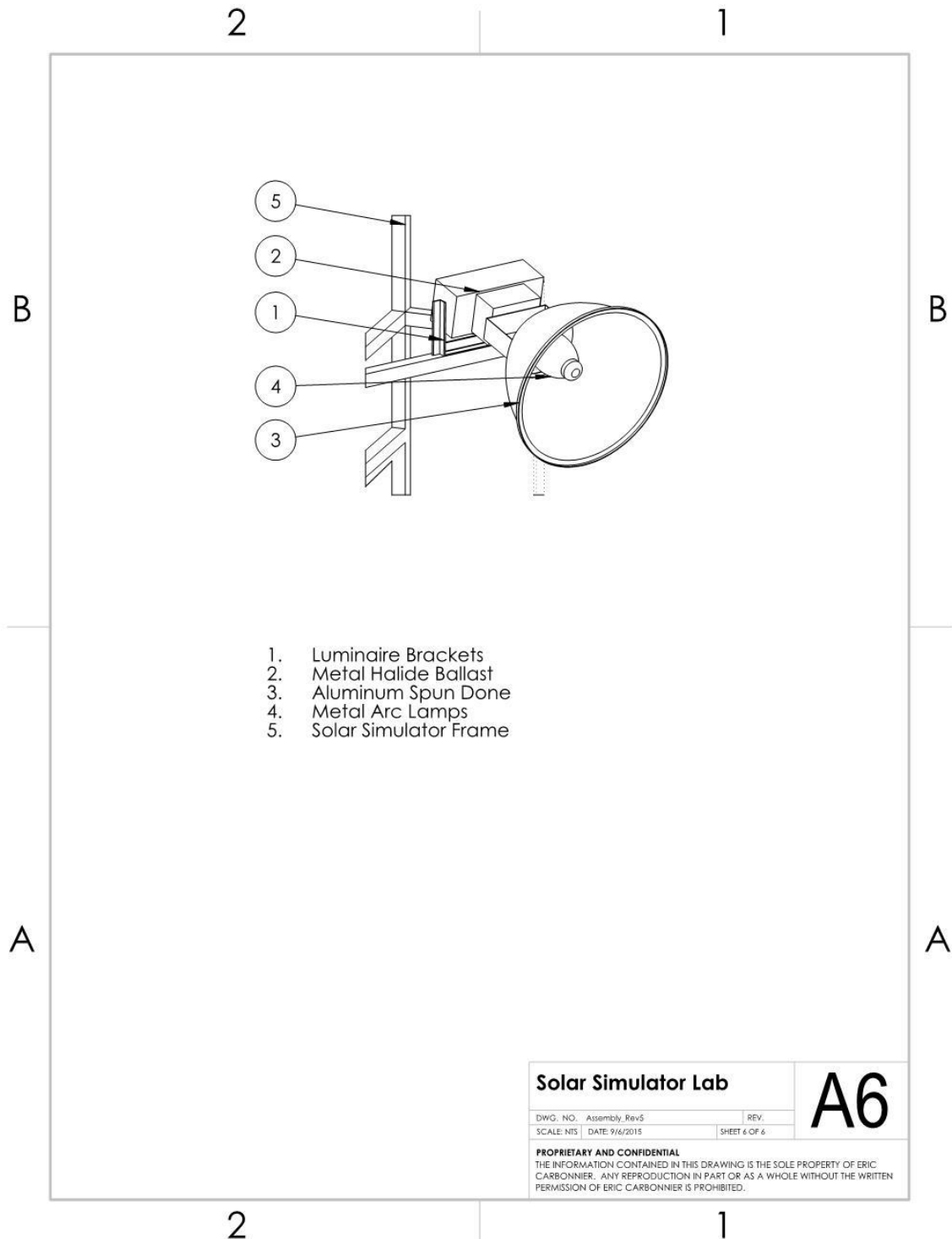


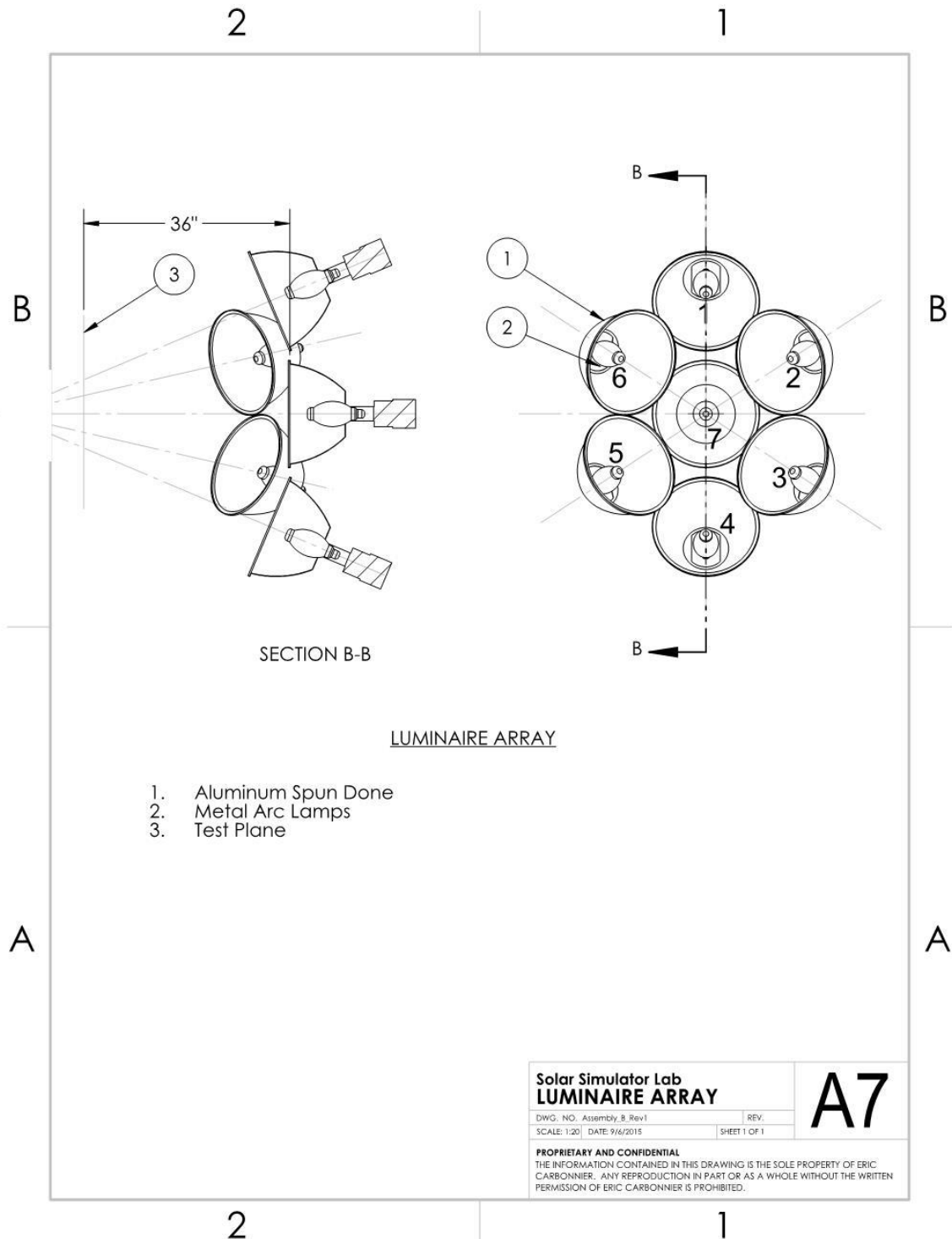














## Appendix H Datalogger Wiring Diagram

CR10XTD/CR10XPB Terminals, channels, wiring diagrams, sensors, and units used in conjunction with the dissertation. Campbell Scientific PC200W and ShortCut used to generate the following tables.

