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UNIVERSITY

COLLEGE OF ENGINEERING
Department of Mechanical Engineering

Senior Design Project

Thermal Reflectivity in Solar Collector Prototype

Final Report
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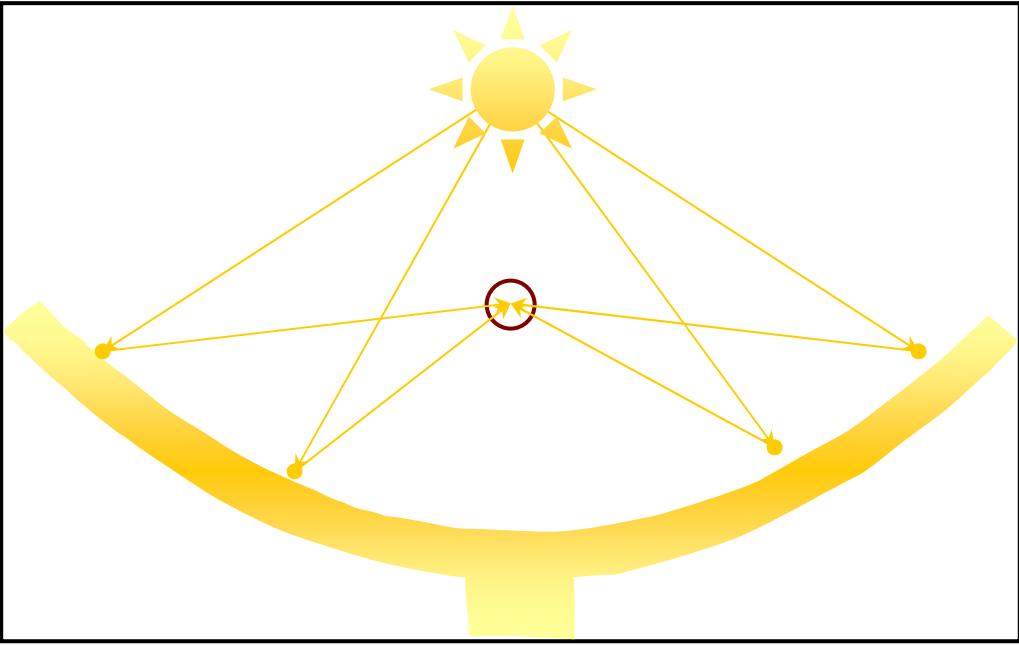


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INEXPENSIVE REFLECTORS IN CONCENTRATING SOLAR COLLECTOR PROTOTYPE



Figure 1: The solar collector trough has thermocouples attached to the computer.

Abstract

This prototype parabolic trough concentrating solar collector tests the reflectivity of various materials. The concentrating solar collector (CSC) was designed in SolidWorks and analyzed in Cosmos. The A- frame structure (Fig. 1) holds a pivoting parabola with removable reflectors which focuses the sun's energy on a highly radiation absorbent central receiver. Thermocouples measure the temperature of the water before and after flowing through the absorber. Electricity from a photovoltaic (PV) panel energizes the pump. This wheeled heat exchange device was custom built in the San Diego State University metal shop with intricate machining, precision cutting and aluminum welding.

Simple temperature increase in water traveling over three feet of copper pipe showed heat transferred to the working fluid. The best reflective material was reflective film, stainless steel was next and chrome powder coat delivered the least heat. This senior project and experiment was funded by an American Public Power Association (APPA.org) Demonstration of Energy-Efficient Developments (DEED) Scholarship. Anaheim Public Power moderated the progress and fund distribution.

Introduction

Concentrating solar power equipment has proven to work, but it is expensive to build. The parabolic trough is currently used instead of boilers in commercial solar power organic Rankine generators such as Nevada Solar One and the Saguaro power plant. The trough design is not commonly used for residences. Industry uses trough collectors to make steam, process heat and hot water.

The ideal application is Arizona Power Service's 1 MW solar trough plant at the Saguaro Power Plant, where the sunshine heats mineral oil to between 250° and 500°F in a tube called an absorbing central receiver at the focus point long reflecting troughs. The heated oil flows closed loop through a heat exchanger and around through the solar collector. Inside the power plant, the heat vaporizes pentane to the turbine genset in a separate closed loop.



Figure 2: At APS's Saguaro Generating Station, six rows of 15-foot-high mirrors generate electricity by heating oil to drive steam turbines. (Photo by Arizona Public Service Company)

It was postulated that the expensive curved mirrors could be replaced by less-expensive materials. Extremely polished stainless steel, reflective paint, and reflective film were tested. Funding through the American Public Power Association specified that the project be useful to public utility companies. To begin, the position of solar energy conversion in a utility company world view is defined.

Relevance To Utility Companies

In many parts of the U.S., the capacity of the electricity transmission grid has nearly been reached, while demand for additional power is growing rapidly. The Southern California area has experienced blackouts and rolling brownouts. The inability of the utilities to supply power usually coincides with hot weather, ideal for solar power production. Concentrating solar collector (CSC) technology is a viable choice to increase the power production capacity of utility companies.

The solar radiation supply, although not unlimited, is vast enough for the needs of all humans, plants and animals combined. More energy from the sun is available daily than the total worldwide reserves of oil, gas, coal and uranium. Compared to fossil fuels, CSC has lower maintenance, quieter operation and minimal emissions. Worldwide, the economic threat of global warming makes governments turn away from fossil fuel power plants and mandate renewable sources of energy. Damage to buildings, destruction of forests and lakes and damage

to health all due to fossil fuel combustion air pollution are some of the high indirect costs not included in power prices. The serious drawbacks are lack of sun energy supply during the night and expensive startup costs. The clinching advantage is free fuel, solar radiation.

Governments are encouraging solar power conversion. Domestic and industrial hot water are the low hanging fruit for the AB32 Carbon Caps in California. AB1470 Solar Water Heating Act of 2007 insists that all new residences use the sun. Only in San Diego County are funds from the California Solar Initiative applicable to solar hot water.

Recently passed federal 30% Investment Tax Credit incentives open the opportunity wider for 8 more years. The market forces are excellent for all kinds of solar systems, electrical and thermal. Since sunlight is a free energy source, the equipment efficiency is wrapped inside the installation cost per kW or per therm.

Literature Review

Czanderna, Masterson and Thomas [1] claim that research in mirrors is “significant” for solar thermal applications. Since solar mirrors are subject to much harsher conditions than indoor cosmetic mirrors manufactured commonly, the first goal of mirror testing is ranking performance.

Tuszynski et al [2] wrote a very helpful paper including a solar trough as part of a custom made refrigerator with solar heat to expand the refrigerant.

Science Applications International Corporation (SAIC) explored a Faceted Stretched-Membrane Dish at Sandia National Solar Thermal Test Facility with 3M’s ECP 305 silver-acrylic film. Twelve 3-meter diameter facets (84.8 m²) concentrated 61.4 kWt thru a half meter aperture. They changed to thin glass mirrors for durability and economic reasons [3].

Beninga and Davenport [4] report that the best reflector of the day, silvered acrylic reflective film (3M’s ECP 305) laminated to stainless steel has a useful life of 5-7 years. In 1993, it cost more than \$2/square foot. Thin glass mirrors were comparable in cost, with excellent abrasion resistance, very smooth and easily cleaned surface and of course, excellent specular reflection. Neither glass nor film has durability if water invades the silver layer. Organic sealants were tested and ruled out due to discoloration with age. Glass has the advantages of extremely long life (approx 30 years) when properly protected [4].

Several more valuable studies are listed in Appendix A.

Test Panel Coupons

Each very thin reflective coupon (1’ x 1’ sample) easily bends into the parabolic trough shape when inserted into the parabolic coupon holder. Then it springs back almost to flat when

removed. 3M's ECP 305 silver-acrylic film applied to thin aluminum sheet metal was tested. Two mirrored films were tested. The old film was aged for 10 years outdoors before it was donated for this testing. It might be Solatube material. It was leftover from a daylighting system. It was really scratched, but the best reflector of the four.

One material tested, highly polished stainless steel, looks like a perfect mirror, without distortion. It is durable and does not corrode.

