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SUSTAINABLE DESIGN RETROFIT FOR THE VISITOR CENTER AT THE OAK RIDGE NATIONAL LABORATORY

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ACKNOWLEDGEMENT

ABSTRACT

It is estimated that existing buildings consume 40% of the world's total primary energy [8]. As this number grows, it becomes increasingly important to create structures and technology that are environmentally responsible as well as resource efficient. While we continue to create new green buildings, it is also important to look at retrofitting and renovating older structures. The visitor's center at the Oak Ridge National Lab, also known as "The Lantern", is extremely inefficient from an energy consumption standpoint. The immediate objective of this research project is to conduct a feasibility study for retrofitting "The Lantern" for decreased overall energy consumption. A secondary objective of this research project is to collect data at the University of Tennessee's Solar Decathlon house, a zero energy building, in order to determine if these technologies can be applied to "The Lantern" and other buildings.

1. INTRODUCTION

In the United States, commercial structures account for over 40% of the overall energy consumption [8]. This exorbitant rate of consumption has forced the innovation of high efficiency building techniques that are implemented into the design of modern commercial buildings. While these systems help to greatly reduce the energy consumption of new construction, existing structures still demand energy at rates that are no longer acceptable. As high rates of energy consumption fall out of practice, existing commercial structures will need to be retrofitted with building systems capable of increasing the overall energy efficiency of the structure while integrating within existing structural elements. To reinforce the necessity for change, the Department of Energy has mandated that Oak Ridge National Labs reduce their annual energy consumption by 20% over the next five years. Building 5200, more commonly referred to as "The Lantern", proves to be an excellent location to begin implementing such energy efficient systems because a sizable portion of the building envelope is comprised of a single pane window system that spans multiple elevations. Retrofitting "The Lantern" with modern building techniques will not only help in the effort to meet the Department of Energy's mandate, but also function as a central location to showcase the capabilities of modern building technology.

To maximize the efficiency of "The Lantern", three separate technologies were integrated to form a system capable of dramatically increasing the overall energy efficiency of the building. The first technology considered was that of the Fresnel solar collector. The primary goal of a Fresnel solar collector is to heat a working fluid by directing concentrated amounts of the sun's irradiance into concentric tubes housing the fluid. The energy captured by the working fluid can then be exchanged to preheat potable water or generate the steam necessary to power a steam turbine/generator. In addition to Fresnel solar collectors, evacuated tube solar collectors were also considered. Evacuated tube solar collectors are similar to Fresnel solar collectors in the fact that both serve to transfer solar energy into usable heat energy, except evacuated tube solar collectors do not have the ability to concentrate solar irradiance as Fresnel solar collectors do. The benefit of evacuated tube solar collectors lies in the overall size of each unit. Evacuated tube solar collectors are small in comparison to a Fresnel solar collector and are easily located where a Fresnel solar collector could not be. While relatively small, evacuated tube solar collectors are still capable of producing temperatures high enough to preheat potable water. The final technology considered was the transpired solar collector. Transpired solar collectors are composed of two panes, one exterior and one interior, which act as a duct for an air stream of exterior air. The air captures transformed solar energy in the form of heat energy and is then used to preheat make-up air or potable water. The transpired solar collector also acts to increase the efficiency of the building envelope. When combined into one system, these three technologies are capable of generating electricity, preheating make-up air and potable water and improving the efficiency of the building envelope.

Integrating three relatively obscure technologies into one system necessitated the need for modeling. In addition to modeling, data collection was necessary for benchmarking purposes. To accomplish such a task, the Department of Energy's "Living Light" was instrumented for temperature and irradiance measurement. Once all three components were modeled and validated separately, a combined system capable of being retrofitted to "The Lantern" was designed. A Process and Instrumentation Diagram (PID) is shown in Figure 1 and illustrates the general design for each phase of the proposed retrofit. The three technologies are implemented into the system as follows:

1. Fresenel Solar Collector: Working fluid is heated through the collector. This fluid heats the water used for a steam turbine which is in series with an absorption chiller and heat exchanger. The waste water from the turbine is then used by an absorption chiller to cool the water to be used by an HVAC system. During winter months, the waste from the turbine is used to heat water used by an HVAC system.
2. Evacuated Tube Solar Collector: Working fluid is heated by the collectors. The fluid is then used to heat potable water for the building.
3. Transpired Solar Collector: Exterior air enters the air cavity of the transpired solar collector and is heated. The hot air exiting the air cavity is vented so that it can be used to preheat

make-up air in the cooler months and preheat potable water in the warmer months. While the PID expresses some level of detail, an in-depth discussion of Fresnel solar collectors, evacuated tube solar collectors, transpired solar collectors, and data acquisition can be found in the following sections.
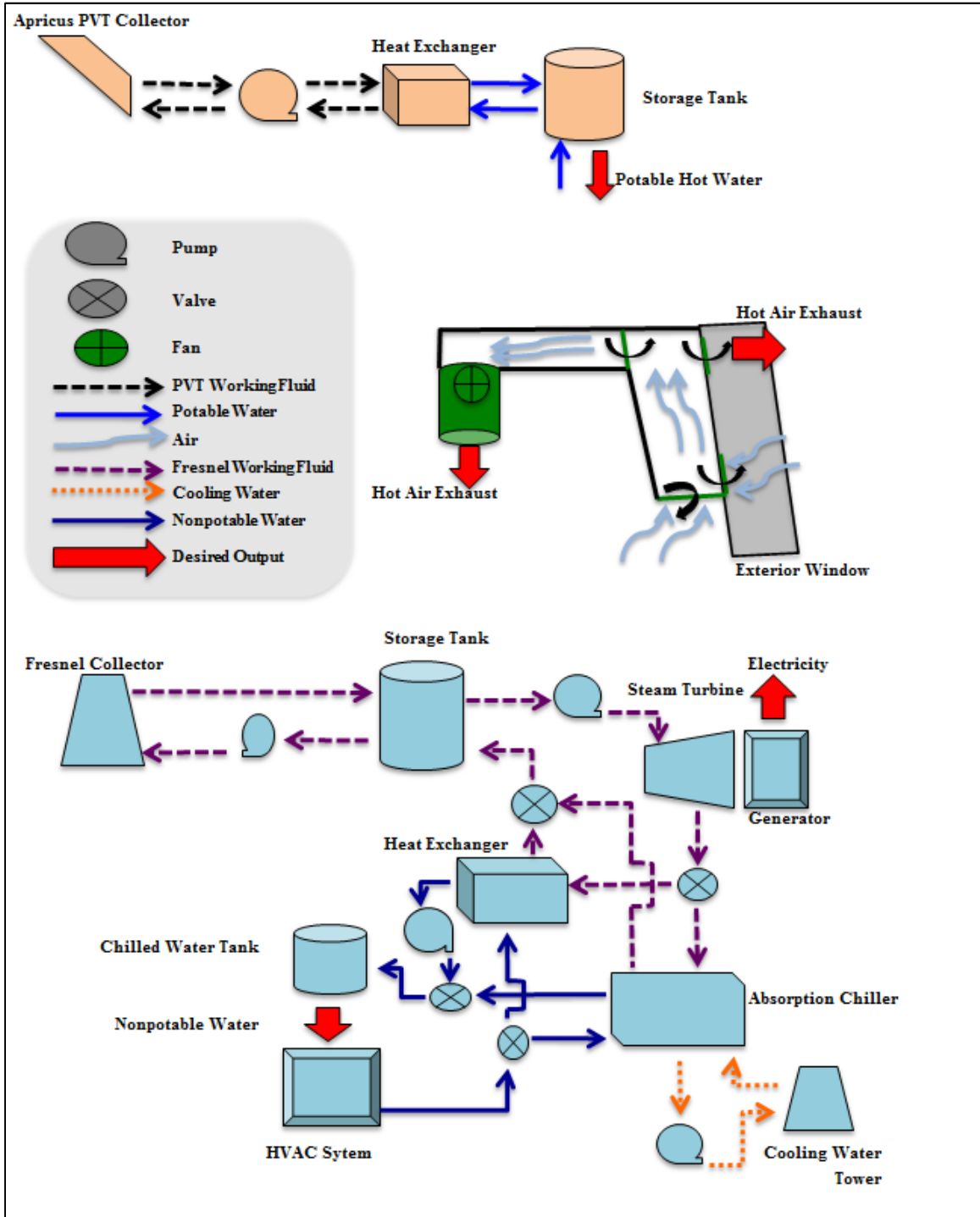
Figure 1: PID Diagram of Proposed Systems for the Visitor's Center at ORNL

2. FRESNEL SOLAR COLLECTORS

2.1 SYMBOLS AND ABBREVIATIONS

Symbol	Description	Units
$c_{p,fluid}$	Specific Heat of Working Fluid	J/kgK
D_1	Glass Tube Outside Diameter	m
D_2	Glass Tube Inside Diameter	m
D_3	Absorber Tube Outside Diameter	m
D_4	Absorber Tube Inside Diameter	m
$h_{conv,1}$	Convection Heat Transfer Coefficient from Outside to Glass Tube	W/m²K
$h_{conv,23}$	Convection Heat Transfer Coefficient in Evacuated Space	W/K
$h_{conv,fluid}$	Convection Heat Transfer Coefficient of Working Fluid	W/K
$h_{rad,1}$	Radiation Heat Transfer Coefficient from Sky to Glass Tube	W/m²K
$h_{rad,23}$	Radiation Heat Transfer Coefficient in Evacuated Space	W/K
L	Collector Length	m
m_{fluid}	Mass Flow Rate of Working Fluid	kg/s
Q_1	Heat Transfer to Exterior Surface Glass Tube	W
Q_2	Heat Transfer to Interior Surface Glass Tube	W
Q_3	Heat Transfer to Exterior Absorber Tube	W
Q_4	Heat Transfer to Interior Surface Absorber Tube	W
Q_5	Heat Transfer to Working Fluid	W
T_1	Surface Temperature at Exterior Glass Tube	K
T_2	Surface Temperature at Interior Glass Tube	K
T_3	Surface Temperature at Exterior Absorber Tube	K
T_4	Surface Temperature at Interior Absorber Tube	K
T_5	Bulk Temperature of Working Fluid	K
T_{CI}	Working Fluid Inlet Temperature	K
T_{Sky}	Sky Temperature	K
$T_{Outdoor}$	Ambient Air Temperature	K

2.2 INTRODUCTION

2.2.1 Objective

In order to increase the use of sustainable energy at the Oak Ridge visitor center, a Fresnel solar collector system was examined as a source of solar energy. Fresnel solar collectors heat a fluid to high temperatures that can be used in absorption cooling and heating systems or for energy generation. This type of system was analyzed to investigate the solar heating process and possible generation loads. The proposed linear Fresnel solar collectors may be integrated with a trigeneration system to heat water used by a steam turbine that will produce electricity. The waste water from the turbine will provide the heating fluid for an absorption cooling system.

2.2.2 Background

Renewable energy has become attractive for many applications as the price of electricity increases and societies grow more aware of the waste generated from traditional generation. Countries have implemented a wide range of restrictions and incentives pertaining to the generation and use of energy. Increased pressure to utilize more efficient means of supplying and using energy for industries, businesses, and residences has presented an opportunity for new technology.

Solar collectors have become widely used in various industries and residential areas over the past

few decades. Typically, solar collectors are used to capture the sun's energy and convert this heat into electricity. This technology has improved to include the ability to heat a working fluid that may be used in other applications as well. Fresnel solar collectors utilize the original solar collector technology to capture the sun's heat with the addition of mirrors. These mirrors reflect the sun's irradiance back onto the solar collector's concentric tubes, ultimately concentrating the sun's energy on these tubes and exposing them to 360 degrees of solar heat.

New multifunctional systems have integrated different technologies to produce desired outputs while minimizing greenhouse gas emissions and utilizing sustainable energy techniques. Solar cogeneration refers to a system that generates electricity and hot water from photovoltaic roof panels and solar thermal collectors. Solar trigeneration expands upon a cogeneration system by adding absorption chillers that can be used with air conditioning systems to heat or cool a building [9].

Trigeneration systems have been implemented in many locations over the past decade.   The city of Austin, Texas installed a trigeneration system at a large power plant that uses the combustion of natural gas to power a turbine generator. The waste from this generator is then used to heat and cool water that are used for the air conditioning system on the campus [3]. ORNL has worked closely with the implementation of these cogeneration and trigeneration plants to assess the performance and economics of these systems [11]. These studies occurred from 1999 to 2007 and found trigeneration systems to obtain greater than 70% efficiency [1].

2.3   APPROACH

The design of a Fresnel solar collector was analyzed to investigate the amount of heat generated from the system. A thermodynamic energy balance on the concentric tubes was used to determine the heat transfer from the sun's energy into each section of the collector. The incoming temperature and flow of the working fluid in the collector was used with this energy balance to calculate the exit temperature of the fluid. Fresnel solar collectors were researched to determine the best model to integrate with a steam turbine and absorption cooler to create a trigeneration system.

The analysis of the Fresnel solar collector was completed by performing an energy balance on each section of the concentric tubes progressing into the interior of the collector as displayed in Figure 2 below. The numbers labeled on Figure 2 below refer to the location at the interior or exterior surface of its respective concentric tube. Labels 1 and 2 reference respectively the exterior and interior of the outmost concentric tube, labels 3 and 4 reference respectively the exterior and interior of the internal absorber tube, and label 5 refers to the bulk state of the working fluid. T_{sky} and $T_{Outdoor}$ reference the sky and local ambient outdoor temperatures. T_{CI} references the inlet temperature of the fluid working in the Fresnel collector.
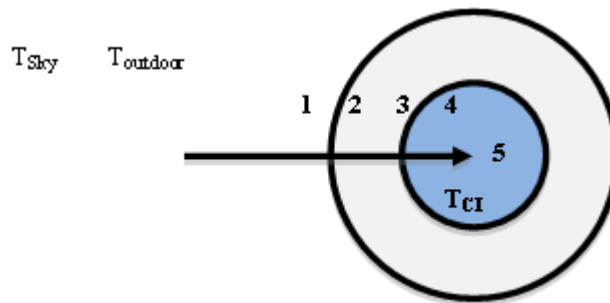
Figure 2: Concentric Tube Photovolatic Solar Collector

This energy balance accounted for convection and radiation from the sun, conduction through the outer tube, convection and conduction through the annulus, conduction through the absorber, and convection to the working fluid. These governing equations were displayed in the following section.

2.3.1   Exterior Concentric Tube

The heat transfer analysis of the exterior tube of the solar collector was relatively straightforward. The radiation heat transfer coefficient was calculated traditionally using relating the Stephan-Boltzmann Law. The Churchill and Bernstein Nusselt number correlation was used to determine the heat transfer coefficient due to forced convection, and similarly, the heat transfer coefficient due to natural convection was calculated using the Nusselt number correlation proposed by Churchill and Chu [5]. Equation (2.1), displayed below, was used to calculate the overall heat transfer at the exterior surface of the outer concentric tube. This equation accounted for the incoming heat from radiation, forced convection, and natural convection.

$$Q_1 = \pi D_1 L [h_{rad,1}(T_1 - T_{Sky}) + h_{conv,1}(T_1 - T_{Outdoor})] \tag{2.1}$$

2.3.2   Evacuated Annulus

The heat transfer at the interior surface of the outer concentric tube and the exterior surface of the absorber tube were considered equal as the space in between was assumed evacuated. The radiation heat transfer coefficient was calculated using the Stephan-Boltzmann Law and an effective emissivity that combined the emissive effects of the interior surface of the outer most concentric tube and the exterior of the absorber tube [5]. The natural convection heat transfer coefficient was derived from correlation equations proposed by Kuehn and R.J. Goldstein [6]. These correlation equations calculated an effective conductivity for the evacuated space, which was then used to calculate the convection coefficient [6]. The overall heat transfer relationship accounting for radiation and natural convection was displayed below in Equation (2.2).

$$Q_2 = h_{rad,23}(T_3 - T_2) + h_{conv,23}(T_3 - T_2) = Q_3 \tag{2.2}$$

2.3.3   Absorber Tube

The heat transfer inside the absorber tube was related to the convection through the working fluid. This heat transfer coefficient was derived from the Nusselt number relationship proposed by either Sieder and Tate or Petukhov depending upon the mass flow rate of the working fluid [5]. The heat transfer at the interior of the absorber tube accounted for the natural convection of the working fluid and the temperature difference between the interior of the absorber tube and the bulk temperature of the working fluid. This was displayed below in Equation (2.3).

$$Q_4 = h_{conv,fluid}(T_5 - T_4) \tag{2.3}$$

The final heat transfer to the working fluid was calculated from the mass flow rate of the working fluid to the difference between its inlet and bulk temperatures. This was displayed below in Equation (2.4).

$$Q_5 = \dot{m}_{fluid} c_{p,fluid}(T_5 - T_{CI}) \tag{2.4}$$

2.4   SIMULATION

A program code was created using Matlab software with these energy equations to iteratively generate the temperature at each surface of the collector and the bulk working fluid temperature of a Fresnel solar collector array. It also generated the amount of heat transfer through each section of the collector.