| CR10XTD/CR10XPB Terminal | Wire/Terminal | Attached Sensor/Device |                   |
|--------------------------|---------------|------------------------|-------------------|
|                          |               | Name                   | Measurements      |
| G                        | Clear         | LI200X                 | SlrW_1, SlrkJ_1   |
|                          | Clear         | (1)                    | SlrW_2, SlrkJ_2   |
|                          | Clear         | LI200X (2)             | Temp_C_1          |
|                          | Clear         | 107 (2)                | Temp_C_2          |
| G                        | Clear         | 107 (3)                | Temp_C_3          |
|                          | Shield        | VoltsDif               | UV_1              |
|                          | Clear         | LI200X                 | SlrBD_W, SlrBD_kJ |
| 1H                       | Red           | LI200X (1)             | SlrW_1, SlrkJ_1   |
| 1L                       | Black         | LI200X (1)             | SlrW_1, SlrkJ_1   |
| AG                       | White         | LI200X                 | SlrW_1, SlrkJ_1   |
|                          | White         | (1)                    | SlrW_2, SlrkJ_2   |
|                          | Purple        | LI200X                 | Temp_C_1          |
|                          | Purple        | 107 (2)                | Temp_C_2          |
| 2H                       | Red           | LI200X (2)             | SlrW_2, SlrkJ_2   |
| 2L                       | Black         | LI200X (2)             | SlrW_2, SlrkJ_2   |
| AG                       | Purple        | 107 (3)                | Temp_C_3          |
| 3H                       | Red           | 107 (1)                | Temp_C_1          |
| 3L                       | Red           | 107 (2)                | Temp_C_2          |
| AG                       |               |                        |                   |
| E1                       | Black         | 107 (1)                | Temp_C_1          |
|                          | Black         | 107 (2)                | Temp_C_2          |
|                          | Black         | 107 (3)                | Temp_C_3          |
| AG                       |               |                        |                   |
| E2                       |               |                        |                   |
| G                        |               |                        |                   |
| G                        |               |                        |                   |
| G                        |               |                        |                   |
| 4H                       | Red           | 107 (3)                | Temp_C_3          |
| 4L                       |               |                        |                   |
| AG                       |               |                        |                   |
| 5H                       | High          | VoltsDiff              | UV_1              |
| 5L                       | Low           | VoltsDiff              | UV_1              |
| AG                       |               |                        |                   |
| 6H                       | White         | LP02                   | SlrBD_W, SlrBD_kJ |
| 6L                       | Green         | LP02                   | SlrBD_W,          |
|                          | Jumper to AG  | LP02                   | SlrBD_kJ          |
| AG                       | Jumper to 6L  | LP02                   | SlrBD_W, SlrBD_kJ |
| E3                       |               |                        |                   |
| AG                       |               |                        |                   |
| G                        |               |                        |                   |
| G                        |               |                        |                   |

|                              |  |                 |
|------------------------------|--|-----------------|
| LI200X (1) - SlrW_1, SlrkJ_1 |  | CR10XTD/CR10XPB |
| Red                          |  | 1H              |
| Black                        |  | 1L              |
| White                        |  | AG              |
| Clear                        |  | G               |
| LI200X (2) - SlrW_2, SlrkJ_2 |  | CR10XTD/CR10XPB |
| Red                          |  | 2H              |
| Black                        |  | 2L              |
| White                        |  | AG              |
| Clear                        |  | G               |
| 107 (1) - Temp_C_1           |  | CR10XTD/CR10XPB |
| Red                          |  | 3H              |
| Purple                       |  | AG              |
| Black                        |  | E1              |
| Clear                        |  | G               |
| 107 (2) - Temp_C_2           |  | CR10XTD/CR10XPB |
| Red                          |  | 3L              |
| Purple                       |  | AG              |
| Black                        |  | E1              |
| Clear                        |  | G               |
| 107 (3) - Temp_C_3           |  | CR10XTD/CR10XPB |
| Red                          |  | 4H              |
| Purple                       |  | AG              |
| Black                        |  | E1              |
| Clear                        |  | G               |
| VoltsDiff - UV_1             |  | CR10XTD/CR10XPB |
| High                         |  | 5H              |
| Low                          |  | 5L              |
| Shield                       |  | G               |
| LP02 - SlrBD_W, SlrBD_kJ     |  | CR10XTD/CR10XPB |
| White                        |  | 6H              |
| Green                        |  | 6L              |
| Clear                        |  | G               |
|                              |  | L               |
|                              |  | A               |
| G Jumper                     |  |                 |

## Appendix I Picture Chronology

Collection of pictures documenting fabrication, installation, and implementation.

### Data Acquisition Center



P1. Top to bottom: Power Supply & Battery, CR10X Data Logger, RS32 Interface.



P2. Data acquisition assembly. Solar simulator in the background.

### Test Chamber



P3. Test chamber composed of RMax 1.5'' thick rigid polyiso insulation.



P4. Temporary wood frame used to retain right-angle cube



P5. Multiple cell test chamber. When complete the nanowindow will be situated in one chamber and fluids displaced and measured in the second chamber



P6. Test chamber situated in front of the solar simulator

#### Luminaire Brackets

Custom brackets are fabricated to allow for vertical adjustment and pivoting about the center of each luminaire.

