ABSTRACT

Design and Validation of a Solar Domestic
Hot Water Heating Simulator

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A growing demand for emerging alternative energy technologies is fueled by
rising energy prices and decreasing energy supplies. Domestic hot water heating is an
industry that continues to benefit from increased research in and improvement of solar
technology. This thesis outlines the implementation of a solar domestic water heating
simulator and the validation of a double and single tank domestic hot water configuration.
The results and procedures were compared to the guidelines of the Solar Rating and
Certification Corporation's (SRCC) OG-300 standards. The Solar Energy Factor for a
double-tank system was found to be 2.64 ±0.043 and for a single tank system 4.46 ±0.06,
which is 12 % and 9 % respectively, below data reported by the SRCC for a comparable
test. These tests will verify the performance of this solar water heating system and
provide a baseline profile for further modifications to improve the efficiency of future
solar domestic hot water heating systems

Design and Validation of a Solar Domestic
Hot Water Heating Simulator

by

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A Thesis

Approved by the Department of Mechanical Engineering

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β Collector Slope

EF   Energy Factor

FrUL   Slope of Collector Linear Efficiency Equation

$Fr\tau\alpha$ Y Intercept of Collector Linear Efficiency Equation

G_T Total Daily Insolation

I_b Beam Radiation

I Current

I_d Diffuse Radiation

$I_{\rho g}$ Ground Reflected Radiation

I_T Hourly Insolation

$K_{\tau\alpha}$ Incident Angle Modifier

η Instantaneous Efficiency

P   Power delivered to STCS

P'   Calibrated Power delivered to STCS

PEX   High Cross Linked Polyethylene

Q_{aux} Auxiliary Element Energy

Q_{del} Energy Delivered to Hot Water Load

Q_{par} Parasitic Energy

R_b Geometric Factor

SEF   Solar Energy Factor

SF   Solar Fraction

SDHW	Solar Domestic Hot Water
STCS	Solar Thermal Collector Simulator
SRCC	Solar Rating and Certification Corporation
T_i	Collector Inlet Temperature
T_a	Dry Bulb Temperature
TMY2	Typical Meteorological Year
UDP	Universal Datagram Protocol
V	Voltage
VI	Virtual Instrument

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CHAPTER ONE

Introduction

Background

As the demand for all forms of energy quickly outpaces the ability to provide it,

more reliable supplies are necessary to ensure consistent technological and economic

growth. The notion of dwindling energy supplies prompts technological innovation to

delay or avoid the onset of an energy crisis (Anderson, [1]). Efficiency of producers and

conservation by consumers is complementary to developing alternative sources of

reliable energy. The home is one of the largest and most inefficient consumers of energy

demanding approximately 10,600 kWh of energy per year (EIA, [2]). The breakdown of

a typical home's energy consumption shows that hot water heating currently accounts for

14% to 25% of the total energy demand (ACEEE, [3]). There exists a great opportunity

for solar thermal technologies to reduce this demand yet still provide reliable and

efficient energy for comfort in the home. The Solar Rating and Certification Corporation

estimates that solar thermal systems will also benefit utility companies by reducing the

peak demand load by 0.5 kW for each system installed. Conventional electric and gas

water heaters have high efficiencies of approximately 90% and 60% respectively;

however, these loads are large and often powered by non-renewable energy sources.

Solar thermal systems have the ability to utilize seemingly inexhaustible supply of solar

radiation to deliver efficient thermal energy to the home. Increasing efficiency of

appliances, space, and water heating by using solar energy is a simple and effective way

to conserve energy and reduce the load felt by the producer. The purpose of this study is

to design a simulation facility that can accurately produce repeatable performance for a domestic solar hot water heating system. The thermal efficiency ratings for a single and double tank configuration will be validated against computer simulation data from the Solar Rating and Certification Corporation.

Domestic hot water heating is an industry that has been slowly taking advantage of solar technologies over the past 25 years. In the late 1970s during the Arab oil embargo, a 50% federal energy tax rebate was issued that prompted thousands of manufacturers and contractors to install solar thermal systems. However, many of the original designs were flawed and malfunctioned frequently with a tendency to consume more energy than their rated savings (Lane, [4]). Installation problems, such as roof damage and leaks, also heavily contributed to consumer distrust of the industry. A lack of serious research coupled with immediate implementation of this technology fostered a period of 'learning by doing' that resulted in many unsuccessful designs at the expense of the homeowner. The sudden flooding of the market along with faulty products and cunning salesman created several purchasing obstacles including consumer ignorance, poorly designed products, and fraud. The skilled and qualified professionals were overshadowed during the sudden growth of this deregulated technology. In order to overcome these obstacles and promote a promising technology, the solar thermal industry formed the Solar Ratings and Certification Corporation (SRCC) in 1980.

The SRCC is an independent, non-profit organization that has developed efficiency ratings for consumers, contractors, manufacturers, and governments to evaluate and compare the performance of domestic solar hot water heating components and systems. The SRCC ratings provide consumers with confidence that the products

they purchase are reliable and have been tested for efficiency. They also provide

manufacturers and contractors with credibility and a fair market by establishing standards

by which to certify equipment. Finally, the SRCC ratings provide a standard for

government to structure tax credits, which are an incentive to encourage implementation

of residential solar technology.

The SRCC determines efficiency ratings for solar domestic hot water systems by

subjecting each component of the system to individual tests to determine key parameters.

Then, using those results and standardized conditions as inputs to a computer simulation,

the whole system performance is modeled. This is a sufficient process for theoretical

performance; however, for actual performance, location specific data is necessary. The

Solar Thermal Collector Simulator (STCS), Figure 1, constructed by Bolton [5] at Baylor

University, simulates repeatable collector performance and can be integrated into a

domestic hot water configuration to simulate a complete residential system.
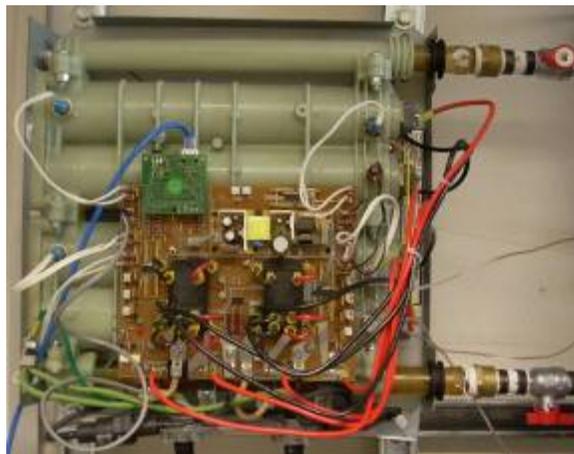
Figure 1. Solar Thermal Collector Simulator at Baylor University.

The STCS can be extremely useful for universities or research institutions

wishing to conduct performance and efficiency research on solar domestic hot water

systems. By implementing a repeatable solar collector simulator, new configurations and components of solar domestic hot water systems can be assembled and system performance can be evaluated.

The SRCC's main performance rating, the Solar Energy Factor (SEF), compares the amount of energy the system can provide to the amount of energy necessary to maintain system temperatures. An SEF rating of one indicates that the amount of solar thermal energy provided to the system is equal to the amount of non-renewable energy used by the system. SEF ratings greater than one, indicate that the system will provide more thermal energy than the minimal auxiliary assistance of pumps and heaters resulting in higher efficiencies. This rating can be used to compare different solar thermal systems, including single and double tank configurations, regardless of size or location. The SEF assists in choosing an appropriate system for specific load and environmental conditions by providing a standardized performance rating that approximates the net energy savings.

Theory

A solar thermal system utilizes the energy produced by the sun to heat water for domestic uses such as radiant floor heating systems, showers, and dishwashing. A collector, usually mounted on the roof of the home, absorbs the sun's radiation and raises the temperature of the working fluid. Solar radiation on a tilted flat plate collector, integrated over one hour, is known as insolation and is measured in kilowatt –hours per square meter (kWh/m^2). Typical values of insolation for central Texas fall within the range of 5.0-5.5 kWh/m^2 per day (NREL, [6]). Along with the solar collector, a basic system usually has some form of thermal storage for the heated water.
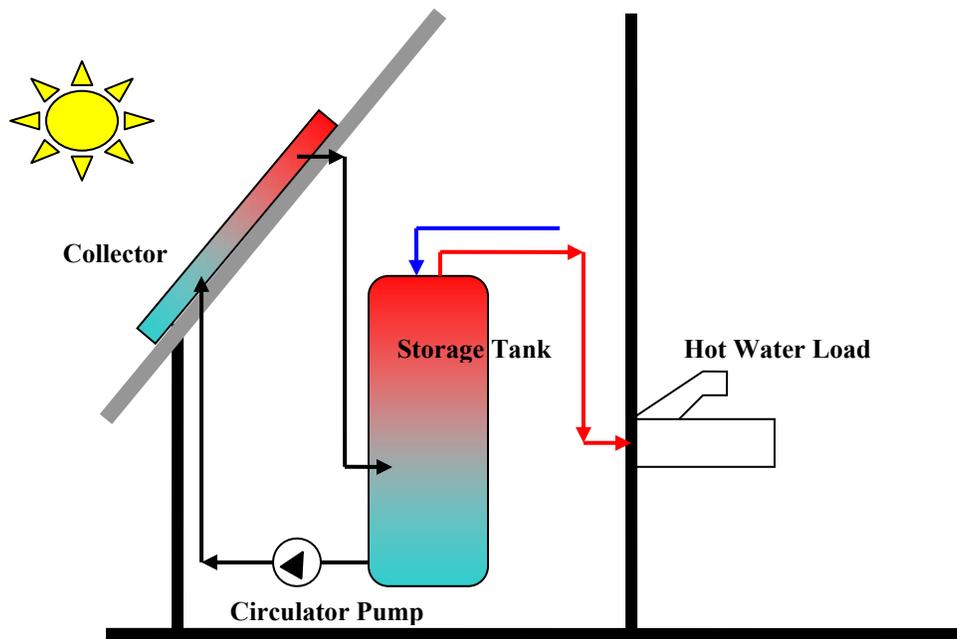
Figure 2. Active solar domestic hot water heating configuration

As shown in Figure 2 , the hot fluid flows to thermal storage either directly or through a heat exchanger. Systems that involve external sources of energy to pump the fluid and contribute supplementary heat to the water are considered active systems ([7]). As the stored water gains energy, it heats up, and, upon reaching the desired temperature, is ready to be drawn for domestic use. Conventional hot water heating systems use electricity to energize resistive heating elements to heat the water directly. In contrast, solar thermal systems use electric energy as supplemental heating elements for auxiliary back up only. If the water is below the system set point or minimum desired temperature, then the electric element will provide the extra heat necessary to achieve the desired water temperature. Two very common configurations found in residential applications are a single tank and double tank system. A single tank system, shown in Figure 3, usually has the storage and auxiliary element within the same tank.
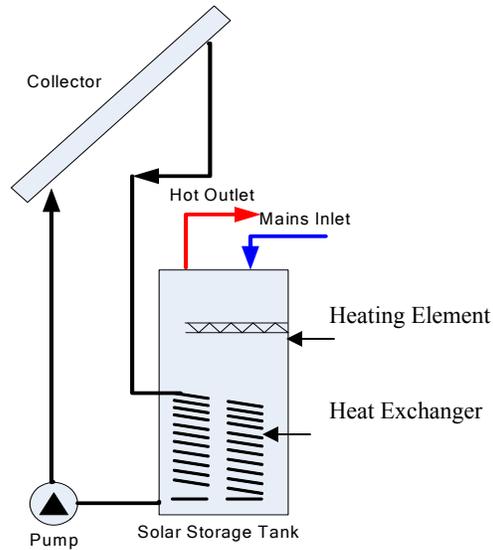
Figure 3. Single tank configuration

In the double tank system, shown in Figure 4, the auxiliary tank contains a pair of heating elements and receives preheated water from the solar storage tank.
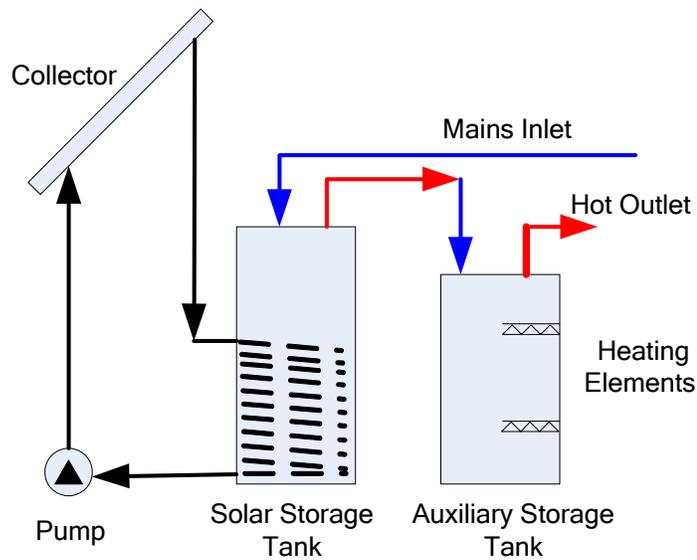
Figure 4. Double tank configuration

The water is heated in the first tank using solar energy and as the water flows into the auxiliary storage tank, the electric power required by the element in the second tank is significantly reduced.

The SRCC rating method for collectors, components, and systems allow

comparisons regardless of system configuration. The performance rating for Solar

Domestic Hot Water systems is the Solar Energy Factor, which describes the ratio of

energy delivered for a domestic hot water load to the external energy contribution of the

system. Typical values range from 2 to 5 depending on the working fluid used, total

collector area, and configuration. Systems that have extremely large SEF ratings, greater

than 10, are usually accompanied with large collector areas. The Solar Energy Factor is

defined by Equation 1

$$SEF = \frac{Q_{del}}{Q_{aux} + Q_{par}} \qquad (1)$$

where Q_{del} is the energy delivered to the hot water load derived from integrating the test

data from Equation (2) over the period of an energy draw, lasting approximately four

minutes.

$$Q_{del} = mCp\Delta T \qquad (2)$$

The test procedure, outlined in Chapter 3, specifies energy to be drawn six times from the

system over a 24 hour period, simulating domestic hot water usage. The total energy

delivered is the result of an energy balance of the heat added to the system. The heat can

be calculated from the product of m, the mass of water extracted during a draw, Cp is the

specific heat of water, and ΔT is the temperature difference between the average steady

state inlet temperature from the mains and system outlet. The energy collected over each

of the six draws is then summed to provide the total energy delivered to the hot water

load.

The daily amount of energy provided to the auxiliary heating elements, Q_{aux}, is

defined by Equation (3)

$$Q_{aux} = P_{aux}t_{on} \tag{3}$$

where P_{aux} is the power delivered to the auxiliary element multiplied by the period of time the element operated. A single tank system will quantify the amount of time the heating element on the solar storage tank is energized, while a double tank system will measure the time energized for both heating elements on the auxiliary tank.

Finally, Q_{par} is the amount of energy provided to external parasitic devices in the system such as, pumps and controllers, which is defined by

$$Q_{par} = P_{par}t_{on} \tag{4}$$

The power to each parasitic load P_{par}, is multiplied by the period of time that each component is energized. Equations 3 and 4 are only valid for external devices that require P_{par} and P_{aux} to be constant.

The Solar Fraction, *SF*, which is the portion of the water heating load provided by solar energy, is defined in Equation (5) and ranges from 0 for a conventional gas or electric hot water heater to 1 for a completely solar thermal system with no auxiliary input. Most systems have a solar fraction of about 0.55 to 0.7, which corresponds to a SEF of 2 to 3 respectively.

$$SF = 1 - \frac{EF}{SEF} \tag{5}$$

The SRCC defines the Energy Factor (EF) for conventional electric auxiliary tanks as 0.9 (GAMA, [8]). The Solar Fraction can also be used to determine the potential amount of energy saved by using solar energy versus conventional energy such as electricity or natural gas. The Solar Fraction and Solar Energy Factor are non-dimensional parameters that can be used to compare systems regardless of storage capacity or collector area. This is important to ensure correct pairing of systems to loads,

because insolation, ambient and mains temperature, and utility prices all vary by location. Thus, the Solar Energy Factor is critical in determining the annual economic and energy savings a solar thermal system will provide.

System Overview

The Solar Domestic Hot Water (SDHW) system simulator replicates a domestic solar hot water heating configuration. The main components of the actual SDHW system, shown in

Figure 5, consist of a Solar Thermal Collector Simulator (STCS), an 80 gallon solar hot water heating tank with a heat exchanger, a 40 gallon standard hot water heating tank, and an inline circulator pump. The user can control and monitor the system from an external computer.

Figure 5 shows the first storage tank of the SDHW with an integrated wrap around heat exchanger, to which the STCS and the circulator pump are connected, completing a closed heat exchange loop. The heat exchanger consists of 120 ft of copper tubing wrapped around the bottom half of the first storage tank. An inline pump provides the flow in the closed loop through the STCS and heat exchanger to transfer energy to the stored water. The second storage tank is a conventional electric auxiliary tank with two heating elements that may be bypassed for single tank testing. Water from the mains flows through the storage tanks and back to the drain through a series of valves located on the inlet and outlet of the system.
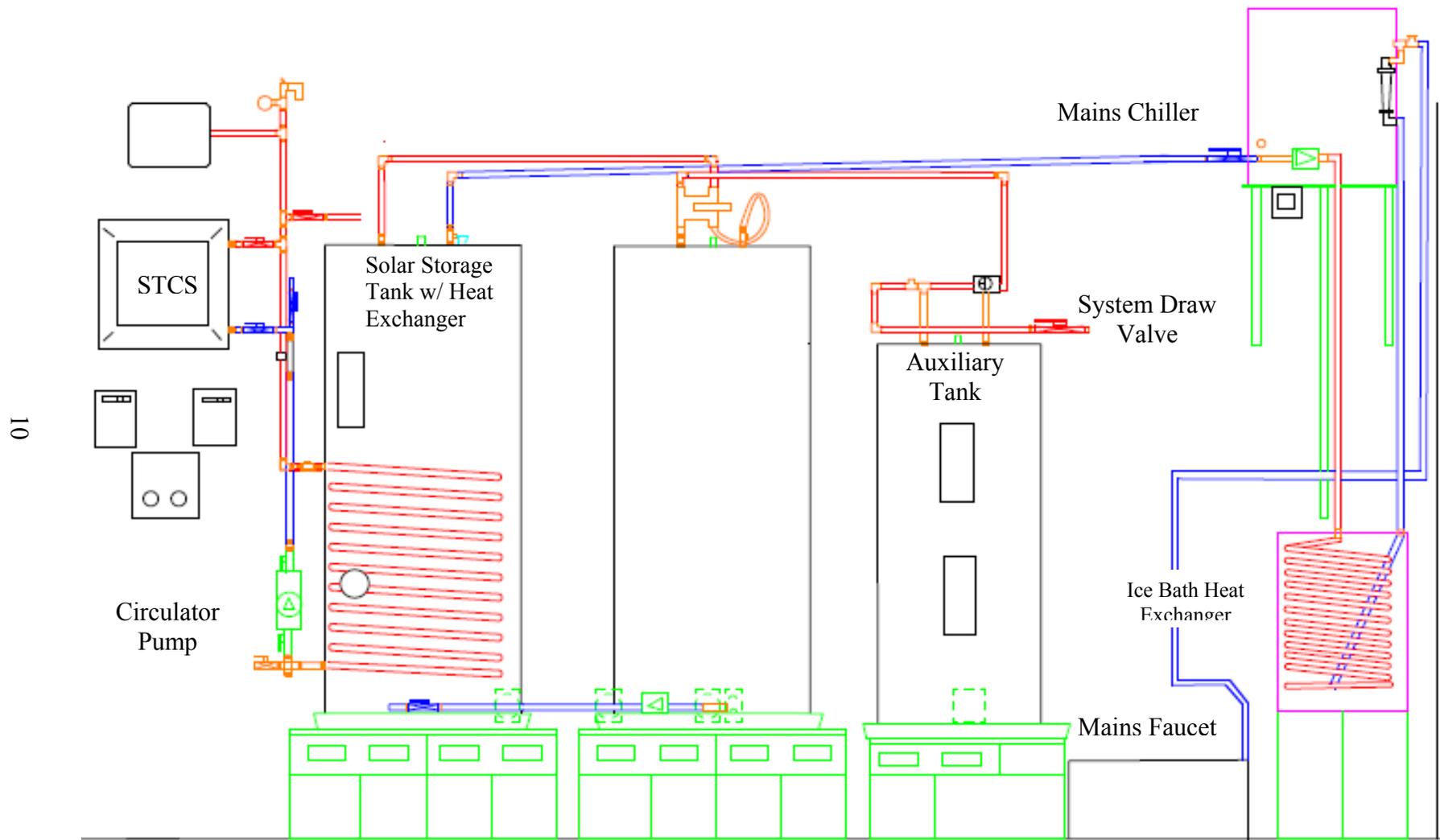
Figure 5. System apparatus overview

In processing the data for this experiment, there were several key assumptions that were made to simplify the calculations and provide reasonable results. Current SRCC guidelines provide a standardized yet approximated profile of solar insolation, ambient temperature, and incidence angle on a given day, regardless of location, which can be found in Appendix E. For laboratory conditions, a standardized weather profile provides a good metric to compare multiple systems; however, for testing actual performance of systems, this metric may not give accurate results for a given location. The SRCC assumes in Section 7.3 of OG 300 the same conditions as the U.S. Department of Energy's test for water heaters with several modifications. A standardized solar profile has been incorporated, which contains the solar time, ambient temperature, solar radiation, and incidence angle. Each solar 'day' consists of approximately 4700 Whr/m^2, which is about 15% less than the typical annual value in central Texas. This profile simplifies the necessary calculations involved in determining total insolation on a surface as well as providing a standard to which all systems are subject regardless of location. Domestic hot water usage is simulated by extracting a known amount of energy from the system in the form of drawing hot water. When constructing a schedule for energy drawn from a system, several factors need to be considered including daily volume, timing, flow rate, and variability. Previous studies have shown that variability and flow rate are not of concern due to the volume of hot water drawn being the most significant variable (Burch and Hendron, [9]). When volume and timing are the most influential variables determining the energy required by the system, a simple hourly draw schedule is

appropriate. Solar thermal systems are affected mostly by the timing and volume of the draws, due to the availability of insolation and storage dynamics. The SRCC specifies six draws to be taken, beginning at 9:30 am solar time, each approximately 7,217 kJ. The draw schedule can be found in Chapter 3 and is based on the Gas Appliance Manufacturer Association's Consumers' Directory of Certified Efficiency Ratings for Residential Heating and Water Heating Equipment (ASHRAE, [10]). The test conditions can be found in Table 1 and are guidelines for a standard operating environment and energy draws.

Table 1. SRCC OG 300 rating conditions (sec 7.3) [11].

Test Condition	Criteria
Environmental Temperature	19.7°C
Auxiliary Set Temperature	57.2°C
Water Mains Temperature	14.4°C
Draw Type	Energy
Total Energy Draw	43.302 MJ
Approximate Total Draw Volume	64.3 gallons
Draw Rate	3.0 gpm
Number of Draws	6 – one at the beginning of each hour starting at 9:30 am

Solar radiation energy on a sloped surface integrated over a one hour period is known as insolation, I_T. The radiation energy incident on a surface is affected by interactions with clouds, dust, and water vapor in the atmosphere. Capturing all of these factors in one model is challenging and is best accommodated through a simplified model. In order to accurately model the sky and determine total insolation, the isotropic diffuse sky model was chosen which assumes a clear sky conditions and that the radiation incident on a tilted surface can be broken down into three

components: direct beam (*Ib*), isotropic diffuse (*Id*), and ground reflected (*Iρg*)as seen in Figure 6.
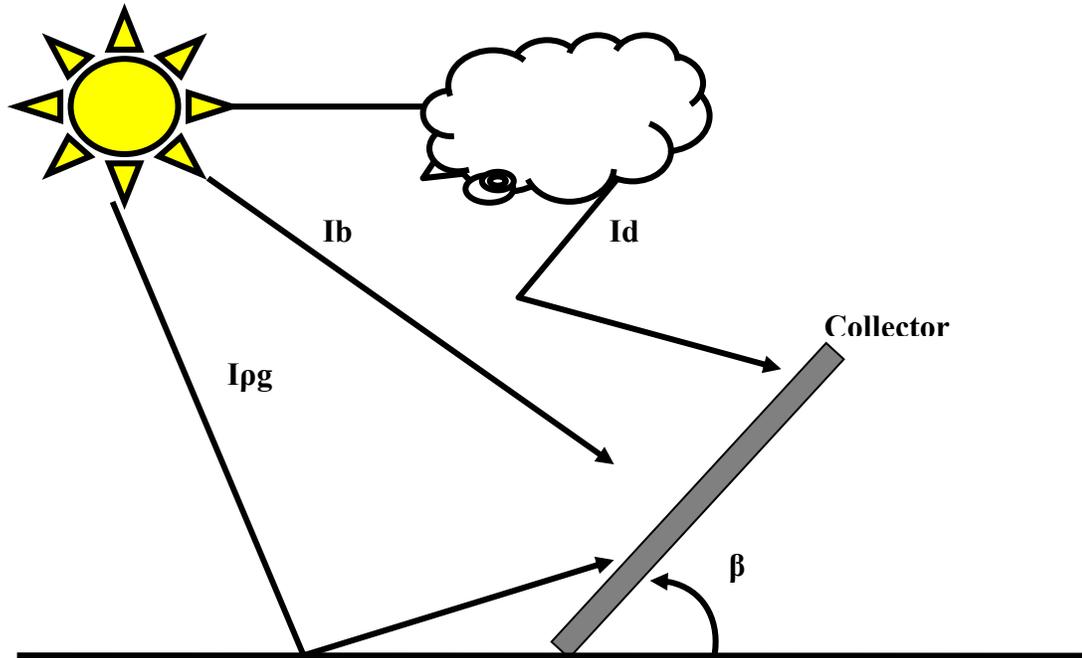
Figure 6. Components of incident radiation on a tilted surface.

The amount of diffuse and reflected radiation incident on the collector is related to the collector angle through its respective view factors for the sky and ground (Beckman and Duffie, [12]). Equation (6) is the isotropic diffuse model of the sky

$$I_T = I_b + I_d\left(\frac{1 + \cos\beta}{2}\right) + I\rho_g\left(\frac{1 - \cos\beta}{2}\right) \tag{6}$$

where I_T is the insolation on the surface, I_b is the beam component normal to the surface, I_d is the diffuse radiation component, and I_{pg} is the diffuse radiation reflected from the ground. Finally, β is the slope of the collector and is the main variable in

determining the view factors for the diffuse and reflected components of radiation. It is important to note that the solar profile provided by the SRCC contains a value for total insolation, however the control software has the option of using specific weather data where the isotropic diffuse model is utilized.

Several designs of solar thermal collectors are currently available however, the flat plate style was chosen as the collector under analysis because they are the simplest to model and most widely implemented in homes and businesses. A flat plate collector, shown in Figure 7, consists of copper tubing placed inside an insulated box that has a protective glass cover. The useful output power from a collector is dependent on many quantities such as location, insolation, angle of incidence, and flow rate. The SRCC collector specification sheets estimate thermal performance for several given atmospheric conditions and temperature differences across the collector. For the collector used in this analysis on a mildly cloudy day with an average temperature difference between the inlet and ambient temperatures, the Solene Chromagen SLCR-40 is expected to output 39 MJ/panel per day.
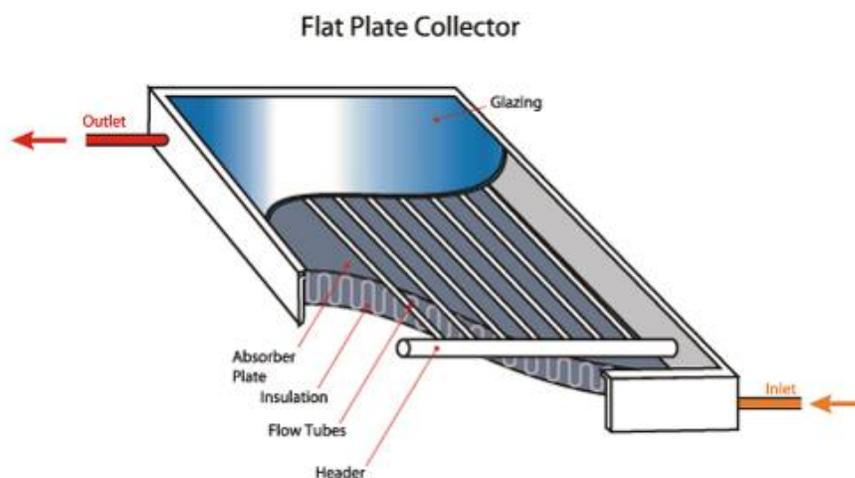
Figure 7. Cross section of a general flat plate thermal collector.

The SDHW system is assumed to be connected by high temperature piping in a way that equalizes the flow rate of the working fluid through the collector array. This will simplify the flow rate and power calculations by ensuring consistent flow and a continuous temperature distribution throughout the collector. All of the pipes within the system are insulated and assumed to have negligible temperature loss. Domestic collector configurations commonly do not have any solar tracking controls so a fixed orientation facing due south with a tilt of 40 degrees is determined by the SRCC document RM-1, Methodology for Determining the Thermal Rating of Thermal Collectors [12].

The pump on the closed circulator loop is a constant speed, impeller driven pump. By fixing the flow rate, a constant speed pump simplifies initial testing and eliminates the need to control and correct for different flow rates throughout the system (Beckman and Duffie, [13]). The initial flow rate of 3.75 gpm within the closed loop causes residences time within the STCS to be limited and, thus, reduce the amount of energy delivered to the water. In an actual collector array, higher flow rates are acceptable, because instantaneous efficiency is dependent on the surface temperature of the collector and thus, higher flow rates will increase the heat transfer rate from the collector to the working fluid (Beckman and Duffie, [13]). In most active systems, a controller operates the initiation of the pump by comparing the temperature on the bottom of the solar storage tank to the outlet of the collector. If there is a significant temperature differential, then energy can be gained and the pump is activated. The current system does not contain a controller, and the pump is assumed to be turned on at the beginning of the solar 'day' when insolation is present,

and is turned off at the onset of solar 'night'. Since the operation of the pump

influences the Q_{par} term of the SEF, a correction was made for the controller, by

comparing the outlet temperature of the STCS to the temperature at the bottom of the

solar storage tank. Whenever this temperature differential is above 2.75°C, the pump

is considered 'on'. This temperature differential is chosen as a conservative estimate

for the setting on an average controller. Since this data is recorded throughout the test,

a conservative correction can be made afterward, for the parasitic energy consumed

by the pump.

Chapter Descriptions

This thesis outlines the implementation of a solar thermal collector simulator

with a multi-tank system and calculates the efficiency of a single and double tank

system. The goal behind these experiments is to confirm the feasibility of testing

solar domestic hot water systems with the STCS and achieving results validated by

SRCC data. The SRCC efficiency ratings will provide a baseline standard to compare

test results to similar commercial systems that are currently available. A testing

procedure has been developed that follows as closely as possible to SRCC guidelines.

Chapter two outlines the specifications and performance of each component of the

current set up. Chapter three explains the SRCC standards and the test methods used

in achieving those values. The results are discussed in chapter four and conclusions

for system modifications and future research are presented in the final chapter. A

detailed description of the LabVIEW code is found in Appendix A and B which

contain descriptions of each virtual instrument along with flow diagrams of the code

architecture.

CHAPTER TWO

System Apparatus

Solar Thermal Collector Simulator (STCS)

In any solar thermal system the collector determines the overall performance. It is the most important component in the system. Previous research completed at Baylor University by Bolton [5], created a Solar Thermal Collector Simulator for a small array of flat plate solar thermal collectors, shown in Figure 8.
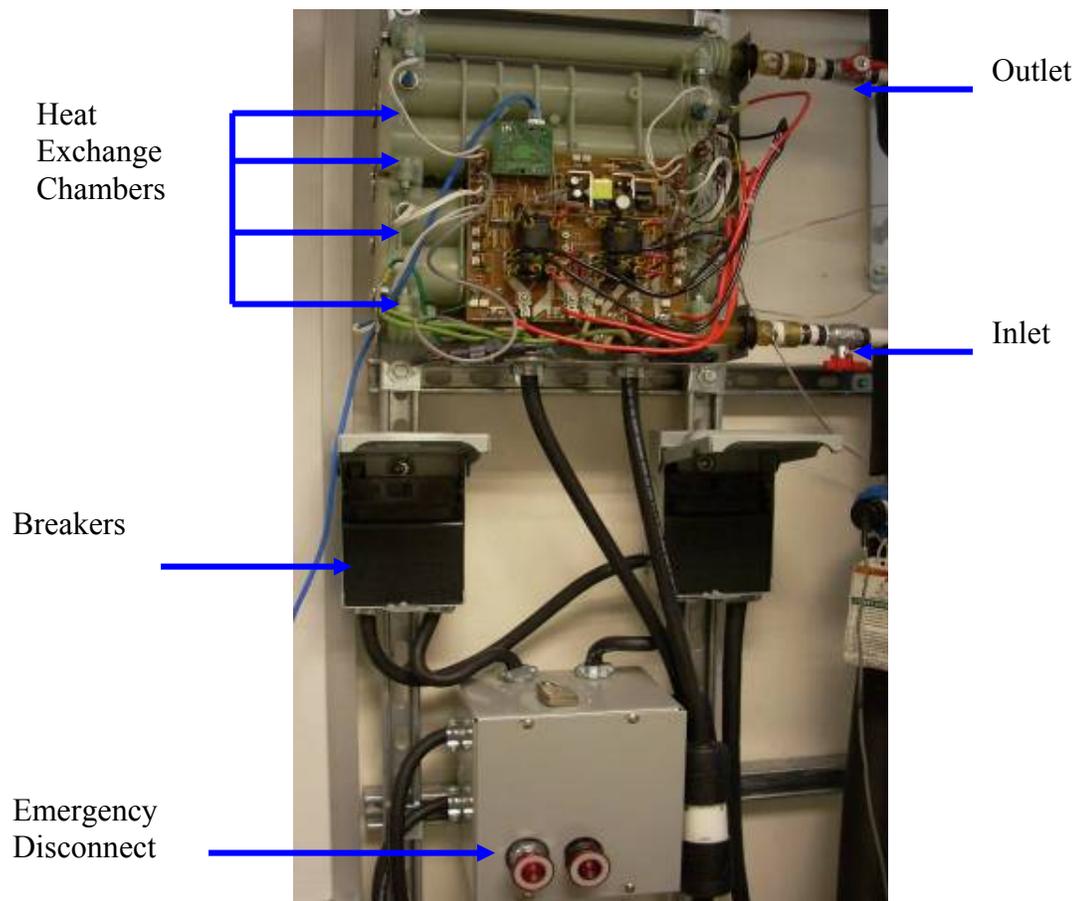
Figure 8. Solar Thermal Collector Simulator assembly [5].