2.4.1 Results

A simulation of the heat transfer process in a Fresnel solar collector was performed using Matlab coding software. The working fluid inside the absorber tube was assumed to be water. The ambient and initial conditions affecting the tube may be seen below in Table 1.

Table 1: Simulation Initial Conditions

$T_{Outdoor}$	T_{Sky}	T_{CI}	I_{Sun}	V_{Wind}	V_{Inlet}
35 °C	35 °C	21 °C	1000 W/m²	5 m/s	5 gal/min

The outermost tube of the concentric Fresnel collector was assumed to be glass while the interior absorber tube was assumed to be copper. The dimensions and thermodynamic properties were displayed below in Table 2.

Table 2: Simulation Material Specifications

Material	L (m)	# of Segments	$D_{outside}$ (m)	D_{Inside} (m)	k (W/m-K)	ε	α	R	T
Glass	10	10	0.05	0.04	0.917	0.076	0.076	0.076	0.848
Copper	10	10	0.025	0.015	401	0.050	-	-	-

The resulting temperature and heat transfer at each surface of the Fresnel collector was iteratively solved until the temperature solutions converged within a ten thousandth degree. These final temperatures and heat transfers were displayed below in Table 3

Table 3: Resulting Temperatures and Heat Transfer

Location	Outside	1	2	3	4	5	Inlet
Temp. (°C)	35.00	40.24	46.20	26.94	26.93	26.93	21.00
Heat (W)	-	312.29	73.50	73.50	739.52	739.52	-

This study showed a small increase in water temperature of 5.93°C. The simulation was repeated with the addition of an irradiance concentration factor of 20 and the design specification of an Industrial Solar (formerly Mirroxx) Fresnel collector as four meters long [13]. The resulting temperatures and heat transfer from this simulation were displayed below in Table 4.

Table 4: Industrial Solar Simulation Temperatures and Heat Transfer

Location	Outside	1	2	3	4	5	Inlet
Temp. (°C)	35.00	158.25	205.65	70.35	70.15	62.25	21.00
Heat (W)	-	2813.8	272.5	272.5	5600.7	5600.7	-

These results illustrated the large increase in heat transfer due to the Fresnel lens that concentrates the irradiance on the solar tubes. The exit temperature of the working fluid in a Fresnel collector was 131.2% larger than the estimated exit temperature in a normal solar collector. The effect of the length of solar collectors on the exit temperature with and without this Fresnel concentration factor was displayed below in Figure 3.
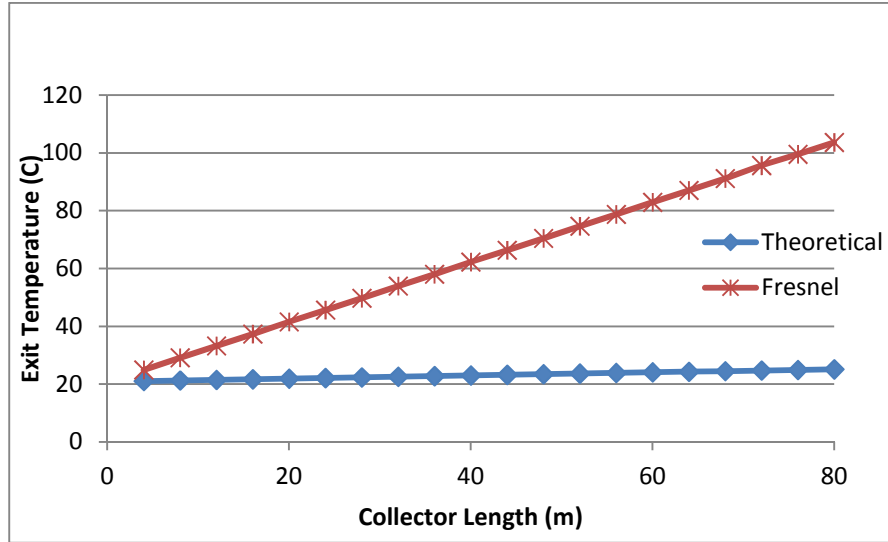
Figure 3: Effects of Collector Lengths

As seen in the previous figure, the Fresnel collector increases the heating performance of the system. The temperature increases at a much higher rate than with a normal solar collector as the length increases. This study estimated a normal solar collector to gain only 0.55 (°C) every ten meters while the Fresnel collector theoretically would experience an exit temperature gain of 10.7 (°C) every ten meters. The Fresnel collector provides larger amounts of heat gain for smaller amounts of material.

2.5 CONCLUSION

Fresnel solar collectors increase the heat transfer to the working fluid. This heat gain can be applied to multifunctional systems in order to generate energy and supply the working fluid for heating and cooling applications. Trigeneration systems have been found to be over 70% efficient while drastically lowering greenhouse gas emissions. A trigeneration system consisting of an array of Fresnel solar collectors, a steam turbine unit, and an absorption chiller are recommended for integration with the existing system.

Industrial Solar Fresnel solar collectors have previously been integrated into existing systems to provide process heating, power generation, and water heating to customers. Their small trough and Fresnel solar collectors are typically used for industrial process heat solar cooling, commercial water heating, and distributed power generation. This apparatus produces exit temperatures from 130°C to 220°C. The Industrial Solar solar collectors are appealing to the eye and may be used as a showpiece for green energy efforts. An array of four of these Fresnel solar collectors was displayed below in Figure 4.

o Length: modular in steps of 4m	o Height: 4m
o Total Width: 7.5m	o Weight: 27 kg/m²
o Aperture Width: 5.5m	o Peak Power: 500 W/m²
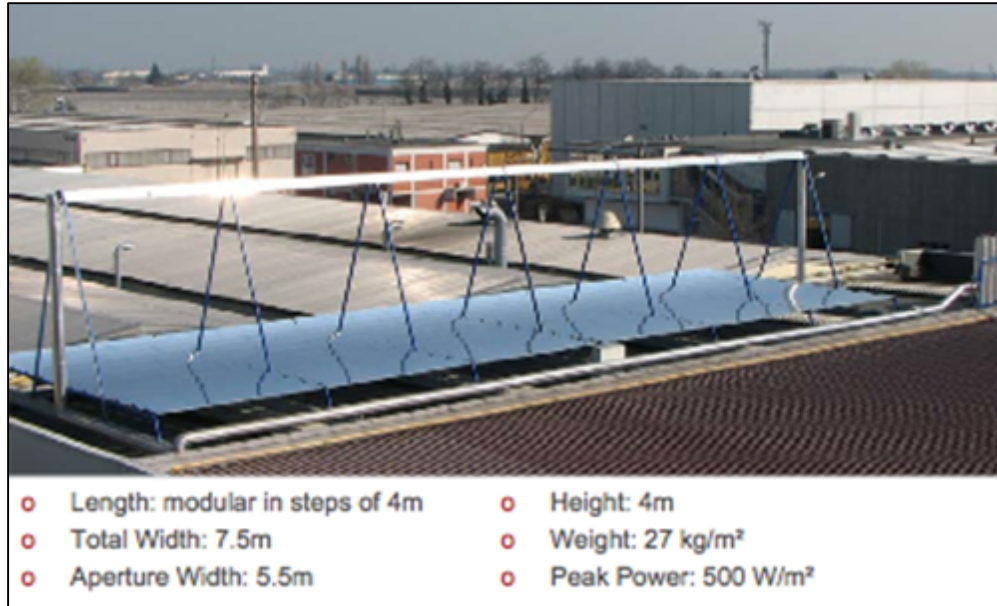
Figure 4: Industrial Solar Fresnel Collector Module *[Zahler]*

The main components that are included with the Fresnel solar collector system are the supporting structure, the primary reflectors, the receiver and control systems for reflector tracking and solar array output. Additional components that are recommended are a performance monitoring package and a hydraulic circuit designed to meet specific applications [12]. It is recommended the Fresnel collectors run with mineral oil as the working fluid to allow peak exit temperatures. This fluid will be able to heat water through a heat exchanger that can power a motor generator. A Coppus Engineering steam turbine unit with a 15 kW Kato synchronous generator may be found from Atlantic Equipment and used with the Fresnel collector.

3. EVACUATED TUBE SOLAR COLLECTORS

3.1 INTRODUCTION

3.1.1 Objective
For this study, the evacuated tube solar collectors are being used to transform energy from the sun into the collectors to produce hot water for the visitor's center at ORNL. This system will work to supplement the hot water system that is already in place at this building. Apricus Solar Hot water solutions is the provider of these solar collectors that will aid in the process of heating the water.

3.1.2 Background
An evacuated tube solar collector takes the sun's energy and transforms that into usable heat. Each evacuated tube is comprised of a heat pipe, surrounded by a glass tube. The air is vacuumed out of the glass tube, minimizing convection, which transfers energy to the pipe more efficiently. An absorber coating is placed on the inside of glass to aid in absorbing sunlight and converting it into heat energy. The tubes are then wrapped completely with a circular insulation to prevent any heat to escape to the ambient air. A cross section of one evacuated tube is shown in Figure 5.
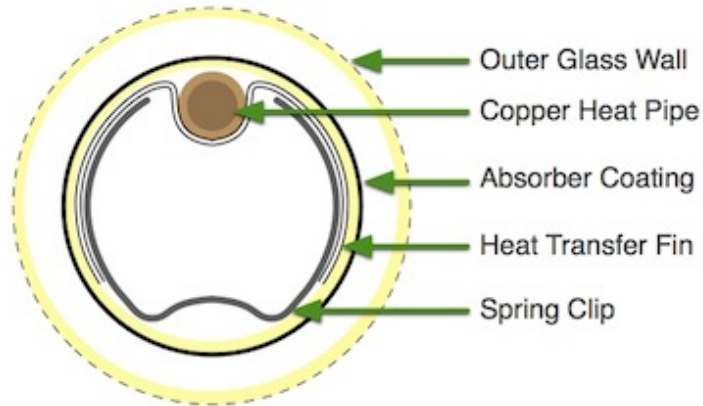
Figure 5: Evacuated Tube Cross-Section

Figure 6 shows the process of the copper heat pipe transferring heat to the working fluid. The air inside the copper heat pipe is removed, thus creating a vacuum, which lowers the waters boiling point so that it requires less energy to heat up the fluid passing through. Once the water inside the pipe reaches its boiling point, the vapor rises to the top. Energy is then moved to the cooler liquid and the condensed vapor falls to the bottom of the pipe, and the whole process is repeated again.
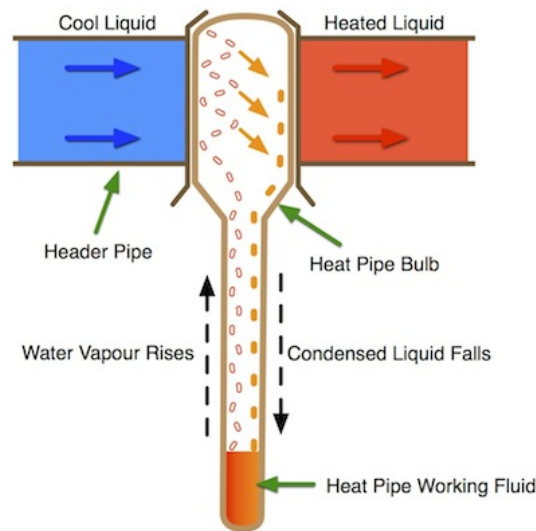
Figure 6: Copper Pipe Heat Flow Diagram

3.2   APPROACH

In this study, the collectors will be set up in a closed loop system. A closed loop system uses a working fluid to transfer energy to water by a brazed plate heat exchanger. Figure 7 shows the entire process of the system. Once the working fluid is heated, it is then passed through a pumping station. The pumping station is linked up to an automated controller that is designed to turn the system on or off depending the time of day or ambient temperature. After the heated working fluid leaves the pumping station, it is then passed through a brazed plate heat exchanger. The fluid passes through the heat exchanger and transfers the heat to the water. The water is finally sent to a hot water tank where it is stored until needed.
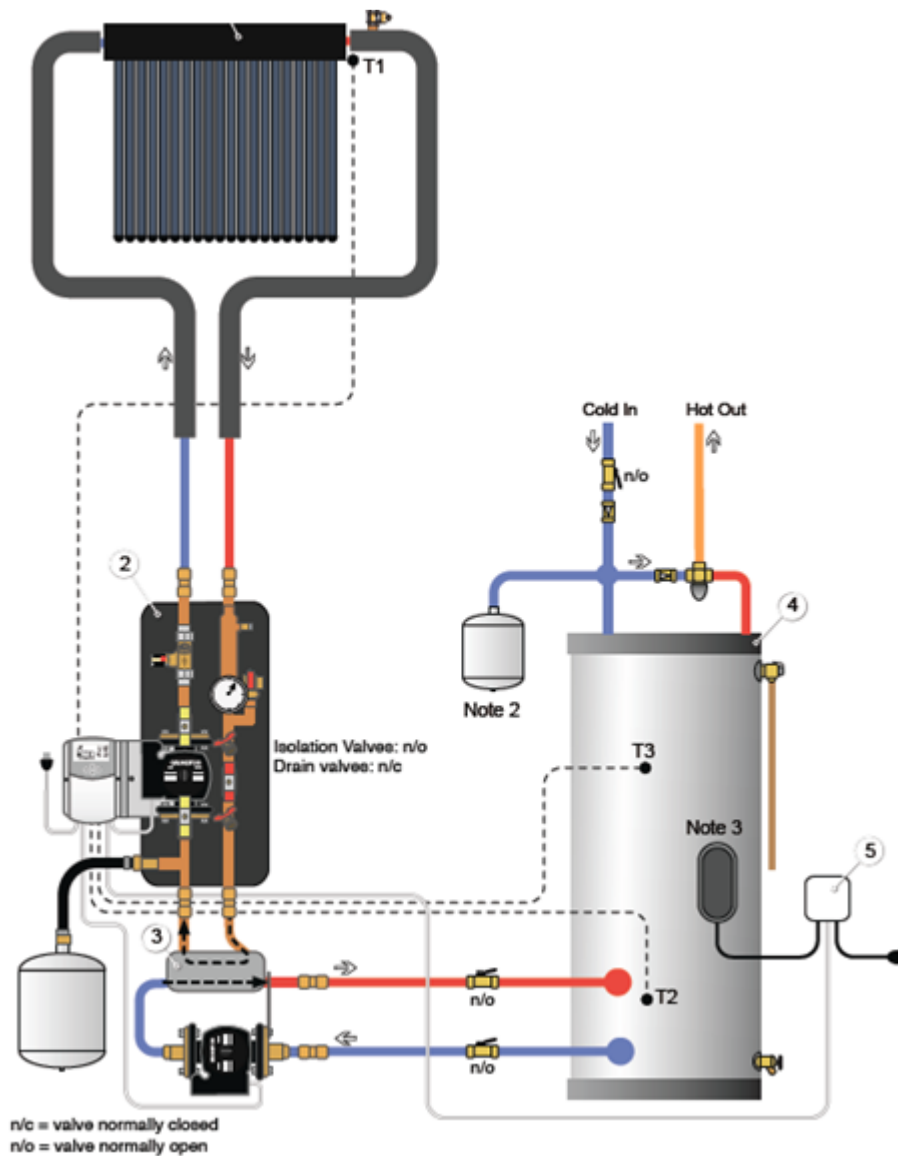
Figure 7: Evacuated Tube Collector System Schematic

The evacuated tube solar collectors will be located on the roof of the visitor's center. Here, the collectors will receive the maximum amount of sunlight without the possibility of something casting a shadow upon them. The other components of the system will be located in the mechanical room, which is on the first floor of the visitor's center behind the kitchen. The view of the visitor's center with the solar collectors on the roof is seen in Figure 8. These solar collectors will be aligned west facing so that they will receive the maximum amount of sunlight per day. They will be alighted in series because this will maximize the amount of hot water they are able to produce.
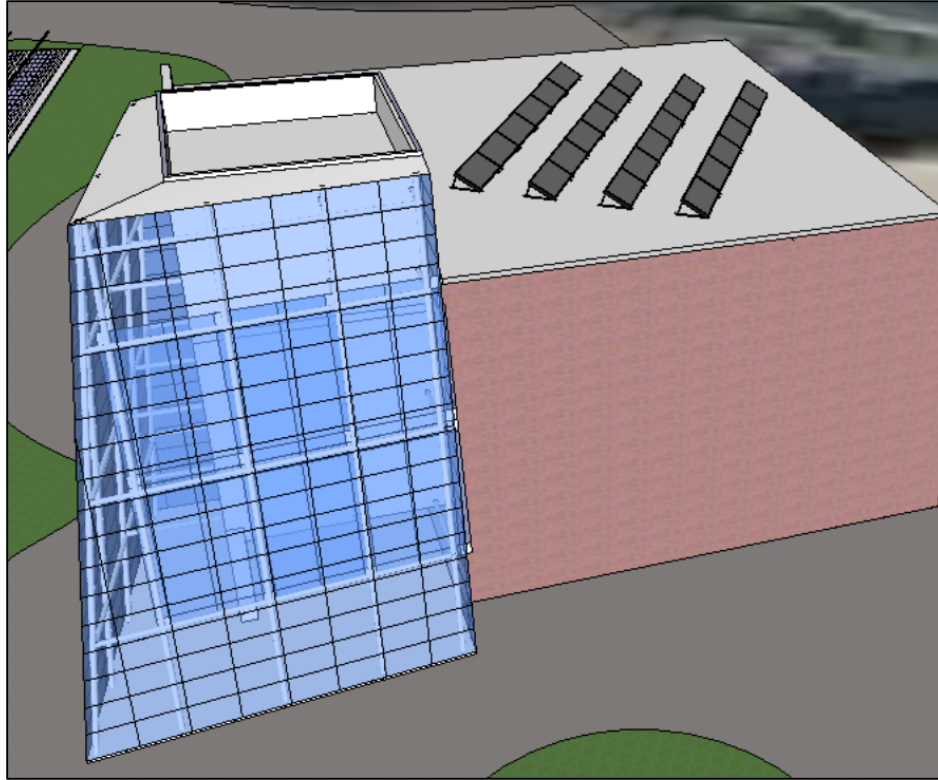
Figure 8: Proposed Placement of Evacuated Tube Solar Collector System on the Roof of the Visitor's Center

3.3   RESULTS

Table 5 details how much water is used annually at the visitor's center. In a year's time, the visitor's center goes through approximately 198,950 gallons of water. This equates to roughly 765 gallons of water each working day.