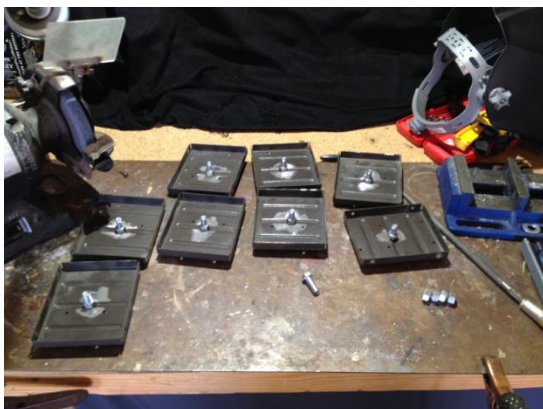


P7. Seven brackets fabricated from 1"x1"x16 gauge steel angles

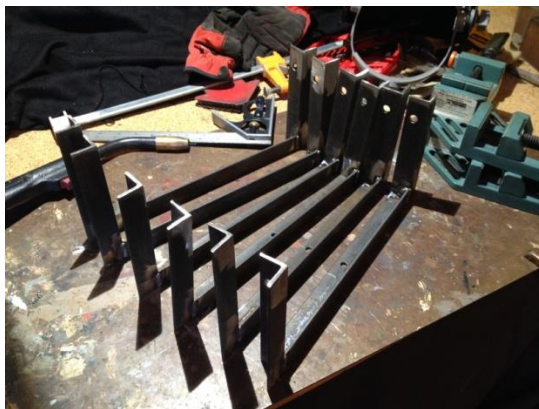


P8. Frames during fabrication





P9. Each ballast box was disassembled and equipped with pivot pins that slip into the custom frames.

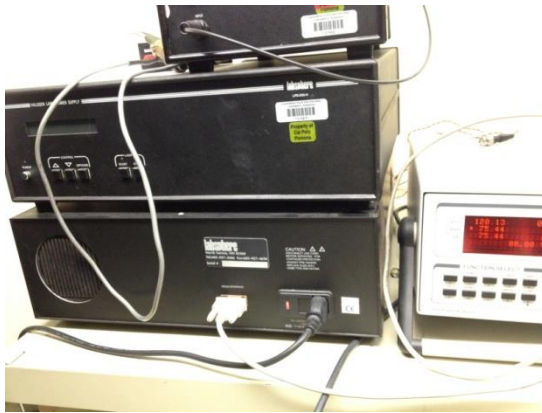


P10. Finished frames

### California Polytechnic University, Pomona – Lighting Lab Integrated Sphere



P11. 72" Integrating sphere and spectroradiometers used during the exercise.



P12. Top: Spectral Lamp Measurement System (SLMS)



P13.Right: Voltage regulator

## Solar Simulator



P14. Solar Simulator under canopy





P15. Temporary aluminum foil to block direct line of sight.



P16. Light source and thermal chamber in the background.

#### Installation

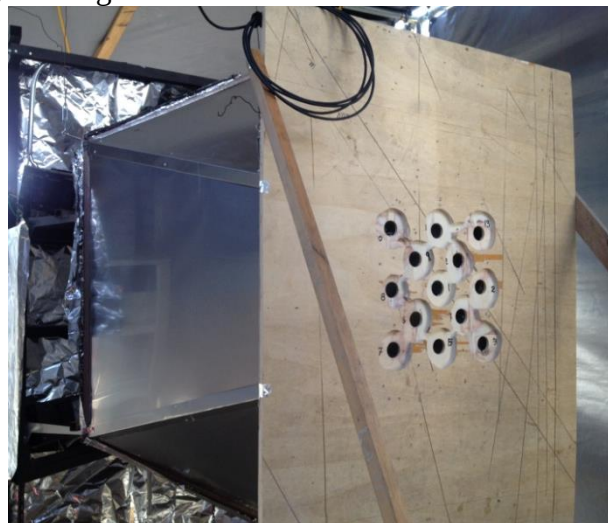
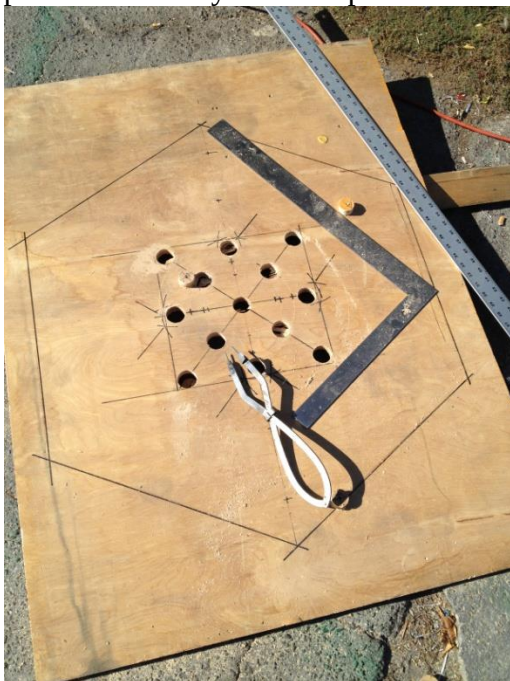


P17. Luminaires installed on custom rack.



P18. Seen from behind electrical conduits running between electrical panel and each luminaire.

### Spatial Uniformity and Temporal Stability Testing



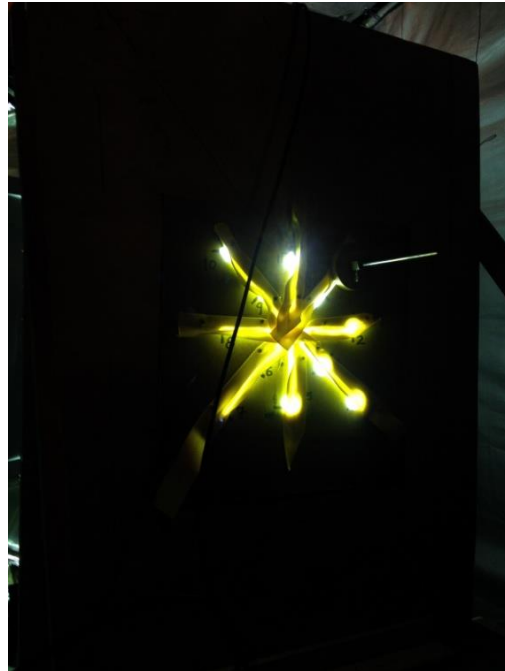
P19. (Left) Test Plane Template w/13 apertures to receive pyranometer.

P20. (Top) Test Plane placed in front of solar simulator and concentrator.





P21. Supplemental guide plate over the back of the Test Plane to guide pyranometer without taking it out at each of the 13 measurement points.  
Concentrator



P21A. Taken while simulator on.



P22. Two hexagonal frames in place to receive the TALBREM mirror.



P23. Mirror placement



P24. Concentrator complete



P25. Concentrator suspended from canopy and situated in front of luminaire array.

#### Array Frame



P26. A custom frame to receive the seven luminaires was custom fabricated.



P27. Designed with flexibility to adjustable height





P28. Array frame in place on the metal deck and under canopy.



P29. First of seven luminaires tentatively placed.