The STCS simulates the interaction between the sun and the solar thermal collectors usually found on the roof of a home and provides repeatable collector specific performance output for a given time period within 7.8 % of theoretical calculations. This is an extremely valuable asset when researching solar technologies, because it allows the user to test various models of thermal collectors and systems without the expense or effort of installing an actual array. The STCS consists of a modified Seisco RA-18 on-demand hot water heater that allows the amount of power delivered to the working fluid to vary depending on the amount of theoretical output power that is desired. The STCS has four heat exchanger chambers and has been modified to output 13.5 kilowatts at maximum power due to the voltage at the available power outlet. Water, the working fluid, is pumped through the chambers shown in Figure 8, gaining energy as it flows. The inlet and outlet temperatures of the collector simulator are measured as well as three intermediate temperatures that monitor for over-temperature conditions. Five R25 thermistors, shown in Figure 9, make up the STCS temperature sensing system, which monitors the inlet, outlet, and three intermediate temperatures.
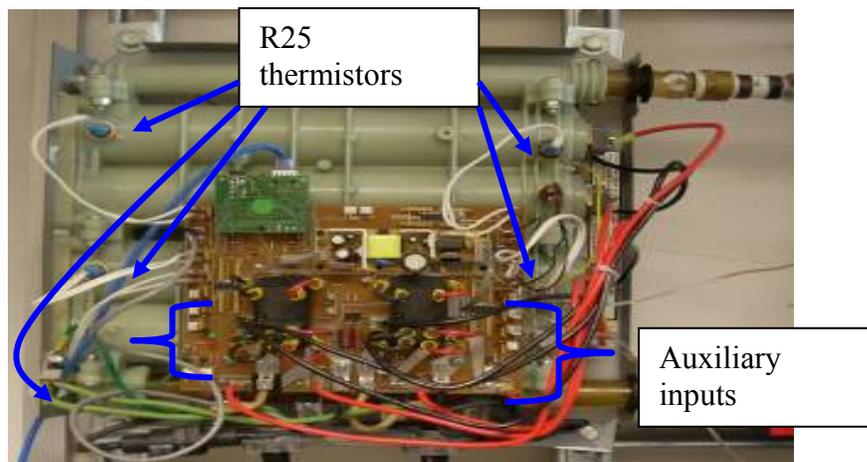
Figure 9. STCS control circuit with temperature sensors.

Seven auxiliary inputs are available on the STCS for additional temperature monitoring throughout the system. Figure 9, displays the location of the auxiliary inputs on either side of the control circuit. Each auxiliary input has three pins: an input, ground, and a 5 volt. A jumper is located next to each port that allows the auxiliary input to be subject to the same current conditions as the five permanent thermistors. If the jumper is removed, the 5V pin provides a signal to the input pin. The inlet and outlet temperatures were calibrated to an accuracy of ±1.015 °C (Bolton [5]). Three K-type thermocouples were used to measure inlet and outlet temperatures of the system as well as the solar storage tank. The inlet and outlet of the STCS is connected to the closed circulator loop on the SDHW system with PEX (High Cross-linked Polyethylene) high temperature pipe and fittings. Multiple safety precautions are implemented on the STCS due to the proximity of 208 V outlets and up to 120 gallons of water. Two breakers and two emergency shutoff switches comprise the manual shutdown of the system. The automatic safety precautions consist of an over temperature switch that operates if the fluid temperature reaches 93.3°C, as well as, a leak detection sensor that eliminates power to the elements if activated. Extreme caution must be taken to ensure that water is *always* in the heat exchanger chambers whenever the STCS is in operation. Damage to the heating elements, controls, and structure of the STCS can occur if operated without a heat transfer medium or if left to stagnate with a no flow condition while power is delivered to the elements. Controlling the STCS is accomplished by communicating power levels, temperatures, and operating codes with an external computer.

LabVIEW User Interface

A computer utilizing National Instruments LabVIEW 8.0 control software

manages the STCS during tests. LabVIEW controls the useful output power from the

collector and monitors system performance. The control software calculates

theoretical output power of an array of flat plate collectors and communicates these

control values to the STCS via Ethernet Universal Datagram Protocol (UDP).

Appendix A contains a detailed user's manual for the LabVIEW program. Appendix

B details the calculations performed in LabVIEW.

Table 2 lists the inputs requested by the user and the outputs provided by the

control software. The user begins by loading a weather data file, followed by location

and collector orientation information.

Table 2. Software inputs and outputs with respective units.

Inputs	Units	Outputs	Units
Weather Data	N/A	Hour of Day (std/solar)	hr
Collector Slope	deg	Total Insolation	kWh/m^2
Collector Azimuth	deg	STCS Inlet Temperature	°C
Collector Area	m^2	STCS Outlet Temperature	°C
Quantity of Collectors	N/A	Ambient Temperature	°C
Incident Angle Modifier	N/A	Mains Temperature	°C
Collector Efficiency Slope	W/m^2°C	Solar Tank Temperature	°C
Collector Y intercept	W/m^2°C	System Outlet Temperature	°C
Tested Flow Rate	Kg/s	STCS Power	W
		Energy Gain	MJ
		STCS Flow Rate	kg/s
		Instantaneous Efficiency	N/A
		Warnings	N/A

LabVIEW displays many outputs that describe the current system behavior

and environmental conditions. Every solar thermal collector commercially

manufactured in the United States must be rated and documented by the SRCC.

Collector data sheets are provided by the manufacturer and specific data from these

sheets regarding the collector efficiency equation, incident angle modifier, and the

tested flow rate must be input to LabVIEW. The specific collector used in this

experiment is a Solene Chromagen SLCR 40 with a total panel area of 7.4 m^2. The

collector parameters can be found in Table 3 and the data sheet in Appendix E.

Table 3. Solene/Chromagen SLCR-40 collector specifications.

Specification	Quantity	
Gross Area	7.4	m^2
Y Intercept	0.735	W/m^2°C
Slope	-5.365	W/m^2°
Incident Angle Modifer ($K_{\alpha\tau}$)	-0.19	
Test Flow Rate	0.82	gpm

The software runs two independently timed loops, one for calculating the

insolation and the other for calculating power to the STCS. Each loop is run on a real

time basis to simulate an actual solar day. The primary goal in simulating an actual

day is to subject the system to energy inputs and outputs that simulates domestic hot

water use. Accurate timing is also critical to ensure available insolation occurs during

the solar 'day' and coincides with energy draws so the tanks can be recharged and

then maintain storage temperatures. The main loop samples once an hour to calculate

solar time, incidence angle, and total insolation. The SRCC document, TM-1,

recommends that critical temperatures are read once every thirty seconds, so the

second loop samples at this frequency and receives a data packet containing twelve

temperature readings, two flow meter outputs, and any error codes that the STCS

sensed ([14]). The desired sampled temperatures are then used to calculate and send

the most updated power required to the STCS.

Storage Tanks

The storage tanks in a solar thermal system are the second most important

component and care in selecting the proper models is crucial to maximizing

performance [7]. A domestic solar hot water heating system normally contains only

one or two tanks, depending on location, budget, and hot water load. The current

configuration at Baylor University contains three tanks; however the middle storage

tank, seen in Figure 10, is bypassed and not utilized during this experiment.
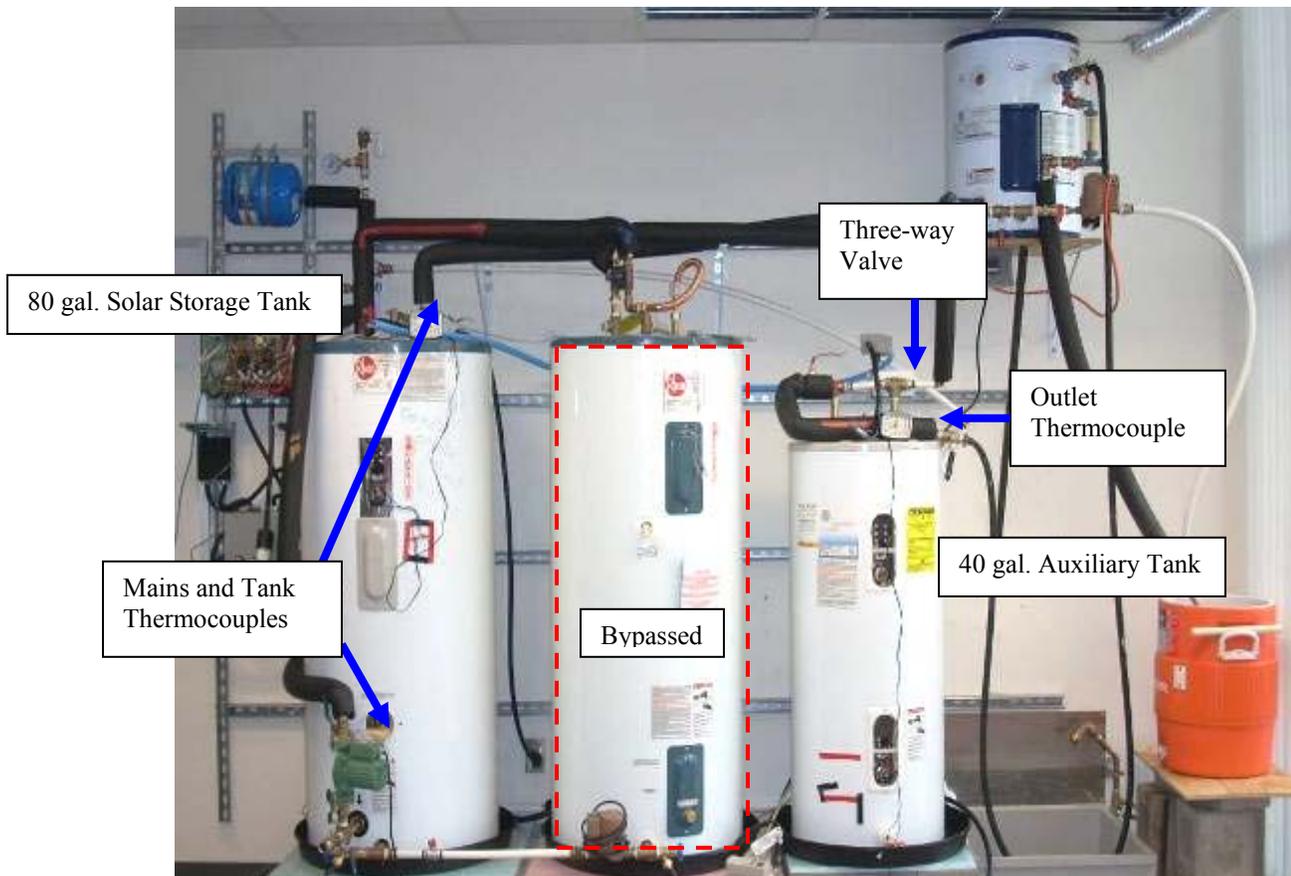
Figure 10. Solar Domestic Hot Water heater simulator.

The SDHW consists of one 80 gallon storage tank and a 40 gallon auxiliary

tank. This allows for testing a single or double tank configuration, which are two of

the most common systems found in domestic solar hot water heating. The solar storage tank is a Rheem 80 gallon solar water heater with an integral wrap around, double wall heat exchanger located on the lower half of the tank. This tank receives power directly from one of the 208 V outlets to energize a single 3300 W auxiliary heating element located at the top of the tank and also contains the mains cold water inlet for the system. The auxiliary tank is a General Electric SmartWater 40 gallon conventional electric water heater. For a single tank configuration, the auxiliary tank is bypassed and the hot water is drawn directly from the solar storage tank. A three-way automated valve is located on the cold inlet port of the auxiliary tank, but it is disabled and manually overridden for switching configurations. A detailed procedure to switch the orientation of the automated valve can be found in Appendix F.

A two tank system will use the solar storage tank to preheat the water, and if necessary, provide additional energy in the auxiliary tank to bring the water to the system set point temperature by energizing two 3300 W resistive heating elements. The tanks are secured on insulated concrete bases with drain pans and have sloped drainage piping. There are three K-type thermocouples in the tank array that are connected to auxiliary ports on the STCS, shown in Figure 9. The inlet from the mains, solar storage tank temperature, and the system outlet temperature are reported to the user once every thirty seconds so the SEF and SF may be calculated and a temperature profile of the system behavior may be monitored. An Omega flow totalizer is installed on the system outlet at the auxiliary tank to monitor the volume of water drawn during each solar 'day'.

Circulator Pump

An active system requires components that are externally powered such as pumps, controllers, and automatic valves. For the closed circulator loop, a 1/8 hp Taco 009 cartridge pump capable of 0-8 gpm and 0-34 feet of head was selected. It is located at the base of the solar storage tank and will force water through the STCS and the heat exchanger on the closed loop as shown in Figure 11. The low power consumption of the pump is an important variable to consider when researching high efficiency systems.
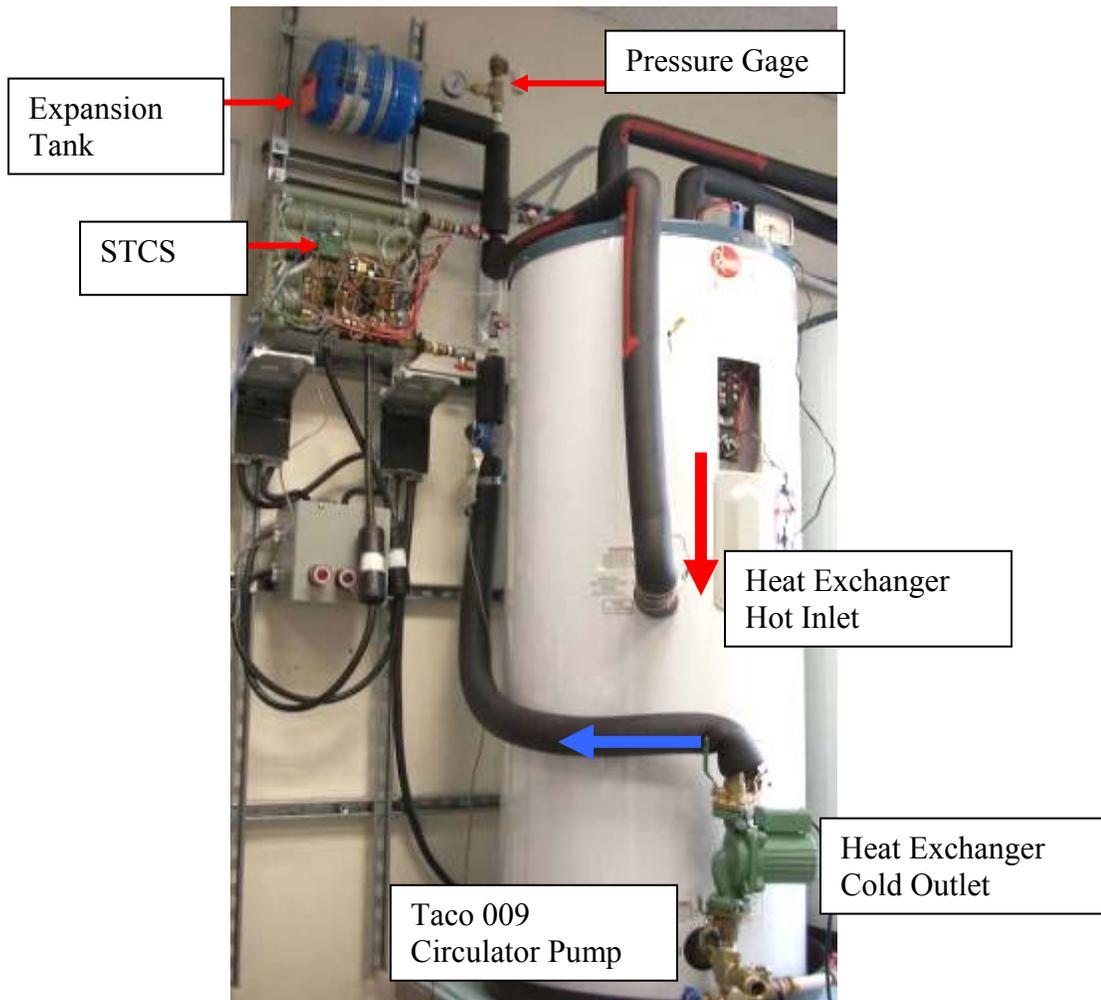
Figure 11. Closed circulator loop assembly.

The Taco pump is also recognized for extremely low maintenance and ease of servicing, which will benefit future research on this system. The 009 model is an impeller driven, constant speed circulating pump that is located at the exit of the heat exchanger. There are two ball valves on the pump, one located on both the inlet and exit flanges, which greatly assist filling and pressurizing the closed heat exchanger loop. The pump will be manually controlled to simplify parasitic energy calculations. Whenever insolation is present in the solar profile and power can be calculated, the pump will be activated. Insolation occurs from 8:00 am through 5:00 pm in the OG 300 profile, thus providing a quantifiable amount of power be delivered to the system, otherwise the power will be zero and the pump can be turned off. This will avoid any possible damage to the STCS and the system. A correction factor to account for the absence of a differential controller is implemented to conservatively estimate the time the pump would have been turned off due to a temperature difference less than 2.75°C between the outlet of the STCS and the bottom of the solar storage tank.

Expansion Tank

A given amount of losses are inherent in the closed loop system requiring extra head to be overcome by the pump. In order to ensure safety and longevity of the pump, precautions must be taken to avoid cavitation. A WellSaver diaphragm tank is placed after the hot side exit of the STCS. This tank is pressurized to 20 psi and absorbs any pressure surges due to initial start-up of the pump by compressing a cushion of air within the tank. This cushion of air is separated from the water by a rubber diaphragm in the middle of the tank. The closed loop pressure can be monitored from a pressure gage located near the expansion tank. For any closed loop

system being heated, a small amount of thermal expansion of the working fluid will occur. An increase in volume of a pressurized closed loop can be potentially dangerous if temperatures and pressures get too high. City mains will pressurize the system to 60 psi, however this pressure will not benefit performance so the pressure should be reduced to below 60 psi for safety precautions. The closed loop pressure can be monitored on a pressure gage mounted at the top of the loop.

Flow Meters

A Signet 8510 Rotor-X Flow Sensor measures the actual flow rate of the closed heat exchanger loop through a paddle wheel style flow sensor that has accuracy of 1% full-scale linearity. The flow sensor is a pulsed output variety, meaning that for every gallon of water that passes through the sensor, a given number of 5 volt pulses are sent to the STCS, counted, and then reported to the user. The K-Factor, which is the calibrated number of pulses per gallon for ¾ in PVC pipe, is 272.72. This sensor is placed after the exit of the pump on the cold side of the heat exchanger at least 50 inside pipe diameters downstream to ensure fully developed flow. The Rotor-X is used in conjunction with a Signet 8550 Flow Transmitter to visualize the current flow rate and condition the signal to the STCS with an accuracy of $\pm$ 0.5Hz. The K-Factor is manually programmed into the transmitter to accurately measure the signal from the Rotor-X. The combination of flow sensor and transmitter provide an uncertainty in the flow rate readings of the closed loop of $\pm$ 0.0459 gpm. The flow meter measurements are used in updating power calculations.

Mains Chiller

Testing conditions dictate the water entering the solar storage tank from the mains to be 14.4 °C to simulate an average mains temperature that may be encountered in various locations. The temperature of the mains at Baylor University varies from 15 °C to 21 °C depending on time of day and year, water load in the building, and location in the building. The sporadic nature of the mains presents a difficult challenge for repeatable results that must be compared to strict SRCC data. In order to overcome this, a chiller was developed and implemented that effectively reduces and maintains the temperature of the mains water to approximately 14 °C.

In Figure 12, the mains are connected to an upper inlet port through which a gate valve controls the flow rate to the SDHW system. The lower port contains the outlet for the chilled water and heat exchanger loop. Each energy draw consists of approximately 11 gallons of heated water which must be replenished by the mains while simultaneously maintaining system pressure. Over-sizing the chiller tank, provides three advantages: a more consistent thermal mass of cool water to refill the storage tank, less time required to chill the water for the next test, and a higher resistance to temperature increase during mixing with the pressurized mains. A K-type thermocouple probe, shown in Figure 12, was inserted into a thermowell to monitor the temperature of the bottom of the tank. This will monitor the coldest region of the tank and also the initial thermal mass of water to enter the solar storage tank during energy draws.
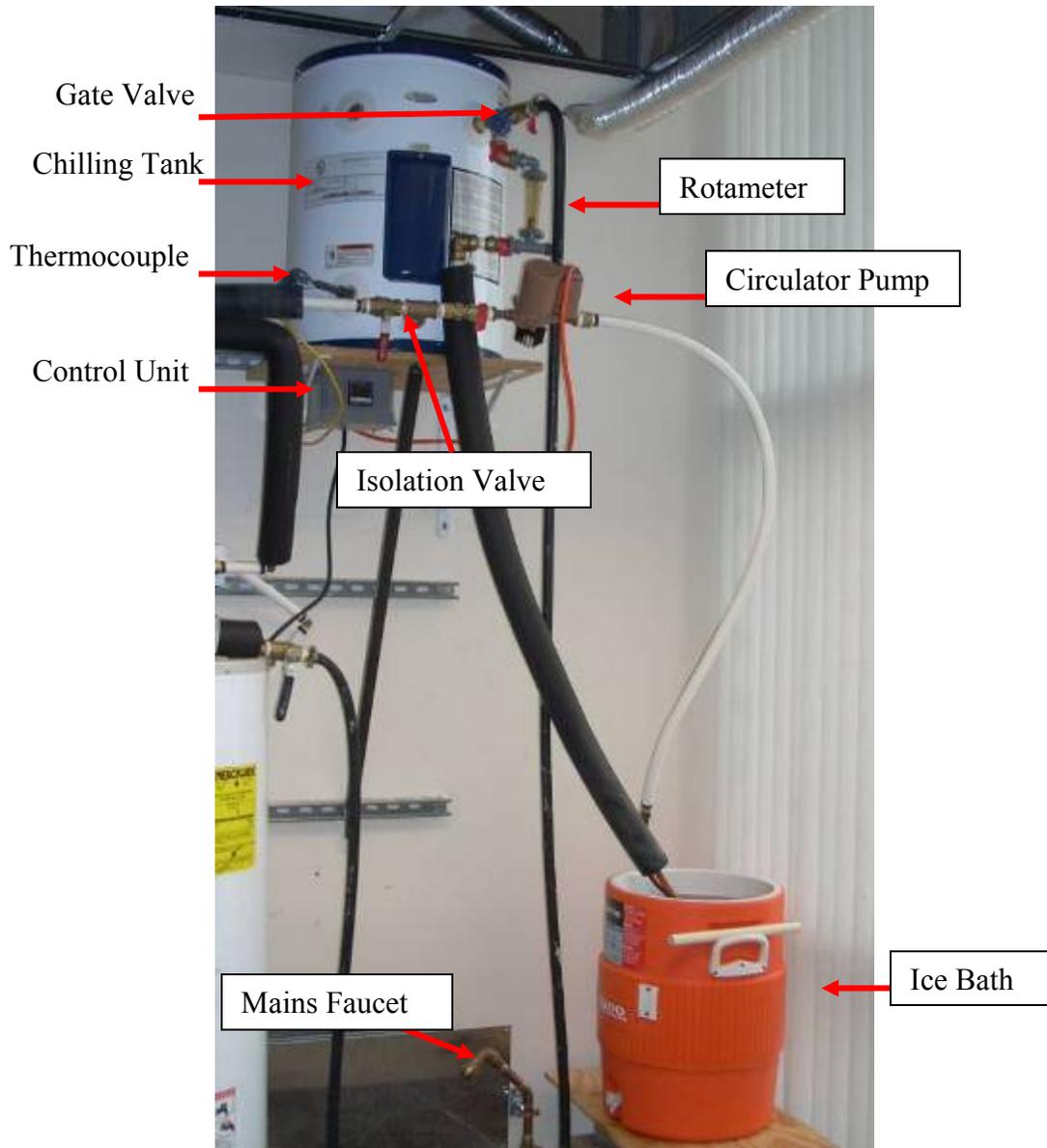
Figure 12. Mains Chiller Assembly

A Dwyer-Love temperature control unit acts as a solid state relay, with input from the thermocouple, to restrict AC power to the pump when the set point is reached. The Taco 003 circulator pump is capable of 0-5 gpm with a range of 0-5 feet of head. Water is circulated through the bottom of the tank into an insulated ice bath containing a heat exchanger, consists of 60 ft of 0.5 in. diameter copper tubing,

and then back to the top of the tank to mix. This cycle continues until the set point temperature is reached and the pump is shut off by the controller. The chiller is isolated from the mains during operation by two valves on the inlet and outlet of the tank. When a draw is initiated, the isolation valves are opened and the mains pressure forces chilled water in the solar storage tank, expelling an equal volume of hot water to the system outlet. A single valve controlling the flow presents an over-determined system where temperature will change as a function of flow rate. Since an approximate temperature of 14°C is desired, the water can be chilled below this point to account for mixing and any other increases in temperature. The pump and heat exchanger are connected in parallel with the tank, mains, and SDHW system, thus, presenting resistance to flow and a possibility of back flow into the pump causing damage. A check valve was placed after the pump to avoid this situation and force flow through the tank initially. A small rotameter is placed before the inlet to the tank to indicate flow through the circulator pump. After the second draw, more ice will need to be added to the insulated container to maintain the ice bath near 0°C. Detailed drawings, wiring diagrams, and calculations can be found in Appendix F regarding design of the mains chiller.

Kill-a-Watt Power Meters

The Taco 009 circulator pump will operate during the solar hours where insolation is available. The Solar Energy Factor defines parasitic loads to be pumps and any other devices that require external power. The energy consumed by these devices must be recorded and included in the calculation of Q_{par} from Equation 2, in Chapter 1. A P3 International Kill-A-Watt power meter is utilized for these readings.

The Kill-A-Watt plugs into a standard110V wall outlet and any device requiring 110V and less than 15 A can be plugged directly into the meter. A variety of measurements including voltage, current, power, and frequency along with energy can also be read directly from the meter. The display can be calibrated to measure energy in units of kilowatt hours (kWh) with an accuracy of 0.2% of the reading. As long as the unit is energized it will meter a continuous reading. Unplugging it, will clear all previous data, care must be taken with timing and operation to ensure accurate readings. At the conclusion of the test, the total energy consumed by the pump can be read from the display and recorded.

Analog Power Meters

The auxiliary energy to each resistive heating element is a critical value that is necessary when calculating the solar energy factor. A pair of analog clock timers has been developed to activate when the element receives current. Each clock has been modified from operating on 110V to operating on 208 V by adding a bank of six 33kΩ resistors as seen in Figure 13.
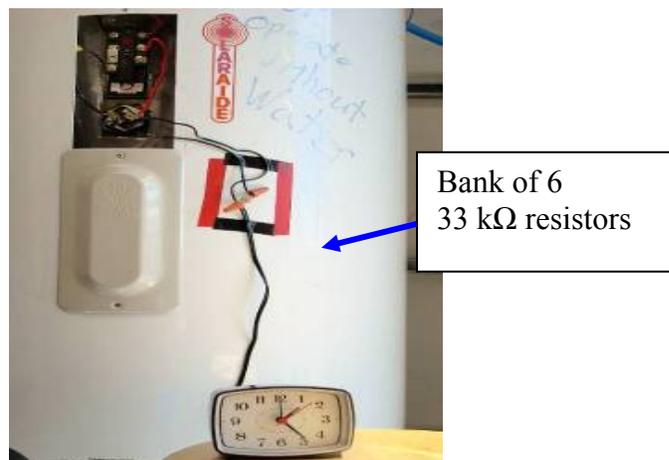
Figure 13. Analog power meters.

Each clock is wired to the terminals of a resistive heating element and the time can be zeroed for each test. For a single tank test, only one analog meter will be used on the upper element of the solar storage tank. At the conclusion of each test the time elapsed can be read from the position of the hour and minute hands. It is important to record the exact time the element was active at the conclusion of each test, because the clocks will continue to log time as long as power is provided to the tanks. This value, along with the power for each element which is initially measured with an Amprobe ACD-41PQ power meter, is used in calculating the auxiliary energy consumed by the heating elements. For the double tank configuration, two clocks were implemented on the auxiliary tank, one for the upper and lower element respectively.

CHAPTER THREE

Experimental Methods

The SRCC OG 300 document pertains to strict guidelines that must be followed in order to accurately rate the performance of commercially available solar thermal systems. This procedure adheres as closely as possible to these guidelines utilizing commercially available storage tanks, circulator pumps, piping, and connections. It also accounts for laboratory methods and modifications such as the installation of flow meters, power meters, and thermowells. The current configuration will allow any flat plate collector array with a maximum power output of 13.5 kW utilizing the SRCC OG 300 solar profile to be evaluated.

Before any testing may occur, the STCS circulator loop and the storage tanks must be filled with water to prevent any damage to the system. An air relief valve is located at the highest point in the system after the outlet of the STCS. Figure 14 follows the closed loop sequence listed below.

Closed Loop Filling Procedure

1. Connect the filling hose from the mains to the filling valve beneath the inlet of the pump.
2. Ensure that the air relief valve on the outlet of the STCS is open, as well as, the filling valve and the valves on either side of the pump.
3. Slowly turn the mains water completely on until water flows consistently out the air relief pipe to the drain and that the STCS is filled.
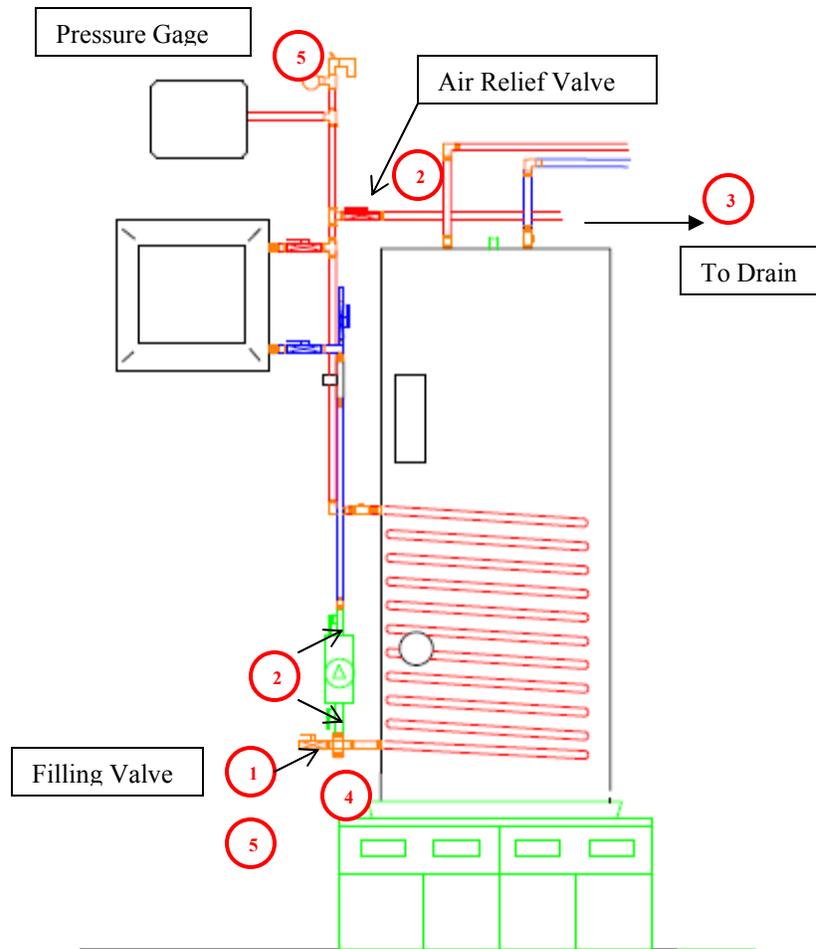
Figure 14. Filling procedure diagram.

4. Close the air relief valve and then close the filling valve when the loop pressure is approximately 40 psi for safety. Ensure the loop retains pressure and any air is prevented from entering the system.

5. Turn the mains faucet off. The pressure in the closed loop may be monitored by the pressure gage near the expansion tank and reduced by slightly opening the filling valve.

6. Finally, turn the pump on and listen for air bubbles, the pump should be running silently. If air bubbles do exist, repeat steps 2-5 until there are no air bubbles.

Storage Tank Filling Procedure

Once the closed heat exchanger loop is filled, proceed to filling the storage tanks. For the majority of operation, this procedure will be performed once, unless maintenance must be performed on one of the tanks or thermocouples. It is essential to fill the chiller system first and ensure that all air bubbles are removed from the heat exchanger coil to avoid vapor locks in the pump. A diagram outlining the valves and connections on the mains chiller can be found in Figure 15.

1. First, ensure the mains chiller is connected to the water faucet and that the isolation valve is closed and the gate valve is open. Unscrew one of the auxiliary port plugs on the top of the chiller to allow air to escape. Ensure the rotameter is fully open as well.

2. Turn on the mains and allow the chiller to fill paying close attention to the level of the water. Once the chiller is full, close the gate valve and replace the auxiliary port plug on the top of the tank.

3. With the isolation valve and gate valve closed, activate the controls, and let the pump run, to flush out any air bubbles. If necessary, open the gate valve to increase pressure in the chiller to free any trapped air.