Sheets of 0.020 inch 301 stainless steel were sent out to Goodrich Technology Corp. for powder coating by a cold application process. The durability has been tested for 3 years in Florida as automotive aluminum wheel coating. This chrome "paint" has been used on ships at sea for 10 years without problems. Automotive chrome has been in use for decades. Flexing the panels did not harm the powder coat.

Each very thin reflective material easily bends into the parabolic trough shape. The highly radiation absorbent central receiver is delicate glass tubing concentrically surrounding a copper pipe. Electronic sensors horizontally mounted measure the changing water temperature before and after it flows inside the central receiver. Many minutes of data will be collected from each material rotating in the frame at the slow speed of the daily sun transit. No operation will be unattended. The experiment stops before the temperature reaches boiling. Mathematical software analysis will show graphs of reflectivity, temperatures, and flow rates. The concentrating solar collector has an easily disassembled plumbing setup for transportation safety. Our testing will be on one portion of solar equipment, the collector. Each material tested in the trough has superior reflectivity, higher than 90%. For this project, glass mirrors are not being studied.

Reflectivity of Metals and Diminishing Waves

The sunbeam is always leaving air ($n=1$) and striking the trough surface. The trough material has three choices: transmit, reflect or absorb the energy.

$$100\% = 1 = \text{Tau} + \text{rho} + \text{alpha}$$

Metals are usually highly absorbing, but the stainless steel is highly polished.

Let transmitted energy, $\text{Tau} = 0$ because light does not shine through a metal.

In materials (like glass) with zero electrical conductivity, perfect dielectrics, waves go on and on undiminished. But in metals, a propagating wave attenuates. As the wave dies, kappa (K), is the extinction coefficient of the wave in the medium. The wave traveling through a medium is called evanescent as it spills energy. The traveling wave form becomes heat. This absorbed energy is exponential. As a result of absorption, the intensity decays as

$$\exp(-ax)$$

And absorption has a simple relationship to kappa at each wavelength.

$$\alpha = 4 \pi K / (\lambda^0)$$

If an incident beam has no specific polarization, the reflectivity is an average of the parallel and perpendicular components [5].

When one is calculating radiative properties, the electromagnetic theory is invalid for frequencies of the order of molecular vibration frequencies. So wavelengths are restricted to longer than 700 nm [5 Siegel p 84]. The Maxwell's Equations have assumption piled upon assumption. Temperature measurements in energy balance equations are likely more accurate. Wave theory says that temperature is a good measure of energy.

Energy Available

Incident energy flux on an element in earth orbit has been measured at 1332 to 1374 W/m² [5].

The definition of insolation is long-term average intensity of incoming solar radiation [6].

- Average insolation for anywhere on the Earth's surface is approximately 250 (W/m²) watts per square meter = 6 (kW·h/m²)/day

Field measurements of solar energy were made with a [pyranometer](#) standardized according to the [ISO 9060](#) standard. Fig. 3 shows 15 days of the pyranometer data from San Diego State University's field station. The instantaneous energy per square meter was recorded once each 15 minutes, 10 miles from the test site.

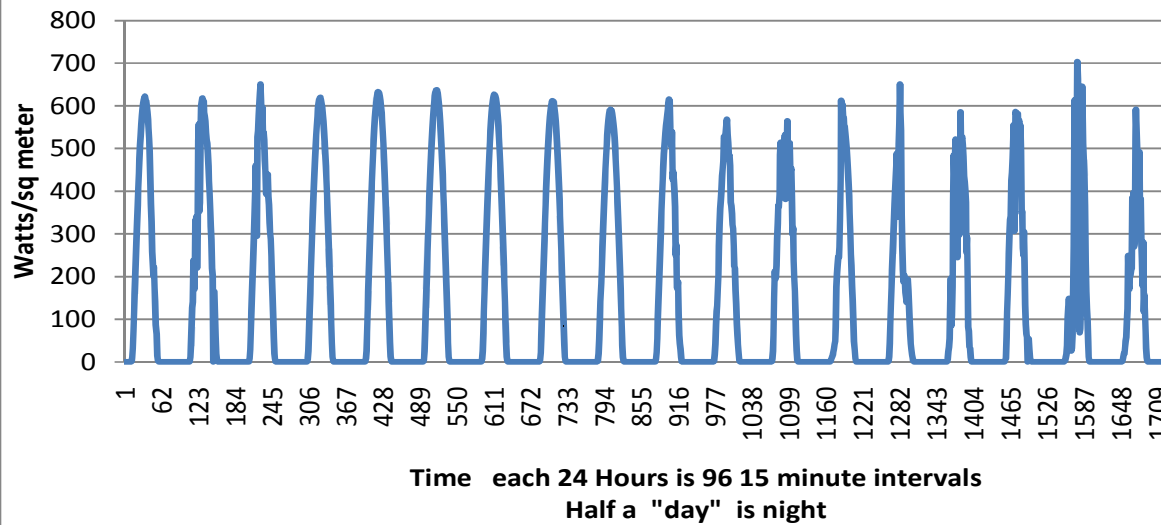
Midday standard rating conditions are estimated as incident solar radiation of 1,000 W/m² (Btu/ft²)

Range of frequencies : portion of sunshine

- | | |
|---------------|------------|
| – Very short | negligible |
| – Ultraviolet | |
| – Visible | |
| – InfraRed | |
| – Longer | negligible |

Infrared rays can pass through clouds.

**Figure 3: Sunshine 550 to 700 Watts/sq meter
Maximum each Day. Nights show zero.
Nov 11 - 20, 2008
Collected by Pyranometer at SDSU
ringtail.sdsu.edu**



Real Time Sun Energy Data on Internet

The sun energy in watts/meter squared from a pyranometer is listed under the fourth field “solar” in the field station database.

- 1) Go to <http://ringtail.sdsu.edu/station.php?net=SDSUF&netname=San%20Diego%20State%20University%20Main%20Campus&sta=Solar1&staname=Physics%20Building%20Solar%20Panels>
- 2) Click on the data channel you're interested in (e.g, SOLAR)
- 3) Click on the "text" link next to "Last 24 hrs:"
- 4) Save as a txt file
- 4) Instead of just opening the txt file with Excel, invoke the tiny menu with “open” and go thru import data with the delimiter as a space
- 5) Save as an Excel file

This raw data from the last 24 hours has two columns: unix timestamps and watts/square meter. The [Coordinated Universal Time](#) (UTC) counts seconds elapsed (900 seconds in 15 minutes, etc.) one reading of the pyrheliometer is recorded each 15 minutes.

Our mirrors collect only direct radiation. This pyrheliometer is collecting energy from the whole hemisphere of the sky. Quaschnig [8] says to estimate diffuse radiation as 20%. So 80% of the reported energy is considered available to our experimental surface. The solar trough is not a square meter, it is about half that. The energy / time in Btu/hour available to this trough is shown in Fig. 4.