Table 5: ORNL Visitor's Center Annual Water Usage

Device Type	Floor	Number	Uses/Day	Consumption/Use (Gallons)	Days/Wk	Weeks/Yr	Total (Gallons/Yr)
Toilets	1	14	10	1.6	5	50	56,000
Urinals	1	2	20	1.0	5	50	10,000
Faucets	1	14	20	0.5	5	50	35,000
Hose Bibs	1	4	1	10.0	1	25	1,000
Toilets	2	13	10	1.6	3	25	15,600
Urinals	2	3	20	1.0	3	25	4,500
Faucets	2	12	20	0.5	3	25	9,000
Hose Bibs	2	1	1	10.0	1	25	250
Total Building				26.2			**131,350**

Dishwasher	1	1	1	150.0	5	52	39,000
Faucets	1	15	5	1.0	5	52	19,500
Drink Fountain	1	3	50	0.1	5	52	3,900
Ice Maker	1	2	1	10.0	5	52	5,200
Total Kitchen				161.1			**67,600**
Grand Total							**198,950**

From the output model provide by Apricus, the amount of energy required to heat 765 gallons of water by an average temperature rise of 63 degrees Fahrenheit is 117 kWh, seen below in Table 6. An AP-30 collector, which has 30 evacuated tubes, is able to produce 9 kWh per day (from NASA Surface Meteorology). This means that in order to provide the visitor's center with 100% of the hot water loading in the summer, there needs to be 13 AP-30 collectors in total.

Table 6: Amount of Energy Required to Heat the Daily Water Load by an Average Temperature Rise of 63 Degrees Fahrenheit

Water Vol (US gal)	Temp Rise (oF)	Energy Required	
765	63	101333	kcal
		117.86	kWh
		402127	Btu
		424.28	MJ

To ensure that the maximum amount of sunlight is hitting the collectors they need to be spaced a certain distance apart and at a specific angle. Since the sun is highest in the summer and lowest in the winter months, the collectors should be set at different angles during those times. The angles for the summer and winter months are 21.6 and 68.5 degrees respectively. The spacing for the summer should be set at 22 inches apart and in the winter 141 inches apart.

Each collector weighs approximately 209 pounds and has an area of 47.4 ft^2, which equates to a load of 4.4 lbf/in2. This is well below the loading threshold of the roof membrane, which is approximately 25 lbf/in2.

3.3.1   Bill of Materials

Table 7 shows a brief overview of the bill of materials needed to complete the project. The total price of copper tubing is not calculated due to the fact that the amount of copper to be used is undetermined.

Table 7: Estimated Bill of Materials for the Evacuated Tube Solar Collector System

Part	Description	Price	
Collector	Apricus AP 30 X 13 collectors	7527.00	dollars
Pump	Grundfos UPS 15-58FC	82.00	dollars
Controller	Watts Radiant Solar Control	166.00	dollars
Tank	Using Existing Tank	0	dollars
Expansion Tank	Watts Radiant ETX 30	30.35	dollars
Expansion Tank 2	Watts PLT-12 (Potable Water)	41.85	dollars
Heat Exchanger	Hrale B3-14DW-12-3.0(Dual Wall)	120.00	dollars
Heat Transfer Fluid	Whitlam Solar HI-Temp Dowfrost HD Clairiant SOL HT 5 gallons	219.22	dollars
Piping	Copper or Stainless Steel @ 5 dollars/ foot	5.00	dollars/foot
Check Valve	NSF/CSA Approved 3/4" Valve	20.12	dollars
mixing Valve	NSF/CSA Approved 3/4" Anti-Scald Valve	148.41	dollars
Pressure Relief valve	Watts 3/4" Pressure Relief Valve, 75 psi	87.17	dollars
Pump Station	Temp gague, Automatic Air vent, Coltroller expansion tank and connetion kit, flow setter Pre Plummed and wirel, drain and fill valves	203.00	dollars
Instrumentation	Watts Radiant DPTG-3 Temperature & Pressure Gage	39.55	dollars
Frame	Adjustable Frame X 13 collectors	1599.00	dollars
Total		10288.67	Dollars

This entire system is available Commercial Off The Shelf (COTS) and can be found on the internet or at a local hardware supply store. This is beneficial in that the parts are easy to find in case replacement or maintenance is required.

3.4   CONCLUSION

Solar thermal technology is a great way to transform the suns energy in order to heat water for domestic purposes. This system is a perfect way to lower the visitor's centers yearly energy costs with the instillation of the evacuated tube solar collectors. Once installed, these solar collectors will immediately begin to supplement the hot water loading at the visitor's center. Since these systems require little to no maintenance after installation, they are a perfect way to aid in the production of hot water.

4. TRANSPIRED SOLAR COLLECTOR

4.1 SYMBOLS AND ABBREVIATIONS

Symbols		Description	Units
B	-	Day Correlation Coefficient	(dimensionless)
c_p	-	Specific Heat of Air	(J/kgK)
E	-	Equation of Time	(min)
h_i	-	Heat Transfer Coefficient at i^{th} Location	(W/m²K)
$\bar{h}_L$	-	Average Heat Transfer Coefficient	(W/ m²K)
I_b	-	Beam Radiation	(W/m²)
I_d	-	Diffuse Radiation	(W/m²)
I_N	-	Total Irradiance Normal to Surface	(W/m²)
k_g	-	Thermal Conductance of Glass	(W/mK)
L_{loc}	-	Longitude of Location in Question	(degrees)
L_{st}	-	Standard Meridian for Local Time Zone	(degrees)
L_w	-	Length of Window	(m)
$\dot{m}$	-	Mass Flow Rate of Air Stream	(kg/sec)
n	-	Day of the Year	(dimensionless)
$\overline{Nu}_L$	-	Average Nusselt Number	(dimensionless)
Pr	-	Prandlt Number	(dimensionless)
q_i	-	Rate of Energy at i^{th} Location	(W)
$q_i^{''}$	-	Long Wave Radiation at i^{th} Location	(W/m²)
$q_{o,i}^{''}$	-	Short Wave Radiation at i^{th} Location	(W/m²)
R_b	-	Ratio of Beam Radiation	(dimensionless)
Re_L	-	Reynolds Number	(dimensionless)
$Re_{x,c}$	-	Critical Reynolds Number	(dimensionless)
T_i	-	Temperature at i^{th} Location	(K)
W_w	-	Width of Window	(m)
α_i	-	Absorptivity at i^{th} Location	(dimensionless)
A_i	-	Absorbed Short Wave Radiation at i^{th} Pane	(dimensionless)
β	-	Slope of Surface in Question	(degrees)
δ	-	Declination Angle	(degrees)
Δ_g	-	Thickness of Glass Pane	(m)
ε_i	-	Emissivity at i^{th} Location	(dimensionless)
θ	-	Angle of Incidence	(degrees)
θ_z	-	Zenith Angle	(degrees)
ρ_i	-	Reflectivity at i^{th} Location	(dimensionless)
τ_i	-	Transmissivity at i^{th} Location	(dimensionless)
$\square$	-	Latitude of Location in Question	(degrees)
ω	-	Hour Angle	(degrees)

4.2   INTRODUCTION

4.2.1   Objective

The envelope of "The Lantern" is extremely inefficient in terms of the required cooling and heating loads. In order to comply with the Department of Energy's current mandate to reduce energy consumption, new energy efficient building systems must be implemented. It is proposed that "The Lantern" be retrofitted with a transpired solar collector (TSC).

4.2.2   Background

The primary goal of the TSC is to reduce the rate of heat transfer at the envelope of the building. The secondary goal of the TSC is to use the air stream flowing through the cavity to capture energy that would otherwise be unused. This energy is then used to preheat make-up air in the cooler months and preheat potable water in the warmer months. The TSC is proposed to be constructed on the interior of building, so that the existing structural elements and single pane window system (SPWS) can be reused. In order to determine the viability of retrofitting "The Lantern", a model was designed to determine the overall loading based on the existing SPWS and the proposed TSC. A general schematic of a TSC is presented in
Figure 9.
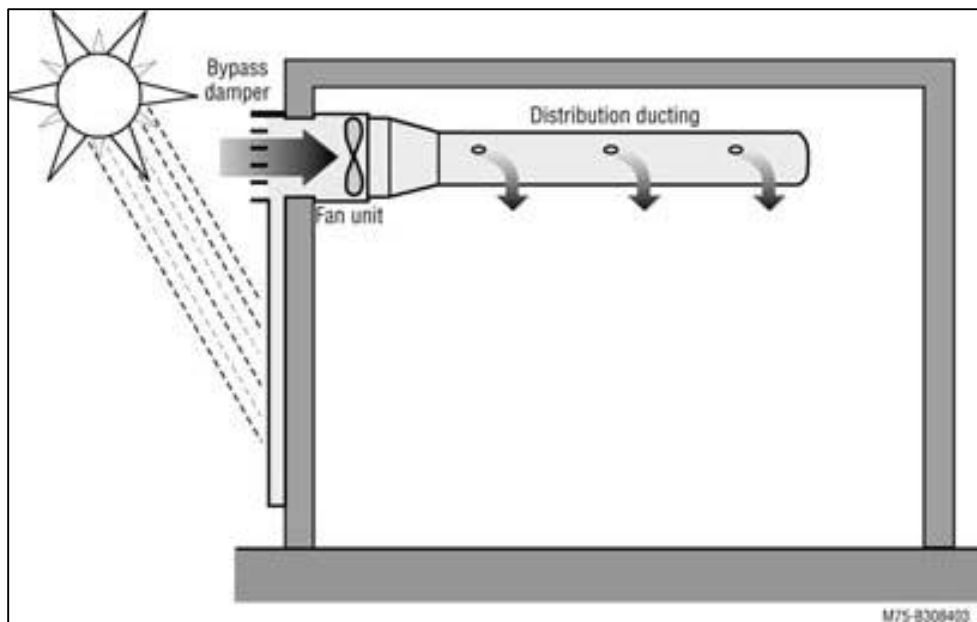
Figure 9: General Schematic of Transpired Solar Collector.
Figure from www.oregon.gov

4.3   MODELING

Modeling the TSC required the integration of two separate models. The first model was designed to calculate the total solar irradiance normal to each exterior surface of the building as a function of time. The second model utilized the calculated irradiance to determine the total rate of heat transfer into "The Lantern" for both the existing SPWS and the proposed TSC. The combination of these two models allowed for the generation of monthly cooling and heating loads for both existing and proposed scenarios.
The total solar irradiance normal to a surface was calculated as a function of standard time. All sun-angle relationships require the use of solar time, so it was necessary for standard time to be

converted into solar time. Equations (4.1-4.3) were used for the conversion of standard time into solar time.

$$B = (n-1)\frac{360}{365} \tag{4.1}$$

$$E = 229.2(0.000075 + 0.001868\cos B - 0.032077\sin B \\ -0.014615\cos 2B - 0.04089\sin 2B) \tag{4.2}$$

$$solar\ time = standard\ time + 4(L_{st} - L_{loc}) + E \tag{4.3}$$

The earth rotates at a rate of 15° per hour, thus it is necessary to define the angular displacement of the sun relative to the plane created by the local meridian. The hour angle is used to define such an angular displacement and was determined using Equation (4.4).

$$\omega = 15(solar\ time - 12) \tag{4.4}$$

The declination angle is used to define the angular displacement of the sun relative to the plane created by the equator and was found using Equation (4.5).

$$\delta = 0.006918 - 0.399912\cos B + 0.070257\sin B \\ -0.006758\cos 2B + 0.000907\sin 2B \\ -0.002679\cos 3B + 0.00148\sin 3B \tag{4.5}$$

The angle between the beam radiation on a surface and the normal to that surface is defined as the angle of incidence and was calculated using Equation (4.6).

$$\cos\theta = \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma \\ + \cos\delta\cos\phi\cos\beta\cos\omega + \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega \\ + \cos\delta\sin\beta\sin\gamma\sin\omega \tag{4.6}$$

The zenith angle is defined as the angle of incidence of beam radiation on a horizontal surface and was determined using Equation (4.7).

$$\cos\theta_z = \cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta \tag{4.7}$$

The total irradiance normal to a surface was found using Equations (4.8) and (4.9).

$$R_b = \frac{\cos\theta}{\cos\theta_z} \tag{4.8}$$

$$I_N = I_b R_b + I_d\left(\frac{1+\cos\beta}{2}\right) \tag{4.9}$$

The beam and diffuse radiation data was sourced from EnergyPlus and imported into a MATLAB program. The program utilized Equations (4.1-4.9) to calculate the total irradiance normal to the north and west surfaces of "The Lantern" for 8760 hours of a typical year [2].

The rate of heat transfer into "The Lantern" was modeled using basic energy balances. The heat transfer model was divided into two phase in order to calculate the loading for both the existing

SPWS and the proposed TSC. The first phase of the model was designed to handle the loading aspects of the SPWS. Figure 10 shows the energy diagram of the SPWS.
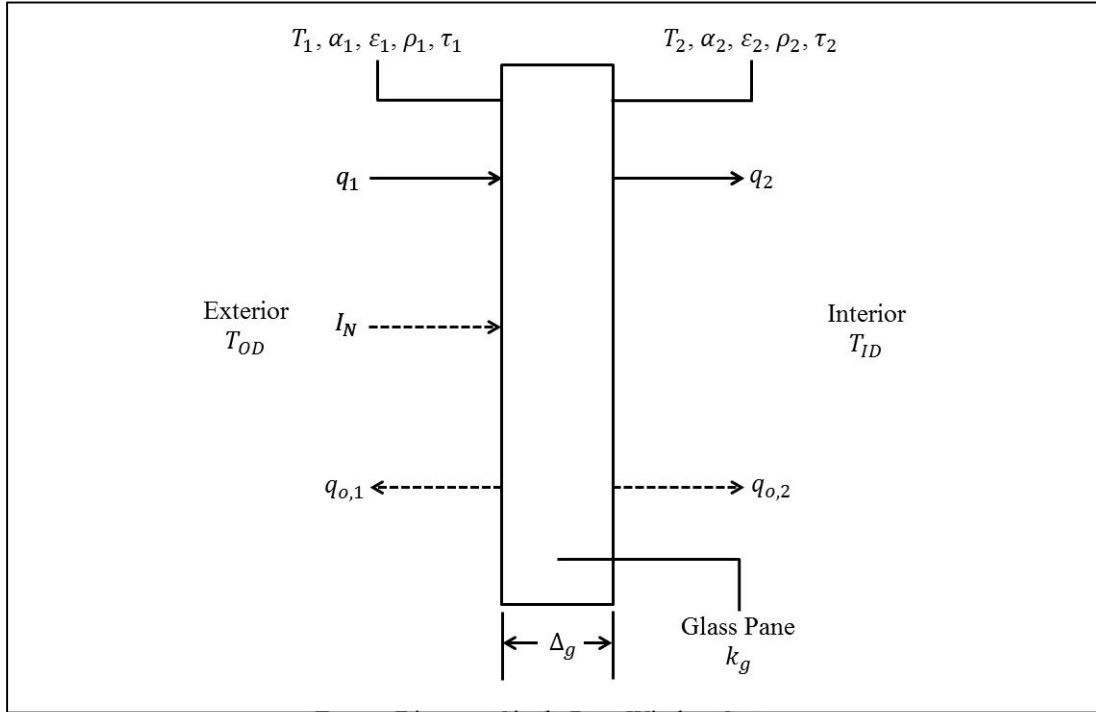
Figure 10: Energy Diagram of a Single Pane Window

Equations (4.10) and (4.11) were derived by performing an energy balance of the short wave radiation using the envelope of the pane as a control volume.