4. Next, open the draw valve and then the isolation valve to allow the storage tanks to fill with water from the mains.

5. When the tanks are full, water will flow consistently out the draw valve. Close the draw, isolation, gate, and mains valve sequentially to pressurize the system as shown in Figure 16. This sequence will also be used to conclude energy draws.
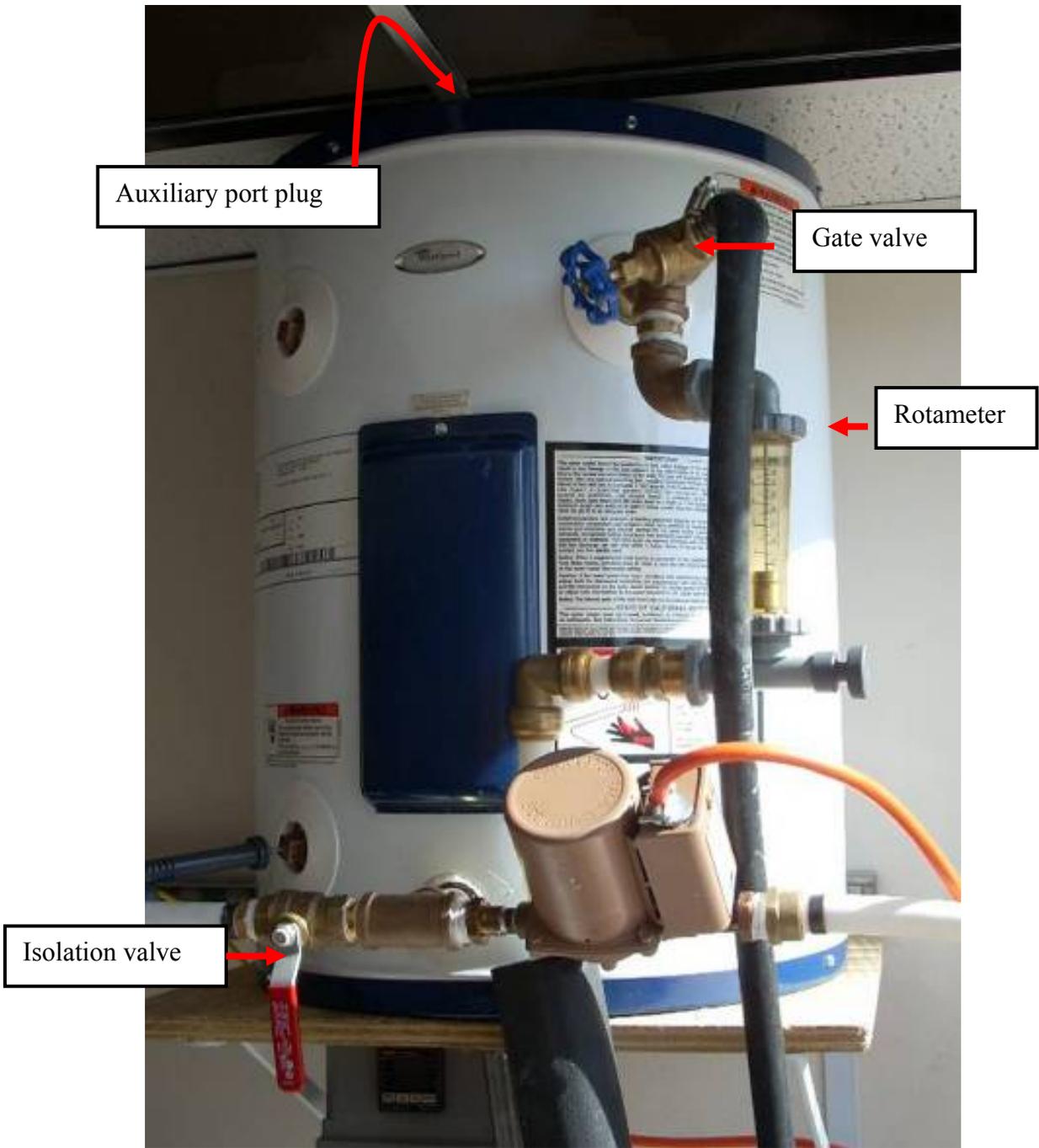
Figure 15. Mains chiller tank and valve assembly.
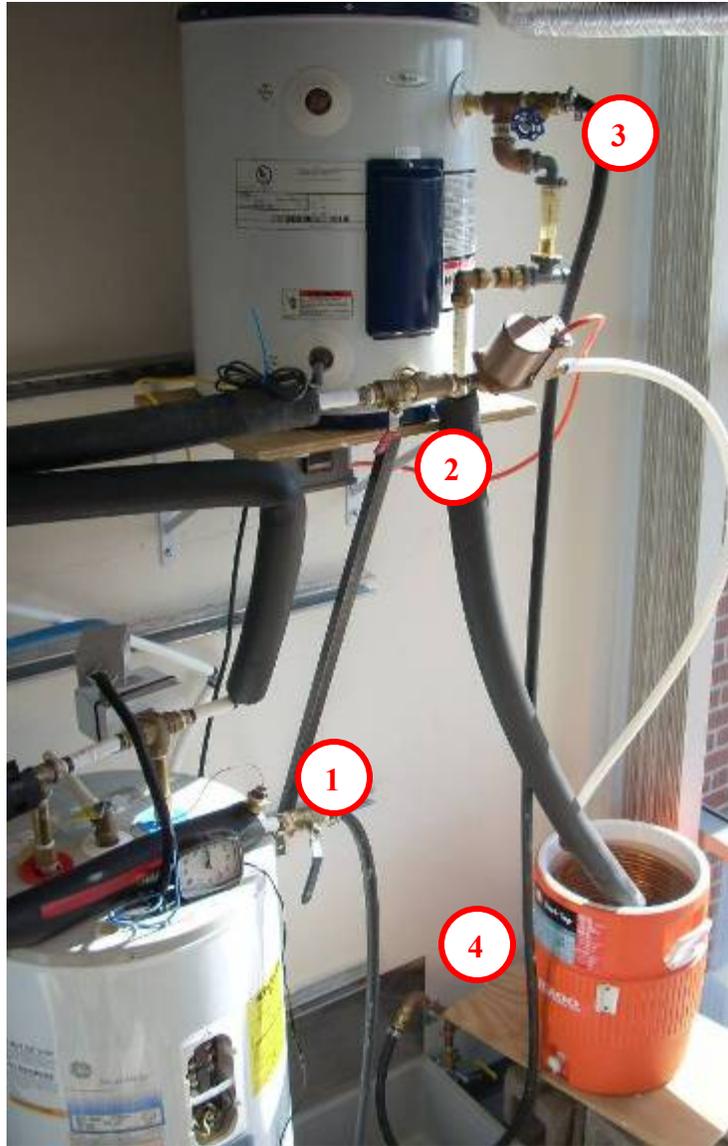
Figure 16. Sequential draw valve procedure.

After the circulator loop and storage tanks are filled, the system must be configured to either a double or single tank system by switching the automated valve found on top of the auxiliary tank and appropriately wiring the water heating thermostats. A procedure for sequencing the automatic valve can be found in Appendix F. The following diagrams illustrate the wiring configuration and procedure used to appropriately wire the system.

Single Tank System Wiring Diagram

1. Make sure that the water heater is unplugged. Remove the thermostat cover on the solar storage tank and identify the following terminals found in Figure 17.

2. Connect the black element wire to the lower terminal 2 on the thermostat and the red element wire to the upper terminal 4 on the temperature limit control.

3. Ensure that the extra red and black wires that energize the auxiliary tank are removed from terminals 1 and 3 and protected with electric tape or wire nuts.

4. Unscrew the terminal of the heating element, being careful not to drop the screws into the insulation.

5. Attach the ring connectors of the analog power meters to the respective terminals, securing each with the element terminal screws. It does not matter which wire of the power meters goes to which terminal on the element.

6. Plug the system into an available 208 V wall outlet.
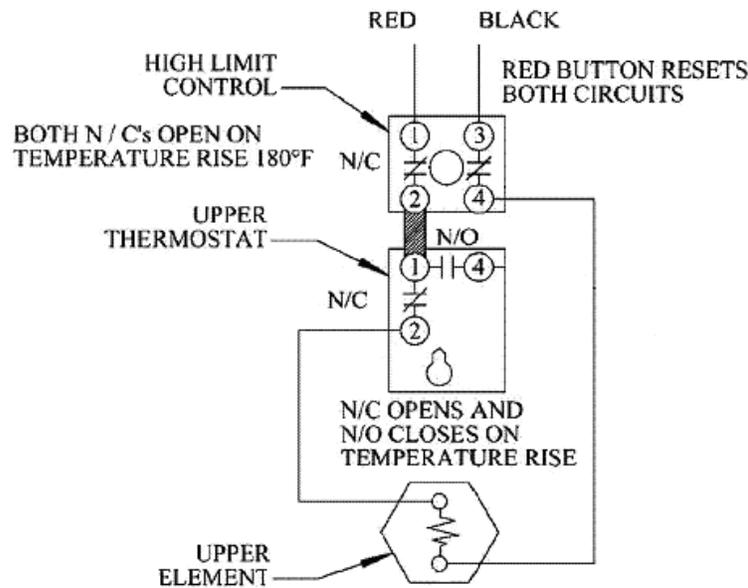
Figure 17. Single tank wiring diagram.

Double Tank Wiring Diagram

1.   Make sure that the water heater is unplugged. Remove the upper and lower thermostat covers on the auxiliary tank and solar storage tank and locate the terminals found in Figure 18.

2.   Disconnect the element of the solar storage tank and connect the auxiliary red power wire to the upper terminal 3 and the auxiliary black power wire to the lower terminal 2.

3.   On the auxiliary tank ensure that the black power wire is connected to the upper terminal 1 and the red power wire is connected to the upper terminal 3.
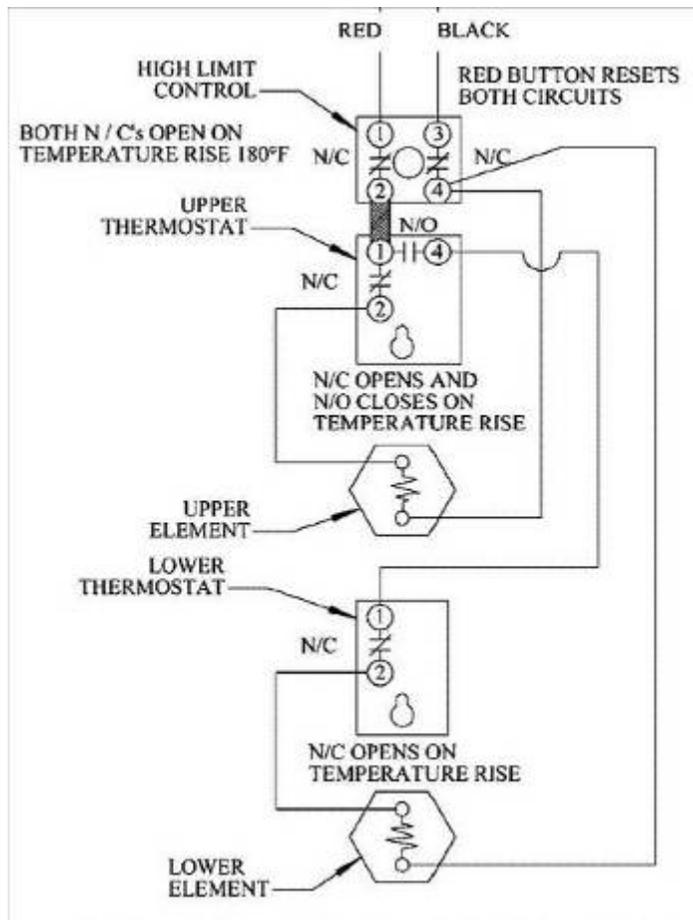
Figure 18. Double tank wiring configuration.

4. Connect the yellow element wire to the lower terminal 2 on the thermostat and the blue element wire to the upper terminal 4 on the temperature limit control.

5. A red wire and black wire is located to the right of the upper thermostat and energizes the lower element. Connect the black wire to the lower terminal 4 on the thermostat and the red to the upper terminal 4 on the temperature limit control along with the blue wire from the upper heating element.

6. Unscrew the terminals of the upper and lower element and attach the ring connectors of the analog power meters to the respective terminals, securing each with the element terminal screws. It does not matter which wire of the power meters goes to which terminal on the element.

7. Plug the system into an available 208 V wall outlet.

The SRCC guidelines specify that the draw flow rate be approximately 3 gpm. A stop is placed on the mains valve to throttle the flow rate, while the gate valve on the mains chiller is for fine adjustments. In order to calibrate the position of the gate valve, a volume of water is allowed to collect in a bucket over a one minute period out of the draw valve to determine the mass flow rate. The bucket is weighed and the mass of water collected is converted to gallons. Approximately 11.4 kg or 25 lbs of water should be collected over a one minute period. Appropriate adjustments are made to the position of the gate valve depending on the sampled flow rate. The position is recorded and the valves are closed. An exact flow rate of 3 gpm is not crucial to attain accurate results, because the total mass of water drawn determines the net energy extracted from the system. The mass of water drawn can be adjusted

throughout the test by monitoring the Omega flow totalizer to allow a greater volume of water to exit in order to achieve the desired net energy.

After filling the circulator loop, storage tanks, and respectively wiring the system, several initial measurements must be made before the testing can begin. During testing the elements on the storage tanks will be energized and the power they receive must be measured in order to calculate the Q_{aux} term of the SEF. To do this, each respective element is turned on with the thermostat set to approximately 57.2°C and the power is measured using an Amprobe 41PQ power meter. This procedure is performed on the single element of the main storage tank or both elements of the auxiliary tank during the preheating period.

In normal operation of a water heater, the system must reach the system set point temperature in order to provide enough hot water to the load and simulate preheating from the previous solar 'day'. A steady state temperature of 57.2°C ± 2.8°C specified by SRCC OG 300 section 7.3 will be the initial set point for this experiment. Set the thermostat on the respective tank to the approximate location of 57.2°C. The resolution on commercial hot water heaters is very poor and an approximation shown in Figure 19 is used as the set point of 57.2°C. The temperature on the upper and lower portion of the auxiliary tank can be monitored using surface mounted thermocouples. Steady state on the solar storage tank can be achieved the same way as the auxiliary tank, except for the lower half of the tank which does not posses an element. To preheat the bottom of the tank, the circulator pump is turned on and 1500 W is hardwired to the STCS from the control software

and the STCS is allowed to operate until the thermocouple inside the bottom of the
tank reads the appropriate temperature of 57.2°C.
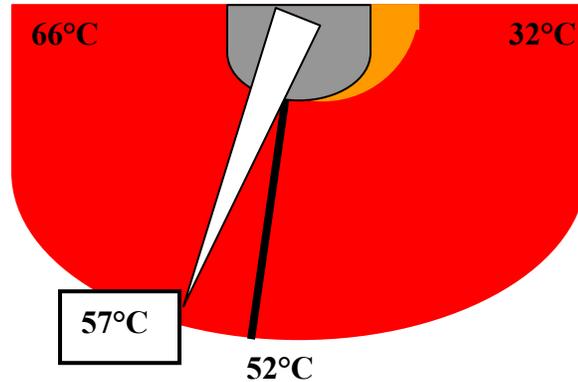
Figure 19. Auxiliary element thermostat set point.

The system will take approximately two hours to reach a steady state
temperature of 57.2 °C. Exact temperatures are not critical for this portion of the test,
because a uniform temperature distribution in this range cannot be determined due to
thermostatic control limits and tank stratification. However, care should be taken to
achieve 57°C to maintain consistency in testing conditions. Once the system has
reached steady state conditions, return each analog power meter to the zero position
of 12 o'clock by adjusting the appropriate knob on the back of the timer.

Ambient system environmental conditions are also specified to be 19.7°C by
the OG 300 section 7.3 displayed in Table 1. The temperature in the lab has been
adjusted by Baylor University Facilities Department to approximately 19°C.

The weather and collector specifications can now be input to the LabVIEW user
interface following the detailed instructions found in Appendix A. Once the input

data has been entered, the testing can begin. LabVIEW will monitor system temperatures, flow rates, output power of the STCS, and timing of the system.

Mains Chiller procedure

Once the main storage tanks have reached steady state conditions and the beginning of the solar 'day' is reached, the mains chiller can be initiated by the following procedure. The most convenient time to activate the mains chiller is during the first hour of insolation preceding the first energy draw.

1. Fill the insulated container to the top with ice adding water until a thick slurry is formed. More ice must be added to maintain a constant temperature of 0°C.

2. Ensure the thermocouple probe is inserted into the thermowell with good contact being made with the wall. *Note* the probe *must* be connected to the controls before they are turned on to ensure the self-test procedure operates appropriately.

3. With the isolation and gate valves closed from the storage tank filling procedure, activate the controls by plugging them into an open 110V outlet. The process variable will display the current temperature above the set point variable. The pump will activate if the current tank temperature is above the set point and will deactivate when the set point is achieved.

4. Program the Dwyer-Love controls to a set point of 13.8°C using the procedure found in Appendix F. *Note* the set point is lower than the test specifications to account for mixing and temperature gains in the piping.

The chiller system will be active throughout the portion of the solar 'day' requiring energy draws. More ice will be necessary to maintain the ice bath

temperature at 0°C and can be procured from Aramark facility services at the Bill Daniel Student Union Building at Baylor University. After the final energy draw, the mains chiller can be deactivated by simply unplugging the controls from the outlet. The 19 gallons of water in the mains chiller will cool to the set point temperature in approximately 35 minutes. Calculations pertaining to the prediction of the performance of this basic heat exchanger can be found in Appendix F.

In order to quantify the energy delivered to the load, the SRCC has designed a set of energy draws that represent average home hot water usage. The six draws are scheduled to begin at 9:30 am solar time proceeding an hour after the first and consist of approximately 7,217 kJ and 11 gallons of water at a flow rate of 3 gpm. Each draw will last approximately four minutes depending on the flow rate. A net energy draw of 43.302 MJ is desired and can be achieved by adjusting the volume of water collected during each hour. LabVIEW will indicate when each draw should occur with a green light indicator and that occurs for five minutes beginning at each draw. Along with providing a visual sign, the indicator also activates a LabVIEW control to concatenate a 'D' on the end of each temperature measurement to specify that a draw has occurred for simplified data reduction. According to the SRCC OG 300 solar profile, insolation does not begin until 8:00 am solar time; at this point the pump must be turned on to begin recording parasitic energy as well as, avoiding stagnation within the STCS heating chambers and potential damage to the system. During solar 'night', there will be no insolation available and, thus, no power calculated so the pump can be turned off.

The schedule in Table 4 defines the times that each draw and recharging cycle of the solar storage tank should occur. The solar profile contains 15 hours of solar 'night' which account for stand-by losses in the tanks and auxiliary element usage.

Table 4. Standard weather profile draw schedule (solar time).

Time	Procedure
12:00-8:00 am	Solar night, beginning of test
8-9:30 am	Insolation begins, pumps activated
9:30 am	1st Draw
9:35-10:30 am	Solar tank charge
10:30 am	2nd Draw
10:35-11:30 am	Solar tank charge
11:30 am	3rd Draw
11:35-12:30 am	Solar tank charge
12:30 pm	4th Draw
12:35-1:30 pm	Solar tank charge
1:30 pm	5th Draw
1:35 pm-2:30 pm	Solar tank charge
2:30 pm	6th Draw
2:35-5:00 pm	Solar tank charge, end of insolation, pumps deactivated
5:00 pm-12:00 am	Solar night, end of test

Energy Draw Procedure

1. From the LabVIEW timer, ensure that the first draw begins at 9:30 am solar time.

2. First, open the mains to the indicated valve stop, then adjust gate valve to the desired flow rate position.

3. Now open the isolation valve fully, then the draw valve to allow 11 gallons to flow into the drain, monitoring the volume by the Omega Flow Totalizer.

4. After finishing the draw, close the draw valve, then the isolation valve, and finally the gate valve in that order. This will allow the system to remain pressurized and the chiller to activate cooling of the next batch of water.

5. Allow the system to recharge for the next hour and perform steps 1-4 again at 10:30 am solar time, continuing to 2:30 pm solar time.

After the final energy draw, the system must be allowed to continue operating until the end of the solar profile, which terminates at solar hour 24 or solar hour 17 depending on the file implemented. The latter part of the test will consist of energy gains from insolation and auxiliary heating to compensate for standby losses.

At the conclusion of the test, the energy consumed by the circulator pump must be recorded from the Kill-A-Watt power meter. Also, for the respective auxiliary element, the time energized must be read from the analog power meters. These values will be incorporated into the calculations regarding parasitic and auxiliary energy loads found in Chapter 1. Throughout the test, LabVIEW records several quantities for further data analysis including inlet and outlet of the STCS, mains temperature, flow rate of the closed loop, solar storage tank temperature, and useful power.

CHAPTER FOUR

Results

The test plan devised for this experiment resulted in two tests each of a single

and double tank configuration to show that the system can produce realistic and

repeatable results. In order to verify the results, each respective system's

performance was compared to solar designs that are commercially available from

Solene. The testing conditions were controlled within experimental limits, according

to Section 7 of the OG 300 document.

Test Conditions

The environmental and procedural test conditions set forth by the SRCC are

referenced to the U.S. Department of Energy's Test Procedure for Water Heaters

[15]. The SRCC leaves out several crucial details found in the OG 300 document

including error limits on all of the specified conditions. Table 5 outlines the current

test conditions in the laboratory, the SRCC specifications, and the Department of

Energy limits.

Table 5. Testing condition criteria

Condition	Baylor	SRCC	DOE
Environmental Temperature	21.2 °C	19.7°C	18.3-21.1°C
Water Mains Temperature	14.5°C	14.4°C	14.4°C ±1.1°C
Auxiliary Set Temperature	57.2°C ±3°C	57.2°C	57.2°C ±2.8°C
Approximate Total Draw Volume	68.2 gal	64.3 gal	64.3 gal
Draw Rate	3 gpm ±0.25gpm	3 gpm	3 gpm ±0.25gpm
Total Energy Draw	42.838 MJ	43.302 MJ	NA

The ambient environmental temperature is difficult to control and must be monitored by facility management at Baylor University. However, this variable has the least impact on the tests since it was only 0.1°C higher than the SRCC and DOE standards. The water mains temperature highly influenced the amount of energy needed to maintain the stored water at the desired temperature. Great care was taken to control this variable by implementing the mains chiller to bring the inlet water to a uniform temperature. The DOE test does not specify a net quantity of energy drawn to simulate hot water usage, but requires a fixed volume of water to be drawn instead. The SRCC modified the test conditions from the DOE requirements to require the draws that simulate hot water usage be based on energy rather than volume. This allows the ability to vary flow rate or draw volume to attain the correct net energy draw.

The auxiliary set temperature for the electric heating elements was the most sensitive variable in the test conditions and was also the most difficult to control due to the low resolution on the commercial thermostats. A true average tank temperature cannot be measured by the surface mounted thermocouples placed near the thermostats. The thermocouples do provide an approximation of the internal tank temperature however, conduction through the metal tank can mask any temperature variation. The solar storage tank did contain a threaded port into which a thermocouple was placed to measure the temperature in the middle of the tank bottom. Figure 20, displays a picture of the thermocouple used to measure the bottom of the solar storage tank and the location of this thermowell with reference to the tank.

Several iterations were made to calibrate the thermostat to the appropriate set point temperature. This was vital to achieve accurate results because the thermostats directly controlled the activation of the auxiliary heating elements.
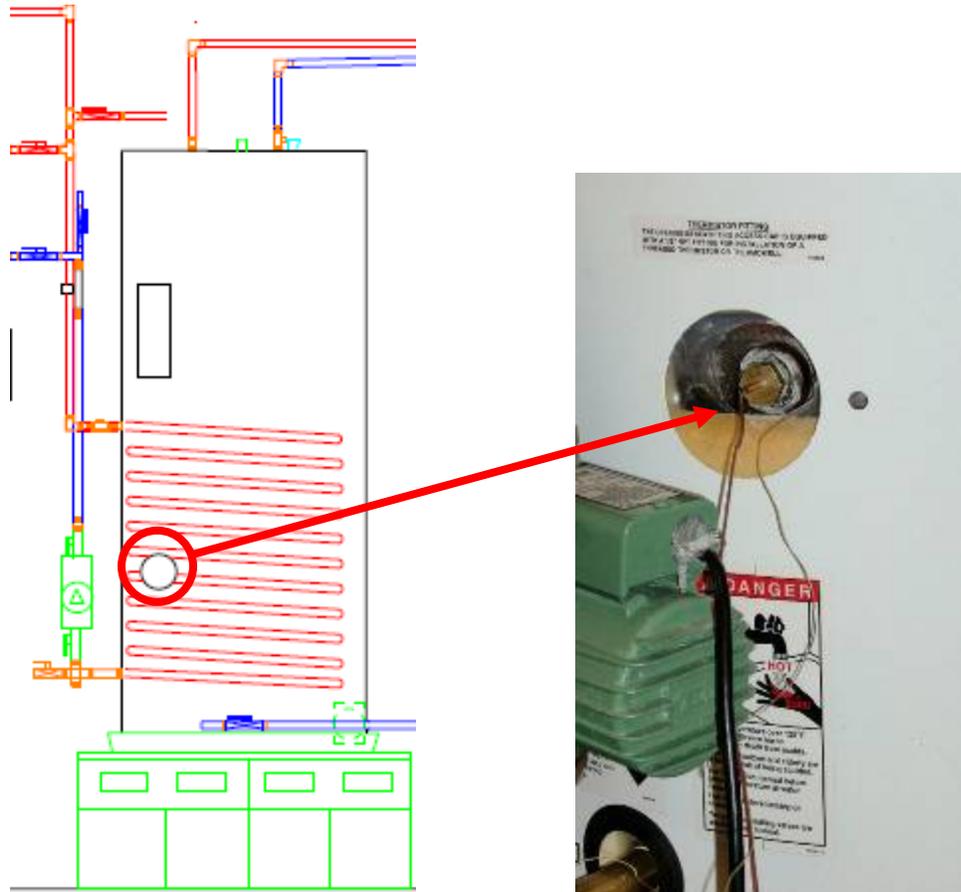
Figure 20. Location of threaded thermowell and surface mounted thermocouple on solar storage tank.

The DOE specifies the test to begin when the tanks are fully mixed to the set point temperature of 57.2°C ± 2.8°C. This condition was reached by varying the temperature of the thermostats and running the STCS at a fixed power level. During preheating and steady state conditions, temperature readings were made based on the thermocouples at the top and bottom surfaces of the tank.

A single tank system was subject to the insolation and ambient temperature data from the solar profile set forth in the OG 300 document and allowed to operate for 24 hours, simulating hot water usage during the solar 'day' and standby losses during solar 'night'. The current configuration was very similar to a Solene SLCR80DC-80DB drain back system shown in Figure 21, using water as the working fluid [16]. The system specification sheet can be found in Appendix E.
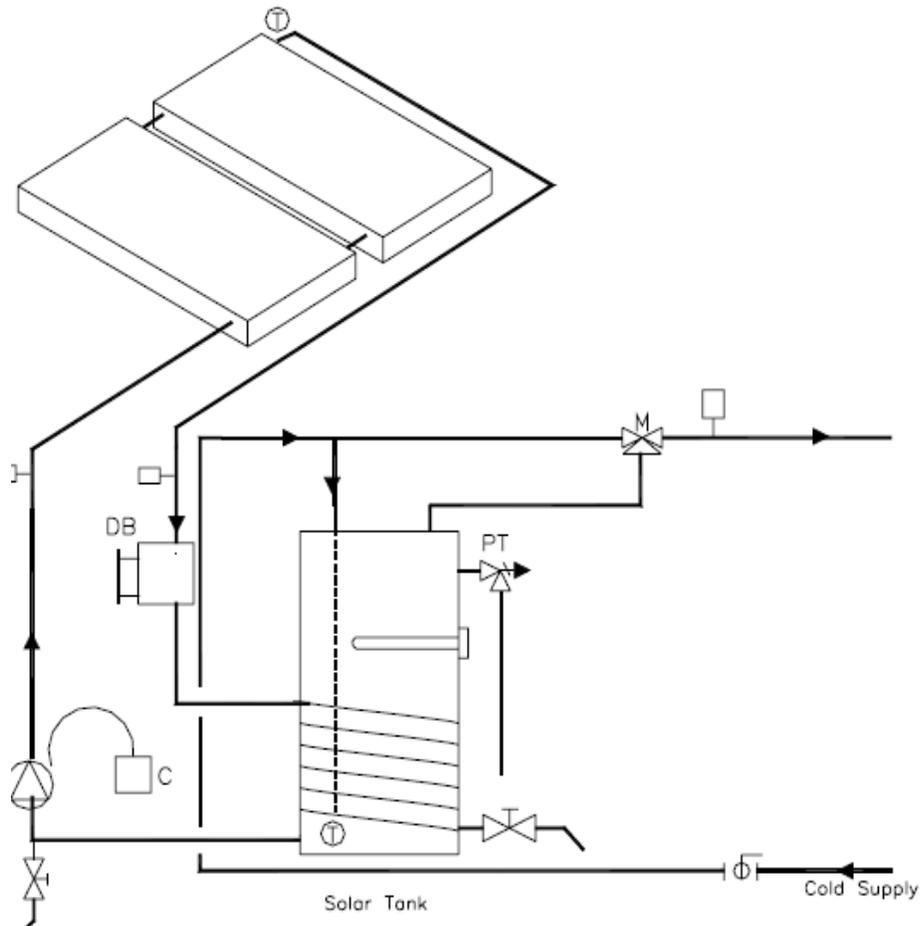
Figure 21. Solene SLCR80DC-80DB single tank drainback system [16].

The Solene system utilizes two Solene Chromagen SLCR -40 panels with a total panel area of 7.4 m². The specifications for these collectors are input to the LabVIEW control software and can be found in Appendix E. The solar storage tank is a Rheem 80 gallon Solaraide and the pump is a Taco 009, both of which are identical equipment to that used in this experiment. The main differences are that the Solene system contains a differential temperature controller, mixing valve, drain back tank, and piping losses associated with the collectors. The absence of a differential temperature controller has the most impact on replicating the system's performance, because it directly controls the amount of parasitic energy consumed and operating the pump for a constant nine hours throughout solar 'day' is not realistic. To account for this, a pump correction factor was implemented during data reduction to turn the pump 'on' when the temperature difference between the bottom of the solar tank and the outlet of the STCS was greater than 2.75°C. Since the pump ran at a constant power level, the time the pump was active was adjusted according to how many differential temperature readings met the controller criteria.

The average Solar Energy Factor for a single tank test was 4.46, which is 9 % lower than the SRCC's rating of 4.9 for the Solene single tank system. Table 6, shows the Solar Energy Factor's of the two tests and the value from the SRCC.

Table 6. SEF test values compared to SRCC values for a single tank test.

Test	SEF	Difference
SRCC	4.9	
Test 1	4.67	-4.7 %
Test 2	4.25	-13.3 %
Avg.	4.46	-9 %

The data in Table 6, conveys that the system is capable of producing repeatable results that are accurate within laboratory expectations. The SEF from the first single tank test was 4.7% below the SRCC value due to the auxiliary element being active for approximately four minutes longer than on equivalent SRCC tests. The second laboratory test was slightly higher on auxiliary element activation time by 30% or 8 minutes, however the pump correction factor lowered the time the pump operated by 14% to 7 hours and 40 minutes from a constant 9 hours, increasing the calculated SEF. The pump correction factor only modified the time the pump was on in the first test by 1 hour and 25 minutes or 14%. Table 7, displays the values of the auxiliary and parasitic energy consumed and the respective time each one was active.

Table 7. Parasitic and auxiliary energy loads and time active for a single tank test.

Test	Parasitic (kJ)	Time (hr)	Auxiliary (kJ)	Time (hr)
Test 1	3664	7.6	5561	0.5
Test 2	3672	7.7	6338	0.57

Both of the tests showed that the results from parasitic, auxiliary, and delivered energies are repeatable for the given system configuration and solar profile.

The Solar Fraction, which is the portion of energy provided by solar sources, is much less dependent on the energy consumed by each component and is influenced solely by the Solar Energy Factor as seen in Equation 5, from Chapter 1.

$$SF = 1 - \frac{EF}{SEF} \tag{5}$$

The Solar Fraction determined by the SRCC is 0.82, meaning 82% of the energy necessary in maintaining hot water is provided by the sun. Table 8, shows the

Solar Fraction's for the two single tank tests, which is very close to the SRCC's data.

This is because the SF is not as sensitive to external components as the SEF is.

Table 8. Solar Fraction for single tank tests and SRCC data.

Test	SF	Difference
SRCC	0.82	
Test 1	0.81	-1.1 %
Test 2	0.79	-3.4 %
Avg.	0.80	-2.4 %

The SF can be used to calculate the total amount of energy provided by

insolation using Equation 7.

$$Q_{solar} = SF * Q_{conv} \qquad (7)$$

The energy used by a standard conventional electric auxiliary tank, Q_{conv}, is assumed

by the SRCC to be 47,865 kJ/day [16]. The Solene single tank configuration is

estimated to provide approximately 38,770 kJ/day or 10.8 kWh of thermal energy to

the stored water. This quantity can be used in economic analysis to estimate the

savings a solar thermal system will provide in comparison to a conventional system.

Assuming an average utility rate of $0.13/kWh, the single tank system is estimated to

provide $500 in annual savings.

Solar Storage Tank Behavior

The behavior of the solar storage tank was closely monitored, in order to

better understand the temperature profile of the storage dynamics of a single tank

system throughout a 24 hr period. The lower internal tank temperature can be

accurately measured by the thermocouple shown in Figure 20, however the top of the

tank is measured with a surface mounted thermocouple at the thermostat, which is

assumed to represent the temperature of the upper portion of the tank. Temperatures

were recorded throughout each test and a time-temperature profile of the tank was

created as shown in Figure 22.
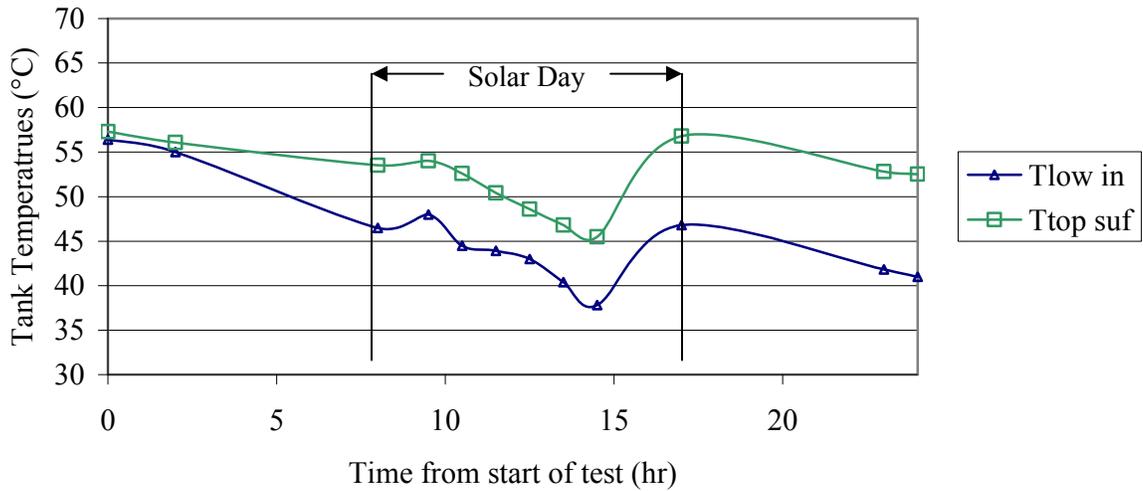
Figure 22. Upper and Lower temperature profiles of the solar storage tank for
a single tank test.