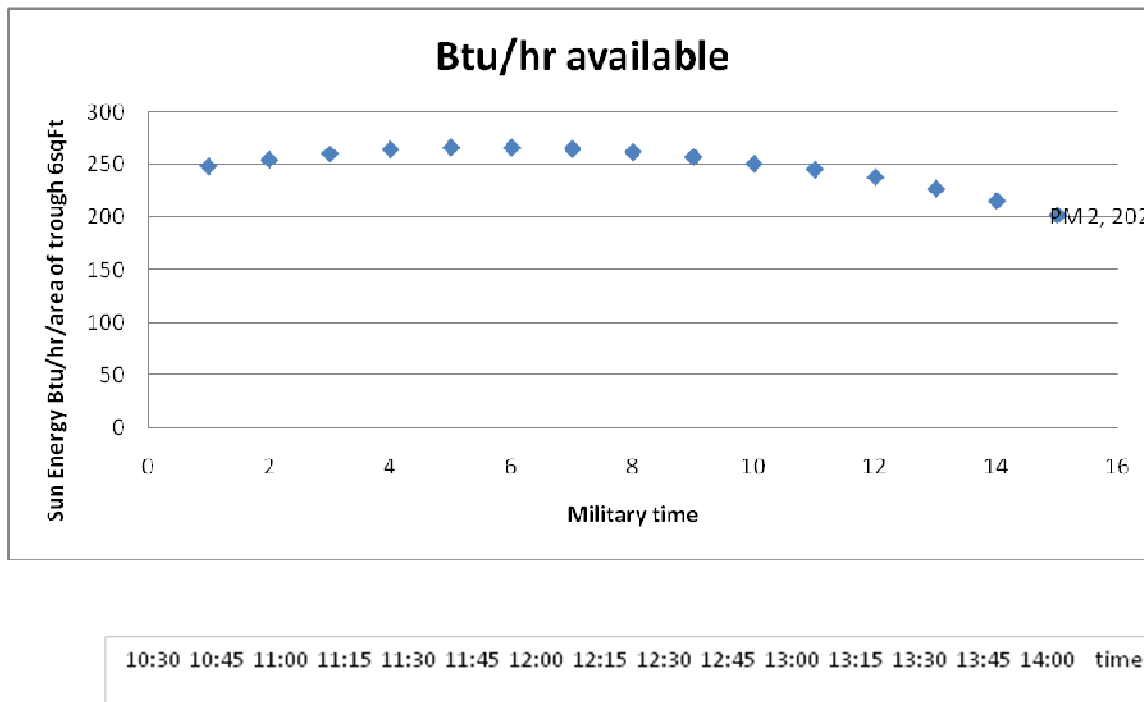


Figure 4: The energy of the sun available for this area of trough on Nov 15th midday.

Some days, only one coupon was used for a several hour duration, such as Nov. 18th. The points we can correlate with the pyranometer are on the quarter hours.

We did not detect the difference in intensity from 11 to noon. We see it in the pyrheliometer data, but not in ours. Nov 18 the difference between the outlet and inlet temperatures were 8.7, 8.65, and 8.3 at half hour intervals as sun intensity decreased in the early afternoon.

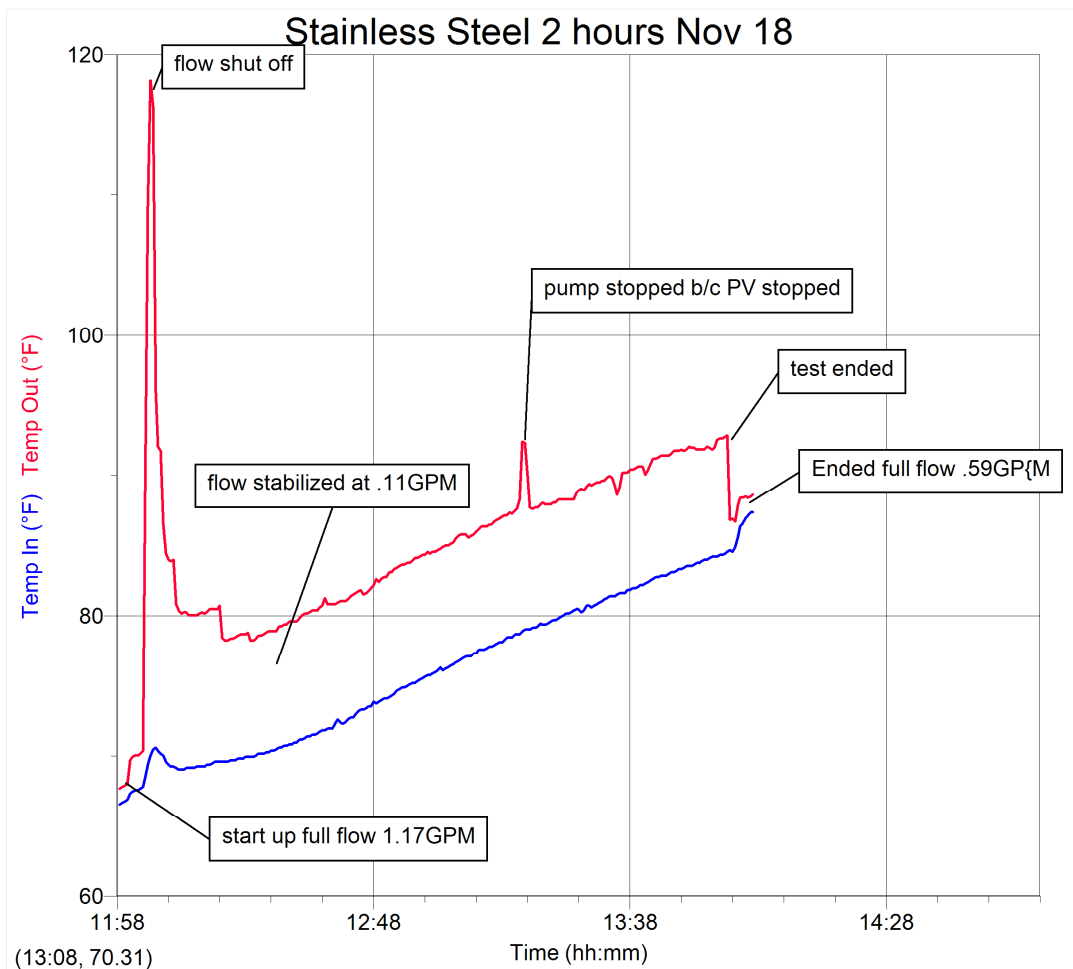


Figure 5: Graph of data collected Nov 18

Advice was received from veteran solar experimenter Roger Davenport. “PV panel is troublesome because sun heat varies.” So, the electrical supply varies. This was found true. The 12 volt battery from the hobby shop was not strong enough to run the 12 volt pump by itself. The 12 volt PV panel could not always make the pump work, or sometimes just a trickle. Together in series, the battery and PV panel held the pump strong so that we could vary the flow by closing the valve.

Mr. Davenport also warned against measuring flow electronically. Too much time is consumed calibrating by timing water running into a graduated cylinder. In September he advised, “I

recommend a bucket and a stop watch.” Which is what we did. Flow was measured consistently.

Design of Experiment

Several weeks were invested in learning to use our equipment, and designing the experiment. Although it was discussed to test for only 30 seconds, polishing the mirrors, checking the aim, controlling the water flow, aiming, voltage, writing notes into journal, aiming and computer display always took at least 10 minutes.

Alignment

More sun is reflected on this absorber when its axis is aligned East to West, which was the case during November testing. With the same flow rate and the same reflectors, the two alignments were tested on November 15th. The heat into the water just from inlet to outlet was almost twice as much with the East to West axis as the North to South. See Fig. 6.

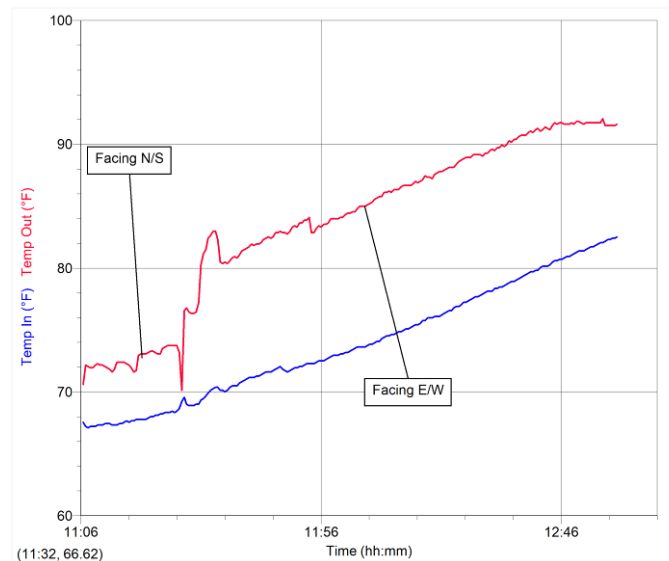


Figure 6: Notice much greater temp difference when the trough long axis was oriented East - West.

To attempt to hold variables steady, various strategies were employed.

- All three types of panels were tested on the same day.
- Water flow was held down to 0.1 gallon/minute.
- Testing was only done on sunny days.
- Mid-day sun before 2 pm used for intensity.

- On Nov 18th the amount of water in the tank was increased to make the inlet temp as flat a curve as possible.
- All testing during Pacific Standard Time, none during Daylight Savings Time was considered.

These restrictions contributed to the steady state conditions.