#### Sensors



P30. Sensors travel from the data acquisition center (P1, P2) to various locations. Sensor lengths are 40-feet and provide ample coverage of the entire Solar Simulator and to Weather Station



P31. Sensor Hub bundled and ready for deployment as needed



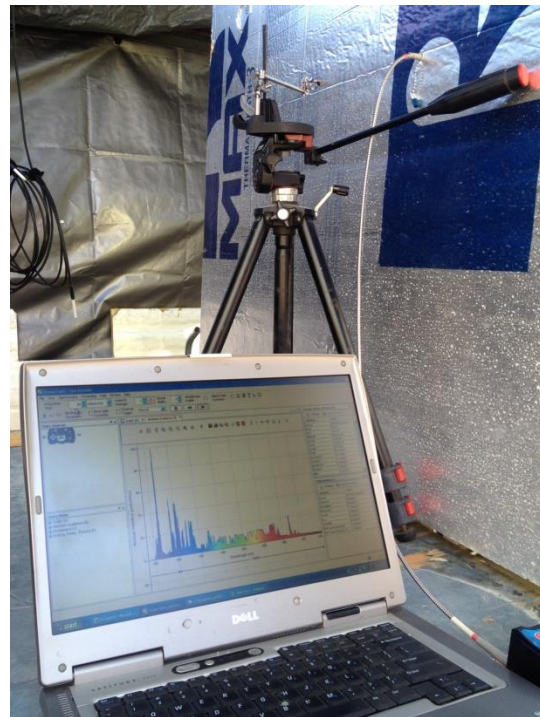
P32. Sensor Hub with two (2) silicon pyranometers and one (1) hemispherical pyranometer and one (1) UV sensors (Left).

### Spectroradiometer Testing

Spectroradiometer setup in front of Solar Simulator. Sensors

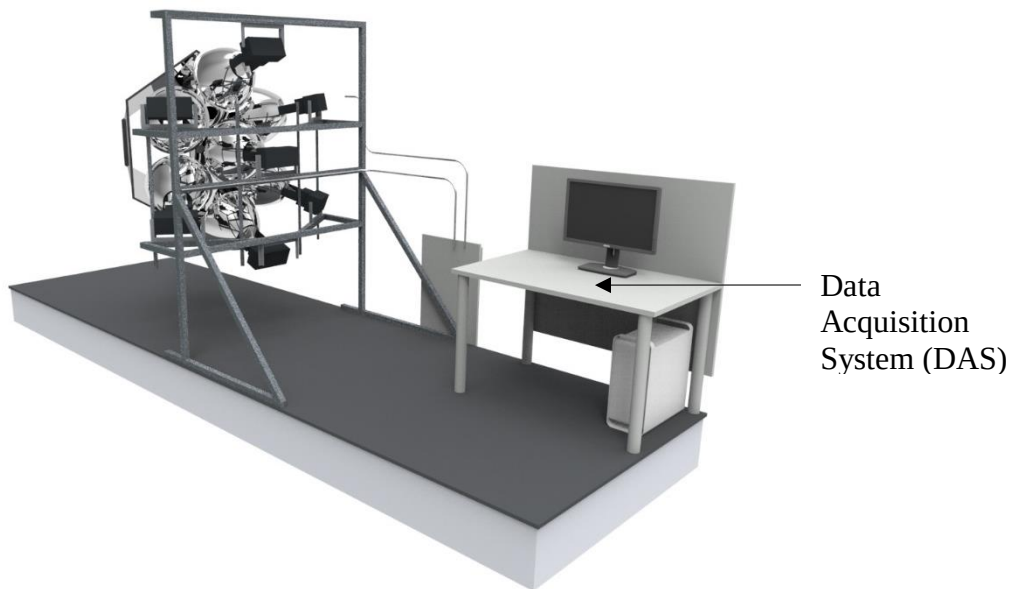


P33. Using the OceanOptics spectroradiometer and fiber optic probe to measure spectral wavelengths of metal arc lamps. Probe attached at the end of a camera tripod.

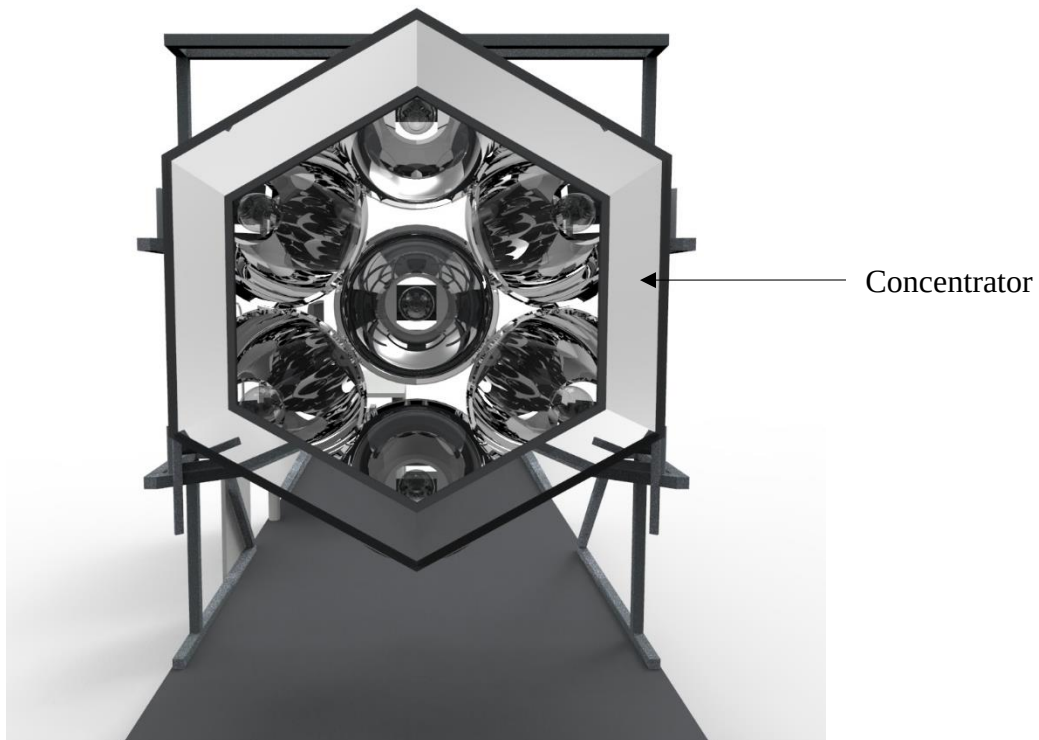


P34. Spectrasuite interface measuring spectral content.