Initially, for a test, the tank is allowed to come to a steady state condition of

approximately 57.2°C, which is a function of the thermostat setting. The first eight

hours on the graph are solar 'night' consisting of standby losses of about 1.2°C/hr or

422 W. From solar hours 8 to 15, the portion of the graph with a steeper slope

represents the draw period of the solar 'day'. The temperature of the lower portion of

the tank dips to below 40°C, which is expected due to mixing of the inlet water from

the mains. After the final draw, near hour 14, the temperature of the tank is the lowest

and the element activates attempting to bring the stored water back to the system set

point temperature

Double Tank Test Results

The double tank analysis is similar to a Solene SLCR80DC-80DB-XE

drainback system shown in Figure 23, using water as the working fluid [16].
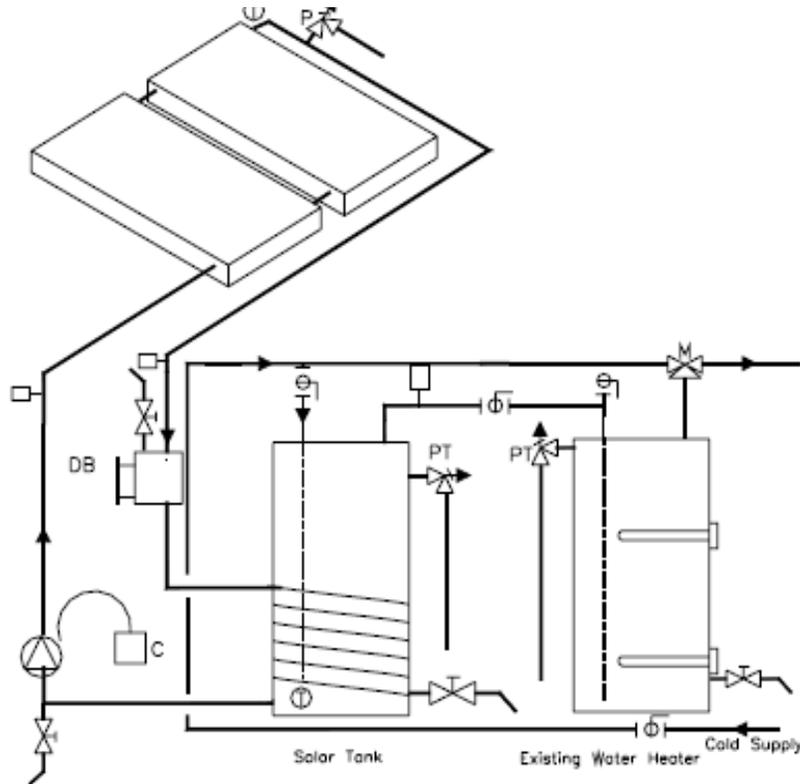
Figure 23. Solene SLCR80DC-80DB-XE double tank drainback system [16].

This system was also subject to the solar profile set forth by the SRCC found

in Appendix E and test conditions as the single tank test. The SRCC system rating

sheet can be found in Appendix E. The Solene XE system consists of the same

components as the single tank configuration with the addition of a conventional 50

gallon hot water heater with two elements. The current system tested in this

experiment has 10 fewer gallons of storage, however this difference is assumed to be

negligible because the same amount of energy is extracted from the system regardless

of size. Although the Solene system is maintaining 10 extra gallons of water, from an

energy balance approach, the difference in standby losses between a 40 gallon tank

and a 50 gallon tank is 16 Watts. Many commercially available double tank systems

are retrofits to existing conventional hot water heaters and the auxiliary tank size may

vary. The increased volume in the Solene configuration will provide a higher heat

capacity to the system, however, it is also accompanied by a slower response to added

energy.

The average Solar Energy Factor for a double tank test is 2.64, which is 12%

below the rating provided by the SRCC of 3.0. This means the system will provide

the same amount of hot water for one third of the electric energy cost that a

conventional system would. Table 9 compares the SEF's of the two double tank tests

with the SRCC data.

Table 9. SEF test values compared to SRCC data for a double tank test.

Test	SEF	Difference
SRCC	3.0	
Test 1	2.44	-18.6 %
Test 2	2.84	-5.5 %
Avg.	2.64	-12 %

The first double tank test provided a SEF of 2.44, which was 18.6% less than

the SRCC data, due to extended element activation times. During the element

activation periods, the temperature of the water, estimated from the thermocouple at

the top of the solar storage tank, was less than 50°C. After mixing and extraction of

11 gallons of hot water, the auxiliary tank temperature dropped below the set point

and activated for a total of 75 minutes. Due to the low resolution of $\pm$ 3°C on the

thermostat, additional element activation time may have accumulated during

temperatures very near to the set point. This data is displayed in Table 10, along with

the parasitic energy consumed by the pumps. The pumps were active with the pump

correction factor for 7 hours and 25 minutes for the first test and 7 hours and 10

minutes for the second test.

Table 10. Parasitc and auxiliary energy loads for a double tank test.

Test	Parasitic (kJ)	Time (hr)	Auxiliary (kJ)	Time (hr)
Test 1	3564	7.4	13,732	1.25
Test 2	3456	7.19	11,767	1.1

The Solar Fraction specified by the SRCC for this system is 0.70, implying

70% of the energy needed to maintain system temperatures is provided by solar

energy. Table 11, shows the Solar Fraction for each of the two double tank tests.

Table 11. Solar Fraction for a double tank test.

Test	SF	Difference
SRCC	0.70	
Test 1	0.63	-9.8 %
Test 2	0.68	-2.5 %
Avg.	0.65	-6.4 %

The values in Table 11, are slightly lower than manufacturer's data due to the

extended operation time for the auxiliary elements. After calculating the energy

provided by solar sources from Equation 7, the double tank system can be estimated

to save 30,155 kJ/day or approximately 8.3 kWh. Assuming an average utility cost of $0.13/kWhr this system will provide an approximate savings of $388 per year.

Solar Storage and Auxiliary Tank Behavior

In the double tank configuration, the temperatures of the solar storage tank and the auxiliary tank were monitored to investigate the storage dynamics of both tanks working together. The auxiliary tank is measured only with two surface mounted K type thermocouples at the upper and lower thermostats. Figure 23 shows the time-temperature profile for the solar storage tank incorporated into the double tank configuration.
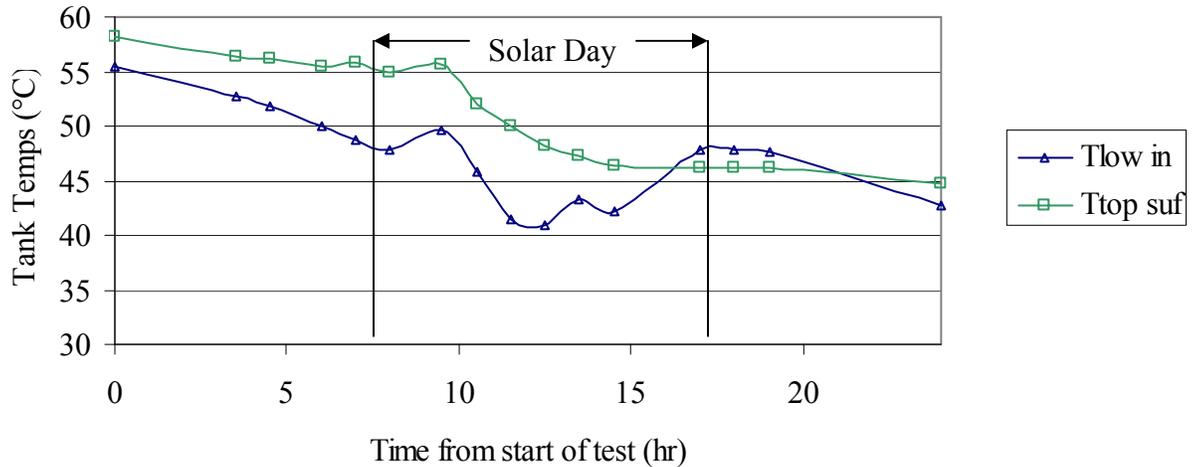
Figure 24. Upper and lower tank temperature profiles for the solar storage tank in a double tank test.

The solar storage tank is allowed to reach steady state conditions, however the element is disabled and the only source of energy input is the useful output from the STCS. This is evident near hour eight in Figure 24, where an increase in temperature

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coincides with the beginning of insolation, followed by a decrease in temperature during energy draws. After the end of insolation, energy is no longer input to the solar tank and it is allowed to diffuse until the end of the test, to approximately 43°C. The auxiliary tank becomes the main storage tank and maintains the system set point temperature throughout solar 'night'.

Figure 25 contains the time-temperature profile for the auxiliary tank during a 24 hour period. It is important to note that the lower element of the tank is the main heat source and the upper only activates if a large amount of energy is necessary. Figure 25 shows temperatures were maintained throughout the initial standby period until the beginning of the energy draws.
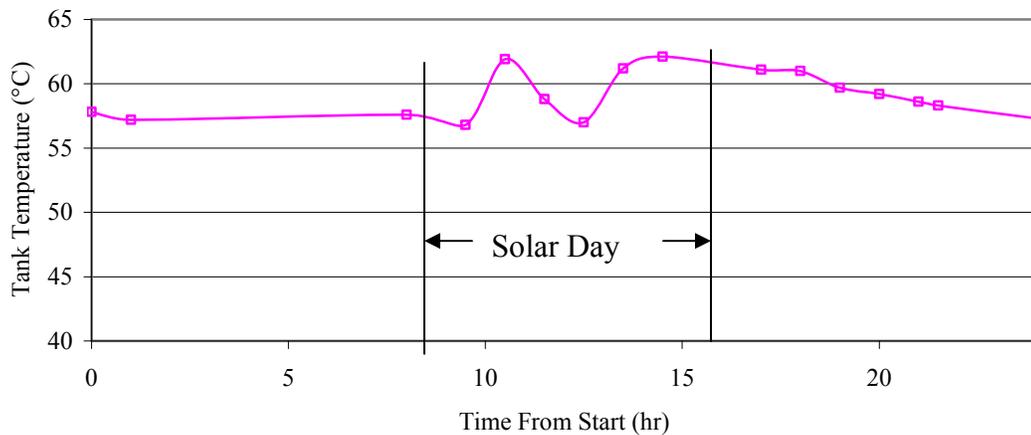
Figure 25. Time vs. Temperature profile for the auxiliary tank during a double tank test.

Hour 10 shows activation of the element after the first draw, compensating for the addition of 11 gallons of cooler water. The element also activated during hours 11 and 12, which is evident in the second peak in the graph.

Discussion

The Solar Energy Factor for a single tank system and a double tank system were nine percent and twelve percent below data published by the SRCC. These results are acceptable within the uncertainty bounds and laboratory conditions. The main purpose was to achieve verifiable data that can be compared to SRCC data so future research can proceed.

From observing the behavior of the tanks, pumps, and outlet temperatures on a double tank test, the SEF was found to be highly sensitive to the activation time of the auxiliary heating element. Although the water entering the cold inlet of the auxiliary tank is preheated from solar energy, the lower thermostat will react to the change in temperature quicker than the upper thermostat due to the buoyancy effects of a stratified tank. Since the SRCC specifies a set amount of energy to be drawn from the system, the SEF is really sensitive to how much the auxiliary elements are active and how long the pumps run.

The sensitivity of the SEF can be analyzed by taking the partial derivative of the SEF with respect to auxiliary energy as shown in Equation 8. This shows that, the SEF is equally sensitive to the square of the auxiliary energy and the parasitic energy, however since the auxiliary power required is 25 times greater than the parasitic, the auxiliary energy is much more influential on the results.

$$\frac{\delta SEF}{\delta Q_{aux}} = \frac{-Q_{del}}{\left(Q_{aux}Q_{par}\right)^2} \qquad (8)$$

For the average single tank test, the SEF is less sensitive to the time that the auxiliary element and parasitic devices are active. In a single tank test, the element operates for a shorter period of time compared to the double tank test. This is due to

the proximity of the thermostat on the upper portion of the tank, constantly near the warmer water. The auxiliary energy and parasitic energy are approximately the same magnitude and thus, have similar influence on the SEF for a single tank system. To account for this, the system set point must be carefully calibrated and the analog power meters must be closely monitored. Several minutes on the analog power meters or a solar storage tank that is initially too cool, may skew the active time for the parasitic and auxiliary energy measurements.

Both system configurations performed as expected, following procedures set forth by the SRCC and DOE. The single tank tests were more accurate to the SRCC data, however, they consistently delivered lower outlet temperatures during energy draws. This can be attributed to the mixing of cold water from the mains inlet and also to the thermostat control.

CHAPTER FIVE

Conclusions and Recommendations

Conclusions

In summary, the Solar Domestic Hot Water Simulator at Baylor University

found the Solar Energy Factor for a single tank to be 4.46 ± 0.06, which is 9 % below

data verified by the SRCC on a similar commercially available system. A double

tank system performed equally as well with a Solar Energy Factor of 2.64 ± 0.043,

which was 12% below the SRCC's rating for a similar system. Both hardware

systems performed equally well for simulating computer generated efficiency results

provided by the SRCC.

It is important to remember that the results provided by the SRCC are

extrapolated from a computer simulation utilizing the Transient Energy System

Simulation Tool (TRNSYS). Detailed parameters are input for each component,

however, there is a limit where the computer simulation cannot encompass the small

losses and the operation of an actual system. SRCC results represent standardized

performance under ideal conditions and tend to be conservative because they are

intended to be a benchmark for performance to assist in choosing the correct system.

Actual performance depends on a wide variety of factors including, geographic

location, hot water usage and timing, quality of system components, and quality of

installation.

The results of these tests show that accuracy and repeatability for the testing

facility at Baylor University is verified. These tests provide a baseline standard for

future research into the development of modifications to the domestic solar hot water heating system.

Future Recommendations

There are several recommendations regarding modifications to the current system for future research. For more accurate results regarding parasitic energy, a differential controller is suggested to control the main circulator pump on the heat exchanger loop. Incorporating this unit to measure the difference between the outlet of the STCS and the bottom of the solar storage tank will better simulate actual performance and provide the actual activation time of the pump. However, care must be taken not to damage the STCS with the controller due to low temperature differences and high stagnation temperatures within the heat exchanger chambers

The inlet, outlet, and tank temperatures are currently recorded manually from digital thermometers. Automation of this system would allow greater convenience in testing and a better temperature profile of the tanks. Since thermocouples output milli-volts, an Omega thermocouple transmitter in conjunction with a precision resistor can be incorporated to provide a 0-5 V signal that can be sampled by the STCS.

During several preliminary tests of the double tank system, SEF values were found to be over 50% greater than the SRCC value. It was determined that the cause of this was a thermostatic set point below 57.2°C. This behavior leads to the suggestion that slightly lowering the set point on the thermostat can greatly improve water heating efficiency and ultimately save money. For future tests, greater thermostatic control would be desired to ensure accurate results.

An array of thermocouples should also be constructed so that they can be inserted into the tanks to provide a better average tank temperature and also be recorded by the STCS and the LabVIEW software. The stratification of the temperatures within the tanks over time can also be measured to provide a more accurate temperature profile of the tank.

The extra storage tank, located between the solar storage and auxiliary tanks, should also be incorporated into future configurations to test how increased thermal storage affects the performance of the system. The automatic three-way valve located on top of the auxiliary tank can be integrated to analyze hybrid single/double tank systems.

Finally, Typical Meteorological Year weather data files should be tested in the LabVIEW control software in order to calculate the performance and behavior of systems with location specific data.

APPENDICES

APPENDIX A

LabVIEW User Manual

National Instruments LabVIEW control software is a program that allows control and analysis code to be written through a combination of wiring inputs and outputs of modular icons to form a logical flow of information between them. Unlike text based codes that execute processes line by line in a control flow manner, LabVIEW is based on a data flow model where functions are not executed until they receive all of the information necessary. Functions in LabVIEW, also known as Virtual Instruments (VI), may be run simultaneously in parallel if they are independent of each other. LabVIEW contains two main sections: the *front panel*, where a user interface including control inputs and outputs are located for analytical purposes, and the *block diagram*, where VIs are created and data is processed.

Front Panel

The front panel of the user interface consists of a window with two tabs: *Control Panel* and *Results*. The tabbed window manages multiple inputs and outputs in an organized interface. The control panel consists of instructions and two sections of inputs, *Weather and Geography* and *Collector Data*, which are entered by the user to determine the output power of a collector. Figure A 1 is a screenshot of the control panel that interfaces with the user.
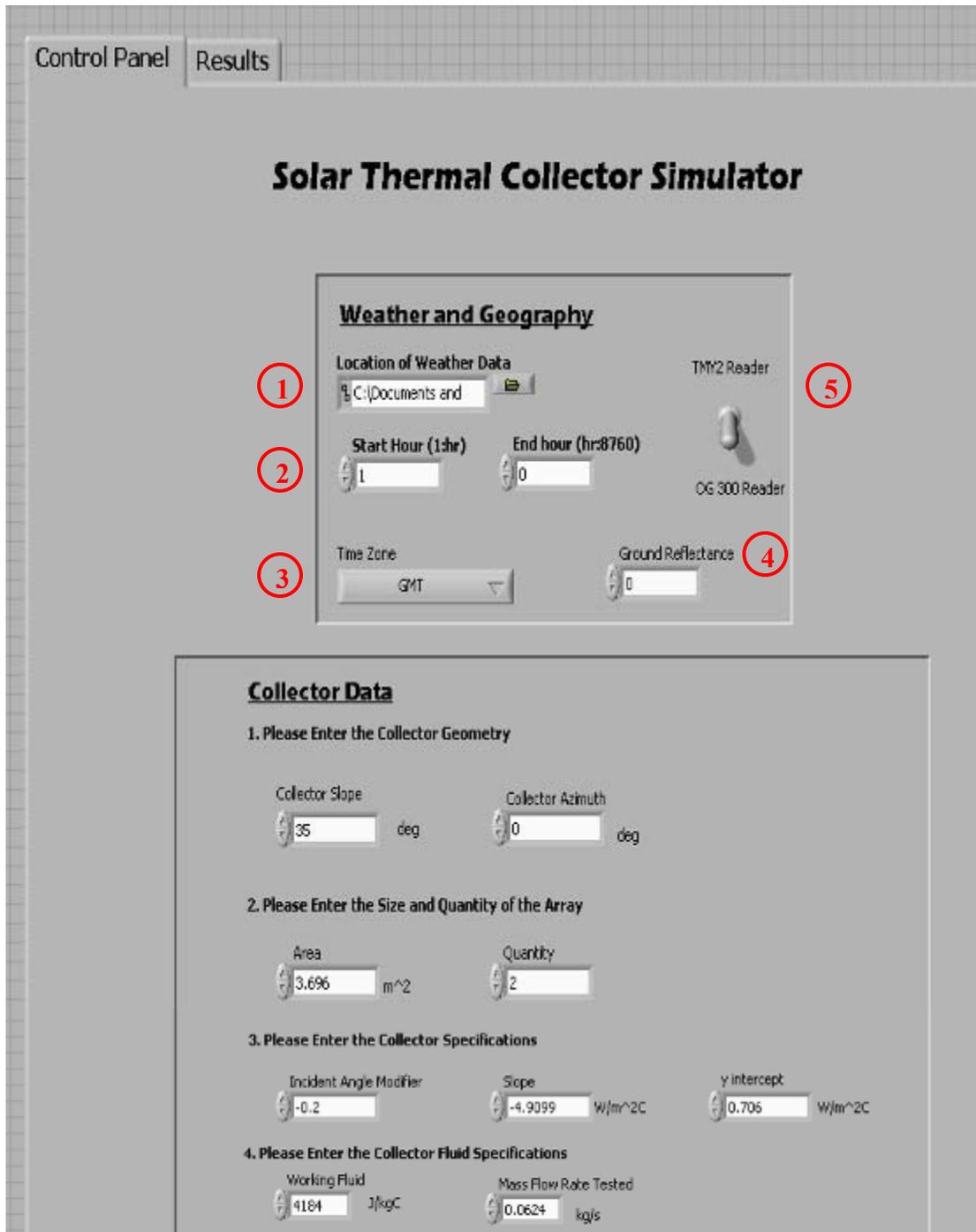
Figure A 1. LabVIEW control panel interface

The *Weather and Geography* section includes a file search dialogue box for

the location of weather data files (1), the time period in hour of the year to be

analyzed (2), a pull down menu for the specific time zone (3), and an input for the ground reflectance of the specific area (4). The control program has been augmented to receive two different types of weather data files, the OG 300 solar profile and a typical meteorological year (TMY2) format. The TMY2 data file is compiled by the National Renewable Energy Laboratory from weather stations specific to a certain location around the world and is comprised of various data such as ambient temperature and direct radiation that is averaged from 1961 to 1990. These files provide the repeatability, consistency, and accuracy that will produce quality location specific results. A toggle switch (5), is implemented to read either format weather files or the standard SRCC OG 300 solar profile. When the OG300 profile is enabled, controls 1-5 are ignored and bypassed because the weather file already contains this information.

The *Collector Data* section consists of four steps:

1. *Enter the Collector Geometry.*

   - The slope and azimuth of the collector are user defined and are input in degrees with the azimuth being referenced east of south as negative and west of south as positive (Beckman and Duffie [12]). For OG 300 tests, the slope is 40 degrees and the azimuth is set to due south at 0 degrees.

2. *Enter the Size and Quantity of the Array.*

   - The size of the specific collector can be found on the data sheet and is input in square meters.

3. *Enter the Collector Specifications.*

- The incidence angle modifier is found on the SRCC specification sheet and is only valid between 0° and 60°.

- The slope and y-intercept of the linear efficiency equation are used in this analysis and can also be found of the SRCC specification sheet for the SLCR-40 found in Appendix E.

4. *Enter the Collector Fluid Specifications.*

- The tested flowrate is found on the SRCC specification sheet and must be converted to kg/s. A correction factor must be calculated since the flowrate that is currently being used is different than the one tested and will not correlate to the values of the collector efficiency equation. This equation can be found in Appendix B.

Once these values are correctly input to the control panel and the STCS is turned on by plugging in the 208 V power cord and switching the electric breakers. The testing may now commence beginning at solar midnight, taking careful note to schedule energy draws at a convenient time during the simulated 24hr period. As the simulation iterates, the results can be viewed simultaneously on graphical outputs.

The *Results* tab, referenced in Figure A 2and Figure A 3, contains a vast array of outputs that convey the behavior of the system under current conditions. The specific latitude and longitude (1) are displayed along with the current hour of the year, day of the year, and time of day (2). Solar calculations occur in an offset time frame known as solar time (3), which accounts for the sun's angular motion across the sky (Beckman and Duffie [12]). This value coincides with actual simulation time and is displayed for reference purposes along with the actual simulation timer (4) to

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coordinate energy draws. An indicator is placed next to the simulation timer to alert

the user when energy draws are supposed to occur.
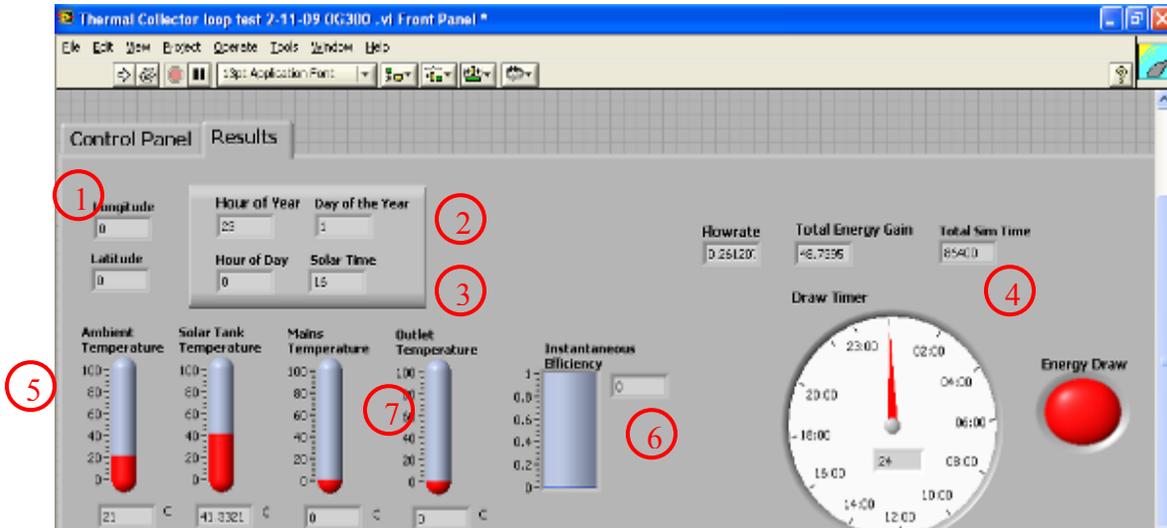
Figure A 2. Upper LabView result panel.

The ambient temperature (5) is extracted from the weather data file. The

instantaneous efficiency (6) is calculated from Equation (A1) and describes the

performance of the collector array at that moment in time. However, this value is not

related to the system efficiency or the solar energy factor.

$$\eta = (Fr\tau\alpha \bullet k\tau\alpha) - \left(\frac{FrUL(T_i - T_a)}{G_T} \right) \qquad \text{(A1)}$$

Frτα is the Y-intercept and *FrUL* is the slope from the collector efficiency equation

and *kτα* is the incident angle modifier, all three of which can be found on the SRCC

collector specification sheet. T_i is the inlet temperature to the collector and T_a is the

ambient temperature of the environment from the weather data file. Finally, G_T is the

total available insolation for that day, for central Texas, an average value would be

5.5 kWh/m^2. The inlet temperature of the collector is the most influential variable in determining instantaneous efficiency. The bottom of the solar storage tank and the outlet of the auxiliary tank are also reported to the user (7). The lower portion of the results panel, shown in Figure A 3, has graphical representations of the inlet and outlet temperatures on the STCS that are recorded for a temperature distribution throughout the day. These values are written to separate text files and are available for further data reduction. The mains inlet temperature is also recorded, but should be a constant temperature, due to the test conditions and the mains chiller. The *Total Insolation* graph conveys the amount of radiation the collector receives for the specific hour of the day. It is calculated based on an average amount of insolation measured at the midpoint of the previous solar hour and provided in the OG 300 profile.
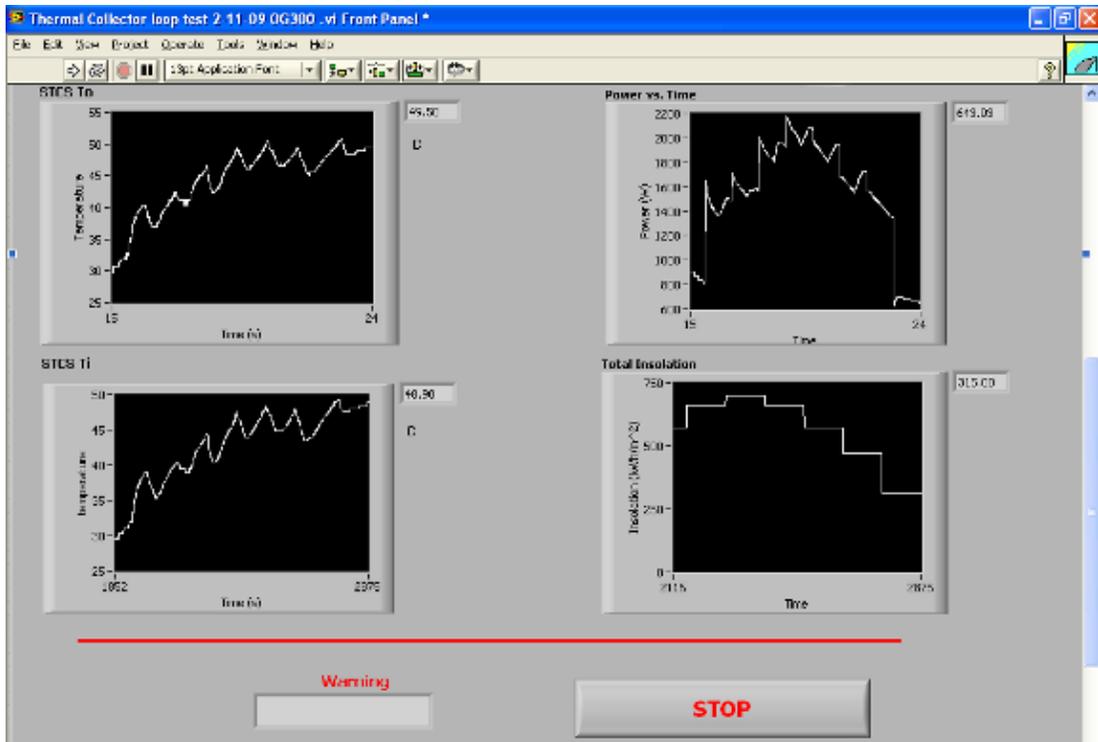
Figure A 3. Lower LabVIEW results panel.

From hourly insolation, the user can determine when the sunniest part of the day is and if it is economical to run the pump for that day. The *Power vs. Time* graph shows the actual power output from the collector array throughout the day and is critical for estimating the energy that will be available from the system. *Total Energy Gain*, is simply the power integrated and converted to kilowatt-hours and represents the total amount of energy that was input to the stored water by the thermal collector. At the bottom of the Results panel is a warning box and a manual stop control. If the STCS encounters an error such as a leak or over temperature warning the user has the option of shutting down the test from LabVIEW rather than the electrical disconnects.

Block Diagram

The block diagram contains the VIs that function as the controls of the system. A flow chart describing the operation can be found in Figure A 4. The main goal of the controls is to accurately time two interdependent loops and communicate between them and an external source. The basic strategy taken with the code is based on a producer/consumer design where the first loop will iterate and send data to the consumer loop, which will not iterate until it has received and processed that data. The primary logic in the controls lies within comparing the current time to the start time. This simple control algorithm is implemented for several processes including the producer and consumer loop, stop sequences, communication with the STCS, and the draw indicator. Two state machine structures were utilized for the producer and consumer loops.

```
                    ┌──────────────┐
                    │  Input Data  │
                    └──────┬───────┘
                           ▼
                    ┌──────────────┐
                    │    Start     │──────────────────────┐
                    └──────┬───────┘                      │
                           ▼                               │
          ┌──────────────┐         +1 hr    ╱╲            │
          │ Read Weather │◄──────────────  ╱    ╲         │
          │     File     │               ╱ t1 <1hr ╲      │
          └──────┬───────┘               ╲        ╱       │
                 ▼                          ╲    ╱         │
          ┌──────────────────┐               ╲╱           │
          │ Calculate        │                │           │
          │ Insolation       │                ▼           │
          └──────┬───────────┘            ┌────────┐      │
                 ▼                         │  Idle  │      │
       ┌──►┌──────────────────┐           └────────┘      │
       │   │ Calculate Power  │                            │
       │   └──────┬───────────┘                            │
       │          ▼                    ╱╲                  │
       │   ┌──────────────────┐       ╱    ╲               │
       │   │ Request STCS Data│◄──── ╱ t2 <30s ╲           │
       │   └──────┬───────────┘      ╲        ╱            │
       │          ▼                    ╲    ╱              │
       │   ┌──────────────────┐          ╲╱                │
       │   │ Communicate with │           │                │
       │   │ STCS             │           ▼                │
       │   └──────┬───────────┘      ┌────────┐            │
       │          ▼                  │  Idle  │            │
       │   ┌──────────────────┐      └────────┘            │
       │   │ Current Time     │                            │
       │   └──────┬───────────┘                            │
       └──────────┤                                        │
                  │                                        │
                  ▼                                        ▼
          ┌───────────────────────────────┐
          │ t_tot=Current-Start Time      │
          └──────────────┬────────────────┘
                         ▼
                       ╱╲
                      ╱    ╲
                     ╱        ╲       ┌────────────┐
                    ╱ t_tot <total sim ╲──────►│  Continue  │
                     ╲        ╱        └────────────┘
                      ╲    ╱
                       ╲╱
                        │
                        ▼
                   ┌────────┐
                   │  Stop  │
                   └────────┘
```
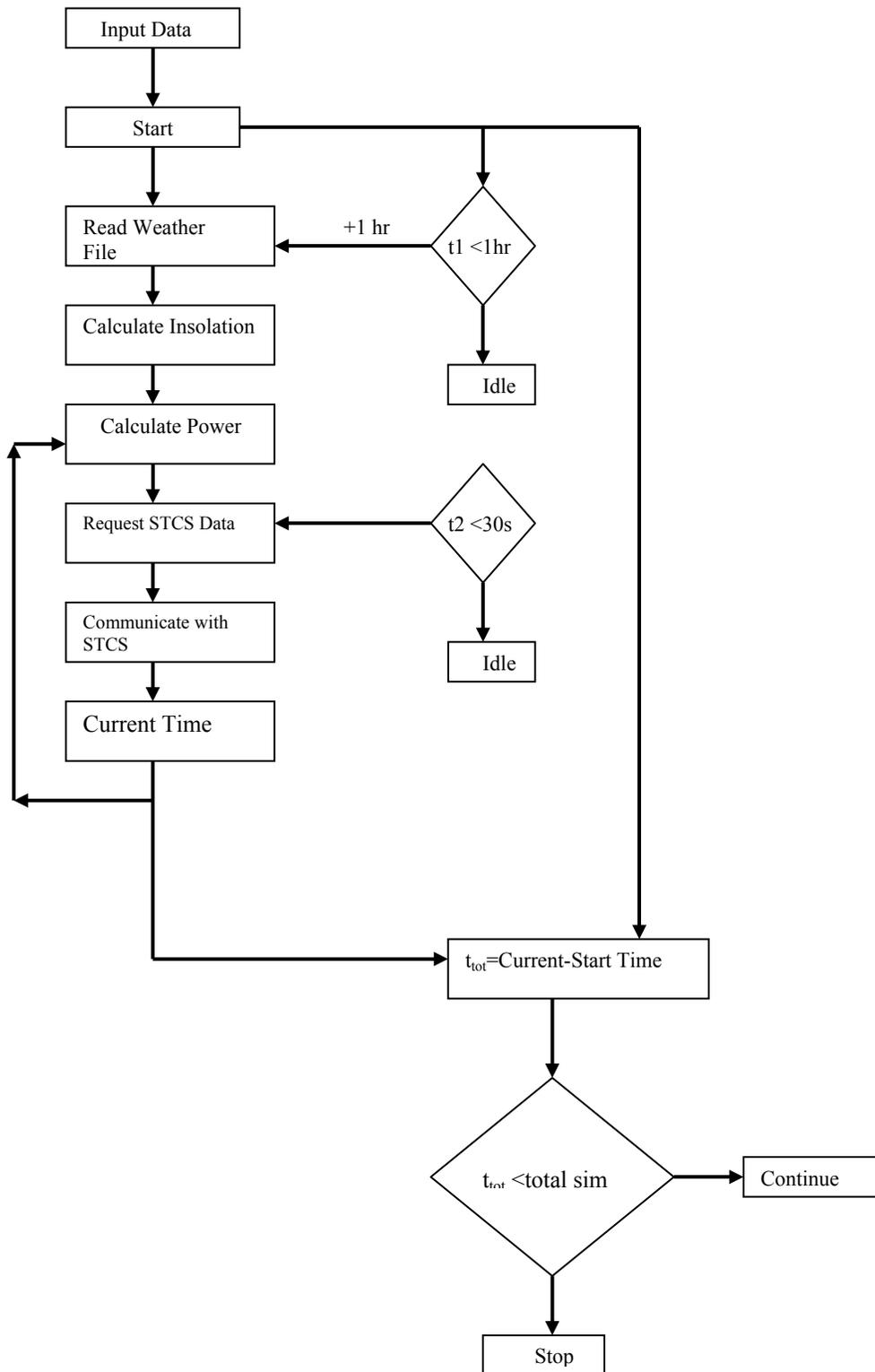
Figure A 4. LabVIEW block diagram flow chart.