Hours of data were collected. Small increments of 2 to 5 minutes were reported. The data on Fig. 7 was selected for flow stability. The standard deviation within the collection is less than 1, meaning flat graphs. Where other things were equal, the data was selected to straddle the quarter hours. The pyranometer on campus only records on the quarter hour. Following is the raw data from November in Fig. 8 A & B

Simple temperature increase in water traveling over three feet of copper pipe showed heat transferred to the working fluid. The best reflective material was reflective film, stainless steel was next and chrome powder coat delivered a little more than half the heat from the 3M film as determined from Fig. 7 and other observations.

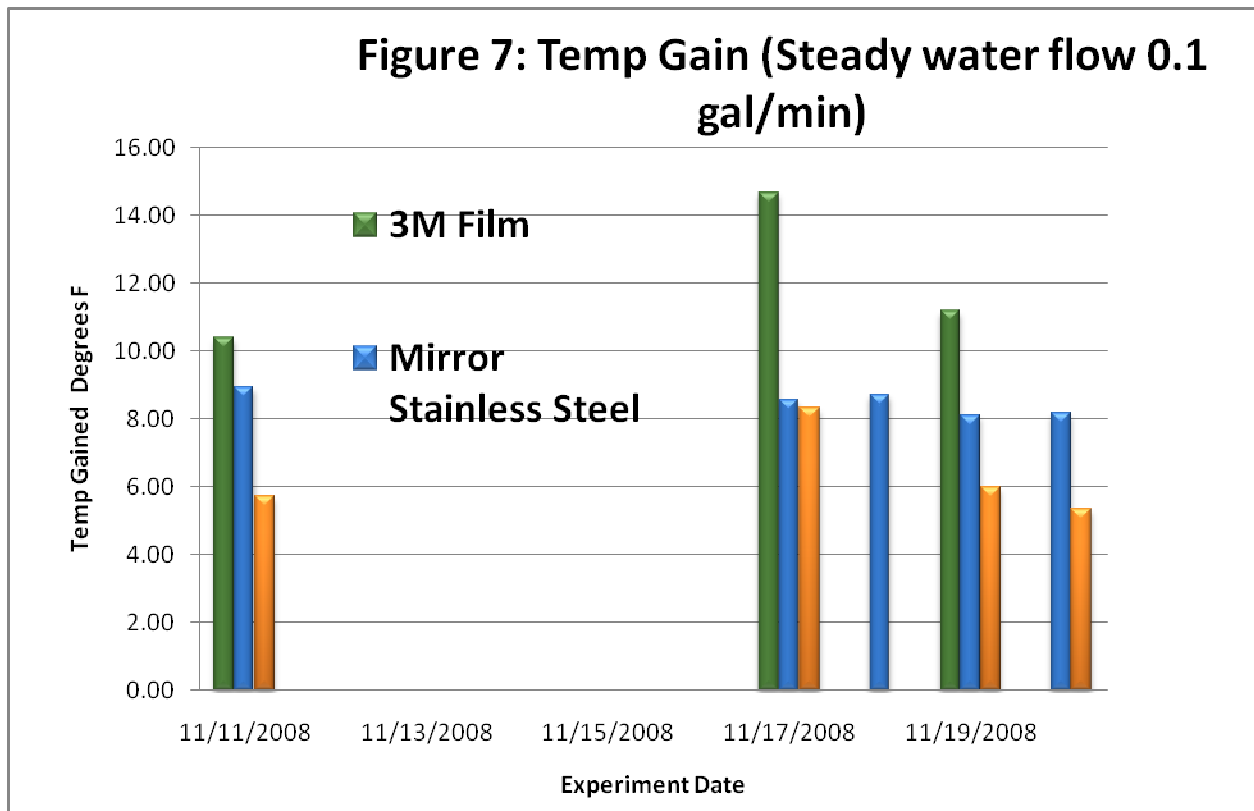


Figure 8A All the data in Date order

Coupon	Date	flow gpm	TempIn Min [F]	TempIn Max	Duration [s]	Start time	data points	Inlet Temp Std Dev	Inlet mean Temp	Outlet Mean Temp
SS	11/7/2008	0.11								
PC	11/7/2008	0.10				12:40	11		76.2	87.9
3M Film	11/7/2008	0.09			300	13:42	10		83.7	92.4
3M Film	11/8/2008	0.21				10:45			70.6	75.3
PC	11/8/2008	0.20			296	11:15	10		75.0	78.5
SS	11/8/2008	0.20			321	11:58	11		80.7	85.8
PC	11/11/2008	0.11	64	64.2	122	12:12	244	0.07	64.1	69.8
SS	11/11/2008		59	59.2	150	11:28	300	0.05	59.2	68.2
3M Film	11/11/2008	0.11	69	68.9	129	12:57	258	0.01	68.8	79.2
ss	11/15/2008	0.11				11:59	11		73.3	84.4
ss	11/15/2008	0.10				12:29	11		78.2	89.5
SS	11/16/2008	0.36	71	71.6	125.5	11:30	251	0.08	71.4	74.4
PC	11/16/2008	0.71	79	79.4	151.5	12:29	303	0.10	79.2	82.3
3M Film	11/16/2008	0.17	83	82.7	98	13:06	196	0.04	82.6	90.1
SS	11/17/2008	0.11	85	85.1	148	12:58	296	0.07	84.9	93.5
PC	11/17/2008	0.12	80	80.2	72	12:15	144	0.04	80.0	88.4
3M Film	11/17/2008	0.11	75	75.4	210	11:41	421	0.17	75.1	89.8
SS	11/18/2008	0.12				12:28	11		70.9	79.6
SS	11/18/2008	0.12				12:58	11		76.1	84.7
SS	11/18/2008	0.11				13:55	4		84.3	92.6
SS	11/19/2008	0.12	70	70.1	138.5	11:45	277	0.04	70.0	78.2
PC	11/19/2008	0.12	74	74.1	123	12:30	246	0.05	74.0	79.9
3M Film	11/19/2008	0.11	76	75.9	94	12:54	188	0.01	75.8	87.0
SS	11/20/2008	0.12	71	71.0	82.5	12:34	165	0.06	71.0	79.2
PC	11/20/2008	0.10	73	73.4	124	13:02	248	0.09	73.2	78.6
3M Film	11/20/2008	0.17	67	67.2	109	11:59	218	0.07	67.0	74.0

Figure 8B All the data in Date order continued									
Coupon	Date	Temp Spread	Outlet TMin	Out Tmax	Outlet Temp StdDev	air Temp	zenith angle	Battery Parallel w/ PV [Volts]	
SS	11/7/2008	7.0				70		13.11	
PC	11/7/2008	11.7				72		12.30	
3M Film	11/7/2008	8.8				74		13.18	loose film
3M Film	11/8/2008	4.7							loose film
PC	11/8/2008	3.6							
SS	11/8/2008	5.1							
PC	11/11/2008	5.7	69.7	9.9	0.08	72		15.53	
SS	11/11/2008	9.0	67.9	68.3	0.10	73		14.81	
3M Film	11/11/2008	10.4	79.0	79.5	0.11		54	14.49	
ss	11/15/2008	11.1						15.42	
ss	11/15/2008	11.3							
SS	11/16/2008	3.0	74.3	74.5	0.04			17.02	
PC	11/16/2008	3.1	82.1	82.4	0.10		51	14.24	
3M Film	11/16/2008	7.5	90.1	90.4	0.08		54	14.34	
SS	11/17/2008	8.6	93.2	93.7	0.11			15.85	
PC	11/17/2008	8.3	87.9	88.6	0.17			15.54	
3M Film	11/17/2008	14.7	89.5	90.3	0.18				
SS	11/18/2008	8.7				76		16.18	
SS	11/18/2008	8.7				76			
SS	11/18/2008	8.3				76		15.35	
SS	11/19/2008	8.1	78.0	78.4	0.06				
PC	11/19/2008	6.0	79.9	80.0	0.04		53		
3M Film	11/19/2008	11.2	86.9	87.0	0.06		57		
SS	11/20/2008	8.2	79.0	79.3	0.06		53		
PC	11/20/2008	5.3	78.4	78.8	0.13		55		
3M Film	11/20/2008	7.0	73.9	74.2	0.09	69			