$$\begin{bmatrix} q_{o,1}'' \\ q_{o,2}'' \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} \rho_1 \\ \tau_1 \end{bmatrix} \tag{4.10}$$

$$A_1 = \alpha_1 \tag{4.11}$$

Equations (4.12-4.15) were derived by performing an energy balance of the total radiation using the exterior surface of the pane as a control surface and the envelope of the pane as a control volume.

$$q_1'' = h_{ext}(T_{OD} - T_1) \tag{4.12}$$

$$q_2'' = h_{int}(T_2 - T_{ID}) \tag{4.13}$$

$$T_1 = T_{OD} + \frac{I_N(1 - q_{o,1}'' - q_{o,2}'') - h_{int}(T_2 - T_{ID})}{h_{ext}} \tag{4.14}$$

$$T_2 = T_1 - \frac{\Delta_g}{2k_g}(I_N A_1 + 2q_1'') \tag{4.15}$$

The heat transfer coefficients were calculated in accordance to ISO-15099 standards. Equations (4.12-4.15) required the use of Gauss-Seidel iterative techniques. The solar heat gain coefficient (SHGC) was calculated using Equation (4.16).

$$SHGC = q_{o,2}'' + \frac{q_2''(I_N=0) - q_2''(I_N \neq 0)}{I_N} \tag{4.16}$$

The total rate of heat transfer through the SPWS was found using Equation (4.17).

$$q_{tot} = L_w W_w (q_{o,2}'' + I_N SHGC) \tag{4.17}$$

The second phase of the model focused on the proposed TSC which was also modeled using Equations derived from energy balances. Figure 11 shows the energy diagram of the TSC.
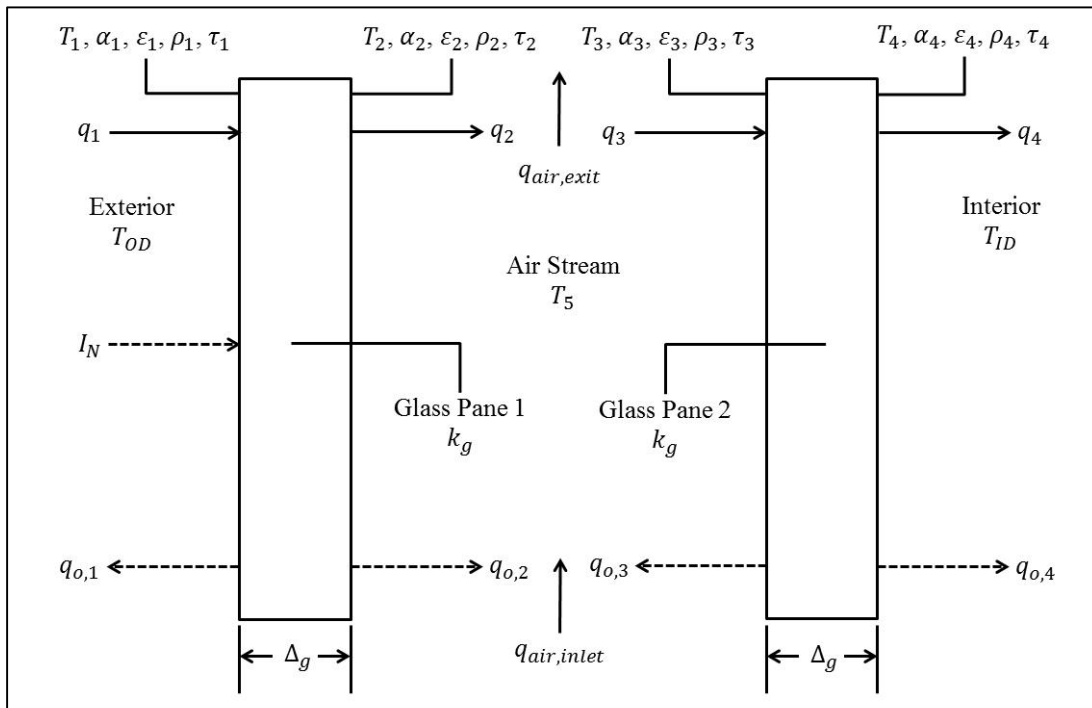
Figure 11: Energy Diagram of Transpired Solar Collector

The radiometric properties for the TSC were calculated by performing energy balances of the short wave radiation using the envelope of each pane of glass as a control volume. Equations (4.18-4.20 show the combined results of the energy balances.

$$\begin{bmatrix} q_{o,1}'' \\ q_{o,2}'' \\ q_{o,3}'' \\ q_{o,4}'' \end{bmatrix} = \begin{bmatrix} 1 & 0 & -\tau_1 & 0 \\ 0 & 1 & -\rho_2 & 0 \\ 0 & -\rho_3 & 1 & 0 \\ 0 & -\tau_2 & 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} \rho_1 \\ \tau_1 \\ 0 \\ 0 \end{bmatrix} \tag{4.18}$$

$$A_1 = \alpha_1 + \alpha_2 q_{o,3}'' \tag{4.19}$$

$$A_2 = \alpha_3 q_{o,2}^{''} \tag{4.20}$$

Equations (4.21-4.26) represent the long wave radiation components derived by performing energy balances of the total radiation using the exterior surface of each pane as a control surface, the envelope of each pane as a control volume and the air stream as a control volume.

$$q_1^{''} = h_{ext}(T_{OD} - T_1) \tag{4.21}$$

$$q_2^{''} = h_{for,cav}(T_2 - T_5) + h_{rad,cav}(T_2 - T_3) \tag{4.22}$$

$$q_3^{''} = h_{for,cav}(T_5 - T_3) + h_{rad,cav}(T_2 - T_3) \tag{4.23}$$

$$q_4^{''} = h_{int}(T_4 - T_{ID}) \tag{4.24}$$

$$q_{air,inlet} = \dot{m}c_p T_{OD} \tag{4.25}$$

$$q_{air,exit} = \dot{m}c_p T_5 \tag{4.26}$$

Equations (4.27-4.31) represent the temperatures at each location and are a product of the previously mentioned energy balances.

$$T_1 = T_{OD} + \frac{I_N(1 + q_{o,3}^{''} - q_{o,1}^{''} - q_{o,2}^{''})}{h_{ext}} - \frac{h_{for,cav}(T_2 - T_5) + h_{rad,cav}(T_2 - T_3)}{h_{ext}} \tag{4.27}$$

$$T_2 = T_1 - \frac{\Delta_g}{2k_g}(I_N A_1 + 2q_1^{''}) \tag{4.28}$$

$$T_3 = \frac{I_N(q_{o,2}^{''} - q_{o,3}^{''} - q_{o,4}^{''})}{h_{for,cav} + h_{rad,cav}} + \frac{h_{for,cav}T_5 + h_{rad,cav}T_2}{h_{for,cav} + h_{rad,cav}} - \frac{h_{int}(T_4 - T_{ID})}{h_{for,cav} + h_{rad,cav}} \tag{4.29}$$

$$T_4 = T_3 - \frac{\Delta_g}{2k_g}(I_N A_2 + 2q_3^{''}) \tag{4.30}$$

$$T_5 = \frac{\dot{m}c_p T_{OD} + h_{for,cav}L_w W_w(T_2 + T_3)}{\dot{m}c_p + 2h_{for,cav}L_w W_w} \tag{4.31}$$

The interior and exterior heat transfer coefficients were calculated in accordance with ISO-15099 standards. The heat transfer between the two panes was treated as parallel flow over a flat plate after initial calculations revealed that the two boundary layers would not meet using the proposed dimensions. Equations (4.32) and (4.33) represent the forced convection heat transfer correlations used for laminar and mixed boundary layer flow respectively [4].

$$\overline{Nu}_L \equiv \frac{\overline{h}_L L}{k} = 0.664 Re_x^{1/2} Pr^{1/3} \tag{4.32}$$

$$\overline{Nu}_L \equiv \frac{\overline{h}_L L}{k} = (0.037 Re_L^{4/5} - 0.037 Re_{x,c}^{4/5} - 0.664 Re_{x,c}^{1/2}) Pr^{1/3} \tag{4.33}$$

The solar heat gain coefficient for the TSC was determined using Equation (4.34).

$$SHGC = q_{o,4}'' + \frac{q_4''(I_N=0) - q_4''(I_N \neq 0)}{I_N} \qquad (4.34)$$

The total rate of heat transfer through the TSC was found using Equation (4.35).

$$q_{tot} = L_w W_w (q_{o,4}'' + I_N SHGC) \qquad (4.35)$$

The rate of energy captured by the air stream was calculated using Equation (4.36).

$$q_{exit} = \dot{m} c_p (T_5 - T_{OD}) \qquad (4.36)$$

Using these equations and the generated solar irradiance data, a MATLAB program was created to generate the hourly cooling and heating loads for the north and west surfaces of "The Lantern" based on both the existing SPWS and the proposed TSC.

4.4   RESULTS

Each phase of the model was individually benchmarked in order to validate the model as a whole. The solar irradiance phase of the model was benchmarked against EnergyPlus data generated for the Department of Energy's Solar Decathlon house, also known as "Living Light". The data generated by the model proved to be very accurate between the hours of 8:00 A.M. to 4:00 P.M. The data generated outside those bounds proved to be inconsistent when compared to EnergyPlus data. These inconsistencies were expected because the model was designed based upon relatively simple equations that were unable to handle the effects of sunrise and sunset. The heat transfer phase of the model was benchmarked via LBNL's WINDOW 6.3. The SPWS portion of the model produced very accurate data when compared to the WINDOW 6.3 data. The TSC portion of the model was benchmarked indirectly, as WINDOW 6.3 does not provide TSC data. Initially, the TSC was treated as a double pane window system and the span between the panes was modeled as an enclosure utilizing natural convection. The double pane window system data generated by the model proved reliable in comparison to the WINDOW 6.3 data, thus validating the governing equations used in the model. Only minor changes were required to treat the span between the panes as an air stream, therefore the data produced by the TSC portion of the model should prove reliable.

The data generated by the model is based on two key assumptions: 1) the existing SPWS was treated as monolithic clear glass, and 2) the interior pane of the TSC was treated as glass with a standard glazing. The first of these two assumptions was made because the properties of the existing SPWS were unknown. The second assumption was based off the thought that a glazing on the interior pane would help guide more energy into the air stream and reduce the penetration of the short wave radiation into "The Lantern". Figure 12 illustrates the monthly loading for "The Lantern" based on both the existing SPWS and the proposed TSC.
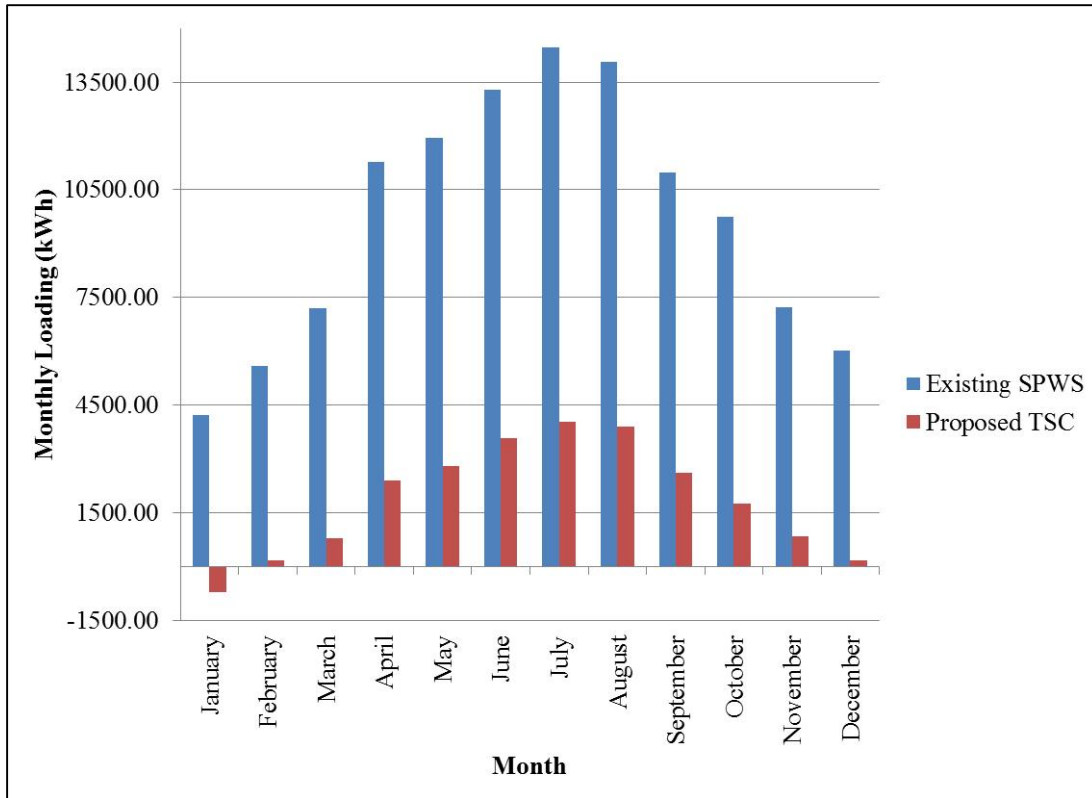
Figure 12: Monthly Loading for "The Lantern" Based on Existing Single Pane Window System and Proposed Transpired Solar Collector

The monthly loading illustrated in Figure 12 is based on a combined surface area of 184.5 m² and a distance of approximately 20 cm between the exterior and interior panes of the TSC. The implementation of the proposed TSC potentially yields an annual reduction of 92,221.8 kWh. Based upon the average rate of 0.10 $/kWh, this reductions translates into an annual savings of $9,221.18. It is noted that no conversion for HVAC efficiency was used (COP of 1). In addition to the reduction in the overall loading, the TSC captures a significant amount of energy. Table 8 shows the monthly energy captured by the air stream operating at a velocity of 1.22 m/s (Re_L of 750,000).

Table 8: Monthly Energy Captured by Air Stream

Month	Energy Captured by Air Stream (kWh)
January	2241.9
February	1677.2
March	1473.0
April	1060.6
May	851.7
June	486.4
July	380.1
August	380.8
September	760.2
October	1227.4
November	1420.6
December	1774.9

As configured, the air stream used by the TSC captures 13,734.7 kWh of energy annually which could be used to preheat make-up air in the cooler months and preheat potable water in the warmer months. It is noted that the velocity of the air stream had very little effect on the overall loading of "The Lantern". For small velocities (less than 2 m/s), the loading change was negligible and the energy captured by the air stream was proportional to the velocity. Based on these findings, the addition of the proposed TSC to "The Lantern" would yield an excellent reduction in annual energy costs and help facilitate ORNL's compliance with the Department of Energy's energy reduction mandate.

4.5   CONCLUSION

Retrofitting "The Lantern" with a TSC would greatly improve the overall efficiency of the building envelope. Implementing the proposed TSC has the potential to reduce annual energy expenses by $9,221.18 while providing the additional benefits of preheating make-up air and potable water. The projected cost of the retrofit is unknown at the present time. The system was designed to be integrated with the current structural elements and SPWS, therefore the overall design was aimed at minimizing costs. In order to improve the accuracy of the model, the properties of the existing glass need to be obtained. Further research is also needed to fully understand the effects of changes in the air stream velocity. In conjunction with the proposed research, there may be a possibility to improve the efficiency of the TSC by venting interior air through the cavity during the cooler months. Although the efficiency of the TSC is not yet maximized, its current state still warrants careful consideration. In closing, the benefits illustrated by the model suggest retrofitting "The Lantern" with a TSC to be a viable option.

5. SOLAR DECATHLON DATA ACQUISITION

5.1 SYMBOLS AND ABBREVIATIONS

Symbol	Description	Units
A_{plate}	Area of the Plate	m^2
A_{window}	Area of the Window	m^2
F_{plate}	View Factor	----------
P_r	Prandlt Number	----------
$Q_{conduction}$	Conduction Heat Transfer	W/m^2
$Q_{convection}$	Convection Heat Transfer	W/m^2
$Q_{radiation}$	Radiation Heat Transfer	W/m^2
R_a	Rayleigh Number	----------
$t_{insulation}$	Thickness of the EPS Insulation	m
ε_{plate}	Emissivity of the Plate	----------
ε_{window}	Emissivity of the Window	----------
$\propto$	Absorptivity of the Plate	----------
g	Gravitational Constant	m/s^2
H	Height of the Plate	m
h	Convection Heat Transfer Coefficient	W/m^2-K
k	Thermal Conductivity	W/m-K
L	Length of Plate	m
Nu	Nusselt Number	----------
T_x^*	Temperature	K
ν	Kinetic Viscosity of the Air	m^2/s
β	$1/T_{air}$	K^{-1}
σ	Stephan-Boltzmann Constant	W/m^2K^4

5.2 INTRODUCTION

5.2.1 Objective

In order to validate current and future programs which analyze the heat transfer through a window system, a data acquisition system was setup at the University of Tennessee's Solar Decathlon house to study the double-skin façade with and without blind attachments. In the future, the data and knowledge obtained from the Solar Decathlon house will benefit the university, manufactures, and research partners.