The state machines allow different processes to be run, depending on the indicated state that is controlled by Boolean operations and the timer as shown in Figure A 5.
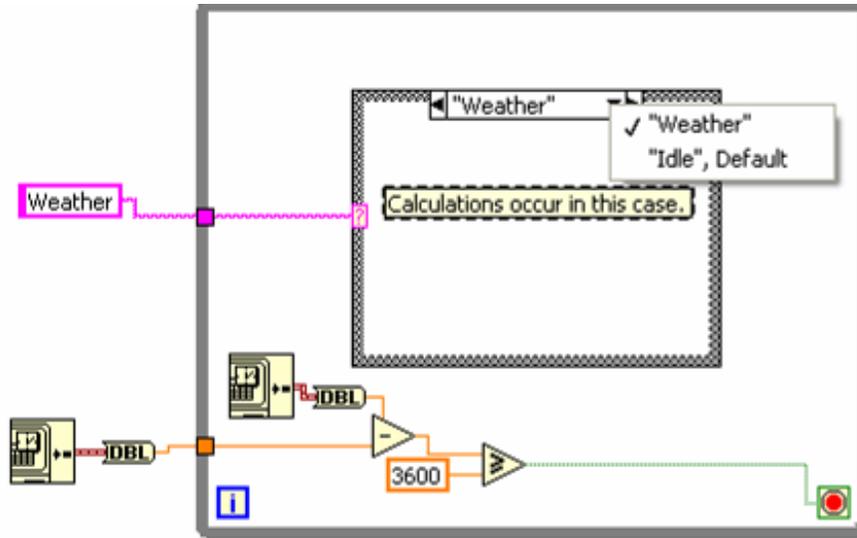
Figure A 5. General state machine example with two states, Weather and Idle

The producer loop reads in the weather file, performs the solar calculations, and sends total insolation, ambient temperature, and the incidence angle modifier ($k\tau\alpha$) to the consumer loop once an hour. The consumer loop takes the producers data, calculates the useful power required, and communicates with the STCS once every thirty seconds. A request is initially made by LabVIEW for inlet and outlet temperatures as well as flow rates from the STCS. Power and element activation codes are then calculated and sent to the STCS. Important data, such as inlet and outlet temperatures, flow rates, power, and any warnings are written to separate text files with time stamps for later reduction and analysis. Accurate timing of the loops is a crucial requirement in order to obtain results that replicate the behavior of an actual home system throughout the day. The producer loop timers control iterations

once per hour, while the consumer loop timers controlled iterations once every thirty seconds.

The control software has two separate stop sequences that are implemented. The first is an automatic stop that halts the iteration of the loops when the time period under analysis is complete. A manual stop has been programmed to send a UDP packet to the STCS containing a zero power code thus eliminating power from the electric elements.

A disadvantage of using UDP to communicate with the STCS is that occasionally a packet will be dropped. This situation must be accounted for so a consistent set of data can be collected. The solution implemented in the code is a case structure with a local variable in one case that saves the previous value. If the received data packet is empty, then the previous value is passed, otherwise the received value is used.

Calibrating the calculated power output to the power delivered by the STCS was necessary due to a lack of resolution within the heating elements at low power levels. At power levels less than 2300 W, the STCS had difficulty distributing less than 20 % of the maximum power over four elements. A three step calibration process, shown in Equation (A2), was used in conjunction with activating a single element to accurately calculate the power delivered.

$$
\begin{aligned}
P' &= 1.0647 * P - 533.02 & P &> 2300W \\
P' &= 0.9704 * P - 109.64 & 150W &< P < 2300W \qquad \text{(A2)} \\
P' &= P & P &< 150W
\end{aligned}
$$

Where *P* is the calculated power and *P'* is the calibrated power. For the last two cases in Equation (A2), only one element in the STCS is energized to account for the resolution of the elements operating range.

The data flow model utilized by LabVIEW greatly facilitated calculation of the parameters involved in determining insolation and power. Many of the calculations necessary in determining the useful power were dependent on one other which made data flow logical. Appendix B, documents each VI utilized in the control software with a description and diagram.

APPENDIX B

LabVIEW Virtual Instrument Documentation

Producer Loop Virtual Instruments

OG 300 Reader.vi
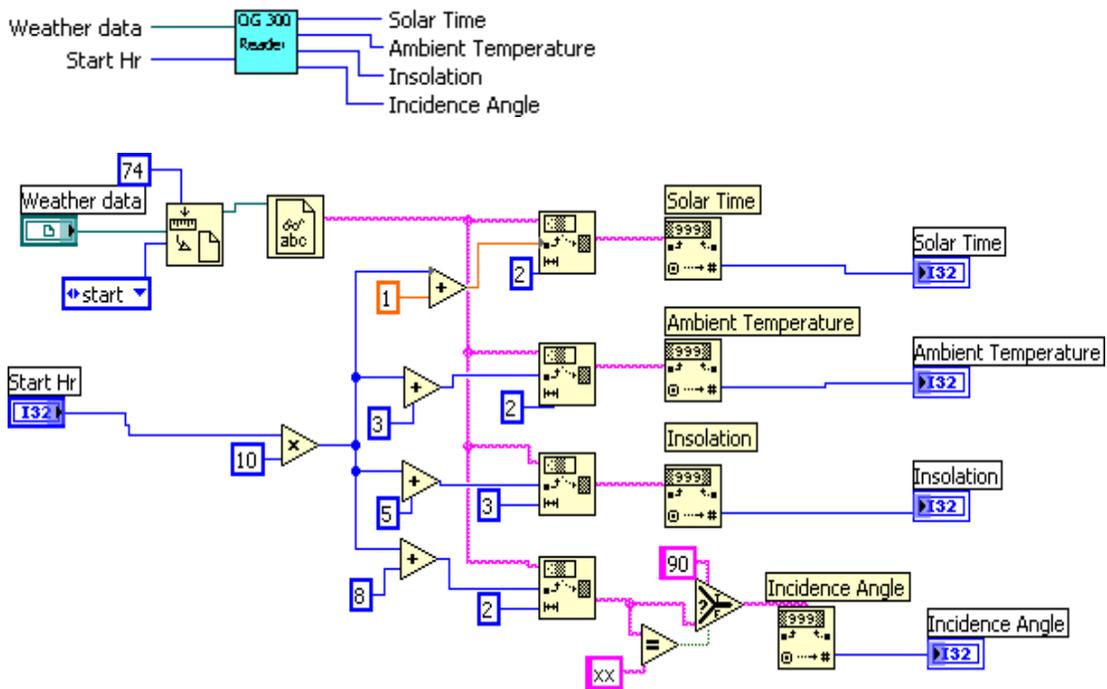
Draw Alert.vi
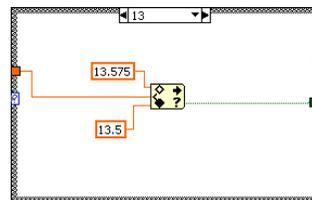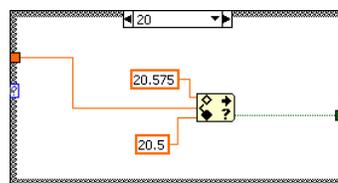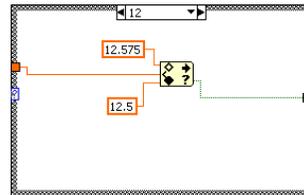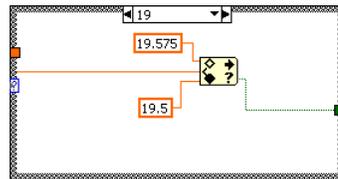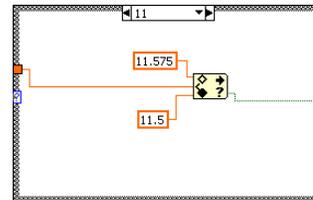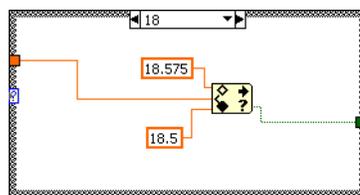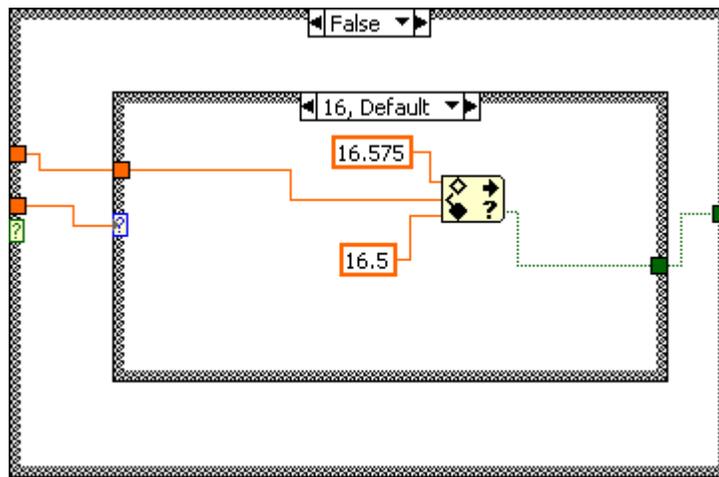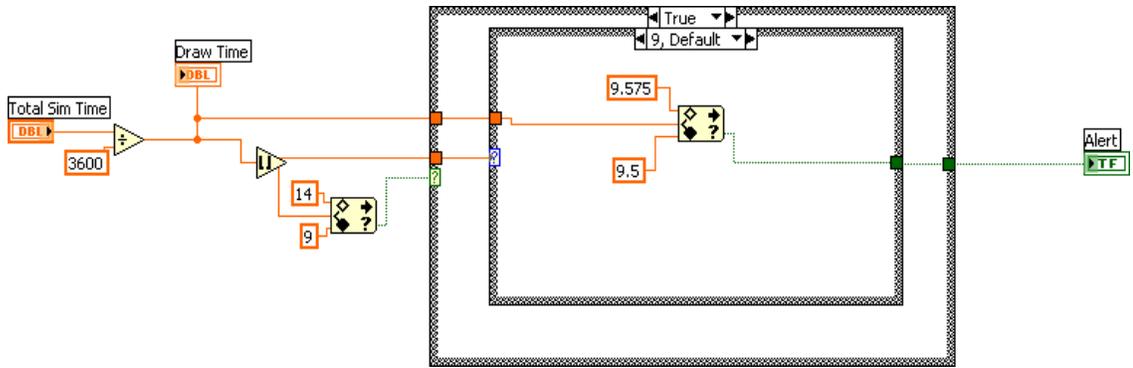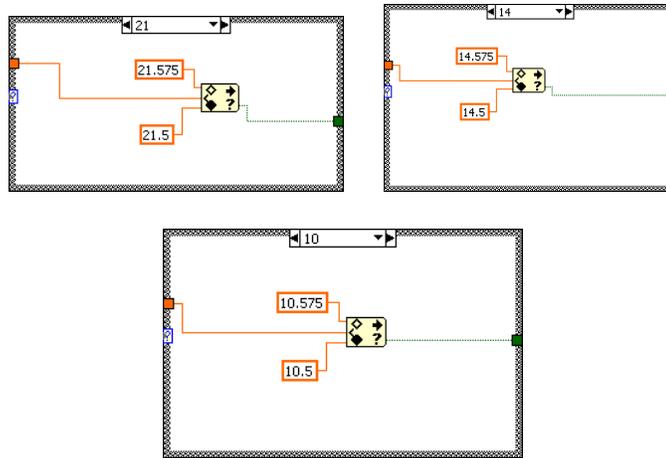
Declination (SubVI).vi

The angular position of the sun at solar noon in radians.

float32 d;
d=(23.45*sin(2*pi*((284+n)/365)))*(pi/180);

Declination has units of radians
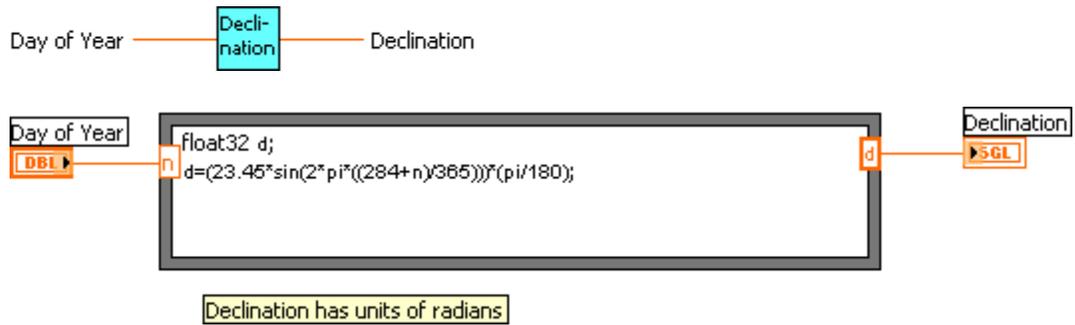
Tsol(SubVI).vi

Calculates the solar time based on the previous solar hour.

Depends on location and day of the year.

All insolation calculations are based on this time scale.
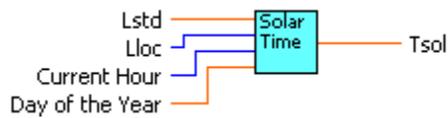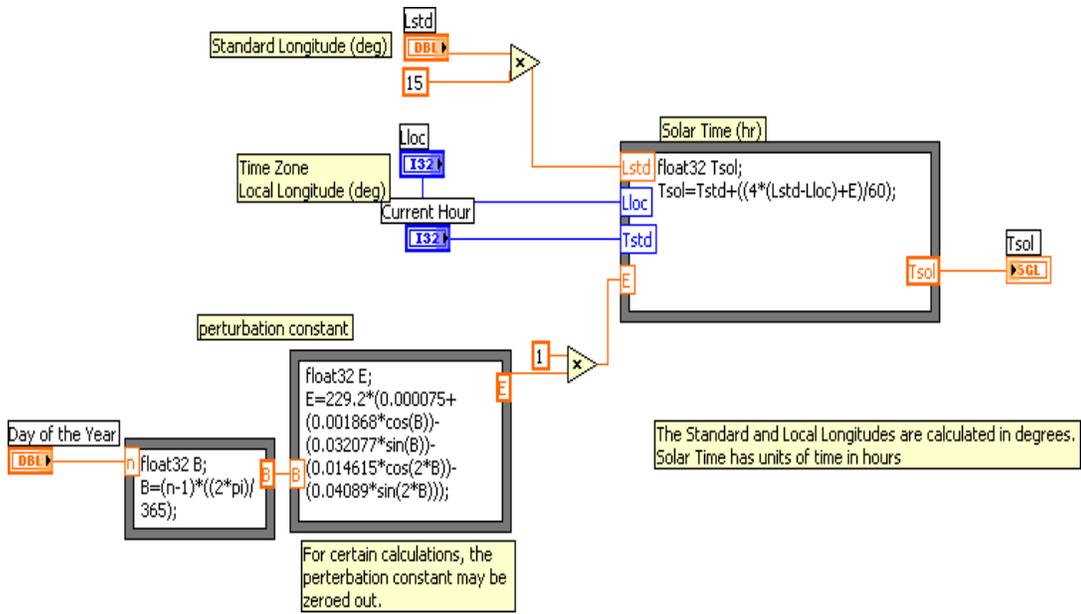
Hour angle (SubVI).vi

Calculates the angle, in radians, from the solar time which describes the angular displacemnet of the sun with respect to the local meridian.

morning is negative

Afternoon is positive
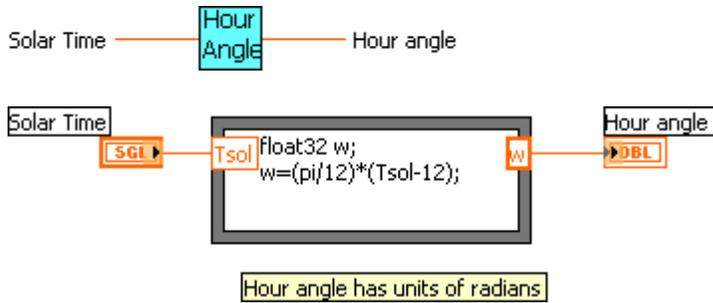
Incident Angle mod (SubVI).vi

The ratio of transmittance-absorptabce (ta) product at some angle to the transmittance-absorptance product at normal incidence.

These calcualtions are found on Data sheet
The Incidence angle modifier is unitless
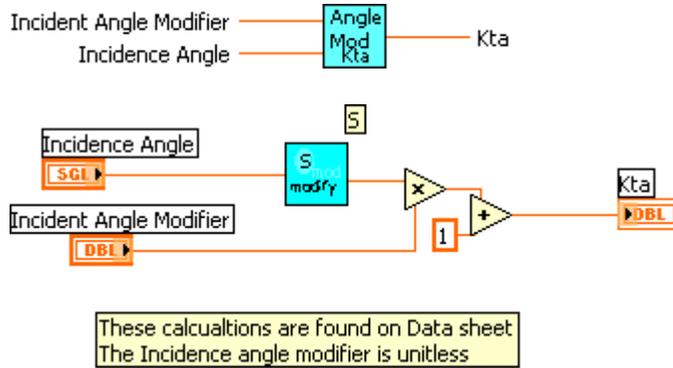
Theta (SubVI).vi

Calculates the angle of between direct radiation on a surface and the normal vecotr of that surface in radians for the midpoint of the solar hour preceding it.


```
float32 cosT;
cosT=(sin(d)*sin(f)*cos(B))-
(sin(d)*cos(f)*sin(B)*cos(g))+
(cos(d)*cos(f)*cos(B)*cos(w))+
(cos(d)*sin(f)*sin(B)*cos(g)*cos(w))
+(cos(d)*sin(B)*sin(g)*sin(w));
```

The Incidence angle has units of radians
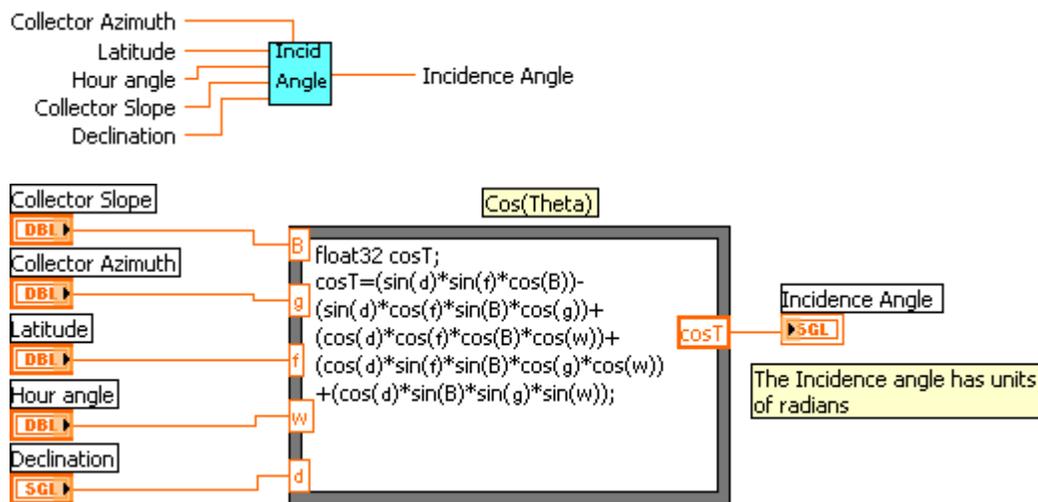
Theta mod (SubVI).vi

Calculates the term that modfies the incident radiation on a surface.

For certain angles this modifier does not apply.

Check with the SRCC specification sheet of the collector.
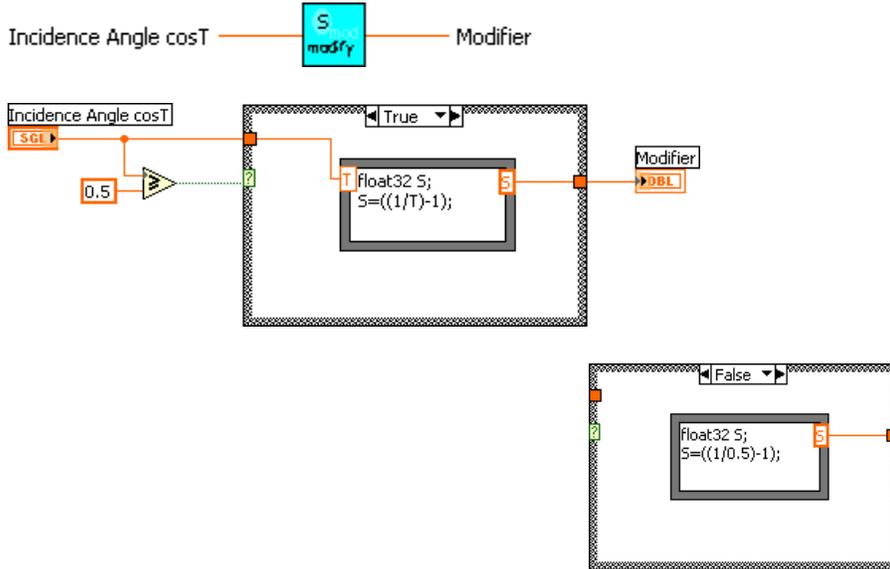
Long_Lat(SubVI).vi

This VI is constructed similarly to the TMY2 reader, except that it only reads the first line containing the location information.

This VI is executed once.

Latitude and Longitude are read in degrees.
Latitude is converted to radians for future calculations
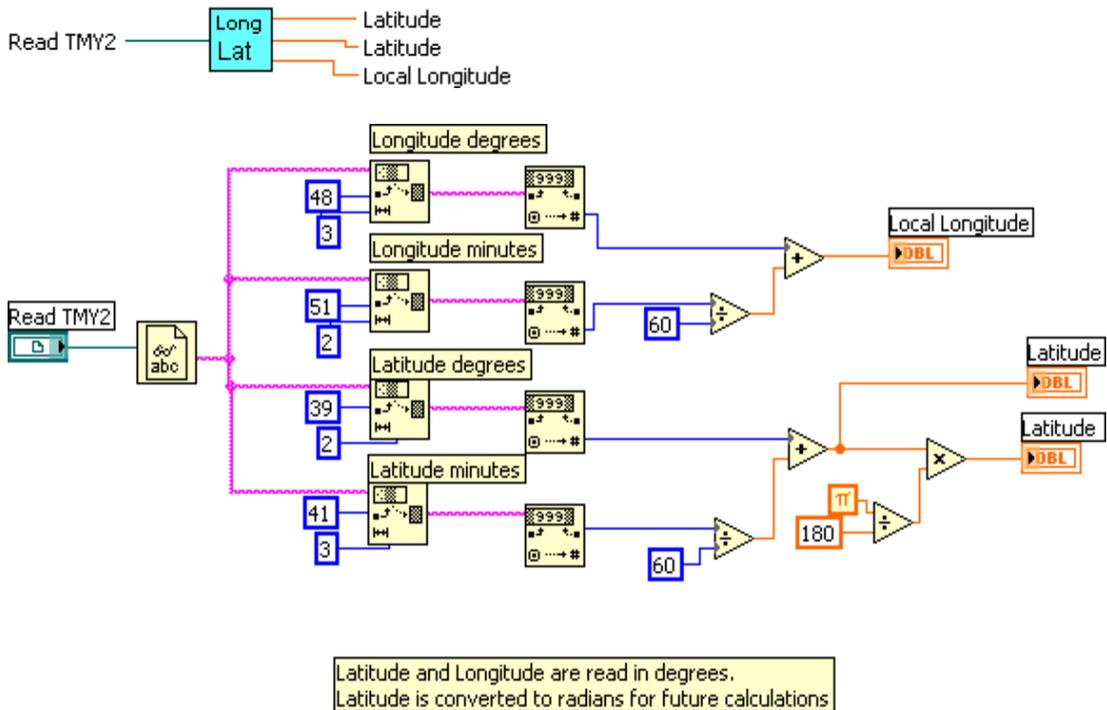
Total Insolation (SubVI).vi

Calculates the Total isolation in Wh/m^2 due to Beam, diffuse, and reflected radiation.

Insolation is a local variable


```
float32 It;
It=(Ibn*cosT)+(Id*((1+cos(B))/2))+(Ipg*((1-cos(B))/2));
```

The Total Insolation has units of W/m^2
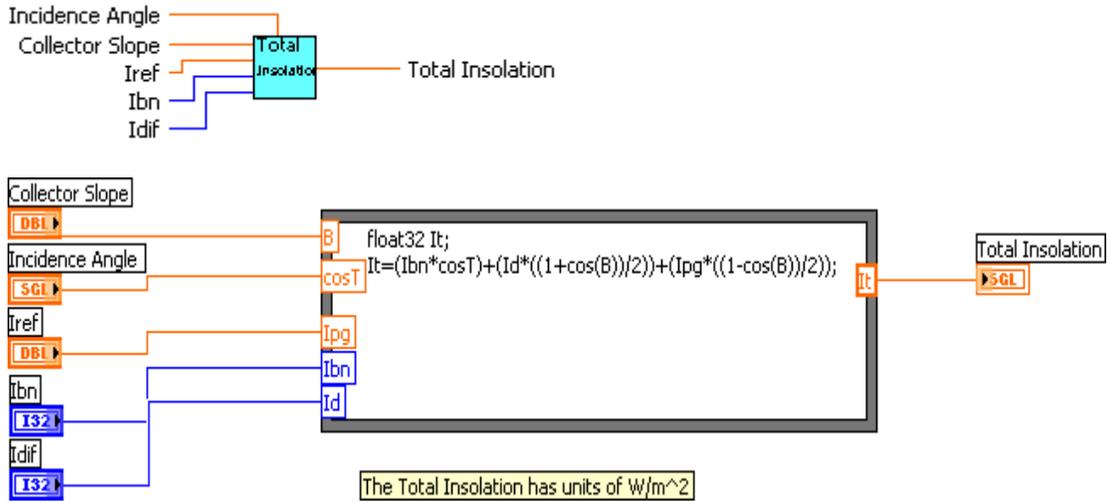
Insolation Integrator.vi

This VI integrates Wh/m^2 to MJ/m^2.

It is mainly for qualitative purposes.

MJ/m^2=XXXWh/m^2*(3600J/Wh)*1x10e-06MJ/J
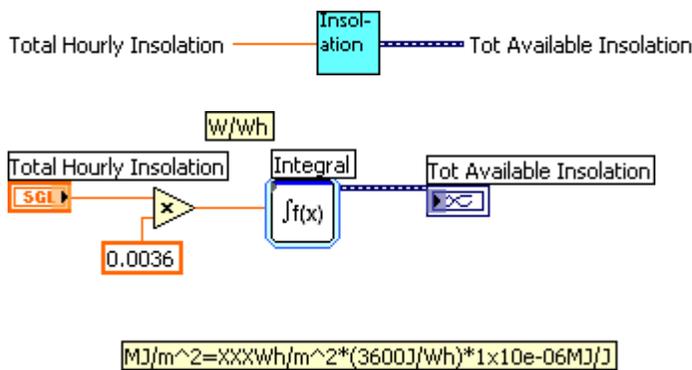
efficiency.vi

The instantaneous efficiency is the ratio of useful power delivered to the system to the available insolation.
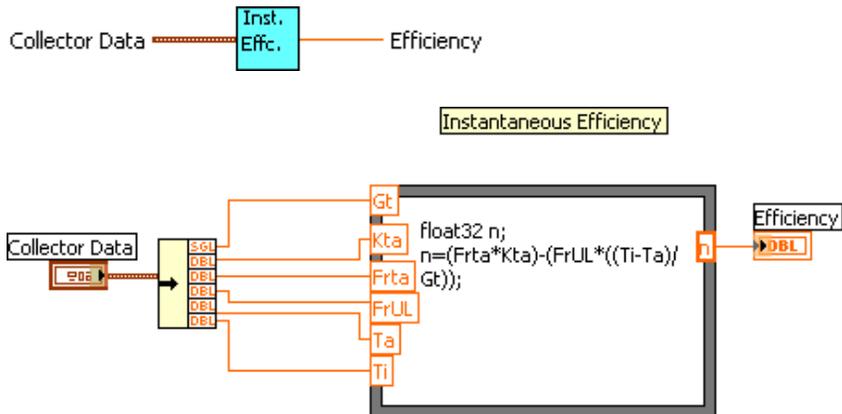
Power (SubVI).vi

This VI calculates the useful power that is delivered by the system.
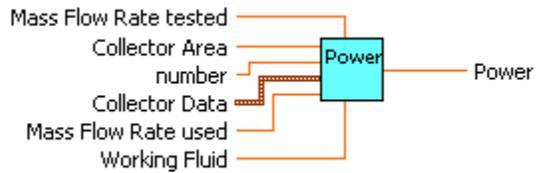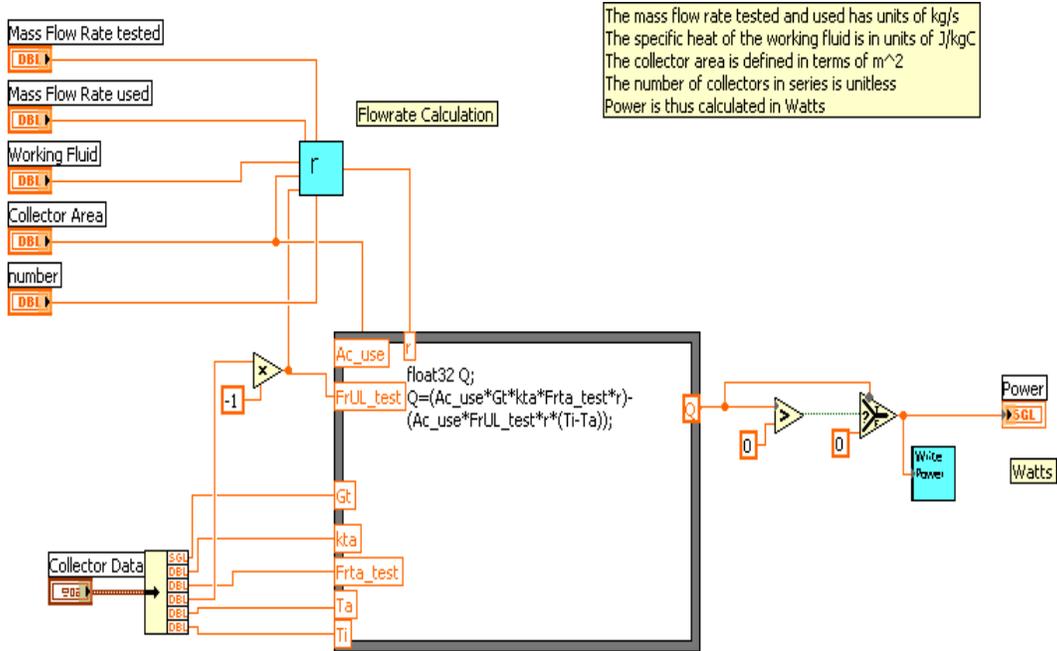
flowratecorrect.vi

This VI calculates the flowrate correction factor.

The SRCC has tested each collector at a certain flowrate, however in most test situations that is not the flowrate used.

The mass flow rate tested and used has units of kg/s
The specific heat of the working fluid is in units of J/kgC
The collector area is defined in terms of m^2
The number of collectors in series is unitless
FrUL_test is defined with units of XXXX
The flow rate correction is unitless

```
float32 FUL;
FUL=((-m_test*Cp)/Ac)*ln(1-((FrUL_test*Ac)/
(m_test*Cp)));
```

```
float32 r;
r=(((m_use*Cp)/(Ac_use*FUL))*(1-exp((-
Ac_use*FUL)/(m_use*Cp))))/(((m_test*Cp)/
(Ac_test*FUL))*(1-exp((-Ac_test*FUL)/
(m_test*Cp))));
```

Write_Power.vi

This VI writes the Useful power with a time stamp to an external file.

C:\Documents and Settings\cemo.DELL260_T\Desktop\LV\power.txt
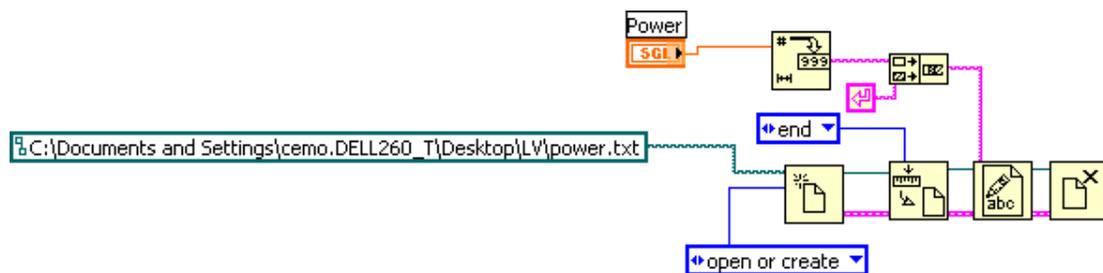
Useful Energy.vi

This VI integrates the useful power to MJ.

Power ——— Energy (useful) ------ Total Energy Gain

Power [SGL]
3E-5
[MJ]

Summation ∫f(x)

Total Energy Gain

Total Useful Energy from the collector

E(MJ)=XXXXJ/s*(30s)*(1x10e-06MJ/J)
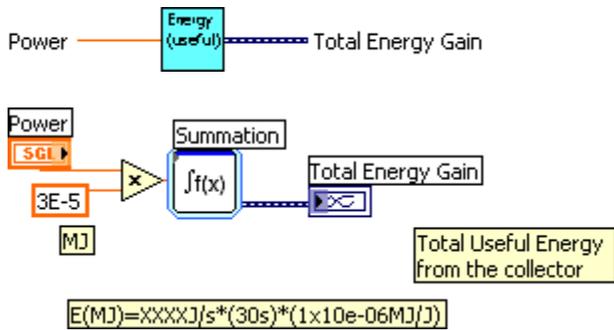
UDPTi_listen(SubVI).vi

This VI listens for the data packet sent by the STCS.