## Appendix J Lab Renderings

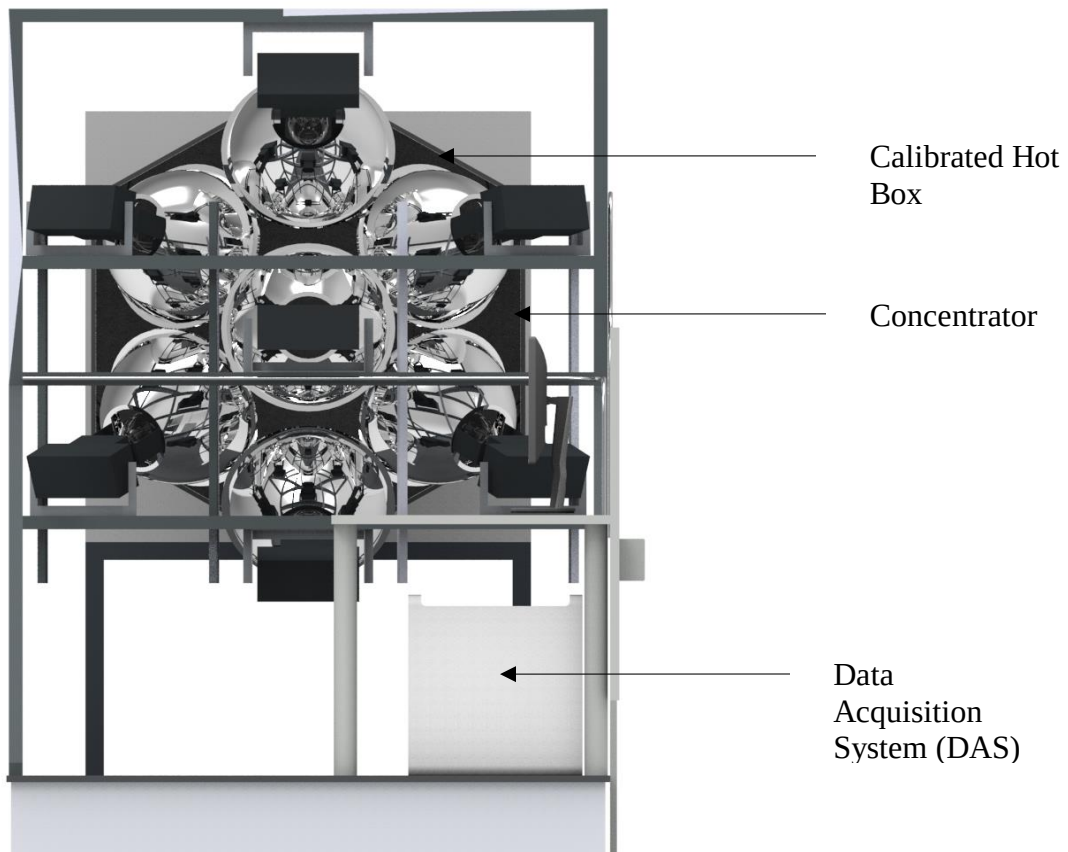


Solar Lab (Shown without Calibrated Hot Box)

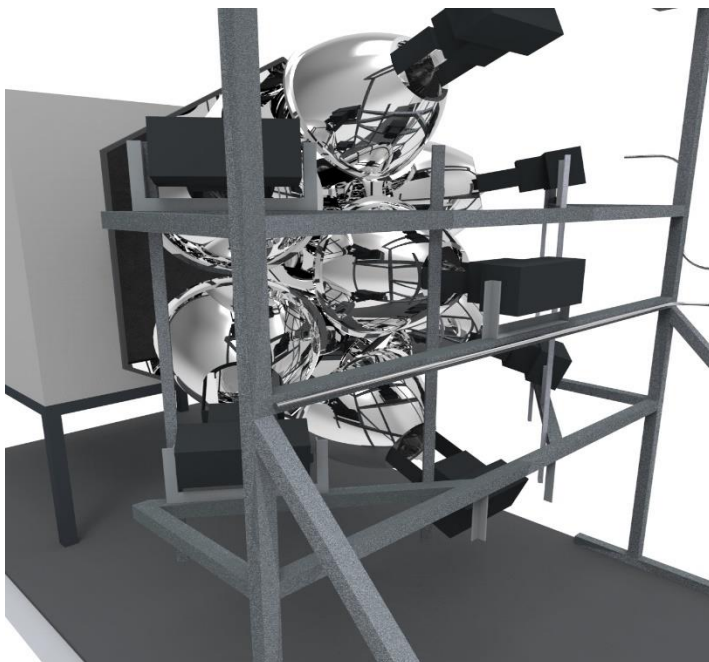


View of concentrator and lamps in the background





View From Data Acquisition System



Close-Up of Lamp Armature

## Appendix K Picture Chronology of Calibrated Hot Box



Fabrication of the test cell using closed-cell polyisocyanurate. Wood frame used to square the cell and later removed.



Initial positioning and centering to solar simulator. Sensors wired into the Climate Chamber and Meter Chamber under way.



Close-up view of Metering Chamber. Heat Flux sensor (red disk) and ambient temperature sensor loosely positioned.



Trail exercise examining alternative treatment around window specimens and sensors attachment.



Metering chamber during normal thermal transmittance testing exercises. Baffle wall not shown but typically place between the heating element and the remaining parts of the metering chamber.

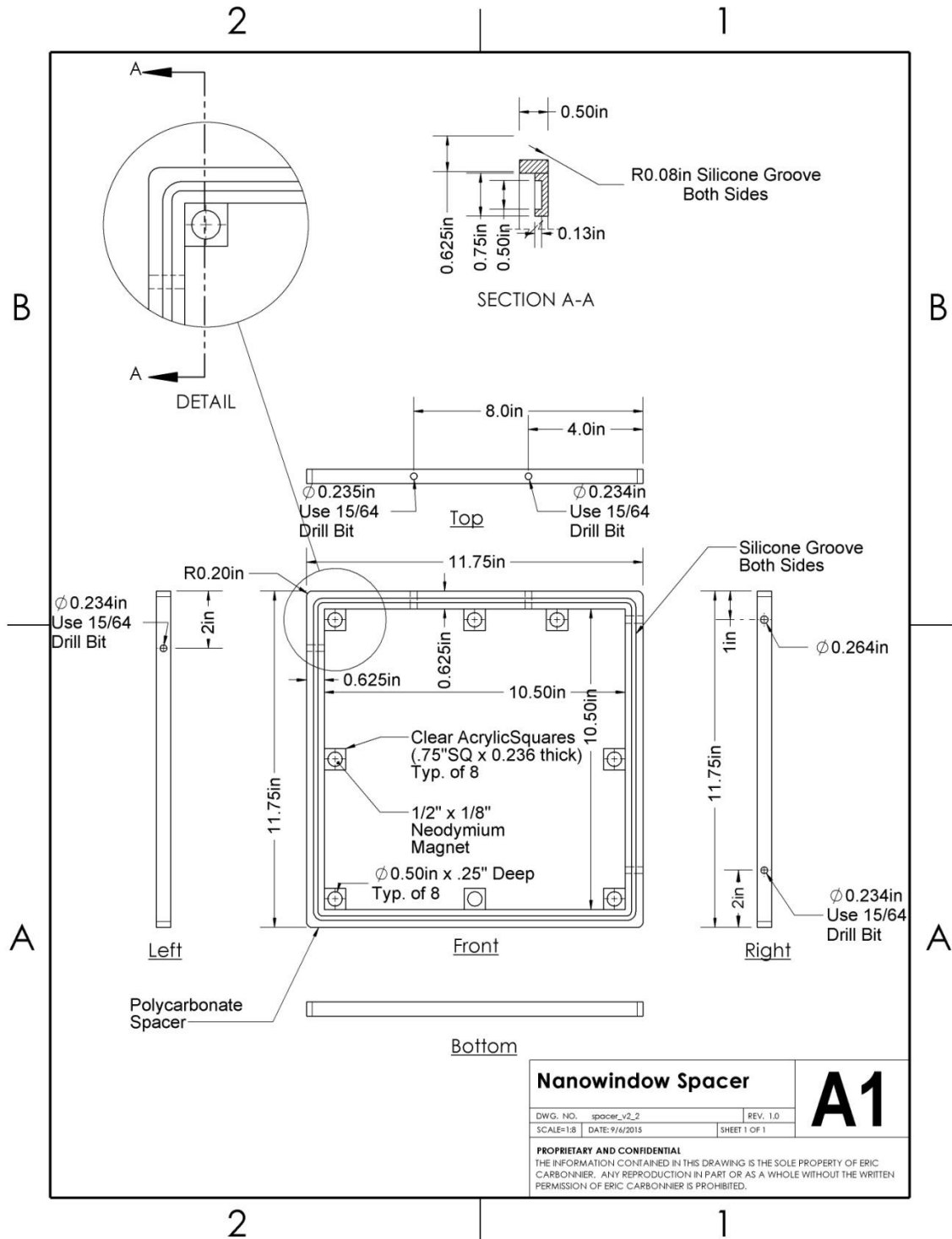
Horizontal insulated lines are the fluid lines that will be discussed in Part 3 of this research.