	A	B	C	D	E	F	G	H
1	Fig. 8C: Sunshine Energy to Hot Water Energy							
2	Testing with old, scratched film-coated panels			Assume water non-compressible				
3	12:18 - 13:38 pm Sunday Oct 19, 2008			Assume complete mixing in tank				
4	12:19 'til 13:14 pm considered here			Assume no thermal stratification in tank				
5	Wispy high cloud reduced intensity around 12:30			Assume Constant density				
6	Clear, blue sky by 1 pm							
7	Energy Balance Calculator (Enter Data into yellow squares)							
8								
9	US Customary Units							
10	6 sq ft					sq ft	6.0	
11	1 atm							
12	density at 25 C (77 F)					lbm/cf	62.2	
13	density at 70 F (20 C) [3]						62.2	
14	Heat Capacity Cp at 300K [kJ/Kg*C] [2]							
15	Heat Capacity Cp at 90F [+A15Btu/(lbm F)]+A39					Btu/(lbm F)	1.0	
16	Inlet Water Temp at beginning						69.5	
17	Inlet Water Temp at end						75.5	
18								
19	deltaT						6.0	
20	Tank volume circulating					gal	6.8	
21						cubic ft	0.9	
22	Mass is vol x density					lbm	56.1	
23								
24	Heat transfer = Q = mass cp ΔT							
25							336.8	Btu
26							0.1	Btu/s
27								
28	[2] Incropera p 949							
29	[3] Cengel. Themo & HT 1997 p 888 p 846							

ASHRAE Standard Testing

ASHRAE standard testing is defined for an equilibrium state within 50 degrees of the ambient. The wind speed should lie between 2.2 and 4.5 m/s (5 and 10 mph) (ASHRAE 93-2003 5.3.1.1.5). The quasi-steady-state conditions are maintained for the 5 minute test period and a 10 min interval prior to the test period. The heat transfer fluid flow rate remains fixed for all data points. The recommended mass flow rate per aperture area for a liquid fluid is 0.02 kg/s-m^2 ($14.7 \text{ lb}_m/\text{hr-ft}^2$). An exception is made for collectors which are designed for special flow rates. These collectors should operate with their design flow rates (ASHRAE 92-2003, 8.3.1.1.6). The flow rate shall be maintained constant at the recommended flow rate within $\pm 0.005 \text{ gpm}$ ($0.000315 \text{ liter/sec}$). (ASHRAE 93-2003, 8.3.3.3).

Solar Collector Operation Instructions

Since $Q_{\text{Dot}} = m_{\text{Dot}} c_p \Delta \text{Temp}$, diligently make m_{Dot} , the water mass flow, a constant.

- Only test one material at a time
- Wait until steady state
- Same measured time span for various tests

Quick Start

- Add measured amount of water
- Measure pump flow
- Start Temperature readings
- Insert Reflecting Coupons
- Start computer record
- Aim
- Stop before water boils.

CAUTION: When the water is not flowing, the solar collector must be turned from the sun to prevent over-heating the thermocouples.

Technical Specifications Thermocouple Go!Temp by Vernier.com

- USB Specification: 1.1
- Range: -20°C to 110°C
- Maximum temperature that the sensor can tolerate without damage: 130°C
- Resolution: 0.07°C
- Accuracy: $\pm 0.5^\circ\text{C}$
- Response time: 4 s (to 90% of full reading in water)

Software

The Logger Pro software from Vernier.com combines real-time graphing, powerful analytical tools, video analysis and other features. The software Logger Pro 3.6.1 detects the Go!Temp thermocouple automatically.

The probe is capable of reporting change after 4 seconds. The software can take hundreds of readings per second, but that frequency is unnecessary. A single reading per second is sufficient. Units cannot be changed during data collection.

File > Open > Tutorial > Getting Started.

Software Setup

> Experiment > Change Units > Go!Temp:1 > °F

> Experiment > Data Collection > Collection

- Mode: Time Based
- check: Continuous Data Collection
- one sample/second
- Done

Instead of the long way >Experiment > Start Collection use the space bar to toggle data gathering.

Beware: The laptop turns off the screen display in its attempt to save energy. Touching the space bar to light up the display starts a new collection and loses the running one.

Once a nicely labeled graph is set up, reuse it with “Save as”.

Rotate the collector one quarter turn of the hand wheel each 3 minutes or sooner. The shadow of the absorber should line up with the center line. When the shadow has traversed the center line, it is time to roll again. Readjust the direction of the PV panel too.

When the pump is working correctly, four red lights glow. If it quits, try adjusting the PV panel first. If clouds have reduced the incoming energy, the pump can stop. Protect the thermocouples from overheating by rolling the trough away from the sun until the pump works again. The flowing water is a coolant. Boiling water is a hazard to be avoided.

Save to Disk

You must use File > Save each time.

Naming convention: type reflector-Month Day-time-operator’s initials

Choose **Store Latest Run** from the **Experiment** menu, saves the most recently collected data in memory allowing you to collect additional data without losing a previous run.

The run labeled **Latest** always contains the most recently collected data and is overwritten when you collect more data. When you store the Latest run, a new data set named Run 1, Run 2, etc. is created and the values of the Latest Data Set are moved to it.

Columns in the latest data set are drawn with bold lines on the graph, while other columns are drawn with thin lines.

Note: Choosing Store Latest Run does not save data to the file, nor will it preserve your data between sessions or when you turn off your computer. You must choose [Save](#) from the **File** menu to save your data.

Shut Down

To prepare for transport:

- Remove the water from the tank.
- Disconnect the solar PV Panel wires.
- Remove the T-Connectors holding the thermocouples.
- Cut the plastic zip ties on the absorber.
- Nestle the absorber in the long box in the bubble wrap.
- The absorber mount brackets can be wound in if necessary for transport, but that necessitates realignment at the next location.
- Remove the coupons.
- Individually wrap them to prevent scratching.

Hazards to System

- Freezing destroys pipes
- Hard water scale ruins valves
- Overheated non-metal components degrade
- Reflective Surfaces easily scratched
 - Decreased efficiency
- Reflective Surfaces get dirty from air pollution
 - Decreased efficiency

Hazards to People

- Scalding
- Eye Damage from concentrated sunlight

Methodology

Different designs for the prototype stand were considered. The design was chosen on the basis that the reflective surfaces could be replaced, the parabolic trough can pivot to the sun's rays, a reservoir and solar pump could be used to pump water through the absorber, and all of it would be contained in a transportable stand. Figure 9 is the design chosen through the initial process.



Figure 9: Solar collector prototype.

Stand

Fabricating the stand required many specialized skills; CAD drawing skills, sheet metal skills, machinist skills, pipefitting skills, and welding skills. The design of the stand was done in SolidWorks, a computer aided design program (CAD). Finite element analysis (FEA) of the frame was also done in the SolidWorks program Cosmos. The FEA justified the use of 6061 aluminum 2 inch square tubing for the frame. See Fig. 10. With a load of 200 pounds the material deformation was within the tolerance required. Material was purchased at an industrial metal supply store. Aluminum is purchased by the pound so the price per pound is reduced by purchasing in volume. Square tubing comes in 21 foot lengths. Nominal cuts were done at the store, to make transport to the San Diego State University Machine Shop (SDSU shop) easier.

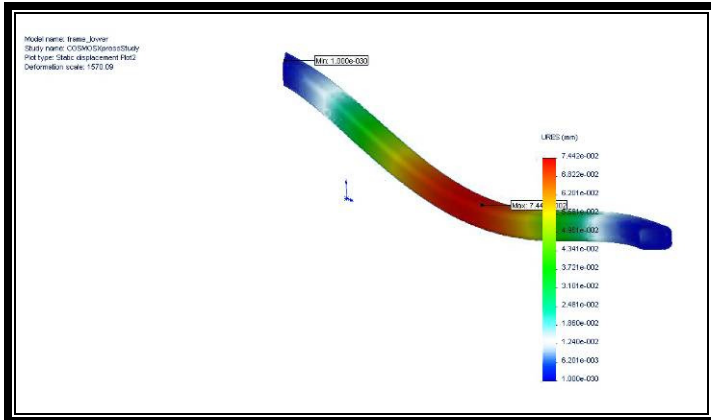


Figure 10: FEA lower frame.

The material was off loaded at the SDSU shop. To cut the angles for the framework, a jig was made for the chop saw with a carbide blade to accommodate the various angles. Otherwise only simple angles could be cut. See Fig. 11.



Figure 11: Chop saw and angle jig.