5.2.2 Background

The UT Solar Decathlon house, named "Living Light", was created in order to compete in the 2011 Department of Energy Solar Decathlon. The competition vests multiple colleges against each other to design and build solar-powered homes that are energy efficient, attractive, and cost-efficient. A picture of the Living Light is shown below in Figure 13. The Living Light house is currently located on the agriculture campus at University of Tennessee in Knoxville, TN. In its current location, the window system on one side of the house faces South-West while the opposing side faces North-East.

Figure 13: The University of Tennessee 2011 Solar Decathlon House

The house consists of a roof-top photovoltaic system, a home automation system, an efficient water system, a double façade window system, and an HVAC system which makes use of an energy recovery ventilator. This study focused on the double façade window system, as it is very similar to the system proposed for the visitor's center at ORNL. The double façade window system also contains automated blinds to control the amount of light and heat allowed through the windows. A detailed sketch of the double façade window system is shown in Figure 14.
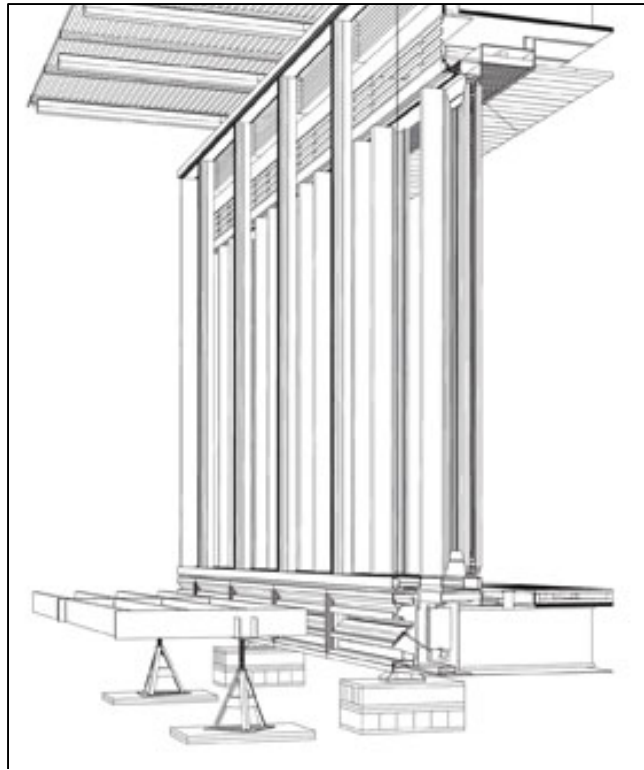
Figure 14: Double Facade Window System Detail [7]

5.3   INSTRUMENTATION SETUP

The data acquisition system at the Solar Decathlon house is partitioned into 4 different sections: the interior of the house, the South-West window façade, the North-East window façade, and a weather station located outside. The center of the data acquisition system is an Obvius Acquisuite data acquisition server housed in a NEMA enclosure at the base of the weather station. A detailed list of the equipment used in the data acquisition system can be found in Appendix X.

5.3.1   Weather Station System

The weather station is located at the east corner of the Living Light house. The weather station collects exterior ambient data and consisted of a pyrgeometer, two pyranometers, an ambient air temperature sensor, a relative humidity sensor, and a wind speed and direction sensor. The pyrgeometer measures the atmospheric infra-red radiation. One of the pyranometers is placed horizontally on top of the weather station to measure the solar irradiance of atmospheric air. The other pyranometer is placed vertically in front of the South-West facing window instrumentation in order to measure the solar irradiance reaching the window. The sensors are connected to an Obvius Flex IO input module which is connected via RS-485 to the Acquisuite.

5.3.2   South-West and North-East Window Facades

The instrumentation in the South-West and North-East double façade window systems is setup symmetrically. For the purpose of this study, the blinds were completely retracted to the top of the cavity. In the future, once a baseline data sample has been collected, data will be collected with the blinds at various positions and angles. This will be very useful in gaining an understanding of the effect of blinds on double façade window systems. Each window system consists of eight T-Type thermocouples placed

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strategically in the window cavity to facilitate the calculation of the temperature differences and convection heat transfer coefficients. T-Type thermocouples (copper-constantin) are rated for -200 to 350 °C. Reflective cones placed around the end of the thermocouple nodes minimized the radiation heat transfer to the thermocouple. In each window system, the thermocouples are connected to an Advantech ADAM analog thermocouple input module. The ADAM is connected to an Obvius Modhopper transmitter which wirelessly transmits the data to the Modhopper connected to the Acquisuite in the weather station enclosure. The approximate placement of the thermocouples is shown in Figure 15.
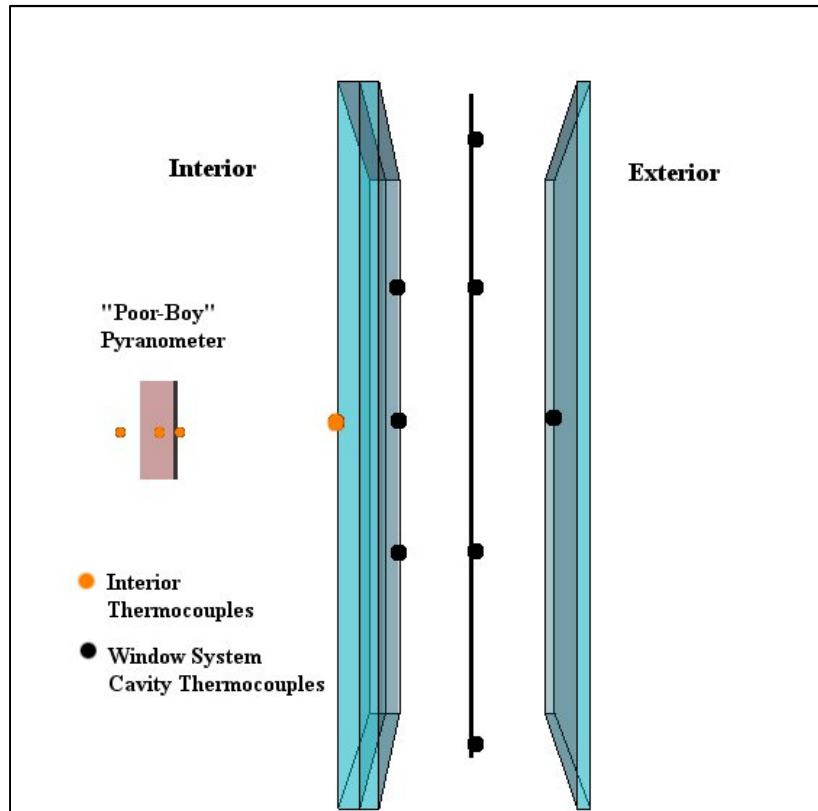
Figure 15: Interior and Window Cavity Thermocouple Setup

5.3.3   Interior
The interior data acquisition consists of two "Poor-Boy" pyranometers and two thermocouples. The "Poor-Boy" pyranometers are a proven, cost-effective method of measuring solar irradiance. Each of the thermocouples is connected to the interior glass on the South-West and North-East facing windows halfway up the glass. There are three thermocouples in each "Poor-Boy" pyranometer system which aid in the calculation of the solar irradiance through the double façade window system. The eight total thermocouples are connected to an interior ADAM module which is connected to a Modhopper wireless transmitter.

5.3.4   Acquisuite Server
The Acquisuite server uses Modbus protocol to communicate between the various data acquisition modules in the system. The server is connected via Ethernet to a computer within the Solar Decathlon house. The Acquisuite samples data at a rate of 10Hz and outputs a log of the average value for each device every 15 minutes. Every 24 hours the data is uploaded to the computer via File Transfer Protocol (FTP). The computer is connected to a Dropbox account which updates and uploads the data automatically. This allows the data to be reviewed or downloaded from anywhere with internet access.

Figure 16 shows the communication and power links between the various Modbus devices.
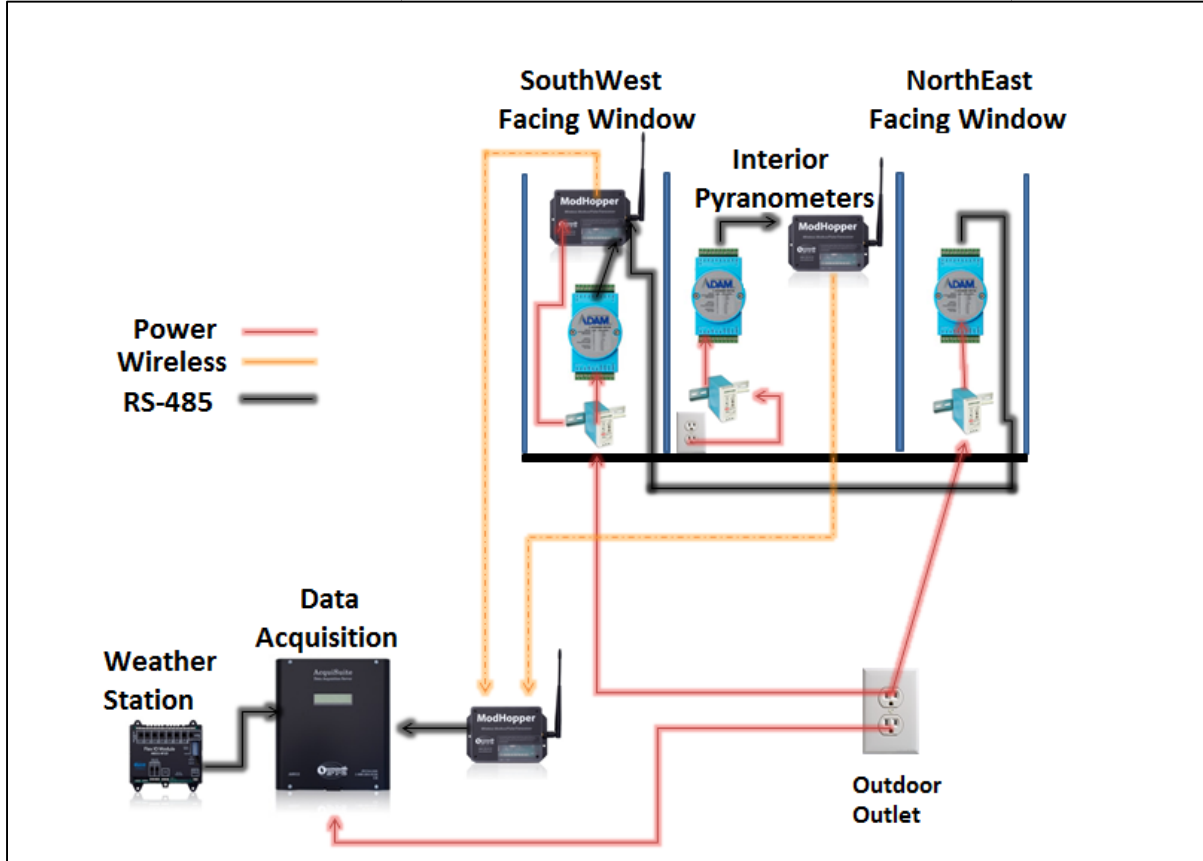
Figure 16: Solar Decathlon House Instrumentation Communication and Power Setup

5.4 DATA REDUCTION

Sensors such as the pyrgeometer and the pyranometers require the outputted data to be further reduced. The full calculations for the data reduction procedure, as well as the data import procedure, can be found in Appendix C. Figure 17 illustrates the heat transfer energy balance used to calculate the irradiance on the "Poor-Boy" pyranometer. The symbols and abbreviations for these calculations are found in Section 5.1. All constants were taken at the temperature of the air inside the Solar Decathlon House.

*Where x is the temperature of the air, plate, insulation, or window
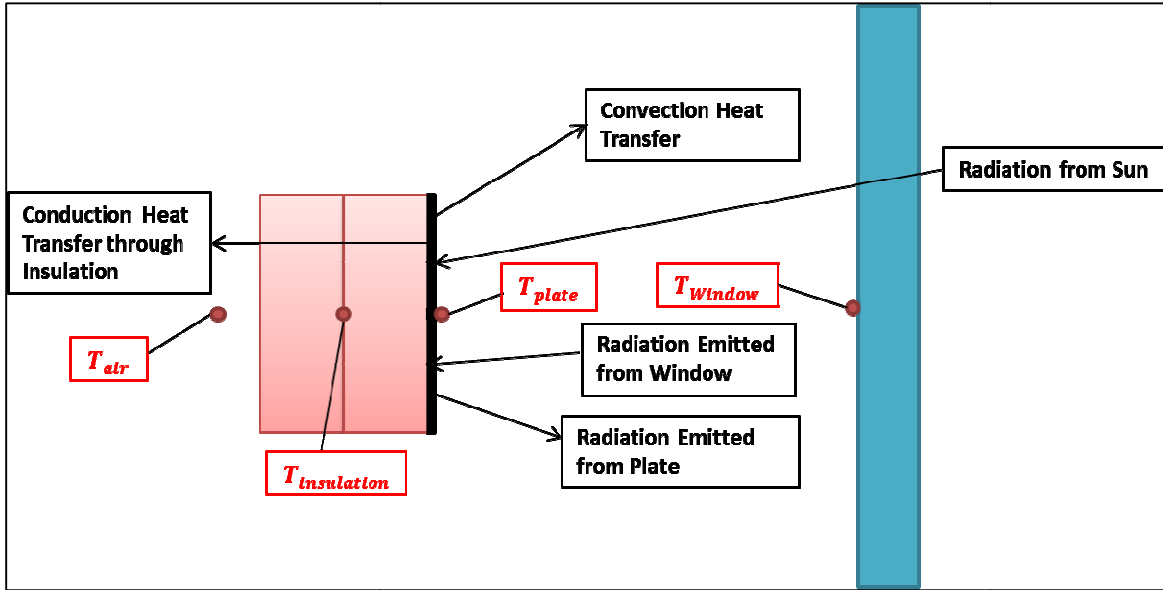
Figure 17: "Poor-Boy" Pyranometer Energy Balance Diagram

The first step in calculating the irradiance through the double façade window system was to sum the radiation, convection, and conduction heat transfer. The radiation heat transfer is summed in Equation (5.1).

In order to calculate the radiation heat transfer, the view factor,   , was calculated. The view factor is defined as the fraction of radiation leaving surface the window that is intercepted by surface of the plate [3]. The view factor was calculated using the Hottel's Cross-String Method [8] which is defined in Equations (5.2) and (5.3). Figure 18 illustrates the dimensions used in Equation (5.2).

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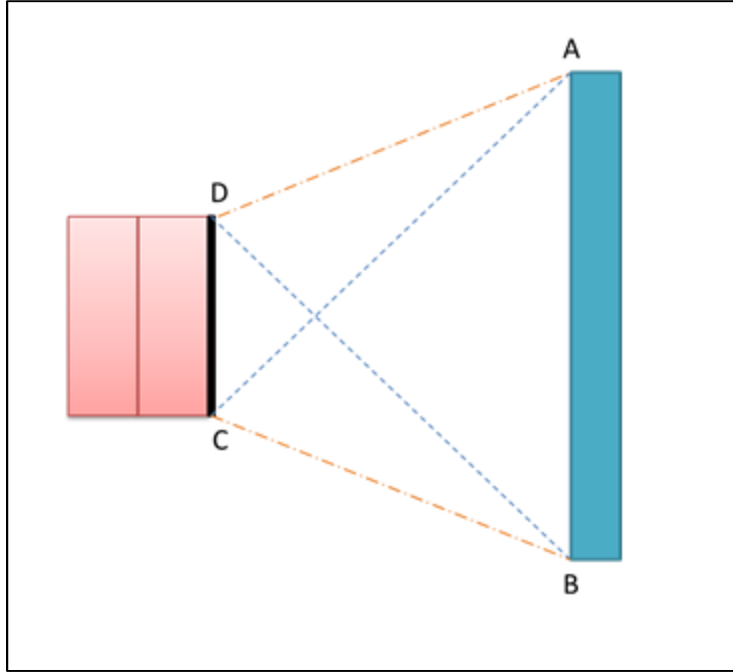
Figure 18: Hottel's Cross-String Method for Calculating View Factor

Computation of the natural convection heat transfer required calculation of the Rayleigh and Nusselt number as shown in Equations (5.4) and (5.5). The Nusselt number was calculated using the correlation from Icropera for a vertical plate in laminar flow.

$$R_a = \frac{g\beta(T_{air} - T_{plate})H^3}{\alpha * v} \tag{5.4}$$

$$Nu = \frac{hL}{k} = \left\{ 0.68 + \frac{0.670 R_a^{1/4}}{\left[1 + \left(\frac{0.492}{P_r}\right)^{\frac{9}{16}}\right]^{4/9}} \right\} \tag{5.5}$$

The convection heat transfer coefficient was then computed using Equation (4.6) from which the convection heat transfer was determined using Equation (5.7).

$$h = \frac{Nu * k}{L} \tag{5.6}$$

$$Q_{convection} = hA_{plate}(T_{air} - T_{plate}) \tag{5.7}$$

The conduction heat transfer through the extruded polystyrene (EPS) insulation was found using Equation (5.8).

$$Q_{conduction} = \frac{kA_{plate}[T_{plate} - T_{insulation}]}{t_{insulation}} \tag{5.8}$$

Equation (5.9) shows the calculation of the irradiation through the window, reaching the plate.

$$I = \frac{Q_{conduction} - Q_{convection} - Q_{radiation}}{\propto A_{plate}}$$ (5.9)

5.5   CONCLUSION

Due to the relatively neoteric trend of creating energy efficient building technology, as well as the competitive nature of the industry, there is a large lack of data regarding these technologies. The data acquisition system currently setup at the 2011 Solar Decathlon House will provide invaluable information regarding the heat transfer through a double façade window system as well as other characteristics of the energy efficient systems in the house. The data acquired will be used to validate future computer models. This information will largely benefit the University of Tennessee and research partners such as the Oak Ridge National Lab.