It checks to see if there is an error and if so, sends a no power signal to the STCS

as well as displaying and writing an appropriate warning message to the user

dt ——— UDP TI listen ---- Temps
Draw ......   Flowrate
                          Warning Message
                          Element Control

UDP Packet Form:
(normal) AxxxxAxxxx...QxxxxxQxxxxx
(error)   EOT#ENFCELDD

Draw

Therm
Read

Temps

"A", Default

Warning Message

dt

100

10

Element Control

1111

Flo
Read

Flowrate

connection ID out

Local Port

4001

UDP

548

UDP

UDP

NO
TIMEOUT

error out

30000

Recieves Data from
the hardware on the
local UDP port.

Prevents the UDP
receiving function
from timing out

"E"

1

3

"OT2"

Thermistor 2 has an error

JAN
01
12:01

C:\Documents and Settings\cemo.DELL260_T\Desktop\LV\error.txt

Writes the error code to error.txt

end

open or create

abc

"OT4"
Thermistor 4 has an error

"NFC"
No Fluid in Chamber!

"OT5"
Thermistor 5 has an error

"LDD"
Leak Detected!

Thermread.vi

The Thermistor reader VI extracts the thermistor readings from the data packet.

If a packet is dropped and is returned empty, a local variable retains the previous value and passes that to the consumer loop to be used in calculations.

Dropped Packet
To_Mains
To
Ti
To_Solar Tank
To_Outlet

Data Out
Draw

Therm Read

True
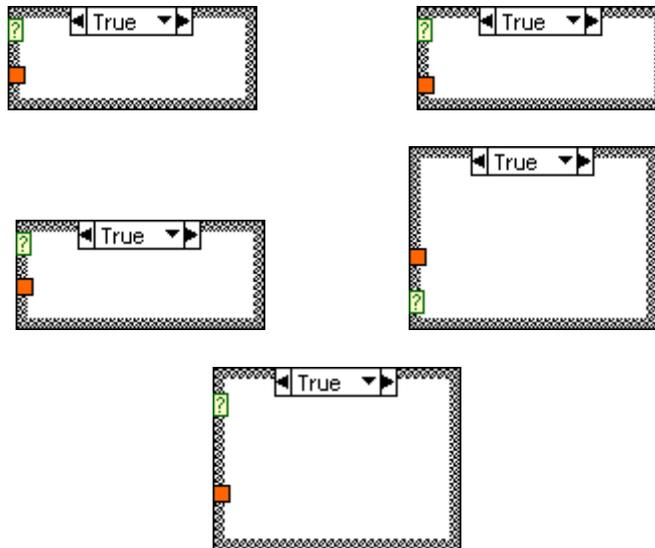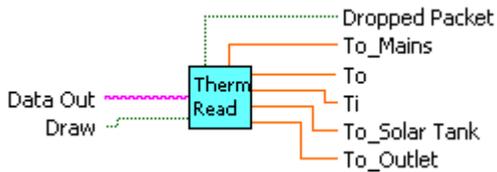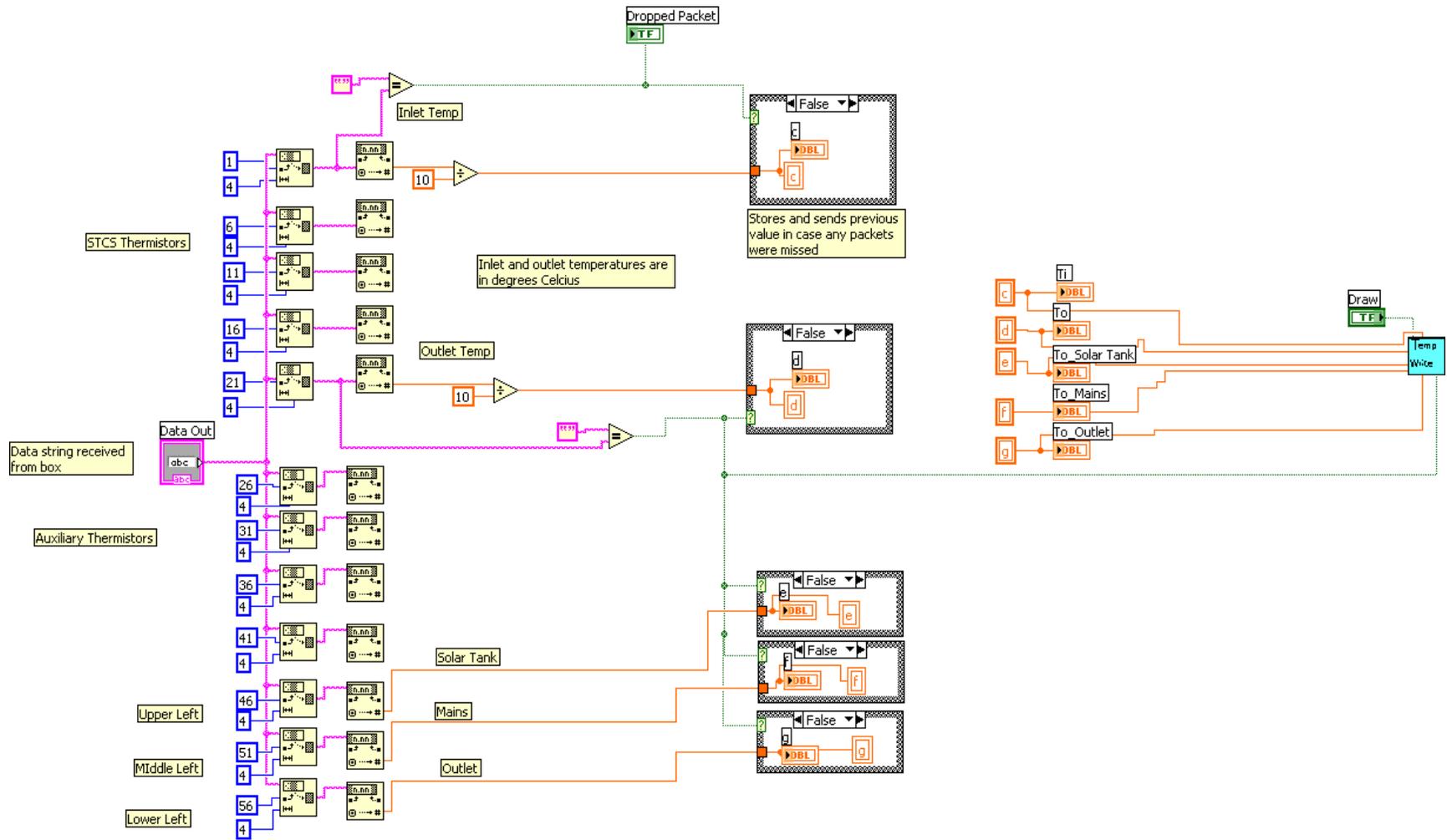
To write.vi

Writes the inlet and outlet temperatures with time stamps to independent external files.
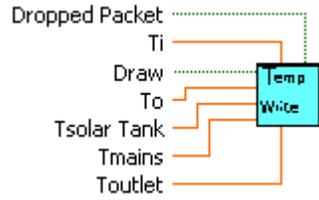
The inlet and outlet temperatures are recorded with an appropriate time stamp for further data reduction

C:\Documents and Settings\cemo.DELL260_T\Desktop\LV\Toutlet.txt
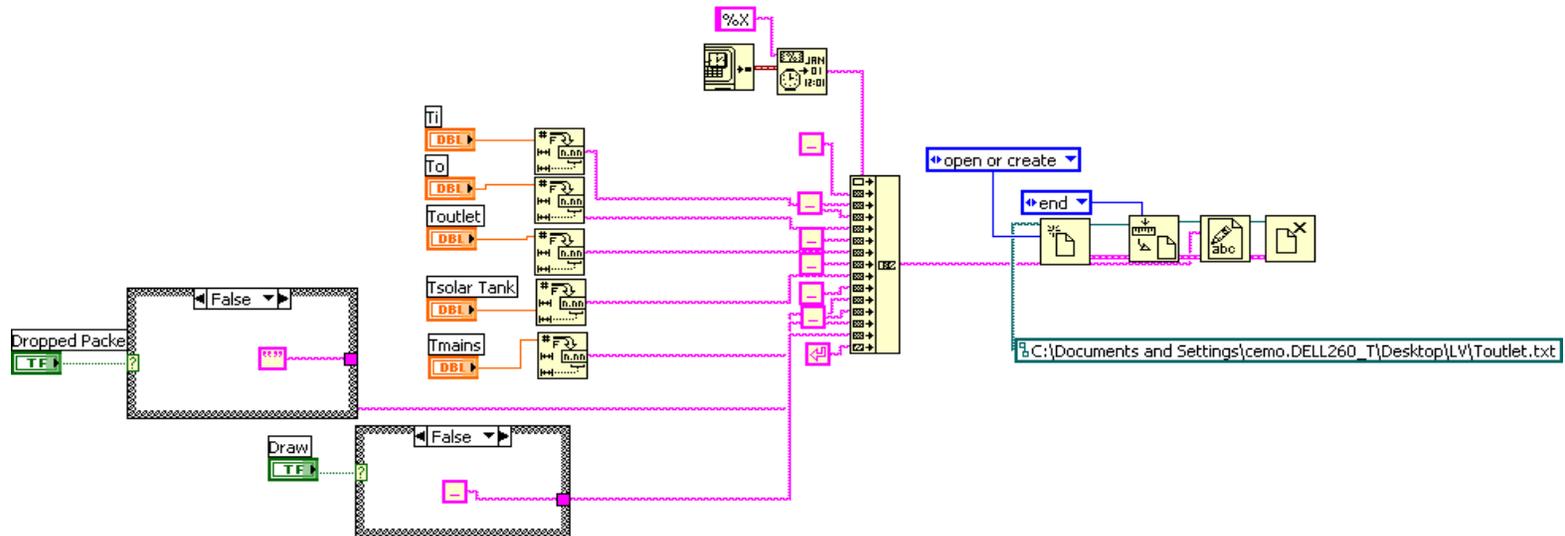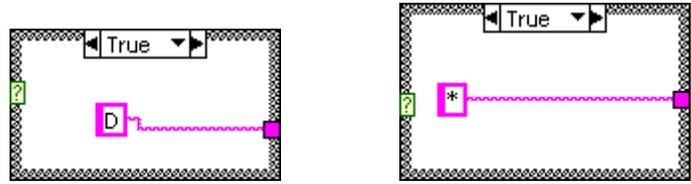
Flowread.vi

A pulse output variety flow sensor sends a 5 V pulse to the STCS every time a prescribed amount of fluid passes through the chamber. This VI converts the accumulated pulses to kg/s.

The Flow reader handles dropped packets, similar to the Thermistor reader VI utilizing local variables.

An average of the past five previous values is created to filter the data received by the STCS.

Flow is written in kg/s
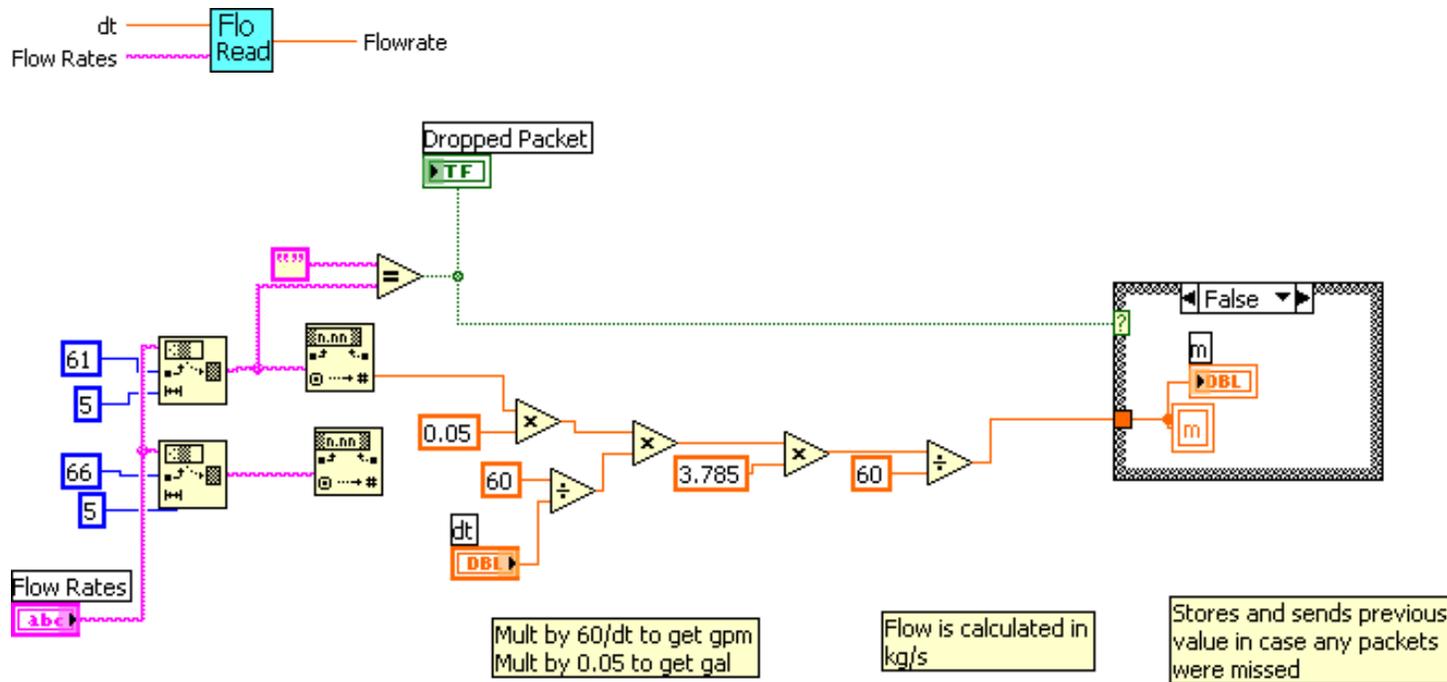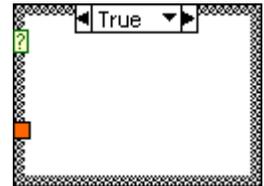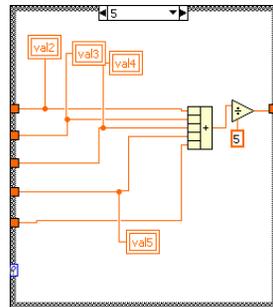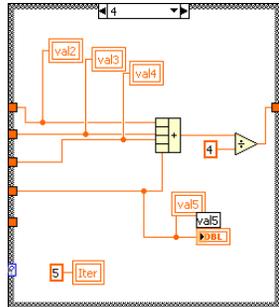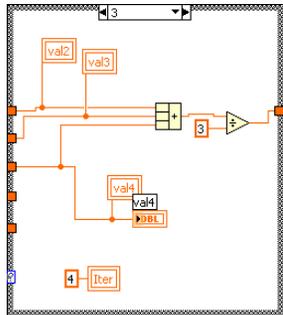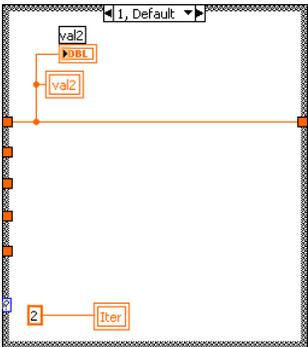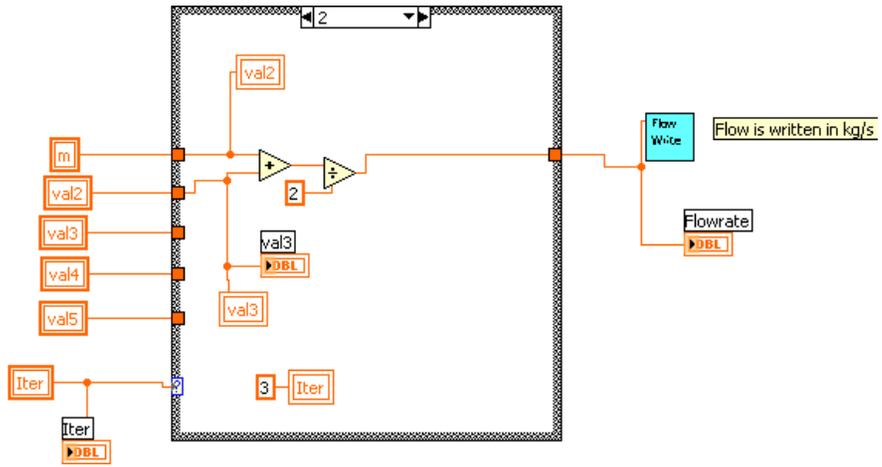
Flowrite.vi

This vi writes the flow rate of the closed heat exchanger loop to a file once ever thirty seconds.
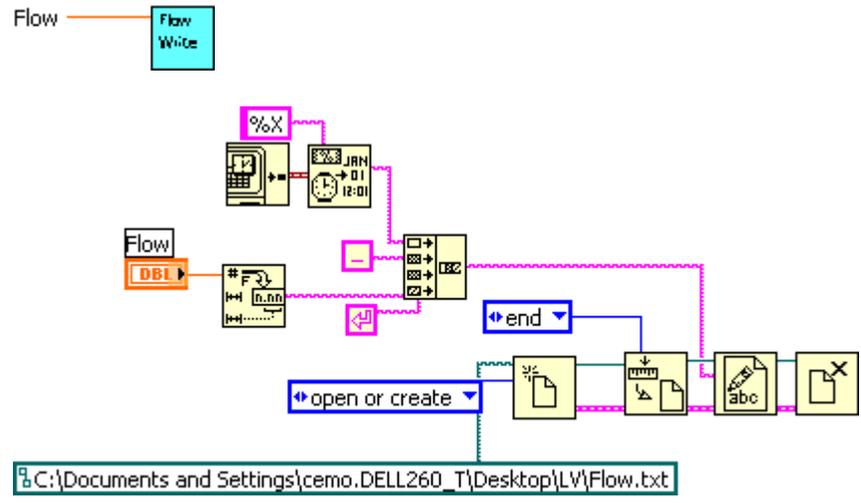
calibrate.vi

This vi calibrates the power calculated from the theoretical collector output to the actual power delivered to the STCS.

Power raw

1.23

Power adj

1.23
SGL

0, Default

9000

2000

1

0

1

0

0, Default

9000

2000

1

0

1

0

1

```
node(float x)
x=w-(0.000000093247287*pow(w,3)-
0.0027738415*pow(w,2)+27.498302*w-
91165.07402);
```

w

x

0, Default

1

```
float32 g;
g=h-(-0.0831*h+243.83);
```

h

g
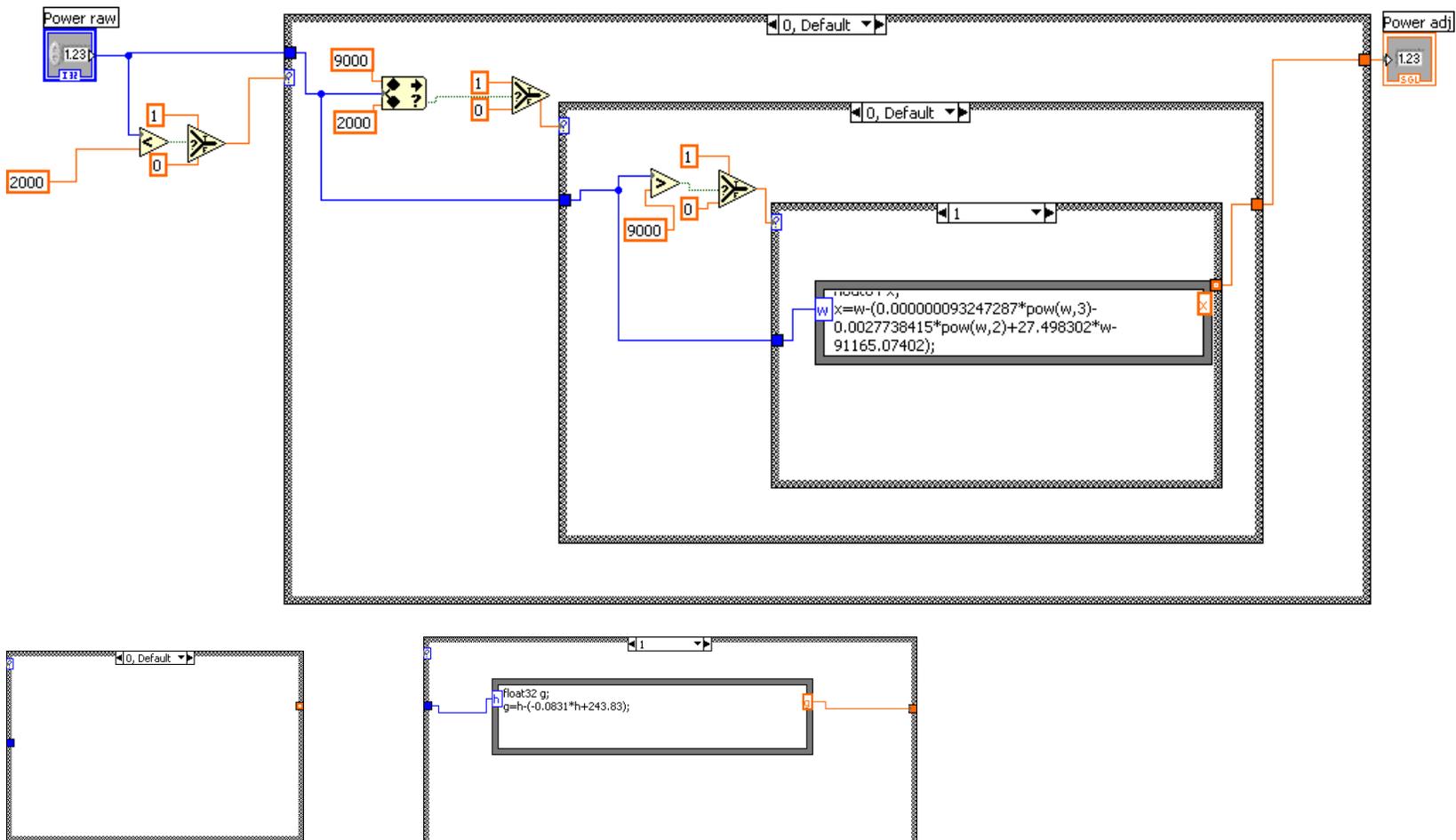
APPENDIX C

Sample Calculations

Single Tank Sample

The calculations involved in determining the Solar Energy Factor are the same for

a single and double tank system.

$$SEF = \frac{Q_{del}}{Q_{aux} + Q_{par}}$$

Parasitic Energy

$Q_{par} := 3664800J$ Parasitic energy usage for a single tank test.

Auxiliary Energy
The auxiliary energy is calculated from five independent measurements of the

auxiliary element power during a single tank test.

$$P := \begin{pmatrix} 3038 \\ 3044 \\ 3032 \\ 3040 \\ 3040 \\ 3040 \end{pmatrix} W \qquad P_{aux} := \frac{1}{6}\left(\sum_{i=0}^{5} P_i \right) = 3.039 \times 10^3 \, W$$

$t_{aux} := 1830s$ Auxiliary element was activated for 45 min during a single tank test.

$Q_{aux} := P_{aux} \cdot t_{aux}$ The energy consumed by the auxiliary element.

Delivered Energy

$V := 11gal$ Single draw volume

Inlet and outlet temperatures were measured once every thirty seconds of the

period of a draw. Data from one draw can be found below.

$$
Ti := \begin{pmatrix} 15.1 \\ 14.4 \\ 14.3 \\ 14.3 \\ 14.2 \\ 14.1 \\ 14.0 \\ 14.2 \end{pmatrix} \qquad To := \begin{pmatrix} 55.5 \\ 56.5 \\ 56.8 \\ 57.1 \\ 56.9 \\ 56.3 \\ 55.8 \\ 55.7 \end{pmatrix} \qquad \Delta T := (To - Ti)K = \begin{pmatrix} 40.4 \\ 42.1 \\ 42.5 \\ 42.8 \\ 42.7 \\ 42.2 \\ 41.8 \\ 41.5 \end{pmatrix} K
$$

In order to calculate the delivered energy, the temperature differences over one draw averaged.

$$
\Delta T_{avg} := \frac{1}{8}\left(\sum_{i=0}^{7} \Delta T_i \right) = 42 K
$$

The energy delivered during one draw is found to be

$$
Cp := 4184 \frac{J}{kg \cdot K} \qquad\qquad \rho := 1000 \frac{kg}{m^3}
$$

$$
Q_{del1} := \rho \cdot V \cdot Cp \cdot \Delta T_{avg} \qquad\qquad Q_{del1} = 7.317 \times 10^6 \, J
$$

The Energy delivered to the hot water load during each of the six draws are as follow

$$
Q_{draw} := \begin{pmatrix} 6973010 \\ 6814580 \\ 6416130 \\ 7701380 \\ 7790920 \\ 7382430 \end{pmatrix} J
$$

The total energy delivered is the sum of the six energy draws.

$$
Q_{del} := \sum_{i=0}^{5} Q_{draw_i} = 4.308 \times 10^7 \, J
$$

The Solar Energy Factor can now be calculated

$$SEF := \frac{Q_{del}}{\left(Q_{aux} + Q_{par}\right)}$$

$\boxed{SEF = 4.669}$

The Solar Fraction can also be easily calculated

$$EF := 0.9$$

$$SF := 1 - \frac{EF}{SEF}$$

$\boxed{SF = 0.807}$

APPENDIX D

Uncertainty Calculations

In order to provide our research with a solid statistical foundation, an uncertainty analysis is performed using the guidance of the methods from Kline and McClintock and Coleman and Steele ([17], [18]). These methods allowed the uncertainty in the volume of water drawn, system uncertainty of the sampling components and the total uncertainty of our measurements to be computed

The basis of the uncertainty comes from Equation D (1), which encompasses the fixed or systematic uncertainty and the random uncertainty.

$$\delta r = \sqrt{Br^2 + tSr^2}$$ D (1)

The fixed uncertainty comes from manufacturer's data and is analyzed using Equation D (2).

$$Br = (\sum (\frac{\delta R}{\delta Xi} \delta Xi)^2)^{\frac{1}{2}}$$ D (2)

The random uncertainty Sr, many times is an approximation of noise, drift, and other uncontrollable phenomena in the devices.

Where the partial derivative of the process equation R represents the sensitivity coefficient, which conveys how sensitive the process is to a variable with uncertainty δXi. The root sum squares method is very important for compiling multiple uncertainties. If the error of an instrument is not given, it is usually assumed to be half of the smallest reading. The following calculations for auxiliary and parasitic energy are performed for one entire test period. The delivered energy uncertainty is calculated based on the average sampled temperature difference per energy draw

Parasitic Energy

$b_{par} := 0.002$

Accuracy of Kill-A-Watt power meter as percentage of reading

$Q_{par} := 4392000J$

Sampled parasitic energy usage for a single tank test.

$\delta_{par} := b_{par} \cdot Q_{par}$

$\delta_{par} = 8.784 \times 10^3 J$

Fixed uncertainty for parasitic energy use

Auxiliary Energy

Random Uncertainty taken from five independent measurements of the auxiliary

element power during a single tank test.

$$P := \begin{pmatrix} 2979 \\ 2977 \\ 2973 \\ 2971 \\ 2972 \\ 2969 \end{pmatrix} W \qquad P_{aux} := \frac{1}{6}\left(\sum_{i=0}^{4} P_i \right) = 2.479 \times 10^3 W$$

Student's t value at 95% confidence for 5 samples and 4 degrees of freedom.

$t := 2.1318$

Standard deviation of power measurements

$\sigma_P := 3.78W$

The random uncertainty for the five power measurements is thus found to be.

$Sr_{Paux} := t \cdot \dfrac{\sigma_P}{5} = 1.612W$

The fixed uncertainty is the accuracy of the Amprobe power meter.

$\delta_P := 0.1W$

Thus it follows that the uncertainty for auxiliary power is found to be

$\delta P := \left(\delta_P{}^2 + Sr_{Paux}{}^2 \right)^{\frac{1}{2}} = 1.615W$

The accuracy of analog power meters is found to be one second.

$\delta_t := 1s$

$t_{aux} := 1320s$

Auxiliary element was activated for 45 min during a single tank test.

$Q_{aux} := P_{aux} \cdot t_{aux}$

The energy consumed by the auxiliary element.

The overall uncertainty of the delivered energy can now be found to be

$$\delta_{aux} := \left[\left(t_{aux} \cdot \delta P \right)^2 + \left(P_{aux} \cdot \delta_t \right)^2 \right]^{\frac{1}{2}}$$

$\delta_{aux} = 3.269 \times 10^3 \, J$

Delivered Energy

$b_V := 0.015$

Accuracy of Omega Totalizer as percentage of reading.

$V := 11 gal$

Single draw volume

$\delta_V := b_V \cdot V$

$\delta_V = 6.246 \times 10^{-4} \cdot m^3$

Fixed uncertainty for draw volume

When measuring temperatures, a K type thermocouple and

Fluke digital thermometer were used.

$b_{Tc} := 2.2K$

$b_{read} := 0.75K$

Accuracies of respective instruments

$$B_{\Delta T} := \left(b_{Tc}^2 + b_{read}^2 \right)^{\frac{1}{2}}$$

Fixed uncertainty of temperature measurement devices

Inlet and outlet temperatures were measured once every thirty seconds

of the period of a draw. Data from one draw can be found below.

$$Ti := \begin{pmatrix} 15.1 \\ 14.4 \\ 14.3 \\ 14.3 \\ 14.2 \\ 14.1 \\ 14.0 \\ 14.2 \end{pmatrix} \qquad To := \begin{pmatrix} 55.5 \\ 56.5 \\ 56.8 \\ 57.1 \\ 56.9 \\ 56.3 \\ 55.8 \\ 55.7 \end{pmatrix} \qquad \Delta T := (To - Ti)K = \begin{pmatrix} 40.4 \\ 42.1 \\ 42.5 \\ 42.8 \\ 42.7 \\ 42.2 \\ 41.8 \\ 41.5 \end{pmatrix} K$$

Standard deviation for the sampled temperature differences $\qquad \sigma_{\Delta T} := 0.983 \ K$

Students t value for 8 samples and 7 degrees of freedom $\qquad t := 1.8945$

Random uncertainty for temperature difference over one draw.

$$Sr_{\Delta T} := \frac{t \cdot \sigma_{\Delta T}}{8} = 0.233 \ K$$

Overall uncertainty for temperature measurements

$$\delta_{\Delta T} := \left(B_{\Delta T}{}^2 + Sr_{\Delta T}{}^2 \right)^{\frac{1}{2}}$$

$$\delta_{\Delta T} = 2.336 \ K$$

In order to calculate the delivered energy, the temperature differences over one draw are averaged.

$$\Delta T_{avg} := \frac{1}{8} \left(\sum_{i=0}^{7} \Delta T_i \right) = 42 \ K$$

The energy delivered during one draw is found to be

$$Cp := 4184 \ \frac{J}{kg \cdot K} \qquad\qquad\qquad \rho := 1000 \ \frac{kg}{m^3}$$

$$Q_{del1} := \rho \cdot V \cdot Cp \cdot \Delta T_{avg} \qquad\qquad Q_{del1} = 7.317 \times 10^6 \ J$$

The fixed uncertainty in the energy delievered during one draw can now be found.

$$B_{del} := \left[\left(\rho \cdot V \cdot Cp \cdot \delta_{\Delta T} \right)^2 + \left(\rho \cdot Cp \cdot \Delta T_{avg} \cdot \delta_V \right)^2 \right]^{\frac{1}{2}}$$

$$B_{del} = 4.215 \times 10^5 \ J$$

The random uncertainty for a set of six draws throughout a solar day can now be calculated

$$Q_{draw} := \begin{pmatrix} 6973010 \\ 6814580 \\ 6416130 \\ 7701380 \\ 7790920 \\ 7382430 \end{pmatrix} J \qquad\qquad Q_{del} := \sum_{i\,=\,0}^{5} Q_{draw_i} = 4.308 \times 10^7 \, J$$

The standard deviation of the six draws is $\qquad \sigma_{draw} := 537900J$

The student's t value for six samples is $\qquad t := 2.0153$

$$Sr_{draw} := \frac{t \cdot \sigma_{draw}}{6} = 1.807 \times 10^5 \, J$$

The overall uncertainty of the energy delivered throughout the day can now be found

$$\delta_{del} := \left(B_{del}{}^2 + Sr_{draw}{}^2 \right)^{\frac{1}{2}}$$

$$\delta_{del} = 4.586 \times 10^5 \, J$$

Overall Uncertainty

Since the SEF is calculated by summing up the energy delivered during six

independent draws, the delivered energy is multiplied by six to provide an

approximate SEF value.

$$U_{SEF} := \left[\left[\frac{\delta_{del}}{\left(Q_{aux} + Q_{par} \right)} \right]^2 + \left[\frac{-\delta_{aux} \cdot Q_{del}}{\left(Q_{aux} + Q_{par} \right)^2} \right]^2 + \left[\frac{-\delta_{par} \cdot Q_{del}}{\left(Q_{aux} + Q_{par} \right)^2} \right]^2 \right]^{\frac{1}{2}}$$

$$\boxed{U_{SEF} = 0.06023}$$

Parasitic Energy

$b_{par} := 0.002$

Accuracy of Kill-A-Watt power meter as percentage of reading

$Q_{par} := 3564000 J$

Sampled parasitic energy usage for a single tank test.

$\delta_{par} := b_{par} \cdot Q_{par}$

$\delta_{par} = 7.128 \times 10^3 J$

Fixed uncertainty for parasitic energy use

Auxiliary Energy

Random Uncertainty taken from five independent measurements of the auxiliary

element power during a single tank test.

$$P := \begin{pmatrix} 3088 \\ 2960 \\ 3023 \\ 3050 \\ 3040 \\ 3028 \end{pmatrix} W \qquad P_{aux} := \frac{1}{6} \left(\sum_{i=0}^{4} P_i \right) = 2.527 \times 10^3 W$$

Student's t value at 95% conficdence for 5 samples.

$t := 2.015$

Standard Deviation of Power measurements

$\sigma_P := 41.96 W$

The random uncertainty for the five power measurements is thus found to be.

$Sr_{Paux} := t \cdot \dfrac{\sigma_P}{6} = 14.092 W$

The fixed uncertainty is the accuracy of the Amprobe power meter.

$$\delta_P := 0.1\,W$$

Thus it follows that the uncertainty for auxiliary power is found to be

$$\delta P := \left(\delta_P^2 + Sr_{Paux}^2 \right)^{\frac{1}{2}} = 14.092\,W$$

The accuracy of analog power meters is found to be one second.

$$\delta_t := 1s$$

$$t_{aux} := 4530s$$
Auxiliary element was activated for 45 min during a single tank test.

$$Q_{aux} := P_{aux} \cdot t_{aux}$$
The energy consumed by the auxiliary element.