Welding

A wooden jig for welding was fabricated out of particle board for assembling the square tubing into the A-frame shape. See Fig. 12. The advantage of this procedure was to assure that the two frame ends were similar and limit the amount of movement during welding. The cut material was deburred and prepared for welding by removing the top layer of aluminum, using a disk sander. This reduces the amount of oxidation present during the welding process.



Figure 12: Welding jig fabricated from particle board.

The SDSU shop supplied a Hobart Cyberwave 300 for tig welding. Radnor tungsten electrodes and argon gas was purchased from a local dealer, to use with the tig welding.

Tig welding setup:

- Set the Hobart welder for alternating current,
- Continuous weld
- 125 max amperage
- The part is grounded to complete the circuit

Argon gas is used (at a rate of 15 psi) to keep the impurities away from the parts while they are being welded and is introduced where the tungsten tip meets the parts. A push pedal is used to increase or decrease amperage to the electrode thereby increasing or decreasing heat to the weld. Once the portion being welded achieves a shiny or molten state the weld rod is introduced. The movement of the tungsten and argon gas at the molten state while adding rod produces a well penetrated weld. Normally this movement is done from right to left and is completed by releasing the pedal and holding the gas on the part until it stops. See figure 13.



Figure 13: SDSU welding area.

Jigs and clamps are then used as necessary to keep your parts from moving, during welding. The clamps are adjusted, using a flat surface, when aligning the fixture. Most alignment is done by eye, as tolerance permitted. See figure 14. By properly measuring, cutting and fabricating jigs, our need for more expensive alignment tooling was not needed.



Figure 14 Alignment and clamping before welding.

Pivot

The pivot and coupon holders required CAD skills, machinist skills, jig and fixtures skills and alignment skills. We started by designing the parabolic shape. We initially chose 12 inch by 12 inch panels (hereby called coupons) to attain the parabolic shape, and then we designed to accommodate those coupons. The parabola equations and parabolic arc length equations were put into a spreadsheet and a chart was created. See Table 1. We were able to view the parabolic shape, the foci point and the arc length by changing the p value. See Fig. 15. The parabola values were used in SolidWorks when designing the coupon holders.

Table 1 Parabola

Input Value for Parabola in yellow box						
$4*p=$	20.91	inches				
x	$4*p=$	y	p = focus			
-20.00	20.91	19.13	5.23			
-19.75	20.91	18.65	5.23			
arc length ABC						
a	b	a^2	b^2	sqrt	ln	Total
5.2275	20.91	27.32676	437.2281	29.57121	0.881374	24.00
$\text{arc length } ABC = \frac{1}{2} \sqrt{b^2 + 16a^2} + \frac{b^2}{8a} \ln \left(\frac{4a + \sqrt{b^2 + 16a^2}}{b} \right)$						
$y = \frac{1}{4p} x^2$						

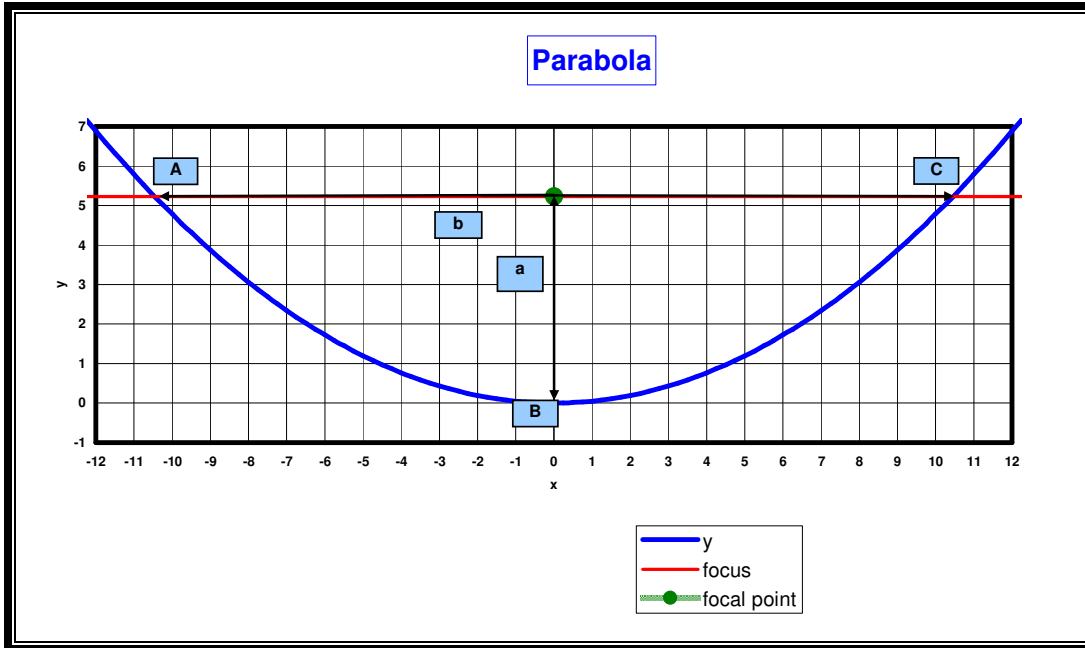


Figure 15: Excel chart of parabolic curve

An FEA analysis was done in SolidWorks; Cosmos verified that aluminum 2024 would perform as needed in this application, as a coupon holder. Very little deflection was noted during extreme loads. See Fig. 16.

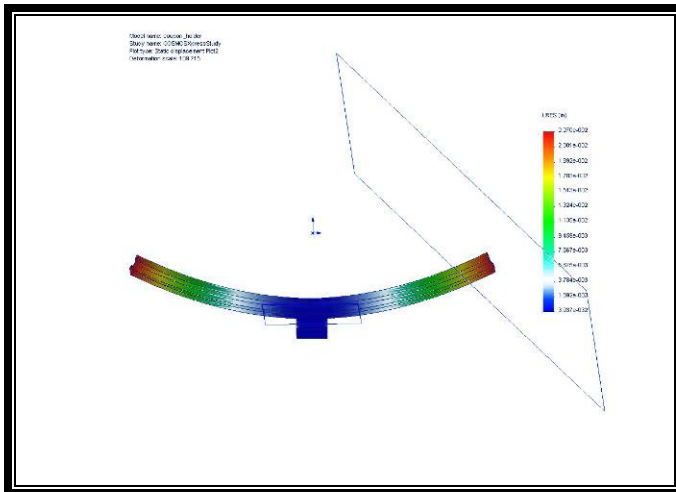


Figure 16: FEA of coupon holder.

The coupon holder CAD drawings were converted to another file (g file) compatible with the computer numerical control mill (hereby called CNC). These files are then manipulated, using appropriate software, to achieve the desired effect on the CNC. See Fig. 17

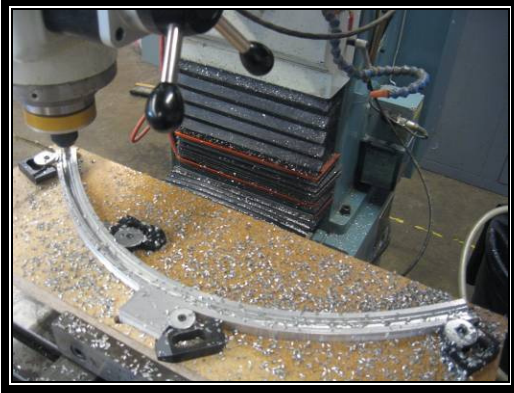


Figure 17: CNC machining of the coupon holder.

There were other parts associated with the coupon holder and pivot which required precision machining. The skill required to square a vise involves mounting the vise to a mill table so the face of the vise is perpendicular to Y axis or the X axis. Mount a dial indicator to the spindle with the probe facing away from you. Move the axis perpendicular to the fixed jaw of the vise into the indicator until the dial revolves one half revolutions. Zero the indicator and transverse the axis you are trying to achieve perpendicularity to, while keeping the indicator on the face of the vise. Upon reaching the other end notice how much the indicator has moved and in which direction. Move the vise to remove half of that movement. Zero the indicator again and transverse to the other end. Verify that the indicator maintains zero movement.