6.   CONCLUSION AND RECOMMENDATIONS

The main objective of this study was to determine a feasible retrofit for the Oak Ridge National Laboratory's visitor center. Fresnel solar collectors, evacuated tube collectors, transpired solar collector, and the data acquisition system were all an integral part of this retrofit. The Fresnel collectors will offset "The Lantern's" energy costs with steam turbine generator providing electricity to the building. The absorption chiller integrated with the Fresnel collectors provides the working fluid for the building's existing HVAC system. The evacuated tube solar collectors located on the roof of the building will heat potable water without any additional energy source.   The addition of the TSC collectors it will decrease the amount of energy required to cool the building in the summer months. The data acquisition system was a viable tool needed in this study to benchmark the TSC system. The collected data played a very important role in determining the heat transfer through the window system in "The Lantern", and will continue to be a viable resource in the future as a validation for computer models.

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APPENDIX A. FRESNEL SOLAR COLLECTOR SYSTEM SIMULATION MATLAB CODE

```matlab
function Output = FresnelCollector
global A
% General Variables
A.Ecc = 0; % Eccentricity of the tubes
A.Eta = 1;
A.FlowRate = 5; % Volumetric flow rate of working fluid (gpm)
A.G = 9.81; % Gravity (m/s^2)
A.I = 20000; % Global horizontal irradiance
A.NumSeg = 10;
A.Relax = 0.001;
A.Sigma = 5.67E-8; % Stefan-Boltzmann coefficient
A.WindVel = 5; % (m/s)

% Dimensions
A.DiaOne = 0.05; % Glass tube outside diameter (m)
A.DiaTwo = 0.04; % Glass tube inside diameter (m)
A.DiaThree = 0.025; % Copper tube outside diameter (m)
A.DiaFour = 0.015; % Copper tube inside diameter (m)
A.L = 4; % Tube Length (m)

% Surface Areas
A.AreaOne = pi*A.DiaOne*A.L; % Glass tube outside surface area (m^2)
A.AreaTwo = pi*A.DiaTwo*A.L; % Glass tube inside surface area (m^2)
A.AreaThree = pi*A.DiaThree*A.L; % Copper tube outside surface area (m^2)
A.AreaFour = pi*A.DiaFour*A.L;

% Temperatures
A.TOD = 308; % Outdoor temperature (K)
A.TSky = 308; % Sky temperature (K)

% Glass Properties
A.AbsG = 0.076;
A.EmisG = 0.076; % Emissivity of glass
A.KG = 0.917;
A.RG = 0.076;
A.TG = 0.848;

% Copper Properties
A.EmisCu = 0.05;
A.KCu = 401;

% Call Functions
TInlet = 294;
for i = 1:A.NumSeg
InitialT = InitialTemperatures(TInlet);
[FinalT Q] = FinalTemperatures(InitialT,TInlet);
TInlet = FinalT(5,1);
end
Output(:,1) = FinalT;
Output(:,2) = Q;
```

```matlab
%% Gas Properties
function [Cp K Mu Rho] = GasProperties(Gas,Temperature)
% Air Properties
if Gas == 1
    Cp = -1.00943963695047E-10*(Temperature^4)+2.81254448599746E-7...
        *(Temperature^3)+0.000202233878276078*(Temperature^2)...
        -0.150072124412419*Temperature+1027.41798;
    K = (-5.06003408212592E-11*(Temperature^4)+1.08784826135716E-7...
        *(Temperature^3)-0.000110704086921651*(Temperature^2)...
        +0.116783926336*Temperature-1.21467105152544)/1E3;
    Mu = (-5.00906635214818E-11*(Temperature^4)+1.02029398752111E-7...
        *(Temperature^3)-9.8527018084526E-5*(Temperature^2)...
        +0.0851631685731635*Temperature-0.493235941959713)/1E6;
    Rho = 1.27800208625529E-10*(Temperature^4)-1.98961711102212E-7...
        *(Temperature^3)+0.000123289191471707*(Temperature^2)...
        -0.0379893623266748*Temperature+5.814548886234;
% Argon Properties
elseif Gas == 2
    Cp = 1.24848866633331E-9*(Temperature^4)-1.82400685601624E-6...
        *(Temperature^3)+0.00102635481552745*(Temperature^2)...
        -0.267916306355151*Temperature+548.676280311701;
    K = (-2.24395880718056E-11*(Temperature^4)+5.61660068374122E-8...
        *(Temperature^3)-6.91534812146228E-5*(Temperature^2)...
        +0.0783405770730539*Temperature-0.775664128555445)/1E3;
    Mu = (-3.05298149796457E-11*(Temperature^4)+7.42045961011657E-8...
        *(Temperature^3)-8.9004403963528E-5*(Temperature^2)...
        +0.0998174471700006*Temperature-0.950109940597378)/1E6;
    Rho = 1.7672390952129E-10*(Temperature^4)-2.75081827424949E-7...
        *(Temperature^3)+0.000170419101831641*(Temperature^2)...
        -0.0524936857355962*Temperature+8.02987170830904;
end
return


%% Liquid Properties
function [Cp K Mu Rho] = LiquidProperties(Temperature)
Cp = (((3944.599877)+((-0.11847174)*(Temperature^2))+((1.14*(10^(-6)))...
    *(Temperature^4))+((-4.9*(10^(-12)))*(Temperature^6))...
    +((6.26*(10^(-18)))*(Temperature^8)))/(1+((-3.02*(10^(-5)))...
    *(Temperature^2))+((2.97*(10^(-10)))*(Temperature^4))...
    +((-1.31*(10^(-15)))*(Temperature^6))+((1.82*(10^(-21)))...
    *(Temperature^8)))));
K = (2.348725541+(-0.03477509*Temperature)+(0.000199393...
    *(Temperature^2))+((-5.07*(10^(-7)))*(Temperature^3))...
    +((6.03*(10^(-10)))*(Temperature^4))+((-2.78*(10^(-13)))...
    *(Temperature^5)))^(0.5);
Mu = (-0.07337594)+((213.3594854)/Temperature)+((-263305.782)...
    /(Temperature^2))+((1.79*(10^(8)))/(Temperature^3))...
    +((-7.23*(10^(10)))/(Temperature^4))+((1.74*(10^(13)))...
    /(Temperature^5))+((-2.31*(10^(15)))/(Temperature^6))...
    +((1.31*(10^17))/(Temperature^7));
if Temperature < 250
    Rho = 1000;
elseif Temperature > 645
    Rho = 425.4;
else
```

```matlab
    Rho = (((7.89*(10^(5)))+((1.36*(10^(1)))*(Temperature^2))+((-3.52*...
        (10^(-5)))*(Temperature^4)))/(1+((6.87*(10^(-6)))...
        *(Temperature^2))+((2.28*(10^(-11)))*(Temperature^4))...
        +((-7.99*(10^(-17)))*(Temperature^6)))))^(1/2);
end
return


%% Exterior Heat Transfer
function [HRad HConvNat HConvFr HTotal] = HeatTransferExterior(T1)
global A
% Properties
TFilm = (A.TOD+T1)/2;
[Cp K Mu Rho] = GasProperties(1,TFilm);
% Radiation
HRad = A.EmisG*A.Sigma*(T1^4-A.TSky^4)/(T1-A.TSky);
% Natural Convection
Beta = 1/TFilm;
GrD = A.G*Beta*abs(T1-A.TOD)*(A.DiaOne^3)*(Rho^2)/(Mu^2);
Pr = Cp*Mu/K;
RaD = GrD*Pr;
NuNat = (0.60+(0.387*(RaD^(1/6)))/((1+((0.559/Pr)^(9/16)))^(8/27)))^2;
HConvNat = NuNat*K/A.DiaOne;
% Forced Convection
ReD = A.WindVel*A.DiaOne*Rho/Mu;
NuFr = 0.3+(0.62*(ReD^(1/2))*(Pr^(1/3)))/((1+(0.4/Pr)^(2/3))^(1/4))...
    *((1+((ReD/282000)^(5/8)))^(4/5));
HConvFr = NuFr*K/A.DiaOne;
% Total Heat Transfer
HTotal = ((HConvNat^3)+(HConvFr^3))^(1/3);
return



%% Annulus Heat Transfer
function [HRad HConvNat HTotal] = HeatTransferAnnulus(T2,T3)
global A
% Properties
TFilm = (T2+T3)/2;
[Cp K Mu Rho] = GasProperties(1,TFilm);
Nu = Mu/Rho;
Alpha = K/(Rho*Cp);
% Radiation
HRad = (A.Sigma*(T3^4-T2^4)*A.AreaThree)/((T3-T2)*((1/A.EmisCu)...
    +(A.AreaThree/A.AreaTwo)*((1-A.EmisG)/A.EmisG)));
% Natural Convection
Beta = 1/TFilm;
Pr = Cp*Mu/K;
RaTwo = (A.G*Beta*(A.DiaTwo^3)*abs(TFilm-T2))/(Nu*Alpha);
RaThree = (A.G*Beta*(A.DiaThree^3)*abs(T3-TFilm))/(Nu*Alpha);
G = (((1+(0.6/(Pr^0.7)))^(-5))+((0.4+2.6*(Pr^0.7))^(-5)))^(-1/5);
NuCondThree = 2/(acosh((A.DiaThree^2+A.DiaTwo^2-(4*A.Ecc^2))...
    /(2*A.DiaThree*A.DiaTwo)));
NuConvNum = 1+2/(((0.518*(RaThree^0.25))*(((1+((0.559/Pr)^(3/5)))...
    ^(-5/12))^15)+((0.1*RaThree^(1/3))^15))^(1/15));
NuConvDen = 1-2/((((((2/(1-exp(-0.25)))^(5/3))+((0.587*G*(RaTwo^0.25))...
    ^(5/3)))^(3/5))^15)+((0.1*(RaTwo^(1/3)))^15))^(1/15));
NuConvThree = 2/log(NuConvNum/NuConvDen);
```

```matlab
NuThree = ((NuCondThree^15)+(NuConvThree^15))^(1/15);
KEq = NuThree/NuCondThree;
KEff = KEq*K;
if KEff < K
    KEff = K;
end
HConvNat = KEff*2*pi*A.L/log(A.DiaTwo/A.DiaThree);
% Total Heat Transfer
HTotal = HRad+HConvNat;
return


%% Bulk Heat Transfer
function HConvFr = HeatTransferBulk(T4,T5)
global A
[CpFilm KFilm MuFilm RhoFilm] = LiquidProperties((T4+T5)/2);
[~,~,MuSurf,~] = LiquidProperties(T4);
FlowRateMetric = A.FlowRate*0.0000630902;
AreaCross = pi*(A.DiaFour^2)/4;
Vel = FlowRateMetric/AreaCross;
ReD = RhoFilm*Vel*A.DiaFour/MuFilm;
Pr = CpFilm*MuFilm/KFilm;
if ReD < 2300
    NuD =
1.86*(((ReD*Pr)/(A.L/A.DiaFour))^(1/3))*((MuFilm/MuSurf)^(0.14));
else
    f = (0.790*log(ReD)-1.64)^(-2);
    NuD = ((f/8)*(ReD-1000)*Pr)/(1+12.7*((f/8)^(1/2))*((Pr^(2/3))-1));
end
HConvFr = NuD*KFilm/A.DiaFour;
return


%% Initial Temperatures
function Temperatures = InitialTemperatures(TInlet)
global A
DeltaT = A.TOD-TInlet;
[~,KAir,~,~] = GasProperties(1,A.TOD);
HGuessOne = 35;
HGuessTwo = 85;
U =
1/((1/(pi*A.DiaOne*A.L*HGuessOne))+(log(A.DiaOne/A.DiaTwo)/(2*pi*A.L*A.KG)
)...
    +(log(A.DiaTwo/A.DiaThree)/(2*pi*A.L*KAir))...
    +(log(A.DiaThree/A.DiaFour)/(2*pi*A.L*A.KCu))...
    +(1/(pi*A.DiaFour*A.L*HGuessTwo)));
Temperatures(1,1) = A.TOD+(U*DeltaT*(1/(pi*A.DiaOne*A.L*HGuessOne)));
Temperatures(2,1) = Temperatures(1,1)+(U*DeltaT...
    *(log(A.DiaOne/A.DiaTwo)/(2*pi*A.L*A.KG)));
Temperatures(3,1) = Temperatures(2,1)+(U*DeltaT...
    *(log(A.DiaTwo/A.DiaThree)/(2*pi*A.L*KAir)));
Temperatures(4,1) = Temperatures(3,1)+(U*DeltaT...
    *(log(A.DiaThree/A.DiaFour)/(2*pi*A.L*A.KCu)));
Temperatures(5,1) =
Temperatures(4,1)+(U*DeltaT*((1/(pi*A.DiaFour*A.L*HGuessTwo))));
return
```

```matlab
%% Final Temperatures
function [FinalTemperatures Q] = FinalTemperatures(InitialTemperatures...
    ,TInlet)
global A
% Preallocate Variables
% T = zeros(5,15000);
% Q = zeros(5,15000);
T(:,1) = InitialTemperatures; % Initial temperatures
ii = 1; % Initialize counter
Error = 1; % Intialize error
FlowRateMetric = A.FlowRate*0.0000630902;
while Error > 0.0001
% Heat Transfer Coefficients
[HRadExt HConvNatExt HConvFrExt] = HeatTransferExterior(T(1,ii));
[HRadAnn HConvNatAnn] = HeatTransferAnnulus(T(2,ii),T(3,ii));
HConvWat = HeatTransferBulk(T(4,ii),T(5,ii));
HConvExt = ((HConvNatExt^3)+(HConvFrExt^3))^(1/3);
Q(1,ii) = A.AreaOne*(HRadExt*(T(1,ii)-A.TSky)+HConvExt*(T(1,ii)-A.TOD));
TNew(1,1) = ((((HRadExt*A.TSky)+(HConvExt*A.TOD))*A.AreaOne)+(A.I...
    *(1-A.RG)*A.AreaOne*A.Eta)-(A.I*A.TG*A.AreaTwo*A.Eta)...
    +(HConvNatAnn*(T(3,ii)-T(2,ii)))+(HRadAnn*(T(3,ii)-T(2,ii))))...
    /(A.AreaOne*(HRadExt+HConvExt));
Q(2,ii) = (HRadAnn+HConvNatAnn)*(T(3,ii)-T(2,ii));
Q(3,ii) = Q(2,ii);
TNew(2,1) =
TNew(1,1)+((Q(2,ii)*log(A.DiaOne/A.DiaTwo))/(2*pi*A.L*A.KG))...
    -(((A.I*A.AbsG*pi*A.DiaOne*A.Eta*A.L)/((pi/4)*((A.DiaOne^2)...
    -(A.DiaTwo^2))))*(1/(4*A.KG))*((((A.DiaTwo/2)^2)*log(A.DiaOne...
    /A.DiaTwo))-(((A.DiaOne/2)^2)-((A.DiaTwo/2)^2))));
TNew(3,1) =
TNew(2,1)+((A.I*A.TG*A.AreaThree*A.Eta)/(HConvNatAnn+HRadAnn))+((HConvWat*
A.AreaFour*(T(5,ii)-T(4,ii)))...
    /(HConvNatAnn+HRadAnn));
Q(4,ii) = A.AreaFour*HConvWat*(T(5,ii)-T(4,ii));
TNew(4,1) = TNew(3,1)+((Q(4,ii)*log(A.DiaThree/A.DiaFour))/(2*pi*A.L...
    *A.KCu))-(((A.I*A.TG*pi*A.DiaThree*A.Eta)/((pi/4)*((A.DiaThree^2)...
    -(A.DiaFour^2))))*(((2*((A.DiaFour/2)^2)*log(A.DiaThree/A.DiaFour))...
    -(((A.DiaThree/2)^2)-((A.DiaFour/2)^2)))/(4*A.KCu)));
[CpWat,~,~,RhoWat] = LiquidProperties((T(4,ii)+T(5,ii))/2);
MassFlow = FlowRateMetric*RhoWat;
TNew(5,1) = ((MassFlow*CpWat*TInlet)+(HConvWat*A.AreaFour*TNew(4,1)))...
    /((MassFlow*CpWat)+(HConvWat*A.AreaFour));
Q(5,ii) = MassFlow*CpWat*(TInlet-TNew(5,1));
Error = sum(abs(T(:,ii)-TNew));
if Error > 0.0001
    T(1,ii+1) = T(1,ii)+A.Relax*(TNew(1,1)-T(1,ii));
    T(2,ii+1) = T(2,ii)+A.Relax*(TNew(2,1)-T(2,ii));
    T(3,ii+1) = T(3,ii)+A.Relax*(TNew(3,1)-T(3,ii));
    T(4,ii+1) = T(4,ii)+A.Relax*(TNew(4,1)-T(4,ii));
    T(5,ii+1) = T(5,ii)+A.Relax*(TNew(5,1)-T(5,ii));
end
FinalTemperatures = T(:,ii);
Q = Q(:,ii);
ii = ii+1; % Update counter
if ii>1000000
    break
```

```
        end
        end
        return
```