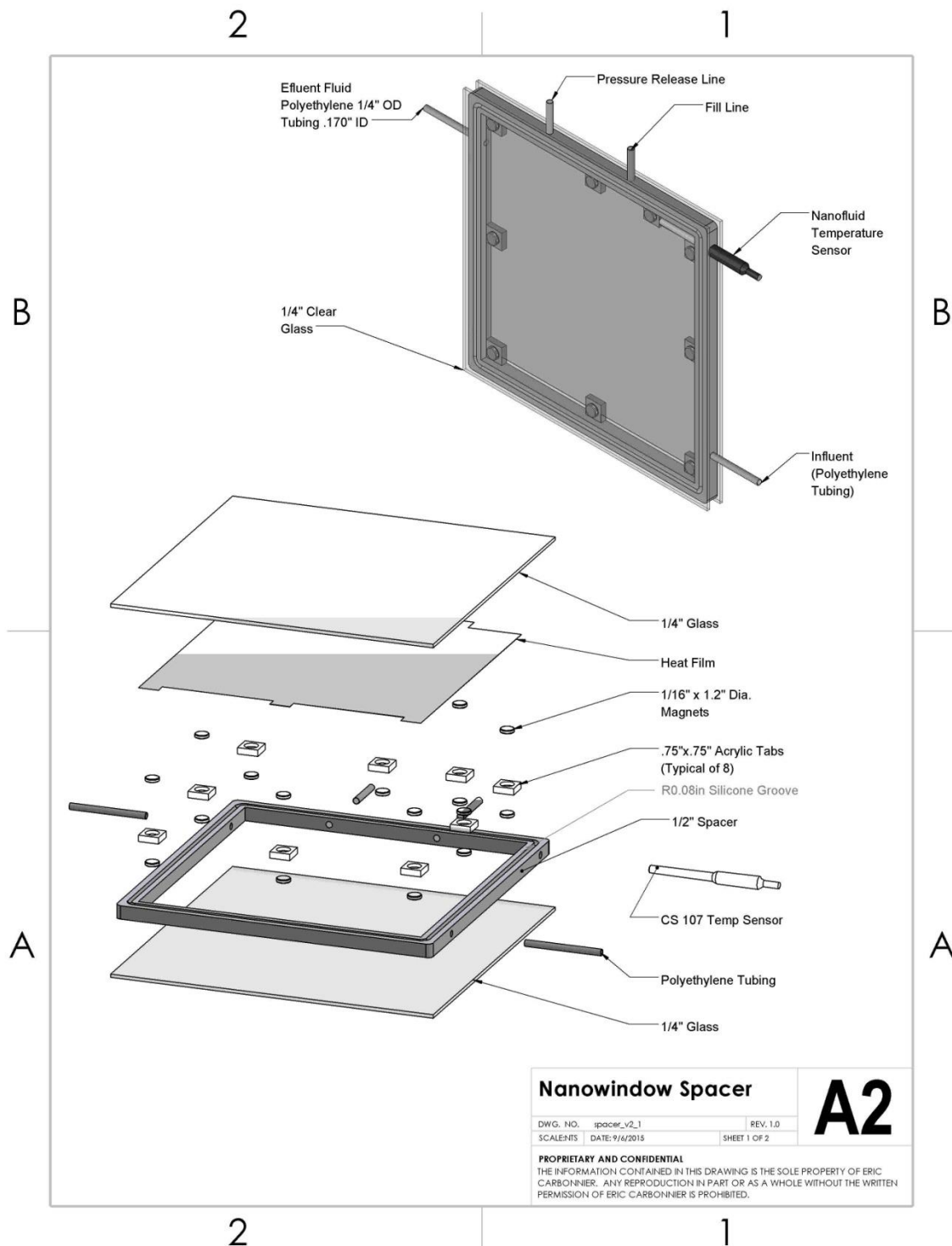




Climate chamber with sample specimen in place with surface temperature sensors.

# Appendix L Nanowindow

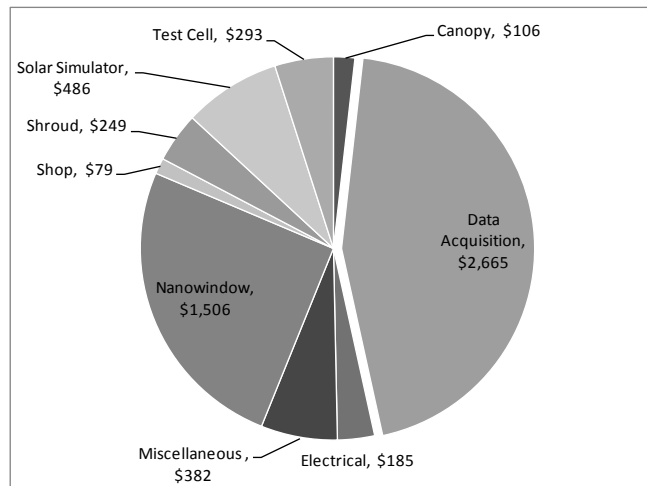




## Appendix M Expenses

Project Costs were meticulously tracked throughout the research. \$5,952.07 was spent on software, fabrication, data acquisition system, and sensors. 45% of project costs were attributed to data acquisition system and sensors. From the research perspective data acquisition equipment is a long-term investment as the equipment can be reused on subsequent research studies.