There is also another skill requiring machining a block of material so that all sides are square. Find a side that has a good surface and put it against the rear vise jaw. Using a circular bar hold the part and tighten the jaws. Machine the top surface using a mill and turn the part upside down to machine the other surface. With two sides parallel, hold them in the jaws and again machine the top surface. Rotate the part again to machine the bottom surface. Rotate the part and machine the other surfaces.

These skills came in useful when fabricating the pivot. To get the best stability for the assembly, the coupon holder was mounted into the 1/8 wall thickness of the 2 inch square tubing of the pivot. This required the machining the wall thickness perpendicular to the length and sides of the square tubing. See Fig. 18. A hole for the bolt of the coupon holder, coming up from underneath, was then machined directly in the middle of the wall thickness cut. The remainder of the pivot parts required use of the previous machining skills; a square block had to be machined for a slip-fit and inset into the end of the square tubing to support the pivoting shaft.

A keyway was machined into the shaft to properly work with the gearbox.



Figure 28: Curved coupon holder inset into pivot.

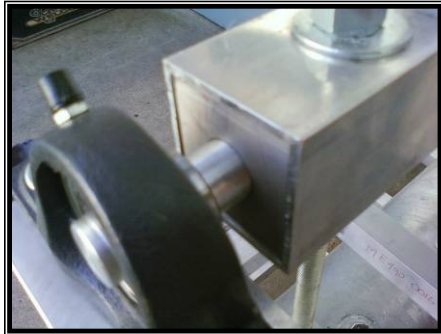


Figure 19: Pivot and shaft support.

Absorber

The absorber seemed like the most difficult portion of our project, although it was simple to assemble once the parts were designed. The main intention in designing this absorber was to limit the amount of heat loss. Once the reflected rays from the sun entered the focus area, they were trapped. The copper tubing surface was coated with an especially absorbent black 3M tape. The glass tubing to encase the copper pipe was difficult to find. We anticipated extreme temperatures in this area so standard glass wouldn't work. Only through Butler Sun Solutions were we able to find Pyrex tubing the diameter and length that we needed. These were donated.

The next design problem required mounting thermocouples to either end of the tubing. This was done with a Swegelok device called a compression tee, which allows for easy removal during transportation. See Fig. 20.

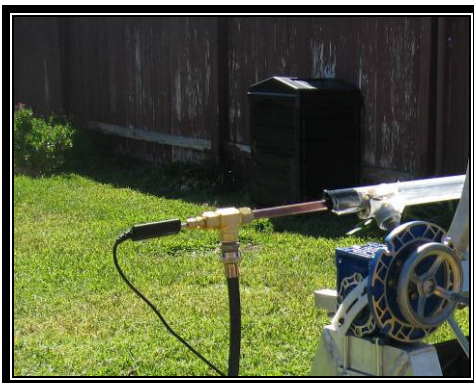


Figure 30: Absorber, tee, and thermocouple

Prototype Assembly

The assembly of the prototype went smoothly, according to the design. A reduction gearbox 30:1 was purchased off of the internet from a company that sells salvaged machinery parts. It can track the sun at the rate of 12 degrees for every turn of the hand wheel. This also allows for a motor to later be attached should a solar tracker be needed. A pillow block bearing suspends the other end of the pivot. These two devices were aligned and installed on either end of the frame. The reservoir was attached using left over square tubing, cut at 45 degree angles, mounted to the lower shelf and clamped to the tubing. The plumbing for the reservoir was ½ NPT pipe fittings using various nipples, elbows, tees, adapters and plugs. The pump used is a 1 GPM DC pump using a 10 watt photovoltaic panel for power in conjunction with a globe valve at the discharge end.


The absorber was cleverly attached to the pivot by means of a tube holding device which allows for accurate alignment of the absorber directly at the foci of the parabola.


Since the black hose kept the flow rate a mystery, clear hose was installed.



Figure 24: Prototype

QTY/ASSEMBLY		ITEM	PART #	DESCRIPTION	SIZE	MATERIAL	COST	VENDOR	VENDOR P/N	EXTENDED
-01			ASSYSCA-01	COLLECTOR, SOLAR						
	-02									
		-03								
4				CASTER, WHEEL	3" WHEEL	STEEL	\$6.31	MCMASTER	22785T48	\$25.24
1				BATTERY		LEAD	\$18.00			\$18.00
1				VOLT METER			\$54.00	PROTEK	6300	\$54.00
1				WELDING GAS	40 CU FT.	ARGON	\$80.00	AIRGAS		\$80.00
1				WELDING ROD		TUNGSTEN	\$60.00	AIRGAS		\$60.00
1				WELDING JIG	5/8 X 4 X 8	WOOD	\$30.00	HOME DEPOT		\$30.00
2			ME490 0008	FRAME, END	2 X 2 X 152	ALUM 6061	\$72.00	IMS		\$144.00
1			ME490 0010	FRAME, SHELF, BASE	2 X 2 X 158	ALUM 6061	\$76.00	IMS		\$76.00

 COLLEGE OF ENGINEERING <i>Department of Mechanical Engineering</i>									
Project: Solar Reflectivity Assembly: Solar Collector Prototype									
Bill of Materials									
Document number: BOMPA002 Rev: A									
QTY/ASSEMBLY	ITEM	PART #	DESCRIPTION	SIZE	MATERIAL	COST	VENDOR	VENDOR P/N	EXTENDED
-01									
	-02								
		-03							
	4		PVC	1 1/8 "	PVC	\$1.00			\$4.00
	1		ME490 0004	GLASS TUBE	1.5" X 36"	GLASS	\$59.00	B. BUTLER	\$59.00
	1			CROSS	3/4" NPT	STEEL	\$3.50	ACE HDWRE	\$3.50
	6			NIPPLES	3/4" NPT	BRASS	\$3.00	ACE HDWRE	\$18.00
	6			PLUG	3/4" NPT	BRASS	\$3.00	ACE HDWRE	\$18.00
	1			TUBING	3/8 X 5	COPPER	\$11.00	ACE HDWRE	\$11.00
	2			TUBING		VINYL	\$3.50	ACE HDWRE	\$7.00
	4			HOSE BARB		BRASS	\$4.00	ACE HDWRE	\$16.00
	4			HOSE CPLING		BRASS	\$3.00	ACE HDWRE	\$12.00
	1			RECEIVER		STEEL	\$240.00	MCMMASTER	\$240.00
	2			SWEGLOK TEE		BRASS	\$18.00	SDFST	\$36.00
	2			SWEGLOK REDUCER		BRASS	\$9.00	SDFST	\$18.00
	1			VALVE, BALL	1/2 NPT	BRASS	\$25.00	ACE HDWRE	\$25.00
	1			VALVE, GLOBE	1/2 NPT	BRASS	\$35.00	ACE HDWRE	\$35.00
	1			PUMP, HOT WATER, PV		SS	\$228.67	IVAN	Ei-Sid-PV-10 \$207.75
	1			PANEL, SOLAR	10.7X16.5X1.13	PH VOLTAIC	\$106.70	POWER UP	BSP-1012 \$207.75
	2			PROBE, THERMOCOUPLE	0.15625 DIA.	SS	\$39.00	VERNIER	GO TEMP \$78.00