APPENDIX B. TRANSPIRED SOLAR COLLECTOR MATLAB CODE

```matlab
function DoubleSkinFacade
global A
% Solar Angle Variables
BetaNorth = 79.72; % Slope of north window surface  relative to horizontal
(degrees)
BetaWest = 79.72; % Slope of west window surface relative to horizontal
(degrees)
GammaNorth = 152; % North window surface azimuth angle (degrees)
GammaWest = 47; % West window surface azimuth angle
A.LongStandard = 75; % Standard Meridian for EST (degrees)
A.LongLocation = 83.938611; % Location longitude (degrees)
A.Phi = 35.944444; % Location latitude (degrees)

% Window Variables
A.AirGap = 0.203; % Facade air gap spacing (m)
A.AlphaW = [0.091;0.091;0.382;0.497]; % Absorbtivity
ANorth = 92.25; % North window surface area (m^2)
AWest = 92.25; % West window surface area (m^2)
A.DeltaW = [0.003048;0;0.003048]; % Spacing (m)
A.Emis = [0.840;0.840;0.840;0.840]; % Emissivity
A.GammaW = 79.72; % Window angle (degrees)
A.Height = 9.28; % Window height (m)
A.kPanes = [1;1]; % Thermal conductance (W/m)
A.R = [0.075;0.075;0.395;0.280]; % Reflectivity
A.Relax = 0.35; % Relaxation factor
A.TempID = 294; % Indoor air temperature (K)
A.TempRM = 294; % Room wall temperature (K)
A.T = [0.834;0.223]; % Transmisivity
A.Vel = 5.5; % Exterior air velocity (m/s)
A.VelFd = 1.22117; % Facade air stream velocity (m/s)
A.Width = 9.94; % Window width (m)

% Import Irradiance and Outdoor Temperature Data
A.IBeam = xlsread('Solar Data','F10:F8769'); % Beam component (W/m^2)
A.IDiff = xlsread('Solar Data','H10:H8769'); % Diffuse component (W/m^2)
TempOD = xlsread('Solar Data','C10:C8769')+273; % Outdoor temperature (K)

% Generate Solar Angle Data
[NorthCosTheta NorthCosThetaZ NorthRb NorthINorm]...
    = SolarAngle(BetaNorth,GammaNorth); % North
[WestCosTheta WestCosThetaZ WestRb WestINorm]...
    = SolarAngle(BetaWest,GammaWest); % West

% Generate Short Wave Data
[SingleqSW SingleAbsorb] = ShortWaveRadiometrics(1); % Single pane
[FacadeqSW FacadeAbsorb] = ShortWaveRadiometrics(2); % Facade

% Generate Single Pane Loading Data
[NorthSHGC NorthQLW NorthQSW NorthQTotal] = SingleLoading(NorthINorm...
    ,TempOD,SingleqSW,SingleAbsorb,ANorth); % North
[WestSHGC WestQLW WestQSW WestQTotal] = SingleLoading(WestINorm...
    ,TempOD,SingleqSW,SingleAbsorb,AWest); % Westa
```

```matlab
% Generate Facade Loading Data
[NorthFacadeSHGC NorthFacadeQLW NorthFacadeQSW NorthFacadeQTotal...
    NorthFacadeTMax NorthFacadeQAirStream] = FacadeLoading(NorthINorm...
    ,TempOD,FacadeqSW,FacadeAbsorb,ANorth); % North
[WestFacadeSHGC WestFacadeQLW WestFacadeQSW WestFacadeQTotal...
    WestFacadeTMax WestFacadeQAirStream] = FacadeLoading(WestINorm...
    ,TempOD,FacadeqSW,FacadeAbsorb,AWest); % West

% Sort Single Pane Loading Data
[NorthCooling NorthHeating] = Sort(NorthQTotal); % North
[WestCooling WestHeating] = Sort(WestQTotal); % West

% Sort Facade Loading Data
[NorthFacadeCooling NorthFacadeHeating] = Sort(NorthFacadeQTotal); % North
[WestFacadeCooling WestFacadeHeating] = Sort(WestFacadeQTotal); % West

% Write Data to Excel Spreadsheets
xlswrite('Lantern Data',[NorthCosTheta NorthCosThetaZ NorthRb
NorthINorm...
    NorthSHGC NorthQLW NorthQSW NorthQTotal NorthCooling...
    NorthHeating],'North Single','D3:M8762') % North Single
xlswrite('Lantern Data',[NorthCosTheta NorthCosThetaZ NorthRb
NorthINorm...
    NorthFacadeSHGC NorthFacadeQLW NorthFacadeQSW NorthFacadeQTotal...
    NorthFacadeCooling NorthFacadeHeating NorthFacadeTMax...
    NorthFacadeQAirStream],'North Facade','D3:O8762') % North Facade
xlswrite('Lantern Data',[WestCosTheta WestCosThetaZ WestRb WestINorm...
    WestSHGC WestQLW WestQSW WestQTotal WestCooling...
    WestHeating],'West Single','D3:M8762') % West Single
xlswrite('Lantern Data',[WestCosTheta WestCosThetaZ WestRb WestINorm...
    WestFacadeSHGC WestFacadeQLW WestFacadeQSW WestFacadeQTotal...
    WestFacadeCooling WestFacadeHeating WestFacadeTMax...
    WestFacadeQAirStream],'West Facade','D3:O8762') % West Facade




%% Solar Angle
function [CosTheta CosThetaZ Rb ITotalNorm] = SolarAngle(Beta,Gamma)
global A
% Preallocate variables
CosTheta = zeros(8760,1);
CosThetaZ = zeros(8760,1);
Rb = zeros(8760,1);
ITotalNorm = zeros(8760,1);
% Loop through days and hours
for n = 1:365
    for StandardTime = 1:24
        % Data Position
        Pos = StandardTime+24*(n-1);
        % Solar Time
        B = (n-1)*(360/365); % B in E equation for solar time
        E = 229.2*(0.000075+0.001868*cosd(B)-0.032077*sind(B)-
0.014615*cosd(2*B)...
            -0.04089*sind(2*B)); % E for Solar Time in mins
        EAdj = E/60; % E for Solar Time in hours
        LongChange = 4*(A.LongStandard-A.LongLocation); % Correction for
```

```matlab
longitude in mins
        LongChangeAdj = LongChange/60; % Correction for longitude in hours
        SolarTime = StandardTime+LongChangeAdj+EAdj; % Solar time in hours
        % Declination
        DeltaRad = 0.006918-0.399912*cosd(B)+0.070257*sind(B)-
0.006758*cosd(2*B)...
            +0.000907*sind(2*B)-0.002679*cosd(3*B)+0.00148*sind(3*B); %
Declination in radians
        Delta = DeltaRad*180/pi; % Declination in degrees
        % Hour Angle
        Omega = (SolarTime-12)*15; % Hour angle in degrees
        % Cos of Angle of Incidence
        CosTheta(Pos,1) = sind(Delta)*sind(A.Phi)*cosd(Beta)-
sind(Delta)...
            *cosd(A.Phi)*sind(Beta)*cosd(Gamma)+cosd(Delta)*cosd(A.Phi)...
            *cosd(Beta)*cosd(Omega)+cosd(Delta)*sind(A.Phi)*sind(Beta)...
            *cosd(Gamma)*cosd(Omega)+cosd(Delta)*sind(Beta)*sind(Gamma)...
            *sind(Omega);
        % Cos of Zenith Angle
        CosThetaZ(Pos,1) = cosd(A.Phi)*cosd(Delta)*cosd(Omega)...
            +sind(A.Phi)*sind(Delta);
        % Rb Ratio
        Rb(Pos,1) = CosTheta(Pos,1)/CosThetaZ(Pos,1);
        % Total Normal Irradience
        if StandardTime >= 8 && StandardTime <= 16
            if Rb(Pos,1) > 0
                ITotalNorm(Pos,1) =
A.IBeam(Pos,1)*Rb(Pos,1)+A.IDiff(Pos,1)...
                    *((1+cosd(Beta))/2);
            else
                ITotalNorm(Pos,1) = A.IDiff(Pos,1)*((1+cosd(Beta))/2);
            end
        else
            ITotalNorm(Pos,1) = 0;
        end
    end
end
return



%% Air Properties
function [Cp k mu rho] = AirProp(Temp)
Cp = -1.00943963695047E-10*(Temp^4)+2.81254448599746E-7*(Temp^3)+...
    0.000202233878276078*(Temp^2)-0.150072124412419*Temp+1027.41798;
k = (-5.06003408212592E-11*(Temp^4)+1.08784826135716E-7*(Temp^3)-...
    0.000110704086921651*(Temp^2)+0.116783926336*Temp-...
    1.21467105152544)/1E3;
mu = (-5.00906635214818E-11*(Temp^4)+1.02029398752111E-7*(Temp^3)-...
    9.8527018084526E-5*(Temp^2)+0.0851631685731635*Temp-...
    0.493235941959713)/1E6;
rho = 1.27800208625529E-10*(Temp^4)-1.98961711102212E-7*(Temp^3)+...
    0.000123289191471707*(Temp^2)-0.0379893623266748*Temp+5.814548886234;
return



%% Convection Coefficients
```

```matlab
function h = hCoeff(NumConv,Loc,T1,T2)
global A
if NumConv == 1 % exterior forced convection coeff
    hconv = 4+4*A.Vel;
    hrad = A.Emis(1,1)*5.6703E-8*(T2^4-T1^4)/(T2-T1);
    h = hconv+hrad;
elseif NumConv == 2 % air gap forced convection coeff
    EmisEff = 1/(1/A.Emis(Loc,1)+1/A.Emis(Loc+1,1)-1);
    h = EmisEff*5.6703E-8*(T1^2+T2^2)*(T1+T2);
elseif NumConv == 3
    [Cp k mu rho] = AirProp(T2);
    ReL = A.Height*A.VelFd*rho/mu;
    Pr = Cp*mu/k;
    if ReL < 5*(10^5)
        Nu = 0.680*(ReL^(1/2))*(Pr^(1/3));
    elseif ReL > 5*(10^5)
        ReCrit = 5*(10^5);
        B = 0.037*(ReCrit^(4/5))-0.664*(ReCrit^(1/2));
        Nu = (0.037*(ReL^(4/5))-B)*(Pr^(1/3));
    end
    h = Nu*k/A.Height;
elseif NumConv == 4 % interior natural convection coeff
    Tfilm = A.TempID + 0.25*(T1-A.TempID);
    [Cp k mu rho] = AirProp(Tfilm);
    Beta = 1/Tfilm;
    Pr = Cp*mu/k;
    nu = mu/rho;
    Gr = (9.8*Beta*abs(T1-A.TempID)*A.Height^3)/nu^2;
    RaH = Gr*Pr;
    RaCV = 250000*(exp(0.72*A.GammaW)/sind(A.GammaW))^0.20;
    if RaH <= RaCV
        Nu = 0.56*(RaH*sind(A.GammaW))^0.25;
    elseif RaH > RaCV
        Nu = 0.13*(RaH^(1/3)-RaCV^(1/3))+0.56*(RaCV*sind(A.GammaW))^0.25;
    end
    hconv = Nu*k/A.Height;
    hrad = A.Emis(Loc,1)*5.6703E-8*(T1^4-A.TempID^4)/(T1-A.TempID);
    h = hconv+hrad;
end
return


%% Initial Temperatures
function Temp = InitialTemp(NumPanes,TempOD)
global A
if NumPanes == 1
    hID = 2.5;
    hOD = 2.5;
    TempDiff = TempOD-A.TempID;
    U = 1/((1/hOD)+(A.DeltaW(1)/A.kPanes(1))+(1/hID));
    Temp(1,1) = TempOD-(U*TempDiff*(1/hOD));
    Temp(2,1) = Temp(1,1)-(U*TempDiff*(A.DeltaW(1)/A.kPanes(1)));
elseif NumPanes == 2
    [~,kAirInit,~,~] = AirProp((A.TempID+TempOD)/2);
    hID = 2.5;
    hOD = 2.5;
```

```matlab
        TempDiff = TempOD-A.TempID;
        U = 1/((1/hOD)+(A.DeltaW(1)/A.kPanes(1))+(A.DeltaW(2)/kAirInit)+...
            (A.DeltaW(3)/A.kPanes(2))+(1/hID));
        Temp(1,1) = TempOD-(U*TempDiff*(1/hOD));
        Temp(2,1) = Temp(1,1)-(U*TempDiff*(A.DeltaW(1)/A.kPanes(1)));
        Temp(3,1) = Temp(2,1)-(U*TempDiff*(A.DeltaW(2)/kAirInit));
        Temp(4,1) = Temp(3,1)-(U*TempDiff*(A.DeltaW(3)/A.kPanes(2)));
        if TempOD > 294
            Temp(5,1) = TempOD;
        else
            Temp(5,1) = A.TempID;
        end
end
return


%% Short Wave Radiation
function [qSW Absorb]= ShortWaveRadiometrics(NumPanes)
global A
if NumPanes == 1
    a = [1 0;0 1];
    b = [A.R(1);A.T(1)];
    qSW = a\b;
    Absorb = A.AlphaW(1,1);
elseif NumPanes == 2
    a = [1 0 -A.T(1) 0;0 1 -A.R(2) 0;0 -A.R(3) 1 0;0 -A.T(2) 0 1];
    b = [A.R(1);A.T(1);0;0];
    qSW = a\b;
    Absorb(1,1) = A.AlphaW(1,1)+A.AlphaW(2,1)*qSW(3,1);
    Absorb(2,1) = A.AlphaW(3,1)*qSW(2,1);
end
return


%% Long Wave Radiation
function [qLW TMax QExhausted]=
LongWaveRad(NumPanes,I,TempOD,q_out,Absorb,TempInit)
global A
if NumPanes == 1
    q = zeros(2,10000);
    ii = 1;
    T(:,ii) = TempInit;
    err = 1;
    while err > 0.0001
        hExt = hCoeff(1,1,T(1,ii),TempOD);
        hInt = hCoeff(4,2,T(2,ii),0);
        q(1,ii) = hExt*(TempOD-T(1,ii));
        q(2,ii) = hInt*(T(2,ii)-A.TempID);
        TNew(1,1) = (I*(1-q_out(1,1)-q_out(2,1))-hInt*(T(2,ii)-...
            A.TempID))/hExt+TempOD;
        TNew(2,1) = TNew(1,1)-(A.DeltaW(1,1)/(2*A.kPanes(1,1)))*...
            (I*Absorb(1,1)+2*q(1,ii));
        Diff = T(:,ii)-TNew;
        err = sum(abs(Diff));
        if err > 0.0001
            T(1,ii+1) = T(1,ii)+A.Relax*(TNew(1,1)-T(1,ii));
```

```matlab
                T(2,ii+1) = T(2,ii)+A.Relax*(TNew(2,1)-T(2,ii));
            end
            qLW = q(2,ii);
            ii = ii+1;
        end
    elseif NumPanes == 2
        q = zeros(4,10000);
        ii = 1;
        T(:,ii) = TempInit;
        err = 1;
        while err > 0.0001
            hExt = hCoeff(1,1,T(1,ii),TempOD);
            hRad23 = hCoeff(2,2,T(2,ii),T(3,ii));
            hFrConvFd = hCoeff(3,2,T(2,ii),T(5,ii));
            hInt = hCoeff(4,4,T(4,ii),TempOD);
            q(1,ii) = hExt*(TempOD-T(1,ii));
            q(2,ii) = hRad23*(T(2,ii)-T(3,ii))+hFrConvFd*(T(2,ii)-T(5,ii));
            TNew(1,1) = TempOD+(I*(1+q_out(3,1)-q_out(1,1)-q_out(2,1))...
                -hRad23*(T(2,ii)-T(3,ii))-hFrConvFd*(T(2,ii)-T(5,ii)))/hExt;
            TNew(2,1) = TNew(1,1)-(A.DeltaW(1,1)/(2*A.kPanes(1,1)))*...
                (I*Absorb(1,1)+2*q(1,ii));
            q(3,ii) = hRad23*(T(2,ii)-T(3,ii))+hFrConvFd*(T(5,ii)-T(3,ii));
            q(4,ii) = hInt*(T(4,ii)-A.TempID);
            TNew(3,1) = (I*(q_out(2,1)-q_out(3,1)-q_out(4,1))...
                +hRad23*TNew(2,1)+hFrConvFd*T(5,ii)-hInt*(T(4,ii)...
                -A.TempID))/(hRad23+hFrConvFd);
            TNew(4,1) = TNew(3,1)-(A.DeltaW(3,1)/(2*A.kPanes(2,1)))*...
                (I*Absorb(2,1)+2*q(3,ii));
            TempInlet = TempOD;
            [~,~,~,rho] = AirProp(TempInlet);
            MassFlow = A.VelFd*A.AirGap*A.Width*rho;
            Cp = AirProp((TNew(2,1)+TNew(3,1))/2);
            TNew(5,1) = (MassFlow*Cp*TempInlet+hFrConvFd*A.Height*A.Width...
                *(TNew(2,1)+TNew(3,1)))/(MassFlow*Cp+2*hFrConvFd*A.Height...
                *A.Width);
            Diff = T(:,ii)-TNew;
            err = sum(abs(Diff));
            if err > 0.0001
                T(1,ii+1) = T(1,ii)+A.Relax*(TNew(1,1)-T(1,ii));
                T(2,ii+1) = T(2,ii)+A.Relax*(TNew(2,1)-T(2,ii));
                T(3,ii+1) = T(3,ii)+A.Relax*(TNew(3,1)-T(3,ii));
                T(4,ii+1) = T(4,ii)+A.Relax*(TNew(4,1)-T(4,ii));
                T(5,ii+1) = T(5,ii)+A.Relax*(TNew(5,1)-T(5,ii));
            end
            qLW = q(4,ii);
            TMax = T(5,ii)-273;
            QExhausted = MassFlow*Cp*(T(5,ii)-TempInlet);
            ii = ii+1;
        end
    end
end
return


%% Single Pane Loading
function [SHGC QLW QSW QTotal] = SingleLoading(INorm,TempOD,qSW...
    ,Absorb,Area)
```

```matlab
% Preallocate Variables
qLW = zeros(8760,1);
QLW = zeros(8760,1);
QSW = zeros(8760,1);
QTotal = zeros (8760,1);
SHGC = zeros(8760,1);
% Loop through 8760 hours
for n = 1:365
    for StandardTime = 1:24
        % Data Position
        ii = StandardTime+24*(n-1);
        if StandardTime >= 8 && StandardTime <= 16
            % Initial Temperatures
            TempInit = InitialTemp(1,TempOD(ii,1));
            % Long Wave for I=0
            qLWZero = LongWaveRad(1,0,TempOD(ii,1)...
                ,qSW,Absorb,TempInit);
            qLW(ii,1) = LongWaveRad(1,INorm(ii,1),TempOD(ii,1)...
                ,qSW,Absorb,TempInit);
            SHGC(ii,1) = qSW(2,1)+((qLWZero-qLW(ii,1))...
                /INorm(ii,1));
            QLW(ii,1) = qLW(ii,1)*Area;
            QSW(ii,1) = SHGC(ii,1)*INorm(ii,1)*Area;
            QTotal(ii,1) = QLW(ii,1)+QSW(ii,1);
        else
            SHGC(ii,1) = 0;
            QLW(ii,1) = 0;
            QSW(ii,1) = 0;
            QTotal(ii,1) = 0;
        end
    end
end
return


%% Facade Loading
function [SHGC QLW QSW QTotal TMax QAirStream] = FacadeLoading(INorm...
    ,TempOD,qSW,Absorb,Area)
% Preallocate Variables
qLW = zeros(8760,1);
QAirStream = zeros(8760,1);
QLW = zeros(8760,1);
QSW = zeros(8760,1);
QTotal = zeros (8760,1);
SHGC = zeros(8760,1);
TMax = zeros(8760,1);
% Loop through 8760 hours
for n = 1:365
    for StandardTime = 1:24
        % Data Position
        ii = StandardTime+24*(n-1);
        if StandardTime >= 8 && StandardTime <= 16
            % Initial Temperatures
            TempInit = InitialTemp(2,TempOD(ii,1));
            % Long Wave for I=0
            qLWZero = LongWaveRad(2,0,TempOD(ii,1)...
```

```matlab
                ,qSW,Absorb,TempInit);
            qLW(ii,1) = LongWaveRad(2,INorm(ii,1),TempOD(ii,1)...
                ,qSW,Absorb,TempInit);
            SHGC(ii,1) = qSW(4,1)+((qLWZero-qLW(ii,1))...
                /INorm(ii,1));
            QLW(ii,1) = qLW(ii,1)*Area;
            QSW(ii,1) = SHGC(ii,1)*INorm(ii,1)*Area;
            QTotal(ii,1) = QLW(ii,1)+QSW(ii,1);
            [~,TMax(ii,1),QAirStream(ii,1)] = LongWaveRad(2,INorm(ii,1)...
                ,TempOD(ii,1),qSW,Absorb,TempInit);
        else
            SHGC(ii,1) = 0;
            QAirStream(ii,1) = 0;
            QLW(ii,1) = 0;
            QSW(ii,1) = 0;
            QTotal(ii,1) = 0;
            TMax(ii,1) = 0;
        end
    end
end
return


%% Sort Loading
function [PosLoad NegLoad] = Sort(QTotal)
% Preallocate Variables
PosLoad = zeros(8760,1);
NegLoad = zeros(8760,1);
for ii = 1:8760
    if QTotal(ii,1) > 0
        PosLoad(ii,1) = QTotal(ii,1);
        NegLoad(ii,1) = 0;
    elseif QTotal(ii,1) < 0
        PosLoad(ii,1) = 0;
        NegLoad(ii,1) = QTotal(ii,1);
    end
end
return
```