The expense ratio was in line with the Façade Testing Device designed and built by University of Michigan researcher resulted in a 40/60 split between equipment and construction material respectively (Cho et al., 2006, p. 71).



Comparatively the cost of pre-engineered solar simulators of this magnitude can be significantly more expensive and offer higher accuracy. The Atlas SolarConstant Series 4000 can produce similar solar radiation using Metal Halide Global lamps and can exceed \$17,000. National laboratories with solar simulators were approached and it was found to be in compatible with available funding, schedule, and self driven experimentation. National laboratories lacked flexibility to self conduct the experiments and rightfully so.

The single most instrumental investment was in the rapid prototyping<sup>64</sup> that saved tremendous amount of time and effort. Similar research inquiries are highly advised to rapid prototype the planning, layout, and fabrication to anticipate and optimize results.

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<sup>64</sup> SolidWorks 2015 was used to prototype the layout, solar simulator, and Nanowindow.

## Appendix N Calibrated Hot Box Fabrication & Sensor Placement

The hot box was sized to fit on the lab platform as illustrated in Figure 40, and sized to accommodate the aperture solar simulator's concentrator. The hot box was fabricated from 2-inch thermal insulation board composed of a closed-cell polyisocyanurate<sup>65</sup> (polyiso) foam core bonded to reinforced aluminum foil facers on each side. The ASTM C518 test method rated the 2-inch polyiso R-value at 13.1 °F/ft<sup>2</sup>hr/Btu. This was evaluated in the calibration section of this chapter.

The hot box apparatus measures 4-feet x 4-feet x 4-feet, 64ft<sup>3</sup> (1.81m<sup>3</sup>) and all joints were caulked and sealed with 3-inch foil tape inside and outside to minimize air infiltration and flanking loss. Similar to Stanley et al., foil faced polyiso at the corners and edges were peeled back when joining the panels to avoid unwanted thermal bridging (Stanley, Gatland II, William, & Dragan, 1997, p. 76). Foil tape was used to match the emissivity of the aluminum faced polyiso. All breaches for sensor wires were caulked to reduce air infiltration and foil taped for a secure seal. The hot box was situated on a table that was reclaimed from scrap metal and leg heights adjusted so that the center of the specimen was centered on the concentrator and solar simulator.

The CHB was divided into two chambers and served two distinct purposes. The dividing chamber wall was used to test for thermal transfer (U-factor), while the face of the

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<sup>65</sup> RMax Thermasheath-3 utilizes a CFC-, HCFC- and HFC-free blowing agent that has zero Ozone Depletion Potential (ODP) and negligible Global Warming Potential (GWP).  
[http://www.rmax.com/files/8914/3957/2554/Thermasheath-3\\_Data\\_Sheet\\_2015-08.pdf](http://www.rmax.com/files/8914/3957/2554/Thermasheath-3_Data_Sheet_2015-08.pdf)

metering chamber opposing the solar simulator was used for solar heat gain coefficient (SHGC), visible transmittance (VT), and determining the heat exchange potential of the Nanowindows.



**Figure 128:** Meter Chamber  
Meter Chamber (Left). Climate Chamber (Right)

The Meter Chamber, also referred to as the hot side, was equipped with a 600watt stainless steel heating element salvaged from an electric grill (Figure 129). The heating element was situated behind a radiant baffle to reduce radiant fields impacting sensors and to dissipate thermal energy throughout the chamber with no direct impact on the Nanowindow. The heating element was equipped with a temperature regulator with

maximum and minimum settings. Throughout the experiment the heating element remained on low. Power to the heating element was controlled by the Data Acquisition System (DAS) that is described later in this section.



**Figure 129:** Heating Element

The climate chamber was cooled using the upcycling of a mini-refrigerator's components. The upcycled system was a 444 Btu compressor, 110-115V, ~60Hz, 1PH, 4.5A, system with a 3.9 displacement capability. The refrigerator was disassembled without breaching the refrigerant loop<sup>66</sup> and transplanted into the climate chamber. The compressor was situated outside the climate chamber so that no additional sensible heat was added to the climate chamber. The evaporator plate was situated on the opposite wall of the access door and placed at mid height. The thermostat was located inside the chamber furthest from the evaporator plate, but did not serve as the primary control for cooling effect. The thermostat was overridden by a second temperature sensor in the

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<sup>66</sup> Caution: Refrigerant systems are under pressure and can cause severe harm if punctured. Always wear gloves and goggles. Also note that refrigerant is also known to cause cancer.



climate chamber connected to the Data Acquisition System (DAS) that is described later in this section. Power to the refrigeration system was also controlled by DAS.



Upcycled mini-refrigerator stripped down to the core components: Compressor, evaporator, refrigeration lines, and thermostat.



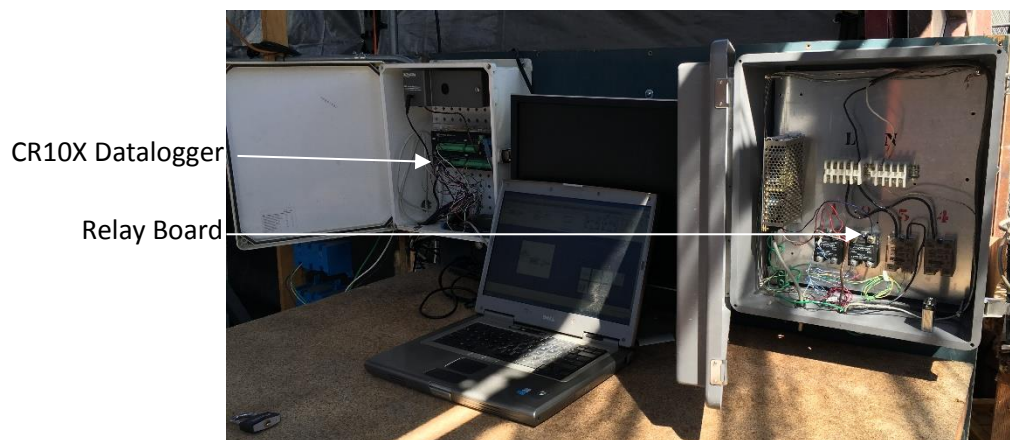
Refrigeration components then transplanted into the Climate Chamber. Thermostat on the right and evaporator midway on the far wall. Compressor on the outside behind the evaporator.

**Figure 130:** Refrigeration System

## Data Acquisition System (DAS)

The Data Acquisition System (DAS) was described in Part IV. In summary, all sensors, AC power, and DC power running to the hot box interfaced with DAS and the custom made relay control board. The relay controller allows the datalogger to activate AC or DC devices such as the Nanowindow's pump, and chamber's heating element, and refrigeration equipment.