 COLLEGE OF ENGINEERING <i>Department of Mechanical Engineering</i>									
Project: Solar Reflectivity Assembly: Solar Collector Prototype									
Bill of Materials									
Document number: BOMPA003 Rev: A									
QTY/ASSEMBLY	ITEM	PART #	DESCRIPTION	SIZE	MATERIAL	COST	VENDOR	VENDOR P/N	EXTENDED
-01									
	-02								
		-03							
	4		ME490 0003	COUPON, HOLDER		ALUM 2024	\$60.00	IMS	\$240.00
	1		ME490 0011	FRAME, PIVOT	2X2X48	ALUM 6061	\$23.00	IMS	\$23.00
	2		ME490 0012	PIVOT	1.75 X 1.75 X 4	ALUM 2024	\$20.00	IMS	\$40.00
	1			GEARBOX		ALUM	\$140.00	MOTOVARIO	V040 \$140.00
	1			PILLOW BLOCK BEARING		STEEL	\$30.00	MARSHALL	\$30.00
	1			CRANK WHEEL	3/4 X 4 1/2	ALUM	\$13.50	MARSHALL	\$13.50
	50			THUMBSCREW	1/4 X 20	STEEL	\$0.38	MARSHALL	\$19.00
	1			MACHINE TOOLING		TOOL STL	\$60.00	D&D TOOL	\$60.00
	2			ALLTHREAD	1/2 X 24	STEEL	\$3.50	ACE HDWRE	\$7.00
	4			NUT	1/2 "	STEEL	\$0.25	ACE HDWRE	\$1.00
	4			WASHER	1/2 "	STEEL	\$0.20	ACE HDWRE	\$0.80
	6		ME490 0015	COUPON,STAINLESS	12 X 12	STAINLESS	\$5.00	HOME DEPOT	\$30.00
	7		ME490 0015	COUPON,POWDERCOAT	12 X 12	1020 STEEL	\$30.00	GOODRICH	\$210.00
	6		ME490 0015	COUPON,MYLAR	12 X 12	ALUM	\$10.00	NIELSEN ENT.	10 MIL \$60.00
	6		ME490 0015	COUPON,3M	12 X 12	ALUM	\$10.00	BUTLER	3 MIL \$60.00
	1		ME490 0014	BEARING MOUNT	1.5 X 3 X 6	ALUM 2024	\$10.00	IMS	\$10.00

The Bill of Materials

The Bill of Materials in three pages lists purchased products and manufactured parts which were acquired for almost \$2,500:

Fig.	Welded Al Frame, battery, photovoltaic panel
Fig.	Absorber glass tubing, hosing, pump
Fig.	Machined parabolic coupon holder, coupons, gearbox

Reflectivity Rank	Cost /sf	Durability [years]
Acrylic Silver Film (1)	\$2.29	5-7
Mirrored Stainless Steel	\$13.33	10
Chrome Powder Coat	\$31.00	10

The cost included one dollar for a square foot for very thin steel plate for both film and powder coat.

Observation

Oct 20, 2008, the solar trough was under the tarp, in the full sun on a warm morning. When uncovered, the reflective aluminum surfaces were cool to the touch, but the copper tubing was warm. Therefore, the sun's energy was going through the tarp. The trough is an infrared detector.

Sources of Error

- Galvanized steel gets hot in the sun. It does not reflect very well. Absorption alpha = 65% per Incropera [Fundamentals of Heat and Mass Transfer. 2007 p956]. The water tank was in the sun, uninsulated, gathering heat. During some tests we used a reflective patio awning cloth to shield the computer and tank from the sun. But we did not record which days.
- The thermocouples had limited sensitivity.
- Flow rate changed too randomly. The steady state conditions defined in the ASHRAE 93-2003 Standard are very challenging. Our flow rate was perhaps steady to one decimal place for 5 minutes, but never to ± 0.005 gpm over a duration.
- Accidentally standing in front of the PV made the pump slow or stop.

- The magnetic pump stalled completely if the electricity was interrupted. A disconnect was required to restart. While the pump was not working, the thermocouples were in danger with the high temperatures.
- Human errors in starting and stopping the test left flow rate timing vulnerable to criticism. Meticulous procedures made flow rate measurement accurate to one second and a quarter ounce. $.25 / 128 \text{ ounce} = \pm 0.002 \text{ gallon}$.
- The highest source of error was neglecting to aim the rig promptly as the sun moved in the sky.
- The sun changes in intensity. The power source varied even more when we tested during minor wispy cloud conditions.
- Although the literature warned of problems with the film layers separating, and told of many chemicals applied to the edges to prevent such things, none were used. The film panels had some minor delamination.
- Computer data was lost at least once.
- No automated sun tracking was installed. For very short duration measurements, no harm done.

Challenges

The high tech central absorber tube described by 2 companies on the internet was not commercially available in quantity of one. While choosing materials, an acrylic tube for the absorber was debated. This material expands when heated, but it is supposed to transmit the electromagnetic waves, not absorb them. Glass tubing was received from Butler Sun Solutions, thank you.

The black tape on the absorber copper tube slowly deformed during October, bubbling up on one edge. The tape was removed and the tubing painted flat black before the November testing began. High temperature tolerant spray paint was used. So October results were different than November by that physical ability to absorb.

The glass tube around the copper tubing showed condensation throughout all testing, at the beginning each morning.

During the precious few hours of maximum sunlight, swapping out the panels took too long. There were 8 thumb screws for 6 panels to loosen and then tighten. Ideas for redesign include:

- Springs pressing on each thumbscrew spot, tightened by one hinge mounted fastener
- reflective surfaces the size of two coupons, 2' x 1' instead of 1' x 1'

Revised roof mount idea into movable experimental test rig.

All parts were custom made.

Although the original plan included glass mirrors, they can only be custom made in parabola shape. We did not order them.

Successes

Meticulous data collection was quite successful.

The literature suggests the frame should be inclined South at the same angle as the latitude, 33° , but horizontal was chosen. During October testing with the frame long axis North to South, it was observed that six inches of the absorber were never lit because of the angle of reflection. Testing with the frame long axis East to West allowed the full length of the absorber to be lit. This orientation was used during November testing.

The Go!Temp thermocouples and Vernier software Logger Pro3.6.1 were incredibly easy to use. The instantly produced graphs and single button statistics allowed the time to collect more data, instead of hours of number crunching.

There were no injuries.

Manufacturing went smoothly.

We are still friends.

Many thanks are extended to the donors and suppliers.

Conclusion

A reflectivity test device in the shape of a solar collector was designed and fabricated. Each very thin reflective panel (coupon) easily bends into the parabolic trough shape. The highly radiation absorbent central receiver is delicate glass tubing concentrically surrounding a copper pipe. Electronic sensors measure the changing water temperature before and after it flows inside the central receiver. Many minutes of data were collected from each material. Water temperature does increase in the absorber.

Four reflective materials have been tested, including extremely polished stainless steel, 3M reflective film on steel base, chrome powder coat and Solatube aged reflective film on aluminum. Least cost is the driving metric. Manufacturability, durability and low weight are other main criteria. Reflective film is so much cheaper than the metals that cost of labor to replace it is the deciding factor. If thin glass mirror could be found below \$3/sf, it would be the best choice.

Testing is finished. The old, scratched reflective film on aluminum was the best. Among the three known materials, the best reflective material was 3M reflective film on aluminum (even $1/10^{\text{th}}$ delaminated). The stainless steel ranked second and powder coat chrome delivered the least heat and they were more expensive.

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http://www.solel.com/products/pgeneration/tkey_fields/ Feb 25, 2008
- Solel <http://www.solel.com/faq/> 2/14/08

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TEL: (619) 297-3705

Appendix A: Solar Literature Review

TOPIC	AUTHOR	SOURCE	PAGE NUMBER OR WWW
Absorber Design. Collector efficiency is higher for lower overall temp gain, as found with higher flow velocity. Concentrating collectors defined.	Glasstone, Samuel	<u>Energy Deskbook</u> Van Nostrand Reinhold Co. 1983	330-334
Brief history of parabolic trough commercial installations, SEGS 1984 – 1990	Boyle, Godfrey	<u>Renewable Energy</u> Oxford Press. 2004	55
Standard Test Conditions for PV. Air Mass 1.5 has a electromagnetic energy distribution of sun at 48 degrees from zenith	Boyle, Godfrey	<u>Renewable Energy</u> Oxford Press. 2004	70
Solar Energy Equipment Chapter When circulation pump stops, fluid drains for freeze protection. Don't run "cool" water into empty collector in peak solar conditions, to avoid thermal stress on equipment. Collector efficiency equations Protect steel tank against electrochemical corrosion with a sacrificial anode of magnesium (inspected annually). Copper fittings corrode a steel tank. Heat loss from tank 2% in 12 hr. Liquid expansion may burst pipes if overheated during low usage. Wind and Snow loading are support structure concerns.		2004 ASHRAE Handbook HVAC Sys and Equip	33.2-18
Standard Calc Method: Solar collector efficiency		Directory of SRCC Certified Solar Collector Ratings	1-30
San Diego 33 degree tilt better than Flat		Array Technologies WattSun.com	www

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Solar Energy Applications	Kutz	<u>Mechanical Engineers'</u> Handbook Wiley 1998 p1408	
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Radiative transfer for BlackBody	Siegel	<u>Thermal Radiation Heat Transfer</u>	
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