The overall uncertainty of the delivered energy can now be found to be

$$\delta_{aux} := \left[\left(t_{aux} \cdot \delta P \right)^2 + \left(P_{aux} \cdot \delta_t \right)^2 \right]^{\frac{1}{2}}$$

$$\delta_{aux} = 6.389 \times 10^4\,J$$

Delivered Energy

$$b_V := 0.015$$
Accuracy of Omega Totalizer as percentage of reading.

$$V := 11\,gal$$
Single draw volume

$$\delta_V := b_V \cdot V$$

$$\delta_V = 6.246 \times 10^{-4} \cdot m^3$$
Fixed uncertainty for draw volume

When measuring temperatures, a K type thermocouple and Fluke digital thermometer were used.

$$b_{Tc} := 2.2K$$

$$b_{read} := 0.756K$$
Accuracies of respective instruments

$$B_{\Delta T} := \left(b_{Tc}^2 + b_{read}^2 \right)^{\frac{1}{2}}$$
Fixed uncertainty of temperature measurement devices

Inlet and outlet temperatures were measured once every thirty seconds

of the period of a draw. Data from one draw can be found below.

$$Ti := \begin{pmatrix} 15.1 \\ 14.3 \\ 14.3 \\ 14.5 \\ 14.4 \\ 14.8 \\ 14.7 \\ 14.7 \end{pmatrix} \qquad To := \begin{pmatrix} 58.1 \\ 58.3 \\ 58.3 \\ 58.2 \\ 57.9 \\ 57.8 \\ 57.2 \\ 55.2 \end{pmatrix} \qquad \Delta T := (To - Ti)K = \begin{pmatrix} 43 \\ 44 \\ 44 \\ 43.7 \\ 43.5 \\ 43 \\ 42.5 \\ 40.5 \end{pmatrix} K$$

Standard deviation for the sampled temperature differences $\sigma_{\Delta T} := 1.15 K$

Students t value for 8 samples $t := 1.86$

Random uncertainty for temperature difference over one draw.

$$Sr_{\Delta T} := \frac{t \cdot \sigma_{\Delta T}}{8} = 0.267 \ K$$

Overall uncertainty for temperature measurements

$$\delta_{\Delta T} := \left(B_{\Delta T}^{\ 2} + Sr_{\Delta T}^{\ 2} \right)^{\frac{1}{2}}$$

$$\delta_{\Delta T} = 2.342 \ K$$

In order to calculate the delivered energy, the temperature differences over one draw are averaged.

$$\Delta T_{avg} := \frac{1}{8} \left(\sum_{i=0}^{7} \Delta T_i \right) = 43.025 \ K$$

The energy delivered during one draw is found to be

$$Cp := 4184 \ \frac{J}{kg \cdot K} \qquad\qquad \rho := 1000 \ \frac{kg}{m^3}$$

$$Q_{del1} := \rho \cdot V \cdot Cp \cdot \Delta T_{avg} \qquad\qquad Q_{del1} = 7.496 \times 10^6 \ J$$

The fixed uncertainty in the energy delievered during one draw

$$B_{del} := \left[\left(\rho \cdot V \cdot Cp \cdot \delta_{\Delta T} \right)^2 + \left(\rho \cdot Cp \cdot \Delta T_{avg} \cdot \delta_V \right)^2 \right]^{\frac{1}{2}}$$

$$B_{del} = 4.232 \times 10^5 \, J$$

The random uncertainty for a set of six draws throughout a solar day

$$Q_{draw} := \begin{pmatrix} 7132590 \\ 8280350 \\ 8048080 \\ 7494990 \\ 4548610 \\ 6755540 \end{pmatrix} J \qquad Q_{del} := \sum_{i=0}^{5} Q_{draw_i} = 4.226 \times 10^7 \, J$$

The standard deviation of the six draws is $\qquad \sigma_{draw} := 1345968 \, J$

The student's t value for six samples is $\qquad t := 2.015$

$$Sr_{draw} := \frac{t \cdot \sigma_{draw}}{6} = 4.52 \times 10^5 \, J$$

The overall uncertainty of the energy delivered throughout the day

$$\delta_{del} := \left(B_{del}^2 + Sr_{draw}^2 \right)^{\frac{1}{2}}$$

$$\delta_{del} = 6.192 \times 10^5 \, J$$

Overall Uncertainty
Since the SEF is calculated by summing up the energy delivered
during six independent draws, the delivered energy is multiplied by
six to provide an approximate SEF value.

$$U_{SEF} := \left[\left[\frac{\delta_{del}}{\left(Q_{aux} + Q_{par} \right)} \right]^2 + \left[\frac{-\delta_{aux} \cdot Q_{del}}{\left(Q_{aux} + Q_{par} \right)^2} \right]^2 + \left[\frac{-\delta_{par} \cdot Q_{del}}{\left(Q_{aux} + Q_{par} \right)^2} \right]^2 \right]^{\frac{1}{2}}$$

$$\boxed{U_{SEF} = 0.043}$$

APPENDIX E

Equipment Manuals

Table E 1. SRCC Solar Profile

The outdoor ambient temperature, solar radiation, and incident angle profiles are defined as follows:

Solar Time (hour)	Ambient Temperature ($^\circ$C)	Ambient Temperature ($^\circ$F)	Solar Radiation (W-hr/m^2)	Solar Radiation (Btu/hr-ft^2)	Incident Angle
0 - 1	13	55.4	0	0	--
1 - 2	12	53.6	0	0	--
2 - 3	11	51.8	0	0	--
3 - 4	10	50.0	0	0	--
4 - 5	9	48.2	0	0	--
5 - 8	8	46.4	0	0	--
8 - 9	8	46.4	315	100	60
9 - 10	11	51.8	470	150	45
10 - 11	13	55.4	570	180	30
11 - 12	15	59.0	660	210	15
12 - 13	17	62.6	700	220	0
13 - 14	19	66.2	660	210	15
14 - 17	21	69.8	570	180	30
15 - 16	21	69.8	470	150	45
16 - 17	21	69.8	315	100	60
17 - 18	20	68.0	0	0	--
18 - 19	19	66.2	0	0	--
19 - 20	18	64.4	0	0	--
20 - 21	17	62.6	0	0	--
21 - 22	16	60.8	0	0	--
22 - 23	15	59.0	0	0	--
23 - 24	14	57.2	0	0	--

SOLAR WATER HEATING SYSTEMS CERTIFICATION AND RATING	CERTIFIED SOLAR WATER HEATING SYSTEM
SRCC OG-300	**SUPPLIER:** Solene 927 Fern Street Suite 1500 Altamont Springs, FL 32701 (407) 831-1941 (407) 831-1208 Fax **SYSTEM NAME:** Solene/Chromagen Drain Back **SYSTEM TYPE:** Indirect Forced Circulation

Description: Glazed Flat-Plate Collector, Differential Controller, Tank Wrap Around Heat Exchanger with a Double Wall and Positive Leak Detection, No Load Side Heat Exchanger, Fluid Class I, Freeze Tolerance: -23.3 C (-10 F), Electric Auxiliary Tank

System Model Name	Cert 300-#	Cert Date	Collector Panel Manufacturer	Collector Panel Name	Total Panel Area (Sq-m)	Total Panel Area (Sq-ft)	Solar Tank Vol (l)	Solar Tank Vol (gal)	Aux Tank Vol (l)	Aux Tank Vol (gal)	SEF
SLCR64DC-120DB-XE	2006030E	11/7/2008	Solene	SLCR-32	5.9	64.0	454	120	189	50	2.0
SLCR64DC-80DB-XE	2006030C	12/7/2006	Solene	SLCR-32	5.9	64.0	303	80	189	50	2.3
SLCR80DC-120DB-XE	2006030F	11/7/2008	Solene	SLCR-40	7.4	80.1	454	120	189	50	2.4
SLCR80DC-80DB-XE	2006030D	12/7/2006	Solene	SLCR-40	7.4	80.1	303	80	189	50	3.0

OG300 System Reference: 2006030C

SOLAR WATER HEATING SYSTEMS CERTIFICATION AND RATING	CERTIFIED SOLAR WATER HEATING SYSTEM
SRCC	SUPPLIER: Solene 927 Fern Street Suite 1500 Altamont Springs, FL 32701 (407) 831-1941 (407) 831-1208 Fax
SRCC OG-300	SYSTEM NAME: Solene/Chromagen Drain Back SYSTEM TYPE: Indirect Forced Circulation

Description: Glazed Flat-Plate Collector, Differential Controller, Tank Wrap Around Heat Exchanger with a Double Wall and Positive Leak Detection, No Load Side Heat Exchanger, Fluid Class I, Freeze Tolerance: -23.3 C (-10 F), Electric Auxiliary Tank

System Model Name	Cert 300-#	Cert Date	Collector Panel Manufacturer	Collector Panel Name	Total Panel Area (Sq-m)	Total Panel Area (Sq-ft)	Solar Tank Vol (l)	Solar Tank Vol (gal)	Aux Tank Vol (l)	Aux Tank Vol (gal)	SEF
SLCR60DC-80DB	2006001E	3/15/2006	Solene	SLCR-30	5.6	60.6	303	80			2.9
SLCR64DC-120DB	2006001F	11/7/2008	Solene	SLCR-32	5.9	64.0	454	120			2.5
SLCR64DC-80DB	2006001C	3/15/2006	Solene	SLCR-32	5.9	64.0	303	80			3.0
SLCR80DC-120DB	2006001G	11/7/2008	Solene	SLCR-40	7.4	80.1	454	120			3.2
SLCR80DC-80DB	2006001D	3/15/2006	Solene	SLCR-40	7.4	80.1	303	80			4.9

OG300 System Reference: 2006001C

SOLAR COLLECTOR CERTIFICATION AND RATING

SRCC OG-100

CERTIFIED SOLAR COLLECTOR

SUPPLIER: **Solene**
927 Fern Street Suite 1500
Altamont Springs, FL 32701

MODEL: Solene/Chromagen SLCR-40
COLLECTOR TYPE: Glazed Flat-Plate
CERTIFICATION #: 100-2004-014C

COLLECTOR THERMAL PERFORMANCE RATING

Megajoules Per Panel Per Day				Thousands of Btu Per Panel Per Day			
CATEGORY (Ti-Ta)	CLEAR DAY 23 MJ/m²·d	MILDLY CLOUDY 17 MJ/m²·d	CLOUDY DAY 11 MJ/m²·d	CATEGORY (Ti-Ta)	CLEAR DAY 2000 Btu/ft²·d	MILDLY CLOUDY 1500 Btu/ft²·d	CLOUDY DAY 1000 Btu/ft²·d
A (-5°C)	55	41	28	A (-9°F)	52	39	26
B (5°C)	53	39	25	B (9°F)	50	37	24
C (20°C)	46	32	19	C (36°F)	44	31	18
D (50°C)	28	15	4	D (90°F)	26	15	4
E (80°C)	8			E (144°F)	7		

A-Pool Heating (Warm Climate) B-Pool Heating (Cool Climate) C-Water Heating (Warm Climate) D-Water Heating (Cool Climate) E-Air Conditioning

Original Certification Date: November 4, 2004

COLLECTOR SPECIFICATIONS

Gross Area:	3.721	m²	40.05	ft²	Net Aperture Area:	3.469	m²	37.34 ft²
Dry Weight:	68.9	kg	152	lb	Fluid Capacity:	3.8	l	1.0 gal
Test Pressure:	1103	kPa	160	psig				

COLLECTOR MATERIALS

Frame: Aluminum
Cover (Outer): Low Iron Tempered Glass
Cover (Inner): None
Absorber Material: Tube - Copper / Plate - Copper Fin
Absorber Coating: Black Chrome
Insulation (Side): Polyurethane [Foil-faced]
Insulation (Back): Mineral Wool & Polyurethane

PRESSURE DROP

Flow		ΔP	
ml/s	gpm	Pa	in H₂O

TECHNICAL INFORMATION

Efficiency Equation [NOTE: Based on gross area and (P) = Ti-Ta]

							Y Intercept	Slope	
S I Units:	η =	0.704	-1.7983	(P)/I	-0.0470	(P)²/I	0.735	-5.365	W/m²·°C
I P Units:	η =	0.704	-0.3169	(P)/I	-0.0046	(P)²/I	0.735	-0.945	Btu/hr·ft²·°F

Incident Angle Modifier [(S) = 1/cos θ - 1, 0°≤ θ ≤60°]

$K_{\alpha\tau}$ = 1.0   -0.2011 (S)   +0.0069 (S)²
$K_{\alpha\tau}$ = 1.0   -0.19 (S)   (Linear Fit)

Model Tested: SLCR-30
Test Fluid: Water
Test Flow Rate: 52 ml/s   0.82 gpm

REMARKS:

July, 2007
Certification must be renewed annually. For current status contact:
SOLAR RATING & CERTIFICATION CORPORATION
c/o FSEC ♦ 1679 Clearlake Road ♦ Cocoa, FL 32922 ♦ (321) 638-1537♦ Fax (321) 638-1010

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Submittal Data Information

Model 003 Cartridge Circulator

Effective: September 1, 2003

Supersedes: December 1, 2002

Job: _____ Engineer: _____ Contractor: _____ Rep: _____

ITEM NO.	MODEL NO.	IMP. DIA.	G.P.M.	HEAD/FT.	H.P.	ELEC. CHAR.

Features

- Reduces Erosion, Corrosion and Flow Noise in shorter pipe run applications
- Standard High Capacity Output-Compact Design
- Quiet, Efficient Operation
- Direct Drive-Low Power Consumption
- Unique Replaceable Cartridge Design-Field Serviceable
- Self Lubricating
- No Mechanical Seal
- Unmatched Reliability-Maintenance Free
- Bronze Construction with Sweat, Threaded or Union Connections

Materials of Construction

Casing (Volute):	Bronze
Stator Housing:	Steel
Cartridge:	Stainless Steel
Impeller:	Non-Metallic
Shaft:	Ceramic
Bearings:	Carbon
O-Ring & Gaskets:	EPDM

Model Nomenclature

B	-	Bronze, Sweat
BC	-	Bronze, Sweat, Panel Mount Tappings
BT	-	Bronze, Threaded
BC-1	-	Bronze, Union, Panel Mount Tappings

Performance Data

Flow Range: 0 – 6 GPM

Head Range: 0 – 5 Feet

Minimum Fluid Temperature: 40°F (4°C)

Maximum Fluid Temperature: 220°F (104°C)

Maximum Working Pressure: 125 psi

Connection Sizes: 1/2" Swt, 3/4" Swt, 3/4" NPT, or Union

UL LISTED c(UL)us

FOR INDOOR USE ONLY

Application

The Taco 003 is designed for circulating hot or chilled fresh water in open or closed loop, lower flow applications. Flow characteristics are ideal for Domestic Hot Water Recirculation, Heat Recovery units, Water Source Heat Pumps, and Potable Water systems. The unique, replaceable cartridge contains all of the moving parts and allows for easy service instead of replacing the entire circulator. The compact, low power consumption design is ideal for high efficiency jobs.

Pump Dimensions & Weights

Model	Conn	A in.	A mm	B in.	B mm	C in.	C mm	D in.	D mm	F in.	F mm	G in.	G mm	Ship Wt. lbs.	Ship Wt. Kg
003-B4	3/4"Swt	5-1/8	130	4-1/8	105	2-3/16	56	3-1/16	78	3-5/16	84	4-13/32	112	6.0	2.7
003-BC4	1/2"Swt	5-1/8	130	4-1/8	105	2-1/8	54	3-1/16	78	3-5/16	84	4-1/4	108	6.0	2.7
003-BT4	3/4"NPT	5-5/8	143	4-7/8	124	2	51	3-1/16	78	3-5/16	84	4	102	6.0	2.7
003-BC4-1	Union	5-5/32	131	4-11/32	110	2-31/32	76	3-1/16	78	3-5/16	84	5-15/16	151	6.0	2.7

Mounting Positions

Standard   Optional   OK if over 20 psi
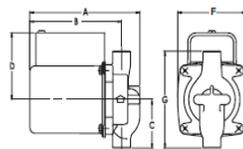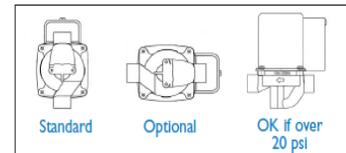
Electrical Data

Model	Volts	Hz	Ph	Amps	RPM	HP
003 All Models	115	60	1	.43	3250	1/40

Motor Type	Permanent Split Capacitor Impedance Protected
Motor Options	220/50/1, 220/60/1, 230/60/1, 100/110/50/60/1

Performance Field - 60Hz

Do it Once. Do it Right.

Taco, Inc., 1160 Cranston Street, Cranston, RI 02920   Telephone: (401) 942-8000   Fax: (401) 942-2360

Taco (Canada), Ltd., 6180 Ordan Drive, Mississauga, Ontario L5T 2B3   Telephone: (905) 564-9422   Fax: (905) 564-9436

Visit our website at: www.taco-hvac.com

Taco *00 CIRCULATORS*

FLOW-M3/H

TOTAL HEAD-METERS

FLOW-GPM

TOTAL HEAD-FEET

①	003B
②	005
③	006
④	006B
⑤	007
⑥	008

Submittal Data Information

Model 009 Cartridge Circulator

101-032

Effective: September 1, 2003

Supersedes: July 1, 2003

Job: _____ Engineer: _____ Contractor: _____ Rep: _____

ITEM NO.	MODEL NO.	IMP. DIA.	G.P.M.	HEAD/FT.	H.P.	ELEC. CHAR.

Features

- Standard High Capacity Output-Compact Design
- Quiet, Efficient Operation
- Direct Drive-Low Power Consumption
- Unique Replaceable Cartridge Design-Field Serviceable
- Self Lubricating
- No Mechanical Seal
- Unmatched Reliability-Maintenance Free
- Universal Flange to Flange Dimensions
- Cast Iron or Bronze Construction

Materials of Construction

Casing (Volute):	Cast Iron or Bronze
Stator Housing:	Aluminum
Cartridge:	Stainless Steel
Impeller:	Non-Metallic
Shaft:	Ceramic
Bearings:	Carbon
O-Ring & Gaskets:	EPDM

Model Nomenclature

F – Cast Iron, Flanged
BF – Bronze, Flanged
Variations:
Z – Zoning Circulator
J – Bronze Cartridge with Cast Iron Casing

Performance Data

Flow Range: 0 – 8 GPM
Head Range: 0 – 34 Feet
Minimum Fluid Temperature: 40°F (4°C)
Maximum Fluid Temperature: 230°F (110°C)
Maximum Working Pressure: 125 psi
Connection Sizes: 3/4", 1", 1-1/4", 1-1/2" Flanged

FOR INDOOR USE ONLY

Application

The Taco 009 is designed for a wide range of Residential and Light Commercial higher-head/lower-flow water circulating applications. Typical uses include Hydronic heating, Radiant In-Floor/Panel heating and closed-loop Solar heating systems. The Bronze 009 can be used in higher-head/lower-flow Heat Recovery, open-loop Solar heating and Light Commercial Domestic Water Recirculation systems. The unique replaceable cartridge contains all of the moving partsand allows for easy service, instead of replacing the entire circulator. Compact, direct-drive, low power consumption design is ideal for high-efficiency jobs.

Pump Dimensions & Weights

		A		B		C		D		F		G		Ship Wt.	
Model	Casing	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm	lbs.	Kg
009-F5	Cast Iron	7	178	5-11/16	144	3-3/16	81	3-5/16	84	4-1/8	105	6-3/8	162	9.5	4.3
009-BF5	Bronze	7	178	5-11/16	144	3-3/16	81	3-5/16	84	4-1/8	105	6-3/8	162	9.5	4.3

Mounting Positions

Standard · Optional · OK if over 20 psi
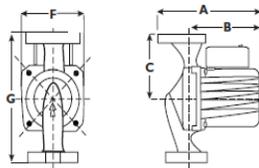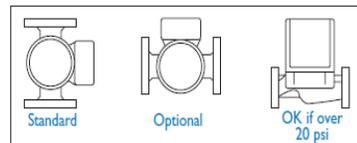
Electrical Data

Model	Volts	Hz	Ph	Amps	RPM	HP
009-F5	115	60	1	1.40	3250	1/8
009-BF5	115	60	1	1.40	3250	1/8
Motor Type	Permanent Split Capacitor Impedance Protected					
Motor Options	220/50/1, 220/60/1, 230/60/1, 100/110/50/60/1					

Flange Orientation
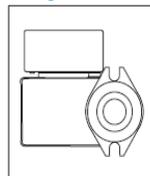
Performance Field - 60Hz
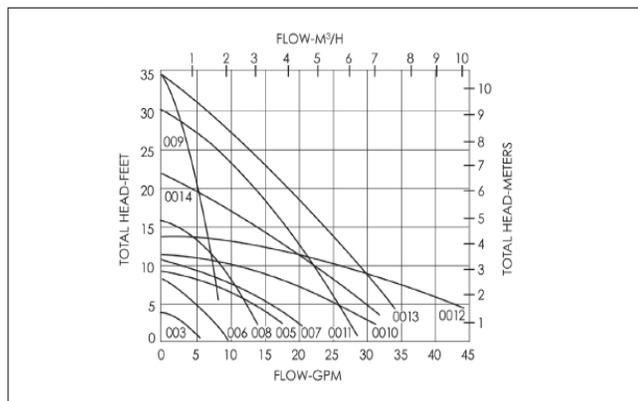
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Taco 00 CIRCULATORS
FLOW-M3/H

TOTAL HEAD-METERS

TOTAL HEAD-FEET

FLOW-GPM

1	009
2	0010
3	0011
4	0012
5	0013
6	0014
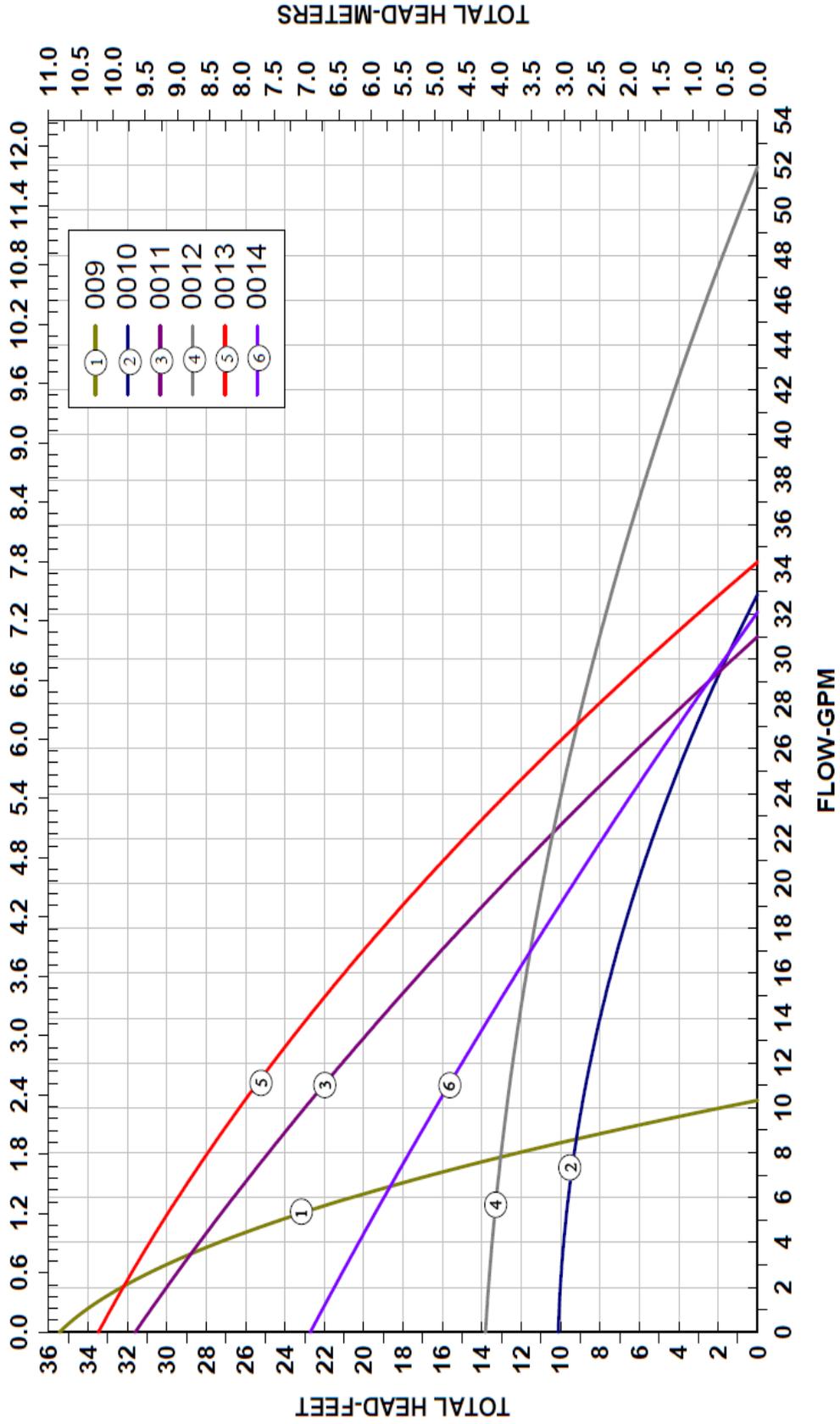
Solaraide™ HE Solar Heat Exchanger, Solar Tank, or Electric Storage Water Heater

Available in 80 and 120 Gallon Models

▶ **6-Year Limited Tank and Parts Warranty***

- Brass drain valve
- Choice of two models…storage tank or single element water heater specifically engineered for installation with residential indirect solar systems
- Temperature and pressure relief valve included
- Collector feed and return fittings located at front of tank for convenient installation
- Isolated tank design for better heat retention
- High efficiency heating element
- Rheemglas® tank lining resists corrosion and prolongs tank life
- Heat exchanger: copper tubing wrapped around and secured to the tank. Double wall, vented design for positive leak detection

- Cold water inlet brings cold water to tank bottom to prevent mixing with heated water
- Anode rod equalizes aggressive water action for prolonged tank life
- Cold water inlet, hot water outlet, relief valve and anode rod at top of tank for easy access and fast, economical installation
- Automatic temperature control
- Over temperature protector

* See Residential Warranty Information Brochure for complete warranty information.

TYPE	GAL. CAP.	DESCRIPTION		ROUGHING IN DIMENSIONS (SHOWN IN INCHES)			ENERGY INFORMATION
		MODEL NUMBER	ELEMENT WATTAGE UPPER	HEIGHT A	DIAMETER B	APPROX. SHIP WT. (LBS.)	APPROX. R-FACTOR
	80	81V80HE-1	4500 W*	58-3/4	24-1/2	222	R-17.3
	80	81V80HE-T	Storage only	58-3/4	24-1/2	222	R-17.3
	120	82V120HE-1	4500 W*	62	28-1/4	380	R-17.3
	120	82V120HE-T	Storage only	62	28-1/4	380	R-17.3

* Heaters furnished with standard 240 volt AC, single phase non-simultaneous wiring and 4500 watt heating element.
- **If heating elements of different wattages than those shown are demanded by zone requirements, they must be specifically requested.**
- To prevent corrosion, proper pH levels in transfer fluid must be maintained.
- Solaraide models meet all current state requirements for solar storage tanks.
- The tanks are Rheemglas lined and are designed to operate up to 150 PSI.

A special 1/2" NPT opening is provided for installation of a "probe type" thermostat.

COPPER COIL DATA (Type L Copper)
Maximum pressure = 150 PSI
Maximum temperature = 185° F
Tube I.D. = 5/8"

Solaraide HE Tank Capacity	Coil Capacity Gallons	Length of Tubing Around Tank (Ft)
80 Gallons	2.2	120
120 Gallons	2.6	143

PRESSURE DROP THROUGH COIL (Feet of H₂0)		
	Head Loss (Feet)	
Flow Rate	80 Gallon	120 Gallon
1 GPM	1.3	1.6
2 GPM	4.8	5.7
3 GPM	10.0	12.0

WATER CONNECTION NIPPLES ALL 3/4" N.P.T.

RELIEF
HOT VALVE COLD

COLD INLET
HOT OUTLET
COLLECTOR RETURN
COLLECTOR FEED

SOLAR ENERGY COLLECTOR SUITABLE FOR POTABLE WATER AND PROPYLENE GYLCOL SOLUTION

WATER CIRCULATOR (REQUIRED FOR NON-GRAVITY SYSTEMS)
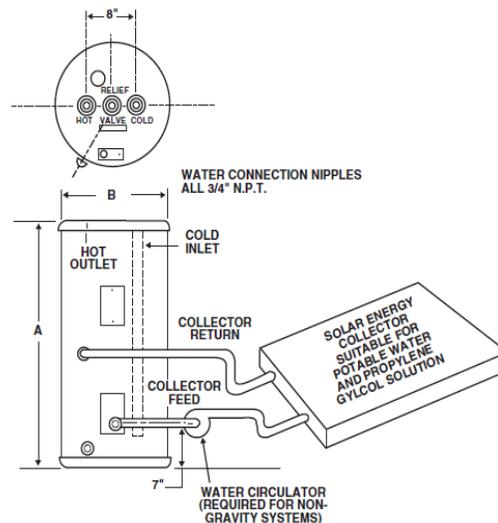
In keeping with its policy of continuous progress and product improvement, Rheem reserves the right to make changes without notice.

P4400 Kill A Watt ™ Operation Manual

Congratulations on your purchase of the Kill A Watt™ Power Meter. Cared for properly, this unit will provide you with years of service.

1. The LCD shows all meter readings: Volts, Current, Watts, Frequency, Power Factor, and VA. The unit will start to accumulate KWH and powered duration time (hour) after power is applied.

2. Press Volt Key for true RMS Voltage (Volts) display.

3. Press Amp Key for true RMS output current (Amps) display.

4. The Watt/VA Key is a toggle function key. Press the Watt/VA key once to display Watt meter, then press key to display VA meter. The LCD will display Watts as the active power, where VA is the apparent Power. (VA=Vrms Arms)

5. The HZ/PF is a toggle function key. Press the HZ/PF key once to display the frequency (Hertz), then press key to display the Power Factor. HZ is the Frequency of output Voltage, where PF is the Power Factor (PF=W/Vrms Arms).

6. The KWH/Hour is a toggle function key. Press the KWH/Hour key once to show the cumulative energy consumption since power was applied to the unit. Then press key to display the cumulative time since power was applied to the unit.

7. Consumption will be displayed in Kilowatt-Hours (from 0.01 KWH to 9999 KWH). Time will initially be displayed as Hours:Minutes (from 00:00) and switch to Hours (to 9999). Counters will recyle to zero when they reach their maximum. To reset, remove power from unit momentarily.

WARNING: Do not exceed maximum ratings as detailed on label.
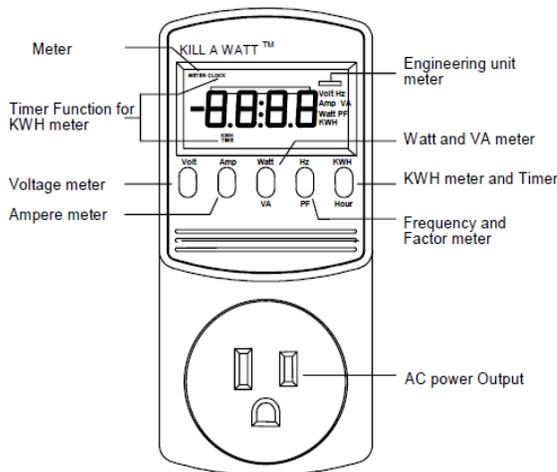
P3 INTERNATIONAL CORPORATION LIMITED WARRANTY

P3 INTERNATIONAL CORPORATION ("P3") warrants to the original retail purchaser only, that its product is free from defects in material or workmanship under the condition of normal use and service for a period of six (6) months from the date of purchase. In the event that a defect, malfunction or failure occurs or is discovered during the warranty period, P3 will repair or replace at its option the product or component part(s) which shall appear in the reasonable judgment of P3 to be defective or not to factory specifications. A product requiring service is to be returned to P3 along with the sales receipt or other proof of purchase acceptable to P3 and a statement describing the defect or malfunction. All transportation costs shall be borne by the owner and the risk of loss shall be upon the party initiating the transportation. All items repaired or replaced thereunder shall be subjected to the same limited warranty for a period of six (6) months from the day P3 ships the repaired or replaced product. The warranty does not apply to any product that has been subject to misuse, tampering, neglect, or accident or as a result of unauthorized alterations or repairs to the product. This warranty is void if the serial number (if any) has been removed, altered, or defaced. This warranty is in lieu of all warranties expressed or implied, including the implied warranties of merchantability and fitness for a particular purpose which are expressly excluded or disclaimed. P3 shall not be responsible for consequential, incidental or other damages, and P3 expressly excludes and disclaims liability for any damages resulting from the use, operation, improper application, malfunction or defeat of any P3 product covered by this limited warranty. P3's obligation is strictly and exclusively limited to the replacement or repair of any defective product or component part(s). Some states do not allow the exclusion or limitation of incidental or consequential damages, so the above limitation or exclusion may not apply to you. P3 does not assume or authorize anyone to assume for it any other obligation whatsoever. Some states do not allow limitation on how long an implied warranty lasts, so the above limitations may not apply to you. It is the owner/user's responsibility to comply with local, state, or federal regulations, if any, that may pertain to P3 products or their use. This warranty gives you specific legal rights, and you may also have other rights which vary from state to state.

If you experience difficulty in the operation of your unit, or if your unit requires repair please contact:

P3 INTERNATIONAL CORPORATION
TECHNICAL SUPPORT
71 West 23rd Street
Suite 1201
New York, NY 10010-4102
Tel: 212-741-7289
Fax: 212-741-2288

Email: techsupport@p3international.com

Labels: Meter · KILL A WATT ™ · Engineering unit meter · Timer Function for KWH meter · METER CLOCK · Volt Hz / Amp VA / Watt PF / KWH · Watt and VA meter · Voltage meter · Volt Amp Watt Hz KWH / VA PF Hour · KWH meter and Timer · Ampere meter · Frequency and Factor meter · AC power Output

Crimp Systems, continued

Making The Connection With The Large Crimp Tool

Note: Use the crimp tool only to install PEX tube/fitting systems meeting ASTM F1807 for brass or copper insert fittings and F2159 for plastic insert fittings.

⚠️ **Important:** Always refer to the tube manufacturers' product assembly instructions when using the crimp tool.