The relay control board is vital in the communication between the CR10X datalogger and sensors, pumps, heating elements, fans, and refrigeration system. Unfortunately, the datalogger can only send low voltage excitation ( $\pm 5\text{ma}$ ) that needs to be switched to a higher electrical power be it AC or DC, and rated at high currents loads.



**Figure 62: Relay Control Board**

The Relay Controller (RC) was situated in a reclaimed weather enclosure and located adjacent to the DAS enclosure. The RC was equipped with two Mean Well switching

power supplies<sup>67</sup> providing a broad range of low voltage options ranging from  $\pm 12$  V to  $\pm 24$  V at a maximum of 2.5 amps to accommodate a range of low-voltage demand. In addition to low voltage supply the RC was equipped with a dedicated 120 V/30 amp/Single phase line to operate larger loads such as the refrigeration and heating system.

Ample room was allocated for low voltage and line voltage relays in the enclosure. Crydom D1D07 and D1D12 solid-state relays were used to switch low voltage excitation from the datalogger, and Omron solid-state relays G3NA-205B and G3NA-210B were used to switch low voltage excitation to 120V at 5A and 10A respectively.

## Sensors

An array of sensors were deployed throughout the hot box to measure ambient temperature, mean radiant temperature, fluid temperature, surface temperature, heat flux, and broad band irradiance. Each sensor had ample cable length so they could be reconfigured with ease.

Ambient temperature and mean radiant temperature (MRT) were measured using Campbell Scientific L107 thermistors encapsulated in an epoxy-filled aluminum housing. Ambient sensors were placed out of sight of the solar simulators direct line of sight and equipped with a radiant shield just in case. The climate chamber and metering chamber receive one ambient temperature sensor each and situated 30-inch above the chamber

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<sup>67</sup> Mean Well power supplies S-60-24 and S-60-12 were used and now obsolete

floor. The MRT was located adjacent to the ambient sensor and encased in a 4-inch black cooper sphere.



**Figure 131:** Temperature Probe

Measuring fluid temperature was a vital variable and considerable thought was given to the sensor type and location of the sensor within the system. Initially it was thought that placing the sensor in the Nanowindow would provide the most reliable measurements, but this was found to be incorrect and discussed in analysis section of this research. Knowing that the nanofluid resides in a 0.5” gap between the two panes of glass it made it impractical to use a Campbell Scientific 107 thermistor considering there would not be enough spacer material to form a water tight seal. Instead, a 1099SS Stainless Steel Temperature Probe was deployed. The 1099SS thermistor consists of a probe diameter of 0.16cm by 5.84cm long making it ideal for this application. The probe was inserted through the polycarbonate spacer and sealed using silicone sealant. As with the other sensors the 1099SS works within the  $-40^{\circ}$  to  $70^{\circ}\text{C}$  range and tolerance of  $\pm 0.1\text{C}$ ,  $\pm 0.3\text{C}$ ,

$\pm 0.4^\circ\text{C}$  at  $25^\circ\text{C}$ ,  $50^\circ\text{C}$ , and  $70^\circ\text{C}$  respectively. The sensitivity of the probe sensors made it ideal to compare small incremental changes in the  $\text{H}_2\text{O}$  and nanofluids.



**Figure 132:** Temperature Probe

Two Campbell Scientific 110PV-L surface-mount thermistor surface temperature sensors were positioned in the climate chamber and the metering chamber. The 110PV measures temperature by direct contact through its aluminum face that promotes heat transfer. The surface mount sensor is typically used on photovoltaic panels and has a range of  $-40^\circ$  to  $135^\circ\text{C}$  with a temperature uncertainty of  $\pm 0.2^\circ\text{C}$  within the range of  $-40^\circ$  to  $70^\circ\text{C}$  which is the anticipated surface temperature range.



**Figure 133:** Surface Sensor

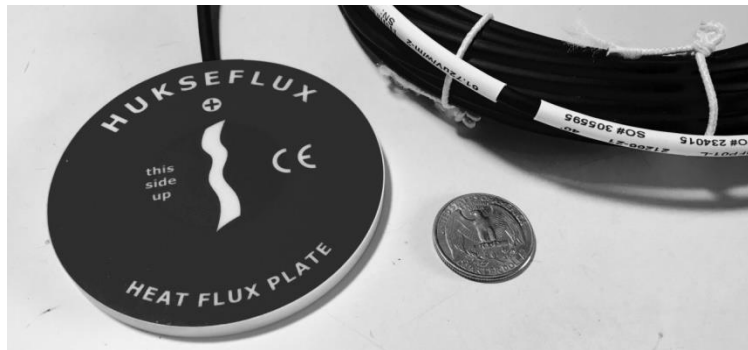
One Hukseflux HFP01 heat flux sensor typically used for measuring heat flux through building material was deployed. The heat flux sensor is a passive thermopile detector used for in-situ measurement of building envelope thermal resistance (R-value) and thermal transmittance (H-value) according to ISO 9869, ASTM C1046 and ASTM 1155 standards. After calibration<sup>68</sup> with the CR10X datalogger the HFP01 generates heat flux in  $\text{W/m}^2$  units.

The heat flux operates in a temperature range of  $-30^\circ$  to  $70^\circ\text{C}$  with measurement accuracy of  $\pm 5\%$ . The use of multiple heat flux sensors is encouraged to improve spatial averaging and increase measurement precision. However, during the Solar Simulator evaluation process it was determined that the test plane experiences  $<2\%$  Spatial Non-Uniformity, meaning that the test plane experiences a relatively equal

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<sup>68</sup> Sensor calibration is traceable to the 'Guarded Hot Plate' of the National Physical Laboratory (NPL) in the UK, in accordance with ISO 8302 and ASTM C177 standards. HukseFlux USA

amount of heat flux across the 12 square inch surface area. Ultimately, the budget for the research cannot accommodate multiple heat flux sensors.



**Figure 134:** Heat Flux Sensor

One (1) hemispherical Hukseflux LP02 Solar Radiation Pyranometer<sup>69</sup> was selected for its compatibility with measuring lamp based solar simulator in-situ experiments.

Specifics of the pyranometer were covered in Part IV. In brief, the LP02 Pyranometer was a blackened thermal-pile under a glass dome sensor and utilized for characterizing indoor solar simulation. See Part IV.



**Figure 135:** Kill-A-Watt

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<sup>69</sup> Hukseflux LP02 Pyranometer is a hemispherical solar radiation sensor with calibration uncertainty  $\pm 0.21 \times 10^{-6} \text{ W/m}^2$ .

Kill-A-Watt logger displays Volts, Current, Watts, Frequency, Power Factor, and VA. It provided kWH and duration time (hh:mm) used to determine kW demand. Two of these were acquired to monitor the heating and cooling side of the calibrated hot box. Since the equipment is not a datalogger, visual recordings were required throughout the logging period and cumulative values were used to generalize the energy input.



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