APPENDIX C. DATA ACQUISITON SYSTEM DATA IMPORT AND REDUCTION EXCEL VBA CODE

```
Sub LoopThroughFiles()
    Dim r As Integer, F As String, directory As String, F2 As String

directory = "C:\Users\Mike\Documents\School\ME 450 Senior Design\Data Acquisition\Import Data
VBA\Data Logs\"
r = 1
Sheets("FileNames").Select
Cells(r, 1) = "FileNames"

'Range("A1:c1").Font.Bold = True
'Get Directory
 Filename = Dir(directory)

Do While Filename <> ""
r = r + 1
Cells(r, 1) = Filename
Filename = Dir()
Loop
Range("A2").Select
    Range(Selection, Selection.End(xlDown)).Select
Cells(4, 7) = Selection.Rows.count - 1
End Sub

Sub import_csv()

'Michael Kerksick
'ME 450/460
'Data Import Code

Dim count As Integer, Filename As String, fileprefix As String, directory As String, ConcanF As String, LR As
Integer

Sheets("FileNames").Select
directory = Range("E7").Value 'Get file directory
count = Range("G4").Value 'Get number of files

For j = 2 To count 'Loop through file names
Sheets("FileNames").Select
    Filename = Cells(j, 1) 'Get Filename.csv
    fileprefix = Left(Filename, 6) '6 digit prefix is the modbus address "mb-xxx"

    ConcanF = directory & Filename 'concatenate the file directory location and .csv file name

    If fileprefix = "mb-101" Then 'if prefix is mb-101, add data to first blank row in Interior sheet
    Sheets("Interior").Select
    LR = Range("A" & Rows.count).End(xlUp).Row + 1


With ActiveSheet.QueryTables.Add(Connection:= _
    "TEXT;" + ConcanF, Destination:=Range("A" & LR))
    .Name = "Filename"
    .FieldNames = True
    .RowNumbers = False
```

```vba
        .FillAdjacentFormulas = False
        .PreserveFormatting = True
        .RefreshOnFileOpen = True
        .RefreshStyle = xlInsertDeleteCells
        .SavePassword = False
        .SaveData = True
        .AdjustColumnWidth = False
        .RefreshPeriod = 0
        .TextFilePromptOnRefresh = False
        .TextFilePlatform = 437
        .TextFileStartRow = 2
        .TextFileParseType = xlDelimited
        .TextFileTextQualifier = xlTextQualifierDoubleQuote
        .TextFileConsecutiveDelimiter = False
        .TextFileTabDelimiter = False
        .TextFileSemicolonDelimiter = False
        .TextFileCommaDelimiter = True
        .TextFileSpaceDelimiter = False
        .TextFileColumnDataTypes = Array(1, 9, 9, 9, 1, 1, 1, 1, 1, 1, 1, 1)
        .TextFileTrailingMinusNumbers = True
        .Refresh BackgroundQuery:=True
    End With


    ElseIf fileprefix = "mb-100" Then
    Sheets("SouthWest Window").Select
    LR = Range("A" & Rows.count).End(xlUp).Row + 1


With ActiveSheet.QueryTables.Add(Connection:= _
        "TEXT;" + ConcanF, Destination:=Range("A" & LR))
        .Name = "Filename"
        .FieldNames = True
        .RowNumbers = False
        .FillAdjacentFormulas = False
        .PreserveFormatting = True
        .RefreshOnFileOpen = True
        .RefreshStyle = xlInsertDeleteCells
        .SavePassword = False
        .SaveData = True
        .AdjustColumnWidth = False
        .RefreshPeriod = 0
        .TextFilePromptOnRefresh = False
        .TextFilePlatform = 437
        .TextFileStartRow = 2
        .TextFileParseType = xlDelimited
        .TextFileTextQualifier = xlTextQualifierDoubleQuote
        .TextFileConsecutiveDelimiter = False
        .TextFileTabDelimiter = False
        .TextFileSemicolonDelimiter = False
        .TextFileCommaDelimiter = True
        .TextFileSpaceDelimiter = False
        .TextFileColumnDataTypes = Array(1, 9, 9, 9, 1, 1, 1, 1, 1, 1, 1, 1)
        .TextFileTrailingMinusNumbers = True
        .Refresh BackgroundQuery:=True
    End With
```

```
    ElseIf fileprefix = "mb-003" Then
    Sheets("NE Window").Select
    LR = Range("A" & Rows.count).End(xlUp).Row + 1


With ActiveSheet.QueryTables.Add(Connection:= _
    "TEXT;" + ConcanF, Destination:=Range("A" & LR))
    .Name = "Filename"
    .FieldNames = True
    .RowNumbers = False
    .FillAdjacentFormulas = False
    .PreserveFormatting = True
    .RefreshOnFileOpen = True
    .RefreshStyle = xlInsertDeleteCells
    .SavePassword = False
    .SaveData = True
    .AdjustColumnWidth = False
    .RefreshPeriod = 0
    .TextFilePromptOnRefresh = False
    .TextFilePlatform = 437
    .TextFileStartRow = 2
    .TextFileParseType = xlDelimited
    .TextFileTextQualifier = xlTextQualifierDoubleQuote
    .TextFileConsecutiveDelimiter = False
    .TextFileTabDelimiter = False
    .TextFileSemicolonDelimiter = False
    .TextFileCommaDelimiter = True
    .TextFileSpaceDelimiter = False
    .TextFileColumnDataTypes = Array(1, 9, 9, 9, 1, 1, 1, 1, 1, 1, 1, 1)
    .TextFileTrailingMinusNumbers = True
    .Refresh BackgroundQuery:=True
    End With

    ElseIf fileprefix = "mb-126" Then
     Sheets("Weather Station").Select
    LR = Range("A" & Rows.count).End(xlUp).Row + 1

    With ActiveSheet.QueryTables.Add(Connection:= _
      "TEXT;" + ConcanF, Destination:=Range("A" & LR))
     .Name = "Filename"
     .FieldNames = True
     .RowNumbers = False
     .FillAdjacentFormulas = False
     .PreserveFormatting = True
     .RefreshOnFileOpen = True
     .RefreshStyle = xlInsertDeleteCells
     .SavePassword = False
     .SaveData = True
     .AdjustColumnWidth = False
     .RefreshPeriod = 0
     .TextFilePromptOnRefresh = False
     .TextFilePlatform = 437
     .TextFileStartRow = 2
     .TextFileParseType = xlDelimited
     .TextFileTextQualifier = xlTextQualifierDoubleQuote
```

```
            .TextFileConsecutiveDelimiter = False
            .TextFileTabDelimiter = False
            .TextFileSemicolonDelimiter = False
            .TextFileCommaDelimiter = True
            .TextFileSpaceDelimiter = False
            .TextFileColumnDataTypes = Array(1, 9, 9, 9, 9, 1, 9, 9, 9, 9, 1, 9, 9, 9, 9, 1, 9, 9, 9, 9, 1, _
            9, 9, 9, 9, 1, 9, 9, 9, 9, 1, 9, 9, 9, 9, 1, 9, 9, 9, 9, 1, 9, 9, 9, 9, 9)
            .TextFileTrailingMinusNumbers = True
            .Refresh BackgroundQuery:=True
        End With


        Else
        Sheets("FileNames").Select
        Cells(j, 2) = 0

    End If


    Next j




End Sub

Sub insert_column()
'
' insert_column Macro
Dim SheetName As Variant, count As Integer
'Insert Corrected Time Column in Each Sheet
SheetName = Array("SouthWest Window", "Interior", "NE Window", "Weather Station")
For m = 0 To UBound(SheetName)

Sheets(SheetName(m)).Activate
Range("A3").Select
    Range(Selection, Selection.End(xlDown)).Select
    count = Selection.Rows.count + 2
    Range("b2").Select
    Worksheets(SheetName(m)).Columns(2).Select
    Range("B2").Activate
    Selection.Insert Shift:=xlToRight, CopyOrigin:=xlFormatFromLeftOrAbove 'insert column B
    Range("B2").Value = "Time (EST)"

    For i = 3 To count 'fill rows with formula below
    Range("B" & i).Formula = "=A" & i & "-0.16666667" 'Subtract four hours from UTC time for eastern
daylight savings time

    Next i

Next m




End Sub
```

```vba
Sub Poor_Boy()

Sheets("Interior").Activate
Range("A3").Select
    Range(Selection, Selection.End(xlDown)).Select
    count = Selection.Rows.count + 2

eplate = 0.84
ewindow = 0.84
rwindow = 0.208
alpha = 1 - rwindow
L = 0.1524 'm
g = 9.81 ' m/s^2
sigma = 5.67 * 10 ^ -8 'stephan-boltzmann constant W/m^2-K^4
areaplate = L ^ 2 'm^2
areawindow = 0.9144 * 2.33045 'm^2
F = 0.976 'ViewFactor
insthickness = 0.0381 'm


For i = 3 To count



AirTemp = Range("E" & i).Value + 273 'K
PlateTemp = Range("C" & i).Value + 273 'K
WindowTemp = Range("J" & i).Value + 273 'K
InsTemp = Range("D" & i).Value + 273 'K

If AirTemp < 300 Then
    cp = ((AirTemp - 250) * (1007 - 1006) / (300 - 250)) + 1006 'J/kg-K
    v = (((AirTemp - 250) * (0.00001589 - 0.00001144) / (300 - 250)) + 0.00001144) 'm^2/s
    Pr = (((AirTemp - 250) * (0.707 - 0.72) / (300 - 250)) + 0.72)
    k = (((AirTemp - 250) * (0.0263 - 0.0223) / (300 - 250)) + 0.0223) 'W/m-K

    Else: cp = 0
    v = 0
    k = 0

    End If


    beta = 1 / AirTemp '1/K
    dT = Abs(AirTemp - PlateTemp)

    Ra = (g * beta * dT * (L ^ (3))) / (alpha * v)

    Nu = 0.68 + ((0.67 * (Ra ^ 0.25))) / ((1 + (0.492 / Pr) ^ 0.5625) ^ 0.4444)

    H = (Nu * k) / L 'W/m^2-K

    Qrad = (sigma * (WindowTemp ^ 4 - PlateTemp ^ 4)) / (((1 - eplate) / (eplate * areaplate)) + (1 / (areaplate *
F)) + ((1 - ewindow) / (ewindow * areawindow)))
    Qcond = (k * areaplate * (PlateTemp - InsTemp)) / (insthickness)
    Qconv = H * areaplate * (AirTemp - PlateTemp)
```

```
Irradiance = (Qcond - Qconv - Qrad) / (alpha * areaplate)


Range("K" & i).Formula = Irradiance
Range("L" & i).Formula = Qrad
Range("M" & i).Formula = Qcond
Range("N" & i).Formula = Qconv
Range("O" & i).Formula = k
Range("P" & i).Formula = Ra
Range("Q" & i).Formula = Pr
Range("R" & i).Formula = Nu
Range("S" & i).Formula = H
Range("T" & i).Formula = cp
Range("U" & i).Formula = v
Range("V" & i).Formula = beta

Next i
```

APPENDIX D. PROJECT CONTRIBUTIONS

Alex Miles-Report Introduction; Transpired Solar Collector Research, Modeling and Report Section; Fresnel Solar Collector Modeling

Anna Davis-PID Diagram; Fresnel Solar Collector Research, Modeling and Report Section; Report Conclusion

Andy Phillips-Evacuated Tube Collector Research and Report Section; Report Conclusion

Michael Kerksick-Data Acquisition System Design, Setup, Import and Reduction Excel VBA code; Report Compilation and Formatting; Report Acknowledgements and Abstract