1) Measure and cut the tube. Be sure you have a square burr-free cut. An uneven or jagged cut may cause an improper connection.
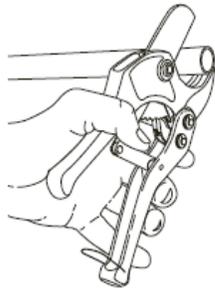
2) Next, slip a copper crimp ring onto the tube. Do not use hose clamps!
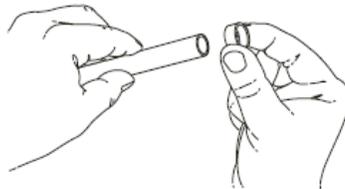
3) Now insert the fitting into the tube up to the fitting shoulder. Position the crimp ring 1/8 inch to 1/4 inch from the end of the tube. An improperly positioned ring may produce a weak connection. Ring may be squeezed to hold it in place until step 4 is completed.

Fitting Shoulder

1/8" to 1/4" Crimp Ring Spacing
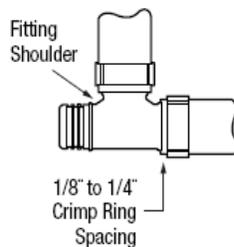
4) Position the tool so the crimp ring is completely covered by the tool jaws. Keep the tool at a 90° angle to the fitting and close it completely. Squeeze handles together to complete the crimp.

5) Open the tool handles to release jaws from the crimped fitting.

6) Measure the crimped ring with Zurn "Go/No-Go" gauge. **See table below.** Do not measure bumps on ring where jaws met. If "Go" on gage does not fit, or if "No-Go" does fit, then cut out connection, replace fitting and ring, adjust and calibrate the tool, and recrimp.
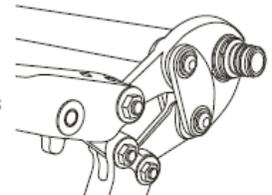
The following dimensions are the ASTM maximum and minimum crimped ring diameters for crosslinked polyethylene (PEX) pipe installations.

Standard Tube Size >	3/8"	1/2"	5/8"	3/4"	1"
Minimum Diameter	0.580"	0.700"	0.815"	0.945"	1.175"
Maximum Diameter	0.595"	0.715"	0.830"	0.960"	1.190"

Variation in ring diameter (out-of-round) should not exceed 0.006".

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Crimp Systems, continued

Using The Zurn Go/No-Go Gauge

After making a crimp connection, use the appropriate opening of this flat "Go/No-Go" Gauge to check your finished crimp. The "Go" opening should go freely across a crimped ring anywhere on its diameter with the possible exception of the upset area on the ring surface caused by the tool jaws closing. Do not force the gauge across the ring. The "No-Go" opening should not go across a crimped ring anywhere. If the crimp fails either test, cut out the fitting and replace.

Go and No Go Openings
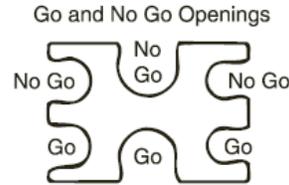
DO:

Always place the gauge opening on the crimp ring at a 90° angle for an accurate check.

Be certain to use the gauge opening sized for the diameter of your tube.

We recommend you check every finished crimp with this gauge.
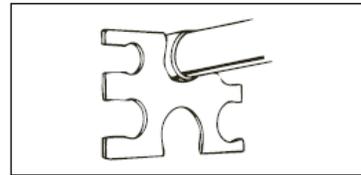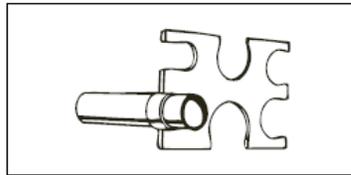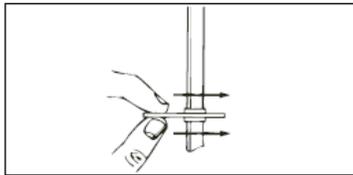
DO NOT:

Do not slide the gauge onto the connection. Push it directly onto the crimp ring.

Do not try to save time by recrimping a crimp that does not gauge properly. The fitting must be cut out and replaced.

Do not modify the gauge opening for any reason. They have been carefully manufactured to .002-inch tolerance.

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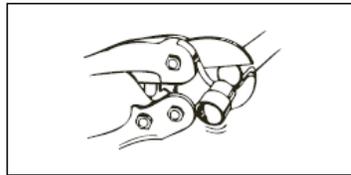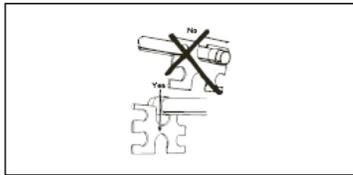
Crimp Systems, continued

Adjusting The Medium Crimp Tool

Note: Zurn Crimp Tools are factory set to provide proper crimps. This should be checked before use by making a test crimp connection and checking it with the crimp gauge. As long as the finished crimp connection gauges properly, there is no need to adjust the tool.

All crimp tools wear, which increases the crimp diameter after many crimps. When the crimps start to approach the maximum ring diameter, adjust the back pin. To adjust for a tighter crimp, remove the E-clip (for example, pop it off with a screwdriver) and slide the back pin head out about 1/4 inch. **Warning: The Adjustment Pin must not be pulled or pushed completely out.** Rotate the back pin until the line on the hex head points to the next highest number on the tool body, push the pin back in, and refit the E-clip. Five adjustments are available.
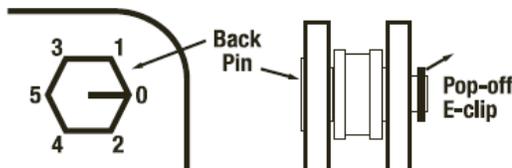
For a tighter crimp, turn mark on pin to the next number:
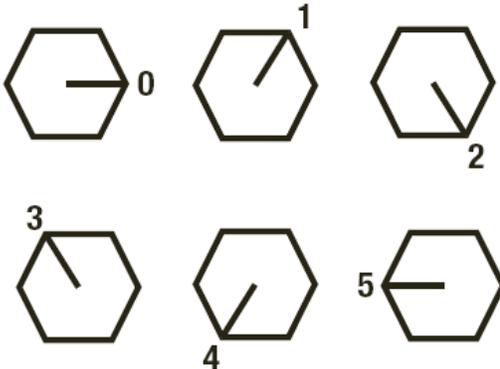
Maintenance

For easier, better crimps and longer tool life, keep tool clean and rust-free inside and out. Lubricate all moving parts frequently with light oil.

Adjusting The Large Crimp Tool

Zurn Crimp Tools are factory set to provide proper crimps. This should be checked before use by making a test crimp connection and checking it with the crimp gauge. As long as the finished crimp connection gauges properly, there is no need to adjust the tool.

1) Loosen the bottom Locking Setscrew two turns using the hex wrench provided with the tool.

2) Close the tool until the jaws just touch and increased resistance is felt. This is the pre-load point.

3) Turn the top Adjusting Setscrew until the distance between the raised "+" marks on the handles is between 7 and 8-1/2 inches for QCRT2T, 3T, JT, and 4T. The distance for QCRT5T should be 13 inches. Tighten the bottom Locking Setscrew. **See Warning for QCRT2T, 3T, JT, 4T, and QCRT5T tool.**

4) Make a test crimp connection and check it with the "Go" and "No-Go" openings of the gauge. If the "No-Go" opening goes over the crimped ring, the tool is too tight. The distance between the "+" marks should be decreased. If the "Go" opening does not go over the crimped ring, the tool is too loose and the distance between the "+" marks should be increased.

5) Apply a light oil to the pivot points each time the tool is adjusted. **Failure to lubricate the tool will shorten its life.**
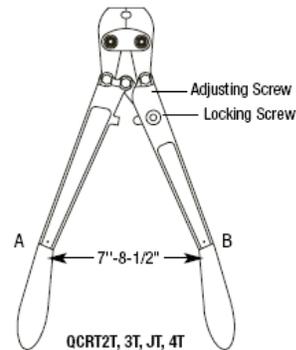
WARNING:

Increasing the pre-load distance beyond 9 inches for the QCRT2T, 3T, JT, 4T or 13 inches for the QCRT5T will make the tool hard to use and shorten tool life because of excessive stress.

Signet 8550-1 Flow Transmitter

English

3-8550.090-1 Rev L 6/06 English

⚠	**WARNING!**	**Contents**

WARNING!
• Remove power to unit before wiring input and output connections.
• Follow instructions carefully to avoid personal injury.

Contents
1. Specifications
2. Installation
3. Electrical Connections
4. Menu Functions

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1. Specifications

Dimensions
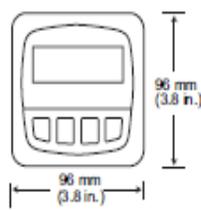
FRONT VIEW
Field Mount &
Panel Mount
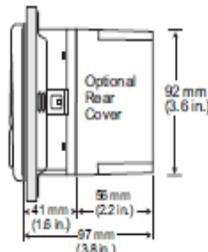
SIDE VIEW
Panel Mount

Optional Rear Cover
96 mm (3.8 in.)
96 mm (3.8 in.)
92 mm (3.6 in.)
41 mm (1.6 in.)
55 mm (2.2 in.)
97 mm (3.8 in.)
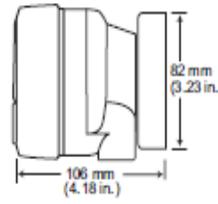
SIDE VIEW
Field Mount w/
8050 Universal base
82 mm (3.23 in.)
106 mm (4.18 in.)
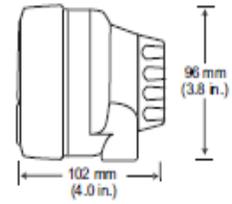
SIDE VIEW
Field Mount w/
8051 Integral kit
96 mm (3.8 in.)
102 mm (4.0 in.)

General
Compatibility: Signet Flow Sensors (w/freq out)

Enclosure:
• Rating: NEMA 4X/IP65 front
• Case: PBT
• Panel case gasket: Neoprene
• Window: Polyurethane coated polycarbonate
• Keypad: Sealed 4-key silicone rubber
• Weight: Approx. 325g (12 oz.)

Display:
• Alphanumeric 2 x 16 LCD
• Update rate: 1 second
• Contrast: User selected, 5 levels
• Display accuracy: ±0.5% of reading @ 25°C
• Thermal sensitivity shift: ±0.005% of reading per °C

Electrical
• Power: 12 to 24 VDC ±10%, regulated
                         61 mA max current

Sensor Input
• Range: 0.5 to 1500 Hz
• Sensor power: 2-wire: 1.5 mA @ 5 VDC ± 1%
                         3 or 4 wire: 20 mA @ 5 VDC ± 1%
                         Optically isolated from current loop
• Short circuit protected

Current output:
• 4 to 20 mA, isolated, fully adjustable and reversible
• Max loop impedance: 50 Ω max. @ 12 V
                         325 Ω max. @ 18 V
                         600 Ω max. @ 24 V
• Update rate: 100 ms
• Accuracy: ±0.03 mA

Open-collector output, optically isolated:
• 50 mA max. sink, 30 VDC maximum pull-up voltage.
• Programmable for:
  • High or Low setpoint with adjustable hysteresis
  • Pulse operation (max rate: 300 pulses/min).

Environmental
• Operating temperature: -10 to 70°C (14 to 158°F)
• Storage temperature: -15 to 80°C (5 to 176°F)
• Relative humidity: 0 to 95%, non-condensing
• Maximum altitude: 2000 m (6562 ft)
• Insulation category: II
• Pollution degree: 2

Standards and Approvals
• CE, UL listed
• Immunity & Emissions: EN61326
• Manufactured under ISO 9001 and ISO 14001

Dimensions

515 Standard Mount Sensor

53.3 mm/ 2.1 in.

26.7 mm/ 1.05 in.

-X0 thru -X2
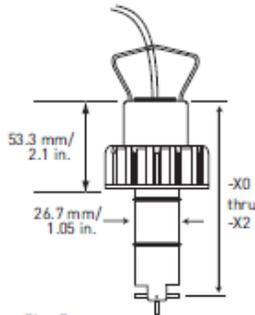
Pipe Range
0.5 to 4 in.: **-X0** = 104 mm/4.1 in.
5 to 8 in.: **-X1** = 137 mm/5.4 in.
10 in. and up: **-X2** = 213 mm/8.4 in.

515 Integral Mount Sensor shown with Transmitter (sold separately)

96 mm (3.8 in.)

102 mm (4.0 in.)

26.7 mm (1.05 in.)

-Y0 or -Y1
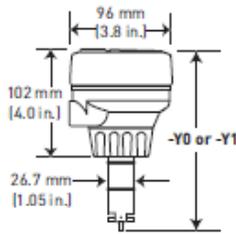
Pipe Range
0.5 to 4 in. **-Y0** = 152mm (6.0 in.)
5 to 8 in. **-Y1** = 185mm (7.3 in.)

515 Wet-Tap Mount Sensor with 3519 Wet-Tap Valve

See more information on the 3519 Wet-Tap Valve, refer to the 3519 product page.

-P3 thru -P5

26.7 mm (1.05 in.)
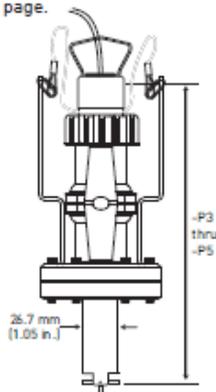
Pipe Range
0.5 to 4 in. **-P3** = 297 mm/11.7 in.
5 to 8 in. **-P4** = 333 mm/13.1 in.
10 in. and up **-P5** = 409 mm/16.1 in.

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Specifications

General
Flow Rate Range:
   0.3 to 6 m/s (1 to 20 ft./s)
Pipe Size Range:
   DN 15 to DN 900 (0.5 to 36 in.)
Linearity: ±1% of full range
Repeatability: ±0.5% of full range
Min. Reynolds Number Required: 4500

Wetted Materials
- Sensor Body:
  Glass-filled PP (black) or PVDF (natural)
- O-rings:
  FPM-Viton® (std)
  optional EPDM or FFPM-Kalrez®
- Rotor Pin:
  Titanium, Hastelloy-C or PVDF; optional ceramic, Tantalum, or stainless steel
- Rotor:
  Black PVDF or Natural PVDF; optional Tefzel® with or w/o Fluoroloy B® sleeve

Electrical
Frequency:
   19.7 Hz per m/s nominal
   (6 Hz per ft/s); sinusoidal
Amplitude:
   3.3 V p/p per m/s nominal
   (1 V p/p per ft/s)
Source Impedance: 8KΩ
Cable Type:
   2-conductor twisted pair with shield (22 AWG)
Cable Length:
   7.6m (25 ft) standard/60m (200 ft) maximum

Application Tips:
- Use PVDF Rotor Pin for use in Deionized Water.
- Use the Conduit Adapter Kit to protect the cable-to-sensor connection when used in outdoor environments. See Accessories section for more information.
- Use a sleeved rotor in abbrasive liquids to reduce wear.
- Sensor plugs can be used to plug installation fitting after extraction of sensor from pipe.

- For liquids containing particles use only Signet Magmeters
- For systems with components of more than one material, the maximum temperature/pressure specification must always be referenced to the component with the lowest rating.

Please refer to Wiring, Installation, Accessories and Fittings sections for more information.

+GF+

Max. Pressure /Temperature Ratings
Standard and Integral Sensor:
- PP: 12.5 bar @ 20°C,
       1.7 bar @ 90°C
  (180 psi @ 68°F, 25 psi @194°F)
- PVDF: 14 bar @ 20° C,
       1.4 bar @ 100°C
  (200 psi @ 68°F, 20 psi @ 212°F)
Operating Temperature:
- PP: -18°C to 90°C (0°F to 194°F)
- PVDF: -18°C to 100°C (0°F to 212°F)

Wet-Tap sensor
- PP: 7 bar @ 20°C, 1.4 bar @ 66°C
  (100 psi @ 68°F, 20 psi @ 150°F)
Operating temperature:
   -18°C to 66°C (0°F to 150°F)
Max. wet-tap sensor removal rating:
   1.7 bar @ 22°C (25 psi @ 72°F)

See Temperature & Pressure Graphs for more information.

Shipping Weight

P51530-X0	0.454 kg	1 lb.
P51530-X1	0.476 kg	1.04 lbs.
P51530-X2	0.680 kg	1.50 lbs.
P51530-X3	0.794 kg	1.75 lbs
P51530-X4	0.850 kg	1.87 lbs.
P51530-X5	1 kg	2.20 lbs.
3-8510-X0	0.23 kg	.50 lbs.
3-8510-X1	0.23 kg	.50 lbs.

Standards and Approvals
- CE
- FM Class I, II, III/Div. 1/groups A-G
- Manufactured under ISO 9001:2000 for Quality and ISO 14001:2004 for Environmental Management

Automated Valve Manual Override

The automated valve is located on the cold inlet of the auxiliary tank and has a three-way bypass configuration that can be rotated 360°. A visual indicator is located on the back and displays the current flow configuration as seen in Figure E1. The following procedure will be a guide to manually bypassing or incorporating the auxiliary storage tank.
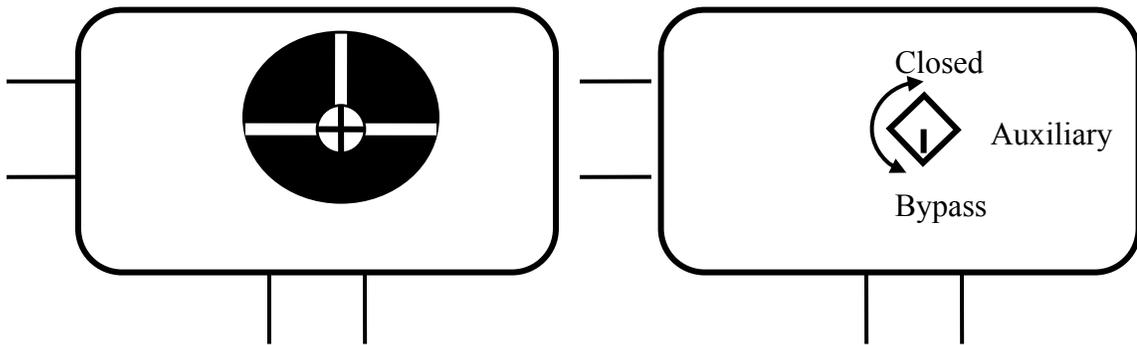
Figure E 1. Automatic valve manual override indicator and procedure.

1. Identify whether the auxiliary tank is being bypassed or incorporated and which way the valve will need to be rotated. *Note*: It is crucial to observe and preserve the orientation of the indicator, because there are multiple orientations possible when replacing it.

2. Remove the indicator with a Philips head screwdriver. A 3/8 in wrench is used to slowly rotate the drive shaft a quarter turn (90°). The positions have been labeled shown in Figure E1 with a small indicator on the drive shaft; however precision is required when rotating the shaft so as not to restrict flow or damage the motor gears.

3. Once the drive shaft has been rotated, replace the visual indicator to the appropriate position and retighten the screw.

Mains Chiller

Mains Chiller Drawings
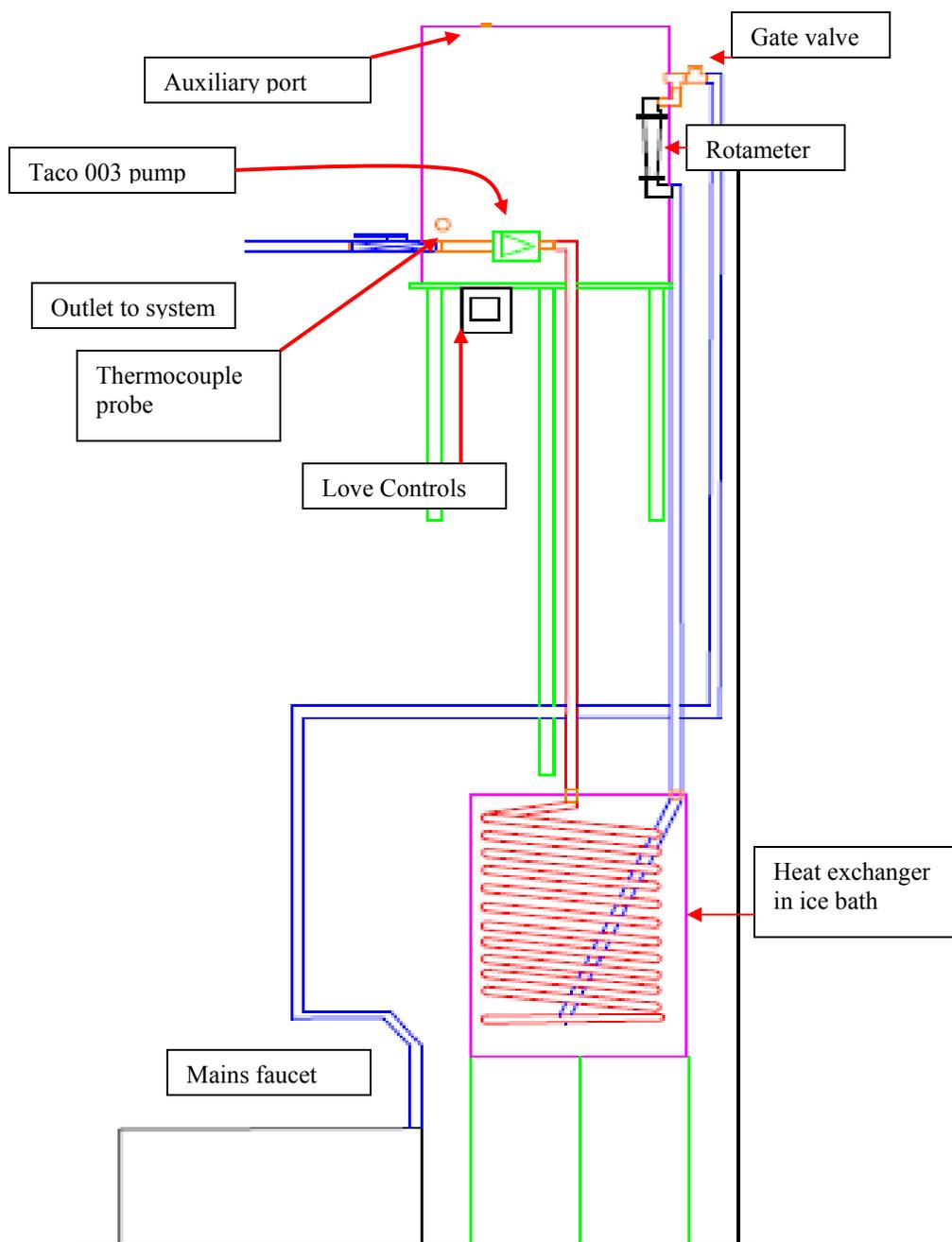
Figure F 1. Mains chiller sketch and operation

Mains Chiller Controls

The 1600 series Love controls are a microprocessor based temperature/process control unit.Figure F 2, is a basic diagram for the different options of temperature measurement available.
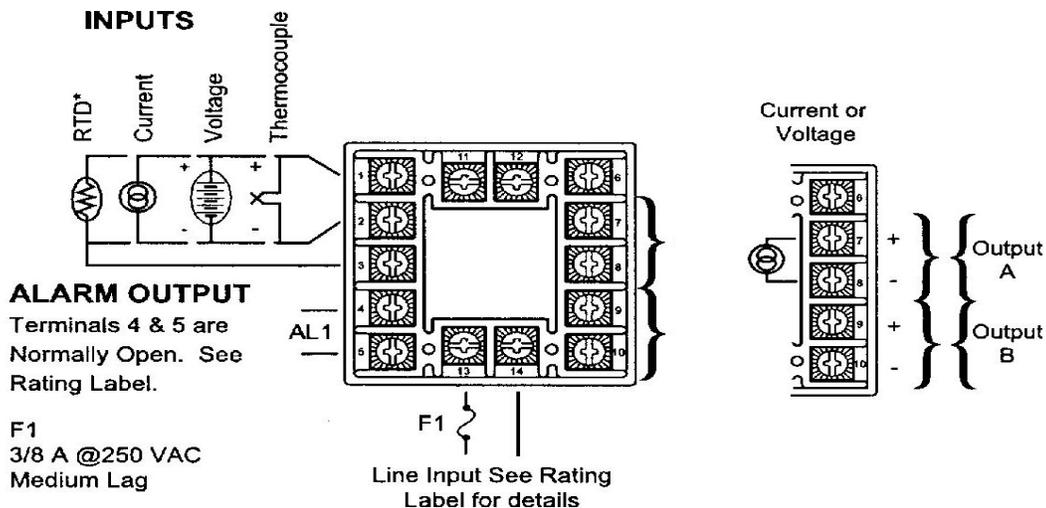
Figure F 2. Love controls wiring diagram.

The current set up requires power to be wired to terminals 13 and 14 and a jumper from terminal 14 to output terminal 8. Output terminal 7, terminates with the white wire on the pump. The yellow wire of the pump is then wired terminal 13. The ground wires are spliced together and run directly to the pump.

Figure F 3 is a guide for the front display of the control unit. The index, up, down, and enter keys will progress the user through the menu and set the specified program. The controls act as a solid state relay, switching 110V AC power on and off to the Taco 003 circulator pump.

FRONT PANEL KEY FUNCTIONS

Set Point 1 Lamp ——
Alarm Lamp —
Set Point 2 Lamp
°F Indicator
°C Indicator

—— Process Variable

—— Set Variable

INDEX: Pressing the INDEX key advances the display to the next menu item. May also be used in conjunction with other keys as noted below.

UP ARROW: Increments a value, changes a menu item, or selects the item to ON in the upper display.

DOWN ARROW: Decrements a value, changes a menu item, or selects the item to OFF in the upper display.

ENTER: Pressing ENTER stores the value or the item changed. If not pressed, the previously stored value or item will be retained.

UP ARROW & ENTER: Pressing these keys simultaneously brings up the **secondary menu** starting at the auto/manual selection. Pressing these keys for 5 seconds will bring up the **secure menu**.

INDEX & DOWN ARROW: Pressing these keys simultaneously will allow backing up one menu item, or if at the first menu item they will cause the display to return to the **primary menu**. If an alarm condition has occurred, these keys may be used to reset the alarm.

INDEX & ENTER: Pressing these keys simultaneously and holding them for 5 seconds allows recovery from the various error messages. The following menu items will be reset:

LPbr: Loop break   **SEnC:** Sensor rate of change

ALIH: Alarm inhibit   **OPEn InP:** Open input error message

ArEA: Area error message   **bAd InP:** Bad input error message

CHEC CAL: Check calibration error message

Correct the problems associated with the above conditions first before using these reset keys. More than one error could be present. Caution is advised since several items are reset at one time.

Figure F 3. Love 1600 Series control panel function.

Programming the controls

1. Press *Index*, and use the *Up* or *Down* arrows to program the set point temperature in °C. Press *Enter* to save the value.

2. Proceed to the Secure Menu by holding the *Up* and *Enter* buttons for 5 seconds. Scroll through the menu by pressing I*ndex*, change the setting using the *Up* or *Down* keys, while saving the value using *Enter*. The following table displays each menu and the setting for the mains chiller application. For a detailed description see the user manual.

Table F 1. Secure menu program settings.

Program	Setting
Inp	CA
Unit	C
dPt	0
InpT	Off
SeNC	70
SCAL	-179
SCAH	1371
SPL	10
SPH	45
SP1o	OUTa
S10t	onof
S1st	dir
S1LP	0 on
AL	OFF

3. Next proceed to the Secondary Menu by pressing the *Up* and *Enter* buttons once simultaneously. Scroll through the menu by pressing *Index*, change the setting using the *Up* or *Down* keys, while saving the value using *Enter*. Table F 2 displays the settings for each program of the Secondary Menu for the mains chiller application.

Table F 2. Secondary menu program settings.

Program	Setting
Auto	ON
ArUP	OFF
ArtE	0.08
PEA	12
VAL	5
Sp1d	1
Pct0	OFF
Program	OFF
Stat	OFF
1rt	0
1St	0
PEND	HOLD
InPC	0
Filt	2
LPbr	OFF

Troubleshooting

Code *SnC bad*

- Turn controls off, ensure all connections are secure and the thermocouple probe is

  connected. Turn the controls back on.

Pump will not activate at desired set point temperature.

- Proceed to the Sp1d (set point 1 differential) in the Secondary Menu as described

  above. Lower and save the value in this program. The sp1d is a program that

  indicates to the unit to switch power when the differential between the process

  variable and the set point variable is at the given amount greater than the set point.

Example: Sp1d=5   Sp1=20°C

       If $Pv \geq Sp1d+Sp1$ (25°C)   :   ON

       Else   :   OFF

There is no flow in the heat exchanger.

- Ensure rotameter is fully open.

- Check pump for vapor locks by opening the gate valve and turning the mains faucet on to increase the pressure within the heat exchanger loop.

- Throttling the gate valve and isolation valve may also need to be performed with the mains on in order to dislodge any trapped air bubbles.

Performance Prediction Calculations

The following calculations were performed in MathCAD to predict the performance of the mains chiller heat exchanger which comprises of a coiled length of copper tubing in an ice bath, where the fluid to be cooled is re-circulated until it reaches a specific temperature. The following procedure can be found in Incropera and Dewitt [19].

Calculations

The following are important constants and defined variables.

$$m_{dot} := 0.1261 \frac{kg}{s}$$

$$d_i := 0.425 \, in = 0.011 \, m$$

$$d_o := 0.5 \, in = 0.013 \, m$$

$$T_{hi} := 22 \, °C$$

$$T_{ho} := 14 \, °C$$

$$T_c := 0 \, °C$$

$$g := -9.8 \frac{m}{s^2}$$

$$\alpha := \frac{k_{H2O}}{\rho \cdot Cp} = 1.429 \times 10^{-7} \frac{m^2}{s}$$

$$v := 19 \, gal = 0.072 \cdot m^3$$

$$Cp := 4184 \frac{J}{kg \cdot K}$$

$$\mu := 0.00108 \, N \cdot \frac{s}{m^2}$$

$$\rho := 1000 \frac{kg}{m^3}$$

$$Pr := 7.56$$

$$k_{H2O} := 0.598 \frac{W}{m \cdot K}$$

$$k_{CU} := 401 \frac{W}{m \cdot K}$$

$$\beta := -0.000006805 \cdot \frac{1}{K}$$

$$\nu := 0.000001788 \cdot \frac{m^2}{s}$$

The energy required to lower the temperature of 19 gallons of water 8 deg C is

found by sing an energy balance approach found in Equation F (1).

$$E := v \cdot \rho \cdot Cp \cdot \left(T_{hi} - T_{ho}\right)$$

F (1)

$$E = 2.407 \times 10^6 \, J$$

Energy balance on the ice and water system is found in Equation F (2).

19 gallons of water=71.92 kg

$$E = 71.92 kg \cdot Cp \cdot dT + m_{ice} \cdot h_{lv}$$

F (2)

If the water remains at 0C temperature differenctial within the ice bath

will be 0 *i.e.* dT=0. Thus the system energy balance becomes Equation F (3).

$$E = m_{ice} \cdot h_{lv}$$

F (3)

The mass of ice necessary to maintain this state is found using the latent

heat of formation for ice in Equation F (4).

$$h_{lv} := 333700 \frac{J}{kg}$$

$$m_{ice} := \frac{E}{h_{lv}} = 7.214 kg$$

F (4)

$$w_{ice} := -m_{ice} \cdot g = 15.894 \, lbf$$

In order to determine the heat transfer within the tubing, the Reynolds number

for internal flow must be determined from Equation F (5). The critical Reynolds

number for turbulent flow is 2300.

$$Red := \frac{4 \cdot m_{dot}}{\pi \cdot d_i \cdot \mu}$$

F (5)

$$Red = 1.377 \times 10^4$$

The Nusselt number is found from the Dittus-Boelter formula in Equation F (6) with n=0.3 for cooling.

$$Nu_d := 0.023 \cdot Red^{\left(\frac{4}{5}\right)} \cdot Pr^{0.3} \qquad\qquad \text{F (6)}$$

$$Nu_d = 86.391$$

The internal heat transfer coefficient is found using Equation F (7).

$$h_i = \frac{k_{H2O}}{d_i} \cdot Nu_d \qquad\qquad \text{F (7)}$$

$$h_i := 4696.53 \frac{W}{m^2 K}$$

The external heat transfer coefficient can be found by first solving for the Rayleigh number in Equation F (8).

$$Ra_d := \frac{g \cdot \beta \cdot \left(T_{hi} - Tc\right) \cdot d_o^{\,3}}{\nu \cdot \alpha} \qquad\qquad \text{F (8)}$$

$$Ra_d = 1.176 \times 10^4$$

The Nusselt number for a heated horizontal cylinder in free convection is found from the method of Churchill and Chu in Equation F (9).

$$Nu_{do} := \left[0.6 + \frac{0.387 \cdot Ra_d^{\left(\frac{1}{6}\right)}}{\left[1 + \left(\frac{0.559}{Pr}\right)^{\left(\frac{9}{16}\right)}\right]^{\left(\frac{8}{27}\right)}} \right]^2 \qquad\qquad \text{F (9)}$$

$$Nu_{do} = 5.453$$

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The free convection heat transfer coefficient of the ice bath is the found using Equation F

$$h_o = \frac{k_{H2O}}{d_o} \cdot Nu_{do}$$ F (10)

$$h_o := 250.84 \frac{W}{m^2 K}$$

Since this is a transient process the length of tubing is specified for simplification.

$$L := 55ft = 16.764m$$

Given Equation F (11), the overall heat transfer coefficient can be found.

$$\left(\frac{1}{h_i \cdot \pi \cdot d_i \cdot L} + \frac{\ln\left(\frac{d_o}{d_i}\right)}{2 \cdot \pi \cdot k_{CU} \cdot L} + \frac{1}{h_o \cdot \pi \cdot d_o \cdot L} \right) = \frac{1}{ua}$$ F (11)

$$UA := 137.87 \frac{W}{K}$$

The average overall temperature difference is assumed

$$\Delta T := 8 \Delta °C$$

The average heat rate for system can now be determined from Equation F (12).

$$Q := UA \cdot \Delta T$$ F (12)

$$Q = 1.103 \times 10^3 \, W$$

The average time to cool water is predicted from Equation F (13).

$$t := \frac{E}{Q}$$ F (13)

$$t = 36.378 \cdot min$$

The heat exchanger modeled is similar to an evaporator where the cold fluid remains the same. However, it is a transient process since the hot inlet will always be changing, making performance difficult to predict. The heat rate of the system will be affected by the changing inlet temperature as well. Time is the only variable that can be calculated, however, even it is an approximation based on the amount of tubing used. During the extent of testing, these predictions proved to be a good approximation of time required to chill the mains water.

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